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

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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

Magnetic Field Vector

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Electric Charge

Charge Velocity Vector

Electric Field Vector

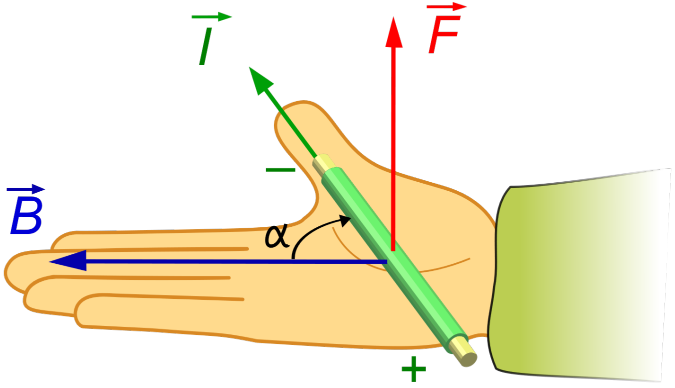
- For a Current Carrying Wire

$$\boldsymbol{F} = l\boldsymbol{I} \times \boldsymbol{B}$$

Magnetic Field Vector

Length of Wire

Electric Current Vector



Source: https://en.wikipedia.org/wiki/Lorentz_force

MEMS Magnetometers

Physical Theory of Operation

- Lorentz Force

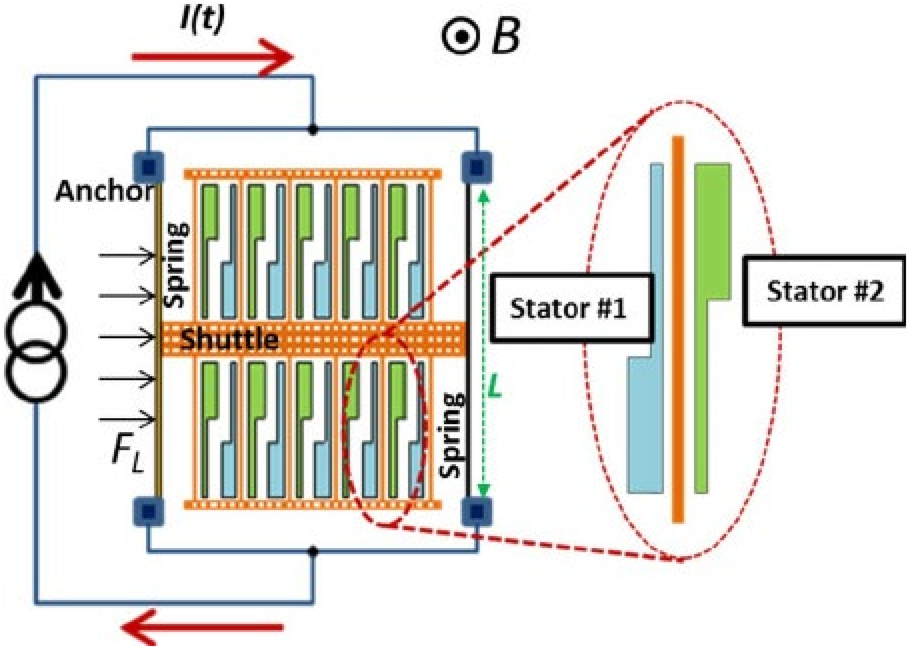
$$F = l\mathbf{I} \times \mathbf{B}$$

Actual Measurement: Displacement

- Relative Capacitance
- LED
- Shift in Resonant Frequency

Measurement Chain

- Relative Capacitance → Spring Displacement
- Spring Displacement & Spring Constant → Spring Force
- Spring Force & Current Magnitude → Mag. Field Strength
- Mag. Field Strength & Alignment → 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

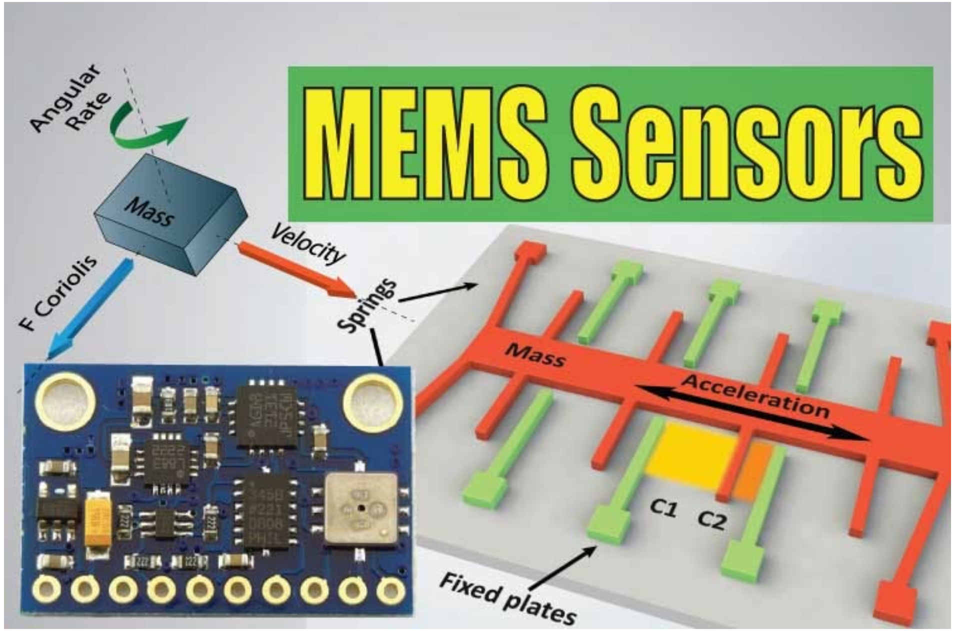
- Ideally, C1 & C2 are equal when displacement is zero
- A bias results when this is not true

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://howtomechatronics.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

$$\boldsymbol{B} = \frac{\mu_0 I}{4\pi}\int_{\omega ire} \frac{d\boldsymbol{l}\times \boldsymbol{r}}{r}$$

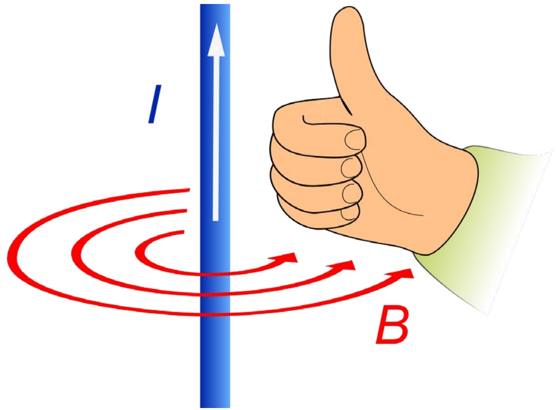
Vector of Infinitesimal Length of Wire in Direction of Current

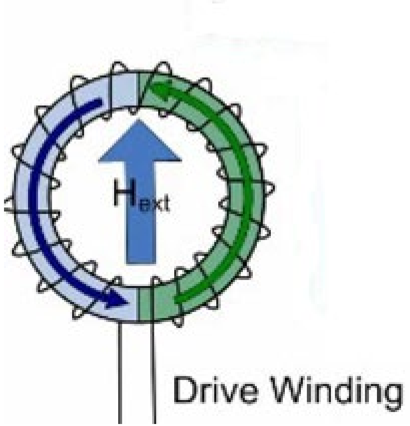
Magnetic Field Vector

Vector position at which field is to be calculated

I = Current magnitude

μ_0 = Magnetic Permeability of Free Space



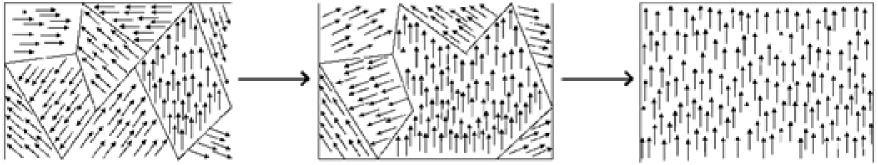


Source: https://en.wikipedia.org/wiki/Magnetic_field#Magnetic_field_and_electric_currents

Fluxgate Magnetometers

Physical Theory of Operation

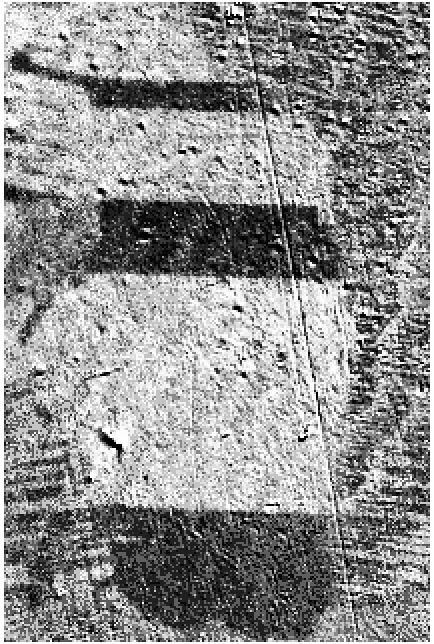
- Core: Ferrous Magnetic Domains



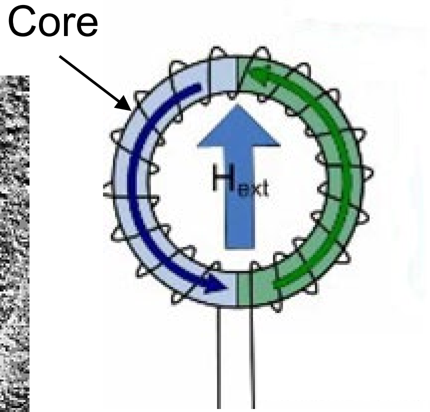
Source: https://en.wikipedia.org/wiki/Magnetic_domain

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

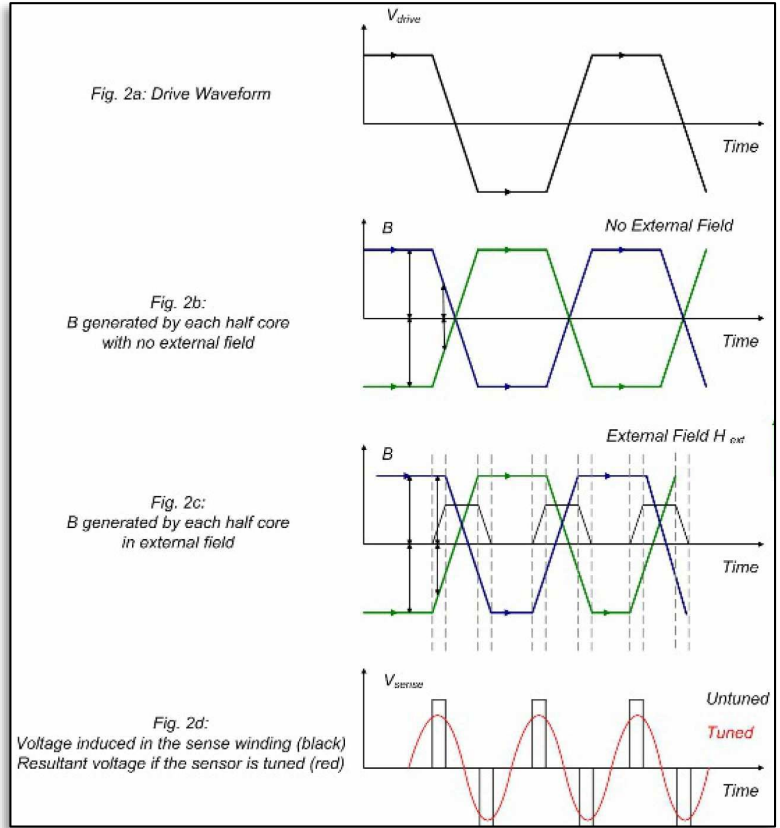
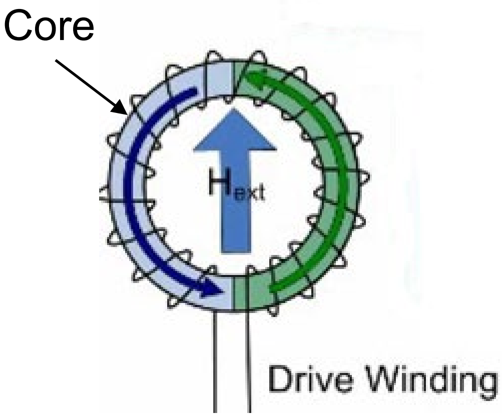


Fig. 2a: Drive Waveform

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)

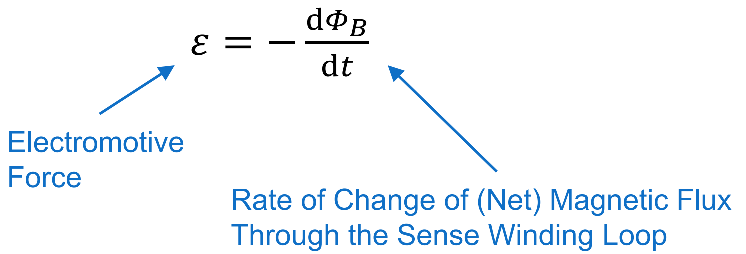


Source: https://www.imperial.ac.uk/space-and-atmospheric-physics/research/areas/space-magnetometer-laboratory/space-instrumentation-research/magnetometers/fluxgate-magnetometers/how-a-fluxgate-works/

Fluxgate Magnetometers

Physical Theory of Operation

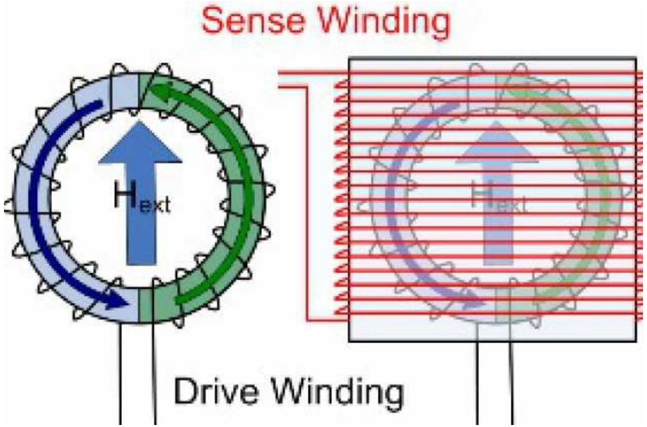
- Sense Winding: Faraday's Law



$$\varepsilon = -\frac{\mathrm{d}\Phi_B}{\mathrm{d}t}$$

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

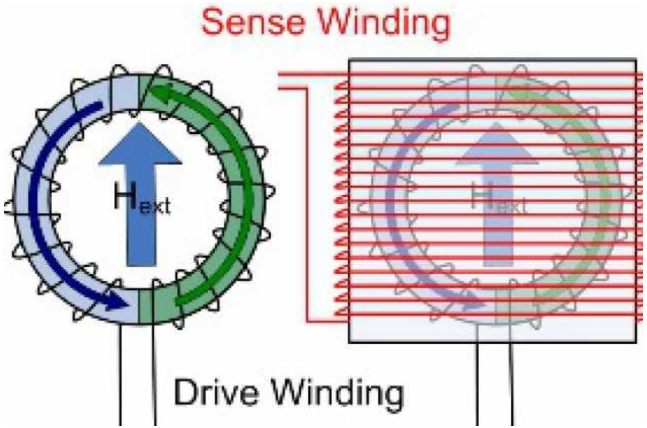
- Drive Winding: Biot-Savart Law
- Core: Ferrous Magnetic Domains
- Sense Winding: Faraday’s Law

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

Expected to have larger <u>uncalibrated</u> temp. dependence, bias, & scale factor error

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

Calibration is used to reduce these errors.

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

Effects of Sensor Mounting on Alignment

Pre-Calibration

Calibration is used to reduce these errors.

MEMS

Expected to have larger <u>uncalibrated</u> temp. dependence

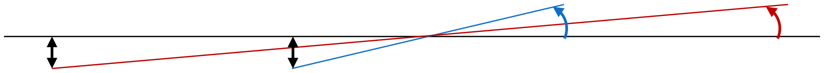
Can be mounted directly to circuit board

- 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



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

Sensor Calibration Process

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

https://www.nov.com/Segments/Wellbore_Technologies/ReedHycalog/Directional_Measurment_and_Steerable_Technologies/Directional_Systems/Tolteq_iSeries_MWD_Solutions/Tolteq_Repair_and_Maintenance/Tolteq_Service_and_Support/Tolteq_Service_and_Support.aspx

Steps

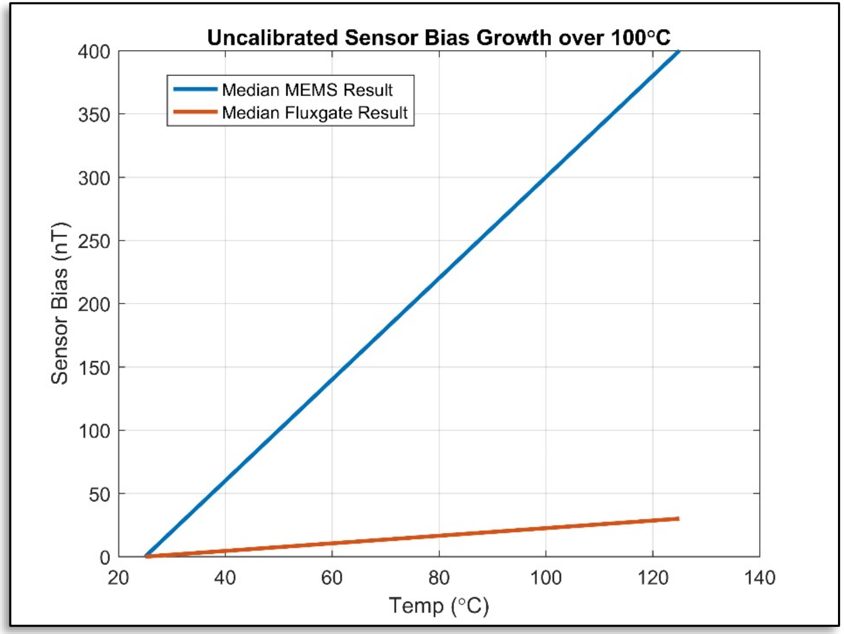
1. Solve for coefficient table at one temperature using total field calibration or some other technique
2. Repeat Step 1 at multiple other temperatures to calculate temperature-based polynomials for each coefficient
3. Write the coefficient table to the tool and perform a verification run

Sample Calibration Results

Temperature Dependence (Average per Brand)

	Bias nT/°C	Scale PPM/°C	Alignments deg/°C
Fluxgates Magnetometers			
Brand A	0.3	225	0.0001
Brand B	0.1	4.7	0.0001
Brand C	0.3	6	0.0003
Brand D	1.5	100	0.0003
Brand E	0.6	250	0.0010
Brand F	0.5	84	0.0002
Brand G	0.15	7	0.0003
Brand H	0.1	90	0.0001
Brand I	0.5	50	0.0006
Brand J	0.2	15	0.0002
MEMS Magnetometers			
Brand A	450	3500	0.0040
Brand B	4	3400	0.0014
Brand C	1.3	10	0.0017

* Actual calibration results



Temperature Tolerances Required to Keep Post-Calibration Error Below OWSG MWD 1-σ Levels

	Bias nT/°C	Scale PPM/°C	Alignments deg/°C
Fluxgates Magnetometers			
Brand A	0.3	225	0.0001
Brand B	0.1	4.7	0.0001
Brand C	0.3	6	0.0003
Brand D	1.5	100	0.0003
Brand E	0.6	250	0.0010
Brand F	0.5	84	0.0002
Brand G	0.15	7	0.0003
Brand H	0.1	90	0.0001
Brand I	0.5	50	0.0006
Brand J	0.2	15	
MEMS Magnetometers			
Brand A	450	3500	0.0040
Brand B	4	3400	0.0014
Brand C	1.3	10	0.0017

Not used for definitive surveys

	Bias (°C) 70 nT / (nT/°C)	Scale (°C) 1600 PPM / (PPM/°C)	Alignments (°C) 0.1 deg / (deg/°C)
Fluxgates Magnetometers			
Brand A	233.3	7.1	872.7
Brand B	700.0	340.4	872.7
Brand C	233.3	266.7	290.9
Brand D	46.7	16.0	290.9
Brand E	116.7	6.4	97.0
Brand F	140.0	19.0	436.3
Brand G	466.7	228.6	349.1
Brand H	700.0	17.8	872.7
Brand I	140.0	32.0	174.5
	350.0	106.7	581.8
MEMS Magnetometers			
Brand A	0.2	0.5	24.9
Brand B	17.5	0.5	69.8
Brand C	53.8	160.0	58.2

Temp. Sensitivity → Calibration Temp. Tolerance

Sensor Calibration Impact

Temp. Must Be Precisely Controlled for MEMS

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

https://www.nov.com/Segments/Wellbore_Technologies/ReedHycalog/Directional_Measurment_and_Steerable_Technologies/Directional_Systems/Tolteq_iSeries_MWD_Solutions/Tolteq_Repair_and_Maintenance/Tolteq_Service_and_Support/Tolteq_Service_and_Support.aspx

Steps

1. Solve for coefficient table at one temperature using total field calibration or some other technique
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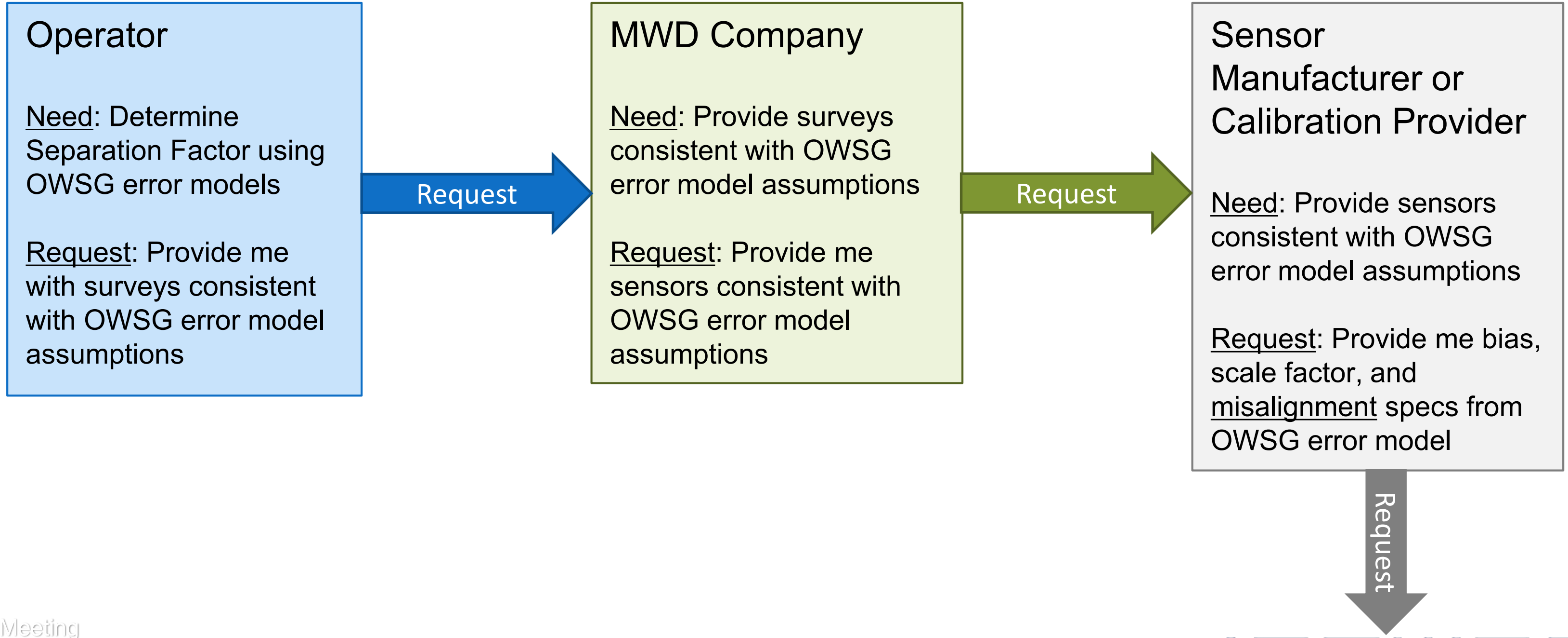
Where the ISCWSA Can Add Value

Guidance For Manufactures and MWD Companies



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 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

ISCWSA

Where the ISCWSA Can Add Value

Guidance For Manufactures and MWD Companies

MEMS vs. Fluxgate Mag Calibration, presented by Chad Hanak

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

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

Conclusions

- MEMS magnetometers expected to have larger sensor errors than Fluxgate magnetometers <u>pre-calibration</u>
- 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