FLUXGATE MAGNETOMETER DATA PROCESSING FOR CLUSTER

F G M – D A P C L U S

CL–IGEP–SN–0001

Data Processing Handbook

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Preface

Compared to other magnetospheric missions the magnetic field experiment on the Cluster S/C is of primary importance, having a key role in the overall scientific concept of the mission. Therefore, the data processing of the Magnetic Field Investigation (FGM) Experiment is a task of greatest importance.

It is the intention of this documentation to provide a detailed description of scientific, software, and hardware aspects of the Cluster FGM experiment as far as data processing and data distribution are concerned. This handbook aims to describe the physical and mathematical principles of the FGM measurements, their inherent errors, and the attemps which have been made to remove them from the actual observations.

This documentation will be developed during the Cluster mission and it will be updated depending on the stage of development of the FGM data processing. It will contain material from different sources, either from already published material or original work from different members of the FGM team. Appropriate references are made where necessary to outline the primary source of information included.

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1	2	December, 1993	vector timing added
1	3	February, 1994	calibration procedure added
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Acronyms

ADC	Analog Digital Converter
ASCII	American National Standards Institute
BB	Body Build (Coordinate System)
BSD	Burst Science Data
CAB	Cluster Acquisition Byte
CD-ROM	Compact Disc - Read Only Memory
CDDS	Cluster Data Disposition System
CoC	Center of Coil
Co-I	Co-Investogator
CSDS	Cluster Science Data System
DDID	Data Delivery Interface Document
DDS	Data Disposition System
DP	Data Processing
DPWG	Data Processing Working Group
EDI	Electron Drift Instrument
EGSE	Electrical Ground Support Equipment
EID	Experiment Interface Document
EM	Engineering Model
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
FGM	Magnetic Field Investigation (Fluxgate Magnetometer)
FS	FGM Sensor (Coordinate System)
FSR	FGM Spin Reference (Coordinate System)
GSE	Geocentric Solar Ecliptic (Coordinate System)
HKD	Housekeeping data
IC	Imperial College (London)
IGM	Institut für Geophysik und Meteorologie (Braunschweig, Germany)
LSB	Least Significant Bit
LTEF	Long Term Event File
LTOF	Long Term Orbit File
MSB	Most Significant Bit
N/A	Not Applicable
NSD	Normal Science Data
OBDH	On-board Data Handler
OS	Orthogonalized Sensor (Coordinate System)
PI	Principal Investigator
RDM	Raw Data Media
SATT	Spacecraft Attitude and Spin Rate
S/C	Spacecraft
SCET	Spacecraft Event Time
SCS	Spacecraft-Sun (Coordinate System)
SR	Spin Reference (Coordinate System)
SRP	Sun Reference Puls
STEF	Short Term Event File
STOF	Short Term Orbit File
TU-BS	Technische Universität Braunschweig
U	Unit (Coordinate System)
UCLA	University of California at Los Angeles
UTC	Universal Coordinated Time

Chapter 1 Theoretical Aspects of the Measuring Process

1.1 Introduction

The main purpose of the raw data processing is the conversion of the digital data words, which have been measured by the FGM instrument and transferred to the ground stations via the S/C's telemetry, into time stamped magnetic field vectors in a scientific coordinate system.

For a better understanding of the physical and mathematical principles of such a measurement we shall develop in this chapter an analytical description of the various distortions of the magnetic field information from the true ambient magnetic field vector represented in an inertial frame of reference to the digital data words delivered to the telemetry system of the S/C. The purpose of this description is twofold. First, it is intended to define all those processes and effects which have influenced the actual measurements, and which must be regarded when doing the inverse transformation during data processing. Second, the construction of simulated data is facilitated according to this description.

This chapter is divided into three sections. The first one is concerned with the coordinate transformation of the magnetic field vector from the inertial system to the sensor aligned coordinate system. The conversion of the magnetic field values into digital data words is described in the second part. In the last part we introduce a simplified model that will be used for routine data processing.

1.2 The Coordinate Transformations of the Magnetic Field Vector

The data received from the FGM are inherently influenced by the actual positions and look-directions of the sensors which vary due to several causes e.g. S/C attitude, spin, boom motions. This can be described by one general coordinate transformation. We will split this general transformation into several steps for a better understanding of the various effects. After each transformation the magnetic field vector will be represented in another coordinate system.

Before describing the individual transformation steps, we will start with an introduction of the various coordinate systems used for the transformations.

1.2.1 Definition of the Coordinate Systems

Unless otherwise stated the described coordinate systems are all right handed and Cartesian.

The following coordinate system have all the centre of the S/C as their origin except for the GSE system, where the centre of Earth is the origin. However, we can assume for all coordinate systems the same origin, because the maximum distance between Earth and S/C (20 R_E) is negligible compared with the distance Sun – Earth. The maximum error of this assumption is about

$$\arctan(20R_E/150.E6\text{km}) = 8 * 10^{-4}\text{rad} = 0.05\text{deg}. \quad (1.1)$$

The FGM Sensor Coordinate System (FS)

The axes of the FGM Sensor Coordinate System are determined by the true directions of the sensor components. This system is not Cartesian because of small deviations from orthogonality due to inaccuracies in the alignment of the magnetometer sensors.

The sensor axes - X_{FS}, Y_{FS}, and Z_{FS} - have been denotated in such a way that they are nominally aligned to the axes of the Spacecraft Mechanical Build System after mounting and when the boom is deployed. The resulting denotations of the Sensor Coordinate System together with the Unit Coordinate System and the Unit Reference Frame System - both described in section 1.2.1 - can be seen in figure 1.1.

The Orthogonalized Sensor Coordinate System (OS)

The Cartesian Orthogonalized Sensor Coordinate System has been derived from the FGM Sensor Coordinate System and is defined as follows

X_{OS}-axis:	same as the X_{FS}-axis
Y_{OS}-axis:	lying in the $X_{FS}Y_{FS}$-plane (roughly aligned with the Y_{FS}-axis)
Z_{OS}-axis:	completing the system (roughly aligned with the Z_{FS}-axis)

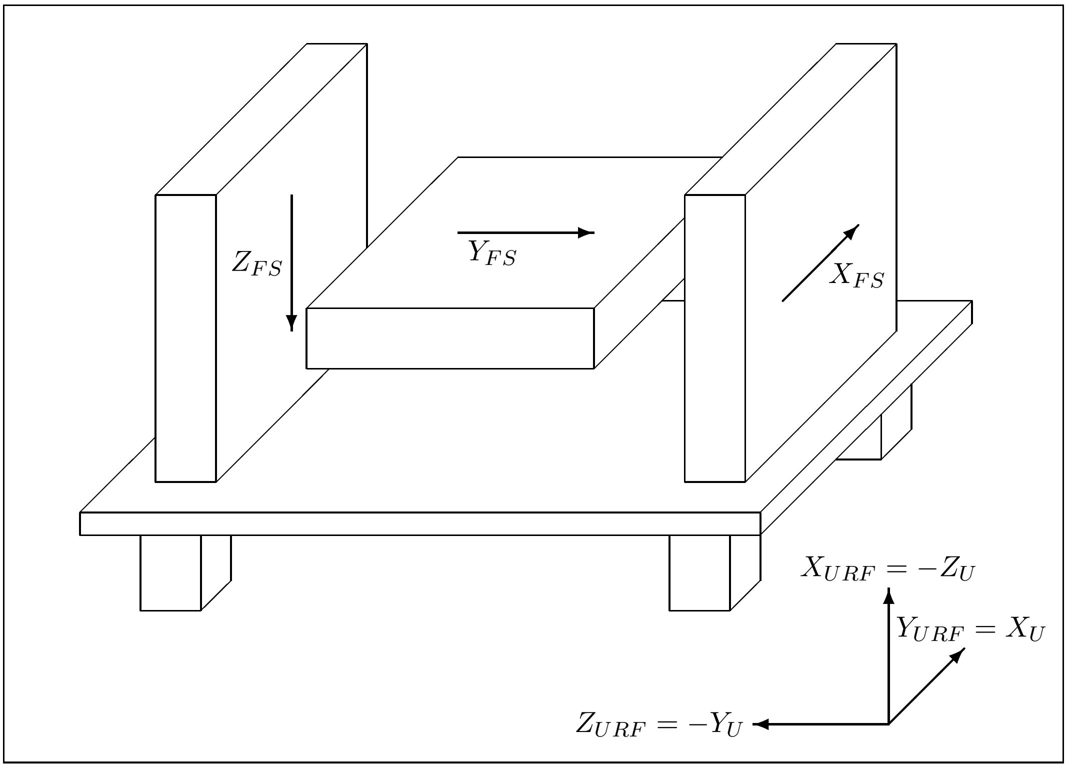

Figure 1.1: *Denotations of FGM Sensor Coordinate System (X_{FS}, Y_{FS}, Z_{FS}), Unit Coordinate System (X_U, Y_U, Z_U), and Unit Reference Frame System ($X_{URF}, Y_{URF}, Z_{URF}$)*

The Unit Coordinate System (U)

The Unit Coordinate System is used to describe the position of the complete magnetometer unit with respect to the Spacecraft Mechanical Build Axes. The axes are defined by the outer geometric form of the magnetometer unit or - this should be the same - by the normal to the faces of the mirror cube which has been rigidly but removably fixed to the legs of the unit during calibration tests.

The axes of the Unit Coordinate System - X_U, Y_U, and Z_U - have been denotated in such a way that they nominally aligned with the Spacecraft Mechanical Build Axes unlike the definition of the Unit Reference Frame (URF) System which is given in [EID Part A], section 2.5.2.1. The different denotations of Unit Coordinate System and URF System are shown in figure 1.1.

Note that the three coordinate systems – Sensor System, Orthogonalized Sensor System, and Unit System – are different for inboard and outboard magnetometer.

The Body Build Coordinate System (BB)

The Body Build System is identical with the Spacecraft Mechanical Build System defined in [EID Part A], section 2.1.1.1. The axes are fixed relative to the S/C geometry, forming a right handed orthogonal coordinate system.

The X_{BB}-axis is the nominal spin axis and the spin direction shall be clockwise around the X_{BB}-axis (looking in the positive X_{BB}-direction). The definition of the Y_{BB}- and the Z_{BB}-axis can be inferred from the figures 2.1.1.a and 2.1.1.b of [EID Part A].

The Spin Reference Coordinate System (SR)

The Spin Reference Coordinate System as defined in [DDID] is aligned with the maximum principal inertia axis and therefore suitable for description of the spin phase. Its definition is

Z_{SR}-axis:	maximum principal inertia axis of the S/C which is the spin axis when nutation and oscillations have been damped out (near to the X_{BB}-axis)
X_{SR}-axis:	normal to Z_{SR} in the plane defined by X_{BB} and Y_{BB}
Y_{SR}-axis:	completing the right handed system

The Spacecraft-Sun Coordinate System (SCS)

The SCS System is a despun version of the Spin Reference Coordinate System. It is used to describe the attitude of the S/C and is defined as follows

Z_{SCS}-axis:	same as Z_{SR}-axis (maximum principal inertia axis)
X_{SCS}-axis:	intersection of the X_{SR}-Y_{SR}-plane with the meridian cantaining the Sun, i.e. the axis points in the general direction of the Sun in the plane defined by the spin vector and the spacecraft-sun line
Y_{SCS}-axis:	completing the right handed system

Note that the SCS System is identical with the SR2 System used in [Hapgood 94].

The Geocentric Solar Ecliptic Coordinate System (GSE)

The output vectors of the FGM data processing are represented in the GSE Coordinate System which is defined as follows

X_{GSE}-axis:	pointing from the Earth towards the Sun
Y_{GSE}-axis:	lying in the ecliptic plane pointing towards dusk
Z_{GSE}-axis:	pointing towards the ecliptic north pole

Algorithms for coordinate transformations from the GSE System to other scientific coordinate systems like GEI or GSM are well defined and can for example be found in [Hapgood 92].

An illustration of the coordinate system in the course of the year is given in figure 1.2.

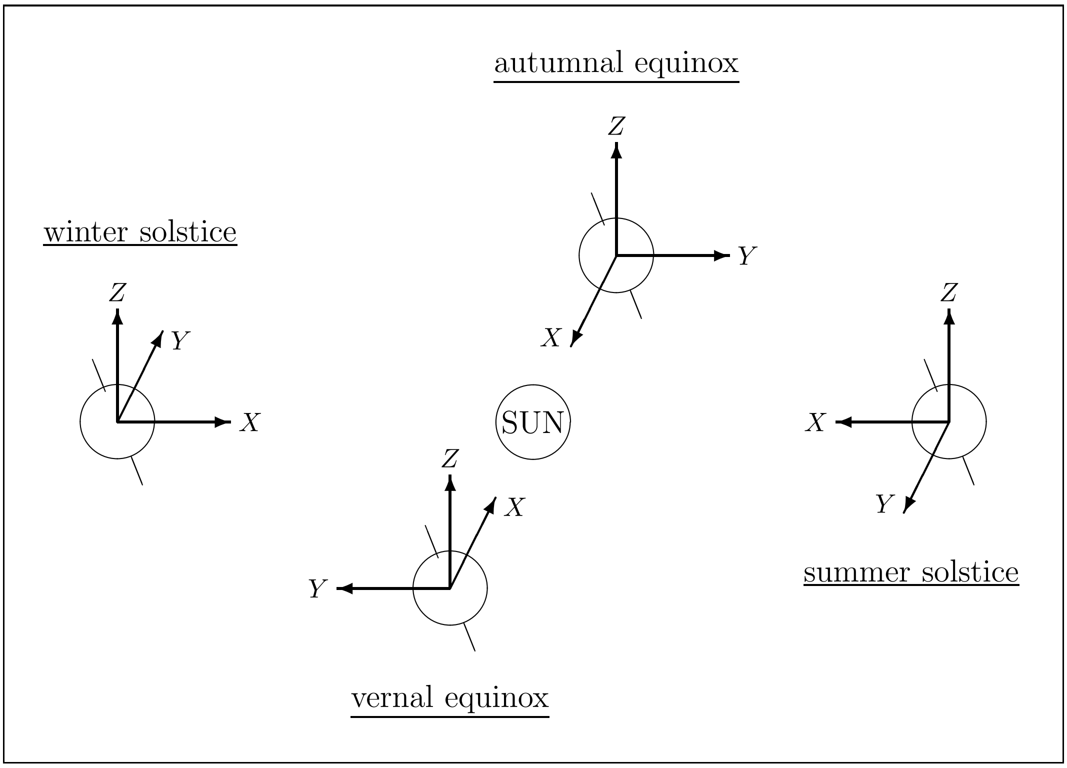

Figure 1.2: *The Geocentric Solar Ecliptic Coordinate System*

1.2.2 The Individual Transformation Steps

After the definition of the required coordinate systems, we can now start to describe the individual transformation steps of a magnetic field vector from an inertial frame of reference to the coordinate system defined by the look-directions of the sensors.

For each transformation we will give the quantities the transformation depends on. This will be helpful to understand the data processing, when we have to do the inverse transformations.

From the GSE to the Spacecraft-Sun-System

All Cluster S/C will have their spin axes pointing roughly toward ecliptic north. So we introduce the Cartesian GSE Coordinate System as the required inertial system. Another reason for this choice is the fact that the final science data shall be represented in the GSE System.

Note that this system is not strictly an inertial system, but has a yearly rotation relative to a true inertial system. Nevertheless, the Z_{GSE}-axis may be considered to be fixed in inertial space.

The transformation is completely defined by the actual attitude of the spin axis, i.e. declination δ and right ascension α of the spin axis, and the fact that the direction from satellite to the Sun, i.e. the X_{GSE}-axis, lies in the X_{SCS}-Z_{SCS}-plane. This is shown in figure 1.3.

From Spacecraft-Sun to Spin Reference System

Since the SCS System is the despun version of the SR System, the transformation is a simple rotation around the common Z axis by the spin phase of the S/C φ:

$$\underline{\mathrm{H}}_{SR} = \begin{pmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix} \underline{\mathrm{H}}_{SCS} \tag{1.2}$$

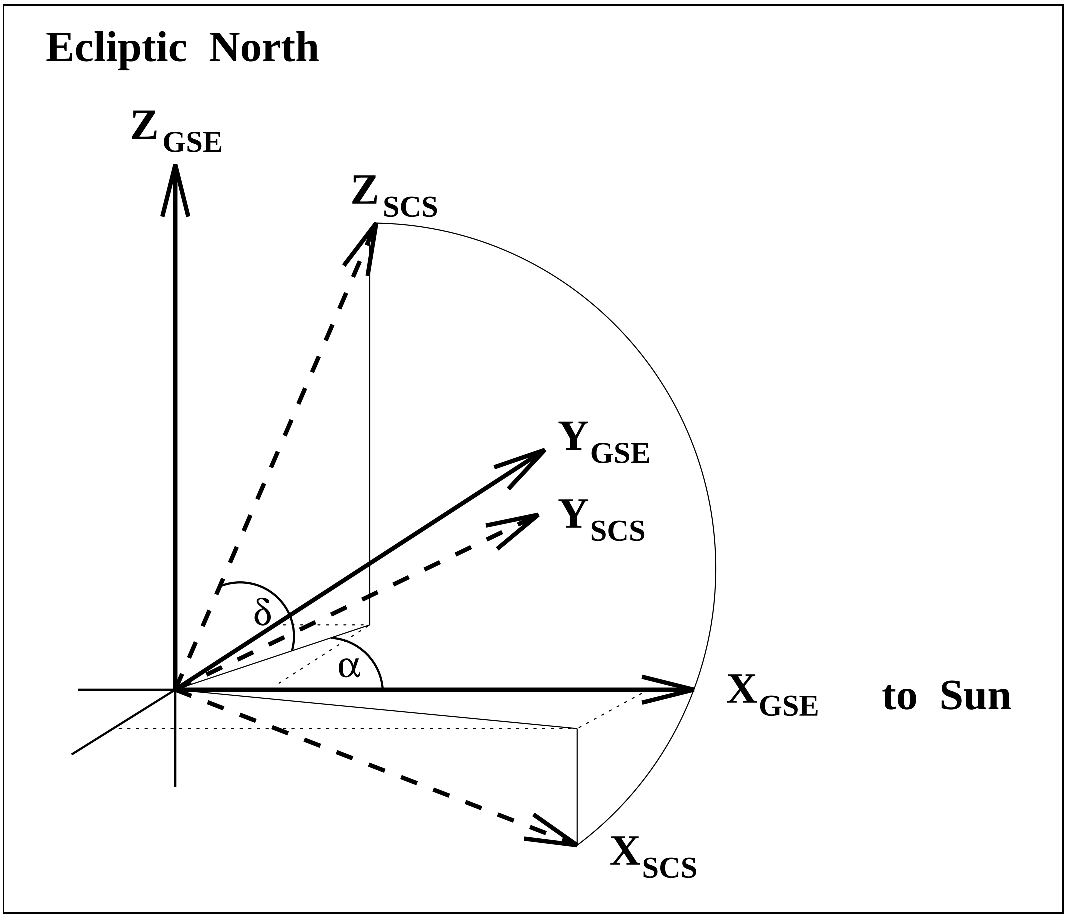

Figure 1.3: *The situation of the SCS System with respect to the GSE System (δ = declination, α = right ascension of the spin axis Z_{SCS})*

According to [DDID], Appendix I, the spin phase of the S/C is defined as:

Rotation angle of the half-plane defined by the maximum principal axis of inertia and the $+Y_{BB}$-axis, around the maximum principal axis of inertia from the time when the Sun direction was contained in this plane.

The determination of the spin phase independent of the FGM measurements is essential for the evaluation and interpretation of the data. Without knowing the correct spin phase neither necessary in-flight data corrections nor three-dimensional interpretation of the data can be carried out.

From Spin Reference to Body-Build System

The X_{BB}-axis is nominally aligned to the spin axis, but the real spin axis, the Z_{SR}-axis, will be the maximum principal axis of inertia. The translation from the SR to the BB System is obtained by two simple rotations as illustrated in figure 1.4.

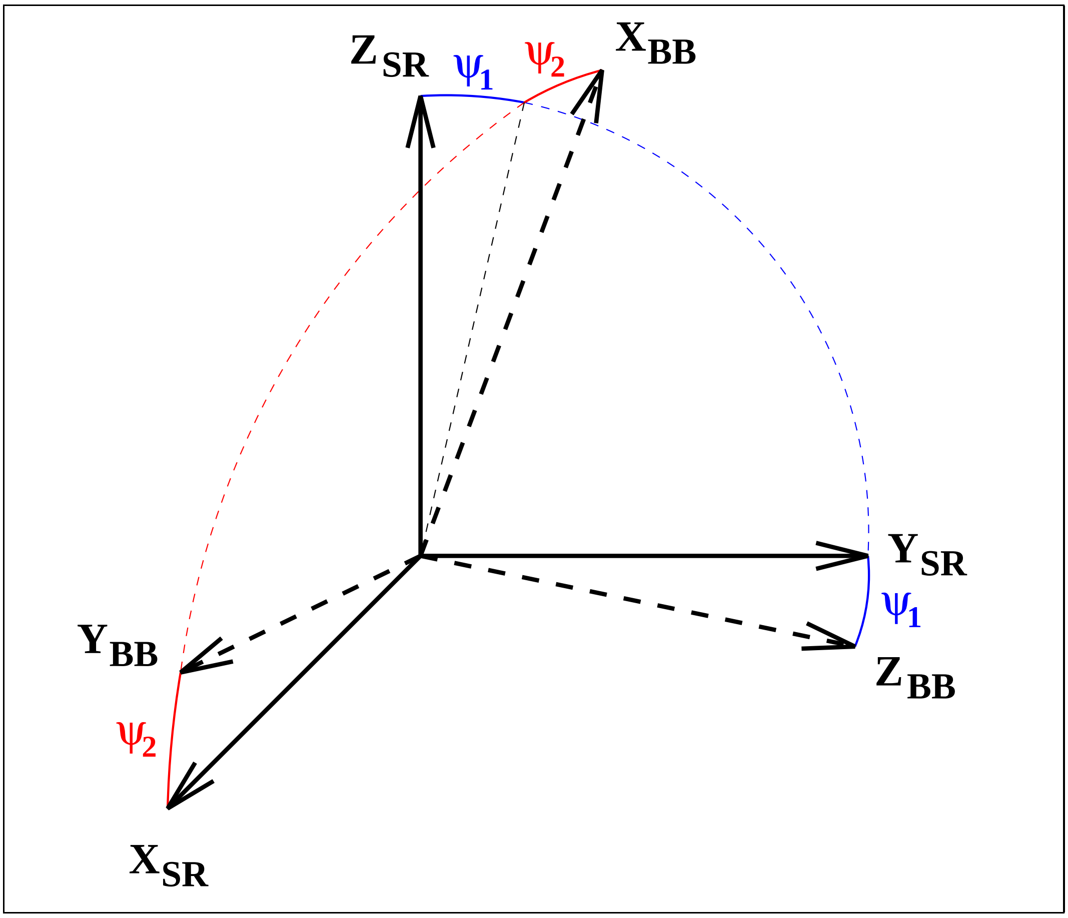

Figure 1.4: *The situation of the BB System with respect to the SR System*
ψ_1, ψ_2: rotation angles describing the deviation of actual spin axis (Z_{SR}-axis) and nominal spin axis (X_{BB}-axis)

The angles have been chosen according to the denotations used in [DDID], Appendix I. Note that the Body-Build System is roughly aligned with to the Spin Reference System, but has a different notation of the axes. The transformation matrix can easily be calculated by a multiplication of the two simple rotation matrices and a matrix changing the denotation of the axes:

$$\underline{\mathrm{H}}_{BB} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \cos\psi_2 & 0 & -\sin\psi_2 \\ 0 & 1 & 0 \\ \sin\psi_2 & 0 & \cos\psi_2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_1 & -\sin\psi_1 \\ 0 & \sin\psi_1 & \cos\psi_1 \end{pmatrix} \underline{\mathrm{H}}_{SR}$$

$$\underline{\mathrm{H}}_{BB} = \begin{pmatrix} -\sin\psi_2 & -\cos\psi_2\sin\psi_1 & \cos\psi_2\cos\psi_1 \\ \cos\psi_2 & \sin\psi_2\sin\psi_1 & \sin\psi_2\cos\psi_1 \\ 0 & \cos\psi_1 & -\sin\psi_1 \end{pmatrix} \underline{\mathrm{H}}_{SR} \quad (1.3)$$

From the Body-Build to the Unit System

This transformation is concerned with the positions of the FGM sensor boxes within the Body-Build System of the S/C. Both FGM units are fixed equally to the outer part of one rigid boom in such a way that (after mounting) the plane of the box containing the mounting lugs nominally coincides with the plane spanned by the X_{BB}-axis and the direction of the outer part of the boom.

The nominal static alignment of the deployed boom is perpendicular to the X_{BB}-axis with its outer part inclined by an angle ϑ of 6.5°clockwise towards the $-Y_{BB}$-axis. This is illustrated in figure 2.1.1.c of [EID Part A].

The position of the sensor boxes will, of course, be affected by boom motions. According to recent informations concerning the possible boom motions it will take more than one day after a flight manoeuvre until the alignment of the boom is within the specifications.

Assuming an ideally mounted box the transformation when no boom motions are considered is defined by

$$\underline{\mathrm{H}}_{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta & -\sin\vartheta \\ 0 & \sin\vartheta & \cos\vartheta \end{pmatrix} \underline{\mathrm{H}}_{BB} \quad (1.4)$$

Note that the transformation matrices for the inboard and the outboard sensor unit will become different and will get a more complicated form, if the real positions of the mounted boxes, boom motions out of the spin plane, or torsion or bending of the boom are taken into account.

From Unit to Orthogonalized Sensor System

The alignment of the Orthogonalized Sensor System with respect to the Unit System can be described by the three rotation angles λ, μ, ν (ref figure 1.5).

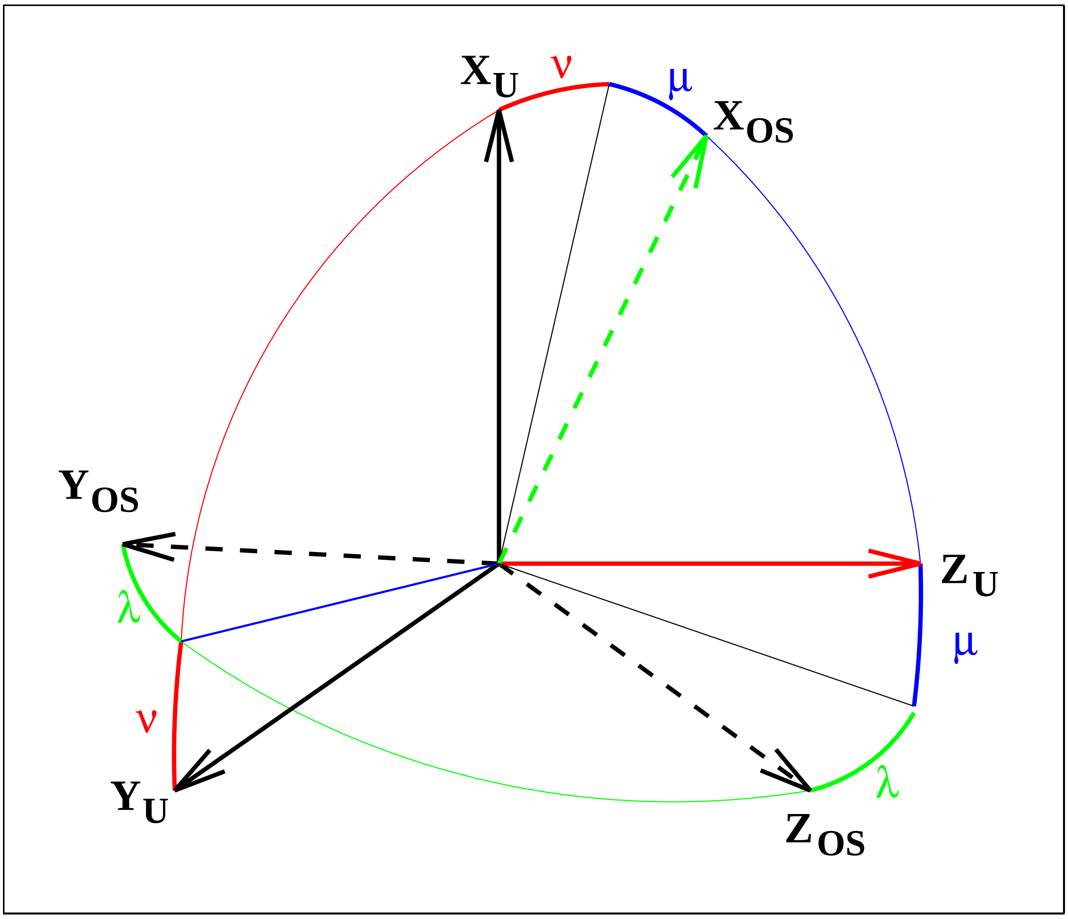

Figure 1.5: *The situation of the Orthogonalized Sensor System with respect to the Unit System*

The matrix for the transformation of vectors from Unit System to Orthogonalized Sensor System can be gained by multiplication of the three Euler rotation matrices.

$$\underline{\text{H}}_{OS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\lambda & -\sin\lambda \\ 0 & \sin\lambda & \cos\lambda \end{pmatrix} \begin{pmatrix} \cos\mu & 0 & \sin\mu \\ 0 & 1 & 0 \\ -\sin\mu & 0 & \cos\mu \end{pmatrix} \begin{pmatrix} \cos\nu & -\sin\nu & 0 \\ \sin\nu & \cos\nu & 0 \\ 0 & 0 & 1 \end{pmatrix} \underline{\text{H}}_U \tag{1.5}$$

From Orthogonalized Sensor to FGM Sensor System

According to the definitions of the coordinate systems, the transformation can be described by three alignment angles β, γ, η or by the three angles defining the internal alignment between the axes of the Sensor System $\chi_{xy}, \chi_{xz}, \chi_{yz}$ (ref figure 1.6).

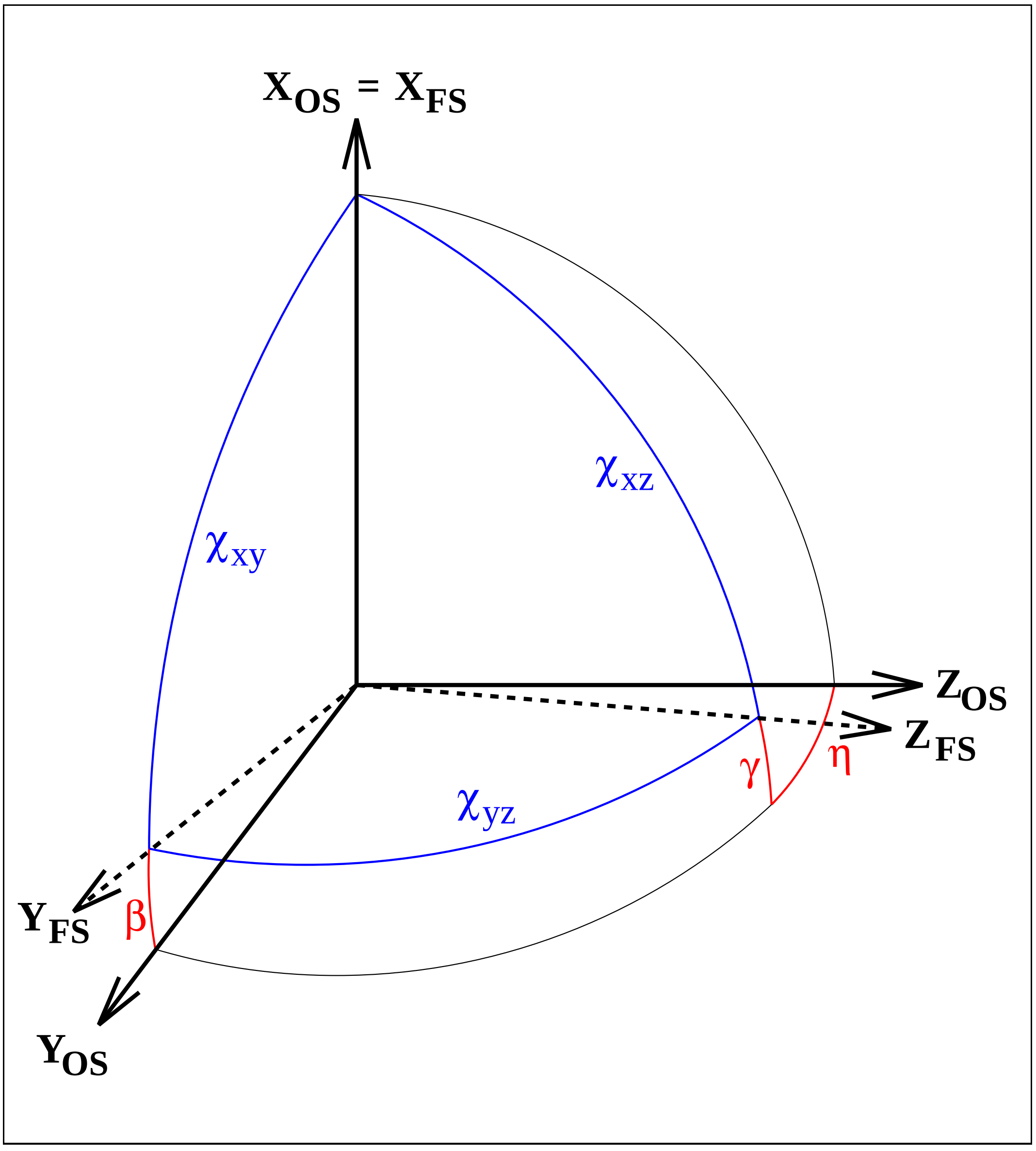

Figure 1.6: *The situation of the FGM Sensor System with respect to the Orthogonalized Sensor System*

Between these angles exist the following relations:

$$\cos\chi_{xy} = \sin\beta \tag{1.6a}$$
$$\cos\chi_{xz} = \sin\gamma \tag{1.6b}$$
$$\cos\chi_{yz} = \sin\beta\sin\gamma + \cos\beta\cos\gamma\sin\eta. \tag{1.6c}$$

The transformation of a vector from the Sensor System to the Orthogonalized Sensor System is given by the equation

$$\underline{\mathrm{H}}_{OS} = \begin{pmatrix} 1 & \sin\beta & \sin\gamma \\ 0 & \cos\beta & \cos\gamma\sin\eta \\ 0 & 0 & \cos\gamma\cos\eta \end{pmatrix} \underline{\mathrm{H}}_{FS} \tag{1.7}$$

Inversion of the matrix yields

$$\underline{\mathrm{H}}_{FS} = \begin{pmatrix} 1 & -\frac{\sin\beta}{\cos\beta} & \frac{\sin\beta\cos\gamma\sin\eta - \cos\beta\sin\gamma}{\cos\beta\cos\gamma\cos\eta} \\ 0 & \frac{1}{\cos\beta} & -\frac{\sin\eta}{\cos\beta\cos\eta} \\ 0 & 0 & \frac{1}{\cos\gamma\cos\eta} \end{pmatrix} \underline{\mathrm{H}}_{OS} \tag{1.8}$$

The angles defining this transformation are different for inboard and outboard unit, but are assumed to be stable during flight.

Summary of the Individual Transformation Steps

The transformation of a magnetic field vector from the GSE System to the sensor aligned FGM Sensor System has been split up into six single transformations to illustrate the various distortions. To get one overall misalignment matrix $\underline{\underline{\mathrm{M}}}_{FS-GSE}$ describing this transformation

$$\underline{\mathrm{H}}_{FS} = \underline{\underline{\mathrm{M}}}_{FS-GSE}\ \underline{\mathrm{H}}_{GSE}\ , \tag{1.9}$$

we have to multiply the individual transformation matrices

$$\underline{\underline{\mathrm{M}}}_{FS-GSE} = \underline{\underline{\mathrm{M}}}_{FS-OS} \cdot \underline{\underline{\mathrm{M}}}_{OS-U} \cdot \underline{\underline{\mathrm{M}}}_{U-BB} \cdot \underline{\underline{\mathrm{M}}}_{BB-SR} \cdot \underline{\underline{\mathrm{M}}}_{SR-SCS} \cdot \underline{\underline{\mathrm{M}}}_{SCS-GSE}$$

We have to notice that the matrices $\underline{\underline{M}}_{FS-OS}$, $\underline{\underline{M}}_{OS-U}$, and $\underline{\underline{M}}_{U-BB}$ are different for outboard and inboard magnetometer unit and that the matrices $\underline{\underline{M}}_{U-BB}$, $\underline{\underline{M}}_{BB-SR}$, $\underline{\underline{M}}_{SR-SCS}$, and $\underline{\underline{M}}_{SCS-GSE}$ vary more or less with the time.

1.3 Conversion of the Magnetic Field Values into Digital Data Words

The conversion of the magnetic field values into digital data words consists of two parts: the conversion of the magnetic field values into voltages by the magnetometer sensor and the following conversion of the voltages into digital data words by the Analog/Digital-Converter (ADC).

The following considerations will be made for one triaxial sensor unit. They can equally be applied to the outboard as well as to the inboard magnetometer unit.

1.3.1 From Magnetic Field Values to Voltages

The voltage output of a real magnetometer sensor seeing a field component $\mathrm{H}_{FS}(t)$ will be given by the scale factor K, the sensitivity S (also often called 'gain'), the frequency transfer function $T(f)$ of the corresponding impulse response function $G(t)$, the zero-offset ZO of the magnetometer, and noise contributions UN due to digitization and residual sensor noise:

$$U(t) = K\,S \int_{-\infty}^{t} \mathrm{H}_{FS}(t')\,G(t-t')dt' + ZO + UN \tag{1.10}$$

The scale factor K is used for the conversion between measured voltages and real magnetic field values and is constant for a given range. For a high quality magnetometer S is a fixed parameter near to 1, and $G(t)$ is a fixed function. UN is small with very weak temporal variations. The zero-offset ZO will exhibit small temporal variations, too, due to temperature effects etc.

The parameter S depends on the sensor j, the measuring range r, and the S/C s, although the differences will be small. The same is true for the impulse response function G. UN is generally different for the six sensors, range dependent, and, of course, varies between the different S/C. We have therefore

$$\left.\begin{array}{c} K^r \\ S_j^{r,s} \\ G_j^{r,s}(t) \\ UN_j^{r,s}(t) \\ ZO_j^{r,s}(t) \end{array}\right\} \qquad j = 1, \ldots, 3 \qquad r = 1, \ldots, 7 \qquad s = 1, \ldots, 4$$

The parameters $S_j^{r,s}$ are known from calibration measurements before launch. The same is true for the functions $G_j^{r,s}(t)$ which are derived from the transfer functions $T_j^{r,s}(f)$

$$T_j^{r,s}(f) = A_j^{r,s}(f)\, e^{i\phi_j^{r,s}(f)} \tag{1.11}$$

The amplitude $A_j^{r,s}(f)$ and the phase $\phi_j^{r,s}(f)$ are determined only for some selected frequencies by calibration measurements before launch. To get a complete transfer function we expand it in a series

$$A_j^{r,s}(f)\, e^{i\phi_j^{r,s}(f)} = \frac{1}{1 + i2z_j^{r,s}\frac{f}{f_{n,j}^{r,s}} - \frac{f^2}{(f_{n,j}^{r,s})^2}} \tag{1.12}$$

The parameters $z_j^{r,s}$ and $f_{n,j}^{r,s}$ can be calculated from the data of the calibration measurements.

The impulse response function $G_j^{r,s}(t)$ is obtained via

$$G_j^{r,s}(t) = \int_{-\infty}^{+\infty} T_j^{r,s}(f)\, e^{+2\pi i f t}\, df$$

which results into

$$G_j^{r,s}(t) = \frac{2\pi f_{n,j}^{r,s}}{\sqrt{1-(z_j^{r,s})^2}} e^{(-2\pi f_{n,j}^{r,s}\, z_j^{r,s}\, t)} \sin\left(2\pi f_{n,j}^{r,s}\sqrt{1-(z_j^{r,s})^2}\; t\right) \quad \text{for } z_j^{r,s} < 1 \text{ and } t \geq 0 \tag{1.13a}$$

$$G_j^{r,s}(t) = \frac{2\pi f_{n,j}^{r,s}}{\sqrt{(z_j^{r,s})^2-1}} e^{(-2\pi f_{n,j}^{r,s}\, z_j^{r,s}\, t)} \sinh\left(2\pi f_{n,j}^{r,s}\sqrt{(z_j^{r,s})^2-1}\; t\right) \quad \text{for } z_j^{r,s} > 1 \text{ and } t \geq 0 \tag{1.13b}$$

$$G_j^{r,s}(t) = 0 \quad \text{for } t \leq 0 \tag{1.13c}$$

In general we have at S/C s for sensor j in range r:

$$U_j^{r,s}(t) = K^r\; S_j^{r,s} \int\limits_{-\infty}^{t} \mathrm{H}_{FS}{}_j^s(t')\, G_j^{r,s}(t-t')\, dt' + UN_j^{r,s} + ZO_j^{r,s} \tag{1.14}$$

The voltages actually measured are influenced by the S/C field components SF_j^s, too. With these S/C field components and expressing $\mathrm{H}_{FS}{}_j^s(t')$ in terms of $\mathrm{H}_{GSE}{}_p^s(t')$ (ref equation 1.9) we obtain

$$U_j^{r,s}(t) = K^r\; S_j^{r,s} \int\limits_{-\infty}^{t} \left(\sum_{p=1}^{3} \mathrm{M}_{FS-GSE}{}_{jp}^s(t') \cdot \mathrm{H}_{GSE}{}_p^s(t') + SF_j^s(t')\right) G_j^{r,s}(t-t')\, dt' + UN_j^{r,s} + ZO_j^{r,s} \tag{1.15}$$

1.3.2 From Voltages to Digital Data Words

The measured voltages are transformed by the 16-bit successive approximation type ADCs of FGM-1 and FGM-2 which are short cycled to 14 bits and assign a digital representation to each element according to the following rules in the ideal case

$$U = N \cdot \Delta U + \delta U \tag{1.16}$$

where ΔU is the digitization window of the ADC and δU the digitization error. For the real ADC we have

$$U = (N(1+E_G) + E_O)\Delta U + \delta U \tag{1.17}$$

where the integer number N is determined such that $|\delta U| < 1/2\,\Delta U(1+E_G)$. The gain-error E_G and the offset error E_O are small with a dependence on temperature determined on the ground. The integer N is limited to the ranges

$$-8192 \leq N \leq 8191$$

From equation 1.15 and equation 1.17 we obtain for $N_j^{r,s}$

$$\begin{aligned} N_j^{r,s} &= \frac{K^r\ S_j^{r,s}}{\Delta U(1+E_G)} \int_{-\infty}^{t} \left(\sum_{p=1}^{3} \mathrm{M}_{FS-GSE}{}^{s}_{jp}(t') \cdot \mathrm{H}_{GSE}{}^{s}_{p}(t') + SF_j^s(t') \right) G_j^{r,s}(t-t')\,dt' \\ &+ \frac{UN_j^{r,s} + ZO_j^{r,s}}{\Delta U(1+E_G)} - \frac{E_O}{1+E_G} - \frac{\delta U_j^{r,s}}{\Delta U(1+E_G)} \end{aligned} \qquad (1.18)$$

We collect the ADC-errors and magnetometer noise and zero-offset in the quantities

$$ENO_j^{r,s} = \frac{UN_j^{r,s} + ZO_j^{r,s}}{K^r\ S_j^{r,s}} - \frac{E_O \Delta U}{K^r\ S_j^{r,s}} - \frac{\delta U_j^{r,s}}{K^r\ S_j^{r,s}} \qquad (1.19)$$

and obtain

$$\begin{aligned} N_j^{r,s} &= \frac{K^r\ S_j^{r,s}}{\Delta U(1+E_G)} \left(\int_{-\infty}^{t} \sum_{p=1}^{3} \mathrm{M}_{FS-GSE}{}^{s}_{jp}(t') \cdot \mathrm{H}_{GSE}{}^{s}_{p}(t') G_j^{r,s}(t-t')\,dt' \right. \\ &\left. + \int_{-\infty}^{t} SF_j^s(t') G_j^{r,s}(t-t')\,dt' + ENO_j^{r,s} \right) \end{aligned} \qquad (1.20)$$

It is the purpose of the data processing procedures to reconstruct the vector components $\mathrm{H}_{GSE}{}^{s}_{p}(t)$ from the $N_j^{r,s}$. This is possible except for the small contribution $\delta U_j^{r,s}$ and small contribution by fast irregular variations in the S/C field $SF_j^s(t)$.

1.4 The Model Used for the Routine Data Processing

1.4.1 The Simplified Instrument Model

It is obvious that the very complex equation 1.20 that takes into account all possible distortions of the magnetic field information can not be used as the basic equation for the routine data processing. So we have to find a simplified model which describes the physical properties of the instrument sufficiently.

The results based on the data gained during ground calibration tests led to the following simplifications:

- the transfer functions (ref equation 1.11) are not depending on the frequency, they are 1 for the relevant frequency area,
- the gain error E_G and the offset error E_O (ref equation 1.17) are negligible.

Note that for advanced scientific interpretation methods, like the wave telescope, this simplified model is possibly not sufficient. In such cases it might for example be necessary to use a frequency depending transfer function.

Equation 1.20 can now be written as

$$N_j^{r,s} = \frac{K^r\ S_j^{r,s}}{\Delta U} \left(\sum_{p=1}^{3} \mathrm{M}_{FS-GSE}{}_{jp}^{s} \cdot \mathrm{H}_{GSE}{}_{p}^{s} + SF_j^s + ENO_j^{r,s} \right) . \qquad (1.21)$$

After introduction of a total offset vector $\mathrm{H_0}{}_j^{r,s}$ as sum of the S/C field and the instrument offset, equation 1.21 can be transferred to

$$\frac{N_j^{r,s}\ \Delta U}{K^r} = \mathrm{V}_j^{r,s} = S_j^{r,s} \sum_{p=1}^{3} \mathrm{M}_{FS-GSE}{}_{jp}^{s} \cdot \mathrm{H}_{GSE}{}_{p}^{s} + S_j^{r,s}\ \mathrm{H_0}{}_j^{r,s} \qquad (1.22)$$

or written as vectors

$$\underline{\mathrm{V}}^{r,s} = \underline{\underline{\mathrm{S}}}^{r,s}\ \underline{\underline{\mathrm{M}}}_{FS-GSE}{}^{s}\ \underline{\mathrm{H}}_{GSE}{}^{s} + \underline{\underline{\mathrm{S}}}^{r,s}\ \underline{\mathrm{H}}_0{}^{r,s} \qquad (1.23)$$

where $\underline{\mathrm{V}}^{r,s}$ is the measured field vector and $\underline{\underline{\mathrm{S}}}^{r,s}$ is a diagonal matrix containing the sensitivities of the three sensor components.

Doing the multiplication of $\underline{\underline{S}}^{r,s}$ with $\underline{\underline{M}}_{FS-GSE}{}^{s}$ and $\underline{\underline{S}}^{r,s}$ with $\underline{H}_0{}^{r,s}$ and leaving out the indices for range and S/C yields the basic equation for a linear instrument model

$$\underline{V} = \underline{\underline{c}}\ \underline{H}_{GSE} + \underline{c}_0 \tag{1.24}$$

For data processing purposes it is advantageous to split the overall transformation matrix $\underline{\underline{c}}$ into three single matrices reflecting the source from which the information has been gained:

1. The sensor matrix $\underline{\underline{c}}^{(sensor)}$ containing the sensitivities of the sensors and the alignment of the three sensor axes with respect to a coordinate system with one axis aligned to the real spin axis, e.g. the FGM Spin Reference System (ref section 1.4.2). The information for this matrix will be derived from calibration measurements, either ground or in-flight.
2. The spin matrix $\underline{\underline{c}}^{(spin)}$ which has the following form, if we assume that the z-axis is the spin axis:

$$\underline{\underline{c}}^{(spin)} = \begin{pmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{1.25}$$

   where φ is the actual spin phase. As already mentioned, the spin phase has to determined independent of the FGM measurements. It will be derived from the measurements of the sun reference sensor.
3. The attitude matrix $\underline{\underline{c}}^{(att)}$ describing the transformation between the spin axis aligned coordinate system and the GSE System. The attitude is derived from special attitude measurements and is documented in separate attitude files.

The basic equation 1.24 can now be written as

$$\underline{V} = \underline{\underline{c}}^{(sensor)}\ \underline{\underline{c}}^{(spin)}\ \underline{\underline{c}}^{(att)}\ \underline{H}_{GSE} + \underline{c}_0\ . \tag{1.26}$$

1.4.2 The FGM Spin Reference Coordinate System (FSR)

The determination of the real spin axis direction can be performed by FGM in-flight calibration methods – even more precisely than with other methods. In-flight calibration methods result in a matrix describing the direct transformation from the FGM Sensor Coordinate System to a spin axis aligned coordinate system, the FGM Spin Reference Coordinate System (FSR). Thus, the data will be represented in the FSR System after the inverse instrument matrix has been applied. This coordinate system has the following properties:

- The x-axis is the real spin axis.
- The direction of the y-axis is determined by the built-in position of the unit. Since it is not possible to calculate the precise position of the unit during flight (after deploying of the boom) by single S/C in-flight calibration methods, we have to assume that the unit is located at its nominal position, ie the y-axis is rotated by 6.5°against the x-axis of the Spin Reference System. However, inaccuracies in the determination of this rotation angle has the same effect as an inaccurate determined zero spin phase φ_0. Both effects can not be distinguished.
- The transformation from the FSR to the SR System can be carried out by a rotation of 6.5°around the x-axis with an interchange of the sensor axes afterwards.

1.4.3 The Basic Equation for the Routine Data Processing

If we split the sensor matrix $\underline{\underline{c}}^{(sensor)}$ into an instrument matrix $\underline{\underline{c}}^{(instr)}$ and a matrix $\underline{\underline{c}}^{(SR-FSR)}$ describing the coordinate tranformation from the FSR into the SR System, equation 1.26 can be written as

$$\underline{V} = \underline{\underline{c}}^{(instr)}\ \underline{\underline{c}}^{(SR-FSR)}\ \underline{\underline{c}}^{(spin)}\ \underline{\underline{c}}^{(att)}\ \underline{H}_{GSE} + \underline{c}_0\ . \tag{1.27}$$

This linear equation can now very easily be transformed to calculate the magnetic field from the measurements:

$$\underline{H}_{GSE} = \underline{\underline{c}}^{(att)^{-1}}\ \underline{\underline{c}}^{(spin)^{-1}}\ \underline{\underline{c}}^{(SR-FSR)^{-1}}\ \underline{\underline{c}}^{(instr)^{-1}}\ (\underline{V} - \underline{c}_0)\ . \tag{1.28}$$

This equation will be used as the basic equation for the routine data processing.

Chapter 2 Instrument Calibration

2.1 Introduction

The analysis of measured data requires the knowledge of all relevant properties of the measuring instrument. It is consequently essential to calibrate an instrument to be able to carry out useful physical measurements.

The calibration of the Cluster FGM instrument is in general made up of two parts: the ground calibration and the in-flight calibration. The former is carried out before launch. It tests the general behaviour of the instrument and produces a first set of calibration parameters. The latter is carried out after launch. It uses different methods to recalibrate the set of calibration parameters from the measured values. The next two sections of this chapter are concerned with these two parts of the instrument calibration.

Another problem that has to been dealt with is the influence of the instrument on the measured quantity. In our case these are the spacecraft generated magnetic fields. They have been investigated in magnetic cleanliness tests during the pre-launch phase and can at least partly be determined by various in-flight methods. The investigations of the spacecraft generated fields is described in section 2.3.

The results of the calibration tests and the S/C field investigations must somehow be made available for the data processing. This will be achieved by the use of calibration files which contain the calibration parameters for the instrument and will be read by the data processing software. The use and the structure of this interface between instrument calibration and data processing is described in section 2.5.

2.2 Ground Calibration

The calibrations of the magnetometers of all four spacecrafts has been carried out at the magnetic coil facility of the Technische Universität Braunschweig. A complete description of all obligatory and optional calibration measurements can be found in [CalProc]. The measurements that have in fact been performed during the calibration tests are described in the relevant test reports [CalRep]. Here we will describe the various types of calibration measurements only in general terms.

The results of the ground calibration tests have been compiled in a series of technical reports [CalRes]. In this document we will only summarize the principal results of the calibration tests that lead to the model used for the data processing (cf section 1.4.1).

The ground calibration of the Cluster FGM is divided in three major parts concerning the response to DC-fields, the frequency response, and the time delay. The first part can once again be devided in two parts: measurements of the offset and determination of the DC transfer function which includes sensitivity, misalignment, and crosstalk.

2.2.1 DC-Field Investigations

Offset Measurements

The offsets are determined separately for the three axes of the magnetometer by two zero-field measurements, where the second one will be carried out after a 180°turn of the magnetometer. The offsets usually depend on the range of the instrument and may also be dependent on the used ADC. Therefore, the offset measurements have been carried out for the range 2, 3, 4 and 5 (not for7) and for both ADCs.

The evaluations lead to the following results:

- The offsets depends on range. The offsets for the ranges 4 and 5 are higher than for ranges 2 and 3.
- The offset instability over 10 days was for all sensor devices smaller than 1.5 nT at every ranges.
- The differences for the offsets when using the other ADC are in the order of smaller than 0.5 nT and are included in the calfiles.

DC-Field Transfer Function

The DC-field transfer function is determined in the following way. The magnetometer is put in the centre of the coil system and optically aligned with the coil axes. Then various static fields are applied, either only along the three axes – so called 'on-axes calibration' – or distributed throughout a spherical volume – so called 'spherical calibration'.

On-axes calibration measurements are usually analysed by using the 'traditional' method where the sensitivity and the misalignment angles are calculated in an iterative process. A more sophisticated method is the fitting of a transfer matrix to the data (e.g. with a least square fit). This can be performed with on-axes calibration measurements, but a better data base for this method can be obtained by spherical calibration measurements. If requested, this transfer matrix can be split unambiguously into three matrices. The first one is a diagonal matrix with the sensitivities of the three single sensors. The second one describes the misalignment of three sensors, i.e. the deviations from the orthogonality. The last one is an Euler rotation matrix giving the alignment of the instrument with respect to the coil axes. Even though this splitting is not necessary for the data processing, because we can always apply the total transfer matrix, it might be useful for some calibration methods or at least for a better illustration of the physical effects.

During the ground calibration 'on-axes' as well as 'spherical calibration' measurements have been carried out for each range and for both ADCs. The influence of the temperature on the transfer function has been investigated with on-axes measurements. The data of all units have been analysed with the fitting method leading to the following results:

- Within the bounds of accuracy both types of measurements had the same results.
- The transfer function of the instruments can sufficiently be described with a linear model for magnetic field magnitudes up to 2000 nT.
- The transfer function depends considerably on the range, but the diagonal elements of the transfer matrix are between 0.95 and 1.07 and the absolute values of the off-diagonal elements are lower than 0.03 for all ranges of the instruments. This means that the sensitivities of the three single sensors are always between 0.95 and 1.07 and the deviations from orthogonality are less than one degree.
- The differences for the matrix elements when using the other ADC are very low (under 1 per cent), but should, however, be taken into account.
- The sensitivities and the misalignment angles are almost linear functions of the temperature for temperatures from -40 to +60 °C. The sensitivities decrease with increasing temperature by approximately $1 \cdot 10^{-4}$ per °C, and the internal alignment angles vary in the range of 3–5 arc seconds per °C. These values are more or less the same for all ranges.

2.2.2 Frequency Response

The AC-field transfer function is determined in the following way. For testing the instrument's digital and analogous response to an input A/C magnetic field, various AC-signals over a wide frequency range are applied to one coil. The sensor is placed in such a way in the coil system that all three sensor axes measure nearly the same amplitude of the applied AC-signal and the device is switched in the 5 modes 16 Hz, 18 Hz, 22 Hz, 67 Hz and HRes in range 3 and 5. The technique is applied to all FGM-models and the detailed results are outlined in documents [CalRep]. The analogous measurements are carried out with an Amplitude&Phase-Analyzer.

Introduction

An optimum set of calibration parameters would minimise the difference between the measured rawdata and the analytical fitdata. Correct calibration parameters are determined using a least square method. Parametric optimisation is used to find a set of design parameters, that can in some way be defined as optimal. In our case this is the minimisation of some system characteristic that is dependent on these parameters. Therefore, an optimisation problem in the Digital Frequency Analysis involves minimising a function, called the objective function, of several variables. Most optimisation problems benefit from good starting guesses. The 11 parameters of the Digital Frequency Measurements determined by fitting parameters are outlined in the following list:

- Offset
- AC magnetic field amplitude
- Sample frequency
- AC magnetic field phase
- Third harmonic AC magnetic field amplitude
- Third harmonic AC magnetic field phase
- Fifth harmonic AC magnetic field amplitude
- Fifth harmonic AC magnetic field phase
- Powersystem Amplitude MRode
- Powersystem Frequency MRode

- Powersystem Phase MRode

Despite the presence of a rather large number of quantities that must be taken from the experiment, the fit model provides a highly accurate description of the signal in all its aspects, also in the Sample Rate.

Calibration Setup

The main setup of the Digital Frequency Measurement in the Cluster II calibration consists of the coilsystem, the magnetometer with the sensor triad in diagonal position at the CoC, the spacecraft simulator and the EGSE. The coilsytem is the Braunbeck-System at IGM/TUB. The coils are adequately supplied with the desired signals in frequency and amplitude. Strictly speaking, only one coil is impinged with the signal and the fluxgate sensor is in diagonal position in the center of the coil.

Results

For the Digital Frequency Response both sensors of the magnetometers, outboard and inboard, show the same characteristic - as expected. In the 22 Hz normal mode the -3 dB point is at 7.6 ± 0.2 Hz and the phase difference between the channels can be neglected up to a frequency of 5 Hz. In the 67 Hz burst mode the -3 dB point is at 18 ± 0.5 Hz and the phase difference between the channels can be neglected up to a frequency of 10 Hz. In the upper frequency range, above 5 Hz respectively 10 Hz, the exact transfer function must be used for special high time resolution investigations, but the inflight calibration has to been done at first.

2.2.3 Time Delay

The measurements of the time delay are intended to determine the 'overall' and the 'interchannel time delay'. The former is the time the signal needs to run through the instrument until it is recorded with the actual time. The latter means the phase shift of the three sensors with respect to each other.

These measurements are carried out with a special electronic device that has been developed for this purpose, the Random/Sync-Generator. During data processing the results of the time delay measurements can be used for a time correction, either for the three vector components separately or for the complete vector. Both corrections might be necessary especially for multi-spacecraft analysis techniques, when the timing of the data must be done very accurately. Because it is assumed, that these values are nearly constant for every S/C, the time delay for both sensors in the most used range is included in the so called const.fgmfile and will be updated as necessary weekly, or more often. The following preflight values which are probably constant during the mission in the most used working mode will be for the 4 satellites (corresponding columns):

4096.0000	4096.0000	4096.0000	4096.0000	„HFC_rate [Hz] “
201.793	201.793	201.793	201.793	„fgm_freq [Hz] “
6.5	6.5	6.5	6.5	„fgm_angle [deg] “
7314000	7314000	7314000	7314000	„timedelay OB R2/3 [ns]“
4014000	4014000	4014000	4014000	„timedelay OB R4/5/7 [ns]“
7314000	7314000	7314000	7314000	„timedelay IB R2/3[ns]“
4014000	4014000	4014000	4014000	„timedelay IB R4/5/7[ns]“
26.3671875	26.3671875	26.3671875	26.3671875	„spinoffset[deg]“

2.3 Spacecraft Generated Magnetic Fields

Detailed magnetic cleanliness tests are required to separate the S/C generated magnetic fields from the ambient fields under investigation. The result of these tests is a magnetic model of the S/C. From this model it is possible to calculate the magnetic field at the sensor position. During the magnetic cleanliness tests all units of each cluster spacecraft were measured in a mobile coil facility at Dornier. The magnetic critical units were compensated by fitting small magnets onto them. After integration each hole spacecraft was measured in the MFSA at the IABG. The measurements were done as received, after deperm, after compensation, after perm and after final deperm. The compensation was done by fitting two magnets, whose moments and positions were chosen by calculations based on the measurement after deperm onto the S/C. The calculated total field at FGMO is lower than 0.2 nT and for the FGMI lower than 1 nT at all S/Cs. The results are written in the reports [CalSR] CL2-IGM-SR001 to -SR004, Iss.1. This reports are available at IGM.

2.4 In-Flight Calibration

The first 3 matrices in equation 1.28 perform coordinate transformations between orthogonal reference systems and are not involved in the in-flight calibration. The fgmhrt data processing module carries out this task.

The in-flight calibration will affect only the factors $[\underline{\underline{c}}^{(instr)^{-1}}\ (\underline{V}\text{-}\underline{c}_o)]$, which give the magnetic field vector $\underline{H}_{FSR}$ in the FSR coordinate system. Both terms in the paranthesis are in digital units. This is the calibration part of the equation and represents a scaling from digital data to nT and coordinate transformation from the unorthogonal sensor system FS to the orthogonal FSR system. The calibration files contain the parameters needed for this transformation and are based as well on the ground calibration measurements as well as on the in-flight determinations.

For a better readability of the calibration file the range dependent scaling is performed before calibration. The modul `fgmtel` is responsable for multiplying the digital vectors $\underline{V}$ with the nominal scaling factor (see Table...)e The output is the vector $\underline{H}_{FS}$ expressed in nominal nT, i.e. $\underline{H}_{FS} = \underline{\underline{M}}_{ST}\ \underline{V}$. This vector is the input for the S/W modul `fgmcal`, which applies the calibration correction and generates the offset corrected magnetic field vector in the spin aligned sensor system $\underline{H}_{FSR}$.

The calibration parameters to be determined by the inflight calibration are based on the values obtained from the ground calibration procedures. The parameters are affected by the time behaviour of the physical characteristics of the magnetometer itself, which influences scale and misalignment, as well as by the S/C offset. Therefore the calibration matrix is built up from a set of submatrices which describe the dependence of the measured values on fgm-number, range, sensor $out - /inboard$, sensor-component, ADC-number and SC-number. The offset is also built up from offsets generated by different sources.

The matrix $\underline{\underline{c}}^{(instr)^{-1}}$ divided by the nominal range dependent scaling factor named as the calibration matrix $\underline{\underline{c}}^{cal}$ and the offset $\underline{c}_o$ scaled and transformed into the FSR system vector, called the calibration offset $\underline{o}^{cal}$ will be written in the calibration files. The calibration matrix is a 3x3 matrix, so together with the offsets, we have 12 calibration parameters for each range, sensor, ADC combination.

To calibrate means to apply the following equation (S/W module `fgmcal`)

$$\underline{H}_{FSR} = \underline{\underline{c}}^{cal}\ \underline{H}_{FS} - \underline{o}^{cal} \tag{2.1}$$

to the vectors output by `fgmtel`.

The decomposition in submatrices of the calibration matrix is as follows:

$$\underline{\underline{c}}^{cal} = \underline{\underline{M}}_{SC}\ \underline{\underline{M}}_{ROT}\ \underline{\underline{M}}_{SR}\ \underline{\underline{M}}_{ORT}\ \underline{\underline{M}}_{ADC} \tag{2.2}$$

and for the offset vector:

$$\begin{aligned}\underline{o}^{cal} = \underline{\underline{c}}^{cal}\ \underline{\underline{M}}_{ST}\ \underline{c}_o\ = \underline{O}_{SC} \quad &+ \quad \underline{\underline{M}}_{SC}\ \underline{\underline{M}}_{ROT}\ \underline{O}_R \\ &+ \quad \underline{\underline{M}}_{SC}\ \underline{\underline{M}}_{ROT}\ \underline{\underline{M}}_{SR}\ \underline{\underline{M}}_{ORT}\ \underline{\underline{M}}_{ADC}\ \underline{O}_{ADC}\end{aligned} \tag{2.3}$$

value given in nT.

Introducing in 2.1 the decomposition of the calibration matrix and offset and regrouping the terms we can emphasize the sources of the different errors.

$$\underline{H}_{FSR} = \underline{\underline{M}}_{SC}\,\underline{\underline{M}}_{ROT}\,\left(\underline{\underline{M}}_{SR}\,\underline{\underline{M}}_{ORT}\,\underline{\underline{M}}_{ADC}\,\left(\underline{H}_{FS} - \underline{O}_{ADC}\right) - \underline{O}_{R}\right) - \underline{O}_{SC}. \quad (2.4)$$

with:

$\underline{H}_{FSR}$	Calibrated magnetic field vector in FSR system in nT
$\underline{\underline{M}}_{SC}$	SC influence on scale factor, due to soft magnetic material onboard
$\underline{\underline{M}}_{ROT}$	Rotation matrix to transform from orthogonalized FS to FSR coordinate system
$\underline{\underline{M}}_{SR}$	Range dependence of the scale factors
$\underline{\underline{M}}_{ORT}$	Orthogonality matrix, converts to orthogonal sensor system
$\underline{\underline{M}}_{ST}$	Standard (nominal) range dependent scaling factors
$\underline{\underline{M}}_{ADC}$	Scaling changes from ADC1 to ADC2
$\underline{H}_{FS}$	Magnetic field in unorthogonalised sensor system in nT, the nominal scaling was applied
$\underline{O}_{ADC}$	ADC-offset (default from Magnetsrode) in nT
$\underline{O}_{R}$	Offset from range (default from Magnetsrode) in nT
$\underline{O}_{SC}$	Spacecraft offset due to permanent magnetic material in nT

The spin axis offset determination is one of the most difficult task for recalibration. Different techniques are going to be used: statistical correlation technique in the solar wind region and the use of independent measurement of other instruments on-board. The comparison with EDI time of flight measurements will be one of them.

The calibration will be done only with the help of the high resolution data.

2.5 The Calibration Files

As mentioned already in the previous section, the calibration files contain the calibration matrix elements and the offset vector components.

2.5.1 Naming Convention

The naming convention were chosen to correspond to a calibration level, which relates to the use of the data processing (DP) S/W routinely:

- Level 0: Only the nominal scale factors are applied in the module `fgmtel`; no calibration file(s).
- Level 1: Ground calibration level, 1 file per spacecraft: „`Cn.fgmcal` “, n=1-4. These files contained initially only ground calibration parameters and were intended to be used till launch. However they constitute default calibration files by the `fgmcal` software module and therefore they have been updated during the commissioning phase with in flight parameters. Because since 2008 FGM measures also in range 6 and 7 we had to change the calibration files format, see section 2.5.2
- Level 2: Normal daily calfiles with increasing version numbers Vxx; „`Cn_yyyymmdd_Vxx.fgmcal` “
  V00 is reserved for special usage, the official version numbering starts with V01.
- Level 3: Special calfiles with begin and end time of validity of the calibration; „`Cn_yyyymmdd_hhmmss_hhmmss_Vxx.fgmcal`“
  Used for science investigations with high resolution data.

Thus, level 0 is provided only for test purposes, level 1 is used as fall back when no daily calibration files are available. Level 2 means one calfile used per day and SC. Level 2 is used in the data centers for PP/SP and PSDS data production. Because these level 1 calfiles are updated infrequently, we recommend to the users who want to process data before the daily calibration files (level 2) become available to rename the most recent calfile „`Cn_yyyymmdd_Vxx.fgmcal` “to the default name „`Cn.fgmcal` “.

2.5.2 Structure of the Calibration Files

As mentioned already, there is one calibration file for every S/C. It contains 12 calibration coefficients for each sensor, range and for the 2 ADC's. The first header line contains the information of used the ADCnumber and the valid time period (the first line will be updated again by FGM Team): adc–nr time–of–change, normally:

`1 24:00:00`
The file is a table of 5 columns of numbers (corresponding to the ranges) + 1 column alpha-numeric information about the content of the row and 48 rows:
12 (calibration coefficients) x 2 sensors (OB/IB) ADC 1
12 (calibration coefficients) x 2 sensors (OB/IB) ADC 2

Some information, which is not necessary for the `fgmcal` program, but may be helpful for raw data calibration is included on the bottom like:
`S1 = OB + ADC1, S2 = IB + ADC1, S3 = OB + ADC2, S4 = IB + ADC2.`
`Ranges 2, 3, 4, 5, 7 corresponds to 64, 256, 1024, 4096, 65000 nT.`
`Fn-fsr, data from raw data file Magnetsrode, September 1999.` At the beginning of the mission the use of the ranges 6 and 7 has not been planned. However due to the extension of the mission the orbits of the spacecraft changed such that the spacecraft entered higher magnetic field regions since September 2008. An important change of the calibration software and of the format of calibration files followed. The fifth column that contained ground range 7 parameters have been replaced firstly by a fixed set of range 6 parameters determined at Imperial College. These calfiles have version number `V02`; they will be replaced gradually with version `V03` files that contained parameters determined in IGEP. The information at the bottom of the calibration files have been changed accordingly.
`S1 = OB + ADC1, S2 = IB + ADC1, S3 = OB + ADC2, S4 = IB + ADC2.`
`Ranges 2, 3, 4, 5, 6 correspond to 64, 256, 1024, 4096, 16000 nT.`
In order to calibrate range 7 an additional set of 4 calibration files „`Cn_range7.fgmcal` “have been produced. This contains only the 12 calibration parameters corresponding to S1=OB+ADC (outboard sensor and ADC 1). This range is also calibrated regularly, resulting in the production of some „`Cn_yyyymmddrange7.fgmcal` “files. The parameters are averaged and input in the „`Cn_range7.fgmcal` “, which are required by the calibration software. When better calibration is needed the IGEP Braunschweig team has to be contacted to obtain a daily calibration range 7 calfile. Note that this must be renamed to the default name. The calibration files are available on the UK Daata Centre site and on the IGEP, TUBS ftp-server.

2.5.3 Input Parameters for Calculation of the Calibration Files

The start values of all parameters that appear in 2.4 have been taken from the ground calibration. They are the basis for the in flight calibration and are updated at each run of the calibration software. They are 4 such tables for each spacecraft corresponding to the 4 possible combinations of the 2 sensors(inboard, outboard) and ADC(1,2). However during the mission the use of ADC1 and outboard sensor became standard and only these input tables are updated regularly.

Offset_r2=	-5.05000	0.88000	-0.12000
Offset_r3=	-5.06000	1.02000	-0.13300
Offset_r4=	-32.8000	20.40000	-5.57000
Offset_r5=	-32.8000	21.20000	-4.75000
Offset_r7=	0.00000	0.00000	0.00000
Offset_SC=	2.4500000	6.4000000	0.1900000
Matrix_r2=	1.0523500	0.0000000	0.0000000
Matrix_r2=	0.0119843	1.0521800	0.0000000
Matrix_r2=	0.0196858	-0.0109872	1.0355500
Matrix_r3=	1.0333000	0.0000000	0.0000000
Matrix_r3=	0.0111954	1.0337400	0.0000000
Matrix_r3=	0.0167732	-0.0112807	1.0190300
Matrix_r4=	1.0213400	0.0000000	0.0000000
Matrix_r4=	0.0117305	1.0156300	0.0000000
Matrix_r4=	0.0170876	-0.0110434	1.0048600
Matrix_r5=	1.0034000	0.0000000	0.0000000
Matrix_r5=	0.0112674	0.9980000	0.0000000
Matrix_r5=	0.0164569	-0.0111590	0.9884000
Matrix_r7=	1.0000000	0.0000000	0.0000000
Matrix_r7=	0.0000000	1.0000000	0.0000000
Matrix_r7=	0.0000000	0.0000000	1.0000000
Matrix_SC=	1.0000000	0.0000000	0.0000000
Matrix_SC=	0.0000000	1.0000000	0.0000000
Matrix_SC=	0.0000000	0.0000000	1.0000000
Matrix_rot=	1.0000000	0.0000000	0.0000000
Matrix_rot=	0.0000000	1.0000000	0.0000000
Matrix_rot=	0.0000000	0.0000000	1.0000000
Matrix_xyz=	0.3909000	0.6510500	0.0000000

Table 2.1: Calibration parameters without range 6

Until September 2008 range 6 and 7 were not included in the calibration matrices because the instruments never reached these ranges (tab 2.1). From September 2008 range 6 and, one year later, range 7 were included as shown in (tab. 2.2).

Offset_r2=	-5.05000	0.88000	-0.12000
Offset_r3=	-5.06000	1.02000	-0.13300
Offset_r4=	-57.80000	20.40000	-5.57000
Offset_r5=	-56.80000	21.20000	-4.75000
Offset_r6=	-675.00000	284.00000	-44.00000
Offset_r7=	-675.00000	297.60000	-31.60000
Offset_SC=	2.4500000	6.3600000	0.0400000
Matrix_r2=	1.0523500	0.000000	0.0000000
Matrix_r2=	0.0119843	1.0521800	0.0000000
Matrix_r2=	0.0196858	-0.0109872	1.0355500
Matrix_r3=	1.0333000	0.0000000	0.0000000
Matrix_r3=	0.0111954	1.0337400	0.0000000
Matrix_r3=	0.0167732	-0.0112807	1.0190300
Matrix_r4=	1.0213400	0.0000000	0.0000000
Matrix_r4=	0.0117305	1.0156300	0.0000000
Matrix_r4=	0.0170876	-0.0110434	1.0048600
Matrix_r5=	1.0034000	0.0000000	0.0000000
Matrix_r5=	0.0112674	0.9980000	0.0000000
Matrix_r5=	0.0164569	-0.0111590	0.9884000
Matrix_r6=	1.0200000	0.0000000	0.0000000
Matrix_r6=	0.0100000	1.0180000	0.0000000
Matrix_r6=	0.0180000	-0.0083360	1.0100000
Matrix_r7=	1.0030000	0.0000000	0.0000000
Matrix_r7=	0.0060000	1.0007000	0.0000000
Matrix_r7=	0.0014000	-0.0083600	0.9933000
Matrix_SC=	1.0000000	0.0000000	0.0000000
Matrix_SC=	0.0000000	1.0000000	0.0000000
Matrix_SC=	0.0000000	0.0000000	1.0000000
Matrix_rot=	1.0000000	0.0000000	0.0000000
Matrix_rot=	0.0000000	1.0000000	0.0000000
Matrix_rot=	0.0000000	0.0000000	1.0000000
Matrix_xyz=	0.3909000	0.6510500	0.0000000

Table 2.2: Calibration parameters for all ranges

Chapter 3
Acquisition and Timing of the Science Data

3.1 Introduction

In this chapter all items concerning the acquisition and the timing of the science data which might be necessary for the data processing will be described.

Before starting the descriptions some definitions are useful to avoid confusion:
A *sample* means a single measurement of one component (X, Y, or Z) of the inboard or outboard-sensor. A triaxial measurement represented by three successive samples (X, Y, and Z) is called a *triple*. The final triaxial measurements (after a possible filter process) to be supplied to the OBDH (On-Board Data Handling System) are called *vectors*.
The magnetometer with the higher sampling rate is the *primary* sensor. This is usually the outboard-sensor. The other one is called the *secondary* sensor.

3.2 Data Acquisition

More detailed hardware and software aspects of the data acquisition are given in [EID Part A], [EID Part B], [FGM SRD], and the FGM instrument paper. We will only describe the items that are relevant for the data processing. In particular these are range definitions, vector rates, and filter procedures.

3.2.1 General Information about the Data Acquisition

The data acquisition of the primary as well as the secondary triples is triggered by the FGM-clock.

The acquisition of the primary triples is always performed at a constant rate of approx. 201.75 Hz, the exact calculation is given in section 3.3. This data rate will be reduced by a following filter process or by taking spot values to match the rate of the transmitted vectors to the available telemetry rates. Because the allocated telemetry resources vary with the different spacecraft telemetry modes, the experiment has four telemetry options with different vector rates, the telemetry options and the corresponding filters are described in section 3.2.3 and 3.2.4 respectively. In order to ensure the essential requirement that the sampling of the primary vectors is carried out at equal time intervals, the FGM-clock acts as the master clock not only for the data sampling, but also for the sequencing of the deterministic FGM operating software.

The acquisition of the secondary triples are carried out at lower rates that vary with the different telemetry options. The triples are never be filtered. They are always spot values. So the secondary triple is already the secondary vector for the telemetry frame.

The data are transmitted from the instrument as 16 bit words with bit zero as the most significant bit. In the case of bytewise transmission of data, i.e. telemetry packets, the most significant byte is transmitted first.

3.2.2 Ranges

The magnetometers have eight possible operating ranges. Range switching is either automatic, controlled by the instrument Data Processing Unit, or set by ground command. When in the automatic mode, a range selection algorithm running in the DPU continuously monitors each sample. If any sample exceeds a fraction (set at 90%) of the range, an uprange command is generated and transmitted to the sensor at the start of a new telemetry format. (All three components are always measured in the same range.) Downranging is implemented only if all three components are smaller than 10% of the current range for the duration of a telemetry reset period (5.152222 sec). This duration was selected to exceed a complete spin period (4 sec) in order to prevent downranging due to spin modulation of the two spin-plane components. The autoranging facility can be overridden by ground command: the two magnetometers can be commanded independently into a fixed range. The resolution of eight ranges are reported in table 3.1.

The highest range (-65536 to 65528 nT) was first used for ground testing and is used since 2008 also for in flight data production. Range 6 (-16384 to 16382 nT) is used in flight since September 2008 and is being calibrated since them. The auto ranging facility does not switch to the lowest range 1. This range can only be switched on as a fixed range by ground command. Range 1 has not been calibrated by pre-launch calibration procedures due to its smallness. Range 0 signifies not valid field data.

range	range (nT)	nT/digit	comment
7	-65536 to +65528	8	used since 2008
6	-16384 to +16382	2	calibrated since 2008-09
5	-4096 to +4095.5	0.5	
4	-1024 to +1023.9	$1.25 \cdot 10^{-1}$	
3	-256 to +255.97	$3.125 \cdot 10^{-2}$	
2	-64 to +63.992	$7.813 \cdot 10^{-3}$	
1	-16 to +15.998	$1.953 \cdot 10^{-3}$	cannot autorange to; not calibrated
0	not used		signifies: *'Not valid field data'*

Table 3.1: Resolution of the different ranges

3.2.3 Telemetry Resources and FGM Telemetry Options

The telemetry reset period is 5.152222 seconds, i.e. one telemetry frame is completed every 5.152222 sec. The length of a telemetry frame, i.e. the telemetry resources that are available for data, depends on the spacecraft telemetry mode. For filling the telemetry resources a maximum of 16 options is identified each indicated by a hexadecimal number.

Given the allocated telemetry mode resources in the different modes, the possible telemetry options of the instrument are shown in table 3.2.

spacecraft telemetry mode	FGM telemetry resources bits(words)/frame	bits/sec	possible FGM telemetry option
normal mode 1,2 or 3	6240(390)	1211.13	2,3,4,A,B,C
burst mode 1	17856(1116)	3465.69	D
burst mode 2	6944(434)	1347.77	2,3,4,A,B,C
burst mode 3	28768(1798)	5583.61	F

Table 3.2: The S/C telemetry modes and the possible FGM telemetry options

Options A, B, and C (normal data modes) shall be duplicated as option 2, 3, and 4 respectively. They differ only in one respect when the event recognition is enabled. If an event is triggered and MSA data becomes available, then the instrument shall auto-switch from option 4 and 3 to option 2, thus allowing the MSA data to be down-linked, because in option 3 and 4 no telemetry resources are allocated to MSA vectors. When MSA is empty, the instrument shall auto-switch back to option 4 or 3. This auto-switching is disabled, when operating in option A to C. Option D is used for burst data and option F for MSA dump.

A summmary of the acquisition and the allocation rates of the FGM telemetry options is given in table 3.3.

FGM option (hex)	primary sensor vectors			secondary sensor vectors			MSA vectors
	acquisition		allocation	acquisition		allocation	
	$\left(\frac{\text{vecs}}{\text{s}}\right)$	$\left(\frac{\text{vecs}}{\text{reset}}\right)$	$\left(\frac{\text{vecs}}{\text{reset}}\right)$	$\left(\frac{\text{vecs}}{\text{s}}\right)$	$\left(\frac{\text{vecs}}{\text{reset}}\right)$	$\left(\frac{\text{vecs}}{\text{reset}}\right)$	$\left(\frac{\text{words}}{\text{reset}}\right)$
2	15.519	79.957	81(13)	1.091	5.619	6(185)	128
3	18.341	94.497	95(11)	6.957	35.843	37(29)	0
4	22.416	115.492	116(9)	3.011	15.514	16(67)	0
A	15.519	79.957	81(13)	1.091	5.619	6(185)	128
B	18.341	94.497	95(11)	6.957	35.843	37(29)	0
C	22.416	115.492	116(9)	3.011	15.514	16(67)	0
D	67.249	346.481	348(3)	7.759	39.979	41(26)	0
F	0	0	0	0	0	0	1781

Table 3.3: The structure of the FGM telemetry options

The number put in brackets () indicates the decimation level, based upon the sampling rate of 201.75 Hz. If this level will be reached for the primary vectors by filtering, the filter will be shifted this number of samples between each filter process.

3.2.4 Filtering

The full bandwidth of the sampled triples cannot be routinely transmitted via the telemetry because of the limited telemetry rate allocation. Therefore, the sampled data rate is reduced by a Gaussian digital filter to match the rate of the transmitted vectors to the available telemetry rates. In fact, the filter process is a weighted sliding averaging.

Four different filter functions are supplied for the four different FGM telemetry options. The decimation level, based upon the sampling rate of 201.75 Hz, is determined by the filter shift, i.e. the number of triples the filter function slides between two filter processes. The filter functions are generated in such a way that the filter lengths are always four times the filter shift. So every triple takes part in four filtering processes.

The coefficients for the weighting are selected from stored sets corresponding to the four different FGM telemetry options. The standardization factor of the filter functions, i.e. the sum of the filter coefficients, is always $2^{16} = 65536$. The standardization of the vectors will be carried out by the DPU before putting the vectors in the telemetry frame. A summary of the FGM telemetry options and their corresponding filter coefficients are given in tabular 3.4.

telem. option	data rate (vecs/s)	filter shift	filter coefficents			
2 & A	15.519	13	0	0	0	0
			0	1	2	4
			8	17	34	64
			115	200	331	526
			802	1172	1641	2204
			2838	3503	4146	4704
			5118	5338	5338	5118
			4704	4146	3503	2838
			2204	1641	1172	802
			526	331	200	115
			64	34	17	8
			4	2	1	0
			0	0	0	0
3 & B	18.341	11	0	0	0	0
			1	2	5	13
			30	64	130	248
			446	757	1212	1830
			2605	3495	4423	5337
			5936	6294	6294	5936
			5337	4423	3495	2605
			1830	1212	757	446
			248	130	64	30
			13	5	2	1
			0	0	0	0
4 & C	22.416	9	0	0	0	1
			3	8	23	61
			147	324	654	1211
			2051	3183	4524	5890
			7021	7667	7667	7021
			5890	4524	3183	2051
			1211	654	324	147
			61	23	8	3
			1	0	0	0
D	67.249	3	0	8	183	1958
			9550	21064	21064	9550
			1958	183	8	0

Table 3.4: The filter coefficients for the primary vectors

These filter values are plotted in figures 3.1 to 3.4.

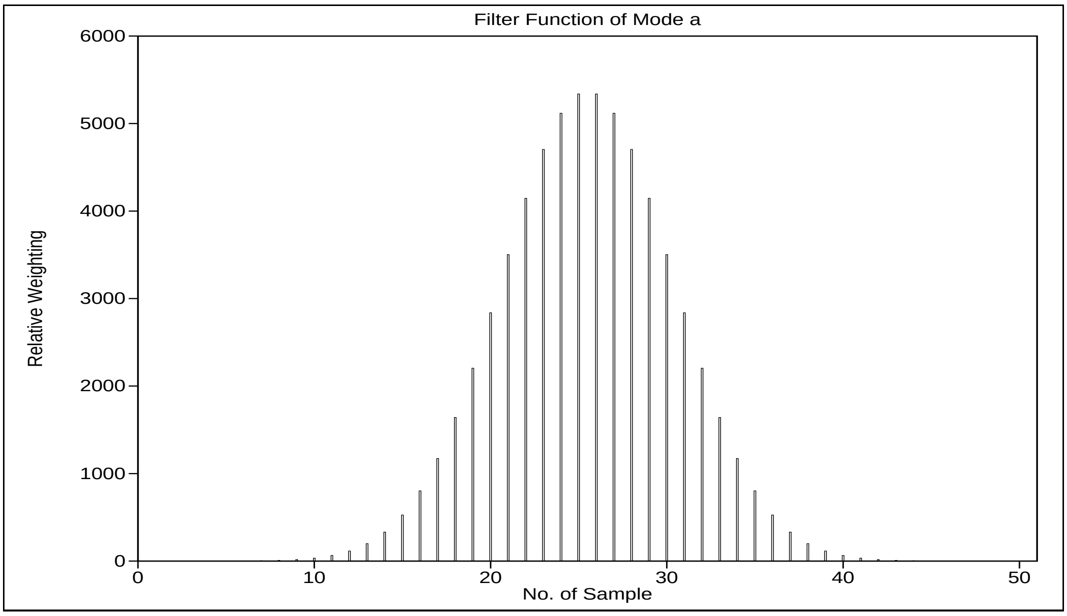

Figure 3.1: Filter values of mode 2 & A

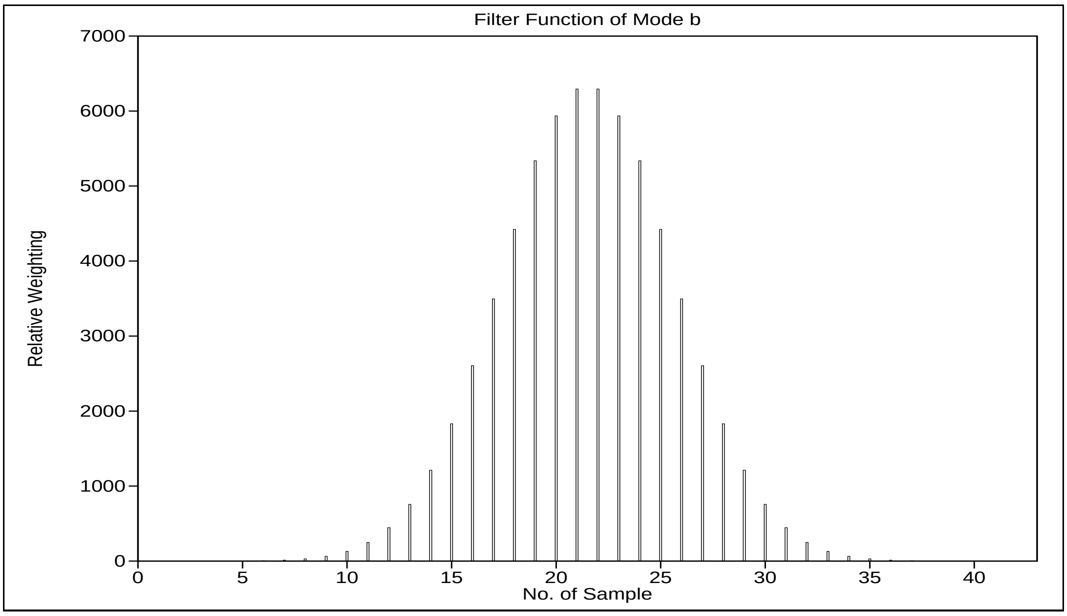

Figure 3.2: Filter values of mode 3 & B

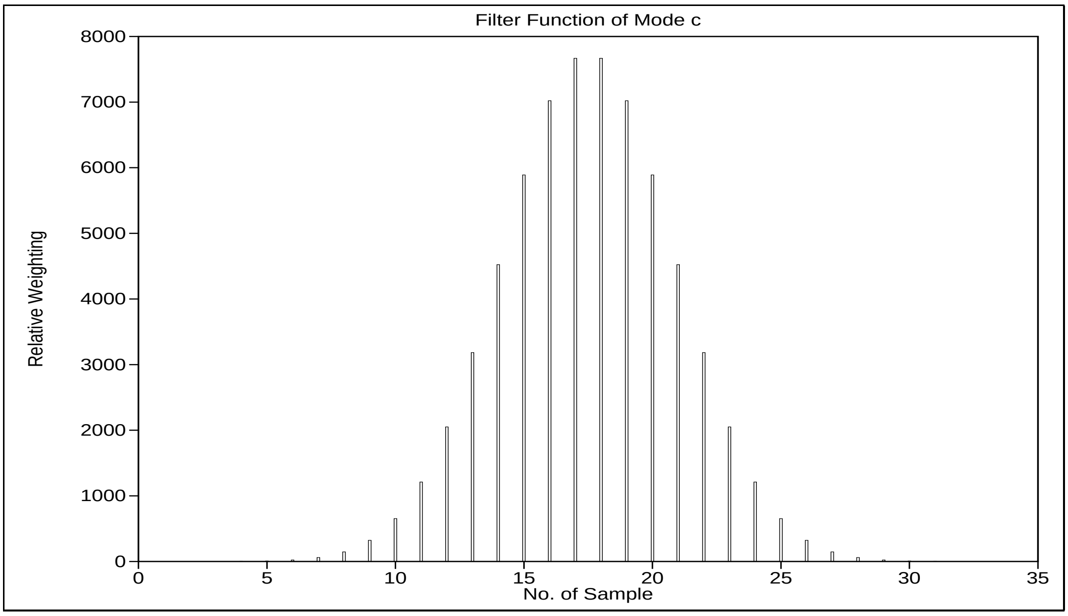

Figure 3.3: Filter values of mode 4 & C

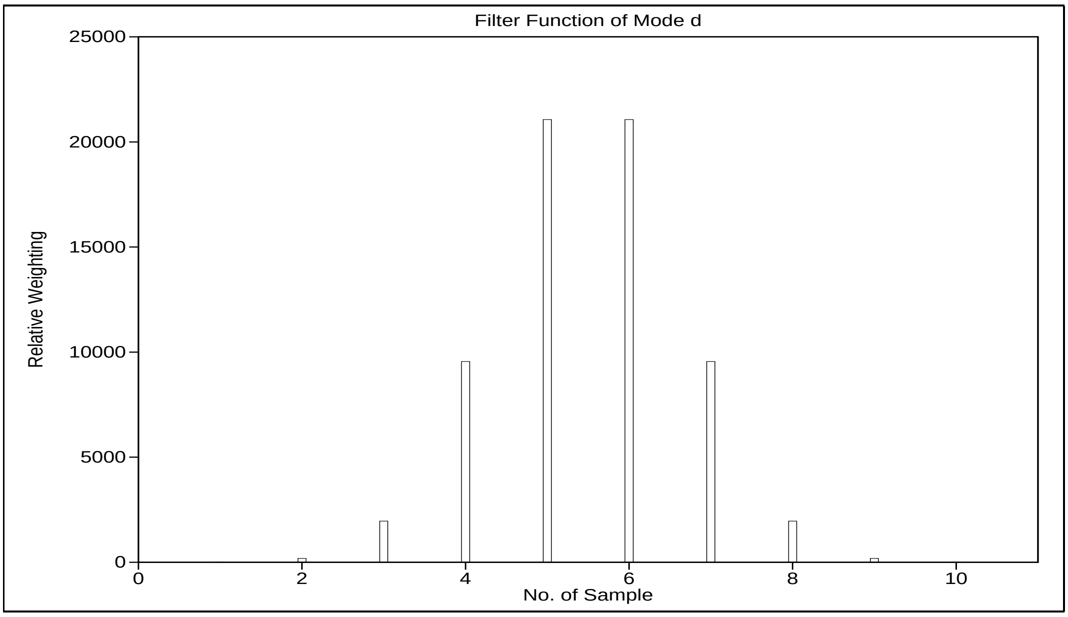

Figure 3.4: Filter values of mode D

3.3 Data Timing

It is a primary task of the raw data processing to determine the time at which samples and triples etc. have been measured. To enable an as precise timing as possible in the following a description of the data acquisition and its timing is given.

As written in section 3.2.1 acquisition of primary and secondary triples is triggered by the FGM-clock. This clock runs at 2^{23} Hz $= 8.3886 \cdot 10^6$ Hz and is divided down by 35 and then by 4. The resulting counter thus runs at $5.9919 \cdot 10^4$ Hz, that is one tick every $1.6689 \cdot 10^{-5}$ s.

After each 10 counts of this experiment internal clock, that is every $1.6689 \cdot 10^{-4}$ s, a sample of a primary triple is taken (see Fig. 3.5). Taking the samples for each triple starts with the X-, then the Y-, and finally the Z-component. Between the acquisition of two primary triples 277 counts of the FGM-clock occur, that is between the acquisition of the same sample in two successive triples time proceeds by 297 counts or $4.9567 \cdot 10^{-3}$ s or 4.9567 ms (= 201.75 Hz) for the primary sensors. The final primary vector acquisition rate, however, depends on the telemetry options and the filtering applied.

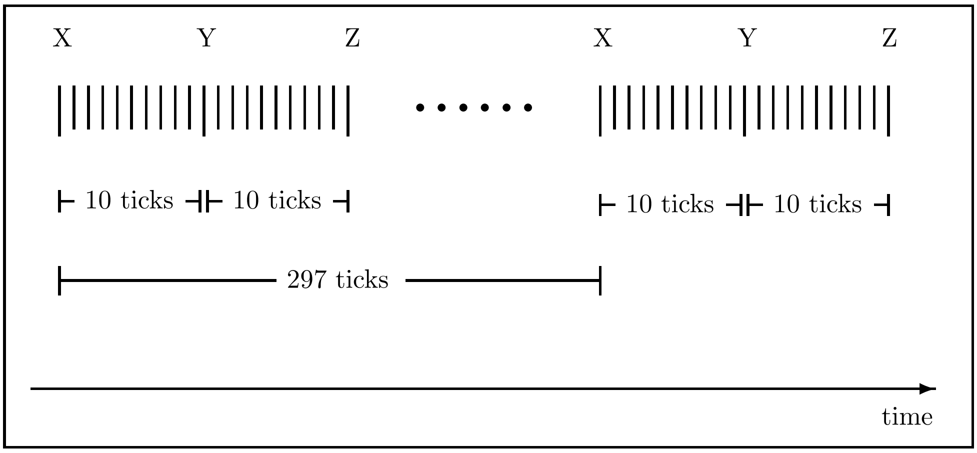

Figure 3.5: Timing of the sample acquisition of the primary vectors

As mentioned in section 3.2.3 the acquisition rate of the secondary triples are suitably reduced for the different telemetry options. The four different acquisition rates are obtained in the following way: The acquisition of a secondary triple starts always a well defined number of FGM-clock counts after the start of the acquisition of the previous secondary triple. Then the three samples are acquired immediately after each other in the order X, Y, Z. The option depending number of FGM-clock counts between the beginnings of the acquisition of two successive secondary triples results from the decimation level, based upon the sampling rate of 201.75 Hz, multiplied by 297. Since no filtering is applied to the measurements of the secondary sensor, the resulting acquisition rate is already the final secondary vector acquisition rate, displayed in the following table 3.5:

FGM option	decimation level	FGM-clock counts	acquisition rate $\left(\frac{\text{vecs}}{\text{s}}\right)$	acquisition rate $\left(\frac{\text{vecs}}{\text{reset}}\right)$
2	185	54945	1.091	5.619
3	29	8613	6.957	35.843
4	67	19899	3.011	15.514
A	185	54945	1.091	5.619
B	29	8613	6.957	35.843
C	67	19899	3.011	15.514
D	26	7722	7.759	39.979

Table 3.5: Acquisition rates of the secondary vectors

The HFC (High Frequency Clock), the central on-board clock, runs at 2^{17} Hz = $1.3107 \cdot 10^5$ Hz. It is divided down by 32 to 4096 Hz and available to the DPU in a register as a 16 bit counter which rolls over every 16 seconds. Each triple, primary and secondary, is time-stamped during acquisition of the Z-sample with the actual HFC-counter number $\mathbf{n}_p$ and $\mathbf{n}_s$, respectively.

The primary triples are stored in a (virtual) filter buffer where the (Gaussian-shaped) filter is applied to each component (x, y, and z) seperately (ref section 3.2.4). The time assigned to the resulting filtered vector is the counter number $\mathbf{n}_p$ of the last participating triple (ref fig 3.6).

The vectors are put in the telemetry frame and the time-tags $\mathbf{n}_p$ and $\mathbf{n}_s$ of the first primary and the first secondary sensor vector are written in the frame header.

The telemetry frame is closed by the next reset pulse. All reset pulses are time-stamped with the actual number $\mathbf{m}$ of the 16 bit HFC-counter. This $\mathbf{m}$ is also written in the frame header. The time of a reset pulse, i.e. the time of an $\mathbf{m}$, will be correlated by the ground processing facilities of the satellite operating system with Universal Time (UTC) at an accuracy of 2 msec.

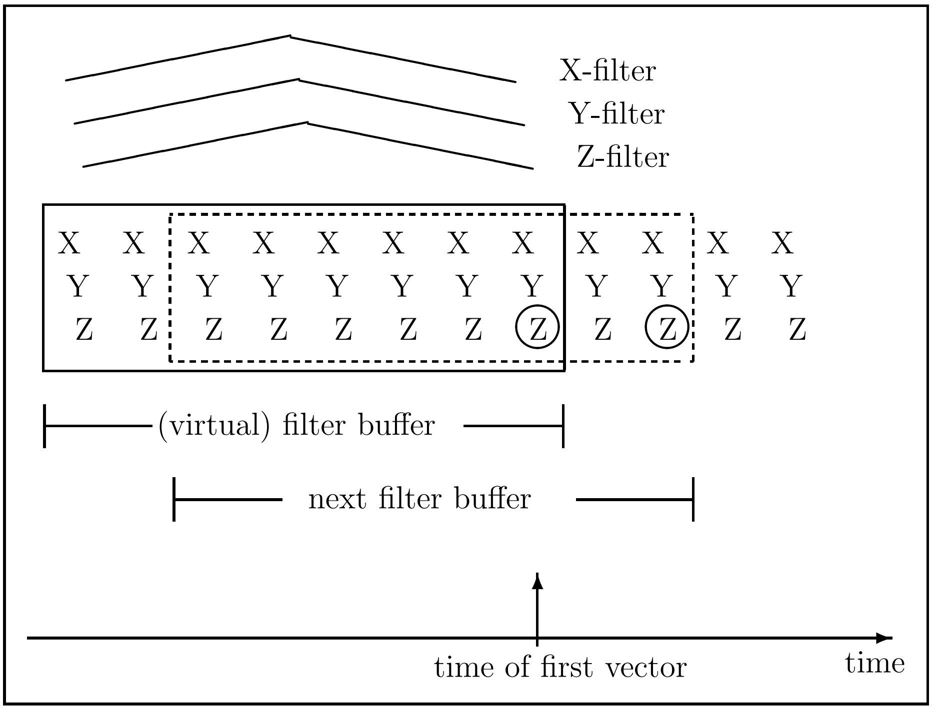

Figure 3.6: Timing of the filtered vectors

If T_{UTC} is the time belonging to $\mathbf{m}$, we can reconstruct T^1_{pv}, the UTC of the first primary vector in a frame, by

$$T^1_{pv} = T_{UTC} - \frac{\mathbf{m} - \mathbf{n}_p}{f_c} - \frac{1}{2}\frac{k_f(\text{mode}) - 1}{f_a} \tag{3.1}$$

where:

— f_c is the counter rate of the 16 bit HFC counter (4096 Hz)

— $k_f(\text{mode})$ is the mode depending number of elements in filter

— f_a is the data acquisition rate (201.75 Hz).

In the above equation the first subtraction takes into account the position of the vector within the telemetry frame, and the second term should be added, because the time of a primary vector is determined by the last triple of the filter process, which has, in case of a Gaussian-shaped filter, very little weighting (ref fig 3.6). By subtraction of half the filter length the centre time of the filter will be made the vector time. The fact that the last sample (Z-sample) of a triple is time-stamped can be disregarded, because the temporal resolution of the HFC-counter (4096 Hz) is below the sample acquisition rate ($59919 \cdot 10^3$ Hz).

Since the data acquisition rate is well known, the time of every other primary vector in the frame can be calculated from the time of the first one by:

$$T_{pv}^{j} = T_{pv}^{1} + \frac{(j-1)\ \delta s(\text{mode})}{f_a} \tag{3.2}$$

where:

— j is the number of primary vector in frame (starting with number 1)

— δs(mode) is the mode depending number of triples of the filter progress
— (equivalent to a quarter of the filter length)

— f_a is the data acquisition rate (201.75 Hz).

The time of the secondary vectors in the frame can be calculated in a similar way using the fact that the vectors are not filtered and that the acquisition rate is mode depending:

$$T_{sv}^{1} = T_{UTC} - \frac{\mathbf{m} - \mathbf{n}_s}{f_c} \tag{3.3a}$$

$$T_{sv}^{j} = T_{sv}^{1} + \frac{j-1}{f_a(\text{mode})} \tag{3.3b}$$

Equations 3.1 to 3.3b thus allow to determine in an accurate way the timing of each measured sample, triple, and vector.

The following figure 3.7 tries to give a summary of the meaning and the origin of the timing informations.

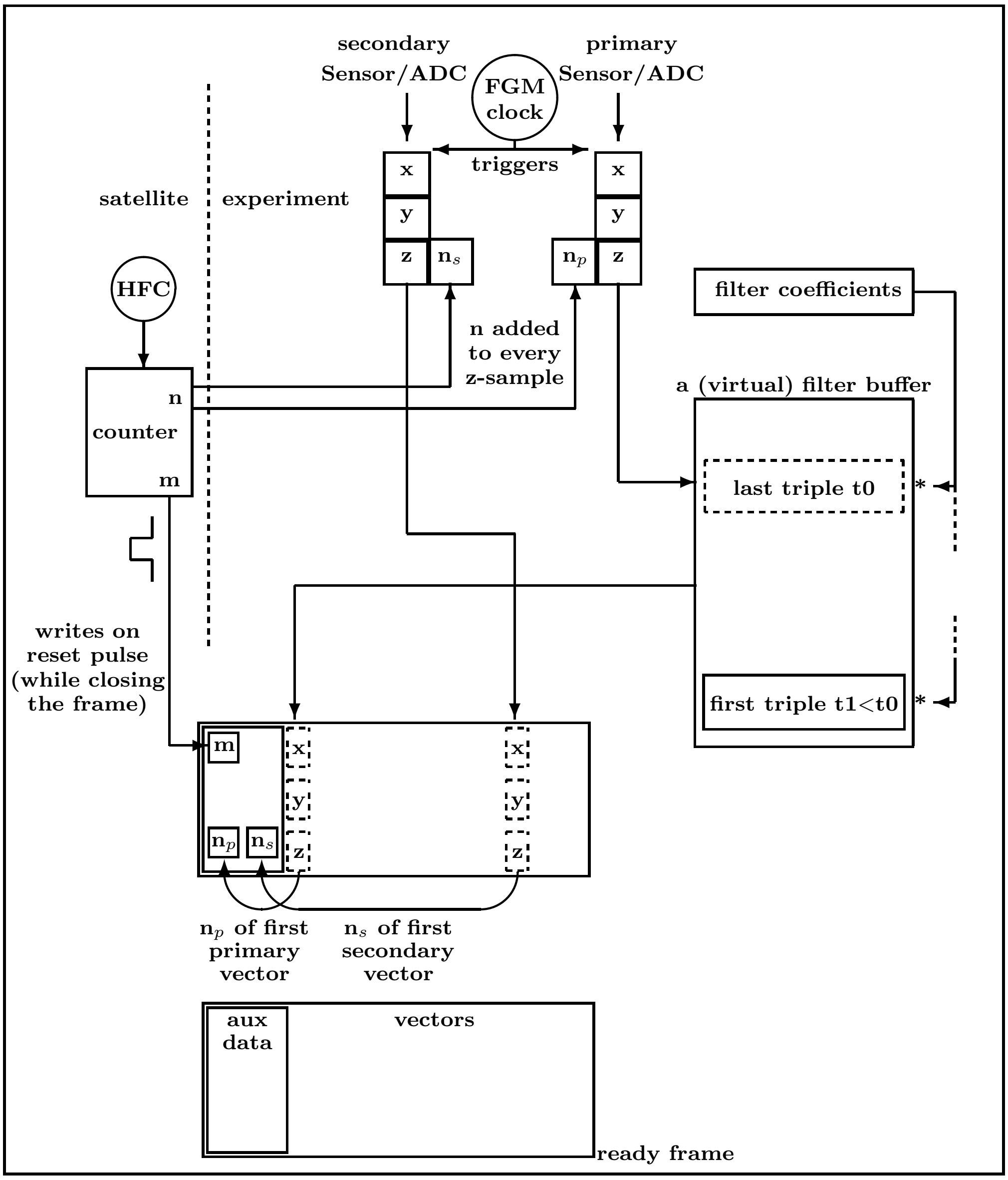

Figure 3.7: The assignment of the time

Chapter 4 Raw Data Processing

4.1 Introduction

This part of the handbook is concerned with the processing of the raw data as received from ESOC up to a first set of calibrated data in a geophysical coordinate system. It is the purpose of the raw data processing to reverse the distortions in the FGM data described in chapter 1 with only a small error left due to digitization uncertainties, sensor noise and by far most importantly due to remaining uncertainties in the spacecraft magnetic field variations.

The following main tasks of the raw data processing software have been identified:

1. transforming the raw data from a representation resulting from transport by telemetry into a format suitable for further processing on standard computer systems
2. reconstruction of the time at which the data have been measured
3. performing the inverse instrument transformation by application of calibration parameters
4. transformation of the field vectors into standard geophysical coordinate systems (GSE, GSM, SM, J2K)

Moreover there are some additional features the raw data processing should provide:

- attachment of the S/C position
- averaging magnetic field over different time intervals
- procedures for changing the data representation to match the different interface definitions of the various data products

After the presentation of the general concept of raw data processing we will describe the software that has been developed at TUBS. This includes the way of using the software, the required input, and the possible outputs.

4.2 General Concept of Raw Data Processing

The raw data processing of the FGM experiment is based on a modular structure. Starting from the raw data distributed by ESOC several modules are applied to the data to achieve the correct values of the magnetic field. Every single module represents one step of the data correction procedure, e.g. the transformation from a S/C aligned to a physical coordinate system. In this way it will be possible to supplement, improve or correct the procedure in an easy manner, if new knowledge forces to do so. Another advantage of a modular structure is the possibility of developing the single steps of the process separately, possibly by different members of the FGM team.

As mentioned earlier the main input to the data processing are the FGM normal or burst science raw data files, distributed by ESOC. Auxiliary input files required by different modules will be mentioned in their respective descriptions. Here is a summary: 'const.fgm', calibration file, short/long term event file, attitude file, spacecraft housekeeping file, short/long term orbit file. The last four items are delivered by ESOC on the raw data media together with the FGM data.

At this point we have to make some remarks concerning the implementation of the instrument's calibration:
The calibration of the FGM instrument, i.e. the determination of the calibration parameters describing the inverse instrument transformation, will be completely detached from the standard raw data processing. The interface between these two separate processes are the *calibration files*. Thus, the raw data processing is a straight-forward process only using the calibration files as input. The structure of the calibration files and how they will be determined from calibration measurements is described in this document, section 2.5. The calibration files, as well as the *'const.fgm'* file are produced and updated by the FGM team.

4.3 The Raw Data Processing Software

4.3.1 General Information

The software described in the following has been developed on *Sun, SPARCstations* using *Solaris* [1]. Most of the programs are written in *C* but some of them, especially those handling attitude or orbit information, use *FORTRAN* subroutines. The *GNU*

[1] *Sun* and *Solaris* are (registered) trademarks of Sun Microsystems, Inc. *SPARCstation* is a trademark of SPARC International Inc and is licensed exclusively to Sun Microsystems Inc.

ANSI C compiler 'gcc' and the *Sun FORTRAN 77 compiler 'f77'* have been used for compiling the programs.

As mentioned above the data processing has a modular structure. Each module is an entire program. Since most of the modules use *stdin* and *stdout* as input and output files respectively, a complete data processing chain can easily be built by piping together several modules.

The data representation between the different modules is always the same and will be described in section 4.3.2. This does not apply to the modules, which name begin with dds(they handle the RD telemetry files) and to the igmvec.c module, which uses the extended binary structure, created by fgmpos.c. Thus, single modules can be omitted or added in a pipe, with some restrictions regarding their order. The presence of fgmtel is mandatory, since this module creates the `fgmtvec_t` binary structures. One could, for example, create non calibrated output vectors by ending the pipe with *fgmtel* or *fgmtel* and *fgmvec*.

The following figure 4.1 tries to give a summary of the raw data processing chain.

FGM DATA PROCESSING FLOW CHART

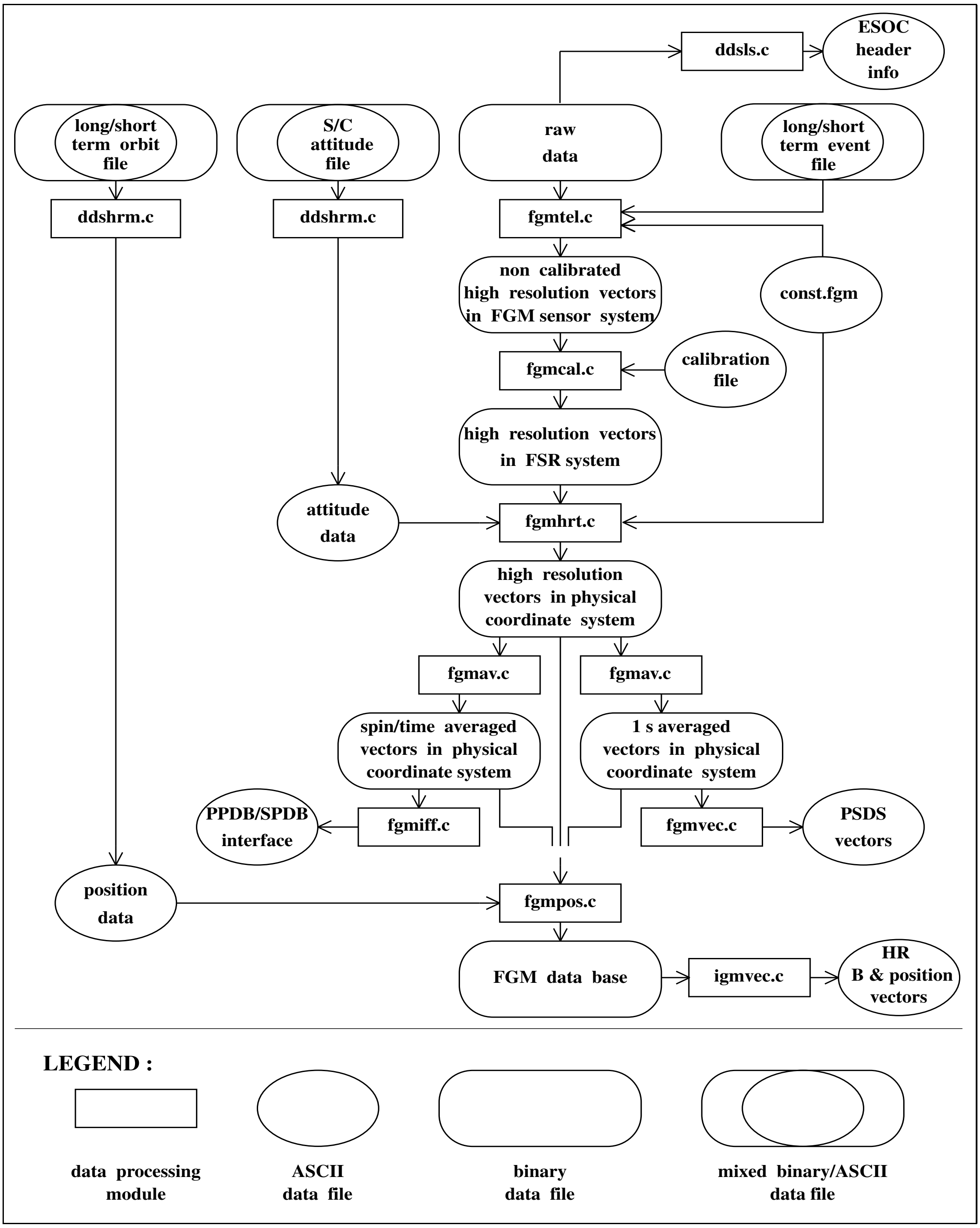

Figure 4.1: Cluster raw data processing plan

4.3.2 The Data Structure of the FGM Raw Data Processing

For setting up the data processing pipe described in the previous section it is essential that the definition of the data structure used for representing the data between the different modules is defined in such a way that all necessary information are assigned to each vector.

The data structure used for one vector in the FGM data processing is a binary stream of 4-byte (integer and real) words with the following content (in C-notation):

```
/*
 * Time-stamped FGM vector with spin phase or variance
 */
typedef struct fgmtvec {
        int             stat;     /* status and id word */
        timespec_t      tv;       /* POSIX time */
        float           b[3];     /* magnetic field */
        float           phavar;   /* spin phase or normalized
                                     magnetic variance: total */
        float           magvar;   /* raw data variance or normalized
                                     magnetic variance: magnitude */
} fgmtvec_t;
```

The size is machine dependent and the statement is valid only on *Sun, SPARCstations*. Main differences are caused by the different /`timespec_t`/sizes, due to the different number of bytes in `long`.

Since the resolution of the instrument is 14 bits, three 4-byte floats are sufficient for storing the components of the magnetic field. The field is always given in nT. The used coordinate system, as well as the contents of `phavar` and `magvar` are controlled and reported in the `status and id word` (ref section 4.3.2).

The time is represented in the POSIX time format (from library `<sys/time.h>`) which is defined as

```
/*
 * Time expressed in seconds and nanoseconds
 */
typedef struct timespec
  {
    time_t      tv_sec;     /* seconds */
    long        tv_nsec;    /* nanoseconds */
  }
timespec_t;
```

The seconds are counted from the 'UNIX epoch' January 1st, 1970, 0 UT. Being an IEEE standard, this representation avoids alignment problems in contrast to the representation of the CCSDS Day Segmented (CDS) time code format used in the raw data. Moreover standard library functions for conversion of the seconds into more human-readable formats are available on most computer systems (see e.g. `man gmtime`).

It should however be noted that the value of `tv_sec` can not be addressed as the *number of seconds since 1970-01-01, 0 UT*, because it does **not** take into account any leap seconds. The exact definition of `tv_sec` is

$$\texttt{tv\_sec} = \texttt{nday} \times 86400 + \texttt{nsod} \tag{4.1}$$

where `nday` is the number of days since 1970-01-01, and `nsod` is the number of seconds of the day.

For averaged data `tv` represents the centre of the averaging intervall.

Whether the vectors are filtered or not, is reported in the `status and id word` (ref section 4.3.2).

The Status and ID Word

The contents of the FGM status and id word is described in the following table. Some bits are set by the FGM data processing software, others are directly taken from the FGM raw data. If the data have been averaged, the status bits of the first vector are used. The present definition of the fgm status word is used by the s/w released the 29th January 2001 (`fgmdp` V1.0, resp. `fgmpsds` V6.2, `fgmppdb` V6.2/V6.1, which use `fgmtel` V6.5.)

If bit 23 is zero, the data are high-resolution data, i.e. they were not averaged. In

content	start bit	end bit	length
spacecraft id (0–3)	30	MSB=31	2
primary (0) or secondary (1) sensor	28	29	1
if set: S/C in shadow (eclipse)	27	27	1
if set: mark data due to range change	26	26	1
calibration level	24	25	2
high-resolution (0) or averaged (1) data	23	23	1
quality of averaging	19	22	4
coordinate system of magnetic field	16	18	3
if set, filter out marked vectors due to (half/)eclipse	15	15	1
if set, filter out vectors sampled in calibration-mode	14	14	1
if set, filter out vectors during range changes	13	13	1
if set: science filtering on	12	12	1
if set: MSA filtering on	11	11	1
if set: OB calibration mode on	10	10	1
if set: IB calibration mode on	9	9	1
id number of ADC in use	8	8	1
sensor is OB (0) or IB (1)	7	7	1
range (0–7)	4	6	3
telemetry option	LSB=0	3	4
IB: inboard sensor, OB: outboard sensor			

Table 4.1: The status and ID word of the data structure used for FGM data processing

this case the `phavar` word of the data structure contains the spin phase (i.e. the spin angle rotated since the last sun reference pulse (SRP) given in rad) and the `magvar` word contains the variance of the raw data (i.e. the variance of the component of the primary sensor which is nearly aligned with the spin axis). If bit 23 is set, the data were averaged. In this case the `phavar` word contains the normalized variance of the total magnetic field, which is computed according to

$$\sigma_t = \frac{\langle \underline{B} \cdot \underline{B} \rangle - \langle \underline{B} \rangle \cdot \langle \underline{B} \rangle}{\langle \underline{B} \cdot \underline{B} \rangle} = \frac{\left\langle |\underline{B}|^2 \right\rangle - |\langle \underline{B} \rangle|^2}{\left\langle |\underline{B}|^2 \right\rangle} , \tag{4.2}$$

and the `magvar` word contains the normalized variance of the magnetic field magnitude, which is computed according to

$$\sigma_b = \frac{\langle \underline{B} \cdot \underline{B} \rangle - \langle |\underline{B}| \rangle \langle |\underline{B}| \rangle}{\langle \underline{B} \cdot \underline{B} \rangle} = \frac{\left\langle |\underline{B}|^2 \right\rangle - \langle |\underline{B}| \rangle^2}{\left\langle |\underline{B}|^2 \right\rangle} .$$

The calibration level (bits 24–25) shows what kind of calibration has been applied to the data, i.e. which sort of calibration file has been used to calibrate the data. Table 4.2 lists the various sorts of calibration files with the corresponding bit settings of the status and ID word. For more information about the different sorts of calibration files see section 2.5.

24 . . . 25	value	meaning
0 0	0	raw calibration, nominal scaling applied
0 1	1	default calibration file
1 0	2	daily inflight calibration file
1 1	3	special calibration file

Table 4.2: The applied calibration as reported in the status and id word

The bits 19 to 22 (quality of averaging) are only sensible, if the data have been averaged, i.e. if bit 23 is set. In this case these bits indicate the number of high-resolution data points that were missing when computing the average. So the quality of averaging is best when this value is 0; it is worst when this value is 15.

22 . . . 19	value	number of missing data points
0 0 0 0	0	0 %
0 0 0 1	1	$>$ 0 %, $<$ 1 %
0 0 1 0	2	$\geq$ 1 %, $<$ 3 %
0 0 1 1	3	$\geq$ 3 %, $<$ 6 %
0 1 0 0	4	$\geq$ 6 %, $<$ 10 %
0 1 0 1	5	$\geq$ 10 %, $<$ 15 %
0 1 1 0	6	$\geq$ 15 %, $<$ 20 %
0 1 1 1	7	$\geq$ 20 %, $<$ 25 %
1 0 0 0	8	$\geq$ 25 %, $<$ 30 %
1 0 0 1	9	$\geq$ 30 %, $<$ 40 %
1 0 1 0	10	$\geq$ 40 %, $<$ 50 %
1 0 1 1	11	$\geq$ 50 %, $<$ 60 %
1 1 0 0	12	$\geq$ 60 %, $<$ 70 %
1 1 0 1	13	$\geq$ 70 %, $<$ 80 %
1 1 1 0	14	$\geq$ 80 %, $<$ 90 %
1 1 1 1	15	$\geq$ 90 %

Table 4.3: The quality of averaging as reported in the status and id word

The coordinate system of magnetic field is reported in bits 16–18. The following coordinate systems are applicable:

The FS system is the non-orthogonal, spinning system in which the instrument

18 . . . 16	value	system	meaning
0 0 0	0	FS	(FGM sensor)
0 0 1	1	FSR	(FGM spin reference)
0 1 0	2	SR	(spin reference)
0 1 1	3	SCS	(spacecraft sun)
1 0 0	4	GSE	(geocentric solar ecliptic)
1 0 1	5	GSM	(geocentric solar magnetospheric)
1 1 0	6	SM	(solar magnetic)
1 1 1	7	J2K	(geocentric equatorial inertial of epoch J2000.0)

Table 4.4: The coordinate system as reported in the status and id word

records the magnetic field vectors.

The FSR system is the system into which these vectors are transformed when the calibration (matrix and offsets) has been applied.

The SR system is defined in the DDID; it is achieved from the FSR system by a rotation about the spin axis by 6.5° and a renaming of the axes.

The SCS system is defined as the system you get when you despin the SR vectors, using the spin phase offset ϕ_0 given in the attitude file.

The GSE system is obtained from the SCS system by taking into account the direction of the spin axis as given in the attitude file.

The GSM and SM systems are obtained from the GSE system. They are defined in such a way that the geomagnetic dipole axis is lying in the X-Z-plane (GSM) or is parallel to the Z axis (SM). A time dependent dipole position is used as agreed within the Cluster community.

The J2K system is the inertial system used in the attitude and orbit files.

The Expanded Data Structure for Output Vectors

The `fgmtvec_t` structure does not allow to store the position of the vector, which might often be very useful, e.g. for plot routines. In this section we will give a short description of an expanded data structure used as one representation of the final output data. This format, called `fgmtrec_t`, is used at IGM as standard data format to store the magnetic field data of satellite missions.

The core of `fgmtrec_t` is the `fgmtvec_t` structure described above. This structure has been expanded for an additional 4-byte-integer identification word at the front and for a three dimensional position vector at the end.

```
/*
 * Time-stamped FGM vector with spin phase or variance and position
 */
typedef struct fgmtrec
  {
    int           id;       /* mission id word */
    int           stat;     /* satellite status word */
    timespec_t    tv;       /* POSIX time */
    float         b[3];     /* magnetic field in [nT]*/
    float         phavar;   /* spin phase or normalized
                               magnetic variance: total */
    float         magvar;   /* raw data variance or normalized
                               magnetic variance: magnitude */
    float         r[3];     /* position vector in [km]*/
  }
fgmtrec_t;
```

content	start bit	end bit	length
record contains data (0) or comment (1)	31	MSB=31	1
mission id (0–32767)	16	30	15
coordinate system of magnetic field (0–31)	11	15	5
coordinate system of position (0–15)	7	10	4
(not used)	2	6	5
measured (0) or simulated (1) data	1	1	1
high-resolution (0) or averaged (1) data	LSB=0	0	1

Table 4.5: The mission id word for the extended fgmtrec_t structure

The `mission id word` contains among other things information about the coordinate system used for the position and the magnetic field vector (which need not to be the same) and a number specifying the mission.

The codes of the possible coordinate systems in this id-word (bytes 7–10, 11–15) are:

	absolute systems
1	geocentric solar ecliptic (GSE)
2	geocentric solar magnetospheric (GSM)
3	solar magnetic (SM)
4	geocentric equatorial inertial (GEI)
5	geocentric geographic (GEO)
6	geomagnetic (GM = MAG)
15	specific to the mission
	local systems
16	mean field aligned (MFA)
17	geomagnetic VDH (radial, east, north)
18	geographic NEC (north, east, center)
30	minimum variance
31	specific to the mission

Table 4.6: The codes of the coordinate systems in the mission id word

The mission id's are 1,2,3,4 for Cluster 1,2,3,4 satellites.

`stat` is a satellite specific status word and corresponds, for Cluster data to the `stat and id word` of the `fgmtvec_t` structure, described in the previous section.

The position is given in km.

4.3.3 The Raw Data Processing Modules

We will now describe in detail the modules used for the raw data processing. The complete process has already been outlined in figure 4.1. The modules can be split up into following categories:

category	purpose	elements
main processing modules	fulfil the main data processing tasks that have been identified in section 4.1	fgmtel.c fgmcal.c fgmhrt.c
output modules	change the `fgmtvec_t` structure to output data representations that match the different requirements	fgmpos.c fgmvec.c fgmiff.c igmvec.c
data rate module	change the data rate of the vectors by averaging	fgmav.c
info modules	extract informations, either from the raw data or from data out of the processing chain	ddsls.c fgmls.c
special modules	perform special tasks for the data processing	ddscut.c ddshrm.c ddsmrg.c fgmcut.c
aux data modules	handle the spacecraft attitude and orbit files (merge and put them in the correct directories)	mrgatt.f mrgorb.f putsatt.c putstof.c putltof.c
master modules or standard pipelines	put together the single data processing modules to build up a complete data processing chain	fgmdp.c fgmpsds.c fgmppdb.c

Description of each module is given in the next section. It contains a short summary of the purpose and the actions carried out by the program, the needed input and the resulting output and the usage of the module together with the possible options that can be chosen by command line arguments. Error and warning messages are written to *stderr* by each module and we don't repeat this possible output in the description.

Important Notes

- Each module has got a short help modus that can be activated by running the program with the command line argument `-h`.
- The actual version of the program will be displayed on *stdout*, if the program is called with the command line argument `-V`.
- The descriptions refer to the actual release of the data processing modules. The actual versions of the main modules are : VERSION 6.2 (2001-01-29) for PPDB and PSDS sofware and V1.0 (2001-01-29), for FGMDP.

The Main Modules

The Module `fgmtel`

Purpose

The program extracts the raw data from the telemetry files and converts the vectors into the data structure of the FGM data processing (ref section 4.3.2).

Actions

- fill the following bits of the `status and id word`:

bits	content
30 – 31	spacecraft id
29	primary or secondary sensor
26 – 27	mark 'BAD' vectors due to range change, resp. eclipse
16 – 18	coordinate system (= 0 for sensor system)
9 – 11	information bits
11 – 13	allow selective output of marked data
7	sensor is outboard or inboard
4 – 6	range
0 – 3	telemetry option

- reconstruct the vector time and correct for a filter and analog delay
- calculate the field values by multiplying the digital vectors with the range depending scale factor, so that the output vectors are given in nT, but without any calibration information
- determine the spin phase by using the time tags of the sun reference pulses
- mark and filter out 'BAD' data

'BAD' data are considered those which satisfy one of the following criteria:

1. Instrument is turned OFF and the first two resets after POWER-ON
2. Range changes in autoranging mode
3. Calibration mode: ON. NOTE: Even if these vectors are strictly speaking, not 'BAD', they are not measurements of the external magnetic field
4. S/C is in shadow or half-shadow cf. short term event file (STEF)
5. Incomplete last vector in reset

Option '-a' allows the selective output of data marked 'BAD', cf. criteria 2–4.

Input

- FGM raw data files (normal and burst science) from *stdin* or from files; The name patterns on CDROM are *fn*, resp. *fb*.
- *'const.fgm'* file containing instrument characteristics
- STEF/LTEF - short/long term event file, with information on eclipse and half-eclipse.
- Environment variable: `FGMPATH`, pointing to the location of *'const.fgm'* and of the calibration files.
- Environment variable: `SATTPATH`, pointing to the location of the STEF/LTEF files, if option '-e' not used.

Output

- `fgmtvec_t` binary structures to *stdout*

Usage and Options

```
 fgmtel [-a <int>] [-e <ecl>] [-s] [list] | ...

 The program reads CLUSTER FGM data from telemetry files given in list
 (default stdin) and writes the primary vectors to stdout using the
 'fgmtvec_t' data structure.
 The range depending scale factor is already taken into account. Thus, the
 output vectors are given in nT.

 If the option -s is given, the secondary vectors are extracted instead of
 the primary vectors.

OPTIONS:

  -a     output all vectors, if <int> missing or <int>=0 or 7.
        <int> is a 3-bit integer, each bit corresponding to a selection rule
        <int>=1 (bit 0), output marked vectors at range changes
        <int>=2 (bit 1), output marked vectors in calibration mode
        <int>=4 (bit 2), output data during eclipses
         DEFAULT: ouput only non-marked vectors

  -e     read eclipse info from file <ecl> (name pattern: *ta* on CDROM).
         Default is '$SATTPATH/s{|l}tef.cl#', where #=1,2,3,4.

  -s     extract vectors of the secondary sensor

  -v     verbose mode

  -V     print the version number on stdout, then exit.
```

The Module `fgmcal`

Purpose

The program reads the calibration parameters from the calibration file and applies the calibration to the magnetic field vector.

The calibration file(s) will be searched automatically in the directory specified by the environment variable `FGMPATH`.

The name(s) of the used calibration file(s) can be stored in an info file for further data processing purposes.

Actions

- search for the correct calibration file(s)
- write the name(s) of the calibration file(s) in an info
- apply the calibration
- set the calibration level of the `status and id word`
- set the coordinate system bits of the `status and id word` to FSR

Input

- `fgmtvec_t` binary structures from *stdin*
- calibration file
- environment variable: `FGMPATH`, pointing to the location of *'const.fgm'* and of the calibration files.

Output

- `fgmtvec_t` binary structures to *stdout*
- used calibration file name info file

Usage and Options

```
 ... | fgmcal [-a] [-c <calfile>] [-i <infofile>] | ...

 The program reads CLUSTER FGM data (in fgmtvec_t format) from stdin,
 applies the calibration, and writes them to stdout.

 Unless explicitely specified, calibration information is searched in the
 directory specified by the environment variable FGMPATH. The highest version
 of daily calfile is chosen. If no daily calfile then ground calfile is used

OPTIONS:

  -a     process ‘all’ data, i.e., process data even if they are marked ‘BAD’.
         Default is to process only valid data
```

```
-c      use <calfile> as calibration file.
        Default is to search for a daily calibration file and --if not
        found-- for a ground calibration file, using the standard names,
        in the directory specified by the environment variable FGMPATH.

-i      store the name(s) of the used calibration file(s) in <infofile>.
        If '-i', but no name given, use default name: 'cal.log'.
        Default is not to store the name(s).
```

The Module `fgmhrt`

Purpose

The program performs a coordinate transformation on high-resolution FGM vectors (in `fgmtvec_t` format).

On input, the vectors may be in one of the following coordinate systems that has to be reported in the `status and id word`:

- FSR (FGM spin reference)
- SR (spin reference).

For the output one of the following coordinate systems can be chosen:

- SR (spin reference)
- SCS (spacecraft-sun)
- GSE (geocentric solar ecliptic)
- GSM (geocentric solar magnetospheric)
- SM (solar magnetic)
- J2K (geocentric equatorial inertial of epoch J2000).

The preprocessed attitude file will be searched automatically in the directory specified by the environment variable `SATTPATH`. The preprocessing removes the DDS-headers and merges in increasing time order the attitude data into an flat ASCII historry file. (see putsatt) If option '-a' used, the raw attitude file may be input.

Actions

- determine the input coordinate system
- search for the correct attitude file and get attitude information
- do the coordinate transformation by using the attitude information and the spin phase
- set the coordinate system bits of the `status and id word`

Input

- `fgmtvec_t` binary structures from *stdin*
- raw attitude file or merged attitude file
- environment variable: `FGMPATH`, pointing to the location of *'const.fgm'* and of the calibration files.
- environment variable: `SATTPATH`, pointing to the location of the merged attitude file, if option '-a' not used.

Output

- `fgmtvec_t` binary structures to *stdout*

Usage and Options

```
... | fgmhrt [-a <attfile>] [-d <delta>] [-s <sys>] | ...

The program performs a coordinate transformation on high-resolution
(non-averaged) CLUSTER FGM vectors (in fgmtvec_t format).

On input, the vectors may be in one of the following coordinate systems:
‘fsr’ (FGM spin reference), or ‘sr’ (spin reference).

If in the FGM status word, the bit for ‘averaged data’ is set, fgmhrt
proceeds from the non-spinning version of the input coordinate system.
In this case, if fgmhrt has to despin the data, it will use a fixed
spin phase value of 0.0, and it will clear the bit for ‘averaged data’,
again.  Therefore, this program should not be used with data that has
really been averaged!

OPTIONS:

 -a     use <attfile> as attitude file (*ga* on the CDROM). The file may,
        or may not contain DDS-headers. Default is to use the filename:
        ‘$SATTPATH/satt.cl#’(#=1,2,3,4), which contains preprocessed
        attitude file, DDS-headers beeing removed.

 -d     use <delta> as the number of seconds after which new transformation
        matrices to GSE, GSM, and SM are computed.  Default is 1 sec.

 -s     select the output coordinate system.  <sys> may be
        ‘sr’   for spin-reference system,
        ‘scs’  for spacecraft-sun system,
        ‘gse’  for geocentric solar ecliptic system (default),
        ‘gsm’  for geocentric solar magnetospheric system,
        ‘sm’   for solar magnetic system, or
        ‘j2k’  for geocentric equatorial inertial system of epoch J2000.0.
```

The Output Modules

The Module fgmpos

Purpose

The program adds the satellite position and the additional identification word to the magnetic field vectors according to the `fgmtrec_t` structure described in section 4.3.2.

On input, the vectors may be given either in the SCS, GSE, GSM, SM, J2K coordinate system. The coordinate system of the vectors will not be changed for the output vectors.

The position vector will have the same coordinat systemis as the magnetic filed, save in case of SCS, when the position will be in the GSE system.

The orbit file for determing the satellite's position will be searched automatically in the directory specified by the environment variable `ORBITPATH`, or input explicitly using option '-p'.

Actions

- determine the coordinate system of the input vectors and set the coordinate system bits of the `mission id word`
- search for the correct orbit file and get orbit information
- calculate the position at the time of the vector
- set the mission number of the `mission id word`

Input

- `fgmtvec_t` binary structures from *stdin*
- orbital position (STOF/LTOF) file
- environment variable: ORBPATH, pointing to the location of the merged position files, if option '-p' not used.

Output

- `fgmtrec_t` structures to a binary file or to *stdout*

Usage and Options

```
... | fgmpos [-p [<posfile>]] [-o [outfile]]

The program reads CLUSTER FGM vectors (in fgmtvec_t format) from stdin
and adds a mission identifier and the spacecraft's position, creating
output in a common format for spacecraft magnetometer data used at
the Institute of Geophysics and Meteorology of TU Braunschweig.
```

The coordinate system used for the magnetic field vectors may be one of ‘scs’, ‘gse’, ‘gsm’, ‘sm’, or ‘j2k’. For the spacecraft positions, the same coordinate system will be used, unless in case of ‘scs’, where the positions will be given in ‘gse’.

OPTIONS:

-p use <posfile> as orbit file (*ba* on the CDROM)for determing the spacecraft’s position. The file may, or may not contain DDS-headers. Default is to use the short term orbit file ‘$ORBITPATH/stof.cl#’, (#=1,2,3,4) with DDS-headers beeing removed.
If -p is used but <posfile> is omitted, the preprocessed long term orbit file ‘$ORBITPATH/ltof.cl#’ will be used.

-o use <outfile> as the output file. If ’-o’, but no <outfile> given, default name is : C#_yyyymmdd_sys.igm, where #=1,2,3,4 stands for satellite number and sys for the output coordinate system.
Default is to write to stdout.

The Module `fgmvec`

Purpose

The program writes an ASCII output of FGM vectors given in the binary `fgmtvec_t` structure that is used throughout the FGM data processing and has been described in section 4.3.2.

Actions

- determine the ASCII output structure that is defined by command line option
- read the binary input vectors and write the ASCII output

Input

- `fgmtvec_t` binary structures from *stdin*
- calibration file name info file

Output

- ASCII file

Usage and Options

```
... | fgmvec [-t <int>] [-a] [-r ] [-m] [-p] [-v] [-f]
                                          [-i [<cal>]] [-o [<out>]]

 The program reads CLUSTER FGM data (in fgmtvec_t format) from stdin and
 writes the magnetic field vectors as an ASCII listing to stdout.
 Each vector consists of a time string and the three vector components.

 If option -r is used, the number of decimal places of each component will
 depend on the range of the magnetometer, i.e. on the data resolution
 currently used.

OPTIONS:

  -t     print the time information in the following form:
         <int> = 0 : ISO standard time string like '2000-12-02T02:05:15.798Z'
         <int> = 1 : seconds and nanoseconds of the UNIX epoch
         <int> = 2 : (float) seconds of the hour
         <int> = 3 : (float) hours of the day
         <int> = 4 : character string like 'Mon Dec  2 02:05:15 2000'
         Default is the ISO time string.

  -r     choose the number of decimal places according to the data resolution.
         Default is to use a fixed format with a resolution of 0.1 nT.
```

```
-m     add the magnitude to each output vector.

-p     add the phase (for high-resolution data) or
       the normalized variance of the total magnetic field
       (for averaged data) to each output vector.

-v     add the raw data variance (for high-resolution data) or
       the normalized variance of the magnetic field magnitude
       (for averaged data) to each output vector.

-f     add the data acquisition frequency to each output vector.

-a     output all vectors of the fgmtvec_t stream, even if marked 'BAD'.
       Adds TM mode, range, sensor, and data flags to each output record.
       A non-zero value in the last column means 'BAD' vector, 0 else.
       Default is to output only non-marked data.

-i     add calibration filename info to output.
       use <cal> as calfile-name logfile. If '-i', but no name given,
       default name is 'cal.log'. Column name info is appended too.

-o     use <out> as output file. If '-o', but no <out>,
       default name is : C#_yyyymmdd_sys.mag, where #=1,2,3,4 stands for
       satellite number and sys for the output coordinate system.
       Default output is stdout.
```

The Module `fgmiff`

Purpose

The program writes an ASCII output of FGM vectors given in the binary `fgmtvec_t` structure that is used throughout the FGM data processing and has been described in section 4.3.2. The ASCII output is in the standard IFF (interface file format) which can automatically be transformed in the CDF (Common Data Format) in the Cluster Data Centres. The program is used by the fgmppdb (fgmspbd) master module to produce the Prime (resp. Summary) Parameter Data Base.

Actions

- determine the parameters which must be contained in the IFF file header
- read the binary input vectors and write the ASCII output

Input

- `fgmtvec_t` binary structures from *stdin*
- calibration file name info file

Output

- ASCII output to file or *stdout*

Usage and Options

```
 ... | fgmiff <filename> { -p | -s } [-o [<outfile>]]

 The program reads CLUSTER FGM data (in fgmtvec_t format) from stdin
 and writes them on an ASCII file, using the interface file format (IFF)
 for primary or summary parameter data bases.

 <filename> is the name of a file in which the name and day-of-creation
 of the used calibration files have been stored.

OPTIONS:

  -p     produce IFF listing for prime parameter data base.
         The input data must be spin averages.

  -s     produce IFF listing for summary parameter data base.
         The input data must be one-minute averages.

  -o     use <outfile> as output file. If -o is used but <outfile> is
         omitted, output is written to stdout.
         Default is to generate an output file name according to the
         IFF file naming convention.
```

The Module `igmvec`

Purpose

The program writes an ASCII output of FGM vectors given in the binary `fgmtrec_t` structure that is output by the `fgmpos` module and has been described in section 4.3.2.

Actions

- determine the ASCII output structure that is defined by command line option
- read the binary input vectors and write the ASCII output

Input

- `fgmtvec_t` binary structures from *stdin*
- calibration file name info file
- orbital position file (STOF/LTOF)
- environment variable `ORBPATH`, location of the merged position file, if option '-p' not used.

Output

- `fgmtrec_t` structures to *stdout* or to file

Usage and Options

```
 ... | igmvec [-t <int>] [-e] [-s] [-d [<int>]] [-m] [-v] [-f]
                [-i <cal>] [-o <outfile>]

 The program reads CLUSTER FGM data extended with position information
 (in fgmtrec format) from stdin and writes the time stamped magnetic field
 vectors and the satellite positon vectors in cartesian coordinates as an ASCII
 listing to stdout. With option '-s' the output coordinate system is spherical

OPTIONS:

  -t     print the time information in the following form:
         <int> = 0 : ISO standard time string like '2000-12-02T02:05:15.798Z'
         <int> = 1 : (double) seconds of the day
         <int> = 2 : (double) hours of the day
         Default is the ISO time string.

  -e     position vector in Earth radii [Re=6317.2 km]. Default is [km].

  -s     spherical coordinate system output. Angles are in [deg].
         The precision in position is 0.1 km.
```

```
-d      precision for the magnetic field output.
        <int> is the number of decimal places. Possible values: 1,2,3
        If '-d' but no <int> given, default is 1, i.e. 0.1 nT precision.
        Default is to use a format according to the data resolution.

-m      add the magnitude to each output vector.

-v      add the raw data variance (for high-resolution data) or
        the normalized variance of the magnetic field magnitude
        (for averaged data) to each output vector.

-f      add the data acquisition frequency to each output vector.

-i      append calibration filename info & output column names to output.

-o      use <outfile> as output file. If '-o', but no <outfile> given
        default name is : C#_yyyymmdd_sys.txt, where #=1,2,3,4 stands for
        satellite number and sys for the output coordinate system.
        Default is to write to stdout.
```

The Data Rate Module

The Module `fgmav`

Purpose

The program computes averages and the variance of high-resolution FGM vectors. The quality of averaging is computed and filled in the corresponding bits of the `status and id word`, and the flag for averaged data is set.

The averages are calculated separately for the three components and can either be taken over one spin rotation or over a time period. The time period might be specified by command line options or by start and end times read from a time list file.

The time to be assigned to the averaged vector is the centre of the averaging intervall.

Actions

- determine the way of averaging
- determine the averaging intervall and sum up the vector components
- compute the average, the variance, and the centre of the averaging intervall
- calculate the number of expected data points and from that the number of missing data points and the quality of average
- set the bit for averaged data in the `status and id word`

Input

- `fgmtvec_t` binary structures from *stdin*
- spin-time list file, produced from the S/C housekeeping, for option '-t'

Output

- `fgmtvec_t` binary structures to *stdout*

Usage and Options

```
... | fgmav { {-f|-s|-m} [<int>] | -p [<flt>] | -t <tlfile> } | ...

The program reads high-resolution CLUSTER FGM data (in fgmtvec_t format)
from stdin, computes averages and variance, and writes them to stdout.

In the FGM status and id word, the flag for averaged data is set, and
the quality of averaging is indicated by a bit field representing the
number of missing data points.
```

```
OPTIONS:

  -f <int>    compute averages over 1/<int> seconds.  Every <int>th
              averaging interval starts at full UT second.
              <int> must be smaller then the sampling frequency.

  -s <int>    compute averages over <int> seconds.  Averaging intervals
              begin at a UT of <int>, 2*<int>, 3*<int>, ... seconds.

  -m <int>    compute averages over <int> minutes.  Averaging intervals
              begin at a UT of <int>, 2*<int>, 3*<int>, ... minutes.

     <int>    integer number specifying the length of an averaging
              interval in minutes, seconds, or as fraction of a second.
              Default is 1.

  -p <flt>    compute averages over one spin rotation.  Averaging inter-
              vals begin at a spin phase of <flt> degrees.

     <flt>    float number specifying the offset spin angle (in degrees)
              at which a spin averaging interval starts.  Default is 0.

  -t <tlfile> read start, end, and tag of each averaging interval from the
              timelist file <tlfile>.  This is a binary file in the timelist
              format specified by UK CDHF.
```

The Info Modules

The Module `ddsls`

Purpose

The program extracts informations from the DDS packet headers of telemetry data.

Actions

- print the initial entries
- print new values, if an entry has changed,
- determine data gaps, if the data are science or housekeeping data

Input

- binary RD structures from files or *stdin*

Output

- ASCII listing to *stdout*

Usage and Options

```
ddsls [-t <int>] [-a] [-f <file-name>] [-i <cdrom-name>]
                                        [list] | ...

The program reads the DDS packet headers from telemetry
files given in list (default stdin) and writes some
fundamental informations in ASCII code to stdout.

If the input data are not housekeeping or science data, the
time information of each DDS-header found in the data will be
written to stdout. For housekeeping and science data there will
be two time entries in the output indicating a period of time
for which the parameters of the DDS-header have not changed.
If the option -a is used, the time information will be written
for each DDS-header.

-t  print the time information in the following form
     <int> = 0 : ISO standard time string like
                 '2000-12-02T02:05:15.798Z'
     <int> = 1 : (int) seconds of the UNIX epoch,
                 and (int) nanoseconds
     <int> = 2 : (float) seconds of the hour
     <int> = 3 : (float) hours of the day
```

```
     <int> = 4 : character string like
                 'Mon Dec  2 02:05:15 2000'
      default is the ISO time string

-a  print the time information of every packet even if
    these are science or housekeeping data

-f  write <file-name> as input if data are coming from
    stdin
    this can be used, if the input is derived from merged
    files specified by one filename using 'wild cards'

-i  write <cdrom-name> as input if data are coming from
    stdin
    this can be used, if the input is derived from merged
    files of one CD-ROM
```

The Output Format

The output will be an ASCII file with one entry per line, each line starting with one ID character. There are four different groups of entries:

- Parameter Entries

  Each line contains the information for one parameter. The following eight parameters have been identified:

  — input source
  — spacecraft
  — data type
  — data length
  — ground station
  — data stream
  — time calibration
  — telemetry acquisition mode

  A line for a parameter entry consist of three parts: the ID character, an integer value `<val>`, and a describing text. The value is separated from the ID character by a blank character. Between the value and the text stands the character '>'.

  The following chart summarizes the possible entries:

ID	`<val>`	text
I	0	Input data are coming from stdin.
	0	Input data are from file: `<file-name>`
	0	Input data are from CD-ROM: `<cdrom-name>`
	1, ...	Input file `<val>: <filename>`
S	1 ... 4	S/C number `<val>`
D	0 ... 231	`<Data type description>`, ref [DDID]
L	`<length>`	Data packet length: `<val>` bytes
R	0 ... 15	Ground station: `<ground station name>`
V	`<stream nr>`	`<Data stream description>`, ref [DDID]
C	0	ACTUAL TIME
	1	EXTRAPOLATED TIME
	2	CONTINGENCY TIME
A	0 ... 15	Telemetry acquisition mode: `<val>`

There is one initial entry for each parameter and additional entries, if the parameter has changed its value, i.e. the value for a parameter is valid until the next entry for this parameter appears.

- Special Entries
  There are two possible special entries. The first one is an error message that will be written, if the spacecraft ID does not match the data type, e.g. if the S/C ID is 1 and the data type indicates that the data is coming from a different S/C. The second one indicates data gaps.

  The entries have the same structure as the parameter entries:

ID	`<val>`	text
X	0	Error: S/C ID (S/C = `<num>`) DOES NOT MATCH DATA TYPE (S/C = `<num>`)
G	`<number>`	Data gap: `<val>` data blocks missing

- Time Information Entries
  The time information is derived from the packet timestamp. As mentioned above there are two ways of writing the time into the output file.

  1. The time of each packet timestamp is written.
  2. Two time lines are written. One indicating the start and the other indicating the end of a period with no change in the values of the parameters and no errors or data gaps. This way can only be used for housekeeping or science data.

  One time entry consists of two parts: an identifier and the time string. The format of this time string is determined by the command line parameter `-t`. Both parts are separated by a '>'.

The three different entries are in particular:

ID	content
T	single time entry for one DDS-header
B	start of a period with unchanged parameters and no data gaps
E	end of a period with unchanged parameters and no data gaps

- Delimitation Lines
  These lines are used for structuring the output file for more clarity. The ID character for this lines is a '%' to indicate that this is a comment line.

Example Output

The following is an output that has been derived from an FGM normal science data file of the test CD-ROM with the command:

```
ddsls 000823fn.1a1
```

```
%===============================================================
I 1>Input file 1: 000823fn.1a1
S 1>S/C number 1
D 31>Data type: NORMAL SCIENCE DATA FOR FGM ON CLUSTER 1
L 780>Data packet length: 780 bytes
R 1>Ground station: ODENWALD
V 2>Data stream: 02 hex = REAL-TIME VC2
C 0>Time calibration: ACTUAL TIME
A 2>Telemetry acquisition mode: 2
%---------------------------------------------------------------
B 2000-08-23T10:01:56.766Z
E 2000-08-23T11:29:52.650Z
%---------------------------------------------------------------
C 1>Time calibration: EXTRAPOLATED TIME
G 1051> Data gap: 1051 data blocks missing
%---------------------------------------------------------------
B 2000-08-23T13:00:12.798Z
E 2000-08-23T13:00:12.798Z
%---------------------------------------------------------------
C 0>Time calibration: ACTUAL TIME
%---------------------------------------------------------------
B 2000-08-23T13:00:17.950Z
E 2000-08-23T13:49:55.940Z
%---------------------------------------------------------------
G 353> Data gap: 353 data blocks missing
%---------------------------------------------------------------
B 2000-08-23T14:20:19.829Z
E 2000-08-23T14:29:51.727Z
%---------------------------------------------------------------
A 1>Telemetry acquisition mode: 1
G 4> Data gap: 4 data blocks missing
%---------------------------------------------------------------
B 2000-08-23T14:30:17.488Z
E 2000-08-23T21:54:45.437Z
%===============================================================
```

The Module `fgmls`

Purpose

The program extracts informations from a series of high resolution FGM vectors.

Actions

- print the initial entries for the parameters
- print new values, if an entry has changed,
- determine data gaps

Input

- binary `fgmtvec_t` structures from *stdin*

Output

- ASCII listing to *stdout*

Usage and Options

```
... | fgmls [-t <int>] | ...

The program reads FGM vectors of the 'fgmtvec_t' data structure
from stdin and writes some fundamental informations in ASCII
code to stdout.

There will be two time entries in the output indicating a
period of time for which the parameters of the FGM vectors
have not changed.

-t  print the time information in the following form
     <int> = 0 : ISO standard time string like
                 '2000-12-02T02:05:15.798Z'
     <int> = 1 : (int) seconds of the UNIX epoch,
                 and (int) nanoseconds
     <int> = 2 : (float) seconds of the hour
     <int> = 3 : (float) hours of the day
     <int> = 4 : character string like
                 'Mon Dec  2 02:05:15 2000'
      default is the ISO time string
```

The Output Format

The output will be an ASCII file with one entry per line, each line starting with one ID character. There are four different groups of entries:

- Parameter Entries

  Each line contains the information for one parameter. The following ten parameters have been identified:

  — spacecraft
  — magnetometer unit
  — sensor
  — active ADC
  — FGM telemetry option
  — FGM sensor range
  — science filtering mode
  — MSA filtering mode
  — outboard calibration mode
  — inboard calibration mode

  A line for a parameter entry consist of three parts: the ID character, an integer value `<val>`, and a describing text. The value is separated from the ID character by a blank character. Between the value and the text stands the character '>'.

  The following chart summarizes the possible entries:

ID	`<val>`	text
S	1 ... 4	S/C number `<val>`
U	1	outboard magnetometer
	2	inboard magnetometer
D	1	primary sensor
	2	secondary sensor
A	1 ... 2	ADC number `<val>` active
O	2, 3, 4, A, B, C, D, F	FGM telemetry option `<val>`
R	1 ... 7	FGM sensor range `<val>`
F	0	science filtering off
	1	science filtering on
M	0	MSA filtering off
	1	MSA filtering on
C	0	outboard calibration off
	1	outboard calibration on
K	0	inboard calibration off
	1	inboard calibration on

There is one initial entry for each parameter and additional entries, if the parameter has changed its value, i.e. the value for a parameter is valid until the next entry for this parameter appears.

- Special Entries
  There are two kinds of special entries. The first one is used for error messages. They will be written, if one of the error bits has been set in the `status and id word`.
  The second one indicates data gaps. `<val>` will show the number of missing data points, and the text will give the real time period between the two vectors (= vector period) and the expected time period (= sample period).

  The entries have the same structure as the parameter entries:

ID	`<val>`	text
X	0	Error: RANGE CHANGE ERROR
	1	Error: CALIBRATION MODE
	2	Error: (HALF/)ECLIPSE
G	`<number>`	Data gap: vector period: `<float>` sec, sample period: `<float>` sec

- Time Information Entries
  The time information consists always of two entries. One indicating the start and the other indicating the end of a period with no change in the values of the parameters and no errors or data gaps.

  One time entry consists of two parts: an identifier and the time string. The format of this time string is determined by the command line parameter `-t`. Both parts are separated by a '>'.

  The two different entries are in particular:

ID	content
B	start of a period with unchanged parameters and no data gaps
E	end of a period with unchanged parameters and no data gaps

- Delimitation Lines
  These lines are used for structuring the output file for more clarity. The ID character for this lines is a '%' to indicate that this is a comment line.

Example Output

The following is a part of the output that has been derived from an FGM normal science data file of the test CD-ROM with the command:

```
fgmtel 000824fn.1a2 | fgmls
```

```
S  2>S/C number 2
U  1>outboard magnetometer unit
D  1>primary sensor
A  1>ADC number 1 active
O 12>FGM telemetry option C
R  7>FGM sensor range 7
F  1>science filtering on
M  0>MSA filtering off
C  0>outboard calibration off
K  0>inboard calibration off
%---------------------------------------------------------------
B 2000-08-23T23:59:57.306Z
E 2000-08-24T08:05:58.897Z
%---------------------------------------------------------------
G 6007>Data gap: vector period: 267.955068 sec,
               sample period 0.044611 SEC
%---------------------------------------------------------------
B 2000-08-24T08:10:26.852Z
E 2000-08-24T08:59:54.534Z
%---------------------------------------------------------------
C  1>outboard calibration on
G 27373>Data gap: vector period: 1221.100943 sec,
                sample period 0.044611 SEC
%---------------------------------------------------------------
B 2000-08-24T09:20:15.635Z
E 2000-08-24T09:20:36.197Z
%---------------------------------------------------------------
C  0>outboard calibration off
%---------------------------------------------------------------
B 2000-08-24T09:20:36.240Z
E 2000-08-24T09:20:56.802Z
%---------------------------------------------------------------
C  1>outboard calibration on
%---------------------------------------------------------------
B 2000-08-24T09:20:56.845Z
E 2000-08-24T09:21:17.407Z
```

The Special Modules

The Module `ddscut`

Purpose
The program cuts out a time interval of telemetry data.

Actions

- read the packet header and determine the packet time stamp
- compare the packet time stamp with the given period
- write the packet, if it has a corresponding time stamp

Input
- binary RD structures from *stdin*

Output
- binary RD structures to *stdout*

Usage and Options

```
ddscut [-b <beginning>] [-e <end>] [-x] [list] | ...

The program reads telemetry raw data from files given
in list (default stdin), compares each packet's time stamp
with the specified time interval, and writes only those
packets to stdout whose time stamps fall into this interval.

If the modifier '-x' is set, the mode of operation is
inverted: only packets whose time stamps do not fall into
the specified time period are written to stdout. Thus, the
given time interval is excluded from the data.

In both cases, the time interval is inclusive, i.e., the
times <beginning> and <end> belong to the time interval
that is cut out or excluded.

Note that a given end time will be increased by one block
period of 5.152222 seconds to ensure that the complete data
of the selected time interval will be written.

-b  let the string <beginning> specify the beginning of
    the time interval
```

```
-e  let the string <end> specify the end of the time
    interval

     The following formats may be used for these strings:

     If the string contains the letter 'T', it will be
       interpreted as an ISO time string like
       '2000-09-01T12:00:04.012Z'.
     If the date is omitted, i.e. the string starts with
       a 'T', the date is being adopted from the time stamp
       of the first data package.
     If the string does not contain any 'T', it will be
       interpreted as seconds of the UNIX epoch, like
       '978420804.012443596'.

 -x     switch to 'excluding' mode.
```

The Module `ddshrm`

Purpose

The program removes the DDS packet headers of telemetry data files. This module is for example used for creating pure ASCII orbit and attitude files as they are needed for the data processing.

With the command line option `-i` this program can also be used to detect whether the data package has the expected identification number.

Actions

- read the packet header and perform the possible identification number check
- determine the packet length, read and write the rest of the packet

Input

- mixed binary ASCII telemetry files from *stdin*

Output

- ASCII information to *stdout*

Usage and Options

```
... | ddshrm [-i <int>] | ...

The program removes the DDS packet headers from a
telemetry file by reading it from stdin and writing
the same file without the DDS packet headers to stdout.

-i <int> if specified, the program expects the DDS
         packet headers to have a data source/type ID
         of <int> (a value between 0 and 255)
```

The Module `ddsmrg`

Purpose

The program merges telemetry raw data files into one time-sorted data stream.

Actions

- open all input files
- read the headers of the first packet of each file and get the packet time stamps
- write the data packet with the lowest time stamp, if it has not been written before, and read the next packet of that file until end of all input files

Input

- binary RD structures from files

Output

- binary RD structures to *stdout*

Usage and Options

```
ddsmrg <file>... | ...

The program reads telemetry raw data files, sorts
the data packets in ascending order of DDS header time
stamps, and writes them to stdout.

Telemetry packets which are read twice, i.e. packets
with the same time stamp and with the same data source
type, are only written once.
```

The Module `fgmcut`

Purpose

The program cuts out an interval of the `fgmtvec_t` data stream. The interval maybe defined by begin and end time or instrument settings.

Actions

- read a `fgmtvec_t` record from the data stream
- compare the vector time stamp with the given period, or some vector status value with the required one
- write the vector, if it fullfills the condition

Input

- binary `fgmtvec_t` structures from *stdin*

Output

- binary `fgmtvec_t` structures to *stdout*

Usage and Options

```
fgmcut  --  cut out vectors of CLUSTER FGM data

USAGE:

 ... | fgmcut [-b <beginning>] [-e <end>] [-x]
              [-s <sc>] [-a <adc>] [-r <range>] [-u <unit>] | ...

 The program reads CLUSTER FGM data (in fgmtvec_t format) from stdin, compares
 each vector's time with the specified time interval, and writes only those
 vectors to stdout which fall into this time period.

 If the modifier '-x' is set, the mode of operation is inverted: only vectors
 which do not fall into the specified time period are written to stdout.
 Thus, the given time interval is excluded from the data stream.

 In both cases, the time interval is inclusive, i.e., the times <beginning>
 and <end> belong to the time interval that is cut out or excluded.

 When specifying 'sc', 'adc', 'range' or 'sensor' only those vectors will be
 written to stdout that have the specified setting for this parameter.

OPTIONS:
```

```
-b    let the string <beginning> specify the beginning of the time interval.

-e    let the string <end> specify the end of the time interval.

    The following formats may be used for these strings:

    If the string contains the letter ‘T’, it will be interpreted as
      an ISO time string like ‘2000-09-01T12:00:04.012Z’.
    If the date is omitted, i.e. the string starts with a ‘T’, the date
      is being adopted from the time stamp of the first input vector.
    If the string does not contain any ‘T’, it will be interpreted as
      seconds of the UNIX epoch, like ‘978420804.012443596’.

-x    switch to ‘excluding’ mode.

-s    write only vectors from spacecraft <sc> (1-4).

-a    write only vectors measured with ADC number <adc>.
      0 = default ADC unit, 1 = spare ADC unit

-r    write only vectors with range <range> (1-7).

-u    write only vectors from the sensor <unit>.
      0 = outboard sensor unit, 1 = inboard sensor unit

-V    print version number on stdout, then exit.
```

The Auxiliary Data Modules

The Module `mrgatt`

Purpose

The program merges new records of attitude data that are read from *stdin* with an existing attitude file. So it can be used to add new entries to the attitude file or to update existing ones. It is even possible to update only parts of the validity period of an existing entry by splitting the period into smaller intervalls.

If there are competitive entries for a same time period, the records will be merged according to the following quality rules:

1. take reconstituted entry instead of predicted entry
2. take entry with latest time of generation
3. take entry from existing file instead of new entry from stdin

The DDS packet headers must have been removed from the input records!

This program is mainly used as a subprogram for the program putsatt.

Actions

- compare the validity time of the new data record with the validity times of the attitude entries in the file
- if there are competitive entries for a same time period, test which entry has a higher quality level and write the 'best' entry to *stdout*
- if necessary, split the former period of validity into smaller intervalls by inserting additional attitude records
- add new attitude records for new validity periods

Input

- ASCII attitude records from *stdin*
- merged ASCII attitude file `<sattfile>`

Output

- ASCII attitude records to *stdout*

Usage and Options

```
... | mrgatt <sattfile> | ...

The program reads Cluster SATT file records from stdin,
merges them with the specified SATT file <sattfile>,
and writes the merged file to stdout.
```

The Module `mrgorb`

Purpose

The program merges new records of orbit data that are read from *stdin* with an existing orbit file. So it can be used to add new entries to the orbit file or to update existing ones. It is even possible to update only parts of the validity period of an existing entry by splitting the period into smaller intervalls.

If there are competitive entries for a same time period, the records will be merged according to the following quality rules:

1. take reconstituted entry instead of predicted entry
2. take entry with latest time of generation
3. take entry from existing file instead of new entry from stdin

The DDS packet headers must have been removed from the input records!

This program is mainly used as a subprogram for the programs putstof and putltof.

Actions

- compare the validity time of the new data record with the validity times of the orbit entries in the file
- if there are competitive entries for a same time period, test which entry has a higher quality level and write the 'best' entry to *stdout*
- if necessary, split the former period of validity into smaller intervalls by inserting additional orbit records
- add new orbit records for new validity periods

Input

- ASCII position records from *stdin*
- merged ASCII position file `<posfile>`

Output

- ASCII position records to *stdout*

Usage and Options

```
... | mrgorb <orbfile> | ...

The program reads Cluster orbit file records from stdin,
merges them with the specified orbit file <orbfile>,
and writes the merged file to stdout.
```

The Module put{satt|stof|ltof}

Purpose

The program puts attitude or orbit file(s) (with DDS packet headers) into a merged file (without DDS packet headers). So it can be used to create or update a merged attitude or orbit file that can be used with the FGM data processing software.

The records of each input file must be time-ordered, and all input files must belong to the same spacecraft.

Actions

- remove the DDS packet headers from the input file(s)
- merge the input file(s) to one total input file
- create or update the existing attitude or orbit file using the total input file

Input

- raw attitude (SATT) or position (STOF/LTOF) file - environment variable `SATTPATH` or `ORBPATH`

Output

- ASCII merged attitude or position file

Usage and Options

```
putsatt <infile>... [-o [<outfile>]]
putstof <infile>... [-o [<outfile>]]
putltof <infile>... [-o [<outfile>]]

The program 'putsatt' reads Cluster attitude (SATT) files
like those distributed by the Cluster Data Disposition
System, i.e. with a DDS packet header attached to each
record. It creates or updates a merged SATT file in which
these headers are removed.

The program 'putstof' does the same for Cluster short
term orbit files.
The program 'putltof' does the same for Cluster long
term orbit files.

-o  use <outfile> as output file.
    If -o is used but <outfile> is omitted, or if
    <outfile> is '-', output is written to stdout.
```

```
Default is to create or update the file
  '$SATTPATH/satt.cl#',  for 'putsatt',
  '$ORBITPATH/stof.cl#', for 'putstof',
  '$ORBITPATH/ltof.cl#', for 'putltof',
where '#' is replaced by the satellite number (1,2,3,4).
To specify the name of the directory where these
default attitude files are installed, the environment
variable (SATTPATH or ORBITPATH) should be used.
```

The Master Modules

The Module fgmdp

Purpose

This program processes FGM data by putting single data processing modules together to produce various outputs. The input to the program are normal or burst mode science data files containing the raw FGM data, like those distributed on the raw data medium (RDM) and auxiliary files. The output depends on the used options, default is high resolution time stamped magnetic field and position vectors in GSE coordinates, as binary structure `fgmtrec_t` written to a file. The actions performed by the program depend on the selected pipeline. The selection is done through the options ('-b', '-e', -w', '-x'). The used pipeline is written to stdout (display).

Actions

The performed actions are the sum of the actions of to the used modules.

- default (core) pipeline:
  `fgmtel |fgmcal |fgmhrt| fgmpos`
  decodes input data, calibrates, transforms to GSE, adds position in GSE
- if options '-b' and/or '-e' used, the pipeline is extended with the cut module, which takes only the specified time interval:
  `ddscut| fgmtel |fgmcal |fgmhrt| fgmpos`
- option '-w' introduces into the pipeline the averaging module:
  `ddscut| fgmtel |fgmcal |fgmhrt| fgmav| fgmpos`
- option '-x' transforms output format to ASCII by using igmvec module:
  `ddscut| fgmtel |fgmcal |fgmhrt| fgmav| fgmpos|igmvec`

Input

- binary RD FGM telemetry files
- calibration file
- STEF/LTEF file
- SATT file
- STOF/LTOF file
- *'const.fgm'* file
- environment variable `FGMPATH`

Output

- binary `fgmtrec_t` or ASCII file

Usage and Options

```
  fgmdp [<inf>...] [-b <begin>] [-e <end>] [-a <attf>] [-p [<posf>]]
        [-E <eclf>] [ -w [<float>]] [-i] [-x] [-l [<logf>]] [-o [<outf>]]

  fgmdp generates high resolution magnetic field vectors in GSE
                  or averages over a user defined time interval.

  The input file is a normal or burst mode science data file containing
  the raw FGM data, like those distributed on the raw data media (RDM).
  More than one input file may be specified to concatenate data. If no
  input file is given, the data will be read from stdin.  If option '-w'
  not used, default output is high resolution. The default output format
  is binary igm-structure. Use option '-x' to get an ASCII file.
  ASCII output contains date/time, components of the magnetic field in [nT]
  and position vector components [km] in GSE coordinate system

 OPTIONS:

   -b <begin> define the begin of time interval for the output

   -e <end>   define the end of time interval for the output

              The following formats may be used for the  <begin> and <end>
              strings:
                 ISO standard, like '2000-09-01T12:00:04.012Z'
                 ISO standard, without date, like 'T12:00:04.012Z'
                 seconds of the UNIX epoch, like '778420804.012443596'.

   -w <float>  compute averages over <float> seconds. Averaging intervals start
               at full UT second. <float> must be larger then the sampling.
               If option '-w' present, but no <float> specified,
               spin-averages (PPs) are produced.

      <float>  float number specifying the length of an averaging
               interval in seconds. Fractions of seconds are taken into
               account only for subunitary numbers.

   -a   use <attf> as attitude file. <attf> may contain DDS-headers, i.e.
        the raw attitude file from CDROM (*ga*) may be used.
        Default is to use the merged attitude file '$SATTPATH/satt.cl#',
        #=1,2,3,4 is the satellite number.

   -p   use <posfile> as orbit file (*ba* on the CDROM)for determing the
        spacecraft's position. The file may, or may not contain DDS-headers.
        Default is to use the short term orbit file '$ORBITPATH/stof.cl#',
```

```
     (#=1,2,3,4) with DDS-headers beeing removed.
     If -p is used but <posfile> is omitted, the preprocessed long term
     orbit file `$ORBITPATH/ltof.cl#' will be used.

-E   read eclipse info from file <eclf>. <eclf> may contain DDS-headers, i.e.
     the raw attitude file from CDROM (*ta*) may be used.
     Default is '$SATTPATH/s{|l}tef.cl#', where #=1,2,3,4.

-x   ASCII output; default output is binary IGM-format

-i   append calfilename-info to the end of the ASCII output; to be used
     together with option '-x'. Default is to have the used calibration
     file-name written in a separate file: 'cal.log'. A tailstring
     containing output column names is appended too.

-l   re-direct info from stderr to a logfile <logf>;
     if option '-l', but no filename given, default is: 'logfile'

-o   use <outf> as output file. Default is to write to a file called :
     C#_yyyymmdd_sys.igm or C#_yyyymmdd_sys.txt (if '-x'),
     where #=1,2,3,4 stands for satellite number and sys for the output
     coordinate system.
```

The Module `fgmpsds`

Purpose

This program processes FGM data by putting single data processing modules together to produce the PSDS output. The input to the program are normal or burst mode science data files containing the raw FGM data, like those distributed on the raw data medium (RDM) and auxiliary files. PSDS output is an ASCII file containing time stamped magnetic field vectors in SCS system, averaged over 1 second. V6.2 handles the vectors sampled in calibration mode as real data and writes them to the output, while as V6.1 writes only unmarked data to the output. The pipeline consists of the following modules:

`ddsmrg| fgmtel |fgmcal |fgmhrt |fgmav |fgmvec`

Actions

The performed actions are the sum of the actions of the used modules.

Input

- binary RD FGM telemetry files
- calibration file
- STEF/LTEF file
- SATT file
- *'const.fgm'* file
- environment variable `FGMPATH`

Output

- ASCII listing to *stdout* or file

Usage and Options

```
fgmpsds [<infile>...] [-a <attf>] [-e <eclf>]
        [-s <sys>] [-l [<logf>]] [-i] [-o [<outf>]]

fgmpsds generates a Processing Support Data Set, containing
        one second averages of the magnetic field

The input file is a normal or burst mode science data file containing
the raw FGM data, like those distributed on the raw data medium (RDM).
More than one input file may be specified to concatenate data. If no
input file is given, the data will be read from stdin.

OPTIONS:

  -a   use <attf> as attitude file. <attf> may contain DDS-headers, i.e.
       the raw attitude file from CDROM (*ga*) may be used.
```

```
     Default is to use the merged attitude file ‘$SATTPATH/satt.cl#’,
     where ‘#’ is replaced by the satellite number.

-e   read eclipse info from file <eclf>. <eclf> may contain DDS-headers, i.e.
     the raw attitude file from CDROM (*ta*) may be used.
     Default is ’$SATTPATH/s{|l}tef.cl#’, where #=1,2,3,4.

-i   append calfilename-info to the end of the output;
     default is to have the used calibration file-name written in a
     separate file ’cal.log’
     A tailstring, containing output column names, is also appended.

-s   select the output coordinate system, where <sys> may be
     ‘sr’   for spin-reference system,
     ‘scs’  for spacecraft-sun system (this is the default),
     ‘gse’  for geocentric solar ecliptic system,
     ‘gsm’  for geocentric solar magnetospheric system, or
     ‘sm’   for solar magnetic system.
     ‘j2k’  for geocentric equatorial inertial system of epoch J2000.0.

-l   re-direct info from stderr to a logfile <logf>;
     if option ’-l’, but no filename given, default is: ’logfile’

-o   use <outf> as output file.If ’-o’, but no <outf> given,
     use default name : C#_yyyymmdd_sys.mag, where #=1,2,3,4 stands for
     satellite number and sys for the output coordinate system.
     Default is to write to stdout.
```

The Module `fgmppdb`

Purpose

This program processes FGM data by putting single data processing modules to produce an interface file for the CDF production in the Data Centres. The input to the program are normal or burst mode science data files containing the raw FGM data, like those distributed on the raw data medium (RDM) and auxiliary files. The output is an ASCII file in the IFF-format, containing time stamped averages of the magnetic field vector in GSE. The averaging interval is a spin period for the PPBD and 1 minute for the SPDB. V6.2 handles the vectors sampled in calibration mode as real data and writes them to the output, while as V6.1 writes only unmarked data to the output. The pipeline consists of the following modules:

`ddsmrg| fgmtel |fgmcal |fgmhrt |fgmav |fgmiff`

Input

- binary RD FGM telemetry files
- calibration file
- STEF/LTEF file
- SATT file
- STOF/LTOF file
- spin-timelist file, produced from S/C housekeeing, if option '-t'
- *'const.fgm'* file
- environment variable `FGMPATH`

Output

- ASCII listing to *stdout* or file

Actions

The performed actions are the sum of the actions of to the used modules.

Usage and Options

```
fgmppdb [<inf>...] [-a <att>] [-e <ecl>] [-t <tl>] [-l [<log>]] [-o [<out>]]
fgmspdb [<inf>...] [-a <att>] [-e <ecl>] [-t <tl>] [-l [<log>]] [-o [<out>]]

fgmppdb generates an interface file (IFF) for the CSDS Prime Parameter
        Data Base of CLUSTER FGM data, containing spin averages of the
        magnetic field.
fgmspdb generates an interface file (IFF) for the CSDS Summary Parameter
        Data Base of CLUSTER FGM data, containing one-minute averages of
        the magnetic field.

The input file is a normal or burst mode science data file containing
the raw FGM data, like those distributed on the raw data medium (RDM).
```

```
 More than one input file may be specified to concatenate data. If no
 input file is given, the data will be read from stdin.

OPTIONS:

  -a   use <att> as attitude file. <att> may contain DDS-headers, i.e.
       the raw attitude file from CDROM (*ga*) may be used.
       Default is to use the merged attitude file '$SATTPATH/satt.cl#',
       where '#' is replaced by the satellite number.

  -e   read eclipse info from file <ecl>. <ecl> may contain DDS-headers, i.e.
       the raw attitude file from CDROM (*ta*) may be used.
       Default is '$SATTPATH/s{|l}tef.cl#', where #=1,2,3,4.

  -t   use <tl> as timelist file, containing start, end, and tag times
       for each averaging interval.
       Default: fgmppdb will use a spin phase offset of 26.367 degrees
       with respect to the sun reference pulses as start times, whereas
       fgmspdb will use full minutes as start times.

  -o   use <out> as output file. If -o is used but <out> is omitted,
       output is written to stdout.
       Default is to write to a file whose name is generated according
       to the IFF file naming convention.

  -l   re-direct info from stderr to a logfile <log>.
       If -l is used but <log> is omitted, output is written to 'logfile'
```