

Daily calibration of the Fluxgate Magnetometer onboard the Cluster spacecraft

N. Gimmich¹, H.U. Auster¹, O.D. Constantinescu^{1,2},
K.H. Fornacon¹, K.H. Glassmeier¹, and F. Plaschke¹

¹Institute for Geophysics and Extraterrestrial Physics,
TU Braunschweig, Germany

²Institute for Space Sciences, Bucharest, Romania

September 18, 2025

During their 24 years mission of investigating the Earth's magnetosphere the four Cluster satellites delivered high quality magnetic field data measured by the onboard fluxgate magnetometers. To achieve the accuracy required for scientific studies, the raw magnetic field data need to be calibrated on a regular basis. We briefly review the methods used for the Cluster in-flight magnetic field data calibration, introduce the Cluster magnetometer calibration software, and present a statistical analysis of the calibration parameters and their long-term trends. This work aims to serve as a guide for researchers using the Cluster FGM data as well as a general reference for long-term behaviour of the calibration parameters of fluxgate magnetometers.

1 Introduction

The Fluxgate Magnetometer (FGM) calibration is the process of conversion of the raw digital output from a triad of sensor coils aligned along nonorthogonal axes into magnetic field vectors expressed in physical units in an orthogonal frame with a known orientation with respect to the spacecraft.

... Niklas ...

This work is organized as follows: a brief description of the FGM instruments onboard the Cluster spacecraft is given in Section 2. The techniques used for the Cluster FGM in-flight calibration are outlined in Section 3. An introduction to the dedicated FGM


Table 1: Cluster FGM instrument ranges.

range	B_{\max} (nT)	resolution (nT)	in operation since
2	64	1/128	2000
3	256	1/32	2000
4	1024	1/8	2000
5	4096	1/2	2006
6	16384	2	2009
7	65536	8	2009

calibration software is given in Section 4. The long-term behaviour of the instruments is discussed in Section 5.

2 Instrument description


The Cluster FGM experiment (Balogh et al., 1997) consists of eight tri-axial fluxgate sensors and the associated electronics units onboard the four Cluster spacecraft. Each spacecraft accommodates a pair of tri-axial sensors on a 5.2 m long radial boom lying in the spin-plane. The outboard sensor triad is placed at the end of the boom, while the other triad is placed 1.5 m inboard from the boom end. To cover a wide range of magnetic field strengths the instruments automatically switch between six ranges with different digital resolutions, as shown in Table 1. One of two Analog to Digital Converters (ADC) can be selected to translate the measurements from voltages to digital units.

... more details ? .. 

3 In-flight magnetometer calibration

The production of calibrated magnetic field data involves two separate major steps: First, the calibration parameters need to be determined based on pre-flight ground measurements and on analysis of the in-flight data, then the found parameters must be used to calibrate the data.

3.1 The calibration equation


Let $(\hat{\mathbf{S}}_1, \hat{\mathbf{S}}_2, \hat{\mathbf{S}}_3)$ denote the ver  of the sensor coils axes. They define a spinning, nonorthogonal (but nearly orthogonal) sensor system roughly aligned with an orthogonal frame $(\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}})$ solidar to the sensor triad. Given a magnetic field vector \mathbf{B} in the $(\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}})$ frame, the sensor j will measure the projection of \mathbf{B} on the sensor's axis $\hat{\mathbf{S}}_j$, affected by the the sensor's gain G_j and offset O_j :

$$B'_j = G_j \hat{\mathbf{S}}_j \cdot \mathbf{B} + O_j \quad (1)$$

Following the existent Cluster FGM calibration software choice of an orthogonal sensor frame with the x -axis aligned with the spacecraft spin, the components of $\hat{\mathbf{S}}_j$ in the orthogonal frame are:

$$\hat{\mathbf{S}}_j = (\cos \theta_j, \sin \theta_j \cos \varphi_j, \sin \theta_j \sin \varphi_j) \quad (2)$$

The elevation angles θ_j are measured with respect to the spin axis. The azimuth angles φ_j are measured with respect to the y -axis in the spin plane, positive towards the z -axis (i.e. positive in the direction of spin rotation).

Eq.(1) can be written in matrix form as 

$$\mathbf{B}' = \mathcal{T}\mathbf{B} + \mathbf{O} \quad (3)$$

which is the inverse calibration equation. The transformation matrix $\mathcal{T} = \mathcal{T}_{\text{gain}}\mathcal{T}_{\text{ortho}}$ is:

$$\mathcal{T} = \begin{pmatrix} G_x & 0 & 0 \\ 0 & G_y & 0 \\ 0 & 0 & G_z \end{pmatrix} \begin{pmatrix} \cos \theta_x & \sin \theta_x \cos \varphi_x & \sin \theta_x \sin \varphi_x \\ \cos \theta_y & \sin \theta_y \cos \varphi_y & \sin \theta_y \sin \varphi_y \\ \cos \theta_z & \sin \theta_z \cos \varphi_z & \sin \theta_z \sin \varphi_z \end{pmatrix} \quad (4)$$


Because the deviation from orthogonality is small, $\theta_x \approx 0$ and $\varphi_y \approx 0$. It is advantageous to do the following change of variables: $\theta_y \rightarrow \pi/2 - \theta_y \approx 0$; $\theta_z \rightarrow \pi/2 - \theta_z \approx 0$; $\varphi_z \rightarrow \pi/2 - \varphi_z \approx 0$. In addition we introduce the following notations:

$$\begin{aligned} \Delta G_{yz} &= G_y - G_z \approx 0 && \text{spin plane gain mismatch} \\ \Delta \varphi_{yz} &= \varphi_y - \varphi_z \approx 0 && \text{spin plane nonorthogonality} \end{aligned} \quad (5)$$

In practice the digital units from the Analog to Digital Converters (ADC) are already transformed in nominal nT using ground determined parameters before \mathbf{B} is introduced in Eq.(3), therefore the gains are close to unity ($G_j = 1 + \epsilon_j$). With this in mind, the first order approximation of the transformation matrix is:

$$\mathcal{T} = \begin{pmatrix} G_x & \theta_x \cos \varphi_x & \theta_x \sin \varphi_x \\ \theta_y & G_y & \varphi_y \\ \theta_z & \varphi_y - \Delta \varphi_{yz} & G_y - \Delta G_{yz} \end{pmatrix} \quad (6)$$

which is the equivalent of the matrix in Eq.(8) of Kepko et al. (1996).

The calibration equation associated to Eq.(3) is 

$$\mathbf{B} = \mathcal{M}(\mathbf{B}' - \mathbf{O}) \quad (7)$$

where the calibration matrix \mathcal{M} is equal to \mathcal{T}^{-1} . In the first order, the calibration matrix is:

$$\begin{aligned} \mathcal{M} &= \begin{pmatrix} 1 & \theta_x \cos \varphi_x & \theta_x \sin \varphi_x \\ \theta_y & 1 & \varphi_y \\ \theta_z & \varphi_y - \Delta \varphi_{yz} & 1 \end{pmatrix}^{-1} \begin{pmatrix} G_x & 0 & 0 \\ 0 & G_y & 0 \\ 0 & 0 & G_y - \Delta G_{yz} \end{pmatrix}^{-1} \\ &= \begin{pmatrix} 1/G_x & -\theta_x \cos \varphi_x & -\theta_x \sin \varphi_x \\ -\theta_y & 1/G_y & -\varphi_y \\ -\theta_z & -(\varphi_y - \Delta \varphi_{yz}) & 1/(G_y - \Delta G_{yz}) \end{pmatrix} \end{aligned} \quad (8)$$

Eq.(7) in the first order is the basis for both determining the calibration parameters and for the production of calibrated data.

3.2 Determination of the calibration parameters

In-flight calibration consists in determining calibration parameters, i.e., the elements of the transformation matrix \mathcal{M} and of the offset vector \mathbf{O} , in total 12 values. In the ideal case when all gains are equal to one and all sensor coils axes are perfectly aligned with the orthogonal frame axes, the transformation matrix is the unit matrix. Incorrect values of some calibration parameters lead to clear coherent signals at spin and double spin frequency in the calibrated magnetic field (Farrell et al., 1995; Kepko et al., 1996; Auster et al., 2002; Plaschke et al., 2019). Other parameters, if assigned incorrect values lead to flawed measurements contradicting known properties of physical phenomena such as the Alfvén waves in the solar wind (Belcher, 1973; Hedgecock, 1975; Leinweber et al., 2008) or the mirror mode waves in the magnetosheath (Plaschke and Narita, 2016). These are the keys to adjust the calibration parameters to their correct values.

3.3 Specific implementation for Cluster FGM

There are several relevant reference systems for the Cluster FGM in-flight calibration:

- SMB The Spacecraft Mechanical Build system is fixed to the spacecraft body with the x_{SMB} -axis defined by the nominal spin axis. The z_{SMB} -axis leads the y_{SMB} -axis in the direction of rotation.
- FS The nonorthogonal FGM Sensor system is defined by the three sensor coil axes and is roughly aligned with the SMB system. The measurements are made in this system.
- OS The Orthogonalized Sensor system shares the x -axis with the FS system. The y_{OS} is orthogonal to the x_{OS} in the $(x_{\text{FS}}, y_{\text{FS}})$ -plane, and z_{OS} completes the system.
- FSR The FGM Spin Reference system has the x_{FSR} -axis defined by the maximum principal inertia axis. The y_{FSR} and z_{FSR} complete the right-handed orthogonal system roughly aligned with the SMB system.

More information about the reference frames used for the FGM data processing can be found in the FGM Data Processing Handbook (FGMDP, Forné et al., 2011).

The transformation from the digital units produced by the ADC to nominal nT in the FS system involves range-dependent, ADC-characteristic scaling matrices and offsets:

$$\mathbf{B}^{\text{FS}} = \mathcal{M}_{\text{scale}}^{(r)} (\mathbf{D} - \mathbf{O}_{\text{ADC}}^{(r)}) \quad (9)$$

The superscript $^{(r)}$ denotes range dependence. The scaling matrices and the ADC offsets were determined during ground calibration campaigns at the TU-Braunschweig Magnet-rode (reference?) facility and are not subject to be changed by the in-flight calibration.

The in-flight calibration takes the magnetic field resulted from Eq.(9) as starting point and computes the calibrated magnetic field in the FSR system.

$$\mathbf{B}^{\text{FSR}} = \mathcal{M}_{\text{rot}} \mathcal{M}_{\text{sc}} \left(\mathcal{M}_{\text{cal}}^{(r)} (\mathbf{B}^{\text{FS}} - \mathbf{O}^{(r)}) - \mathbf{O}^{\text{sc}} \right) \quad (10)$$

There are two nested calibrations in Eq.(10): First a range specific (inner) calibration is applied to the magnetic field in the nonorthogonal FS system, resulting in an intermediate range-calibrated magnetic field in the OS system. The range-specific parameters are related the orthogonality and to the electronics and do not arise from real physical magnetic fields. The artificial magnetic fields generated by the spacecraft affect all ranges in the same way and are dealt with by the outer calibration. The outer calibration also transforms the measurements into the FSR system by aligning the OS x -axis to the inertial spin axis.

The input calibration parameters are:

\mathcal{M}_{rot} converts from the OS to the FSR system (spin axis alignment). It is determined by two Euler rotation angles: α_y around the y -axis and α_z around the z -axis.

$$\mathcal{M}_{\text{rot}} = \begin{pmatrix} \cos \alpha_z & \sin \alpha_z & 0 \\ -\sin \alpha_z & \cos \alpha_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \alpha_y & 0 & \sin \alpha_y \\ 0 & 1 & 0 \\ -\sin \alpha_y & 0 & \cos \alpha_y \end{pmatrix} \quad (11)$$

\mathcal{M}_{sc} was introduced to correct for any residual nonorthogonality still present after the inner range-specific calibration. However, it was found not to be necessary, therefore \mathcal{M}_{sc} remained set to the identity matrix throughout the mission for all spacecraft and will be ignored from now on.

$\mathcal{M}_{\text{cal}}^{(r)}$ is the range-specific calibration matrix Eq.(8) converting from the FS to the OS system. From the definition of the OS and FS systems results that the angles θ_x and φ_y are equal to zero. Therefore the range-specific calibration matrix is:

$$\mathcal{M}_{\text{cal}}^{(r)} = \begin{pmatrix} 1/G_x & 0 & 0 \\ -\theta_y & 1/G_y & 0 \\ -\theta_z & \Delta\varphi_{yz} & 1/(G_y - \Delta G_{yz}) \end{pmatrix} \quad (12)$$

Any deviation of the x -axis direction from the inertial spin axis is corrected by the \mathcal{M}_{rot} matrix. In this way, the orthogonalization is fully separated from the spin axis alignment.

$\mathbf{O}^{(r)}$ range-specific offset in the FS system

\mathbf{O}^{sc} spacecraft generated offset in the OS system

The calibration parameters have been accurately determined prior to the launch on the ground at the TU-Braunschweig Magnetsrode facility. However, various factors such as temperature changes, mass redistribution due to fuel consumption, and ageing of instrument components lead to changes of the parameters. It is therefore necessary to periodically check and adjust in-flight these calibration parameters.

The calibration parameters can be divided into three categories according to the calibration method used to determine them:

1. Parameters which can be determined through Fourier analysis of the first and second harmonic of the spin tone ω :

$$\omega: \alpha_y, \alpha_z, \theta_y^{(r)}, \theta_z^{(r)}, O_y^{(r)}, O_z^{(r)}, O_y^{\text{sc}}, O_z^{\text{sc}}$$

$$2\omega: \Delta\varphi_{yz}^{(r)}, \Delta G_{yz}^{(r)}$$

2. Parameters which can be determined through solar wind analysis:

$$O_x^{(r)}, O_x^{\text{sc}}$$

3. Parameters which can be determined through comparison with geomagnetic models if close enough to Earth.

$$G_x^{(r)}, G_y^{(r)}$$

In the next subsections we outline the methods used to determine the Cluster FGM calibration parameters in the first two categories.

3.3.1 Power spectrum analysis

As noted above, deviations of the calibration parameters in the first category from their correct values lead to coherent signals at the first and second harmonic of the spin frequency. More precisely, a spin-tone signal results from errors in the elevation angles θ_y and θ_z , or in the spin plane offsets O_y and O_z . Errors in the spin plane gain mismatch ΔG_{yz} and in the spin plane nonorthogonality $\Delta\varphi_{yz}$ result in a signal at the double spin frequency.

These effects do not affect all components of the calibrated magnetic field in the same way, allowing for a more precise decoupling of the calibration parameters. A look at the Eq.(12) shows that errors in the calibration matrix \mathcal{M} cannot lead to coherent spin related signals in the calibrated spin aligned B_x component. They can only affect the spin plane component $B_{yz} = \sqrt{B_y^2 + B_z^2}$. When the first harmonic of the spin frequency is observed in the spin plane component, an ambiguity still arises as of which calibration parameter is responsible for it. Both the spin plane elevation angles θ_y, θ_z and the spin plane offsets O_y, O_z could cause it. However, the effect is dependent on the magnetic field magnitude. Offsets are adjusted for low field intervals, orthogonality is adjusted for high field intervals. A spin tone signal in the spin aligned component can only originate from errors in the spin alignment matrix \mathcal{M}_{rot} .

In summary, the calibration parameters in the first category are determined as follows:

- spin axis alignment α_y, α_z :
minimize spin tone in the spin axis component B_x
- spin plane angles θ_y, θ_z :
minimize spin tone in the spin plane component B_{yz} at high fields
- spin plane offsets O_y, O_z :
minimize spin tone in the spin plane component B_{yz} at low fields
- spin plane nonorthogonality and spin plane gains mismatch $\Delta\varphi_{yz}, \Delta G_{yz}$:
minimize the second harmonic in the spin plane component B_{yz}

3.3.2 Solar wind analysis

The spin axis offset O_x can be determined from the properties of the Alfvén waves (Belcher, 1973; Hedgecock, 1975; Leinweber et al., 2008). Because of their orbits, the Cluster spacecraft are immersed into the solar wind only during the “dayside season” lasting roughly from November to June each year. This precludes the determination of the spin axis offsets on a daily basis. To obtain an accurate offset estimation, the spacecraft should spend intervals of at least one day in the unperturbed solar wind (foreshock excluded). This only occurs towards the middle of the dayside season. Therefore an accurate daily calibration for the spin axis offsets is not possible neither during the dayside season. As a compromise, the spin plane offsets were determined once per year based on several hours interval of measurements in the solar wind for all instrument ranges. For this purpose the instrument was set using ground commands into a special calibration mode which switches through all ranges at low fields. The obtained data was analysed and the offset minimizing the correlation between changes in the field magnitude and changes in the inclination of the field (Hedgecock, 1975) was selected. The determined spin axis offsets were considered valid until the following year solar wind calibration.

As more years of data were collected, it became possible to make a better estimation of the spin axis spacecraft offset O_x^{sc} using all available measurements in the solar wind. The idea is to determine an offset for each dayside season using all the available data and to calculate the daily spin axis offsets through an interpolation of the obtained yearly offsets.

For the selection of the solar wind intervals (SWI) we use the Geospace Region and Magnetospheric Boundary (GRMB) dataset (Grison et al., 2025). For each SWI (with length spanning roughly from 30 min to 30 h) we calculate a set of spin axis offsets using a 6 min window slid with a 10 s step. For each window we apply the Davis-Smith method (Leinweber et al., 2008) and minimize the variation of the calibrated magnetic field magnitude while keeping the spin plane offsets constant at their already calibrated values.

The offset associated with each SWI is obtained through a Kernel Density Estimation (KDE, Scott, 2015) of the resulting set. Since during the dayside season there are typically multiple SWIs in one day, the daily offset is computed as a weighted average of the SWIs offsets in that day. For the weighting, the standard deviation of each set and the SWI length are used.

Since no selection of intervals which are likely to contain Alfvén waves among the SWIs in the GRMB dataset is done, the daily offsets show a significant spread around the real offset. Therefore we use again a kernel density estimation of the daily offsets for each dayside season and we assign the result to the approximate middle of each season, 1st of March. These are the new yearly spin axis offsets.

To arrive at the final daily spin axis offsets we fit a sine function to the yearly offsets. The spin axis offsets relative to their values at the beginning of the mission are shown in Figure 1 for all four Cluster spacecraft. The blue dots are the (dayside season) daily offsets. The orange dots are the yearly offsets, with error bars showing the standard deviation of the daily offsets for the respective season. The final daily offsets

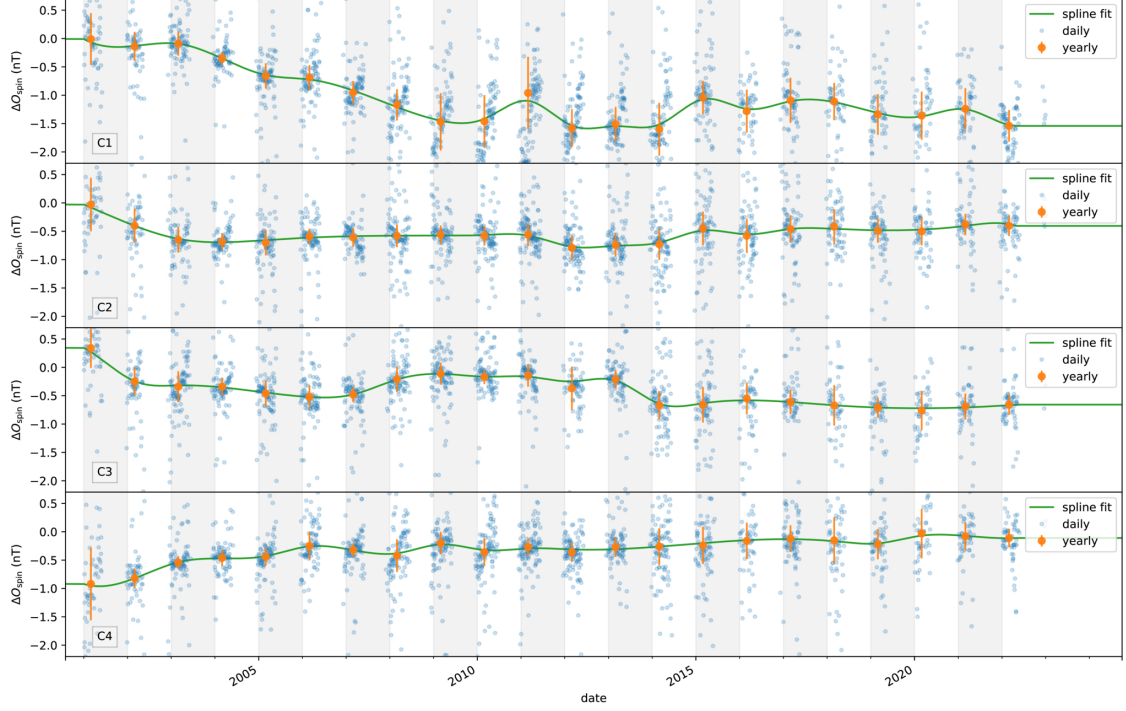


Figure 1: The spin axis spacecraft offsets O_x^{sc} adjustments from the beginning of mission values. The blue dots are the dayside season daily offsets resulted from the Davis-Smith method. The orange dots are the yearly offsets estimated from the maximum KDE of the daily offsets in the respective dayside season. The green line shows the final adjustments to the spin axis offsets.

are depicted with the green line.

4 Cluster FGM daily calibration software

Much of the Cluster FGM calibration and data processing software developed organically inheriting code used for magnetometers onboard other missions such as the FGM onboard the Equator-S spacecraft (Fornaçon et al., 1999; Haerendel, 2000). As a consequence, it includes code written in C, Fortran, IDL, Perl, and Python. The software used to extract the raw data from the telemetry frames, to apply the calibration and to transform the calibrated magnetic field into various coordinate systems is written in C and Fortran. The software used to determine the calibration parameters based on Fourier analysis is written in IDL. Determination of the spin-axis offset in the solar wind is done using software written in Python. Automatization of the daily calibration of the spacecraft offset is done using Perl scripts.

4.1 Calibration applying software

The raw data processing software is composed of modules which can be chained together to form a data processing pipeline. Various pipelines are used to produce the input data for calibration and the final calibrated data. Each module has a detailed manual page and basic usage is printed to the standard output by running the program with the command line argument `-h`. All modules are described in the FGMDP. The modules and the FGMDP can be downloaded from the archive (reference?).

The `fgmcal` module applies the calibration to the measured data. When applying the calibration it is no longer necessary to keep the parameters decoupled. Therefore the calibration equation Eq.(10) is condensed into a simpler form:

$$\mathbf{B}^{\text{FSR}} = \mathcal{M}_{\text{fgmcal}}^{(r)} \mathbf{B}^{\text{FS}} - \mathbf{O}_{\text{fgmcal}}^{(r)} \quad (13)$$

where the range specific calibration matrix $\mathcal{M}_{\text{fgmcal}}^{(r)}$ contains the scaling, the orthogonalization, and the alignment information. From Eq.(10) the first order of $\mathcal{M}_{\text{fgmcal}}^{(r)}$ is:

$$\mathcal{M}_{\text{fgmcal}}^{(r)} = \mathcal{M}_{\text{rot}} \mathcal{M}_{\text{cal}}^{(r)} = \begin{pmatrix} 1/G_x & \alpha_z & \alpha_y \\ -\alpha_z - \theta_y & 1/G_y & 0 \\ -\alpha_y - \theta_z & \Delta\varphi_{yz} & 1/(G_y - \Delta G_{yz}) \end{pmatrix} \quad (14)$$

which is the calibration matrix in Eq.(8) with explicit rotations around the y and z axes. The range offset vector in the FSR frame is:

$$\mathbf{O}_{\text{fgmcal}}^{(r)} = \mathcal{M}_{\text{rot}} \mathbf{O}^{\text{sc}} + \mathcal{M}_{\text{rot}} \mathcal{M}_{\text{cal}}^{(r)} \mathbf{O}^{(r)} \quad (15)$$

The compact form of the daily calibration parameters are read from text files with the `fgmcal` extension.

4.2 Calibration parameters estimation software

The manual tuning of the calibration parameters can be done using the graphical user interface (GUI) of the IDL calibration script `cls.pro` illustrated in Figure 2. The main window serves for the visualization of the calibration results and for running the power spectrum analysis and optimizations described in Section 3.3.1 to determine the calibration parameters. The calibration parameters are shown in a separate window. The parameters can be loaded and saved to text files with the extension `cfgnew`. Each parameter can be individually modified and the result of applying the modified parameters is displayed in the main window.

In addition, the spin axis spacecraft offsets O_x^{sc} must be estimated as described in Section 3.3.2. This is done by the Cluster calibration Python package which can be downloaded from the archive (reference?). The modules and the scripts included in the package contain detailed documentation.

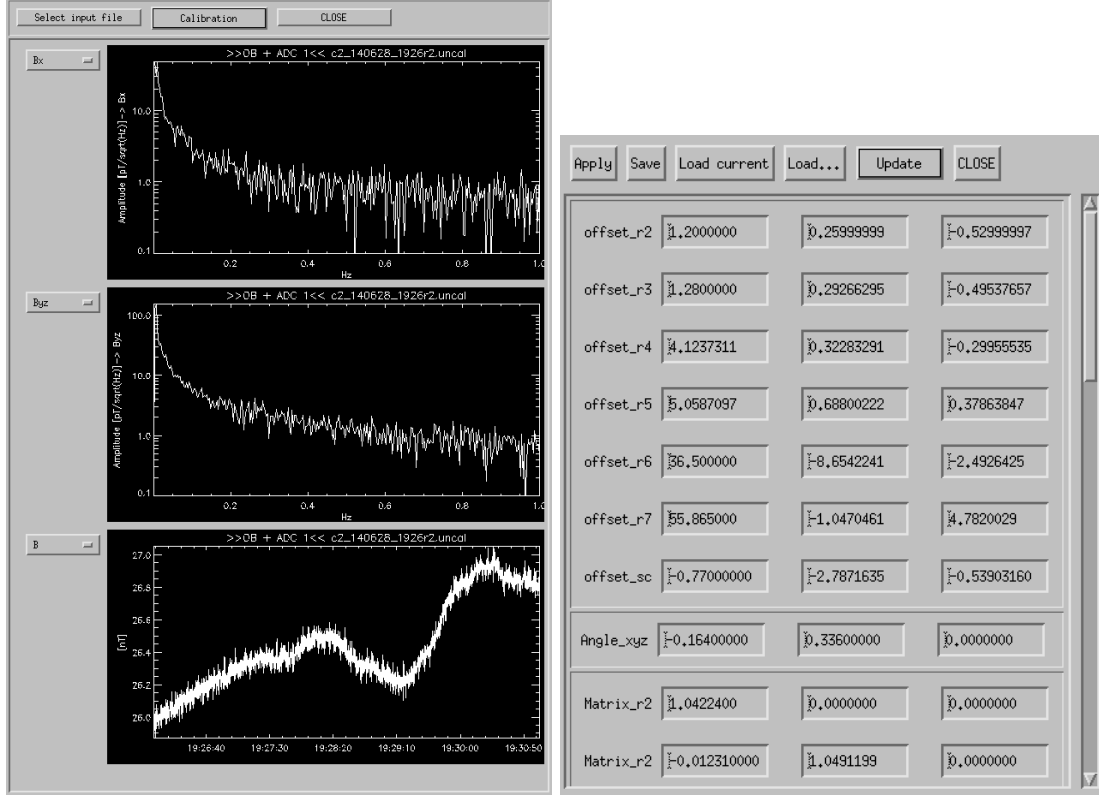


Figure 2: The main window (left) and the calibration parameters window (right) of the IDL `cls.pro` calibration GUI

4.3 Daily calibration automatization software

The routine of daily calibration follows the steps below:

1. Identify daily 5 min long intervals for spacecraft spin plane offsets calibration (O_y^{sc} and O_z^{sc}). These should be quiet, low field intervals with the instrument operating in range 2.
2. Estimate the spacecraft spin plane offsets for these intervals by minimizing the spin plane spin tone.
3. Produce daily spectrograms and time series plots around the range changes.
4. Visually inspect the daily spectrograms and the range change plots.
5. If anomalous spectral power is observed at the first or second harmonic of the spin frequency use the IDL `cls.pro` GUI to adjust the corresponding parameters.
6. If discontinuities are observed in the range changes plots adjust the corresponding parameters.

7. Archive the estimated calibration parameters in both `cfgnew` and `fgmcal` formats.

A number of Perl scripts were developed to automatize the first three items in the list above. All scripts have extensive manual pages and can be downloaded from the archive (reference?). The flowchart of the Cluster FGM daily calibration is sketched in Figure 3. The tasks of the software modules making up the data processing chain are:

`findr2` identifies suitable data intervals for spacecraft spin plane offset estimation.

`mkuncal` produces 5 min long data intervals using the times identified by the `findr2` script.

`cls_ini` estimates the spacecraft spin plane offsets using the data intervals produced by the `mkuncal` script. Saves the calibration parameters in the `cfgnew` and `fgmcal` formats.

`makecal` applies the calibration parameters saved in the `fgmcal` files and produces the spectra for visual inspection.

`listfgm` produces the log files needed to identify instrument ranges.

`findRC` produces 5 min long data intervals around the range changes.

`plotrc` produces the range changes plots for visual inspection.

5 Long-term trends and seasonal variations

The nearly quarter century long dataset of FGM calibration parameters for the four Cluster spacecraft reveals the exceptional stability of the instruments. The long-term variations were already investigated by Alconcel et al. (2014) based on the dataset available at the time, covering the first half of the mission. We extend the survey for the entire duration of the mission and can confirm most of the conclusions reached by Alconcel et al..

For each parameter we produced time series plots of the daily values over the entire mission duration together with the yearly averages and the yearly standard deviations. Only the plots of the spin axis alignment angles, spacecraft offset, range4 offset and range4 matrix for C1 are shown here. The rest of the parameters plots are included in the accompanying Supporting Information (SI).

Basic statistics were computed for each parameter and are presented in Tables 2 to 5. The columns *mission average* and *mean yearly standard deviation* are self-explanatory. The *decadal trend* column aims to quantify systematic overall drift of the parameters from the beginning to the end of the mission. A glance over the parameters plots shows that most parameters do not display an actual increasing or decreasing trend. For these parameters, the trend is set to zero in the tables. The remaining parameters tend to show a higher rate of change in the first years of the mission, followed by a lower rate or even quasi-constant values during the second half of the mission. This behaviour makes

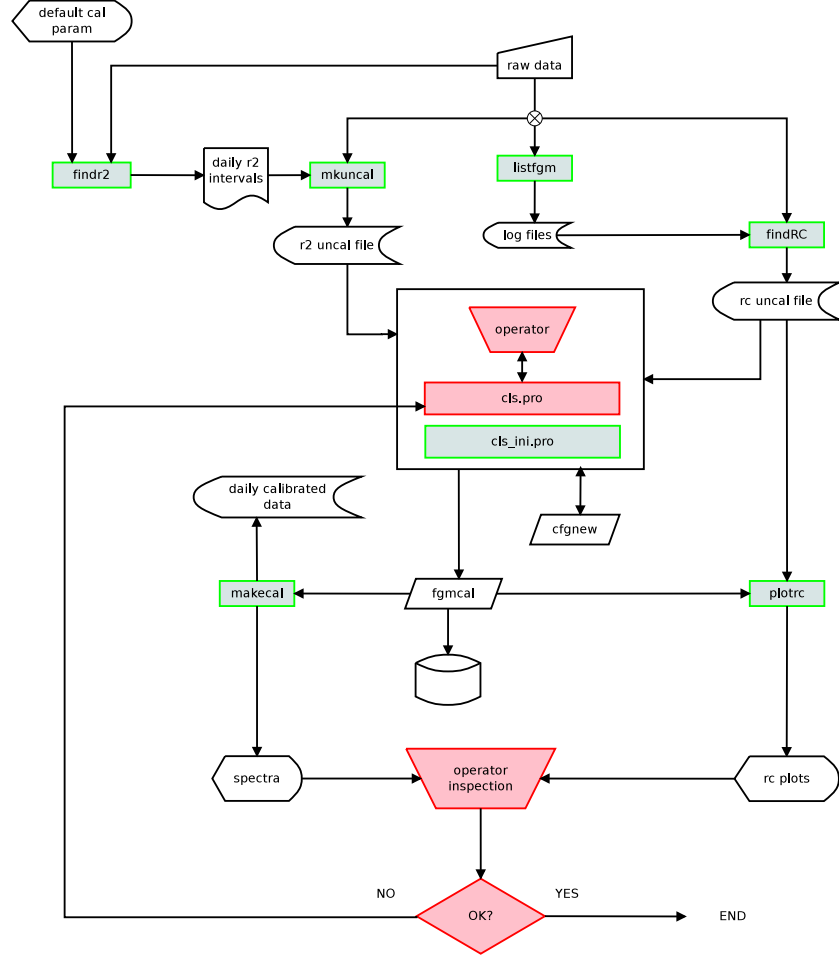


Figure 3: The flowchart diagram of the Cluster FGM daily calibration. The green boxes represent software able to process data from multiple days, usually one month. The red boxes need human intervention.

it problematic to describe the parameters trends. To keep the tables easy to digest, we decided to restrict the presented trend information to the slope of the linear trend. If the overall change is larger than three mean yearly standard deviations of the parameter, it is considered that a trend exists and the ten-year change is filled in the table. Otherwise the trend is set to zero in the table. To aid visualization of the tables, all zero values are greyed-out.

Below we discuss the long-term behaviour of a subset of calibration parameters.

5.1 Spin plane offsets

The spacecraft spin plane offsets O_y^{sc} , O_z^{sc} , as well as the range spin plane offsets $O_y^{(r)}$, $O_z^{(r)}$ are estimated through the minimization of the spin tone signal in the calibrated

spin plane component B_{yz} .

The spacecraft spin plane offsets are illustrated in Figure 4 for C1 and in Figure S15, Figure S28, and Figure S41 of the accompanying SI for the other spacecraft. All spin plane spacecraft offsets exhibit a clear seasonal variation which was linked by Alconcel et al. to the warming/cooling temperature cycles of the sensor temperature. For C1 an overall trend is clearly observable in both components. From Table 2 we see that the trend of the O_y^{sc} component is about $1.7 \text{ nT decade}^{-1}$ and the trend of the O_z^{sc} component is about $-0.8 \text{ nT decade}^{-1}$. The spacecraft spin plane offsets of the other spacecraft do not show any relevant trend, except for the O_z^{sc} component of C4 which has a trend of $-0.3 \text{ nT decade}^{-1}$. Where a trend is present, the rate of change tends to decrease towards the end of the mission.

The yearly standard deviation of the spin plane offsets reflects the amplitude of the seasonal variation which changes significantly over the course of the mission. C1 has the largest mean yearly standard deviation of the spin plane spacecraft offsets, equal to 0.3 nT for O_y^{sc} and 0.2 nT for O_z^{sc} . For the other spacecraft this quantity is around 0.1 nT . The largest peak to peak amplitude of the seasonal cycles, almost 2 nT , is reached for the C1 O_y^{sc} component in the last years of the mission. During the first years the amplitude of the seasonal cycles of both spin plane offset components is significantly lower. The pattern of the seasonal variations is different from spacecraft to spacecraft and from component to component.

Since the spacecraft offsets are always determined using range 2 data, the range 2 offsets are directly tied to the spacecraft offsets and are kept constant during the mission. No trends of the spin plane offsets are observed in range 3 and their overall variation in this range is below 0.3 nT for all spacecraft. The mean yearly standard deviations for the range 3 offsets are insignificant for all four spacecraft (below 0.05 nT).

Reaching values of $2.7 \text{ nT decade}^{-1}$ and $-1.4 \text{ nT decade}^{-1}$ the spin plane offsets of range 4 of C1 display some of the strongest offset trends. Figure 5 shows a very clear long-term trend of all offset components. An overall change in $O_y^{(4)}$ of roughly 8 nT and in $O_z^{(4)}$ of roughly 3 nT takes place before 2012. After this date only seasonal cycles affect the offsets. Similar but much weaker variations can be observed for range 4 of C2 in Figure S17. No significant trends are observed for the spin plane offsets in range 4 of C3 and C4.

Even though range 5 commenced operating only in 2006, the range 5 spin plane offset of C1 behaves similarly to the range 4 spin plane offset, as it can be seen in Figure S5. No clear trends are observed for the range 5 spin plane offsets of the other spacecraft though.

While the variations of the range 6 and range 7 offsets are significant, no clear trend can be identified for these ranges.

5.2 Spin axis offsets

The spacecraft spin axis offsets O_x^{sc} are estimated as described in Section 3.3.2. The estimation procedure obscures potential seasonal cycles likely similar to the spin plane

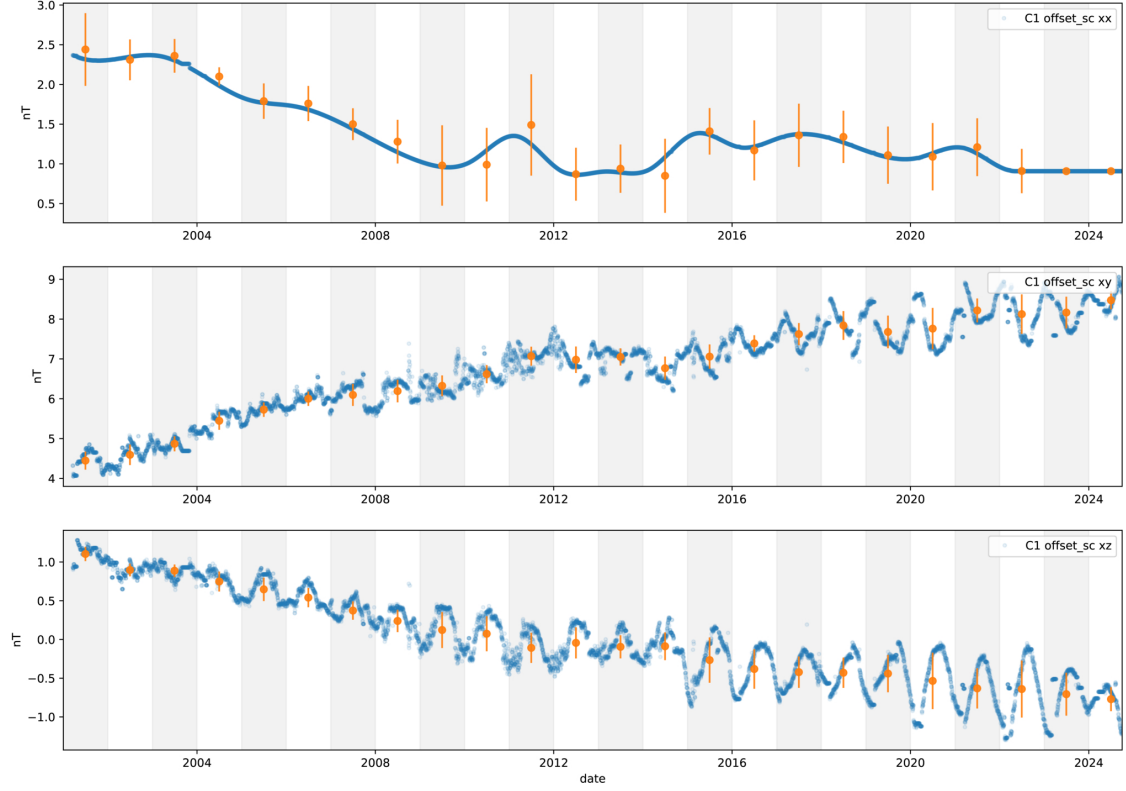


Figure 4: The spacecraft offsets for C1. The daily offsets are represented by the blue dots, the yearly averages are plotted with orange dots. The error-bars are the standard deviations for each year.

component offsets variations. The overall trend however follows the trends observed in the spin plane components.

The spin axis offsets of the ranges are determined by requiring that no discontinuity of the measurements occurs when the instrument switches between the ranges. As in the case of the spin plane offsets, range 2 offsets are kept constant. The spin axis offsets of the higher ranges mirror the behaviour of the spin plane offsets. The range 4 offset of C1 presents the strongest trend among all ranges and all spacecraft reaching over $10 \text{ nT decade}^{-1}$ with the bulk of the change occurring in the first half of the mission.

5.3 Spin axis alignment angles

Despite being placed at the tips of 5 m long booms, the alignment relative to the inertial spin axes of the sensor coils measuring the spin aligned magnetic field is better than 1° . The in-flight determination of the alignment angles is done by minimizing the spin tone signal in the spin axis component of the calibrated magnetic field. If the alignment is done using high field data this method delivers arcsecond order precision. The largest mean yearly standard deviations of the determined spin alignment angles are around $1'$

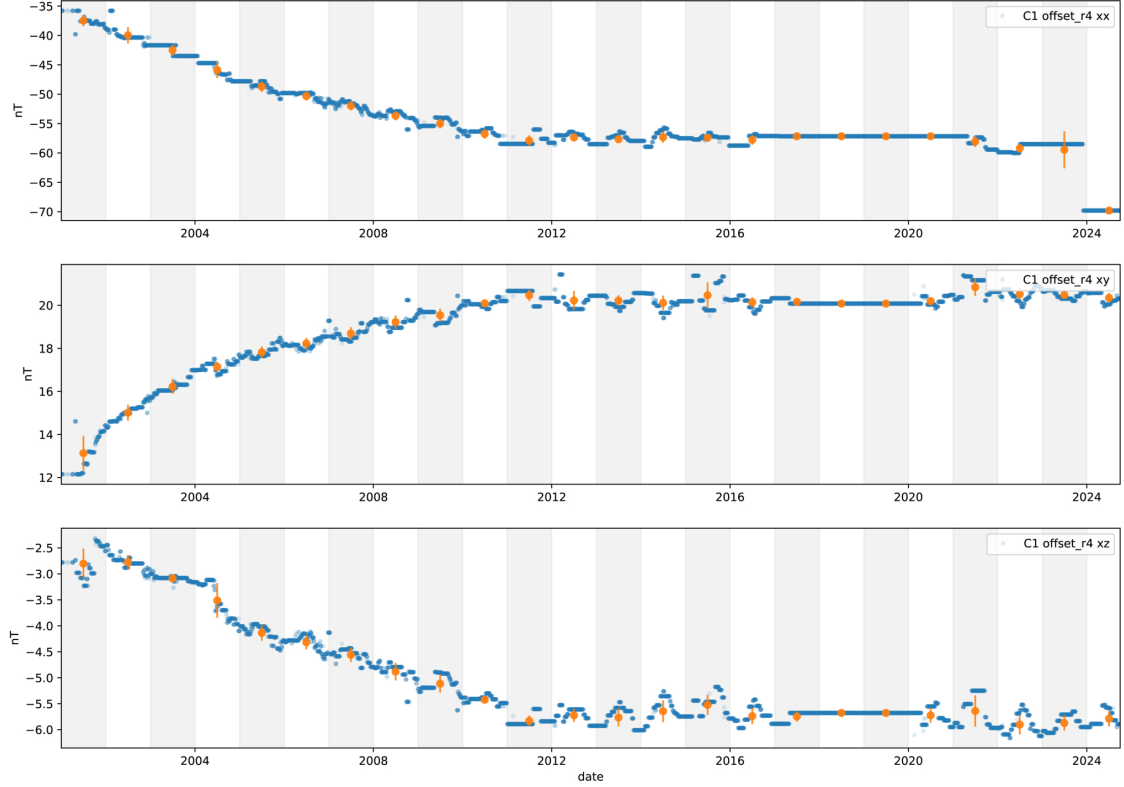


Figure 5: The range 4 offsets for C1. The daily offsets are represented by the blue dots, the yearly averages are plotted with orange dots. The error-bars are the standard deviations for each year.

for C1. For the other spacecraft the mean yearly standard deviations are between $7''$ and $14''$. The long term trends of the spin alignment angles are below $1' \text{ decade}^{-1}$ for all spacecraft.

5.4 Spin plane angles

Figure 7 illustrates the range 4 calibration matrix of C1. The subplots are arranged following the order of the matrix elements. The lower two elements of the first column of the range calibration matrices are linked to the deviations from orthogonality of the angles between y_{FS} and x_{FS} , and between z_{FS} and x_{FS} axes of the FGM sensor system. These elements are determined through the minimization of the spin tone in the spin plane component of the calibrated magnetic field. To separate from the effects of errors in the spin plane offsets, the estimation of the spin plane angles is done using the highest fields measured by the range being calibrated. The variations of these angles over the course of the mission are very low, as are also the observed trends. This applies for the other spacecraft and other ranges too. While the conditions set by us to identify trends are met for some spin plane angle of some of the spacecraft, because the changes

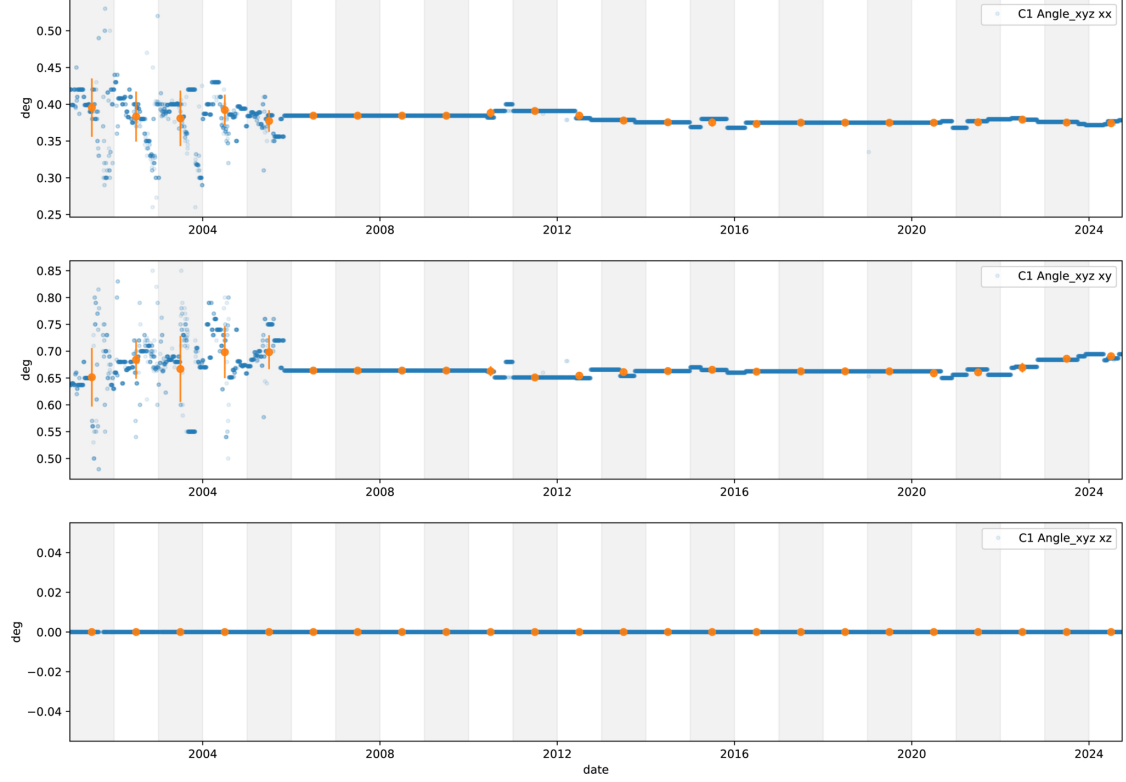


Figure 6: The spin axis alignment angles as rotation angles around the z , y , and x axes in this order for C1. The daily values are represented by the blue dots, the yearly averages are plotted with orange dots. The error-bars are the standard deviations for each year.

of these elements are very small and infrequent, the existence of trends is sometimes not evident from the plots.

5.5 Spin plane nonorthogonality

The deviation from orthogonality of the angle between the y_{FS} and z_{FS} axes of the FGM sensor system affects the middle element of the last row of the calibration matrix $\mathcal{M}^{(r)}$. This element is determined together with its right neighbour by minimizing the spectral power of the second harmonic of the spin frequency. For C1 the long-term variation of the ranges 2 to 5 spin-plane nonorthogonality resembles the variation of the range offsets, with almost all the change concentrated in the first half of the mission. The other spacecraft exhibit similar behaviour in these ranges, albeit not always displaying such a clear variation. Ranges 6 and 7 do not show any consistent trend for neither spacecraft.

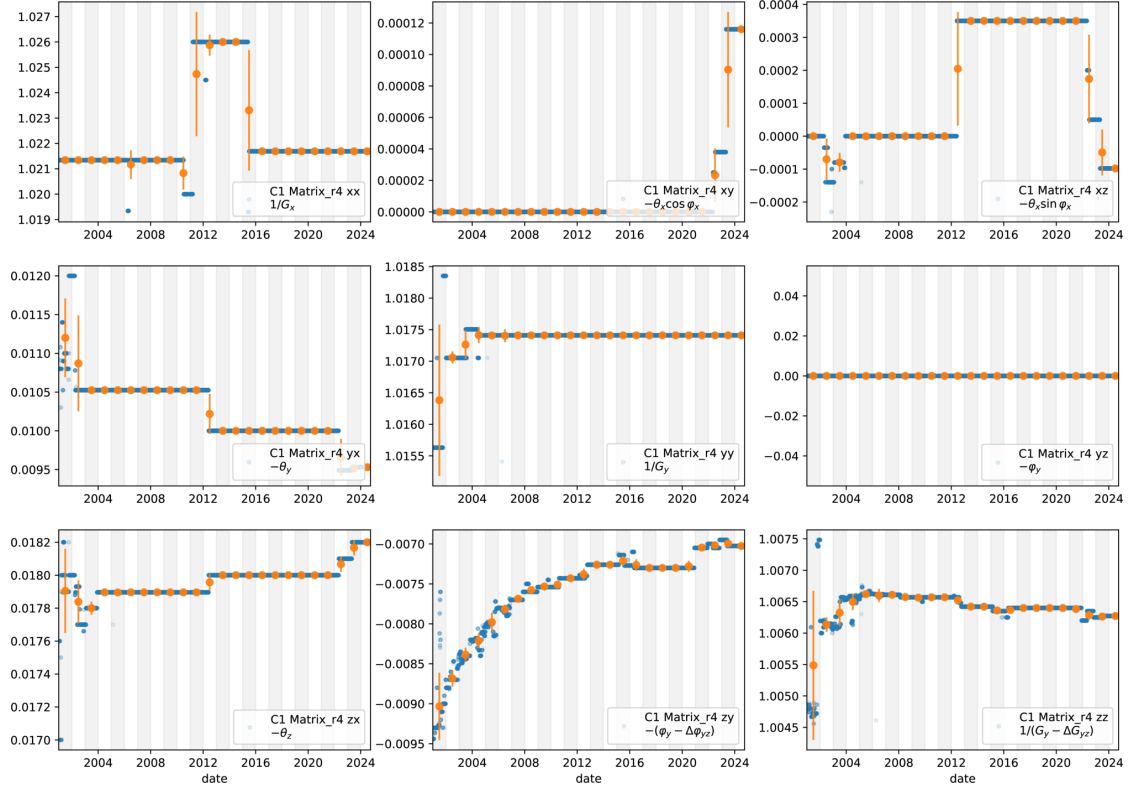



Figure 7: The range 4 calibration matrix for C1. The panel order follows the actual order of the matrix elements. The daily values are represented by the blue dots, the yearly averages are plotted with orange dots. The error-bars are the standard deviations for each year

5.6 Spin plane gain mismatch

The difference between spin plane gains, $\Delta G_{yz}^{(r)}$ affects the other matrix element which is determined through the minimization of the second harmonic, the last diagonal element. The long-term variations of $\Delta G_{yz}^{(r)}$ are less ordered than the variations of the spin plane nonorthogonality with the exception of range 3 of C2 as seen in Figure S22. Both the mean yearly standard deviations and the overall change of the spin plane mismatch during the mission are not significant for any Cluster spacecraft.

5.7 Comparison with previous analysis

Our analysis of the calibration parameters generally agrees with the analysis carried out by Alconcel et al.  is important to note though, that the calibration strategy adopted by Alconcel et al. is slightly different from the procedure presented in Section 3.3. Instead of determining the calibration parameters in Eq.(10), Alconcel et al. determined the elements of the compact calibration matrix Eq.(14) and the offsets Eq.(15).

This approach turns all the calibration parameters in range-specific parameters, mixing in the spacecraft influence with electronics related effects. Moreover, now a change in the spin-axis angles implies a change in the orthogonality. With this in mind, there is a good agreement between the statistical analysis results presented in this work and those of Alconcel et al..

6 Summary and conclusions

This work reviews the theoretical basis of the algorithms used to calibrate the Cluster FGM instruments and presents their specific implementation. In addition, the behaviour of the calibration parameters determined over the course of the 24 years long mission is analysed. The raw magnetic field data, the calibration parameters and the related data processing and calibration software are available for download at (reference?).

The statistical analysis of the long-term variations of the calibration parameters of the Cluster FGM instruments demonstrate a remarkable stability of both the instruments and of the spacecraft over a very long period of space flight. Interestingly, the stability improves in time, with much reduced variations after the first 12 years.

Systematic long-term trends were observed for the spacecraft offsets, most probably stemming from magnetic fields produced by soft magnetic materials onboard the spacecraft. Systematic trends were also observed for range specific offsets, most probably related to the electronics response to temperature changes. The largest trend was about $10 \text{ nT decade}^{-1}$ observed for the C1 range4 spin aligned offset. The largest spacecraft offset trend was about 2 nT decade^{-1} observed for the O_y^{sc} component for the same spacecraft.

Clear long-term trends were also observed for the spin plane nonorthogonality angles for all spacecraft. The largest trend for this parameter was also observed for C1. In range3 the observed trend was about $8'' \text{ decade}^{-1}$.

The long-term trends of the other parameters are negligible.

Seasonal cycles of the spin plane components of the spacecraft offsets were observed for all spacecraft. The largest peak to peak seasonal variation was about 2 nT , observed for C1. Seasonal variations of range offsets were observed only for ranges 4 and 5 of C1 for all offset components. The amplitudes of the cycles were below 1 nT .

Table 2: Cluster 1 FGM calibration parameters statistics over the entire mission lifetime. Offsets are expressed in nT, angles in degrees, matrix elements are adimensional factors.

parameter	mission average			mean yearly standard deviation			decadal trend		
offset_r2	[-5.0	0.9	-0.1]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r3	[-5.1	0.9	-0.1]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r4	[-54.3	19.2	-5.1]	[0.9	0.3	0.2]	[-10.9	2.7	-1.4]
offset_r5	[-52.1	18.9	-4.8]	[1.4	0.5	0.2]	[-6.2	1.1	-0.8]
offset_r6	[-440.4	185.0	-30.0]	[41.2	16.9	3.1]	[0.0	0.0	0.0]
offset_r7	[-688.5	305.1	-31.1]	[14.0	6.0	0.9]	[0.0	0.0	0.0]
offset_sc	[1.4	6.8	0.0]	[0.3	0.3	0.2]	[-0.7	1.7	-0.8]
Angle_xyz	[0.3807	0.6676	0.0000]	[0.0102	0.0168	0.0000]	[0.0000	0.0000	0.0000]
Matrix_r2	1.0523	0.0000	0.0003]	[0.0000	0.0000	0.0004]	[0.0000	0.0000	0.0000]
	0.0106	1.0522	0.0000]	[0.0006	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0179	-0.0035	1.0350]	[0.0002	0.0004	0.0004]	[0.0000	0.0020	0.0000]
Matrix_r3	1.0343	0.0000	0.0002]	[0.0009	0.0000	0.0002]	[0.0000	0.0000	0.0000]
	0.0100	1.0337	0.0000]	[0.0004	0.0000	0.0000]	[-0.0009	0.0000	0.0000]
	0.0181	-0.0030	1.0178]	[0.0001	0.0002	0.0001]	[0.0003	0.0024	-0.0003]
Matrix_r4	1.0223	0.0000	0.0001]	[0.0013	0.0000	0.0001]	[0.0000	0.0000	0.0000]
	0.0102	1.0173	0.0000]	[0.0003	0.0003	0.0000]	[-0.0006	0.0000	0.0000]
	0.0180	-0.0076	1.0064]	[0.0001	0.0001	0.0002]	[0.0001	0.0008	0.0000]
Matrix_r5	1.0062	0.0000	0.0002]	[0.0016	0.0000	0.0002]	[0.0000	0.0000	0.0000]
	0.0105	0.9995	0.0000]	[0.0003	0.0004	0.0000]	[-0.0012	0.0000	0.0000]
	0.0175	-0.0081	0.9896]	[0.0003	0.0002	0.0001]	[0.0009	0.0003	0.0000]
Matrix_r6	1.0184	0.0000	0.0000]	[0.0055	0.0000	0.0001]	[0.0000	0.0000	0.0000]
	0.0063	1.0118	0.0000]	[0.0019	0.0028	0.0000]	[0.0000	0.0000	0.0000]
	0.0113	-0.0052	1.0064]	[0.0026	0.0008	0.0009]	[0.0000	0.0000	0.0000]
Matrix_r7	1.0010	0.0000	0.0000]	[0.0252	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0099	0.9994	0.0000]	[0.0002	0.0242	0.0000]	[0.0000	0.0000	0.0000]
	0.0179	-0.0071	0.9897]	[0.0004	0.0002	0.0241]	[0.0000	0.0000	0.0000]

Table 3: Cluster 2 FGM calibration parameters statistics over the entire mission lifetime. Offsets are expressed in nT, angles in degrees, matrix elements are adimensional factors.

parameter	mission average			mean yearly standard deviation			decadal trend		
offset_r2	[1.2	0.3	-0.5]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r3	[1.3	0.3	-0.5]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r4	[4.0	0.3	-0.2]	[0.1	0.1	0.0]	[0.0	-0.2	-0.3]
offset_r5	[5.1	1.2	0.7]	[0.2	0.1	0.1]	[0.0	0.0	0.0]
offset_r6	[22.9	-5.5	-1.5]	[3.3	1.4	1.0]	[0.0	0.0	-2.3]
offset_r7	[54.3	-0.8	6.8]	[0.2	0.5	0.6]	[0.0	0.0	0.0]
offset_sc	[-1.3	-2.9	-0.7]	[0.2	0.2	0.1]	[0.0	0.0	0.0]
Angle_xyz	[-0.1627	0.3328	0.0000]	[0.0020	0.0025	0.0000]	[-0.0098	0.0065	0.0000]
Matrix_r2	1.0422	0.0000	0.0000]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0123	1.0491	0.0000]	[0.0001	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0047	-0.0115	1.0555]	[0.0002	0.0001	0.0001]	[0.0000	0.0000	0.0002]
Matrix_r3	1.0256	0.0000	0.0000]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0125	1.0316	0.0000]	[0.0001	0.0000	0.0000]	[-0.0002	0.0000	0.0000]
	0.0044	-0.0113	1.0389]	[0.0003	0.0001	0.0001]	[0.0000	0.0002	0.0002]
Matrix_r4	1.0136	0.0000	0.0000]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0125	1.0196	0.0000]	[0.0002	0.0003	0.0000]	[0.0000	0.0000	0.0000]
	0.0045	-0.0113	1.0154]	[0.0001	0.0001	0.0000]	[-0.0003	0.0001	0.0001]
Matrix_r5	0.9962	0.0000	0.0000]	[0.0009	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0121	1.0025	0.0000]	[0.0001	0.0006	0.0000]	[-0.0004	0.0000	0.0000]
	0.0050	-0.0106	0.9994]	[0.0003	0.0002	0.0001]	[-0.0009	0.0000	0.0000]
Matrix_r6	1.0100	0.0000	0.0000]	[0.0021	0.0000	0.0001]	[0.0000	0.0000	0.0000]
	-0.0073	1.0138	0.0000]	[0.0021	0.0028	0.0000]	[0.0000	0.0000	0.0000]
	0.0031	-0.0071	1.0106]	[0.0007	0.0008	0.0013]	[0.0000	0.0000	0.0000]
Matrix_r7	0.9865	0.0000	-0.0002]	[0.0001	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0117	0.9919	0.0000]	[0.0000	0.0001	0.0000]	[0.0000	0.0000	0.0000]
	0.0050	-0.0111	0.9879]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]

Table 4: Cluster 3 FGM calibration parameters statistics over the entire mission lifetime. Offsets are expressed in nT, angles in degrees, matrix elements are adimensional factors.

parameter	mission average			mean yearly standard deviation			decadal trend		
offset_r2	[0.2	-2.0	-0.9]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r3	[0.2	-2.0	-0.9]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r4	[6.5	4.7	4.1]	[0.1	0.1	0.1]	[0.0	0.0	0.0]
offset_r5	[7.4	5.4	4.4]	[0.2	0.1	0.1]	[0.0	0.0	0.0]
offset_r6	[75.1	77.3	63.7]	[27.4	23.8	20.0]	[0.0	0.0	0.0]
offset_r7	[120.4	121.7	95.5]	[2.5	2.6	2.3]	[0.0	0.0	0.0]
offset_sc	[-2.7	-3.1	-1.6]	[0.2	0.1	0.1]	[-0.3	0.0	0.0]
Angle_xyz	[0.8034	-0.1749	0.0000]	[0.0015	0.0023	0.0000]	[-0.0062	0.0057	0.0000]
Matrix_r2	1.0422	0.0000	0.0000]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0057	1.0355	0.0000]	[0.0002	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0068	-0.0135	1.0553]	[0.0001	0.0001	0.0001]	[0.0000	0.0000	0.0000]
Matrix_r3	1.0238	0.0000	0.0000]	[0.0000	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0057	1.0198	0.0000]	[0.0002	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	-0.0068	-0.0134	1.0372]	[0.0002	0.0001	0.0001]	[0.0000	-0.0002	0.0000]
Matrix_r4	1.0041	0.0000	0.0000]	[0.0002	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0059	1.0061	0.0000]	[0.0001	0.0002	0.0000]	[0.0000	0.0000	0.0000]
	-0.0066	-0.0121	1.0194]	[0.0001	0.0001	0.0001]	[0.0000	0.0001	0.0000]
Matrix_r5	0.9890	0.0000	0.0000]	[0.0008	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0053	0.9912	0.0000]	[0.0005	0.0002	0.0000]	[0.0000	0.0000	0.0000]
	-0.0075	-0.0121	1.0024]	[0.0008	0.0001	0.0001]	[0.0000	0.0000	-0.0002]
Matrix_r6	1.0032	0.0000	0.0000]	[0.0013	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0036	1.0060	0.0000]	[0.0024	0.0023	0.0000]	[0.0000	0.0000	0.0000]
	-0.0043	-0.0075	1.0127]	[0.0030	0.0013	0.0023]	[0.0000	0.0000	0.0000]
Matrix_r7	0.9885	0.0000	0.0000]	[0.0240	0.0000	0.0000]	[0.0000	0.0000	0.0000]
	0.0057	0.9937	0.0000]	[0.0001	0.0220	0.0000]	[0.0000	0.0000	0.0000]
	-0.0068	-0.0117	1.0024]	[0.0002	0.0003	0.0221]	[0.0000	0.0000	0.0000]

Table 5: Cluster 4 FGM calibration parameters statistics over the entire mission lifetime. Offsets are expressed in nT, angles in degrees, matrix elements are adimensional factors.

parameter	mission average			mean yearly standard deviation			decadal trend		
offset_r2	[1.4	1.0	1.6]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r3	[1.4	1.1	1.6]	[0.0	0.0	0.0]	[0.0	0.0	0.0]
offset_r4	[9.6	7.5	9.8]	[0.1	0.1	0.1]	[0.3	0.0	0.0]
offset_r5	[10.7	9.0	10.5]	[0.3	0.1	0.1]	[0.7	0.0	0.0]
offset_r6	[97.8	76.9	97.5]	[13.7	8.3	10.4]	[0.0	0.0	0.0]
offset_r7	[161.9	135.5	160.6]	[3.8	3.1	3.4]	[0.0	0.0	0.0]
offset_sc	[-14.4	-4.3	2.7]	[0.2	0.1	0.1]	[0.3	0.0	-0.3]
Angle_xyz	[-0.0070	0.3394	0.0000]	[0.0021	0.0038	0.0000]	[-0.0108	0.0082	0.0000]
Matrix_r2	1.0421	0.0000	-0.0003	[0.0000	0.0000	0.0001]	[0.0000	0.0000	0.0000
	-0.0074	1.0794	0.0000	[0.0002	0.0018	0.0000	[0.0000	0.0000	0.0000
	0.0084	-0.0220	1.0517	[0.0002	0.0001	0.0004]	[-0.0004	0.0002	0.0018
Matrix_r3	1.0235	0.0000	-0.0003	[0.0000	0.0000	0.0001]	[0.0000	0.0000	0.0000
	-0.0075	1.0603	0.0000	[0.0001	0.0000	0.0000	[-0.0002	0.0000	0.0000
	0.0087	-0.0215	1.0342	[0.0002	0.0001	0.0001]	[0.0000	0.0003	0.0000
Matrix_r4	1.0045	0.0000	-0.0001	[0.0005	0.0000	0.0001]	[0.0000	0.0000	0.0000
	-0.0074	1.0458	0.0000	[0.0001	0.0004	0.0000	[0.0000	0.0000	0.0000
	0.0086	-0.0215	1.0178	[0.0002	0.0001	0.0001]	[0.0000	0.0003	-0.0002
Matrix_r5	0.9885	0.0000	-0.0001	[0.0004	0.0000	0.0001]	[0.0000	0.0000	0.0000
	-0.0078	1.0279	0.0000	[0.0003	0.0003	0.0000	[0.0000	0.0000	0.0000
	0.0086	-0.0201	1.0016	[0.0002	0.0003	0.0001]	[0.0000	0.0000	0.0000
Matrix_r6	1.0054	0.0000	0.0000	[0.0037	0.0000	0.0000]	[0.0000	0.0000	0.0000
	-0.0050	1.0305	0.0000	[0.0012	0.0116	0.0000	[0.0000	0.0000	0.0000
	0.0057	-0.0136	1.0145	[0.0015	0.0020	0.0031]	[0.0000	0.0000	0.0000
Matrix_r7	0.9879	0.0000	0.0000	[0.0275	0.0000	0.0000]	[0.0000	0.0000	0.0000
	-0.0072	1.0282	0.0000	[0.0002	0.0258	0.0000	[0.0000	0.0000	0.0000
	0.0086	-0.0211	1.0047	[0.0002	0.0005	0.0253]	[0.0000	0.0000	0.0000



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