MWD a new approach

Angus Jamieson

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SPE International
Wellbore Positioning Technical Section

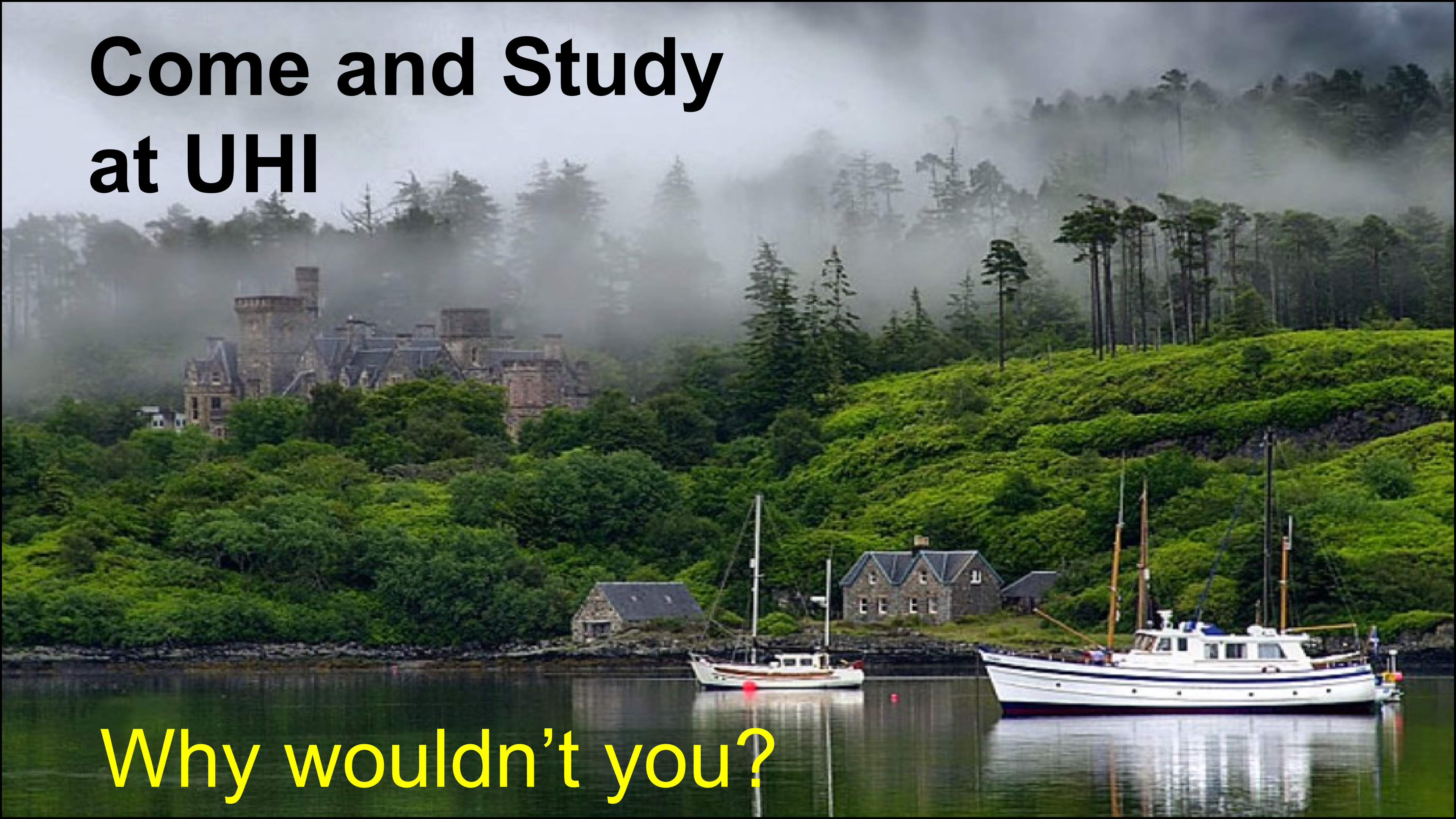
ISCWSA
The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA)

Speaker Information

- Angus Jamieson
- Professor of Offshore Engineering
- September 22nd, 2016
- Member of SPE, Chartered Surveyor RICS

Speaker Bio

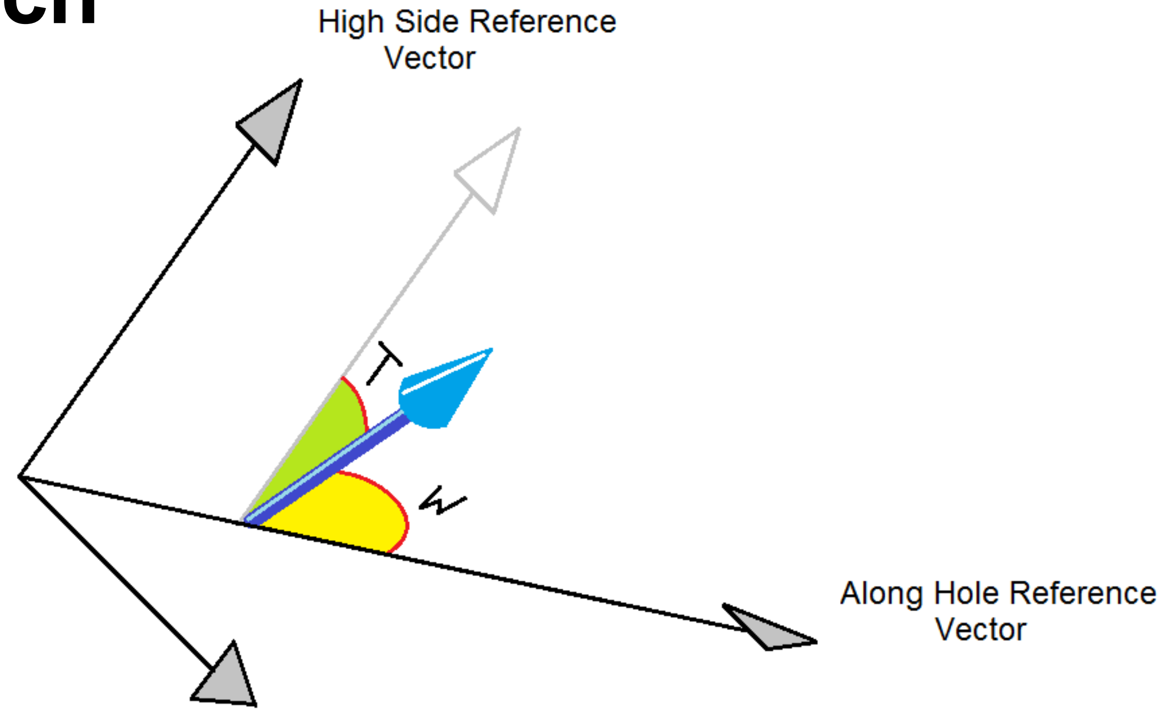
- Introduction
  - AJ Consulting Ltd and UHI University, Inverness
  - 37 years oilfield experience
  - Heriott Watt Bsc in Civil Engineering, FRICS
  - Live in Inverness, Scotland
  - Specialized in
    - Marine and Downhole Surveying
    - Mathematics and Software
    - Directional Drilling


Come and Study
at UHI
Why wouldn’t you?

New Approach Objectives

- 1. Avoid Orthogonality Issues
- 2. Allow for more sensors to be used
- 3. Make Calibrations more accurate
- 4. Speed up Calibration Process
- 5. Improve MWD Accuracy

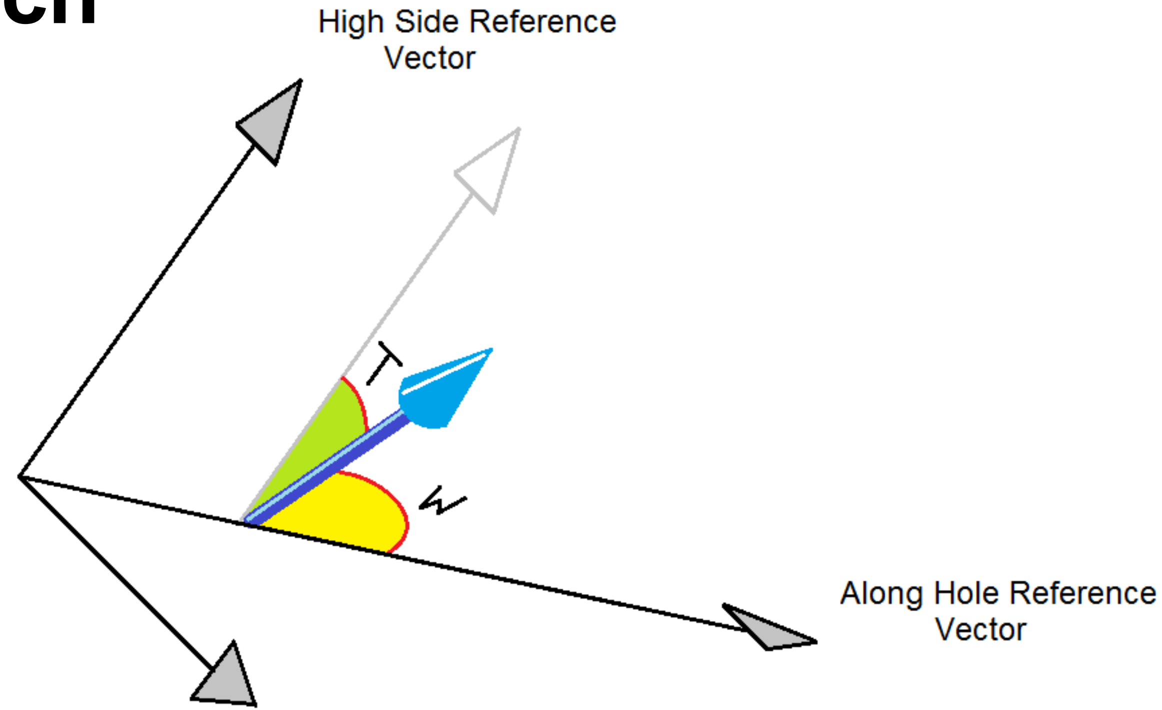
New Approach



New Approach

- For Example

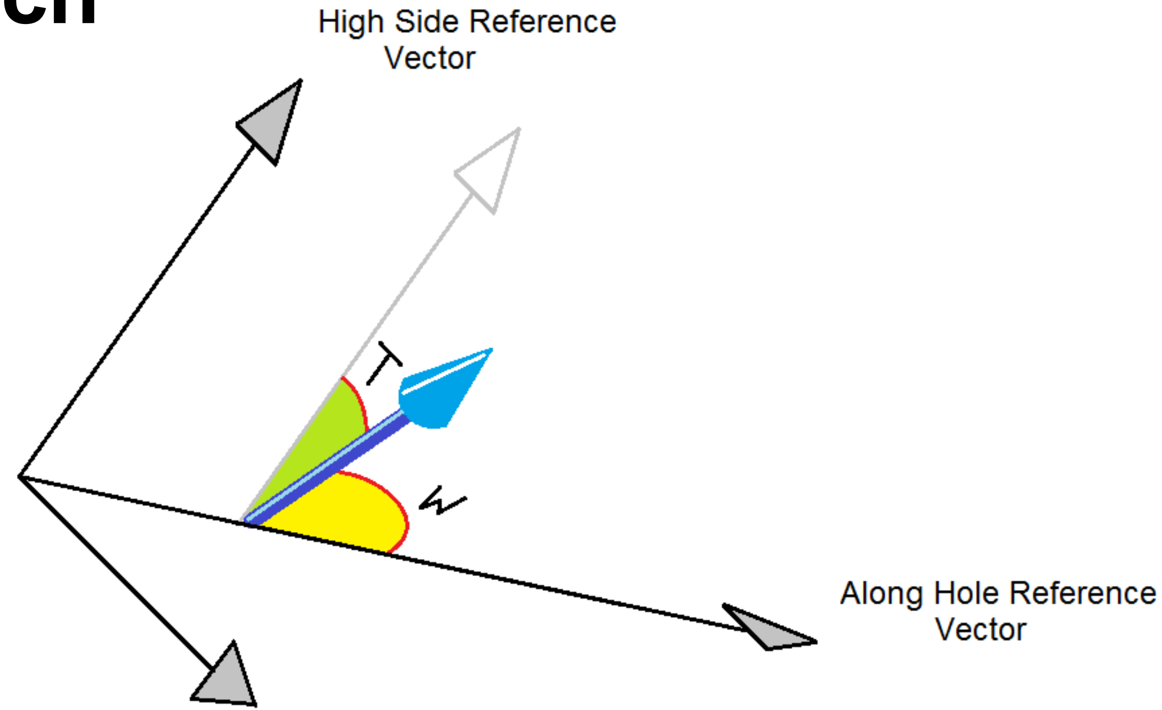
	T	W
• X is	0	90
• Y is	90	90
• Z is	0	0



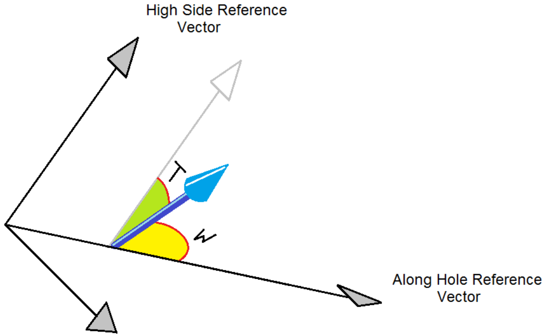
New Approach

- Microtesla 4AM

	T	W
• A is	-30	25
• B is	30	90
• C is	-90	90
• D is	110	150



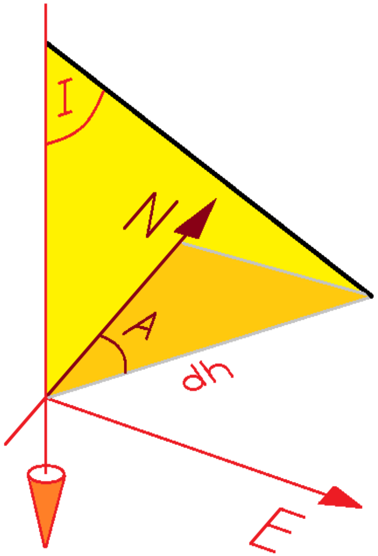
New Approach



- Find the 2 alignments for each sensor
  - Alignment from along hole axis W
  - Alignment from high side axis T
- Include all sensors available in the tool
- Calibrate each sensor's 2 alignments v Temperature using a 'hot' tumble and a 'cold' tumble (Use a linear interpolation for W and T at other temperatures)

New Approach

- Using actual alignments corrected at each temperature
  - Set tool to inc 60, azi 0, Tf -45, heat to 150 and record while cooling
  - Set tool to inc 120, azi 180, Tf 135, heat to 150 and record while cooling
  - Determine least squares best fit polynomials to correct for scale and bias
- In Instrument firmware use temperature corrected sensor data and actual alignments to produce synthetic 3 axis perfectly orthogonal data for surveys



In this diagram the length of the slope is 1 unit. The unit vector describing the along hole axis can be determined from the shifts to North, East and Vertical caused by 1 unit at inclination I, azimuth A.

Let's call the vertical shift dV.

The vertical shift $dV = \cos(I)$

dh is the horizontal shift where $dh = \sin(I)$

The shift to the North dN will therefore be dh cos(A) or, in full,

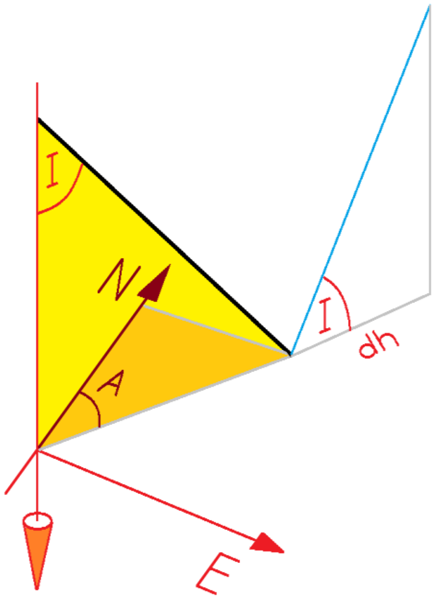
$$dN = \sin(I)\cos(A)$$

the shift to the East dE will therefore be dh sin(A) or, in full,

$$dE = \sin(I)\sin(A)$$

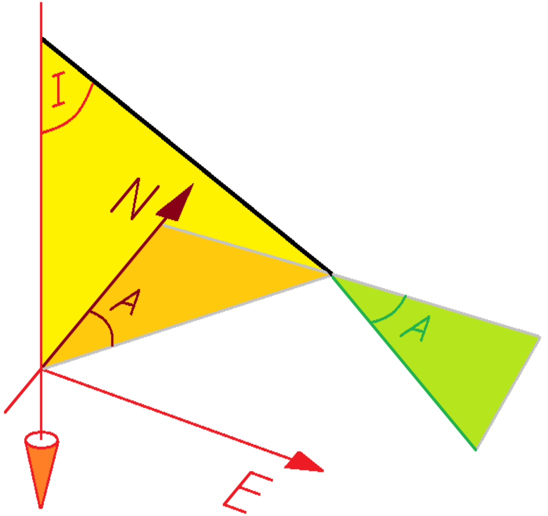
So an along hole axis set at inclination I, Azimuth A, has a unit vector:

$$dE = \sin(I)\sin(A)$$
$$dN = \sin(I)\cos(A)$$
$$dV = \cos(I)$$



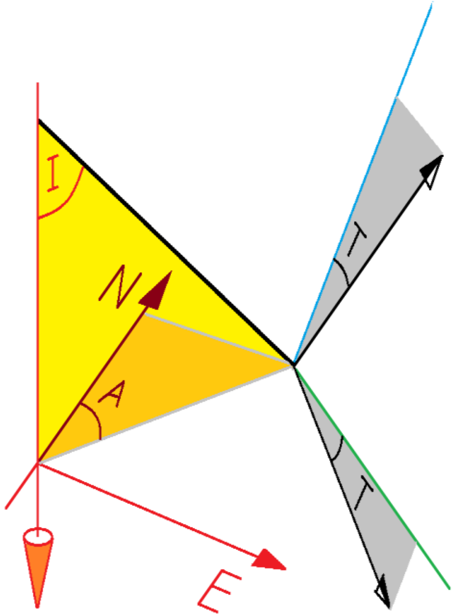
A unit vector to high side can be similarly defined. In this case the horizontal shift dH is 1 unit x cos(I) and the Vertical shift is 1 unit x sin(I) but is back towards the surface so the high side unit vector in full is:

$$dE = \cos(I)\sin(A)$$
$$dN = \cos(I)\cos(A)$$
$$dV = -\sin(I)$$



For a lateral unit vector there is no vertical component so we can say:

$$dE = \cos(A)$$
$$dN = -\sin(A)$$
$$dV = 0$$

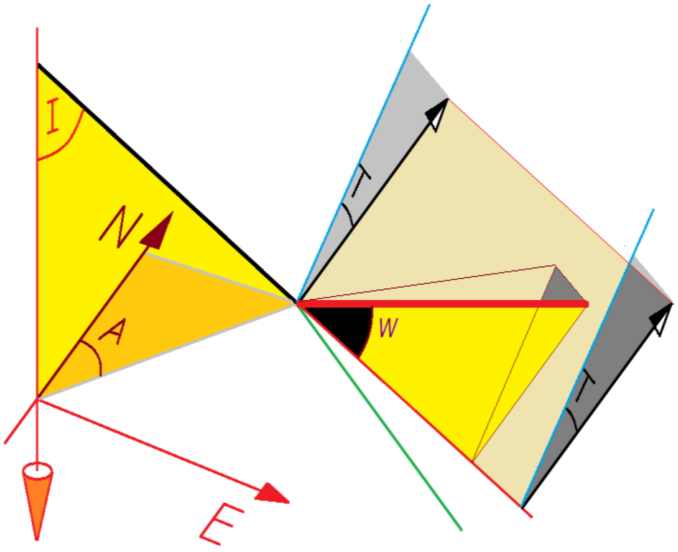


Our X and Y axes will be orientated with the toolface angle T. The X axis is normally pointing along the toolface angle with the Y axis clockwise 90 degrees. So the actual unit vector for the X axis consists of :

Highside Vector x cos (T) + Lateral Vector x sin (T)

and similarly the actual unit vector for the Y axis consists of:

Lateral Vector x cos (T) - High Side vector x sin (T)



In General for any sensor axis aligned at an angle W from the along hole axis and rotated T from the toolface we can determine the attitude vectors from the following construction:

The along hole component will be cos(W)
The offset component will be sin(W)

This will have a high side component sin(W) cos(T)
and a lateral component sin(W) sin(T)

This is a useful result for axes aligned at any angle and so the unit vector for any W and T value set at Inc I, Azimuth A and Toolface Tf can be written as:

$$dE = \cos(W)\,Ae + \sin(W)\cos(T+Tf)\,He + \sin(W)\sin(T+Tf)\,Le$$
$$dN = \cos(W)\,An + \sin(W)\cos(T+Tf)\,Hn + \sin(W)\sin(T+Tf)\,Ln$$
$$dV = \cos(W)\,Av + \sin(W)\cos(T+Tf)\,Hv + \sin(W)\sin(T+Tf)\,Lv$$

where Ae, An, Av describes the Along Hole Vector
He, Hn, Hv describes the High Side Vector
Le, Ln, Lv describes the Lateral Vector

dE = cos(W)sin(I)sin(A) + sin(W)cos(T+Tf)cos(I)sin(a) + sin(W)sin(T+Tf) cos(A)
dN = cos(W)sin(I)cos(A) + sin(W)cos(T+Tf)cos(I)cos(a) + sin(W)sin(T+Tf) -sin(A)
dV = cos(W) cos(I) + sin(W)cos(T+Tf)-sin(i)

so any accel will read the dot product of this vector with the gravity field vector

i.e. de x 0 + dn x 0 + cos(W)cos(I) - sin(W)cos(T+Tf)sin(I).g

each accel contributes an equation cos(W) cos(I) - sin(W)cos(T+Tf)sin(I).g = Accel observation
Unknowns are Tf and I so a least squares best fit Toolface and Inclination can be found

therafter any magnetometer will read the dot product with magnetic field vector

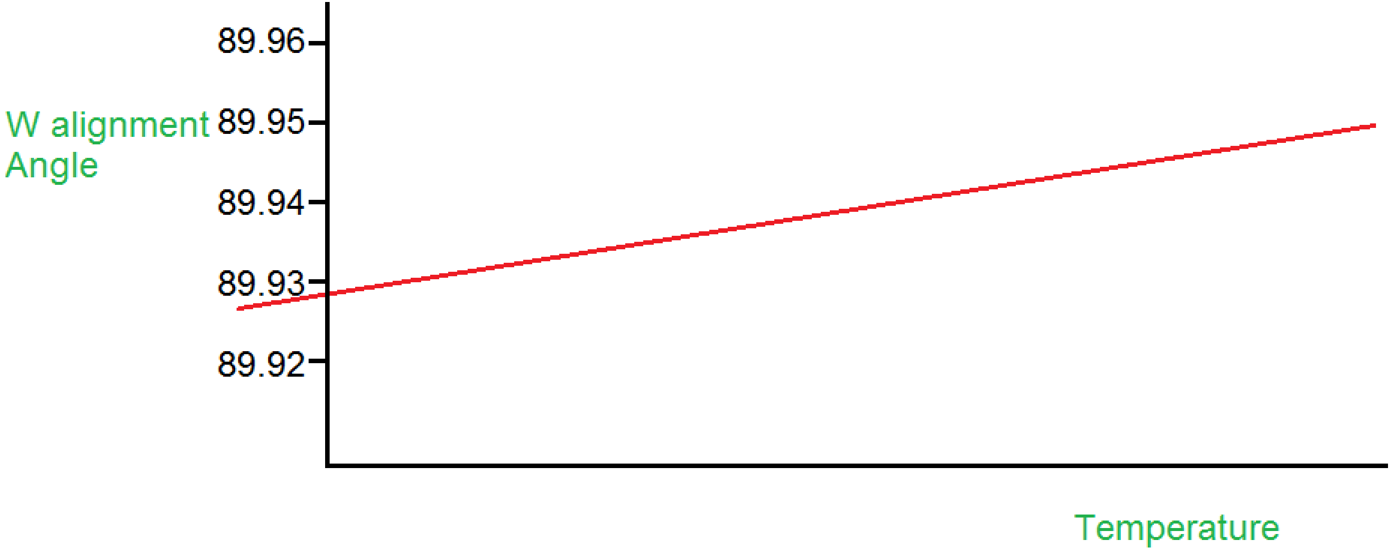
i.e. de x 0 + [cos(W)sin(I)cos(A) + sin(W)cos(T+Tf)cos(I)cos(A) - sin(W)sin(T+Tf)sin(A)] Bt cos(Dip) +
[cos(W) cos(I) - sin(W)cos(T+Tf)sin(I)] Bt sin(dip) = Mag Observed

At this stage the only unknowns are sin(A) and cos(A) which can be solved by oversubscribed simultaneous equations for a least squares best fit azimuth.

Calibration Tumbles

- Set to room temperature
- Set multiple toolfaces, inclinations and azimuths on known orientations (minimum 12)
- Record raw data from all sensors and temperature
- Apply monte carlo scale, bias, T alignment and W alignment to minimise the sum of the errors squared
  - Use W and T corrected for temperature
  - Calculate the unit vector for the sensor in N, E, V
  - Error = dot product with observed field – observed value
  - Sum of errors ^2
- Repeat at 'hot' value say 150 degs C

Use linear fit on T and W for all other temperatures

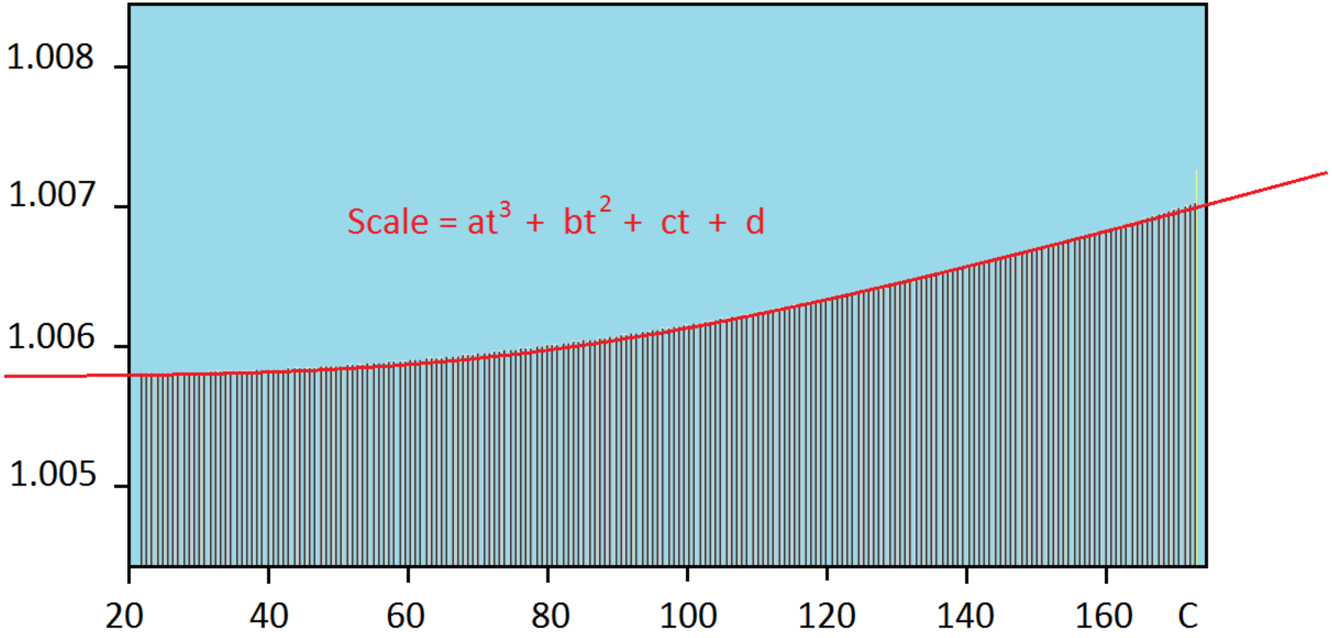


Cooling Curves

- Set inc 60, azi 0, tface -45
- heat to 150 and record while cooling
- Set inc 120, azi 180, tface 135
- heat to 150 and record while cooling

These two orientations will provide enough data to fit a scale and bias polynomial fit through the cooling curves

Typical Cooling Curve Fit



C = Correct Sensor Value   V = observed Value   t = temperature

Each observed value contains a temperature affected scale and bias as follows

$\text{Scale} = at^3 + bt^2 + ct + d \quad \text{Bias} = et^3 + ft^2 + gt + h$

where a,b,c,d and e,f,g,h are polynomial coefficients applied to temperature to fit the scale and bias effects respectively

so in all observations of each sensor the following relationship applies

$V = C\,(at^3 + bt^2 + ct + d) + et^3 + ft^2 + gt + h$

in matrix form each observed value contributes a row of the simultaneous equations:

$$\begin{bmatrix} Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \end{bmatrix} = \begin{bmatrix} V \\ V \\ V \\ V \\ V \\ V \\ V \\ V \\ V \end{bmatrix}$$

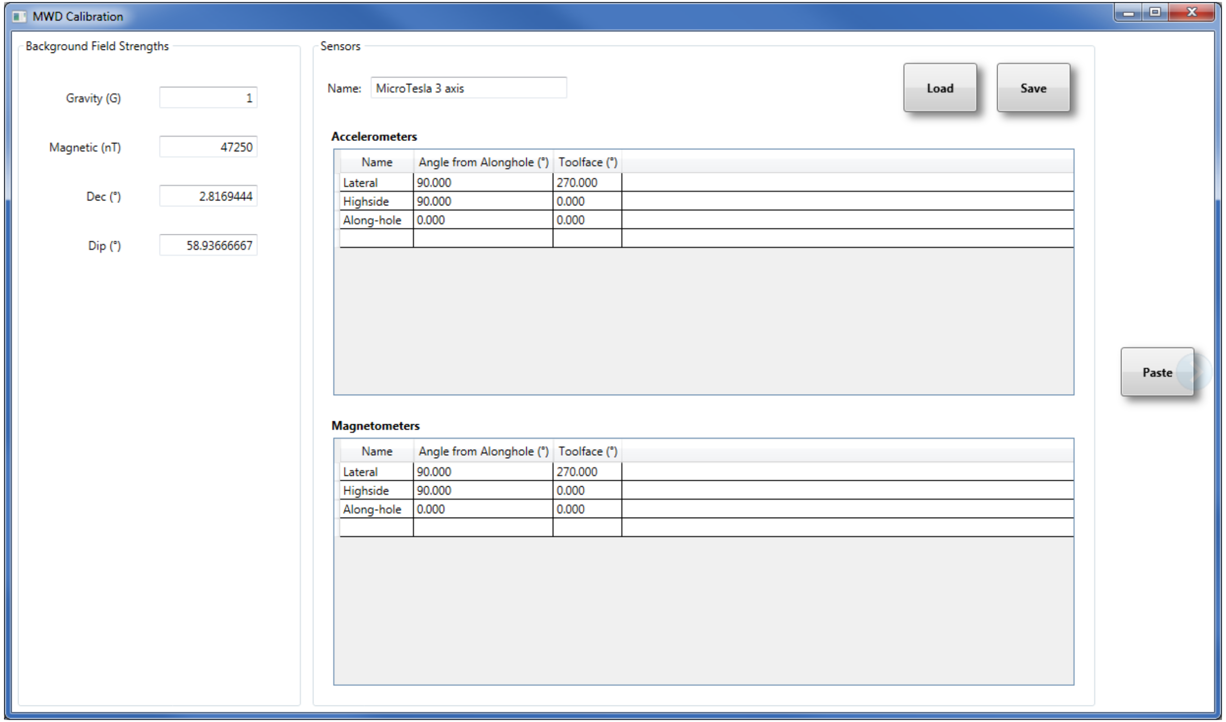
As these will be heavily ovsersubscribed by including the data gathered during the cooling curves, we can premultiply the power matrix and the observation matrix by the transpose of the power matrix to achieve a least squares best fit for parameters a - h

$$\begin{bmatrix} Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 \\ Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 \\ Ct & Ct & Ct & Ct & Ct & Ct & Ct & Ct & Ct \\ C & C & C & C & C & C & C & C & C \\ t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 \\ t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 \\ t & t & t & t & t & t & t & t & t \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \\ Ct^3 & Ct^2 & Ct & C & t^3 & t^2 & t & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \end{bmatrix} = \begin{bmatrix} Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 & Ct^3 \\ Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 & Ct^2 \\ Ct & Ct & Ct & Ct & Ct & Ct & Ct & Ct & Ct \\ C & C & C & C & C & C & C & C & C \\ t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 & t^3 \\ t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 & t^2 \\ t & t & t & t & t & t & t & t & t \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V \\ V \\ V \\ V \\ V \\ V \\ V \\ V \\ V \end{bmatrix}$$

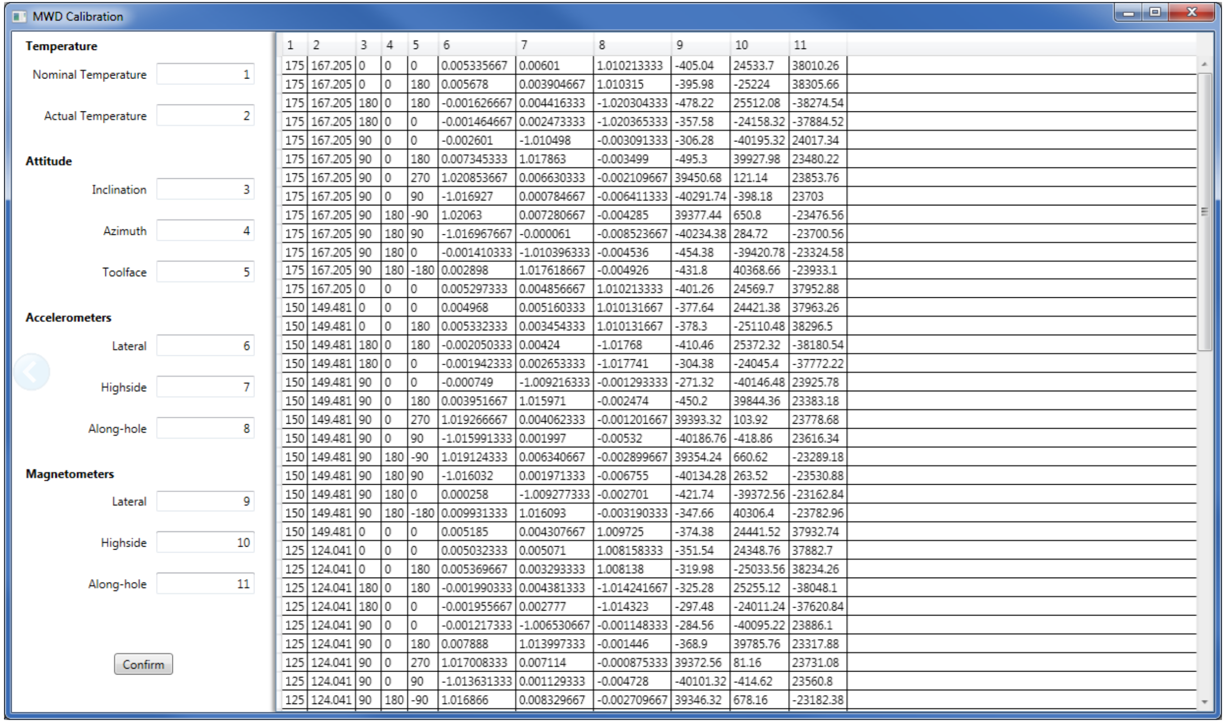
This reduces to the fully subscribed simultaneous equations matrices below

$$\begin{bmatrix} \Sigma C^2t^6 & \Sigma C^2t^5 & \Sigma C^2t^4 & \Sigma C^2t^3 & \Sigma Ct^6 & \Sigma Ct^5 & \Sigma Ct^4 & \Sigma Ct^3 \\ \Sigma C^2t^5 & \Sigma C^2t^4 & \Sigma C^2t^3 & \Sigma C^2t^2 & \Sigma Ct^5 & \Sigma Ct^4 & \Sigma Ct^3 & \Sigma Ct^2 \\ \Sigma C^2t^4 & \Sigma C^2t^3 & \Sigma C^2t^2 & \Sigma C^2t & \Sigma Ct^4 & \Sigma Ct^3 & \Sigma Ct^2 & \Sigma Ct \\ \Sigma C^2t^3 & \Sigma C^2t^2 & \Sigma C^2t & \Sigma C^2 & \Sigma Ct^3 & \Sigma Ct^2 & \Sigma Ct & \Sigma C \\ \Sigma Ct^6 & \Sigma Ct^5 & \Sigma Ct^4 & \Sigma Ct^3 & \Sigma t^6 & \Sigma t^5 & \Sigma t^4 & \Sigma t^3 \\ \Sigma Ct^5 & \Sigma Ct^4 & \Sigma Ct^3 & \Sigma Ct^2 & \Sigma t^5 & \Sigma t^4 & \Sigma t^3 & \Sigma t^2 \\ \Sigma Ct^4 & \Sigma Ct^3 & \Sigma Ct^2 & \Sigma Ct & \Sigma t^4 & \Sigma t^3 & \Sigma t^2 & \Sigma t \\ \Sigma Ct^3 & \Sigma Ct^2 & \Sigma Ct & \Sigma C & \Sigma t^3 & \Sigma t^2 & \Sigma t & \Sigma 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \\ h \end{bmatrix} = \begin{bmatrix} \Sigma VCt^3 \\ \Sigma VCt^2 \\ \Sigma VCt \\ \Sigma VC \\ \Sigma Vt^3 \\ \Sigma Vt^2 \\ \Sigma Vt \\ \Sigma V \end{bmatrix}$$

‘Nominal’ Sensor Orientations Loaded from File



Measurements Pasted from Excel



1	2	3	4	5	6	7	8	9	10	11
175	167.205	0	0	0	0.005335667	0.00601	1.010213333	-405.04	24533.7	38010.26
175	167.205	0	0	180	0.005678	0.003904667	1.010315	-395.98	-25224	38305.66
175	167.205	180	0	180	-0.001626667	0.004416333	-1.020304333	-478.22	25512.08	-38274.54
175	167.205	180	0	0	-0.001464667	0.002473333	-1.020365333	-357.58	-24158.32	-37884.52
175	167.205	90	0	0	-0.002601	-1.010498	-0.003091333	-306.28	-40195.32	24017.34
175	167.205	90	0	180	0.007345333	1.017863	-0.003499	-495.3	39927.98	23480.22
175	167.205	90	0	270	1.020853667	0.006630333	-0.002109667	39450.68	121.14	23853.76
175	167.205	90	0	90	-1.016927	0.000784667	-0.006411333	-40291.74	-398.18	23703
175	167.205	90	180	-90	1.02063	0.007280667	-0.004285	39377.44	650.8	-23476.56
175	167.205	90	180	90	-1.016967667	-0.000061	-0.008523667	-40234.38	284.72	-23700.56
175	167.205	90	180	0	-0.001410333	-1.010396333	-0.004536	-454.38	-39420.78	-23324.58
175	167.205	90	180	-180	0.002898	1.017618667	-0.004926	-431.8	40368.66	-23933.1
175	167.205	0	0	0	0.005297333	0.004856667	1.010213333	-401.26	24569.7	37952.88
150	149.481	0	0	0	0.004968	0.005160333	1.010131667	-377.64	24421.38	37963.26
150	149.481	0	0	180	0.005332333	0.003454333	1.010131667	-378.3	-25110.48	38296.5
150	149.481	180	0	180	-0.002050333	0.00424	-1.01768	-410.46	25372.32	-38180.54
150	149.481	180	0	0	-0.001942333	0.002653333	-1.017741	-304.38	-24045.4	-37772.22
150	149.481	90	0	0	-0.000749	-1.009216333	-0.001293333	-271.32	-40146.48	23925.78
150	149.481	90	0	180	0.003951667	1.015971	-0.002474	-450.2	39844.36	23383.18
150	149.481	90	0	270	1.019266667	0.004062333	-0.001201667	39393.32	103.92	23778.68
150	149.481	90	0	90	-1.015991333	0.001997	-0.00532	-40186.76	-418.86	23616.34
150	149.481	90	180	-90	1.019124333	0.006340667	-0.002899667	39354.24	660.62	-23289.18
150	149.481	90	180	90	-1.016032	0.001971333	-0.006755	-40134.28	263.52	-23530.88
150	149.481	90	180	0	0.000258	-1.009277333	-0.002701	-421.74	-39372.56	-23162.84
150	149.481	90	180	-180	0.009931333	1.016093	-0.003190333	-347.66	40306.4	-23782.96
150	149.481	0	0	0	0.005185	0.004307667	1.009725	-374.38	24441.52	37932.74
125	124.041	0	0	0	0.005032333	0.005071	1.008158333	-351.54	24348.76	37882.7
125	124.041	0	0	180	0.005369667	0.003293333	1.008138	-319.98	-25033.56	38234.26
125	124.041	180	0	180	-0.001990333	0.004381333	-1.014241667	-325.28	25255.12	-38048.1
125	124.041	180	0	0	-0.001955667	0.002777	-1.014323	-297.48	-24011.24	-37620.84
125	124.041	90	0	0	-0.001217333	-1.006530667	-0.001148333	-284.56	-40095.22	23886.1
125	124.041	90	0	180	0.007888	1.013997333	-0.001446	-368.9	39785.76	23317.88
125	124.041	90	0	270	1.017008333	0.007114	-0.000875333	39372.56	81.16	23731.08
125	124.041	90	0	90	-1.013631333	0.001129333	-0.004728	-40101.32	-414.62	23560.8
125	124.041	90	180	-90	1.016866	0.008329667	-0.002709667	39346.32	678.16	-23182.38

Calibration of Accelerometers

MWD Calibration

Sensor: (•) Accelerometer ( ) Magnetometer — Lateral

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (G)	∑Error²
175.0	-0.1980	0.2004	1.0189	0.00180	1.069e-5
150.0	-0.1955	0.2023	1.0176	0.00211	2.608e-5
125.0	-0.1993	0.2116	1.0153	0.00188	7.356e-6
100.0	-0.1916	0.2429	1.0134	0.00242	2.953e-5
75.0	-0.2004	0.2169	1.0112	0.00141	9.938e-6
25.0	-0.1986	0.2416	1.0069	0.00039	5.813e-6

MWD Calibration

Sensor: (•) Accelerometer ( ) Magnetometer — Highside

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (G)	∑Error²
175.0	-0.0458	-0.1862	1.0141	0.00383	5.416e-6
150.0	-0.0266	-0.0910	1.0126	0.00367	5.713e-6
125.0	-0.0228	-0.2006	1.0103	0.00398	4.741e-6
100.0	-0.0059	-0.1738	1.0083	0.00406	2.875e-5
75.0	-0.0191	-0.1119	1.0059	0.00375	1.644e-5
25.0	-0.0084	-0.1774	1.0016	0.00430	3.082e-6

MWD Calibration

Sensor: (•) Accelerometer ( ) Magnetometer — Along-hole

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (G)	∑Error²
175.0	-0.1210	84.7656	1.0153	-0.00484	1.026e-5
150.0	-0.1151	78.1250	1.0138	-0.00344	1.005e-5
125.0	-0.1093	86.3281	1.0112	-0.00297	1.105e-5
100.0	0.1083	-84.3750	1.0090	-0.00305	9.337e-6
75.0	-0.1059	87.8906	1.0067	-0.00188	1.218e-5
25.0	0.1170	-83.5938	1.0026	-0.00125	7.766e-6

Calibration of Magnetometers

MWD Calibration

Sensor

○ Accelerometer ◉ Magnetometer

Lateral

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (nT)	∑Error²
175.0	-0.0248	-0.0608	0.9843	-416.56	21,493.52
150.0	0.0002	-0.0414	0.9825	-376.33	25,085.79
125.0	0.0109	-0.0189	0.9813	-337.42	9,634.23
100.0	0.0109	-0.0225	0.9792	-311.64	10,667.36
75.0	0.0205	0.0080	0.9767	-304.06	9,098.35
25.0	0.0208	-0.0327	0.9714	-371.56	7,447.55

MWD Calibration

Sensor

○ Accelerometer ◉ Magnetometer

Highside

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (nT)	∑Error²
175.0	0.6195	-0.3141	0.9978	206.41	2,110,326.33
150.0	0.6310	-0.3272	0.9952	192.42	1,701,101.29
125.0	0.6109	-0.3527	0.9934	170.08	1,477,662.65
100.0	0.5773	-0.3488	0.9912	155.39	1,434,060.69
75.0	0.6026	-0.3489	0.9884	170.94	1,401,386.94
25.0	0.6142	-0.4491	0.9816	219.84	1,434,734.22

MWD Calibration

Sensor

○ Accelerometer ◉ Magnetometer

Along-hole

Temperature (°C)	w (°)	t (°)	Scale Factor	Bias (nT)	∑Error²
175.0	-0.5101	15.6250	0.9530	27.58	2,964,728.44
150.0	-0.5202	16.4063	0.9500	71.56	2,306,300.86
125.0	-0.5349	16.7969	0.9473	103.13	2,194,799.31
100.0	-0.5480	15.2344	0.9452	158.36	2,204,290.41
75.0	-0.5290	14.8438	0.9429	232.73	2,096,022.31
25.0	-0.4285	-8.5938	0.9386	388.05	2,111,754.01

Solve the simultaneous equations using all available data (inc. cold and hot tumbles)

For Each sensor

- W Alignment is then the actual Alignment from along hole corrected for temperature
- T Alignment is then the actual Alignment from Toolface corrected for temperature
- Scale is at^3 + bt^2 + ct +d
- Bias is et^3 + ft^2 + gt +e
- True observation = (observed – bias) /Scale

Use the T and W vectors to find the inclination, azimuth and toolface that best fit all the observed values by minimising the errors squared.

Finally:

Calculate the theoretical raw readings you would have seen had their been no scale, bias or misalignment from a true orthogonal set of sensors and pulse these to surface.

Advantages

- Much shorter calibration time
- Greater accuracy in the result
- Uses all available sensors in the angles calculation
- Same process regardless of number of sensors
- Same output (perfectly orthogonal raw data or inc azi tface)
- No change to field procedures