Fundamentals of Magnetic Sensor Calibration with Respect to MEMS-Based and Traditional Fluxgate MWD Sensor Systems

Chad Hanak
Speaker Bio

• Chad Hanak
  • President, Superior QC
    • Offices and 24/7 RTOC in Houston, TX
    • Survey management (FDIR)
  • PhD in Aerospace Engineering
  • 10 years at NASA, 8 years in Oil & Gas
    • Guidance, Navigation, & Control
    • Survey Correction algorithms
    • Magnetic Ranging
Agenda

Physical Theory of Operation
- MEMS Magnetometers
- Fluxgate Magnetometers

Pre-Calibration Accuracy Expectations

Calibration Process Description

Sample Calibration Results

Where ISCWSA Can Add Value
MEMS Magnetometers

Physical Theory of Operation

• **Lorentz Force**

\[ \mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]

- Electric Charge
- Electric Field Vector
- Charge Velocity Vector
- Magnetic Field Vector

• **For a Current Carrying Wire**

\[ \mathbf{F} = lI \times \mathbf{B} \]

- Length of Wire
- Electric Current Vector
- Magnetic Field Vector

Source: https://en.wikipedia.org/wiki/Lorentz_force
Physical Theory of Operation
- Lorentz Force
  \[ F = I \times B \]

Actual Measurement: Displacement
- Relative Capacitance
- LED
- Shift in Resonant Frequency

Measurement Chain
- Relative Capacitance \(\rightarrow\) Spring Displacement
- Spring Displacement & Spring Constant \(\rightarrow\) Spring Force
- Spring Force & Current Magnitude \(\rightarrow\) Mag. Field Strength
- Mag. Field Strength & Alignment \(\rightarrow\) Mag. Field Vector Component

Source: IEEE Transactions on Industrial Electronics 60(9):3983-3990 · September 2013
MEMS Magnetometers
Capacitance Measurement Concept Visualization

Each **green** and **red** plate pair forms a capacitor

- Ideally, C1 & C2 are equal when displacement is zero
- A bias results when this is not true

Errors in multiplicative terms form scale factor errors

- Spring constant
- Current measurement

Misalignments have two sources:

- Sensor axis non-orthogonality
- Sensor triad alignment with chassis

Source: [https://howomechatronics.com/how-it-works/electrical-engineering/mems-accelerometer-gyrocope-magnetometer-arduino/](https://howomechatronics.com/how-it-works/electrical-engineering/mems-accelerometer-gyrocope-magnetometer-arduino/)
(image shows an accelerometer, not a magnetometer, but the capacitance vs. displacement concept is the same)
Fluxgate Magnetometers

Physical Theory of Operation

- **Drive Winding: Biot-Savart Law**

\[ B = \frac{\mu_0 I}{4\pi} \int_{\text{wire}} \frac{dl \times r}{r} \]

- **Magnetic Field Vector**
- **L = Current magnitude**
- **\( \mu_0 \) = Magnetic Permeability of Free Space**
- **Vector position at which field is to be calculated**
- **Vector of Infinitesimal Length of Wire in Direction of Current**

Source: https://en.wikipedia.org/wiki/Magnetic_field#Magnetic_field_and_electric_currents
Fluxgate Magnetometers

Physical Theory of Operation

- Core: Ferrous Magnetic Domains

Randomized Magnetic Domains in the Absence of an External Magnetic Field

Saturation in the Presence of an External Magnetic Field

Source: https://en.wikipedia.org/wiki/Magnetic_domain
Fluxgate Magnetometers

Physical Theory of Operation

- Drive Winding & Core Together

Fig. 2a: Drive Waveform

Fig. 2b: $B$ generated by each half core with no external field

Fig. 2c: $B$ generated by each half core in external field

Fig. 2d: Voltage induced in the sense winding (black) Resultant voltage if the sensor is tuned (red)

Source: https://www.imperial.ac.uk/space-and-atmospheric-physics/research/areas/space-magnetometer-laboratory/space-instrumentation-research/magnetometers/fluxgate-magnetometers/how-a-fluxgate-works/
Fluxgate Magnetometers

Physical Theory of Operation

- Sense Winding: Faraday’s Law

\[ \varepsilon = -\frac{d\Phi_B}{dt} \]

Electromotive Force

Rate of Change of (Net) Magnetic Flux Through the Sense Winding Loop

Source: https://www.imperial.ac.uk/space-and-atmospheric-physics/research/areas/space-magnetometer-laboratory/space-instrumentation-research/magnetometers/fluxgate-magnetometers/how-a-fluxgate-works/
Fluxgate Magnetometers

Physical Theory of Operation

- Drive Winding: Biot-Savart Law
- Core: Ferrous Magnetic Domains
- Sense Winding: Faraday’s Law

Measurement Chain

Sense Winding Voltage → Spike Magnitude & Phase

Spike Magnitude & Phase → Mag. Field Strength

Mag. Field Strength & Alignment → Mag. Field Vector Component

Source: https://www.imperial.ac.uk/space-and-atmospheric-physics/research/areas/space-magnetometer-laboratory/space-instrumentation-research/magnetometers/fluxgate-magnetometers/how-a-fluxgate-works/
Sensor Bias & Scale Factor Expectations

Pre-Calibration

MEMS

Bias
• Manufacturing non-homogeneity likely to cause biases

Scale Factor Errors
• Lone measurement chain introduces many chances for error
• Temperature dependence likely on spring constant & current measurement

Fluxgate

Bias
• Internal sensor biases likely to be small (DC signal not used in signal processing)

Scale Factor Errors
• Voltage magnitude reading subject to scale errors and temperature dependency
• Mitigated somewhat if phase of signal is also used

Calibration is used to reduce these errors.
MEMS
Can be mounted directly to circuit board
• Single axis sensors will have greater mounting non-orthogonality
• Small dimensions make accurate angular mounting difficult
• Significant board flexing could degrade calibrated alignment

Fluxgate
Usually dual axis (mounted X-Z and Y-Z)
• How are z-axes handled?
• X-Y non-orthogonality can be an issue
• Lengthier sensor lends itself to more accurate angular mounting

Calibration is used to reduce these errors.

Expected to have larger uncalibrated temp. dependence

Same physical displacement yields large angular mounting misalignment for a shorter sensor
Sensor Calibration Process

Steps

1. Solve for coefficient table at one temperature using total field calibration or some other technique
2. Repeat Step 1 at multiple other temperatures to calculate temperature-based polynomials for each coefficient
3. Write the coefficient table to the tool and perform a verification run

Source: https://tolteq.com/?p=5859

## Sample Calibration Results

**Temperature Dependence (Average per Brand)**

### MEMS vs. Fluxgate Mag Calibration, presented by Chad Hanak

<table>
<thead>
<tr>
<th>Bias nT/°C</th>
<th>Scale PPM/°C</th>
<th>Alignments deg/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fluxgates Magnetometers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand A</td>
<td>0.3</td>
<td>225</td>
</tr>
<tr>
<td>Brand B</td>
<td>0.1</td>
<td>4.7</td>
</tr>
<tr>
<td>Brand C</td>
<td>0.3</td>
<td>6</td>
</tr>
<tr>
<td>Brand D</td>
<td>1.5</td>
<td>100</td>
</tr>
<tr>
<td>Brand E</td>
<td>0.6</td>
<td>250</td>
</tr>
<tr>
<td>Brand F</td>
<td>0.5</td>
<td>84</td>
</tr>
<tr>
<td>Brand G</td>
<td>0.15</td>
<td>7</td>
</tr>
<tr>
<td>Brand H</td>
<td>0.1</td>
<td>90</td>
</tr>
<tr>
<td>Brand I</td>
<td>0.5</td>
<td>50</td>
</tr>
<tr>
<td>Brand J</td>
<td>0.2</td>
<td>15</td>
</tr>
<tr>
<td><strong>MEMS Magnetometers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand A</td>
<td>450</td>
<td>3500</td>
</tr>
<tr>
<td>Brand B</td>
<td>4</td>
<td>3400</td>
</tr>
<tr>
<td>Brand C</td>
<td>1.3</td>
<td>10</td>
</tr>
</tbody>
</table>

*Actual calibration results*
## Temperature Tolerances Required to Keep Post-Calibration Error Below OWSG MWD 1-σ Levels

### Fluxgate Magnetometers

<table>
<thead>
<tr>
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<th>Alignments deg/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>225</td>
<td>0.0001</td>
</tr>
<tr>
<td>B</td>
<td>0.1</td>
<td>4.7</td>
<td>0.0001</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
<td>6</td>
<td>0.0003</td>
</tr>
<tr>
<td>D</td>
<td>1.5</td>
<td>100</td>
<td>0.0003</td>
</tr>
<tr>
<td>E</td>
<td>0.6</td>
<td>250</td>
<td>0.0010</td>
</tr>
<tr>
<td>F</td>
<td>0.5</td>
<td>84</td>
<td>0.0002</td>
</tr>
<tr>
<td>G</td>
<td>0.15</td>
<td>7</td>
<td>0.0003</td>
</tr>
<tr>
<td>H</td>
<td>0.1</td>
<td>90</td>
<td>0.0001</td>
</tr>
<tr>
<td>I</td>
<td>0.5</td>
<td>50</td>
<td>0.0006</td>
</tr>
<tr>
<td>J</td>
<td>0.2</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

### MEMS Magnetometers

<table>
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<tr>
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<th>Alignments deg/°C</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>450</td>
<td>3500</td>
<td>0.0040</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>3400</td>
<td>0.0014</td>
</tr>
<tr>
<td>C</td>
<td>1.3</td>
<td>10</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

### Fluxgate Magnetometers

<table>
<thead>
<tr>
<th>Brand</th>
<th>Bias (°C)</th>
<th>Scale (°C)</th>
<th>Alignments (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>233.3</td>
<td>7.1</td>
<td>872.7</td>
</tr>
<tr>
<td>B</td>
<td>700.0</td>
<td>340.4</td>
<td>872.7</td>
</tr>
<tr>
<td>C</td>
<td>233.3</td>
<td>266.7</td>
<td>290.9</td>
</tr>
<tr>
<td>D</td>
<td>46.7</td>
<td>16.0</td>
<td>290.9</td>
</tr>
<tr>
<td>E</td>
<td>116.7</td>
<td>6.4</td>
<td>97.0</td>
</tr>
<tr>
<td>F</td>
<td>140.0</td>
<td>19.0</td>
<td>436.3</td>
</tr>
<tr>
<td>G</td>
<td>466.7</td>
<td>228.6</td>
<td>349.1</td>
</tr>
<tr>
<td>H</td>
<td>700.0</td>
<td>17.8</td>
<td>872.7</td>
</tr>
<tr>
<td>I</td>
<td>140.0</td>
<td>32.0</td>
<td>174.5</td>
</tr>
<tr>
<td>J</td>
<td>350.0</td>
<td>106.7</td>
<td>581.8</td>
</tr>
</tbody>
</table>

### MEMS Magnetometers

<table>
<thead>
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<th>Bias (°C)</th>
<th>Scale (°C)</th>
<th>Alignments (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.2</td>
<td>0.5</td>
<td>24.9</td>
</tr>
<tr>
<td>B</td>
<td>17.5</td>
<td>0.5</td>
<td>69.8</td>
</tr>
<tr>
<td>C</td>
<td>53.8</td>
<td>160.0</td>
<td>58.2</td>
</tr>
</tbody>
</table>

---

**Not used for definitive surveys**

**Temp. Sensitivity** ➡ **Calibration Temp. Tolerance**
Sensor Calibration Impact
Temp. Must Be Precisely Controlled for MEMS

Steps
1. Solve for coefficient table at one temperature using total field calibration or some other technique
2. Repeat Step 1 at multiple other temperatures to calculate temperature-based polynomials for each coefficient
3. Write the coefficient table to the tool and perform a verification run
Where the ISCWSA Can Add Value
Guidance For Manufactures and MWD Companies

MEMS vs. Fluxgate Mag Calibration, presented by Chad Hanak

Operator
Need: Determine Separation Factor using OWSG error models
Request: Provide me with surveys consistent with OWSG error model assumptions

MWD Company
Need: Provide surveys consistent with OWSG error model assumptions
Request: Provide me with sensors consistent with OWSG error model assumptions

Sensor Manufacturer or Calibration Provider
Need: Provide sensors consistent with OWSG error model assumptions
Request: Provide me bias, scale factor, and misalignment specs from OWSG error model
### Where the ISCWSA Can Add Value

**Guidance For Manufactures and MWD Companies**

**MEMS vs. Fluxgate Mag Calibration, presented by Chad Hanak**

<table>
<thead>
<tr>
<th>Error Type</th>
<th>ISCWSA Mnemonics</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer Bias</td>
<td>ABX, ABY, ABZ</td>
<td>0.004</td>
<td>m/s²</td>
</tr>
<tr>
<td>Accelerometer Scale Factor Error</td>
<td>ASX, ASY, ASZ</td>
<td>0.0005</td>
<td>--</td>
</tr>
<tr>
<td>Magnetometer Bias</td>
<td>MBX, MBY, MBZ</td>
<td>70</td>
<td>nT</td>
</tr>
<tr>
<td>Magnetometer Scale Factor Error</td>
<td>MSX, MSY, MSZ</td>
<td>0.0016</td>
<td>--</td>
</tr>
<tr>
<td>Misalignment of Sensor Frame wrt Tool Axis</td>
<td>MX, MY</td>
<td>0.1*</td>
<td>deg</td>
</tr>
<tr>
<td>Twist</td>
<td>(not in model)</td>
<td>0</td>
<td>deg</td>
</tr>
<tr>
<td>Bend</td>
<td>(not in model)</td>
<td>0</td>
<td>deg</td>
</tr>
<tr>
<td>Accelerometer Non-Orthogonality</td>
<td>(not in model)</td>
<td>0</td>
<td>deg</td>
</tr>
<tr>
<td>Magnetometer Non-Orthogonality</td>
<td>(not in model)</td>
<td>0</td>
<td>deg</td>
</tr>
</tbody>
</table>

* Also models misalignment of survey tool with respect to the borehole
Conclusions

- MEMS magnetometers expected to have larger sensor errors than Fluxgate magnetometers pre-calibration.
- Calibration should be able to make performance comparable:
  - Higher temperature sensitivity may require more precise temperature control during the calibration coefficients.
  - Otherwise, no significant difference anticipated in calibration procedure.
  - Much of the post-calibration performance knowledge remains proprietary (hysteresis levels?)
- ISCWSA could provide better specs on misalignments for sensor manufacturers & calibration providers.