THEMIS
FGM CAL File and Processing

THM-SOC_113_FGM_CALPROC
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Table of Contents

1. Introduction

1.1 Purpose and Scope.

The document describes the calibration procedure from raw data (in a non orthogonal sensor system) into a coordinate system which is defined by spacecraft spin axis and sun sensor direction (SSL). Creation and application of the Cal File is described. The document contains the preflight determined initial values and gives an overview how the L0..L2 data are processed.

1.2 Applicable Documents.

1.	THM_SYS_012_PDMP	THEMIS Project Data Management Plan
2.	THM_SOC_101_TIME	THEMIS TIME Definition
3.	THM_SOC_108_GMAG_L1_VARNAMES	THEMIS GMAG Variable Name Def's
4.	THM_SOC_110_COORDINATES	THEMIS Science Coord. Systems Def.
5.	THM_SOC_111_SUNSENSPROC	THEMIS SUN SENSOR Science Processing
6.	THM_SOC_112_ATTPAIPROC	THEMIS Science ATT & Inertia Determ.
7.	THM_SOC_113_FGM_CALPROC	THEMIS FGM CAL File and Processing
8.	SAI-SPEC-1079A (Oct 26, 2005)	THEMIS Coordinate systems
9.	SAI-RPT-0722a (September, 2006)	Probe Alignment Report (MSSS data, p18)
10.	pturin e-mail on Faro alignment results (9/28/06)	FGM, SCM mag alignments
11.	THM-MB-MEC-005-Magnetometer clocking r7.pdf	MAG clocking angles

2. Definition of quantities (coordinate systems, transformation matrices, offsets)

2.1 Coordinate systems:

FS - non orthogonal sensor system

FGS - orthogonal sensor system (blue system in Figure 1, x-axis and xy-plane unchanged versus FS)

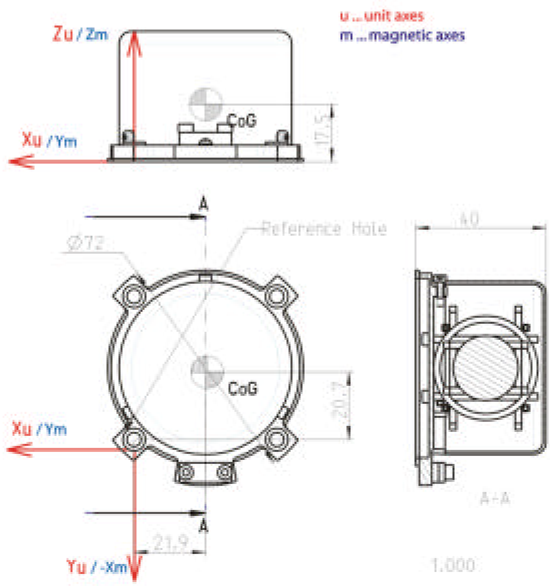

Figure1

UNIT - FGM sensor system as defined by ICD (see red system in Figure 1).

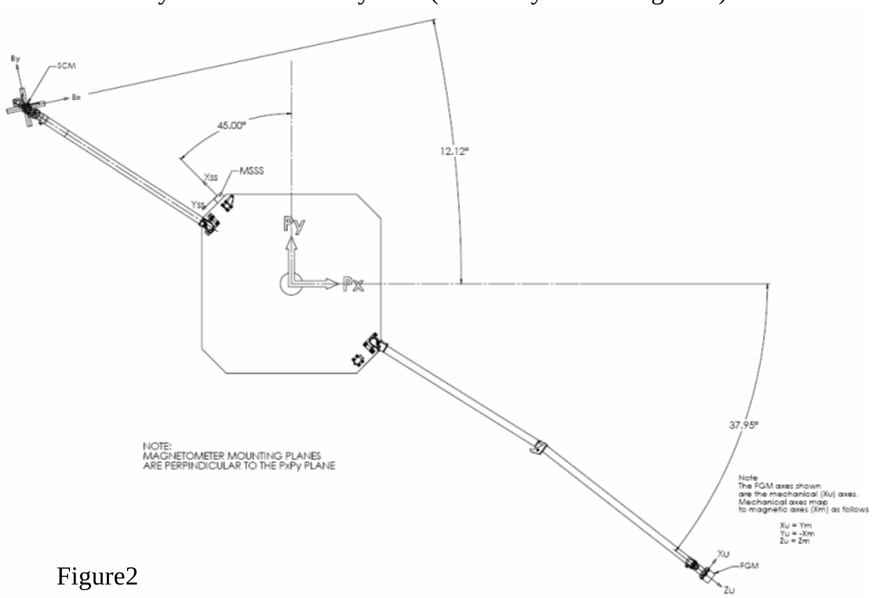

Figure2

SPG - Spinning Probe Geometric (or probe coordinate system) This system is defined by the mechanical designers of the probe in SAI-SPEC-1079A - see Figure 3. The z-axis is directed through the probe normal to the attachment plane. The x-axis is aligned normal to the face sheet of Solar Panel1. This face has an adjacent corner, moving counterclockwise, housing the ESA. In other words the ESA shall fall in the +x/+y quadrant of the probe coordinate system. The y-axis completes a right handed orthogonal triad.

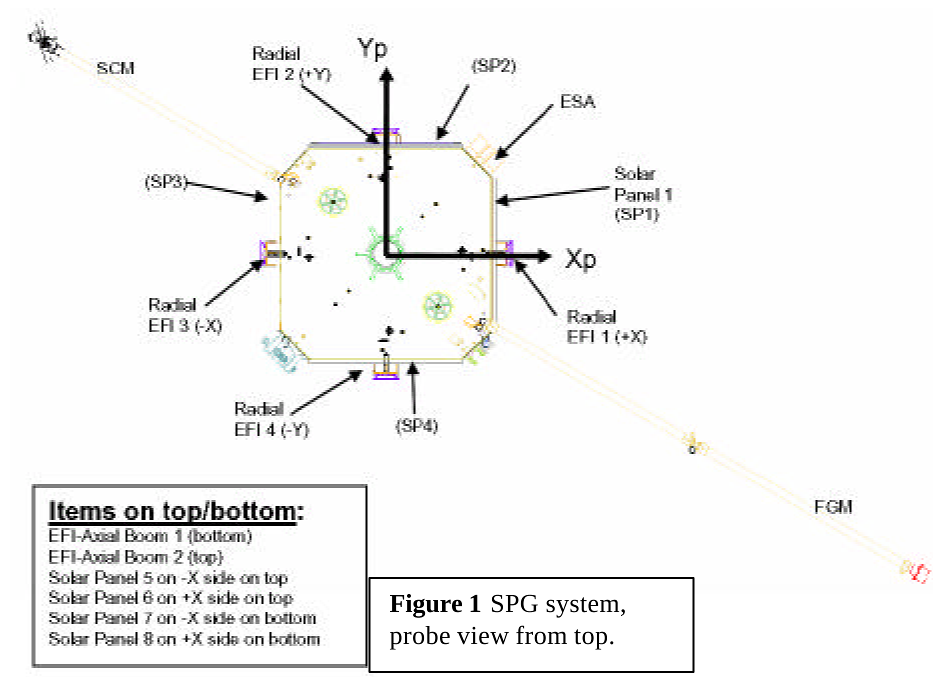

Figure3

Figure 1 SPG system, probe view from top.

SR: - spin aligned spacecraft system. This system points with z along the Spin axis of the probe. (the momentum vector is along the principal axis of inertia). The Izz was measured during spin balance tests at JPL to be within 0.25deg of the geometric axis assuming (by modeling) magnetometer booms have been deployed but EFI booms are stowed. As fuel is consumed this angle is expected to change but not by much. A more precise determination of the difference between geometric Z and spin axis and its function of time will be done during inflight calibration by minimizing the spin tone in the Z component. These two angles are recorded in the daily STATE file.

SSL: - Spinning SunSensor – L-vectorZ. Also this system points with z along the Spin axis of the probe. The x axis of the system points towards the Sun Sensor (Miniature Spinning Sun Sensor) look direction. Theoretical angle between the Sun Sensor look direction and the probe X axis is 135 deg (rotation about spin axis). The pointing of the sun sensor is shown in Figure 2, excerpt from SAI-spec 1079a.

Remark: Names of coordinate systems are partly defined in THM_SOC_110_COORDINATES (UNIT, SPG, SSL) or taken from Cluster nomenclature (FS, FGS, SR).

2.2 Offsets and Transformation Matrices

- Ranging Factor k_r
  derived by range value which has to be extracted from the fgm header.

  $k_r = 50000/2^{(16+range)}$

- Sensor Offset $\mathbf{O}_{fgm} = \begin{bmatrix} O_{fgm\_x} \\ O_{fgm\_y} \\ O_{fgm\_z} \end{bmatrix}$

  Offset in standard mode (closed feedback) depends on feedback “zero” current therefore it is dominated by FGE. Offsets of sensors are close to zero. Offsets are determined by pre-flight calibration and depends on mode. Mode dependency will be not processed because we assume that FGM operates most time in standard mode. Open loop modes are used for health checks and in emergency case only. Pre-flight determined standard mode offsets shall be used as default.

  Table of offsets (derived from pre-flight tests made in Europe, Berkeley and JPL):

	O_{fgm_x}	O_{fgm_y}	O_{fgm_z}
Probe 1 (FGE4)	-5	-11	-
Probe 2 (FGE1)	-6	-8	-5
Probe 3 (FGE2)	-5	-7	-5
Probe 4 (FGE3)	-8	-3	-3
Probe 5 (FGE5)	-3	-3	-3

- Orthogonalisation Matrix $\mathbf{M}_{ort} = \begin{bmatrix} 1 & 0 & 0 \\ a_{xy} & 1 & 0 \\ a_{xz} & a_{yz} & 1 \end{bmatrix}$

  Orthogonality depends on alignment of the feedback coil system, therefore it depends only on FGS. Misalignment is known from ground calibration with high precision, nevertheless it will be updated by inflight calibration.
  Table of angel of non-orthogonality (derived from measurements in JH and Magnetsrode):

	$alpha_{xy}$	$alpha_{xz}$	$alpha_{yz}$
Probe 1 (FGS6)	0.0031	0.0016	0.0023
Probe 2 (FGS1/9)	0.0065	0.0028	0.0107
Probe 3 (FGS2)	-0.0021	-0.0041	-0.0049
Probe 4 (FGS3)	0.0012	0.0085	0.0040
Probe 5 (FGS5)	-0.0090	-0.0016	0.0066

- Sensor Accommodation Matrix $\mathbf{M}_{unit} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{M}_{yz}\ \mathbf{M}_{xz}\ \mathbf{M}_{xy}$

with:

$$\mathbf{M}_{xy} = \begin{bmatrix} Cos(-b_{xy}) & Sin(-b_{xy}) & 0.0 \\ -Sin(-b_{xy}) & Cos(-b_{xy}) & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$$

$$\mathbf{M}_{xz} = \begin{bmatrix} Cos(-b_{xz}) & 0.0 & Sin(-b_{xz}) \\ 0.0 & 1.0 & 0.0 \\ -Sin(-b_{xz}) & 0.0 & Cos(-b_{xz}) \end{bmatrix}$$

$$\mathbf{M}_{yz} = \begin{bmatrix} 1.0 & 0.0 & 0.0 \\ 0.0 & Cos(-b_{yz}) & Sin(-b_{yz}) \\ 0.0 & -Sin(-b_{yz}) & Cos(-b_{yz}) \end{bmatrix}$$

First the individual error of each sensor alignment due to its mounting tolerances has to be eliminated by rotation about preflight determined angles $beta_{xy}$, $beta_{xz}$ and $beta_{yz}$, and second the rotation about the z axis has to be performed. $\mathbf{M}_{unit}$ will be not modified during inflight calibration Table of angel of sensor accommodation (derived from measurements in JH):

	$beta_{xy}$	$beta_{xz}$	$beta_{yz}$
Probe 1 (FGS6)	-0.1166°	0.1218°	-0.1248°
Probe 2 (FGS1/9)	-1.2698°	-0.0398°	-0.3797°
Probe 3 (FGS2)	-0.1368°	0.1480°	0.5058°
Probe 4 (FGS3)	0.3398°	-0.2799°	-0.0473°
Probe 5 (FGS5)	0.2963°	0.0754°	-0.6155°

- Boom Accommodation Matrix $\mathbf{M}_{probe}$

Boom accommodation matrices probe individual and different for stowed and deployed boom. Values are determined by Paul. $\mathbf{M}_{probe}$ will be not modified during inflight calibration.

Table of matrices of boom accommodation (measured by Paul):

	stowed boom	deployed boom
Probe 1 (FGS6)	$\begin{bmatrix} 0.7073 & 0.0588 & 0.7044 \\ 0.7069 & -0.0637 & -0.7044 \\ 0.0035 & 0.9962 & -0.0866 \end{bmatrix}$	$\begin{bmatrix} 0.6225 & 0.0169 & 0.7824 \\ 0.7826 & -0.0026 & -0.6226 \\ -0.0085 & 0.9999 & -0.0149 \end{bmatrix}$
Probe 2 (FGS1/9)	$\begin{bmatrix} 0.7073 & 0.0588 & 0.7044 \\ 0.7069 & -0.0637 & -0.7044 \\ 0.0035 & 0.9962 & -0.0866 \end{bmatrix}$	$\begin{bmatrix} 0.6257 & 0.0085 & 0.7801 \\ 0.7801 & -0.0031 & -0.6257 \\ -0.0029 & 1.0000 & -0.0086 \end{bmatrix}$
Probe 3 (FGS2)	$\begin{bmatrix} 0.7073 & 0.0588 & 0.7044 \\ 0.7069 & -0.0637 & -0.7044 \\ 0.0035 & 0.9962 & -0.0866 \end{bmatrix}$	$\begin{bmatrix} 0.6279 & 0.0082 & 0.7783 \\ 0.7783 & 0.0022 & -0.6279 \\ -0.0069 & 1.0000 & -0.0050 \end{bmatrix}$

Probe 4 (FGS3)	$\begin{bmatrix} 0.7073 & 0.0588 & 0.7044 \\ 0.7069 & -0.0637 & -0.7044 \\ 0.0035 & 0.9962 & -0.0866 \end{bmatrix}$	$\begin{bmatrix} 0.6250 & 0.0057 & 0.7806 \\ 0.7806 & 0.0004 & -0.6250 \\ -0.0039 & 1.0000 & -0.0042 \end{bmatrix}$
Probe 5 (FGS5)	$\begin{bmatrix} 0.7073 & 0.0588 & 0.7044 \\ 0.7069 & -0.0637 & -0.7044 \\ 0.0035 & 0.9962 & -0.0866 \end{bmatrix}$	$\begin{bmatrix} 0.6233 & 0.0063 & 0.7819 \\ 0.7819 & -0.0007 & -0.6234 \\ -0.0034 & 1.0000 & -0.0054 \end{bmatrix}$

- Spin Alignment Matrix $\mathbf{M}_{spin}$

The Z-axis has been fine tuned by rotation about X_{probe} and Y_{probe} to the spin axis.
Initial values can be derived from the measurements by Paul during post I&T spin balance and alignment measurement (see MAG_Sensor_to spin_axis PTVA.xls).

$$\mathbf{M}_{G2S} = \mathbf{M}_g \ \mathbf{M}_b \ \mathbf{M}_a$$

with:

$$\mathbf{M}_a = \begin{bmatrix} Cos(g) & Sin(g) & 0.0 \\ -Sin(g) & Cos(g) & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \quad g = 90{,}xx° \text{ (depends on probe)}$$

$$\mathbf{M}_b = \begin{bmatrix} Cos(b) & 0.0 & Sin(b) \\ 0.0 & 1.0 & 0.0 \\ -Sin(b) & 0.0 & Cos(b) \end{bmatrix} \quad b = 0.25°$$

$$\mathbf{M}_g = \begin{bmatrix} Cos(a) & Sin(a) & 0.0 \\ -Sin(a) & Cos(a) & 0.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix} \quad a = 45.0°$$

The alignment of the x axis to the sun sensor will be done separately see definition of $\mathbf{M}_{sun}$
We separate the spin alignment from the combined spin alignment/sun sensor orientation matrix in the following way:

$$\mathbf{M}_{spin} = \mathbf{M}_g^{-1} \ \mathbf{M}_b \ \mathbf{M}_g$$

This gives us the following initial spin alignment matrix:

$$\mathbf{M}_{spin} = \begin{bmatrix} 1.0 & 0 & 0.0031 \\ 0 & 1.0 & 0.0031 \\ -0.0031 & -0.0031 & 1.0 \end{bmatrix}$$

$\mathbf{M}_{spin}$ will be updated by inflight calibration

- Scale Values Matrix $\mathbf{M}_{scale}$ in dependency of UCLA calibration output
  $\mathbf{M}_{scale}$ will be updated by inflight calibration using input from UCLA Earth field model fitting.

$$\mathbf{M}_{scale} = \begin{bmatrix} 1.0 & 0 & 0 \\ 0 & 1.0 & 0 \\ 0 & 0 & 1.0 \end{bmatrix}$$

- Spacecraft Offset $\mathbf{O}_{sc}$
  $\mathbf{O}_{sc}$ will be updated by inflight calibration, O_{sc_x} and O_{sc_y} are determined by spin tone minimisation, O_{sc_z} by Hedgecock method

$$\mathbf{O}_{sc} = \begin{bmatrix} O_{sc\_x} \\ O_{sc\_y} \\ O_{sc\_z} \end{bmatrix}$$

Initial values for the deployed boom are taken from the magnetic cleanliness measurement

- Sun Pulse Matrix $\mathbf{M}_{sun} = \begin{bmatrix} Cos(j_{sun}) & Sin(j_{sun}) & 0 \\ -Sin(j_{sun}) & Cos(j_{sun}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Direction of sun sensor is determined by Paul for each individual probe. $\mathbf{M}_{sun} = \mathbf{M}_g \ \mathbf{M}_a$
$\mathbf{M}_{sun}$ will not be modified during inflight calibration.
Table of angles ($j_{sun} = a + g$) with respect to sun sensor (measured by Paul):

	stowed boom	deployed boom
Probe 1 (FGS6)	135.00	135.17
Probe 2 (FGS1/9)	135.00	134.88
Probe 3 (FGS2)	135.00	134.98
Probe 4 (FGS3)	135.00	135.07
Probe 5 (FGS5)	135.00	134.92

- Phase Alignment Matrix $\mathbf{M}_{phase} = \begin{bmatrix} 1.0 & 0.0 & 0 \\ 0.0 & 1.0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

The phase of the rotation has to be tuned by rotation about Z_{probe}.
$\mathbf{M}_{phase}$ will be updated by inflight calibration using input from UCLA Earth field model fitting.

- Filter Matrix $\mathbf{M}_{filter} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & d_{filter}^{-1} & 0 \\ 0 & 0 & d_{filter}^{-1} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & Cos(-\alpha_{delay}) & Sin(-\alpha_{delay}) \\ 0 & -Sin(-\alpha_{delay}) & Cos(-\alpha_{delay}) \end{bmatrix}$

The averaging effect of spin plane components has to be compensated by rescaling of X and Y components in dependency on the sampling rate and filter mode ($\mathbf{M}_{filter}$). In filter mode-3 data are calculated by averaging 128Hz raw data. Averaging of data before despinning causes an amplitude error as well as a spin phase error of the components perpendicular to the spin axes. The error depends on the ratio of spin frequency f_{spin} and sampling frequency f_{sample}.

with $d_{filter}^{-1} = \dfrac{f_{sample}}{128} \dfrac{Sin\left(\dfrac{\pi}{128} f_{spin}\right)}{Sin\left(\pi \dfrac{f_{spin}}{f_{sample}}\right)}$ and $-\alpha_{delay} = -\pi \dfrac{f_{spin}}{f_{sample}}$

3. Creation of Cal Files

The following manipulations have to be done with the FGM raw data to calibrate them and to bring them from FS to SSL system

Step	Description	• **Purpose** • **Coordinate system** • **Update by inflight calibration?**
1	Multiplication with k_r	• To eliminate the ranging, range information from header • In FS system • No inflight issue
2	Subtraction of $\mathbf{O}_{fgm}$	• Compensation of sensor offset • In FS system • Only offsets in open loop mode are updated
3	Multiplication with $\mathbf{M}_{ort}$	• Orthogonalisation of sensor system • From FS to FGS system • Update part of inflight calibration
4	Multiplication with $\mathbf{M}_{unit}$	• Compensation of sensor accommodation tolerances and rotation into Unit system by • From FGS to Unit system • No inflight issue
5	Multiplication with $\mathbf{M}_{probe}$	• Compensation of boom accommodation tolerances and Rotation into Probe system • From Unit to Probe system • No inflight issue
6	Multiplication with $\mathbf{M}_{spin}$	• Alignment of Z-axis to spin axis • From Probe to SR-System • Updated by inflight calibration
7	Multiplication with $\mathbf{M}_{scale}$	• Fine tuning of Scale values • In SR system • Inflight calibration
8	Subtraction of $\mathbf{O}_{sc}$	• Compensation of spacecraft offset • In SR system • Inflight calibration
9	Multiplication with $\mathbf{M}_{sun}$	• Rotation in Sun sensor direction • From SR in SSL system • No inflight issue
10	Multiplication with $\mathbf{M}_{phase}$	• Fine tuning of Phase • From preliminary to perfect SSL • Inflight updated by UCLA input
11	Multiplication with $\mathbf{M}_{filter}$	• Compensation of Filter influence, mode information from header (mode and sampling frequency)and from Cal File (spin frequency) necessary • In SSL • No inflight issue

After applying the steps 1-11 the magnetic field $\mathbf{B}_{ssl}$ in SSL system can be written

$$\mathbf{B}_{ssl} = \mathbf{M}_{filter}\ \mathbf{M}_{phase}\ \mathbf{M}_{sun}\ (\mathbf{M}_{scale}\ \mathbf{M}_{spin}\ \mathbf{M}_{probe}\ \mathbf{M}_{unit}\ \mathbf{M}_{ort}\ (k_r * \mathbf{B}_{fs} - \mathbf{O}_{fgm}) - \mathbf{O}_{sc})$$

With exception of $\mathbf{M}_{filter}$ and k_r which depends on sampling frequency, mode and range all other parameters can be summarized in a calibration Matrix $\mathbf{M}_{cal}$ and a calibration Offset $\mathbf{O}_{cal}$ with:

$$\mathbf{O}_{cal} = \mathbf{M}_{phase}\ \mathbf{M}_{sun}\ \mathbf{M}_{scale}\ \mathbf{M}_{spin}\ \mathbf{M}_{probe}\ \mathbf{M}_{unit}\ \mathbf{M}_{ort}\ \mathbf{O}_{fgm} + \mathbf{M}_{phase}\ \mathbf{M}_{sun}\ \mathbf{O}_{sc}$$
$$\mathbf{M}_{cal} = \mathbf{M}_{phase}\ \mathbf{M}_{sun}\ (\mathbf{M}_{scale}\ \mathbf{M}_{spin}\ \mathbf{M}_{probe}\ \mathbf{M}_{unit}\ \mathbf{M}_{ort}$$

Therefore $\mathbf{B}_{ssl}$ can be written as:

$$\mathbf{B}_{sr} = \mathbf{M}_{filter}\ (\mathbf{M}_{cal}\ k_r * \mathbf{B}_{fs} - \mathbf{O}_{cal})$$

The data processing software has to upload the actual $\mathbf{M}_{cal}$ and $\mathbf{O}_{cal}$ from the Calibration File, the factor k_r has to be uploaded from the header information and the Filter Matrix has to be derived by sampling frequency (header) and spin frequency (Cal File).

4. Initial Cal Files:

For THA (Probe 1) the initial Cal File for deployed boom has the following elements:

Time (2007-02-28T09:38:55.123Z) 3.61 11.00 5.35 0.08291 –0.003200 –0.99635 –0.00041 1.00000 0.00116 –0.99654 –0.00292 –0.08448 Spin-period (1.12345)