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Cluster mission: An in-depth view of instrument calibration and cross-calibration

Long-Term Trends in the Calibration of the Cluster Fluxgate Magnetometer Instruments

L.-N. Alconcel¹ , P. Brown², T. Oddy², and C. M. Carr² 

¹School of Metallurgy and Materials, University of Birmingham, Birmingham, UK, ²Department of Physics, Imperial College London, London, UK

Key Points:

- Calibration parameters for the Cluster fluxgate magnetometers have been determined on an orbit-by-orbit basis throughout the 24-year mission
- After correction for temperature effects, there is no clearly measurable offset drift over the mission lifetime
- Comparisons between spacecraft and instruments indicate a relative accuracy better than 1%; absolute accuracy is not well determined

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. M. Carr,
c.m.carr@imperial.ac.uk

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Author Contributions:

Data curation: L.-N. Alconcel
Formal analysis: L.-N. Alconcel
Funding acquisition: C. M. Carr
Investigation: L.-N. Alconcel, C. M. Carr
Methodology: C. M. Carr
Project administration: P. Brown
Resources: C. M. Carr
Software: T. Oddy, C. M. Carr
Supervision: P. Brown
Validation: L.-N. Alconcel
Visualization: C. M. Carr

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Abstract The calibration parameters of the Cluster mission's fluxgate magnetometer instruments have been determined and updated on a per-orbit basis throughout the 24 years of the mission. Since there is no absolute field reference for vector measurements in-flight, various spacecraft-to-spacecraft and instrument-to-instrument comparisons have been used to assess the accuracy of the measurements. Relative accuracy—consistency of the FGM measurements between spacecraft—is typically 1% for fields up to 4,000 nT, which covers most of the key scientific regions visited by the Cluster spacecraft. Absolute accuracy is harder to quantify but may be as good as 2% over the same range. An analysis of long-term trends in the calibration parameters shows variations on annual and mission-length timescales, particularly for sensor offsets, while sensor gains and angles are remarkably stable. Offset variations are correlated with sensor temperature—for the Cluster 1 instrument in particular—and to a lesser extent with electronics temperature; coefficients are of the order 0.1 and 0.01 nT/°C respectively. After correction for temperature effects, there is no clearly measurable offset drift over the mission lifetime. Statistics for all four spacecraft are presented. These data could be used to inform the design and implementation of future missions employing fluxgate magnetometers. The spacecraft are found to be magnetically “clean,” which allows in-flight calibration techniques to be applied with confidence and precision, leading to consistently high-quality magnetic-field data sets available through the Cluster Science Archive.

Plain Language Summary Multi-point measurements of plasma properties by the payload of the 4-spacecraft ESA Cluster mission have allowed a 3-dimensional view on space-plasma processes in the near-Earth environment. Inherently, comparison between instruments onboard each spacecraft, and between spacecraft, have been vital techniques in the exploitation of the data, and hence the relative accuracy of the instruments has been important. The fluxgate magnetometer (FGM) instrument measured the DC to low-frequency magnetic field vector with high time-resolution. We describe the in-flight techniques used to adjust the calibration-parameters which convert the instrument measurements into quantities in physical units resulting in archived data sets. Long-term trends in the calibration parameters are presented. We find that one key parameter—the instrument's offset—is well-correlated with the temperature of the instrument, and after correction for this effect, we find that the calibration parameters have been remarkably stable. Statistics of the calibration parameters will be useful for the understanding of fluxgate magnetometer accuracy in general, and in particular for future missions.

1. Introduction

Cluster has been the first multi-spacecraft mission to study the Earth's magnetosphere in three dimensions (Escoubet et al., 2001). Comprising four spacecraft with an identical scientific payload, Cluster was operational from the beginning of 2001 through to the end of September 2024. The orbits of each satellite started in a nearly polar plane with apogees at about $20 R_E$ (Earth radii), perigees around $4 R_E$, and optimized to have an approximately regular tetrahedral arrangement for a proportion of each orbit. This configuration has allowed the study of both spatial and temporal differences on the various scales of the spacecraft separations, enabling—for the first time—direct measurement of three-dimensional structure and dynamics within the magnetosphere and the boundaries with the solar wind. Amongst the suite of 11 instruments onboard each spacecraft, the dual-sensor fluxgate magnetometer (FGM) (Balogh et al., 1997, 2001) has provided the DC to low-frequency magnetic field vector, which has contributed to many of the key scientific results from the mission (Escoubet et al., 2021).

The FGM instruments were designed to provide high-accuracy magnetic field measurements over the wide dynamic range encountered during each orbit. The fluxgate sensors and their associated electronics produced a

Writing – original draft: L.-N. Alconcel,
C. M. Carr
Writing – review & editing:
L.-N. Alconcel, P. Brown

Table 1
FGM Measurement Ranges

Range	Full-scale field	Digital resolution
2	± 64 nT	7.81 pT
3	± 256 nT	31.25 pT
4	± 1024 nT	125 pT
5	± 4096 nT	500 pT
6	± 16384 nT	2 nT
7	± 65536 nT	8 nT

field-proportional voltage per axis, which was digitized by a 16-bit Analog to Digital Converter (ADC). After anti-alias filtering and decimation, samples were transmitted with 14-bit resolution at cadences of 22.4 or 67.3 per-second (depending on operating mode). In order to balance the digital resolution against the dynamic range of the expected magnetic fields, the fluxgates' electronic design incorporated a gain-control stage, automatically selected depending on field conditions, allowing autonomous switching between six overlapping ranges as shown in Table 1. The range control algorithm was designed with sufficient hysteresis to prevent repeated switching when close to a boundary between ranges.

Range 7, which is capable of measuring the full geomagnetic field at ground-level, was only intended for functional testing before launch, and fields in range 6 were never expected to be seen in the nominal 2-year Cluster mission. Consequently, only ranges 2–5 were subject to full calibration and characterization before launch. However, successive extensions to the mission duration, the evolution of the spacecraft orbital plane, and the lowering of the perigee altitude, have required the use of ranges 6 and 7 during perigee passes. The determination of calibration parameters for these two highest ranges has been performed in-flight. It is important to note that the instruments were designed and optimized for low-field operation, typically fields of tens to hundreds of nanotesla, with expectations of perigee fields no greater than a few thousand nanotesla. Figure 1 shows, for context, an example of measurements taken during a single orbit in June 2012, where all ranges were required.

Though pre-launch calibration was extensive and thorough, the long-term stability of any fluxgate is not guaranteed and in-flight techniques are always needed to adjust the calibration parameters routinely as they fluctuate over time and with temperature. The techniques implemented for Cluster (Alconcel et al., 2014; Gloag et al., 2010), and outlined in Section 2, aggregate data per range and per orbit, with each orbit having a nominal duration of 57 hr at the start of the mission, reducing to 54 hr at the end. Since range 2—the most sensitive range—was by far the most used (typically 75% per orbit), the greatest confidence in the outcome of these analyses is for range 2, with progressively less confidence for the higher ranges. Ranges 6 and 7 were used for a few hundreds of orbits, out of 3,844 orbits in total, and typically they were needed for just a few minutes during each of the perigee passes. It is also important to note that there is no fully independent in-flight method to assess the absolute accuracy of the FGM measurements. Whilst some inter-spacecraft and inter-instrument comparisons can be useful, as described in Section 3, the calibration parameters have been determined independently for each instrument, with no attempt to force inter-spacecraft agreement, and the accuracy of the measurements can never be specified in a truly absolute sense. Nevertheless, in order to provide the users with a general indication of the expected accuracy and limitations of the FGM data set, the estimates given in Table 2 have been provided, with further details given in the FGM User Guide, accessible through the ESA Cluster Science Archive (<https://csa.esa.int/csa-web>). It should be noted that the accuracy figures given in Table 2 are estimates based on the inter-spacecraft comparisons and other methods described in Section 3, and are not guaranteed to be fulfilled under all conditions and all mission phases. Absolute accuracy, in particular, cannot be stated with any quantitative certainty.

2. In-Flight Calibration Methods

Each FGM instrument comprises two fluxgate sensors with one mounted at the end of a 4.9 m boom and a second mounted 1.5 m inboard. The dual-sensor configuration was selected for reasons of redundancy and reliability but also as a means to mitigate any in-flight magnetic contamination from the spacecraft (e.g., Carr et al., 2005; Ness et al., 1971). In practice, the spacecraft have been sufficiently “clean” in respect of magnetic emissions that the

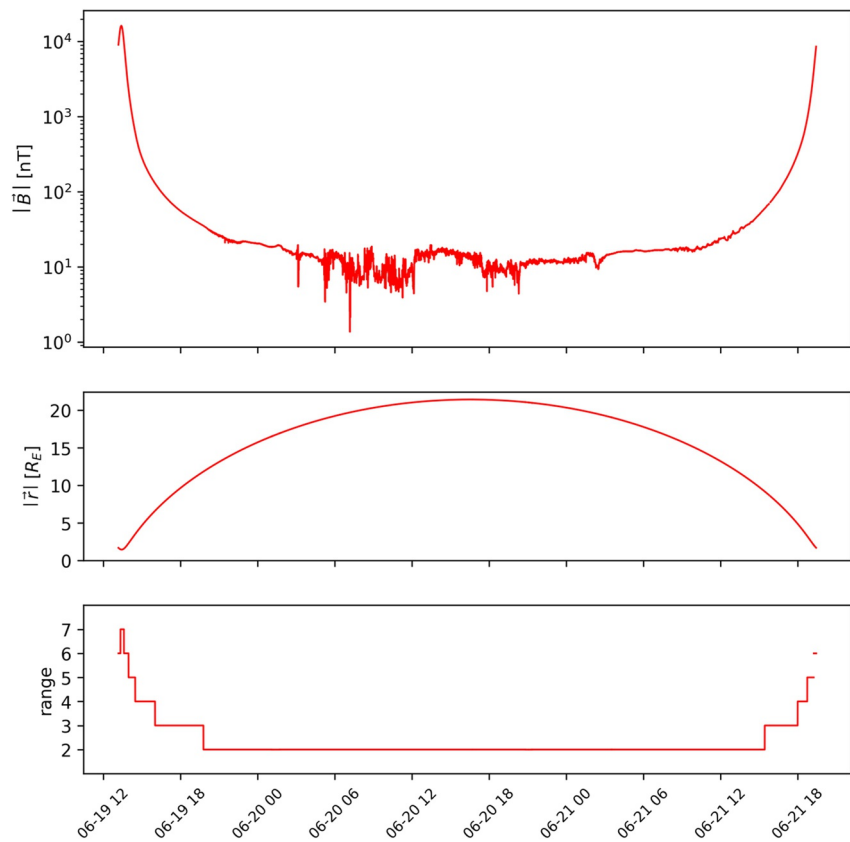


Figure 1. Cluster 2 magnetic field measurements during orbit 1861 (19–21 June 2012). Top panel: magnitude of the field vector, log-scale; middle panel: magnitude of the position vector in earth-radii (R_E); bottom panel: instrument range. Typically, for the majority of the orbital period (54 hr 16 min), the instrument operated in the most-sensitive range 2. Range 7 was required for 15 min.

outboard sensors alone have been used for the collection of science data. It is also notable that there was no failure of any instrument hardware during the mission, nor any degradation in their performance. The sensors and their associated front-end electronics were provided by NASA Goddard Space Flight Center (GSFC) with electronics contributions by the Space Research Institute (IWF) Graz and the Institute of Geophysics and Extraterrestrial Physics (IGEP) of the Technical University of Braunschweig. Overall instrument design, leadership, and data-processing hardware/software have been provided by Imperial College London. During the mission, in-flight calibration has been performed by IGEP and Imperial College London. The IGEP calibration, resulting in a daily calibration file per spacecraft, has been applied primarily for quick-look and prime-parameter data products, processed at spin resolution. For the full-resolution data sets, available through the ESA Cluster Science Archive (CSA), the Imperial College London calibration has been applied. Since the IGEP calibration has been available in advance of that produced by Imperial for the CSA products, the two approaches have been complementary. The techniques and analysis presented here relate to the CSA-archived calibration and data sets (including full time-

Table 2
Estimates for FGM Accuracy Under Typical Operating Conditions

Total field in the range	Estimated relative accuracy	Estimated absolute accuracy
$ \vec{B} < 20$ nT	≥ 0.2 nT	> 0.2 nT
20 nT $< \vec{B} < 4000$ nT	1%	2%

Note. Relative accuracy refers to inter-spacecraft consistency between FGM instruments; absolute accuracy is not well determined but estimates are given for guidance.

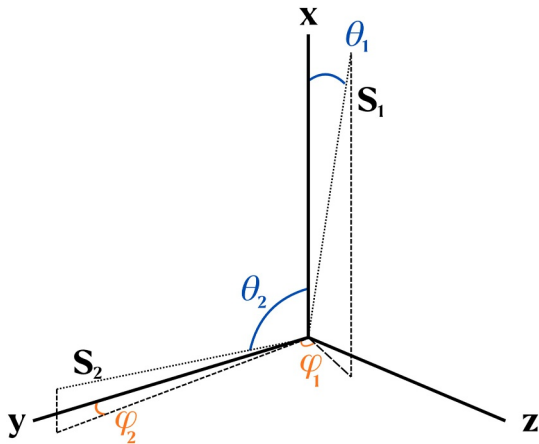


Figure 2. Definition of the sensor (S_1, S_2, S_3) coordinate system with respect to an orthogonal and spin-aligned spacecraft (x, y, z) system. The elevation θ and azimuthal ϕ angles have been defined consistently for each axis. S_3 has been omitted for clarity. Figure reproduced from Alconcel et al. (2014).

resolution products) performed and produced by Imperial, while the IGEP methods are described in a companion paper to be published.

2.1. Definition of the Calibration Parameters

Each sensor comprised a triad of near-orthogonal ring core fluxgates (Acuña, 1974, 2002), with each individual sensor axis denoted as S_1, S_2 and S_3 . The triad was mounted on the boom such that the S_1 axis was aligned with the spacecraft's nominal spin-axis and S_2 and S_3 in the spin-plane. Figure 2 shows the relationship between the sensor axes and the spacecraft coordinate system. The orthogonal (x, y, z) spacecraft system is defined such that x is along the true spin-axis. Each spacecraft was attitude-controlled and oriented such that its spin-axis was approximately perpendicular to the ecliptic plane, though deliberately tilted by a few degrees to avoid boom shadowing of the solar-array. As a consequence, the sensor S_1 measures in a direction roughly parallel to the z -axis in the GSE (Geocentric Solar Ecliptic) system. For each sensor axis, an elevation and azimuth angle θ and ϕ , define the orientation of the sensor axis with respect to the spacecraft system. According to the definitions in Figure 2, the angles should all be either zero or 90° for an ideal system, and only small deviations are to be expected in practice.

The calibration parameters for each sensor axis comprise an offset O , a gain G and the two angles θ and ϕ . The relationship between the measured sensor field $\vec{B}_S$ and the ambient magnetic field $\vec{B} = (B_x, B_y, B_z)$ in the spacecraft system is given by

$$\begin{pmatrix} B_{S_1} \\ B_{S_2} \\ B_{S_3} \end{pmatrix} = \mathbf{M} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} + \begin{pmatrix} O_1 \\ O_2 \\ O_3 \end{pmatrix} \quad (1)$$

where the orthogonalizing and scaling matrix $\mathbf{M}$ is given by

$$\mathbf{M} = \begin{pmatrix} G_1 \cos \theta_1 & G_1 \sin \theta_1 \cos \phi_1 & G_1 \sin \theta_1 \sin \phi_1 \\ G_2 \cos \theta_2 & G_2 \sin \theta_2 \cos \phi_2 & G_2 \sin \theta_2 \sin \phi_2 \\ G_3 \cos \theta_3 & G_3 \sin \theta_3 \cos \phi_3 & G_3 \sin \theta_3 \sin \phi_3 \end{pmatrix} \quad (2)$$

such that the inverse transformation may be used to retrieve the ambient field from the sensor measurements. For each spacecraft, and for each measurement range, there are a total of 12 calibration parameters. The gains express the real-world difference between the ideal and actual sensitivities, per range, as expressed in Table 1, and consequently are expected to be close to unity. Offsets express any zero-level error in the measurements.

2.2. In-Flight Determination of Calibration Parameters

While parameters for ranges 2 to 5 were measured pre-launch at the IGEP “Magnetrode” facility (Braunschweig, Germany), there are two important considerations. First, offsets (in particular) are expected to vary with temperature and time, and are also indistinguishable from any residual spacecraft magnetism which could not be characterized with the required accuracy on-ground. Second, the sensor angles in-flight also account for any mechanical misalignment between the sensor mechanical axes and the spacecraft system. While this was measured on-ground, the deployment of the boom under gravity-free conditions in orbit could not be guaranteed to reproduce the on-ground alignment. Fortunately, offsets and (most) angles could be determined in-flight, allowing their evolution to be tracked with respect to on-ground values. Gains cannot be fully determined in-flight, marking the importance of the acquisition of, and comparison with, pre-launch calibration values. Three in-flight calibration techniques have been applied to the outboard Cluster FGM sensor data, as outlined in the following sections. Throughout the mission, regular cross-calibration workshops were convened by ESA in order

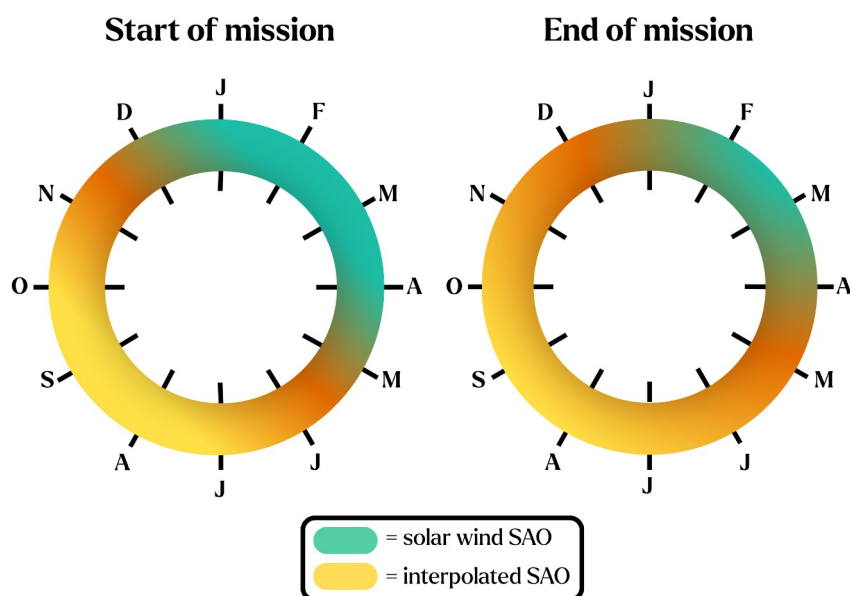


Figure 3. Annual cycle of spin-axis offset (SAO) determination by statistical analysis or interpolation. The “dayside” season is in blue. Calendar months are denoted by their first letter. Left: start of mission; right: end of mission.

to maximize the quality and consistency of all the Cluster instrument data sets submitted to the archive (Laakso et al., 2010). All FGM data sets in the Cluster Science Archive (FGM, 2025) have been validated by the team, including visual-inspection of the data at 5 samples-per-second time-resolution.

2.2.1. Analysis of Rotational Fluctuations in the Solar Wind

While the primary technique for determining most of the calibration parameters used across all ranges was the Fourier analysis (Section 2.2.2), a necessary input that could not be determined from the Fourier technique was the spin-axis offset O_1 parameter in range 2. The solar wind calibration technique, developed by Hedgecock (1975), makes use of natural rotational fluctuations in the solar wind magnetic field, whereby measurements in the spin-axis direction should have no overall correlation with the magnetic field magnitude. By iteration, any error or change in the spin-axis offset could be corrected using this knowledge, through minimizing the correlation between B_{S_1} and $|\vec{B}|$ over a suitable interval of solar-wind data. In practice, this technique required aggregation of data in the solar-wind, where the instrument operated continuously in range 2, over an interval of at least 2 weeks (about 6 orbits) and careful selection of rotational intervals. At the start of the mission, this technique was applied for the period December to April (inclusive) each year; however, evolution of the orbit reduced this to January–March toward the end of the mission (Figure 3). Plaschke (2019) have demonstrated that techniques of this type can determine changes in the offset parameter to a level better than 0.2 nT. Outside of these intervals, the spin-axis offset for range 2 has been set by linear-interpolation. As a consequence, the spin-axis offset is likely to contribute the greatest source of error under low-field (<20 nT) conditions, as the spin-plane offsets are determined continuously and with greater precision (Section 2.2.2).

2.2.2. Fourier Analysis of Spin-Harmonics

Transforming the measurements in a spinning spacecraft frame to a non-spinning inertial frame results in signals at the first and second harmonics of the spin frequency, which can be used to estimate many of the parameters. The method has been described in detail by Kepko et al. (1996) and this was used throughout the mission to estimate parameters on an orbit-by-orbit basis. The first harmonic signal in the spin-axis B_{S_1} component can be used to estimate that axis' angles θ_1 and ϕ_1 , while the first harmonic signal in the spin-plane measurement yields the offsets and elevations of the associated axes, that is, O_2 , O_3 , θ_2 and θ_3 . Furthermore, the second-harmonic signal in the spin-plane components can be used to estimate the ratio of the associated gains G_2/G_3 and the difference between the azimuthal angles $\phi_2 - \phi_3$.

2.2.3. Continuity at Range Transitions

A constraint on the calibration parameters arises from the requirement that measurements at range transitions should be continuous. A method was developed by FGM team members at UCLA to adjust parameters at range transitions to minimize the discontinuity, and this method has been implemented by Imperial College London as a routine step in the orbit-by-orbit calibration analysis. The spin-axis and spin-plane signals are analyzed separately, and suitable range changes over a period of at least 2 weeks are selected by visual-inspection and aggregated to provide adequate statistics. A discontinuity in the spin-axis time-series is associated with an error in the offset O_1 and gain G_1 parameters, while discontinuities in the spin-plane are associated with errors in the associated gain and azimuthal angles. To minimize the overall change to the field magnitude, gain adjustments are applied only to the lower range, while offsets and azimuth angles are applied to the higher range. Importantly, this has the effect of propagating knowledge of the range 2 spin-axis offset upwards to the higher ranges, for which there is no other method to estimate this parameter (Section 2.2.1).

The implementation of these three calibration techniques has been detailed by Gloag et al. (2010) and has formed the basis of the routine orbit-by-orbit calibration analysis throughout the mission. The results of these analyses have been stored in a database of calibration files, available through the Cluster Science Archive (FGM, 2025). Each file—one per orbit per spacecraft—contains the 12 calibration parameters for each range. In an earlier study, Alconcel et al. (2014) presented the trends in these parameters for the first decade of the mission. The remainder of this work presents the complete time-series of the calibration database, with a focus on long-term trends, and the relationship with instrument temperatures.

3. Illustrative Data and Qualitative Assessment of the Calibration Accuracy

A full assessment of the FGM accuracy throughout the various mission phases is beyond the scope of this work, however, some illustrative examples of multi-spacecraft data are presented here to provide context for the calibration parameters discussed in later sections. This also serves to emphasize a key point: each instrument has been calibrated individually and independently—no attempt has been made to force inter-spacecraft agreement. Consequently, multi-spacecraft data, in suitable situations, can give insight into the relative accuracy of the data sets and the precision of the in-flight calibration methods. Further, for limited periods, it has been possible to assess the absolute accuracy of the FGM data through comparison with other instruments onboard the same spacecraft.

3.1. Inter-Spacecraft Comparisons Under Low-Field Conditions in the Solar Wind

During the “dayside” season each year (Figure 3) the Cluster orbits saw apogees at high altitudes above the bow-shock, with significant periods of time in undisturbed solar wind, and with all four FGM instruments operating simultaneously in range 2. Since the solar wind is well-correlated over the typical spacecraft separations (hundreds to thousands of kilometers), and when considering spin-averaged data, plotting the four instrument time-series provides a useful visual assessment of the calibration consistency. In low-magnitude fields, magnetometer accuracy is dominated by the sensor offsets (Narita et al., 2021) hence any relative offsets between the time-series indicates poor offset determination. This was checked periodically during the mission. Additionally, comparison with ACE MAG data (Smith et al., 1998), propagated in time from the ACE orbit to the Cluster locations, provided qualitative assurance of the absolute accuracy of the field measurements. It was assumed that ACE, permanently in the undisturbed solar-wind, should offer the superior calibration in low-magnitude field conditions, since Cluster periods in the solar wind were between 2 and 10 hr per orbit. An example of such a comparison is shown in Figure 4. The ACE data has been propagated to the Cluster formation with the time-shift determined by visual inspection. Numerical checks on such comparisons have been performed at intervals during the mission by resampling to one-minute averages, in order to establish a common time-line, and RMS field-magnitude differences evaluated between spacecraft pairs. In the interval shown, for the period 19:00–20:00, Cluster-ACE differences are no more than 0.15 nT and Cluster pairs differ by less than 0.1 nT.

3.2. Inter-Spacecraft Comparisons Under High-Field Conditions in the Magnetosphere

Solar wind, magnetosheath and magnetospheric measurements were made in ranges 2, 3 and occasionally in range 4. During perigee passes, for the early years of the mission, range 5 was sufficient to cover the maximum magnetic field strengths encountered in the magnetosphere. However, as the perigee altitude decreased, range 6

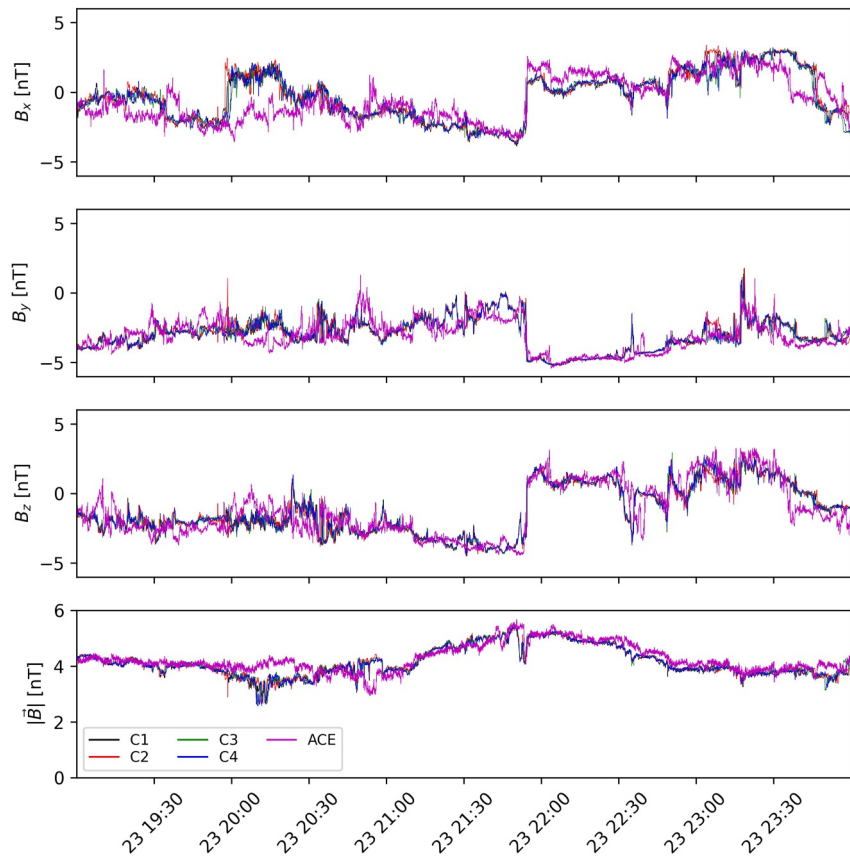


Figure 4. Cluster magnetic field measurements during a 5 hr period in the solar-wind on 23 February 2020, over-plotted with ACE data delayed by 60 min. Cluster data, with traces according to the standard color scheme C1: black, C2: red, C3: green, C4: blue, are spin-resolution with all instruments operating in range 2 during the interval shown. ACE data (magenta trace) is 1 s averages, retrieved from the level 2 database. Magnetic field components are in the GSE coordinate system.

was required from 2008 and eventually range 7 starting in 2009. Inter-spacecraft comparisons at higher fields are more difficult to carry out, due to the significant spatial-gradient in the geomagnetic field at typical Cluster separations. The Cluster spacecraft orbits targeted regular arrangements at higher altitudes, with the consequence that the perigee passes were often seen at significantly different times. However, there were a few occasions when inter-spacecraft comparisons were possible. For example, in September 2013 when Cluster 1 and 3 had a close approach of 4 km at around 09:12 on the 19th. Both FGM instruments were operating in range 5 and recorded magnetic field magnitudes of 925.5 and 927.7 nT respectively, a difference of 0.24% with respect to the background field.

The methods described here provide some assurance of the inter-spacecraft calibration consistency, and the comparison with ACE MAG in the solar-wind gives confidence in the Cluster FGM measurement absolute accuracy at low fields. Furthermore, under limited conditions, it is possible to compare with other instruments onboard the same spacecraft. These methods are outlined in the following sections.

3.3. Single-Spacecraft Comparisons With the EDI Instrument

The EDI instrument emits an electron beam that, after one gyration of the ambient magnetic field, returns to the same spacecraft where its time-of-flight is measured (Paschmann et al., 1997). This time T_g is in principle directly related to the magnetic field magnitude $|\vec{B}|$ by fundamental constants according to the relation

$$T_g = \frac{2\pi m_e}{e|\vec{B}|} \quad (3)$$

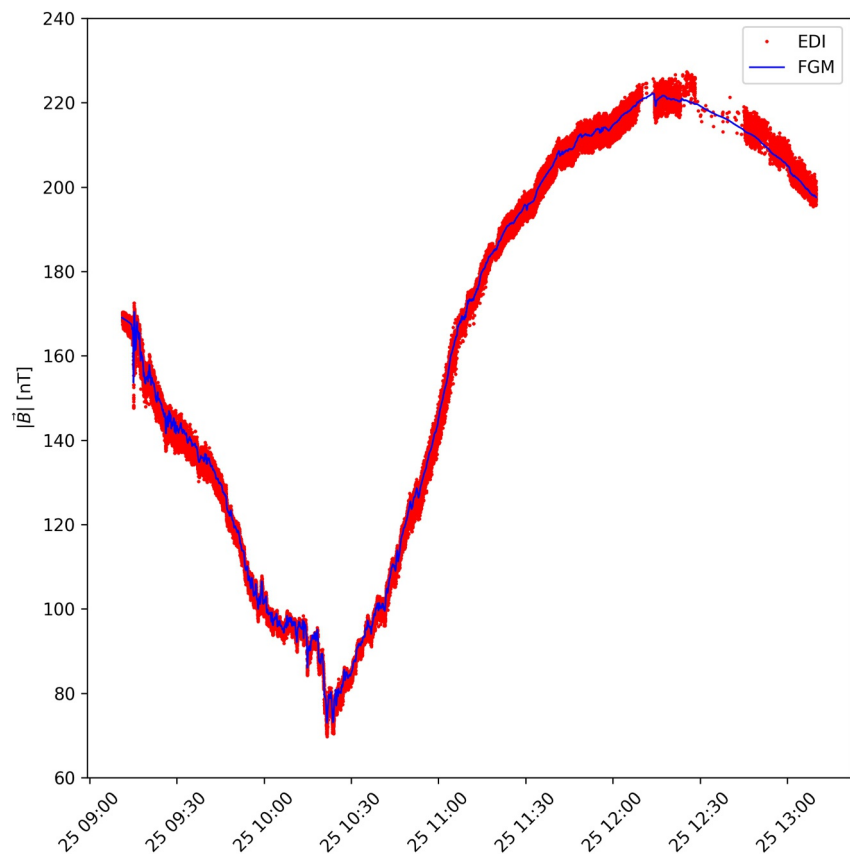


Figure 5. Cluster 3 magnetic field magnitudes measured by FGM (blue trace) and EDI (red trace) on 25 April 2021. The FGM instrument operated in range 3 during the interval shown; data are spin-averages.

where m_e and e are the electron mass and charge respectively. In practice, full knowledge of EDI operating modes and internal instrument effects are required to extract the most accurate estimate of $\vec{B}$ from the EDI time-of-flight data set (Nakamura et al., 2014; Plaschke et al., 2014). Nevertheless, using Equation 3 allows for routine checks of the FGM magnetic field magnitude against the EDI-derived value over a range up to a few hundreds of nT, which includes FGM operations in range 3. An example is shown in Figure 5. The EDI measurements show more variation due to the lower resolution of the technique, which is dependent on both EDI mode and the magnitude and direction of the ambient field. However, the overall agreement gives confidence in FGM range 3 measurements.

3.4. Single-Spacecraft Comparisons With the WHISPER Instrument

The WHISPER instrument is a relaxation-sounder which measures the local plasma frequency (Décr  au et al., 1997). Electric field pulses are transmitted and received via the EFW antennae. Under limited circumstances the electron gyro-frequency $f_{ce} = 1/T_g$ can be retrieved, enabling an additional comparison with FGM (Trotignon et al., 2003). Due to the extensive effort required on behalf of the WHISPER team, extractions of the f_{ce} parameter only occurred at limited times during the early years of the mission. The resulting estimates of magnetic field magnitude from WHISPER, up to a thousand nT or so, allow for a useful corroboration of FGM measurements in range 4. An example is shown in Figure 6.

When such direct comparisons between FGM, EDI and WHISPER have been possible during the Cluster mission science operations, they have shown good agreement with differences typically less than 1%.

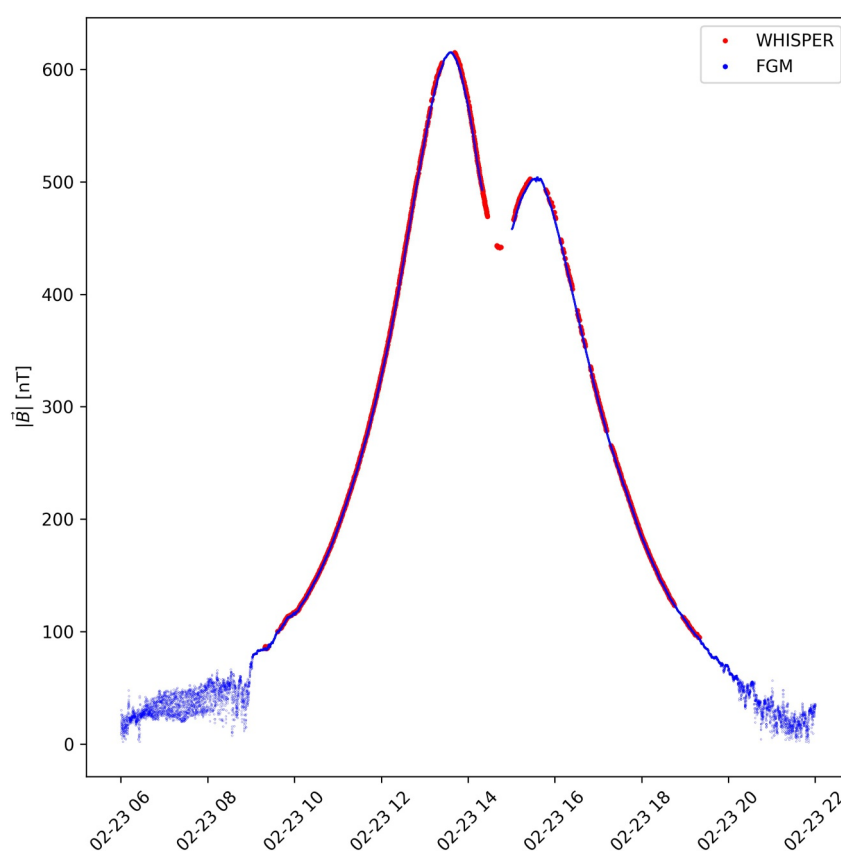


Figure 6. Cluster 1 magnetic field magnitudes measured by FGM (blue trace) and WHISPER (red trace) on 22 February 2001. The FGM instrument operated in ranges 3 and 4 during the interval shown, and all data are spin-averages.

3.5. Single-Spacecraft Comparisons With the STAFF Instrument

The FGM instrument has a bandwidth from DC to 11 Hz by design (Balogh et al., 1997) while the STAFF search-coil magnetometer is sensitive to the frequency range 0.2–180 Hz (Cornilleau-Wehrin et al., 1997). STAFF tends to be more sensitive than FGM at frequencies greater than about 1 Hz and vice-versa. Magnetic field fluctuations in the range 1–10 Hz, often observed in the magnetosphere, can be compared between the two instruments. The STAFF team has performed a comparative analysis through the course of the mission which has shown generally good agreement (results to be published).

4. The Calibration Parameters

The consistency and accuracy demonstrated by the illustrative examples in Section 3 has required significant effort throughout the mission resulting in a database of calibration parameters that have been adjusted and optimized on an orbit-by-orbit basis. The long-term trends in these parameters, and their relationship with instrument temperatures, are the focus for the remainder of this work. Trends and variation over time and temperature can provide insight into the physical processes affecting fluxgate accuracy. Since Cluster has operated four near-identical sets of instruments over two decades, the data presented here may provide a valuable resource for future missions flying fluxgate magnetometers.

4.1. Data and Methods

This study uses Cluster FGM calibration parameters (FGM, 2025) available in the ESA Cluster Science Archive combined with instrument and spacecraft housekeeping parameters available in the ESA Cluster Active Archive. Calibration files are available for each spacecraft and for each orbit for which data has been processed. There were only a few orbits during which FGM data was not obtained. Consequently, there are several thousand calibration

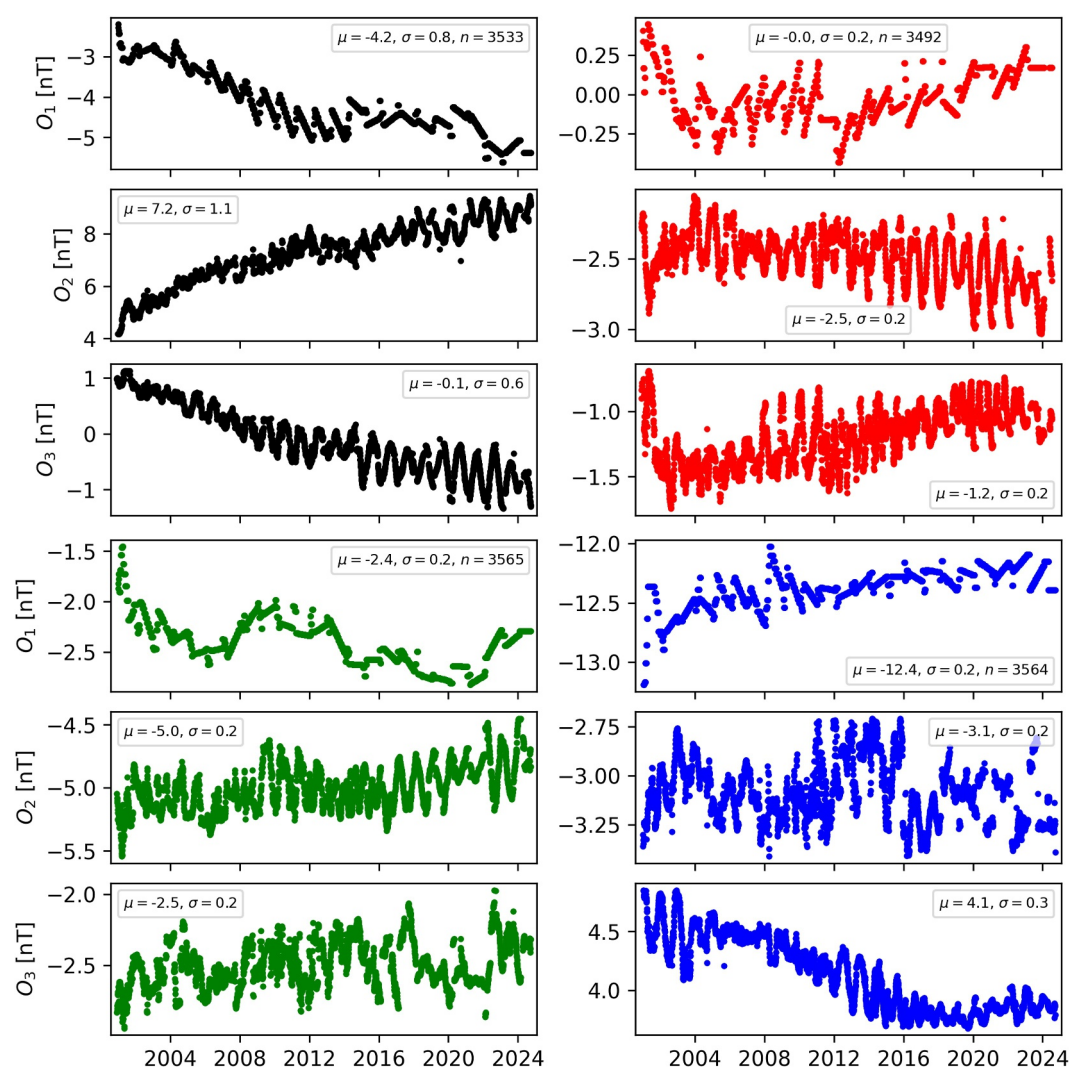


Figure 7. Range 2 offsets, January 2001–September 2024. Top-left: Cluster 1 (black traces); top-right: Cluster 2 (red); bottom-left: Cluster 3 (green); bottom-right: Cluster 4 (blue). The legends provide the mean μ , standard deviation σ in nT, and the number of values n (not repeated for each panel as it is identical for x, y, and z-axes).

files per spacecraft. The orbit start and end times are defined using the reference spacecraft Cluster 3, and these are taken as the start and end of the validity interval associated with each calibration file. Within each file, four calibration parameters—offset, gain and two angles—are recorded for each range and for each axis. Extraction methods are described in Supporting Information S1. The extraction results in a set of time series which are near-continuous throughout the mission for ranges 2–4, and sparse in the cases of ranges 5–7. For each time-series, statistics have been tabulated to record the mean, median, maximum and minimum values, together with sample standard deviation. All time series have been plotted. This study focuses on the range 2 results, as they provide the greatest mission coverage with the FGM instrument operating in its most sensitive and most frequently used range.

Temperature values were recorded separately for the FGM sensor and the electronics box mounted on the spacecraft platform. Technical details and the method for associating a single temperature value with each calibration parameter are given in Supporting Information S1.

4.2. Range 2 Calibration Parameters

Figures 7–10 show the range 2 calibration parameters for all four spacecraft during the period January 2001–September 2024. Each point represents a uniquely determined parameter value for an orbit, with the number of points (n) given by the count of orbits for which FGM data exist in range 2. This is the majority of the 3,844 Cluster orbits. Outside of eclipse seasons, FGM was operated near-continuously, and for most operational orbits, the majority of the time was spent in range 2.

During the course of this study, a number of “outlier orbits” have been identified; these will be reviewed during the post-operations period and data in the archive may be subject to update if considered appropriate. The number of outliers is no more than 20 orbits for any one spacecraft. Many of these are orbits for which there was insufficient data for effective calibration analysis. For the plots in Figures 7–10, in order to have consistency in the presentation, and to allow for comparison between plots, each panel excludes 0.3% of outliers: the y -axis limits for each panel have been set to include the 99.7% of values closest to the mean. Table 3 provides a numerical summary of the data presented in the figures. For completeness, the statistics in Table 3—including min/max values—are calculated on the entire data set (outliers included).

To place the data in context, it is useful to expand the calibration Equation 1 for one of the sensor axes, arbitrarily S_1 , which is the sensor axis most closely aligned with the spacecraft spin-axis. For the case of an ambient magnetic field $\vec{B} = (B_x, B_y, B_z)$ in the spacecraft co-ordinate system, the field measured by sensor S_1 is:

$$B_{S_1} = G_1(\cos\theta_1 B_x + \sin\theta_1 \cos\phi_1 B_y + \sin\theta_1 \sin\phi_1 B_z) + O_1 \quad (4)$$

By design, the S_1 sensors' θ_1 angles are small (ideally zero) and hence the ϕ_1 angle is poorly defined and has vanishing significance as $\theta_1 \rightarrow 0$. In practice, all the θ_1 values are less than 1° for range 2 so a first-order approximation is:

$$B_{S_1} \approx G_1 B_x + O_1 \quad (5)$$

Numerically, the variability in the offset values is of the order 1 part in 10 of the mean value, while the gain values vary by a few parts in a thousand. Consequently, in range 2, where the sensor may be measuring an on-axis field of $B_x = 10$ nT or so, the offset knowledge is the dominant factor in the accuracy of the measurement. An error analysis for vector fluxgate measurements, including the effects of gain and angle uncertainties, has shown that offsets dominate the error budget in low fields (Narita et al., 2021). It is important to note that, at higher fields, the gain and angle uncertainties become more significant. For the Cluster case, the cross-over point occurs at fields higher than about 1,000 nT, that is, range 5 measurements. Since the majority of the Cluster science objectives have been focused on the solar-wind and magnetospheric regions where fields are typically less than a few hundreds of nT, the offset determinations are of particular importance. This is consistent with fluxgate engineering experience which tends to show that the offset is the most variable and least-predictable parameter over time and with fluctuations in temperature (Ripka et al., 2014). The use of magnetic feedback in the fluxgate electronics helps to stabilize the gain and linearize the response, while the offset is driven by a variety of effects including mechanical stresses, temperature changes and external magnetic contamination. Offsets are also subject to discontinuities, sometimes associated with power-cycling of the instrument (Section 6.2.1). As a consequence, the regular and frequent determination of FGM instrument offsets has been a priority throughout the Cluster science operations.

4.2.1. Limitations of the Calibration Techniques

For spinning spacecraft such as Cluster, the Fourier methods described in Section 2.2.2 allow direct determination, every orbit, of the elevation angles for all sensors— θ_1 , θ_2 and θ_3 —as well as the spin-plane gains G_2 , G_3 and offsets O_2 , O_3 . The spin-axis azimuthal angle ϕ_1 can also be estimated. The methods are sensitive to an error in the *difference* between the spin-plane azimuth angles and gains, that is, ϕ_2 versus ϕ_3 and G_2 versus G_3 . The Fourier technique provides no information about the spin-axis gain G_1 or offset O_1 . However, the latter is measured during limited intervals in the solar wind, during the “dayside” season (Figure 3). For orbits during the “nightside” or “tail” season, the O_1 offsets are estimated by interpolating between the values determined during the previous and following solar wind seasons. This effect may be observed in the figures as the “straight-line”

Table 3
Range 2 Summary Calibration Parameters

S/C	Param	Axis	Mean	Median	Std. Dev.	Min.	Max.	Count
1	offset	x	−4.195	−4.424	0.767	−5.622	−1.717	3,533
		y	+7.247	+7.446	1.121	+3.993	+9.448	
		z	−0.106	−0.213	0.566	−1.369	+1.178	
	gain	x	0.95061	0.95074	0.00393	0.92696	0.98350	
		y	0.95075	0.95072	0.00082	0.94682	0.95489	
		z	0.96667	0.96671	0.00112	0.95894	0.97250	
	theta	x	+00.79	+00.77	0.046	+00.48	+01.38	
		y	+90.16	+90.16	0.163	+88.40	+91.46	
		z	+90.36	+90.35	0.177	+88.90	+94.74	
	phi	x	−118.57	−118.68	3.224	−149.55	−077.48	
		y	+000.00	+000.00	0.001	−000.01	+000.01	
		z	+089.82	+089.86	0.093	+089.30	+090.23	
2	offset	x	−0.022	−0.036	0.157	−0.431	+0.588	3,492
		y	−2.489	−2.463	0.178	−3.048	−2.054	
		z	−1.201	−1.194	0.211	−1.745	−0.482	
	gain	x	0.95899	0.95915	0.00223	0.93415	0.96487	
		y	0.95313	0.95305	0.00064	0.95081	0.95660	
		z	0.94733	0.94725	0.00087	0.94413	0.95314	
	theta	x	+00.38	+00.38	0.018	+00.26	+00.66	
		y	+89.46	+89.46	0.099	+88.31	+90.62	
		z	+89.90	+89.89	0.147	+87.72	+91.24	
	phi	x	−063.49	−063.19	2.399	−082.91	−045.16	
		y	+000.00	+000.00	0.005	+000.00	+000.07	
		z	+089.37	+089.38	0.029	+089.09	+089.74	
3	offset	x	−2.403	−2.402	0.242	−2.824	−1.116	3,565
		y	−5.003	−5.024	0.177	−5.547	−4.427	
		z	−2.494	−2.515	0.159	−2.946	−1.937	
	gain	x	0.96008	0.95999	0.00280	0.94647	0.97503	
		y	0.96535	0.96540	0.00061	0.96197	0.96831	
		z	0.94744	0.94746	0.00074	0.93964	0.95545	
	theta	x	+00.83	+00.82	0.018	+00.66	+01.03	
		y	+89.54	+89.53	0.114	+88.58	+91.21	
		z	+89.78	+89.79	0.073	+88.88	+90.54	
	phi	x	+167.64	+167.67	0.859	+158.37	+174.36	
		y	+000.00	+000.00	0.005	+000.00	+000.11	
		z	+089.25	+089.25	0.031	+088.60	+089.62	
4	offset	x	−12.38	−12.36	0.16	−13.53	−12.03	3,564
		y	−3.083	−3.096	0.151	−3.467	−2.667	
		z	+4.131	+4.124	0.310	+3.680	+4.881	
	gain	x	0.95984	0.95996	0.00293	0.94091	0.97042	
		y	0.92825	0.92829	0.00103	0.91638	0.93497	
		z	0.95297	0.95296	0.00112	0.94033	0.96087	
	theta	x	+00.33	+00.32	0.019	+00.19	+00.63	
		y	+89.58	+89.58	0.074	+88.89	+90.34	
		z	+90.12	+90.12	0.088	+88.24	+90.88	

Table 3
Continued

S/C	Param	Axis	Mean	Median	Std. Dev.	Min.	Max.	Count
	phi	x	−088.21	−087.64	3.271	−129.70	−047.46	
		y	+000.00	+000.00	0.009	−000.01	+000.17	
		z	+088.84	+088.84	0.026	+088.63	+089.05	

segments in the O_1 time-series. Note that these solar wind methods require the aggregation of data over multiple passes through the solar wind, typically over a period of 2 weeks, so the O_1 values are determined less frequently than the other parameters.

Gains for all sensors derive from pre-launch calibration values. They are adjusted (for all ranges) to minimize discontinuities at range-change boundaries, as described in Section 2.2.3, and also the G_2/G_3 ratio is adjusted during the Fourier analysis (Section 2.2.2). As described in Section 3, inter-spacecraft and cross-comparison with EDI, WHISPER and STAFF instruments provide some assurance of the gain values, on a case-by-case basis. The azimuthal angles ϕ_2 and ϕ_3 can only be determined relative to each other. The azimuthal orientation of the sensor is also reliant on the accuracy and stability of the boom deployment. This has been carefully measured on-ground

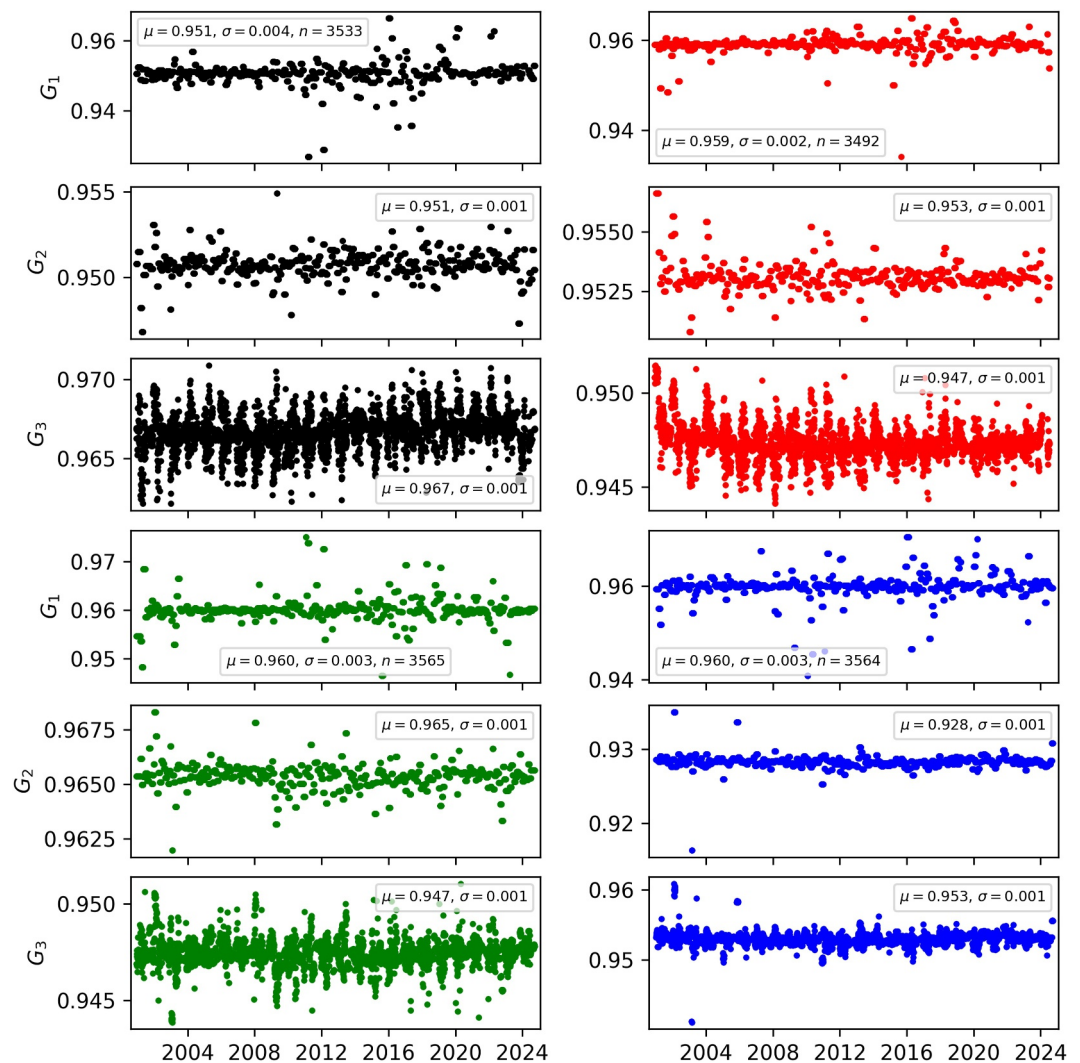


Figure 8. Range 2 gains, January 2001–September 2024, presented as-per Figure 7.

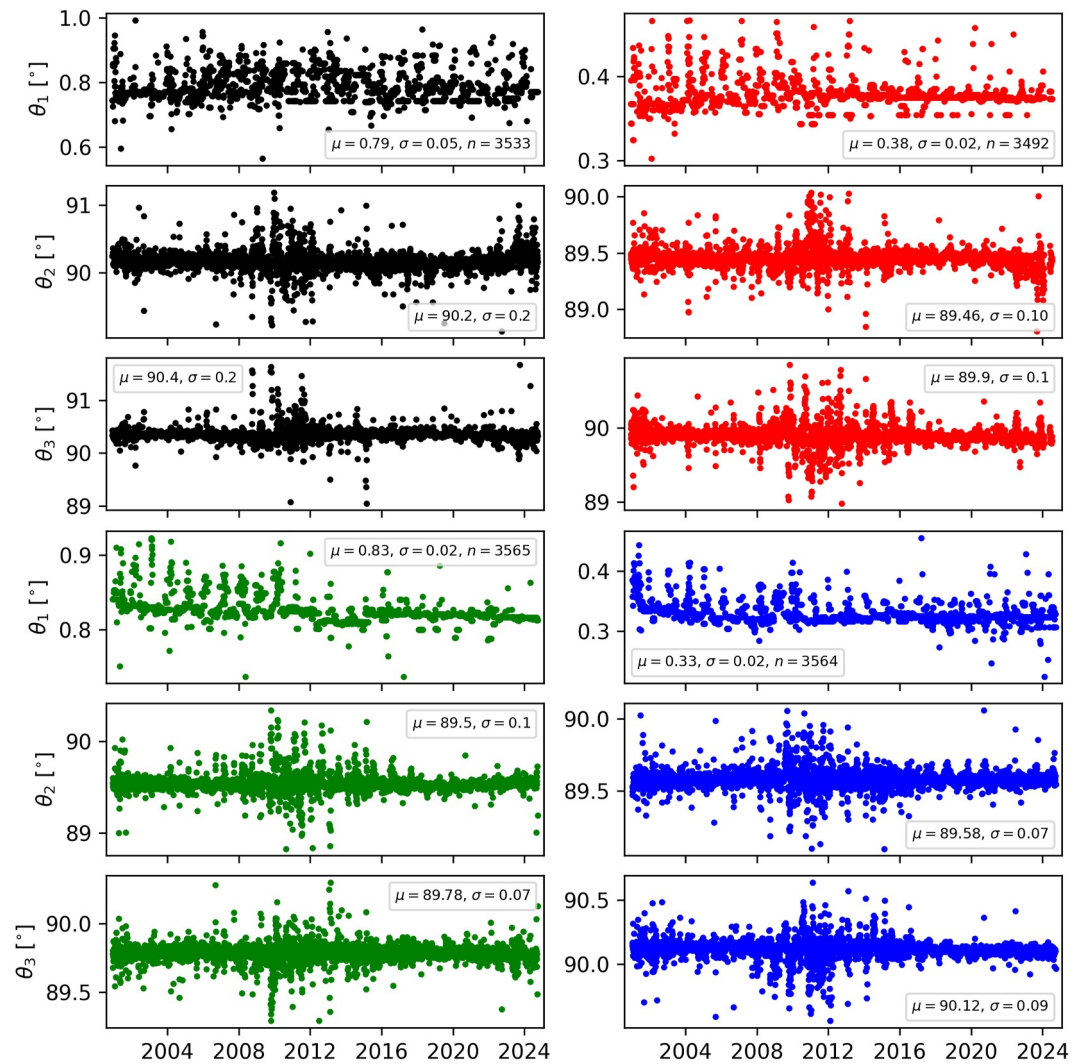


Figure 9. Range 2 theta angles, presented as-per Figure 7.

during spacecraft assembly, but it is not possible to make an in-flight absolute determination of these angles. The approach used during the calibration procedure has been to keep the ϕ_2 angle fixed at its nominal zero value (Figure 10) and to adjust ϕ_3 to minimize the signal associated with their mismatch.

In general, the precision and accuracy of these methods is dependent on both the quantity of data available in each orbit and the ambient field conditions. These conditions vary significantly on an annual basis and as the spacecraft orbital plane has evolved during the mission. To a lesser extent, they also depend on operational conditions as the spacecraft have aged. As a consequence, it is difficult to separate true variations in parameter values—arising from underlying sensor and electronics changes—from variations in the precision of the techniques. The variations seen in Figure 7 should be robust to the conditions and reflect true changes in the sensor offsets. Robustness is less clear for the gains and angles shown in Figures 8–10. The gains, in particular, should be stable over time as they are largely controlled by the sensors' feedback electronics, housed inside the electronics box, with relatively stable thermal conditions. The sensor angles are also thought to be stable. For the gains and angles, the mean values may represent the best estimate of a “true-value” which is constant through the mission. An exception would appear to be the Cluster 1 ϕ_3 angle, which shows some evolution over the first decade of the mission, though it is small (approximately 0.5°).

In summary, the uncertainty in the spin-axis O_1 offset determination is likely to be the dominant source of error in the FGM measurements in low fields, since it is only determined every 2 weeks during the “dayside” season.

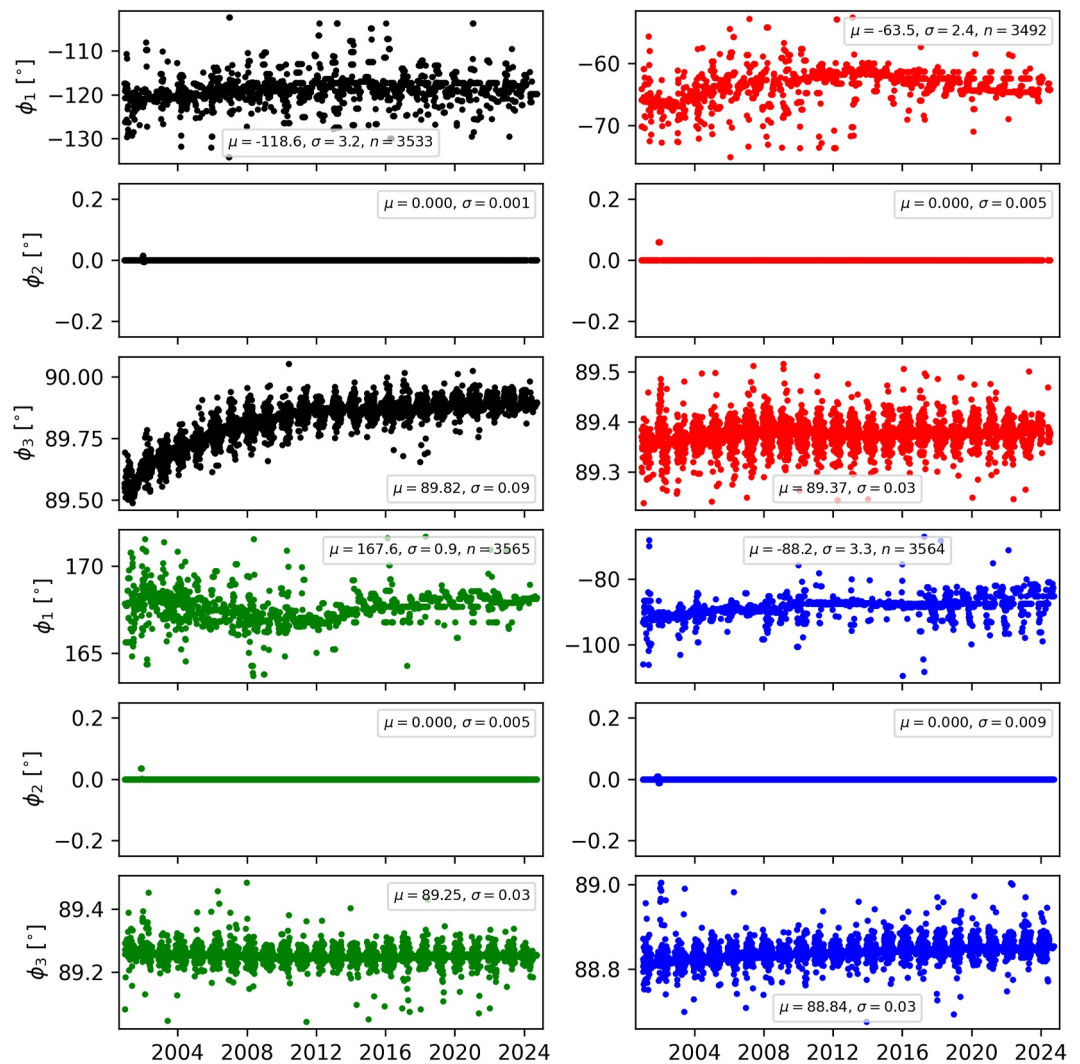


Figure 10. Range 2 phi angles, presented as-per Figure 7.

Annual variations in the gains and angles are thought to be due to variations in the precision of the methods, but annual and longer-term variations in the offsets are thought to be physically genuine, and due to the importance of the offsets for the overall accuracy, this effect has been studied in more detail. In principle, it is very difficult, if not impossible, to separate spacecraft magnetic field from sensor offset, since both effects present as a magnetic field in the spacecraft frame. Offset correlations have been sought against operational and engineering effects, such as instrument voltages, currents, and payload or platform operations. No positive correlations have been found, leading to the conclusion that the spacecraft are remarkably magnetically stable. The only exception to this is a well-characterized magnetic signature associated with the high-power amplifier (HPA) on Cluster 1, which has been shown to cause small DC shifts as the power-level changes. For Cluster 1, this effect has already been compensated in the data-processing and calibration pipeline, that is, the Cluster 1 offsets shown in Figure 7 represent underlying sensor behavior. Correlations versus temperature, however, show significant relationships, as described in the following section.

5. Sensor and Electronics Temperature Dependence

Fluxgate offsets are known to show temperature dependence, although the physical processes involved are not fully understood (Ripka et al., 2014). In the fluxgate sensor, temperature changes may affect the properties of the magnetic core, while mechanical stresses due to differential thermal expansion may plausibly contribute as well.

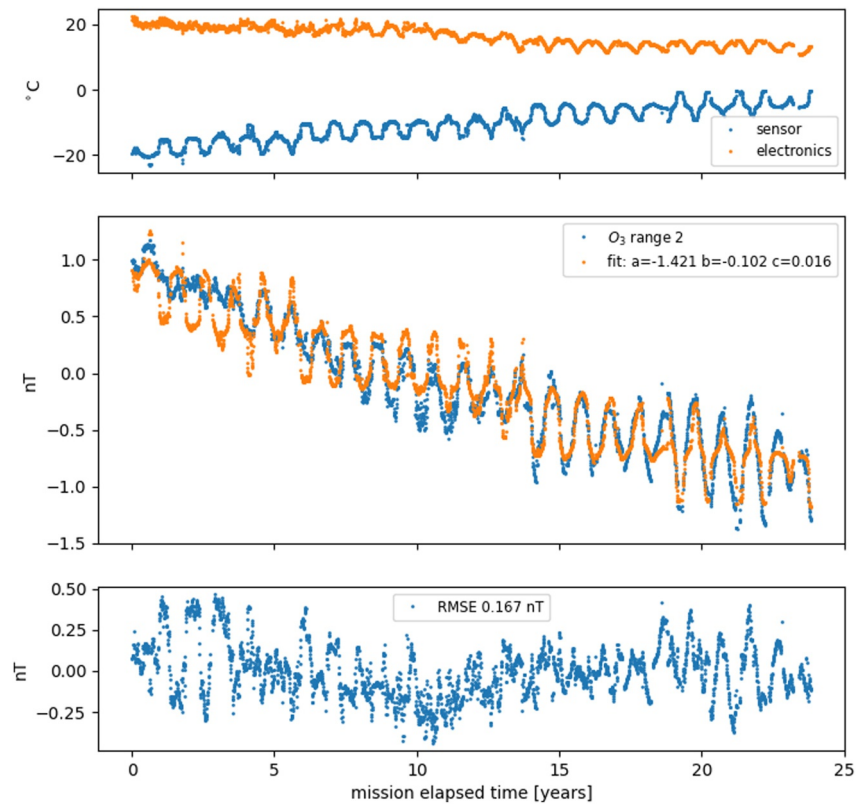


Figure 11. Cluster 1 spin-plane sensor offset O_3 temperature model for range 2. Top-panel: Sensor (blue trace) and electronics (orange) temperatures versus mission-elapsed time; middle: measured offsets (blue) and model-fit (orange); bottom: model residuals. The middle panel's legend provides the fit parameters and the bottom panel shows the RMS error of the fit.

Table 4
Offset Temperature Coefficients for All Sensors in Range 2

S/C	Sensor	r_{r_s}	r_{r_e}	a [nT]	b [nT/°C]	c [nT/°C]	RMSE [nT]
1	1	-0.83	+0.71	-6.255 ± 0.047	-0.103 ± 0.002	$+0.060 \pm 0.004$	0.41
	2	+0.89	-0.78	$+10.761 \pm 0.054$	$+0.151 \pm 0.002$	-0.118 ± 0.004	0.47
	3	-0.95	+0.73	-1.421 ± 0.019	-0.102 ± 0.001	$+0.016 \pm 0.001$	0.17
2	1	+0.08	-0.03	-0.028 ± 0.012	$+0.004 \pm 0.001$	$+0.001 \pm 0.001$	0.16
	2	-0.38	+0.23	-2.546 ± 0.013	-0.019 ± 0.001	$+0.002 \pm 0.001$	0.16
	3	+0.43	-0.43	-0.934 ± 0.014	$+0.017 \pm 0.001$	-0.018 ± 0.001	0.18
3	1	-0.52	+0.61	-3.108 ± 0.021	-0.016 ± 0.001	$+0.040 \pm 0.001$	0.18
	2	+0.36	-0.36	-4.734 ± 0.018	$+0.010 \pm 0.001$	-0.015 ± 0.001	0.16
	3	+0.20	-0.31	-2.228 ± 0.017	$+0.002 \pm 0.001$	-0.016 ± 0.001	0.15
4	1	+0.62	-0.66	-12.049 ± 0.011	$+0.011 \pm 0.001$	-0.021 ± 0.001	0.12
	2	-0.13	-0.02	-2.968 ± 0.013	-0.009 ± 0.001	-0.010 ± 0.001	0.15
	3	-0.78	+0.83	$+3.355 \pm 0.014$	-0.026 ± 0.001	$+0.049 \pm 0.001$	0.15

Note. Columns 3 and 4 provide the Pearson correlation coefficient for offset versus sensor and electronics temperatures respectively. Columns 5 to 7 provide the fit parameters in (6), while column 8 provides the root-mean-square error of the fit.

The sensor drive and sense electronics, inside the electronics box, will also be subject to temperature effects, particularly in the analog signal-processing functions. The outboard Cluster FGM sensor, mounted at the end of the boom, encountered a much more changeable thermal environment than the electronics, although both effects are considered here.

5.1. Offset Temperature Model

To quantify the temperature-dependence of the offsets, a simple linear model has been applied to the offset data. For each spacecraft and each sensor axis, a least-squares fit to Equation 6 has been performed

$$O_i = a_i + b_i T_s + c_i T_e \quad (6)$$

where T_s and T_e are the sensor and electronics temperatures respectively, and a_i , b_i and c_i are the fit parameters for sensor axis i . Results are shown for Cluster 1 O_3 offset in Figure 11 as an illustrative example. Data for all sensors, ranges 2–4, are given in Supporting Information S1, and are shown here for range 2 only (Table 4). Correlations for the higher ranges are considered to be unreliable due to the limited data available.

When interpreting these results, it is important to recall that the measurement of temperature is sampled with quite poor resolution—in Supporting Information S1 gives technical details—and each value is an average over the time in range 2. While this is consistent with the determination of the calibration parameter, which is itself an estimation over the same interval, it should be clear that temperature is measured with relatively poor precision. Nevertheless, the temperature model appears to capture the annual and decadal-scale variations in the offset parameters. The long-term drift that is clearly evident in the Cluster 1 offsets is strongly correlated with the general decrease/increase in the sensor/electronics temperatures respectively. There is no clear pattern in either the sign or magnitude of the coefficients, though it is clear that there is a significant temperature effect for all sensors on Cluster 1, for S_1 and S_3 on Cluster 4, and for S_1 on Cluster 3. For all these cases it is noted that the sensor coefficient is larger than the electronics coefficient, and these values occur in opposite-signed pairs. No explanation is offered for this effect. For Cluster 2, there is little temperature dependence.

The same methods have also been applied to the range 2–4 gains and angles. No correlation is expected because the parameters do not show any long-term drift, and none has been found.

6. Other Factors Influencing the Calibration Parameters

During the Cluster nominal mission (2001–2003), the orbit of approximately $20 \times 4 R_E$ with an inclination close to 90° provided regular passes through the solar wind, magnetosphere, magnetosheath and bow shock. FGM ranges 2–4, which had been carefully characterized on ground, were sufficient to measure the magnetic fields encountered. During successive mission extensions, the orbit evolved—mainly through gravitational perturbations—to lower perigee altitudes, reaching a minimum of a few hundreds of kilometers altitude during the period 2009–2012, before rising again. As a consequence, the FGM instruments were required to operate in a wider range of conditions, with higher magnetic fields requiring more range-changes per orbit. Since all the calibration techniques rely on statistics averaged over an orbit or longer per range, changes in the orbital parameters over the course of the mission have plausibly impacted the accuracy and precision of the methods in ways which are challenging to quantify. In the following section, the impacts on the FGM calibration of these effects are described. Furthermore, there are spacecraft-specific effects that have influenced the calibration parameters for individual spacecraft. These are described in Section 6.2.

6.1. Factors Affecting all Four Spacecraft

6.1.1. Annual Precession of the Spacecraft Orbital Plane and Eclipses

In addition to the quantity of data in each range, the nature of the ambient field impacts the precision of the calibration methods. Since the spacecraft orbital-plane is approximately inertially fixed, the Earth's motion around the Sun results in an apparent precession which rotates the apogee from the “dayside”—roughly January–May, when the spacecraft spend significant time in the solar-wind—to the “nightside”—roughly July to November, when the magnetotail is accessed—see Figure 1 in Escoubet et al. (2001) for context. The changing magnetic environment impacts the efficiency of the techniques. Complex, fluctuating fields impact the Fourier

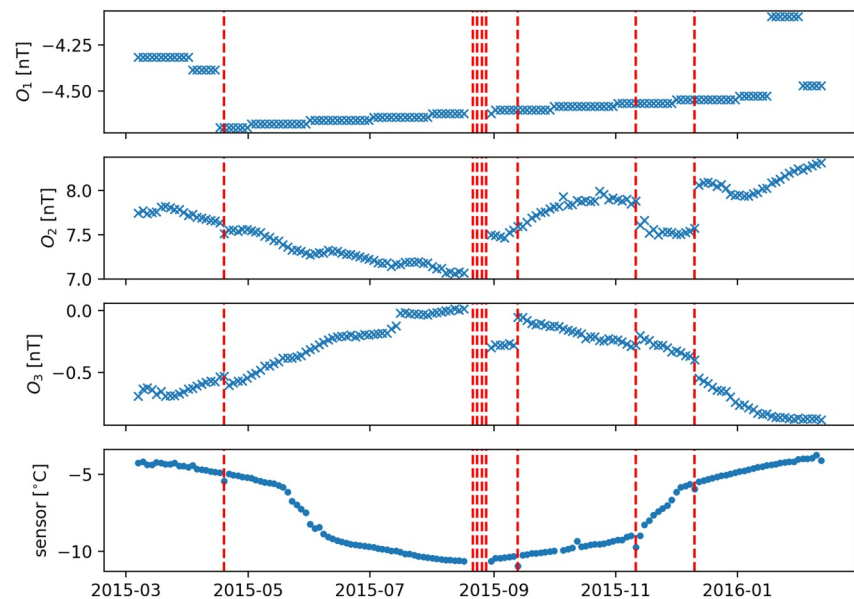


Figure 12. Cluster 1 sensor offsets and temperature for the period 7-March-2015 to 13-February-2016 with FGM power-cycles indicated (red dashed-line). The period chosen places the nightside (long) eclipses in the center of the figure. Top three panels: range 2 offsets for the S1, S2, and S3 sensors; bottom panel: orbitally averaged sensor temperature.

and range-change techniques negatively. For the gain and angle parameters, where there is no clear temperature-dependence, but annual variations are observed (Figures 8–10), it is speculated that these variations arise from reduced precision in the techniques, rather than reflecting any true underlying changes in the parameters. However, this can not be demonstrated conclusively. Furthermore, the spacecraft experience eclipses twice a year: during the dayside season, the eclipses occur around perigee, are short (tens of minutes), and occur on perhaps 5 to 10 successive orbits. 6 months later, on the nightside, the eclipses around apogee may be up to 3 hr but only occur on a few orbits. During the nominal mission, FGM instrument-driven sensor heaters attempted to mitigate the sudden loss of solar input during eclipses, however this practice was discontinued from 2006 due to power constraints. Later in the mission, after the loss of the batteries, the entire spacecraft were powered-down for many (and eventually all) eclipses (Escoubet et al., 2021). It is expected that the sudden temperature changes will have had an impact on both the actual values of some parameters, and also the precision of the techniques. An example of the temperature swing seen during an eclipse is included in Supporting Information S1, together with a figure illustrating the eclipse seasons and durations through the mission.

6.1.2. Increased Number of Ranges Used per Orbit

Up to mid-2006, FGM data was recorded in ranges 2–4 only, with typical usage per orbit of 75%, 15%, and 10% respectively. After the higher ranges were required, the proportions were of the order 3%, 2% and <1% for ranges 5–7 respectively. This highlights the challenges in calibrating data in the higher ranges, where data may only be available for a few minutes per orbit, but it does not impact the time in the lower-numbered ranges. Nevertheless, the increased number of ranges per orbit led to increased use of the range-change calibration method, which adjusts parameters in both the higher and lower ranges to minimize discontinuities. Any effect on the quality is hard to quantify, but it is plausible that the precision of the calibration parameters has been reduced as the number of ranges has increased.

6.2. Factors Affecting Individual Spacecraft

6.2.1. Cluster 1: Spin-Axis Offset Level-Shifts

Fluxgates in general may be subject to offset level shifts associated with power-cycling. The effect is not well-understood but may be due to residual magnetization in the sensor ring-core (Ripka et al., 2014). This effect has been observed for Cluster 1 FGM in particular. Figure 12 shows the range 2 offsets for a roughly 1-year period

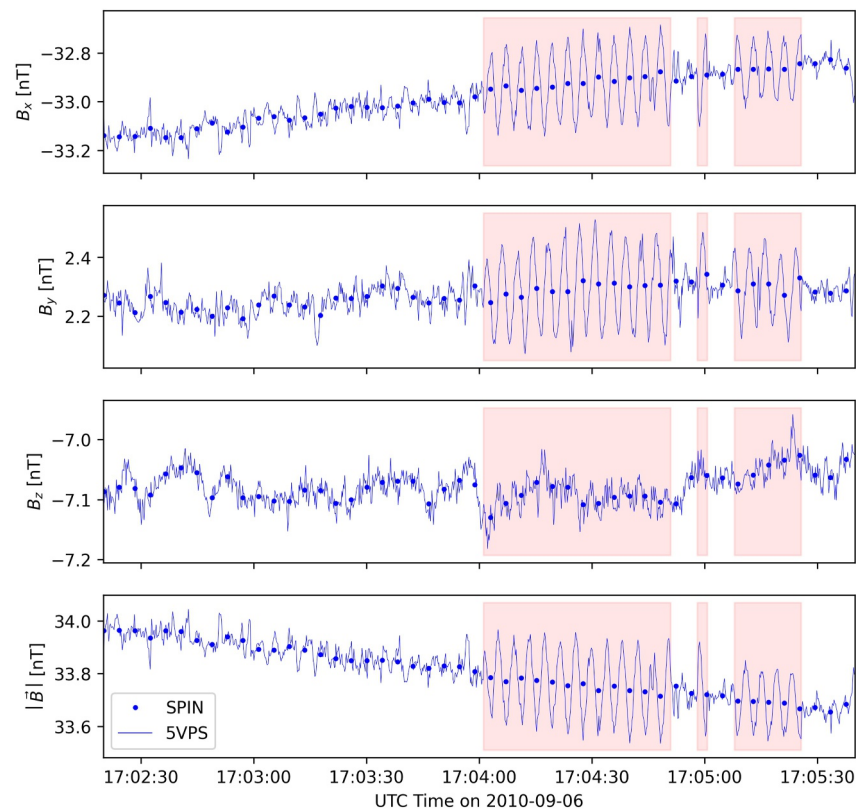


Figure 13. Cluster 4 data at 5 vectors per second time resolution (“5VPS”) for the period 17:02 to 17:05 on 6-September-2010. Field components (top 3 panels) are in the GSE system. Periods of “bursty spin-tone” are highlighted. Solid markers indicate the data averaged to “SPIN” resolution.

between the 2015 and 2016 dayside seasons. While the spin-plane offsets are primarily controlled by the annual temperature variation, there are many distinct level-shifts, most of which are associated with the indicated power-cycling times. Notably, the level-shifts do not appear to accumulate, that is, there is no drift associated with multiple power-cyclings. It should be noted that many of the power-cycles in this period were also associated with “power-down” eclipses where both the sensor and electronics would have seen significant short transient temperature changes, which may have been a contributing factor. The figure illustrates the limitations in tracking the spin-axis offset O_1 : between dayside seasons the values are interpolated; any level-shift occurring during this period can not be detected.

6.2.2. Cluster 1: Perigee Lowering and High-Power Amplifier (HPA) Operational Modes

Following the loss of the original Cluster mission, which was subject to a failed launch attempt in 1996, the rebuilt set of spacecraft made use of some flight-spares hardware from the earlier mission in the construction of the new Cluster 1 spacecraft. While all the spacecraft are remarkably magnetically “clean” (Balogh, 2012), there is a known effect on the Cluster 1 spacecraft associated with the high-power amplifier (HPA) used for RF communications. There is a distinct magnetic signature, visible in the spin-axis S_1 sensor of FGM, of the order 1 nT. The Cluster 1 HPA is of a different design than the other three spacecraft, arising from re-use of flight-spares hardware. The HPA cycles through different power-levels depending on the spacecraft distance from Earth and the data-transmission rate required, resulting in a step-wise DC magnetic signature. As a consequence of the perigee-lowering, HPA mode switches became more frequent from 2009 onwards. This effect has been characterized and compensated by direct removal from the FGM time-series data before calibration. The details are documented in the FGM Calibration Report, which is available on the CSA website.

6.2.3. Cluster 4: Bursty Spin Tone in Full-Resolution Data

On the Cluster 4 FGM instrument there has been an effect apparent only in the sub-spin (high time-resolution) data sets where signals at the spin-frequency appear as transient events; this has been observed since 2010. It has not been possible to eliminate this from the data set hence the archive data-products “FULL” (for full time-resolution) and “5VPS” (data averaged to 5 vectors per second) exhibit this effect as illustrated in Figure 13. Periods, as highlighted in the figure, last from minutes down to a single spin. No definitive cause has been found and there is no correlation with instrument or spacecraft operations. It is speculated that the effect arises from a transient shift of about 0.1 nT in the offset of one of the spin-plane sensors, S_2 or S_3 —since the S_1 axis, which is nominally spin-aligned, does not show the effect.

When the data is processed to “SPIN” time-resolution, these sub-spin signals are removed by the averaging. This also serves to illustrate the need for the greatest precision in the calibration when data is to be presented at higher time-resolution. Users of the data for C4 should be aware of this effect, which remains in the archived “FULL” and “5VPS” data sets, and the associated caveats for the data.

7. Conclusions and Recommendations

Ground-calibration for ranges 2–5 formed the starting point for the in-flight FGM calibration techniques, which tracked changes in the parameters over the 24 years of the Cluster mission. More recent refinements of these methods, for example, Plaschke et al. (2019) might result in incremental improvements at a technical level, and further investigation is warranted, however the methods described here (Gloag et al., 2010; Kepko et al., 1996) have been applied throughout for reasons of consistency across the mission's timespan.

The parameters have shown remarkable stability. Offsets demonstrate temperature-dependence for some sensors (notably on Cluster 1), though after correction for this effect there is negligible true long-term drift in the offsets. Annual variations in the gains and angles are most likely to be due to varying precision in the techniques, as a function of the annual variation in ambient conditions: in general, there is no significant true variation in these parameters. It has been possible to determine the calibration parameters with a high degree of confidence and precision throughout the mission due to the almost-complete data coverage and the magnetic cleanliness of the spacecraft platforms. Greater accuracy in temperature monitoring would have allowed for improved temperature-dependence modeling. For future missions, attention to these points would be beneficial.

The present work aims to document the methods and results of the in-flight calibration activities. FGM data is compared between spacecraft, and also with WHISPER and EDI measurements on individual spacecraft (at limited times and conditions) leading to an overall assessment of FGM accuracy as given in Table 2 which should be understood as guideline values valid under typical operating conditions. The large dynamic range of the fields encountered, the changing physical conditions, and the length of the mission make quantitative statements about accuracy hard to guarantee though this aspect of the present work may be pursued in future studies. Under low-field conditions, up to 200 nT or so, offset uncertainties likely dominate the overall error, with the spin-axis offset—never better than 0.2 nT uncertainty—being the greatest contributor. Under higher-fields, sensor gains are expected to dominate the error, and future work might investigate cross-calibration with geomagnetic field-models derived from high-accuracy magnetic-mapping missions such as SWARM.

Estimating the calibration parameters each orbit for every instrument range has required a substantial effort. While the software has been continuously improved during the mission, much of the work has been manual or at least semi-automated, and required significant human-in-the-loop intervention. Notably, the original Cluster mission duration of 2 years was extended only in stages of 2–3 years at a time, hence the eventual end-of-mission horizon was never sufficiently distant to warrant a complete overhaul of the calibration software and procedures. This may also be a point for future missions to consider.

The FGM team has benefitted from good continuity of personnel over large parts of the mission lifetime, which has helped to retain knowledge of the calibration methods, while documentation has been maintained to a good standard. The implementation by ESA of the Cluster Active Archive (CAA), subsequently the Cluster Science Archive (CSA), has provided a stable platform for data dissemination, with well-documented data products, and the regular cross-calibration workshops have been a vital forum for knowledge exchange between instrument teams. In particular, this focus on archive-quality data has driven the need for robust calibration methods applied with consistency throughout the mission.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Cluster FGM data and calibration files (FGM, 2025) are available at the ESA Cluster Science Archive (<https://csa.esac.esa.int/csa-web>). FGM Instrument temperatures are available for download from the ESA Cluster Active Archive (<https://caa.esac.esa.int/caa>)—the parameter names and descriptions are given in Supporting Information S1.

ACE MAG 1-s data is available at the NASA Space Physics Data Facility (Smith & Ness, 2022).

Plots have been generated with Python and Matplotlib (Matplotlib Development Team, 2025).

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