In-Flight Calibration Processes for the MMS Fluxgate Magnetometers

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Abstract

The calibration effort for the Magnetospheric Multiscale Mission (MMS) Analog Fluxgate (AFG) and Digital Fluxgate (DFG) magnetometers is a coordinated effort between three primary institutions: University of California, Los Angeles (UCLA); Space Research Institute, Graz, Austria (IWF); and Goddard Space Flight Center (GSFC). Since the successful deployment of all 8 magnetometers on 17 March 2015, the effort to confirm and update the ground calibrations has been underway during the MMS commissioning phase. The in-flight calibration processes evaluate twelve parameters that determine the alignment, orthogonalization, offsets, and gains for all 8 magnetometers using algorithms originally developed by UCLA and the Technical University of Braunschweig and tailored to MMS by IWF, UCLA, and GSFC. We focus on the processes run at GSFC to determine the eight parameters associated with spin tones and harmonics. We will also discuss the processing flow and interchange of parameters between GSFC, IWF, and UCLA. IWF determines the low range spin axis offsets using the Electron Drift Instrument (EDI). UCLA determines the absolute gains and sensor azimuth orientation using Earth field comparisons. We evaluate the performance achieved for MMS and give examples of the quality of the resulting calibrations.

Application of Ground Calibration Parameters

The results of the ground calibrations are applied to the data first, to account for the temperature-dependence of the gains, as well as non-linearity.

Thus, the in-flight calibration parameters indicate the change in instrument performance from that which was measured on the ground. These calibrations include:

Gain, as a function of sensor and electronics temperatures.

equation [1]

$$\boldsymbol{B_{123temp} = B_{123} \cdot (g + m_s \cdot T_s) \cdot (1 + m_e \cdot (T_e - T_{eC}))}$$

Non-linearity, as a function of measured field strength.

equation [2]

$$\boldsymbol{B_{123precal} = \sigma_1 \cdot B_{123temp} + \sigma_2 \cdot B^2_{123temp} + \sigma_3 \cdot B^3_{123temp}}$$

Application of In-Flight Calibration Parameters

Parameters are chosen such that it is possible to optimize physical parameters independently rather than jointly.

In contrast to the parameters described in [1], these parameters, for example, allow the thetas to remain constant regardless of how the spin axis changes, relative to the sensor.

equation [3]

[orthogonalization] [absolute gains] [spin plane relative gain] [offset]

$$\boldsymbol{B_{ORTHO}} = \begin{pmatrix} sin\vartheta_1 & 0 & cos\vartheta_1 \\ cos\varphi_{12}sin\vartheta_2 & sin\varphi_{12}sin\vartheta_2 & cos\,\vartheta_2 \\ 0 & 0 & 1 \end{pmatrix}^{-1} \cdot \begin{pmatrix} dg_{SP_abs} & 0 & 0 \\ 0 & dg_{SP_abs} & 0 \\ 0 & 0 & dg_{SA_abs} \end{pmatrix} \cdot \begin{pmatrix} dg_{SP} & 0 & 0 \\ 0 & 1/dg_{SP} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} B_{1precal} & O_1 \\ B_{2precal} & -O_2 \\ B_{3precal} & O_3 \end{pmatrix}$$

Offsets

O1
O2
O3
Offsets in nT, applied to the non-orthogonal, sensors, calibrated to the best knowledge of ground cals.

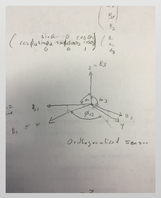
Gains

dg_SP_abs
geometric mean of the spin-plane sensor gains.

dg_SA_abs
gain correction for the spin axis sensor (B3)

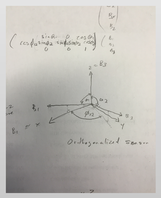
dg_SP
proportional difference in gain of the spin sensors from dg_SP_abs.

Orthogonalization



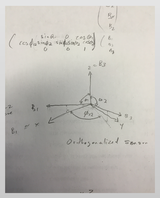
Theta1
Theta2
Phi12
angles relate the sensor positions to the orthogonalized sensor system (ORTHO)

Alignment to Spin Axis

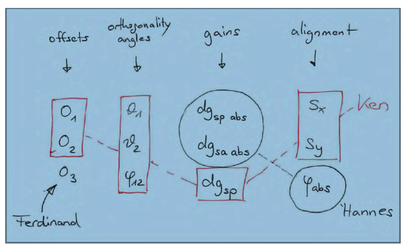


sx
sy
specify the orientation of the B3 sensor in a SPIN ALIGNED (SA) system. This defines a rotation between ORTHO and SA.

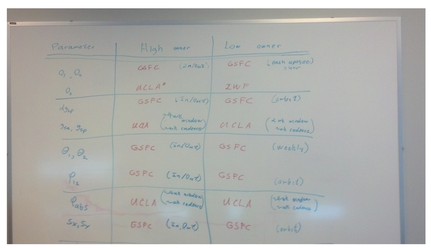
Alignment to spin phase



Phi_abs
defines a rotation that corrects for absolute errors in the phase, as determined by earth field comparison and inter-spacecraft calibration.



Each institution is able to 'own' a set of parameters, which can be determined and updated without affecting the other parameters, although there is a set order for updating each set of parameters.

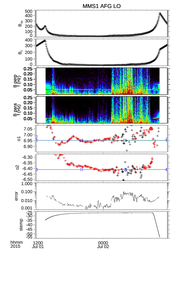


Each parameter is updated at it's own cadence. The tasks performed at UCLA generally require longer integration times. Separate calibration files are maintained for high field range and low field ranges. Low range and High rage are calibrated independently at GSFC.

Orthogonalization

Method For Determining Offsets

- Method
  - Orbit is sub-divided into intervals much shorter than an orbit.
  - Each interval is assigned an error value using an empirical estimate of error.
  - Values of a related pair of parameters that share the same error estimate -- in this case O1 and O2 -- are determined for each interval.
- Plot Panels show
  - Bsp – Modulus of B measured by the spin-plane sensors.
  - Bz – B measured by spin-aligned sensor.
  - Sonograms of each of the above.
  - The two parameters, on separate panels
    - Red + indicates values of parameters that have error estimate < threshold, in this case 0.01.
  - Error Estimate
  - Sensor Temperature



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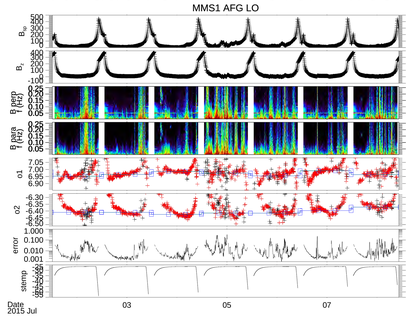
Variation of Offset over 1 week



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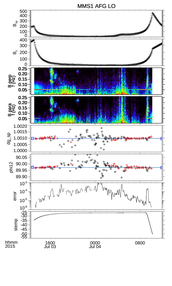
Dg_sp and Phi12

- Some temperature dependence, but a single fit to the full orbit -- using our statistical methods -- gives values that have a good fit for the ROI.



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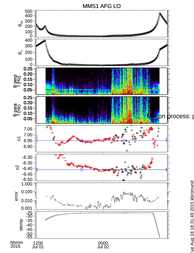
Proposed solution

- **Max error**: Select the population of values with error estimates below a specified fixed threshold (shown in red). Rejects intervals of high geophysical variability.
- **Ranking**: Rank points passing the threshold criterion: select the center 50% of this population. Rejects high and low outliers and retains only the center of the distribution.
- **Weighted mean**: Evaluate the mean of this center 50% of values weighted by 1/sqrt(error). This gives greatest weight to the points in which we have the greatest confidence.



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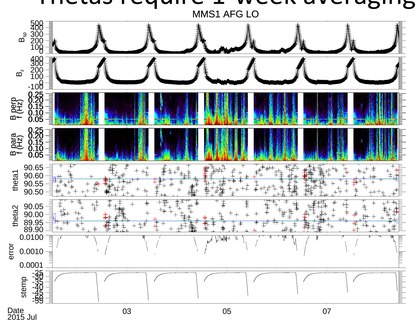
Thetas require 1-week averaging



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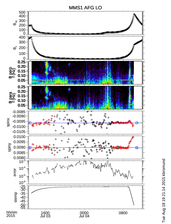
Spin_x and Spin_y

- Significant temperature dependence, but a single fit to the full orbit -- using our statistical methods -- gives values that have a good fit for the ROI.



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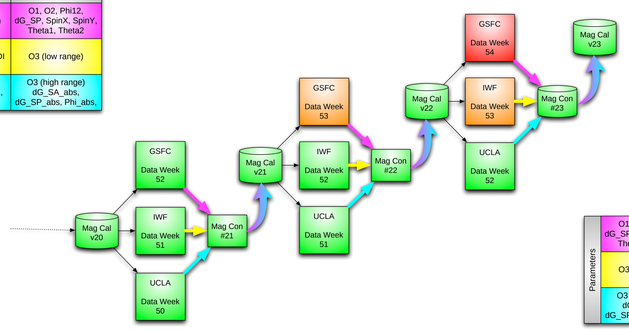
Institution	Process	Parameters Affected
GSFC	Orthogonalization	O1, O2, Phi12, dG_SP, SpinX, SpinY, Theta1, Theta2
IWF	Spin Axis using EDI	O3 (low range)
UCLA	Range Joining, Earth Field Comp., Intercalibration	O3 (high range) dG_SA_abs, dG_SP_abs, Phi_abs,

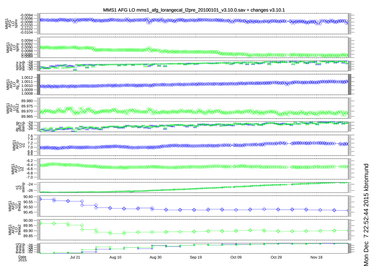


Once the sensors have been orthogonalized, IWF provides the low range spin axis offset, O3, using methods described in [2]. Then Low Range and High Range are matched at UCLA by adjusting O1 and O2 in High range, and Gsp in low range, as in [1]. This process also yields O3 in the high range. The range joining process takes advantage of the fact that by design, AFG transitions to Low range before DFG, and AFG transitions back to High range before DFG. Finally, Earth field comparison and inter spacecraft calibration are performed [4].

Parameters	Data Week 50	51	52	53	54
O1, O2, Phi12, dG_SP, SpinX, SpinY, Theta1, Theta2	v19	v20	v21	v22	v23
O3 (low range)	v20	v21	v22	v23	
O3 (high range) dG_SA_abs, dG_SP_abs, Phi_abs,	v21	v22	v23		

Each week, the inputs from GSFC, IWF, and UCLA are reviewed and merged together into a new calibration file at a MagCon. The approved calibrations become the basis for calibration activities until the next MagCon. Data weeks for which all 12 parameters have been approved (shown in green) can be processed to Level 2.

Trend plot of all the parameters for the mission, including commissioning phase and science phase to date. Sensor Temperature for the integration time of each parameter is also shown, to indicate the degree to which variations do (or do not) correlate with temperature.



References

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[4] Leinweber, H. K., C. T. Russell, and K. Torkar (2013), Precise calculation of current densities via four spinning spacecraft in a tetrahedron configuration, IEEE T. Magn. 49, p. 5264 - 5269..