ESS 261 Spring Quarter 2009
Access and Use of Magnetic Field Data

Magnetometer Operation Principles/Accommodation
Calibration and Noise Sources
Ground and On-Board Spin-Fits
Anti-alias filtering
Amplitude/Phase Frequency Response
Access and Use of Data from Various Regions
Solar Wind, Magnetosphere (Earth, Jupiter),
Ionosphere, Ground

References:
Elphic et al., Magnetic field instruments for the FAST mission, Space Science Reviews, 2001
Auster et al., The THEMIS fluxgate magnetometer, Space Science Reviews, 2008.
Roux et al., The Search Coil Magnetometer for THEMIS, Space Science Reviews, 2008
LeContel et al., First results of the THEMIS search coil magnetometers, Space Science Reviews, 2008

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Alain Roux, Olivier le Contel, Christoffe Coillot, Peter Harvey

Lecture 4 Apr 20, 2009
## Types of Magnetometers

<table>
<thead>
<tr>
<th>Type of magnetometer</th>
<th>Basic Principle</th>
<th>Output quantity / limits</th>
<th>Space application?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical Instruments</td>
<td>manipulation with magnets</td>
<td>field direction (compass) field variation (e.g. QHM) horizontal force (Theodolites) (100pT / \text{(minutes ... DC)})</td>
<td>No</td>
</tr>
<tr>
<td>Search Coil</td>
<td>Faraday’s law of induction</td>
<td>field vector (dB/dt) (0.01..10pT / (50kHz ... 1Hz))</td>
<td>Yes</td>
</tr>
<tr>
<td>Fluxgate</td>
<td>saturated transformer</td>
<td>field vector (10pT / (100Hz ... DC))</td>
<td>Yes</td>
</tr>
<tr>
<td>Optical Pumped</td>
<td>Zeeman splitting, Landou frequency</td>
<td>scalar magnetometer with coil system vector (1pT (1kHz ... DC))</td>
<td>Rubidium in 60th He onboard Cassini</td>
</tr>
<tr>
<td>Proton /Overhauser</td>
<td>proton precession, gyro magnetic ratio</td>
<td>scalar magnetometer with coil system vector (10pT (1Hz ... DC \text{ absolute}))</td>
<td>Yes</td>
</tr>
<tr>
<td>SQUID</td>
<td>Josephson effect</td>
<td>field vector (dB/dt) (0.1pT / (100kHz ... 0.001Hz))</td>
<td>No</td>
</tr>
<tr>
<td>Magneto resistive</td>
<td>Anisotropic Magnetoresistive Effect</td>
<td>field vector (10nT / (100Hz ... DC))</td>
<td>(attitude control)</td>
</tr>
<tr>
<td>Hall</td>
<td>Lorentz Force</td>
<td>field vector (1mT / (30kHz ... DC))</td>
<td>No</td>
</tr>
</tbody>
</table>

B-field measurement - overview
**Fluxgate Magnetometer**

\[
U = \frac{d\Phi}{dt} = \frac{d \left( n A \mu_0 \mu_r(t) H(t) \right)}{dt}
\]

B-field measurement - fluxgate (1)
Fluxgate Magnetometer

• Principle of Operation
  – Magnetic material saturated by symmetric AC (f0) drive current
  – Secondary signal becomes asymmetric if external field disturbs the symmetry by shifting the zero point on the hysteresis
  – Second harmonics of drive frequency is quantity for asymmetry = magnitude of external field
  – Field feedback holds working point close to zero

• Parameters
  – Measurement range: Solar Wind (10th of nT) - Earth field 60.000nT
  – Frequency range: 100Hz ... DC
  – Stability: 1nT...10nT/year
  – Noise: 10pT/sqrt(Hz) at 1Hz – 1/f spectrum

• Application
  – Ground application: e.g. observatories, EMT-sounding, applied physics
  – Space application: all magnetosphere, nearly all planetary missions, attitude control for low Earth missions
Operation Principle
Search Coil Magnetometer

\[ U = \frac{d\Phi}{dt} = \frac{d(nA\mu_0\mu_rH(t))}{dt} \]

B-field measurement - search coil (1)
Search Coil Magnetometer

**Principle of Operation**
- Application of Faraday's law
- Output signal depends on $\mu_r$ (long core to keep the demagnetisation factor low), N (weight of copper) and A (weight of softmagnetic material)
- Sensitivity depends on frequency due to (dB/dt) behaviour and resonance of coil-electronics system.

**Parameter**
- Noise at 1Hz: 10pT/sqrt(Hz)
- Noise at 10 kHz: 0.01pT/sqrt(Hz)

**Application**
- Ground application:
  Audio EMT-sounding
- Space application:
  - all magnetosphere missions
  - partly on planetary missions

Figure 2. Representative magnetic field spectrums for various plasma wave phenomena observed in the Earth's magnetosphere.

[D.A.Gurnett, 1998]
Definition of the Noise Equivalent Magnetic Induction (NEMI):

Equivalent output voltage noise \((e_n)\):

\[ e_n^2 = G_o^2 \times \left( e_{PA}^2 + 4kT \text{Re}[Z] + (Zi_{PA})^2 \right) \]

Output voltage:

\[ V_{out} = TF(j\omega) * B \] \((TF(j\omega):\text{Transfer Function})\)

PSD of output voltage:

\[ \frac{V_{out}^2}{df} = e_n^2 \quad \Rightarrow \quad \frac{(TF(j\omega) * B)^2}{df} = e_n^2 \quad \Rightarrow \quad \frac{B^2}{df} = \frac{e_n^2}{(TF(j\omega))^2} \]

NEMI is then defined as square root of the magnetic field spectral power density:

\[ NEMI = \sqrt{\frac{B^2}{df}} \]

\[ NEMI (T / \sqrt{Hz}) = \frac{e_n (V / \sqrt{Hz})}{TF(j\omega) (V / T)} \]

**NEMI is the ability of the magnetometer to measure weak magnetic fields.**
Search-coil: N turns wound around a high permeability magnetic core.

**Electrokinetic's representation**: Induced voltage $e$

Inductance $L1$, Resistance $R1$ (of the winding), capacitance $C1$

(comes mainly from electrostatic energy stored between layers of the winding)

\[ \omega_o = \frac{1}{\sqrt{L_1 C_1}} \]

\[ V_{out} = e \times \frac{1/jC_1 \omega}{R_1 + jL_1 \omega + 1/jC_1 \omega} \]

Resonance degrades response
Helium Magnetometer
**Electron Larmor Resonance**

Fundamental properties of an electron: $\mathbf{\mu}_L = -\frac{e}{2m_e} \mathbf{L} = -\mathbf{\mu}_B \sqrt{l(l+1)}$

Angular momentum: $\hbar = 6.6 \times 10^{-34} \text{ J s} \quad [\text{or Nsm, or kgms}^{-1}]$

Magnetic moment along B: $\mathbf{\mu} = -\mathbf{\mu}_B m_l = 9.2 \times 10^{-24} \text{ J T}^{-1}$

Relation between both: $\mathbf{\mu} = \gamma_e \hbar$

Gyro magnetic ratio $\gamma_e = -1.76 \times 10^{11} \text{ rad s}^{-1} \text{ T}^{-1}$

Properties of an electron in an external B-field

Torque: $\mathbf{T} = \mathbf{\mu} \times \mathbf{B}$

Relation between $\mathbf{L}$ and $\mathbf{T}$: $\mathbf{T} = \frac{d\mathbf{L}}{dt}$

Precession: $\omega_\gamma = \gamma_e B_0$

This is: 176 rad/s/nT, or 28Hz/nT
Principle of Operation
- Get gas into metastable state that lasts a long time ($10^{-4}$ s)
- Use polarized light to pump one state (magnetize gas along field)
- Use RF signal at FM ~356Hz resonate and de-pump electrons
- De-pumping results in additional absorption of the polarized signal
  - This is detected by a cell on the other side
- Controlling FM frequency center is adjusted to ensure it “tracks” Larmor freq.
- Output is in second harmonic (symmetric) unless FM signal is off-center
- Fundamental amplitude is isolated, integrated and is proportional to frequency shift

Parameters
- Measurement range: Solar Wind (10th of nT) - Earth field 60.000nT
- Frequency range: 10Hz ... DC
- Stability: 0.05nT...0.2nT/year
- Noise: 10pT/sqrt(Hz) at 1Hz – white noise

Application
- Ground application: e.g. observatories, applied physics
- Space application: magnetospheres, ionospheres

**Helium Magnetometer (Scalar)**

SAC-C
scalar magnetometers (2 ea)
**Helium Magnetometer (Vector)**

- **Principle of Operation**
  - Same components as Scalar sensor, except use Helmholz coils to null field
  - Optical axis, Z, along the circularly polarized excitation light has highest sensitivity
  - Coils use to also drive sine-signal on a plane (XZ or YZ) resulting in $\cos^2\theta$ response
  - Output is in second harmonic (symmetric) unless external field present (fundamental)
  - Fundamental amplitude is isolated, integrated and is proportional to $\delta B$ from zero.

- **Parameters**
  - Measurement range: Solar Wind (10th of nT) - Earth field 60.000nT
  - Frequency range: 10Hz ... DC
  - Stability: 0.05nT...0.2nT/year
  - Noise: 10pT/sqrt(Hz) at 1Hz – white noise

- **Application**
  - Ground application: e.g. observatories, applied physics
  - Space application: magnetospheres, ionospheres
Proton Magnetometer (NMR)

Fundamental properties of a proton:

Angular momentum: \( \mathbf{L} = 5.27 \times 10^{-35} \text{ kg m}^2 \text{ s}^{-1} \)

Magnetic moment: \( \mu = 1.41 \times 10^{-26} \text{ Am}^2 \)

Relation between both: \( \mu = \gamma_P \mathbf{L} \)

Gyro magnetic ratio \( \gamma_P = 267515528 \text{ rad s}^{-1} \text{ T}^{-1} \)

Properties of a proton in a B-field

Torque: \( \mathbf{T} = \mu \times \mathbf{B} \)

Relation between \( \mathbf{L} \) and \( \mathbf{T} \): \( \mathbf{T} = \frac{d \mathbf{L}}{dt} \)

Precession:

\( \omega_\gamma = \gamma_P B_0 \)

This is: 0.27 rad/s/nT, or 0.043 Hz/nT
Proton Magnetometer

- **Principle of Operation**
  - Sensor is a bottle of water (alcohol) + coil for polarization and pick up
  - Polarisation aligns all protons
  - Fast change from polarization to pick up provides in-phase precession
  - Frequency is measured, signal amplitude depends on time (relaxation)
- **Parameter**
  - Measurement range: 20.000nT ... 100.000nT
  - Frequency range: 1Hz ... DC
  - Relaxation time: 1sec
  - Accuracy: 0.1nT absolute
- **Application**
  - Ground application: observatories, applied physics
  - Space application: missions investigating the Earth field
Vector measurement by scalar sensors

• Measurement of field components using a scalar magnetometer
  – Sensor has to be equipped with a coil system for bias fields
  – Applying fields in + and - direction, field components can be derived by a set of three scalar measurements: F+, F and F-

\[
F^2 = H^2 + Z^2
\]
\[
F_+^2 = (H + B)^2 + Z^2 = F^2 + B^2 + 2HB
\]
\[
F_-^2 = (H - B)^2 + Z^2 = F^2 + B^2 - 2HB
\]
\[
F_+^2 + F_-^2 = 2\left( F^2 + B^2 \right)
\]
\[
F_+^2 - F_-^2 = 4HB
\]
\[
H = \frac{F_+^2 - F_-^2}{2\sqrt{2(F_+^2 + F_-^2 - 2F^2)}}
\]
• Fluxgate Magnetometer, FGM
  – PI: K.H. Glassmeier, TU-Braunschweig
  – Single sensor (2m boom), digital electronics

• Search Coil Magnetometer, SCM
  – PI: A.Roux, CEPT
  – The SCM 3-axis antennas are located at the end of 1 meter SCM boom

• Instrument Data Processing Unit
  – FGM processing ½ board
  – Digital Fields (full) Board (DFB)
Sensor Accommodation

- **Boom Geometry**
  - 1-3 segment boom (Cluster Double Star, Themis ...)
  - Boom made by spring elements (MMO)
  - Wire Booms (Cluster, Themis ...)

- **Release & launch lock mechanism**
  - Pyro
  - Melting band,
  - Motor driven

- **Deployment force**
  - Centrifugal force
  - Spring driven
  - Motor driven
Required Resources

- Mass

- Power

Requirements on S/C - Resources
Thermal Environment

- Thermal requirements
  - Sensors have wide temperature range
  - Eclipse crossings must be buffered by high thermal capacity
  - Averaged temperature depends on alpha/epsilon of MLI/OSR

![Thermal Environment Diagram]

Sensitivity to Sensor Temperature

Sensitivity to Electronics Temperature
CALIBRATION OF FLUXGATE MAGNETOMETERS
## CALIBRATION OF FLUXGATE MAGNETOMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error Source</th>
<th>typ. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offsets (output at zero field)</td>
<td>asymmetry of sensor and excitation</td>
<td>0-10nT</td>
</tr>
<tr>
<td></td>
<td>offsets of DC electronics, ADC ...</td>
<td>0.2nT/day; 0.05nT/°C</td>
</tr>
<tr>
<td>Scale value</td>
<td>scale value shall depends on feedback circuitry only – current source &amp; feedback coil system</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>depends on temperature</td>
<td></td>
<td>1-30ppm/°C</td>
</tr>
<tr>
<td>Non linearity</td>
<td>at low fb factors: 2f0 non linearity</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>at high fb factors: feedback circuitry non linearity</td>
<td></td>
</tr>
<tr>
<td>Orthogonality</td>
<td>vector compensated: depends on fb coil system</td>
<td>10^{-4}</td>
</tr>
<tr>
<td></td>
<td>single sensors depends on ringcore /pick up coil</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>frequency behavior depends on analogue or digital filter. Has to be switched with telemetry rate</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>should be ringcore property (no contribution of electronics), depends on frequency</td>
<td>10pT/Sqrt(Hz) at 1Hz</td>
</tr>
</tbody>
</table>

1Hz: 28pT rms

128Hz: 80pT rms

0.01nT/Sqrt(Hz) @ 1Hz
Ground Calibration Methods

- Using well controlled, synthesized test fields
  - Sensor placed in coil systems
  - Quiet environment required, Earth field variations as well as technical disturbances under control
  - Precise measurement / setting of coil currents
  - Air conditioning necessary
  - Calibration of coil system by (absolute) scalar magnetometer possible
  - Example: Magnetsrode close to Braunschweig
Ground Calibration Methods (2)

- Using the Earth field measured by a independent magnetometer
  - Sensor placed on a stable (non magnetic) pillar
  - Registration of Earth field in parallel to standard observatory instruments (or between flight models)
- Noise can be checked by short term registration of pulsation
- Drift can be checked after days-weeks registration
- Most of the observatories offer this service
Ground Calibration Methods (3)

- Using „zero“ fields
  - Sensor placed in ferromagnetic can which shields the Earth field
  - Noise and offset stability can be checked
  - If sensor can be rotated offsets in components perpendicular to rotation can be determined
  - Example: transportable mu-metal can, equipped with temperature chamber (Graz)
**Ground Calibration Methods (4)**

- Using a controlled motion of the sensor in the Earth field
  - Rotation about a well defined axis perpendicular to the Earth field
  - Misalignment rotation and magnetic axis results in a sine function
  - Misalignment can be absolutely derived by amplitude and phase

- Using an arbitrary motion of the sensor in the Earth field
  - Assuming a linear transfer function, 9 of 12 elements (offset, scale values, orthogonality) can be derived by comparison with the Earth field magnitude
Inflight Calibration

- Aim of inflight calibration
  - Determination of 12 elements of transformation $B_M$ to $B_{SC}$
  - Assumption: transformation is linear
  - $M_{Cal}$ Calibration Matrix; $O_{Cal}$: Calibration Offset
  \[
  M_{Cal} \left( B_M - Z_{Cal} \right) = B_{SC}
  \]

- Calibration Matrix $M_{Cal}$ shall be split up in three quantities
  - $S$: represents *scale values* with elements in the main axis
  - $O$: represents the *non orthogonality* (triangular matrix)
  - $R$: represents the orientation of the orthogonal system versus S/C system (rotation matrix)
  \[
  O \quad S \left( B_M - Z_{Cal} \right) = R \quad B_{SC}
  \]
Calibration Inputs

- Calibration methods are based on the following relevant inputs
  - No spin and double spin tone in field magnitude
  - Field properties (Earth field model, Alfven waves, …)
  - Knowledge of preflight calibration and MC results
  - Experiment specifics, mode and housekeeping information
  - Independent field measurements
  - Inter-calibration: using spacecraft comparisons (B1=Bn, RotB=0, DivB =0) to level all instruments errors
Methods (1)

Field magnitude has to be independent from sensor motion

\[
\frac{\partial}{\partial (\mathbf{R})} \left[ \mathbf{O} \cdot \mathbf{S} \left( \mathbf{B}_M - \mathbf{Z}_{Cal} \right) \right] \neq 0
\]

• Conditions:
  – \( \mathbf{B}_{external} \) → constant
  – \( \mathbf{R} = R(\varphi, \psi, \vartheta) \) → variable
  – \( \mathbf{O}, \mathbf{S}, \mathbf{Z}_{Cal} \) → doesn't depend on time and external field

• Effects assuming S/C rotation as motion
  – spin and double spin tone in field magnitude (4 equations)
  – All three angle of orthogonality affected
  – Offsets and scale values perpendicular to rotation axis affected
Example

Cluster C4 before calibration
Example

Cluster C4 after calibration

FFT spectrogram, freq.limits=[0.0328 Hz, 1. Hz], freq.res:0.0109 Hz

Calibration - in flight - methods (3) - example
Field magnitude has to be equal to the magnitude measured by an independent (scalar) magnetometer

\[ |O \cdot S \left( B_M - Z_{Cal} \right)| = |R \cdot B_{SC}| = B \]

- **Conditions:**
  - \( B_{external} \) → shall be variable
  - \( R \) → can be arbitrary
  - \( O, S, Z_{Cal} \) → doesn't depend on time and external field

- **Examples**
  - Proton magnetometer on board satellites investigating the Earth magnetic field (low orbits, e.g. Magsat, Oersted, Champ)
  - EDI onboard Equator-S, Cluster and MMS
Example

Calibration - in flight - methods (2) - example
Methods (3)

Measured field vector has to be in agreement with known physical features

\[ f\left( \mathbf{O}, \mathbf{S}, \left( \mathbf{B}_M - \mathbf{Z}_{Cal} \right) \right) = \text{Expectation} \]

- Conditions:
  - \( \mathbf{B}_{\text{external}} \) → shall be variable
  - \( \mathbf{R} \) → can be arbitrary
  - \( \mathbf{O}, \mathbf{S}, \mathbf{Z}_{Cal} \) → doesn't depend on time and external field

- Examples
  - In agreement with Earth field models
  - Alfven waves in solar wind
  - Divergence \( \mathbf{B}=0 \), Cavity of Comets ...
Example

Calibration - in flight - methods (3) - example
Inflight Calibration Procedure

Non orthogonal sensor system
- scale, offset, non orthogonality
  - range, mode

Orthogonal sensor system
- update of sensor parameters

S/C system
- sensor alignment
- boom alignment
- removing of S/C generated offsets

Spin aligned S/C system
- tuning of spin alignment
  - spin tone in spin axis
- tuning of phase alignment
  - comparison with IGRF

Spin and sun aligned system
- sun sensor align.
  - filter type

Calibration - in flight - procedure
Example of Cal File

The following manipulations have to be done with the FGM raw data Bfs (in FS system - FGM Sensor system - a non orthogonal sensor system) to bring the data in the SSL system

Ranging by factor kr (range from fgm header)
kr = 50000/2(16+range)

F5:

\[
\mathbf{O}_{\text{cal}} = \begin{bmatrix}
-4.21 \\
-0.52 \\
3.00
\end{bmatrix}
\]

\[
\mathbf{M}_{\text{cal}} = \begin{bmatrix}
-0.00680 & 0.62017 & 0.78855 \\
-0.00611 & 0.78449 & -0.61497 \\
-1.0 & 0.0 & 0.0
\end{bmatrix}
\]

Calfile:
time, -4.21 -0.52 3.00 -0.00680 0.62017 0.78855 -0.00611 0.78449 -0.61497 -1.00000 0.00000 0.00000 3.12345
Noise Statistic measured inflight: The overall noise was measured for each sensor at quiet field conditions. The sensors are sorted by noise levels at 1Hz and 4 Hz. A noise level less than 30 pT/Sqrt(Hz) at 1Hz was required.
Offset variation on single spacecraft

Offset variation on all spacecraft
Offset Stability

Sensor temperature and offset behaviour after eclipse

Temperature drop down during eclipse

March: -15°C
April: -10°C
May: -6°C
June: -4°C

Probe A, March 7, total influence less than 1 nT; after 4 hours within 0.2 nT
Spacecraft Disturbances

Power system generated interferences:
Although solar cells have been backwired to cancel currents and strings arranged to reduce dipole, there is a remnant power system current loop (battery or IDPU) that is spin-locked.

- Amplitude: 0.2 nT maximum (Probe D)
- Frequency: spin tone & harmonics
- Problem: elimination of spin tone and first harmonics in field magnitude are inflight calibration criteria
- Solution approach: spin tone and second harmonics can be modelled and be removed (after a lot of work) from raw data.
- Expected result: interference will be suppressed below 0.05 nT
- Caution: data cosmetics by modifying calibration parameters to remove spin tones leads to wrong data!
- Spin-phase locked signal (top)
- Removal of spin tone after discerning interference signal and subtraction.
Conducted electromagnetic noise (and solution)

- Conducted interference from particle sectoring
- Reason: sector clock interferes with FGM data processing. A beat frequency effect (aliased from high frequency). Spin-frequency dependent, it is minimized at some frequencies
- Solution: Changed spin frequency, minimized effect.

\[ T_{\text{spin}} = 2.9331 \text{ sec} \]

\[ T_{\text{spin}} = 2.9688 \text{ sec} \]
**Shadow effects (and solution)**

- As spacecraft cools, spin changes but sun-pulse missing (loose lock)
- Solution: Model spin-period, minimize effect.

- spin period model (Edita Georgescu)
  - well-known for short eclipses only
- obstacles
  - long eclipses interesting
  - penumbra: special treatment necessary
  - hump: from boom motion?
Modes / Operation

• Instrument Capabilities
  • Field resolution
  • Ranges (16 of 24bit)
  • Time resolution
  • 128Hz in TMH
  • 4Hz – 128Hz selectable in TML
  • Spin fits
  • Filter modes
  • Boxcar filter
  • Data decimation
  • Combination of both
  • Calibration modes
  • On and off of feedback
  • On and off of feedback relays
  • Step function

• Operation
  • On during boom deployment
  • Ranging orbit dependent

• Modes
  • Slow survey spin fit 0.33Hz
  • Fast survey raw 8…32Hz
  • Particle burst raw 128Hz
  • Wave burst raw 128Hz
Data products

FGM: TML TMH s/e temp.

\[ \text{data preprocessing in IDPU} \]

L0: \(~\text{API}'s(.pkt)\)

FGL FGH Fits FGE HK

8-128Hz 128Hz 1/spin eng.units 2 Temp.

L1: \[ L1 + \text{Cal\_File + State\_File + IDL\_code} = L2 \]

L2:
Anti-alias filtering of FGM data products

The frequency characteristic of the accumulated data is that of a standard average (boxcar) filter without overlapping. The frequency response of the averaging filter can be expressed analytically. It is

\[
|G(\omega)| = \frac{\sin(\omega T N/2)}{N \times \sin(\omega T / 2)}
\]

(1)

where:
- \(N\) is the number of accumulated samples
- \(\omega = 2 \pi f\) is the angular frequency
- \(T\) is the sampling period (1/(4F0))

for the amplitude response and

\[
\text{ang}(G(\omega)) = -\pi N f T
\]

(2)

for the phase response of the filter.

<table>
<thead>
<tr>
<th>TML data rate [Hz]</th>
<th>filter mode 1</th>
<th>filter mode 2</th>
<th>filter mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>64</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>32</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>

Tab. 3-1 TML data rate and filter modes
CALIBRATION OF SEARCHCOIL MAGNETOMETERS
Need to measure for each axis:
- Transfer function (gain and phase)
- Sensitivity (NEMI)
- Exact orientations of the sensor
- Electronic cross-talk/coupling between axes
- Stability

Results form the reference for interpretation of space data

Test environment
- Helmholtz coil system to null Earth field (avoid saturation)
- Table with orientation accuracy of +/-0.5°
- Orientation/cross-talk by measuring response to 1kHz signal at 1 direction
Initial tests take place in small, mu-metal can, to avoid saturation due to Earth field and 60Hz noise.

Next test of entire instrument also take place in small, mu-metal can; test stability using internal CAL signal.

Final test of entire instrument also take place in quiet facility, nulling external field and measuring noise properties as well as G, Phase, NEMI injecting external signal from coils.
**Bottom:** Example of NEMI test on the left, showing the data collection at various frequency bands (to avoid very high data volume needed for otherwise measuring at very high cadence for very long time)

**Right:** Results of calibration including orthogonality test from injecting test signal along Y. Top to bottom are: Gain, Phase and NEMI (Sensitivity) test.

Environment noise not important
**Mechanical alignment:** In addition to the electronic measurement of ortholonality, mechanicam measurements are also made in order to guarantee signals are orthogonal to within requirements.

<table>
<thead>
<tr>
<th>Angle table for THEMIS SCM</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>angles have been measured relatively to the reference axis given in ICD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angles are in degree</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM number*</td>
<td>X axis</td>
<td>Y axis</td>
<td>Z axis</td>
</tr>
<tr>
<td></td>
<td>plane XY</td>
<td>Plane YX</td>
<td>Plane ZX</td>
</tr>
<tr>
<td>FM1 (SC1-PA3)</td>
<td>+0°</td>
<td>+0°</td>
<td>-0.25°</td>
</tr>
<tr>
<td>FM2 (SC4-PA2)</td>
<td>+0.25°</td>
<td>+0.4°</td>
<td>-0.4°</td>
</tr>
<tr>
<td>FM3 (SC6-PA6)</td>
<td>+0.2°</td>
<td>+0°</td>
<td>+0°</td>
</tr>
<tr>
<td>FM4 (SC3-PA4)</td>
<td>+0°</td>
<td>+0°</td>
<td>+0°</td>
</tr>
<tr>
<td>FM5 (SC5-PA5)</td>
<td>+0°</td>
<td>+0°</td>
<td>+0°</td>
</tr>
<tr>
<td>FM6 (SC7-PA1)</td>
<td>+0°</td>
<td>+0°</td>
<td>+0°</td>
</tr>
</tbody>
</table>

*FM number is not directly related to sensor number and PA number, please in case of doubt, verify table correspondance from CETP team in ICD
End-to-end Result: Knowledge of noise level in ADC units and the calibration from nT to ADC values. This is included as a reference value in the preliminary calibration of the raw data as it is converted to nT. Further calibration included an ascii calibration table that may be changed with time but includes a time-dependent calibration of the instrument.
SCM on-board calibration: A free running onboard oscillator generates a 9Hz internal signal (triangular shape) which is used to check the transfer function inflight. Activation by command on “CAL” mode. This provides a response over a number of harmonics at the primary winding, used to check frequency end-to-end response to a known input. Also used during ground functional testing.
SCM calibration process (I)

Different possible outputs (step parameter):

# 0: counts, NaN inserted into each gap for proper ‘tplotting’
# 1: Volts, spinning sensor system, with DC field
# 2: Volts, spinning sensor system, without DC field
# 3: nTesla, spinning sensor system, without DC field
# 4: nTesla, spinning SSL system, without DC field
# 5: nTesla, fixed DSL system, without DC field, filtered <fmin
# 6: nTesla, fixed DSL system, with xy DC field
SCM calibration process (II)

Description of calibration method steps 0-2

# 0 - TM data in counts, separated into gap-free batches of data at same sample rate.

For each gap-free batch, apply the steps 1-6:
# 1 - TM data in volts. (tplot variable with '_volt' suffix)
# 2a - remove spin tone using (interpolated) spin frequency from beginning of batch.
  o Spin period assumed constant for batch, but not assumed constant for full day.
  o Sliding spin fit to \( N_{\text{spinfit}} \geq 2 \) complete spins, using sliding Hanning window.
  o Bdc and misalignment angle calculated from spin fit centered around each point
  o DC field for data within one spin period of the edges is calculated using spin fit to
    first/last two spin periods of the batch.
  o output Bdc and misalignment angle as tplot variables with '_dc' and '_misalign' suffix, respectively.
  o subtract Bdc (in spin plane) from x, y, and z signals.

b - detrend (optionally subtract boxcar average by fixing the detrend frequency parameter Fdet.)
c - clean spin harmonics, power current signals, (to be detailed later)
SCM calibration process (III)

Description of calibration method step 3

# 3 - Conversion volts -> nT
- Cluster: performed for a limited period in Fourier domain by FFT
  \( \text{out}(t) = \text{in}(t) \ast h(t) \) with \( h(t) \) the impulse response of the antenna
  \( \text{out}(f) = \text{in}(f) \ast h(f) \Rightarrow \text{in}(t) = \text{FT}^{-1}[\text{out}(f)/h(f)] \)
  with \( h(f) \) the transfer function or frequency response of antenna
- THEMIS: performed continuously in time domain by convolution
  \( \text{in}(t) = \text{out}(t) \ast c(t) \) with \( c(t) = \text{FT}^{-1}[1/h(f)] \) being called Kernel
  \( nk \) is the size of the Kernel.
  \( \Rightarrow \) a large \( nk \) gives better calibration but time consuming
- Get kernel suitable for use by shifting by \( nk/2 \), applying Hanning window.
  Note: IDL convol function assumes that the center of the kernel is at index \( nk/2 \), so no delay is introduced.
  Edge behavior determined by /edge_zero, /edge_wrap, or /edge_truncate.
  With no /edge keyword, set all data within \( nk/2 \) samples of the edge to zero.
SCM calibration process (III)

Description of calibration method steps 4-6

# 4 - **rotate** from spinning sensor system to SSL

# 5 - **transform** calibrated waveform to DSL using interpolated spin phase, which is calculated from the derived sun pulse data from state files (updated version will use cotrans as EFI).

# 6 - add Bx and By DC field from step 2a.

use `thm_cotrans` to transform step 5 output to other coordinates (GSM, GSE)
Removing spacecraft disturbances

In flight scm data are perturbed by two types of noise:
1) spike at 2*f0 (f0 being the spin frequency) and its harmonics due to power ripples
2) 8/32 Hz tones radiated from IDPU processing

Fortunately these noises are both constant in amplitude and phase-locked
1) spike at 2*f0 is phase locked relative to the spin phase
2) 8/32 Hz are phase locked to 1s clock

2 versions are available, give good results and can be selected by clnup_author keyword:
‘ccc’ written by C. Chaston
‘ole’ written by O. Le Contel (by default)

Both routines perform successively 2 superposed epoch analysis (SEA):
1) First SEA with an averaging window equal to a multiple of the spin period
2) Second SEA with an averaging window equal to a multiple of 1s
SCM: Removing spacecraft disturbances

Cleanup process is included in thm_cal_scm at step 2c with the following keywords:

a) cleanup = ‘spin’ for only cleanup of nxf0 tones, wind_dur_spin fixing the duration of the first averaging window (multiple of spinper)
b) cleanup = ‘full’ for full cleanup and with an additional keyword wind_dur_1s fixing the duration of the second averaging windows
c) commented cleanup keyword corresponds to: no cleanup (default)

Example:

```
thm_cal_scm, probe=satname, datatype=mode+"*", out_suffix = '_cal', $
   trange=trange, $
   ;   nk = 512, $
   ;   mk = 4, $
   ;   Despin=1, $
   ;   N_spinfit = 2, $
   ;   clnup_author = 'ccc' or 'ole'
   cleanup = 'full' or 'spin' or 'none',$
   wind_dur_spin=1.,$
   wind_dur_1s = 1.,$
   ;   Fdet = 2.,$
   ;   Fcut = 0.1, $
   ;   Fmin = 0.45, $
   ;   Fmax = 0.,$
   ;   step = 5, $
   ;   /edge_zero
```
SCM calibration and noise removal process

Tha on April 8th 2007 between 0558-0600 UT

A: raw waveform in volts
B: despinned waveform and spectrum in dBV/sqrt(Hz)
C: Spin phase locked noise built by SEA and spectrum
D: cleaned (only power ripples) waveform and spectrum
E: 1s phase locked noise (SEA)
F: Fully cleaned waveform and Spectrum

Note that some spike still remain which are not phase locked
SCM science data

- Physical quantities (L2 data):
  - In SSL, DSL, GSE, GSM and other coordinates
    - FS waveforms (scf) of Bx, By, Bz
      [8 S/s; Allocation~ 10.8h depending on which probe]
    - PB waveforms (scp) [128 S/s; All.~ 1.2h]
    - WB waveforms (scw) [8192 S/s; All.~ 43s]
    - Filterbank data (fbk) [1comp.; 6 freq.] throughout orbit
    - PB spectra (ffp) [2 comp.; 32 freq.]
    - WB spectra (ffw) [2 comp.; 64 freq.]
## Details about SCM modes

<table>
<thead>
<tr>
<th>Operation modes</th>
<th>IDPU Data type</th>
<th># Comp.</th>
<th># Frequencies</th>
<th>APID</th>
<th>Sample rate S/s (nominal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow survey (SS)</td>
<td>DFB filter banks</td>
<td>1 to 2 (1)</td>
<td>1 to 6 (6)</td>
<td>440  (FBK)</td>
<td>0.0625 to 8 (0.25)</td>
</tr>
<tr>
<td>Relative allocation: 50% (12h P3,P4,P5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast survey (FS)</td>
<td>DFB filter banks</td>
<td>1 to 2 (1)</td>
<td>1 to 6 (6)</td>
<td>440</td>
<td>0.0625 to 8 (4)</td>
</tr>
<tr>
<td>RA: 50 % (10,8h)</td>
<td>DFB waveform</td>
<td>3</td>
<td></td>
<td>444  (SCF)</td>
<td>2 to 256 (8)</td>
</tr>
<tr>
<td>Particle burst (PB)</td>
<td>DFB waveform</td>
<td>3</td>
<td></td>
<td>448  (SCP)</td>
<td>2 to 256 (128)</td>
</tr>
<tr>
<td>RA: 10% of FS (1,2h)</td>
<td>DFB spectra (Bpara &amp; Bperp)</td>
<td>1 to 4 (2)</td>
<td>16 to 64 (32)</td>
<td>44D  (FFP)</td>
<td>0.25 to 8 (1)</td>
</tr>
<tr>
<td>Wave burst (WB)</td>
<td>DFB waveform</td>
<td>3</td>
<td></td>
<td>44C  (SCW)</td>
<td>512 to 16384 (8192)</td>
</tr>
<tr>
<td>RA: 1% of PB (43 s)</td>
<td>DFB spectra</td>
<td>1 to 4 (2)</td>
<td>16 to 64 (64)</td>
<td>44F  (FFW)</td>
<td>0.25 to 8 (8)</td>
</tr>
</tbody>
</table>

### Calibration mode
- A Triangular signal generated by the PA, is applied to the feedback winding installed around each antenna.
- Once per orbit a calibration is run for 30 seconds (default).
- After 60 seconds, the calibration is automatically turned off.
FGM + SCM COMBINED
FGM + SCM Data Combination
David Fischer, Rumi Nakamura (IWF/OeAW)

- Fluxgate: noise + distortion gets worse than the searchcoil at ~ 6 Hz.
- Searchcoil: no DC, but higher sensitivity and less noise for higher freq.
- For Themis: distortion sources near fluxgate sensors (10 ~ 20 Hz).
Discussion

COMBI data not necessary
• If your interested time-scale is longer than spin period
• You can work with freq. spectra (just use SCM for high freq. and FGM for low freq.)

Possible useful area
• Identify sharp boundary structure with resolution better than 0.1 s
• Wave-forms with a few-s timescale
On-board de-spining (spinfits)

**Fit Module (FIT.A)**
The FIT module calculates the E-Field and B-Field vectors by taking 32 points at equal angles and fitting a sine wave least squares fit to the data. The best fit of the data is defined by the formula: \( A + B\cos() + C\sin() \). The module calculates the standard deviation of the fit called Sigma, and the number of points remaining in the curve called N.

In addition, the FIT module averages the Z-axis data (E and B) and provides in the telemetry.

**NOTE #1**
The module determines which data is more than \( x_N \times \sigma_N \) (\( s_N \) = standard deviation) away from fit, and removes those points and repeats the fit. The second time the standard deviation is smaller so the tolerance is increased a bit. The tolerance \( x_N \) varies with try as: \( \text{Alpha} \times \text{Beta} \), where \( \text{A}=1.4 \) and \( \text{Beta}=0.4 \) provide good results. The operation continues until no points are outside the bounds and the process is considered convergent.

**NOTE #2**
Data is obtained by the FIT_SAMP routine getting called at one of 32 sectors in the spin. At each sector call, the FIT_SAMP shall call the EFI and FGM modules to obtain samples of E and B, respectively. Since EFI and FGM operate from a variety of time-based sampling frequencies, both sets of electronics have been designed to produce an ever-present 128 Hz signal. EFI and FGM have access to this data and will return the data upon request from FIT.
NOTE #3
Given a spin rate of, say, 3 seconds, the use of 128 Hz data for spin fitting puts an apparent phase shift of $360/(3 \times 128)$ or roughly 0.9 degrees into the results. While this meets a 1.0 degree requirement, the phase shift correction can be determined on the ground using the spin pulse time data relative to the 1Hz tick which is the basis of the 128 Hz data.

- Developed by: The Peter R. Harvey, SSL/UCB
- Documented in: thm_fsw_217_fit.doc

NOTE #4
The same routine is implemented on the ground in the THEMIS software, to compute ground-processed spin fits.

- Developed by: Kate Ramer
Access and Use: Solar Wind
Access and Use: Solar Wind (P1/TH-B)

cwd,'C:\...\class\Lecture04_Magnetic_Field'
timespan,'2008/08/13',2.,/days
thm_load_fgm,level=2,probe='b'
tplot,'thb_fgs_gsm'
ylim,'thb_fgs_gsm',-30.,30.,0
tplot
tdegap,'thb_fgs_gsm',dt=3.,margin=0.25,newname='thb_fgs_gsm_dg'
tclip,'thb_fgs_gsm_dg',-20.,20.,newname='thb_fgs_gsm_dg_cl'
tdeflag,'thb_fgs_gsm_dg_cl','repeat',newname='B'
tvectot,'B'; creates and stores Btotal component
tplot,'B'
; Obtain components
split_vec,'B'
; Limit data in specific interval
cctime,tlimits; Left-click twice to create time array of 2 values
; Right-click to stop collecting times
;tlimit,tlimits(0),tlimits(1)
timespan,tlimits(0),tlimits(0)
tplot,'B'

Tpwrspc,'B_0'; default newname=B_0_pwrspc
get_data,'B_0_pwrspc',data=Bxpwr
plot,Bxpwr.x,Bxpwr.y,/xlog,/ylog,col=0

Tpwrspc,'B_1'; default newname=B_1_pwrspc
get_data,'B_1_pwrspc',data=Bypwr
plot,Bypwr.x,Bypwr.y,col=1

Tpwrspc,'B_2'; default newname=B_2_pwrspc
get_data,'B_2_pwrspc',data=Bzpwrc
plot,Bzpwrc.x,Bzpwrc.y,col=2

Tpwrspc,'B_3'; default newname=B_3_pwrspc
get_data,'B_3_pwrspc',data=Btpwr
plot,Btpwr.x,Btpwr.y,col=3
makepng,'psd'
Access and Use: Solar Wind (P1/TH-B)

Dynamic power spectrum
Access and Use: Ground/Ionosphere (gmags)

timespan,'2009/02/15',1,/day
thm_load_gmag,site='hots',/subtract_median
options,1,'colors',[2,4,6]
tplot,1

; tdegap,'thg_mag_hots',dt=0.5,margin=0.1,newname='thg_mag_hots_dg'
tclip,'thg_mag_hots_dg','-100.,100.',newname='thg_mag_hots_dg_cl'
tdeflag,'thg_mag_hots_dg_cl','repeat',newname='B'

; ; ; ;

; --------below is same as before-----------------
; Obtain components
split_vec,'B'
; Limit data in specific interval
ctime,tlimits ; Left-click twice to create time array of 2 values
; Right-click to stop collecting times
; tlimit,tlimits(0),tlimits(1)
timespan,tlimits(0),tlimits(0)
tplot,'B'

; tpwrspc,'B_0' ; default newname=B_0_pwrspc
get_data,'B_0_pwrspc',data=Bxpwr
plot,Bxpwr.x,Bxpwr.y,xlog,ylog,col=0

; tpwrspc,'B_1' ; default newname=B_1_pwrspc
get_data,'B_1_pwrspc',data=Bypwr
plot,Bypwr.x,Bypwr.y,xlog,ylog,col=1

; tpwrspc,'B_2' ; default newname=B_2_pwrspc
get_data,'B_2_pwrspc',data=Bzpwro
plot,Bzpwro.x,Bzpwro.y,xlog,ylog,col=2

; tpwrspc,'B_3' ; default newname=B_3_pwrspc
get_data,'B_3_pwrspc',data=BTpwro
plot,BTpwro.x,BTpwro.y,xlog,ylog,col=3
makepng,'psd2'

--------above is same as before----------------------
Access and Use: Ground/Ionosphere (gmags)

From tplot data to GUI data

For better results (control of min/max frequencies of dpwrspc), use command line:

```
; ;CALLING SEQUENCE:
; tdpwrspc, varname, newname=newname,_extra=_extra
;
;CALLING SEQUENCE:
; dpwrspc, time, quantity, tdps, fdps, dps, nboxpoints = nboxpoints, $
; nshiftpoints = nshiftpoints, bin = bin, tbegin = tbegin,$
; tend = tend, noline = noline, nohanning = nohanning, $
; notperhz = notperhz
```