Low Angle Survey Errors

XCL , Random Misalignment & SAGE – ISCWSA Rev 5

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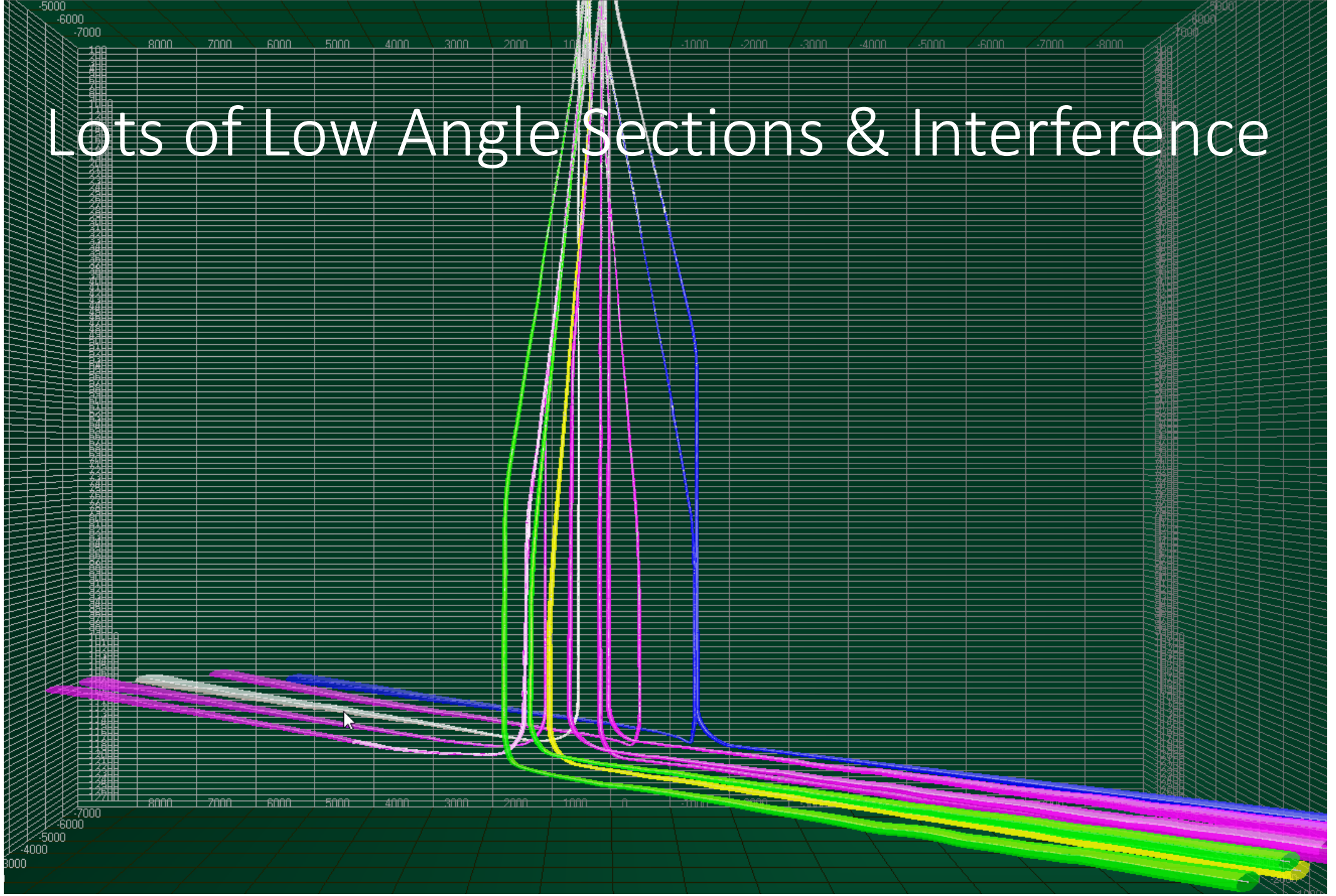
HALLIBURTON

Landmark Software & Services

49th General Meeting
March 8th, 2019
Den Haag, Netherlands

SPE International
Wellbore Positioning Technical Section

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


Lots of Low Angle Sections & Interference

Low Angle MWD Survey Errors

Planned for ISCWSA Rev 5

Table 1 – Highlighted changes to the error model. XYM3 & 4 are changes to the existing misalignment error terms. SAG is a change to the existing weighting function and XCLA and XCLH are new terms for course length effects.

Error Term	Mode	Value	Inclination	Azimuth
XYM1	Systematic	0.1	SinI	0
XYM2	Systematic	0.1	0	-1
XYM3	Random	0.3	CosI CosA	cosI sinA /sinI
XYM4	Random	0.3	CosI Sin A	cosI cosA /sinI
SAGE	Systematic	0.2	$SinI^{0.25}$	0
XCLA	*Random	0.167	0	$Max(abs(A_2-A_1), T (D_2-D_1)/SinI)$
XCLH	*Random	0.167	$Max(abs(I_2-I_1),T (D_2-D_1))$	0
XCLL**	*Random	0.167	0	$Max(abs(A_2-A_1)*SinI, T (D_2-D_1))$

*Position error for XCL terms at station k is only dependent on the station interval D_{k-1} to D_k, (uses tangential calculation – not balanced tangential like other angle error calculations).

** Alternate to XCLA used in compass for lateral error to avoid singularity at zero inclination.

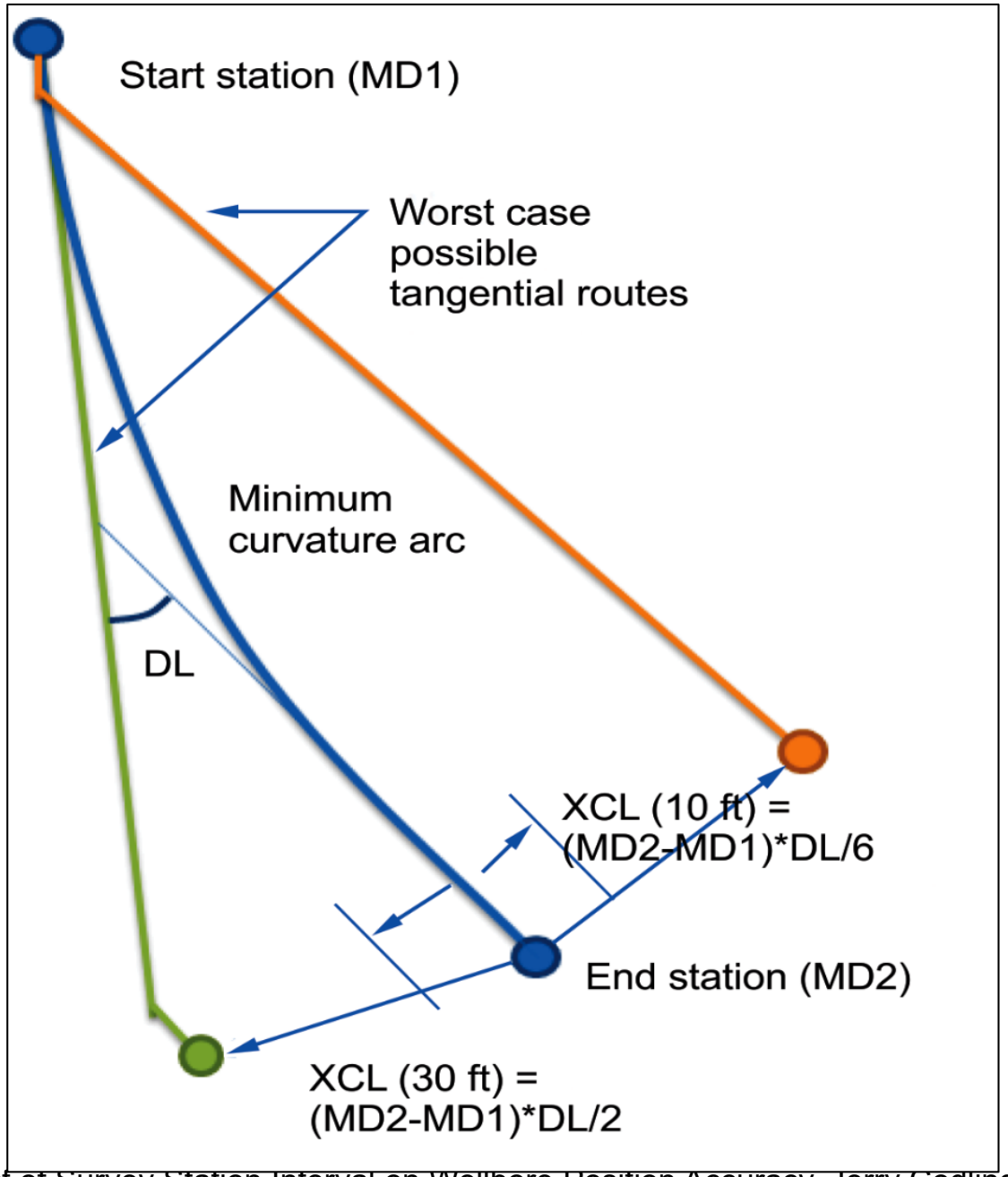
XCL Formulation
Worst Case: Slide Rotate

- Andy Brooks method
- Worst case instantaneous change

- Equivalent to 3 sigma (99.9%)
- Divide by 3… for 1 sigma
- **XCL = (MD2-MD1)*DL /6**

- DL = Angle change Inc /Azi

- Problem: what happens when DL=0? straight sections
- Tortuosity 1 deg/100 - average



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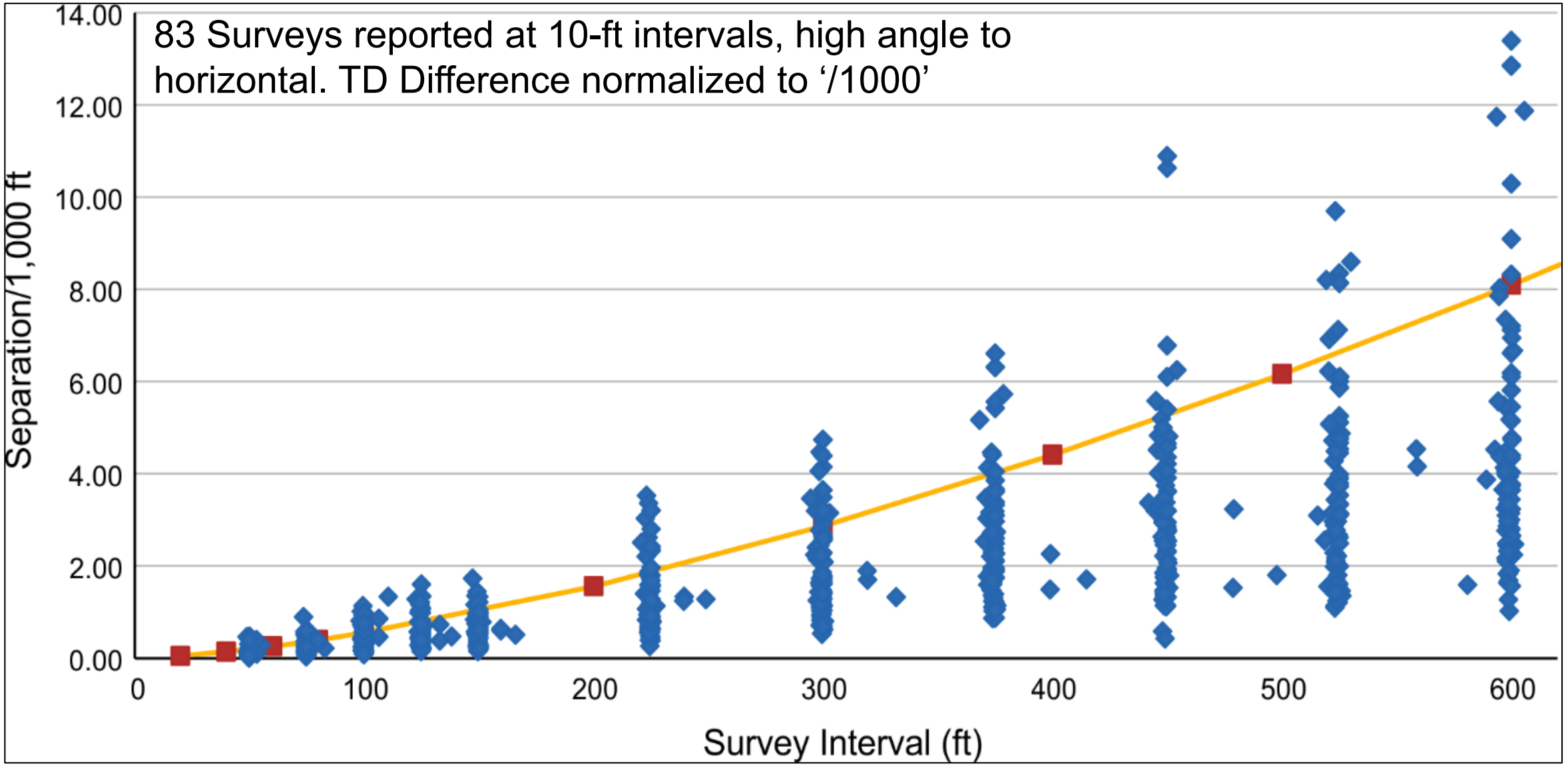
XCL Evidence: Open Hole Continuous Gyro Surveys in DP



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XCL Error Formulation

- It's a position error
- Not an angle error
- Split into Azimuth
- & Highside terms
- Error is 0.167 radians
- Tortuosity is 1°/100'

Highside error.

$$XCL_h \qquad e_{i,L,K} = \sigma_{xclh}(D - D_{k-1}) max\left(\text{abs}(I_k - I_{k-1}), \text{T}(D - D_{k-1})\right) \begin{bmatrix} \cos I_k \cos A_k \\ \cos I_k \sin A_k \\ -\sin I_k \end{bmatrix}$$

Azimuth error

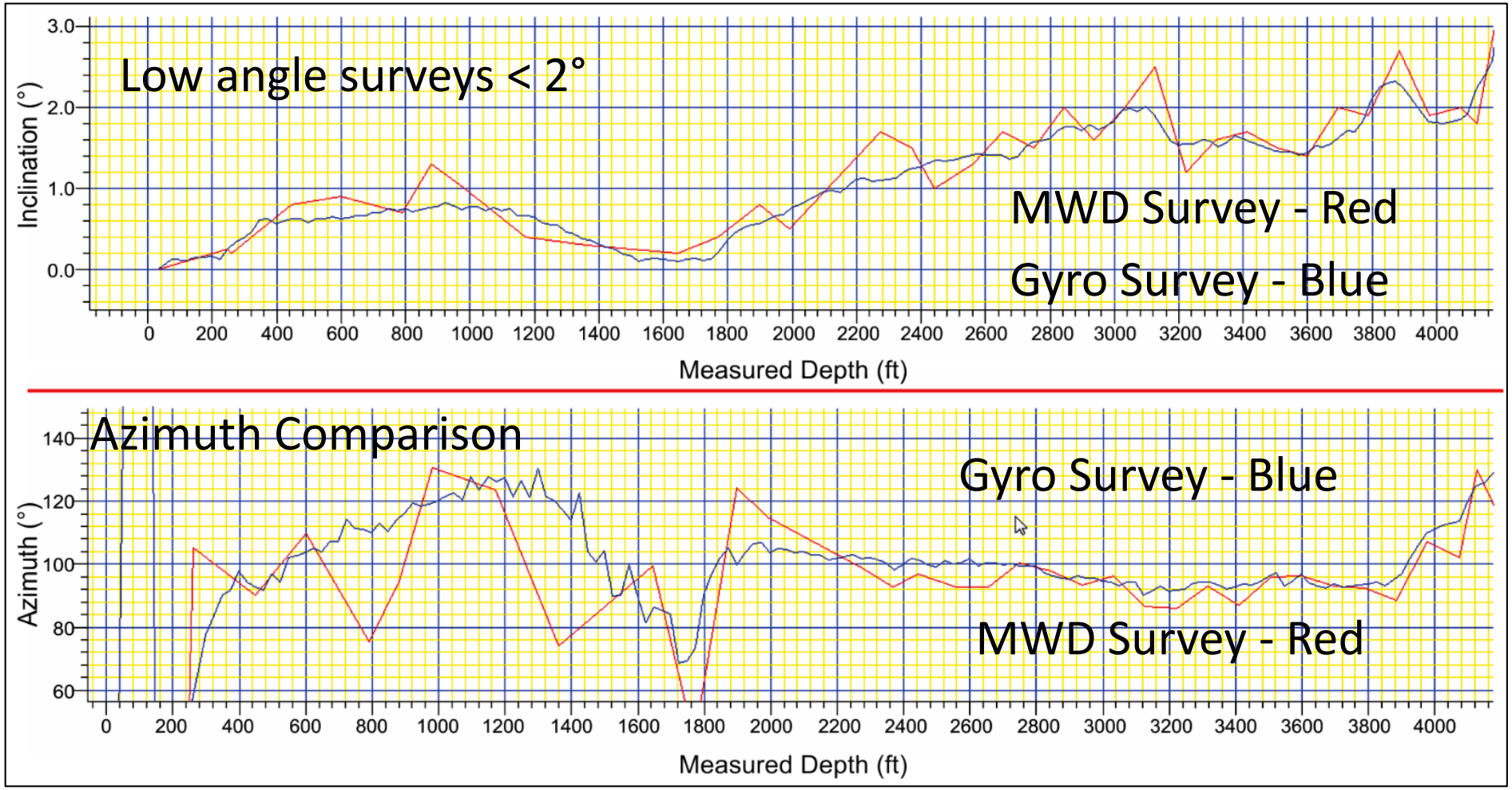
$$XCL_a \quad e_{i,L,K} = \sigma_{xcll}(D - D_{k-1})\, max(\text{abs}(A_k - A_{k-1}), \text{T}(D - D_{k-1})/\sin \text{I}_k) \begin{bmatrix} -\sin I_k \sin A_k \\ \sin I_k \cos A_k \\ 0 \end{bmatrix}$$

**Alternate lateral error (used in compass to avoid singularity)

$$XCL_l \quad e_{i,L,K} = \sigma_{xcll}(D - D_{k-1})\, max\left(\text{abs}(A_k - A_{k-1})\ \sin \text{I}_k, \text{T}(D - D_{k-1})\right) \begin{bmatrix} -\sin A_k \\ \cos A_k \\ 0 \end{bmatrix}$$

$e_{i,L,K}$ = Error at this station only (see SPE 67616, Appendix A-7)
D = Depth
I = Inclination (radians)
A = Azimuth (radians)
k = Index of current station
k-1 = index of previous station
σ_{xcll} = 0.167 (radians)
σ_{xclh} = 0.167(radians)
T = Tortuosity (radians/ft or m: 1deg/100' = 0.00018 if D is feet, or 0.0006 if D is metres)

Misalignment XYM Evidence
Survey Comparisons Gyro vs. MWD



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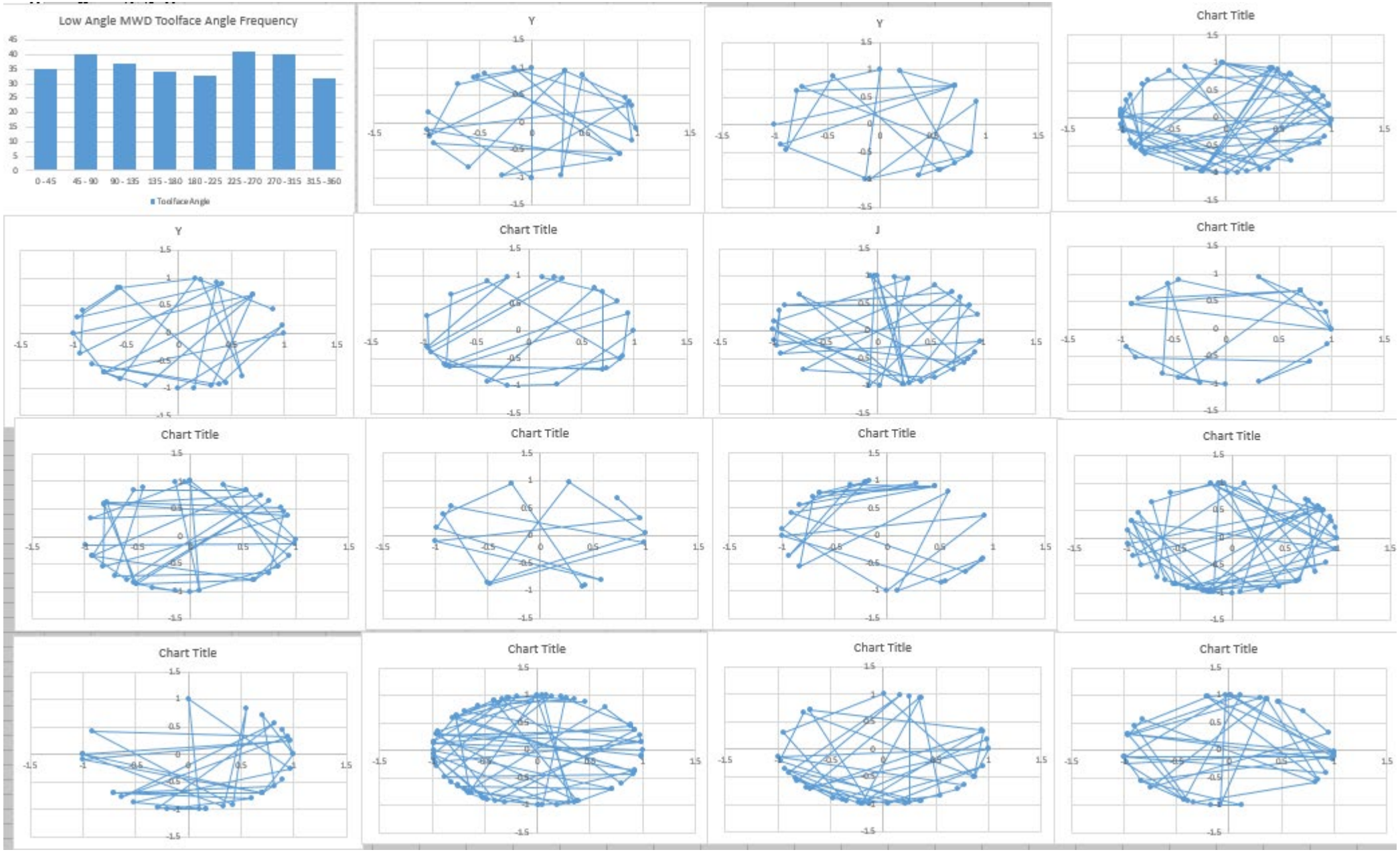
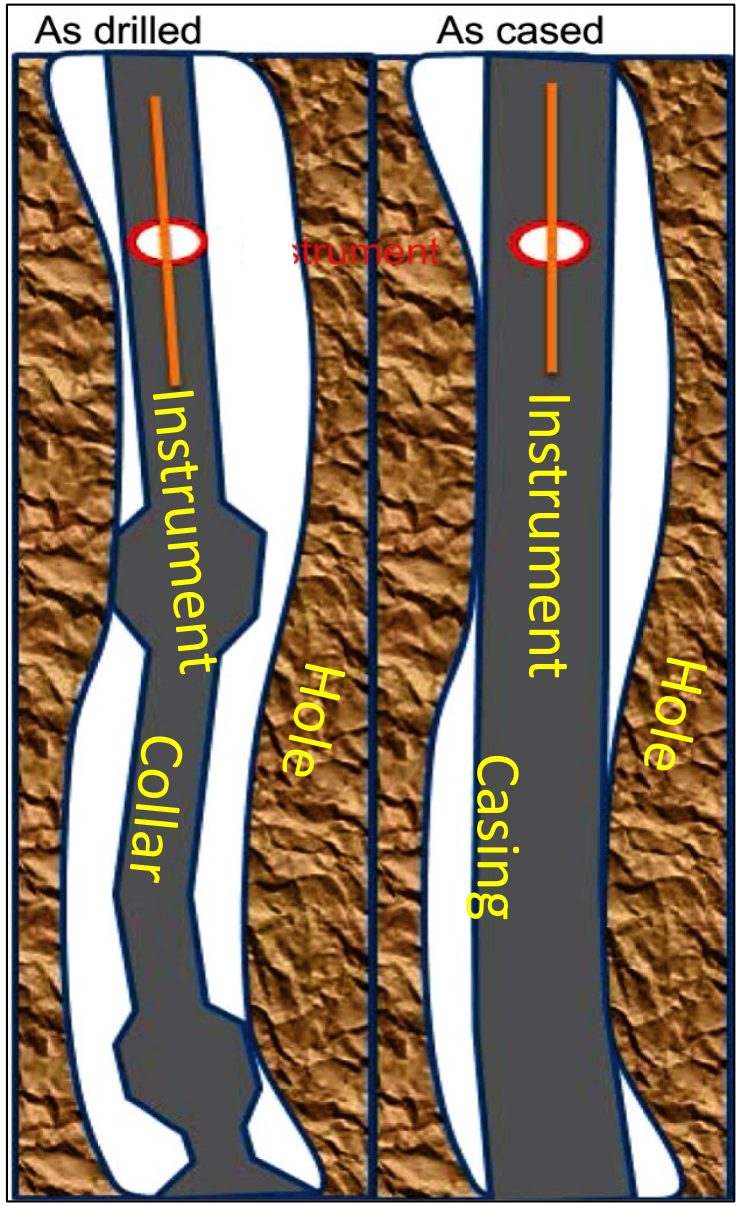
XYM MWD Toolface Scatter Plots – Random



XYM - Worst Case: Vertical Misalignment

- MWD – Collar to hole size over 40 ft.
- Gyro – Casing Connector to hole over 40 ft.
- Table of maximum angle from misalignment…

Type	Hole Size (in.)	Casing Size (in.)	Gauge Conn. (in.)	Collar Size (in.)	Casing Len. (ft.)	Angle Gyro (°)	Angle MWD (°)
Casing	26	20	21	9.5	40	0.60	0.98
Casing	23	18.625	19.625	9.5	40	0.40	0.81
Casing	17.5	13.375	14.375	9.5	40	0.37	0.48
Casing	16	13.375	14.375	9.5	40	0.19	0.39
Casing	12.25	9.625	10.625	8	40	0.19	0.25
Casing	8.5	7	7.677	6.5	40	0.10	0.12
Tubing	6	2.875	3.668	—	40	0.28	—
Tubing	8.5	3.5	4.5	—	40	0.48	—



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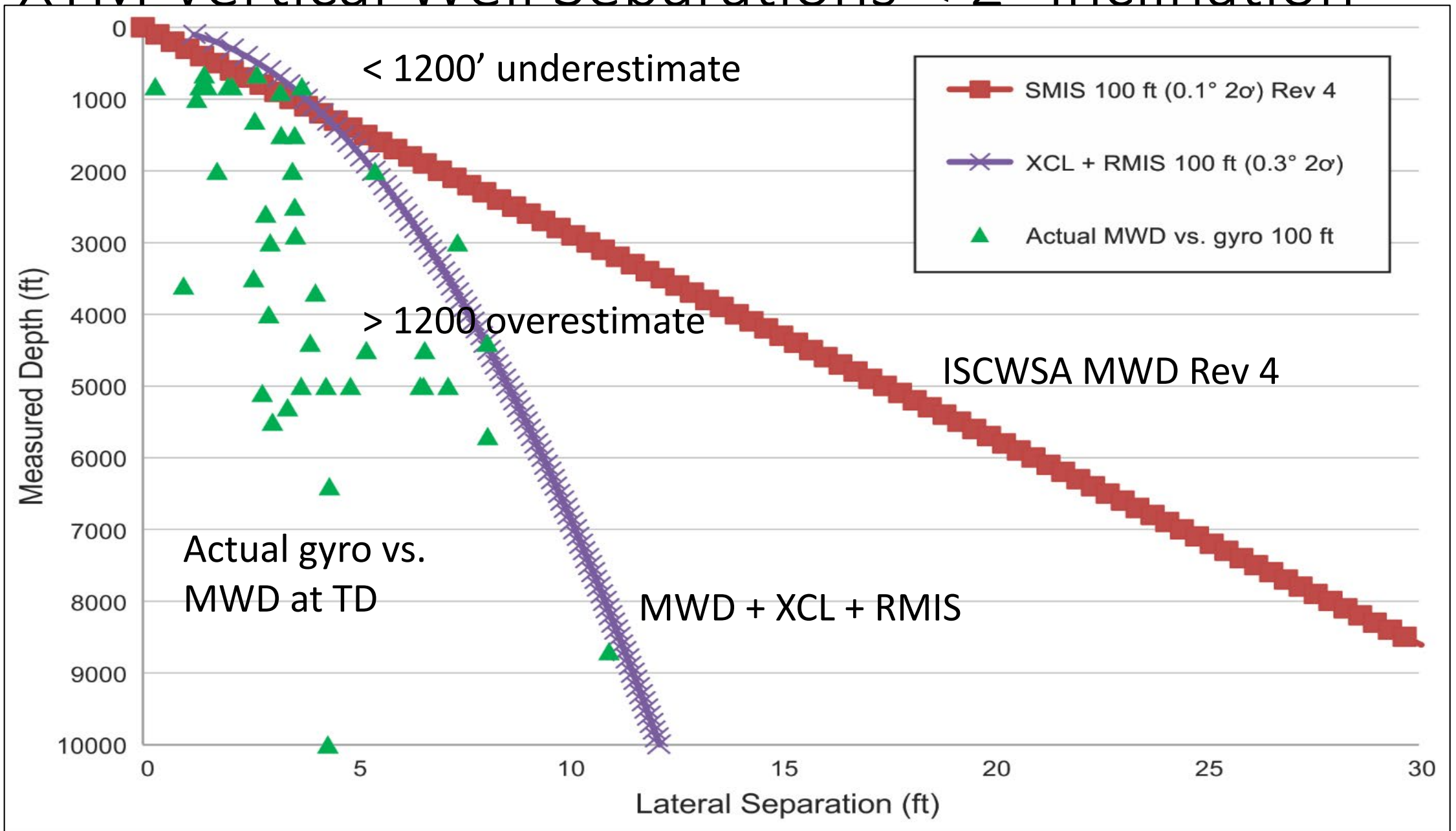
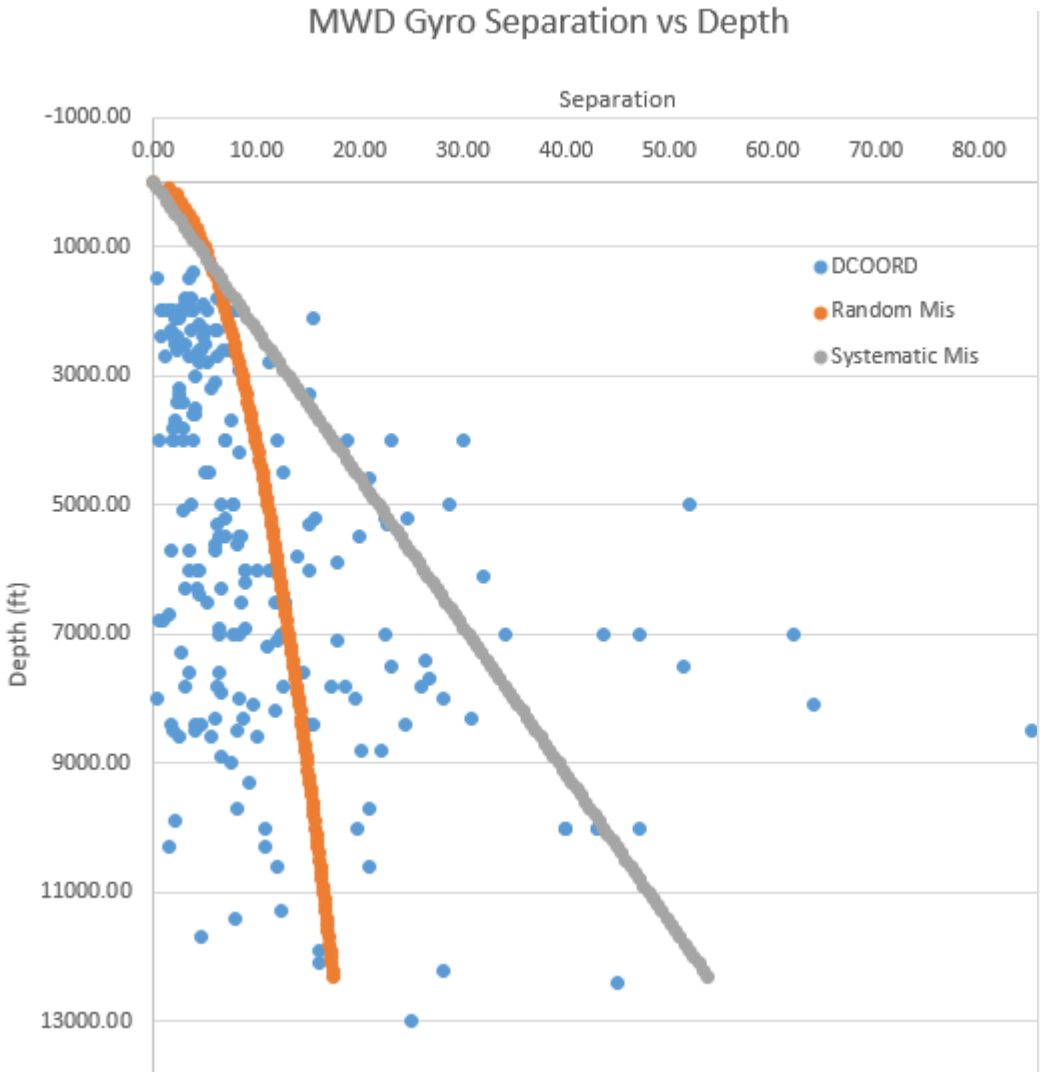
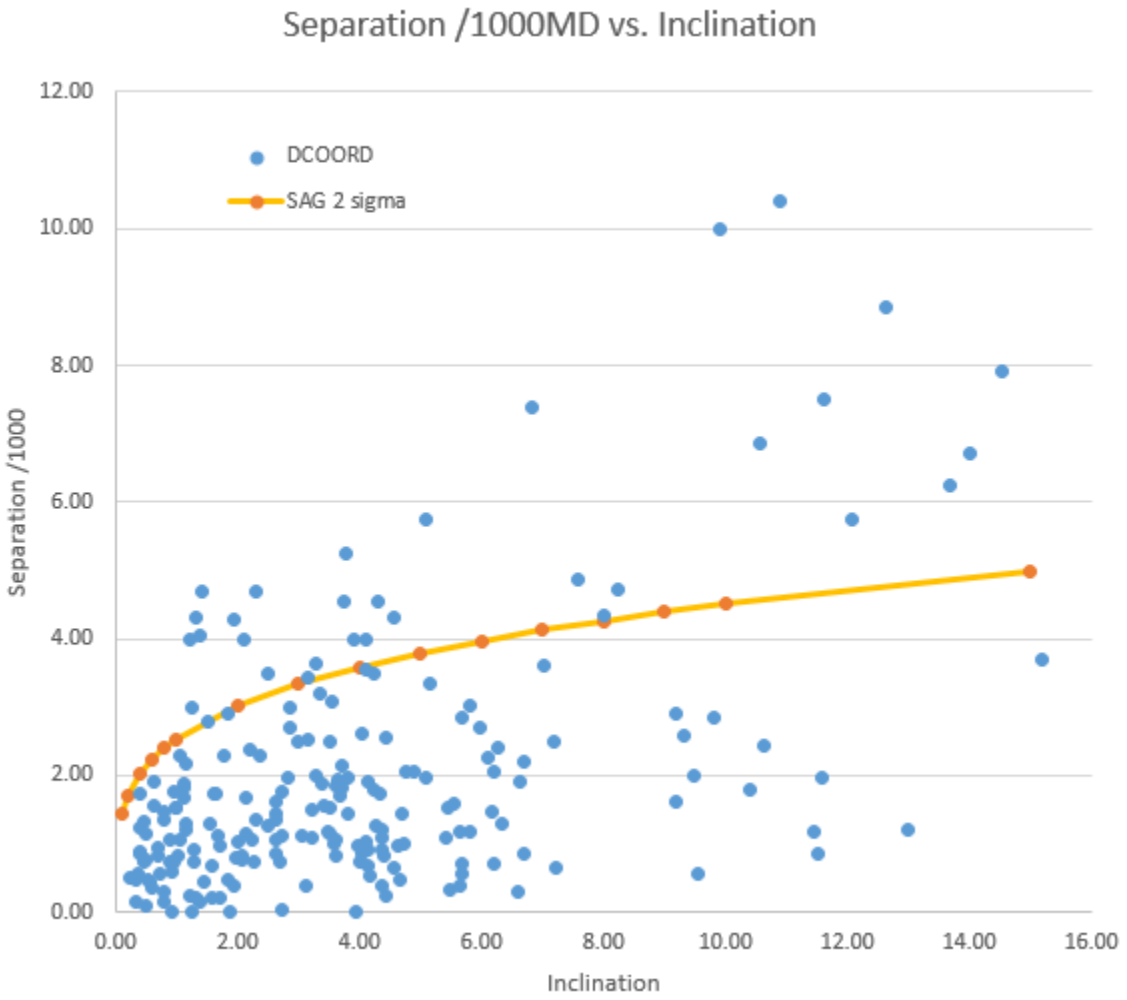
XYM Vertical Well Separations < 2° Inclination

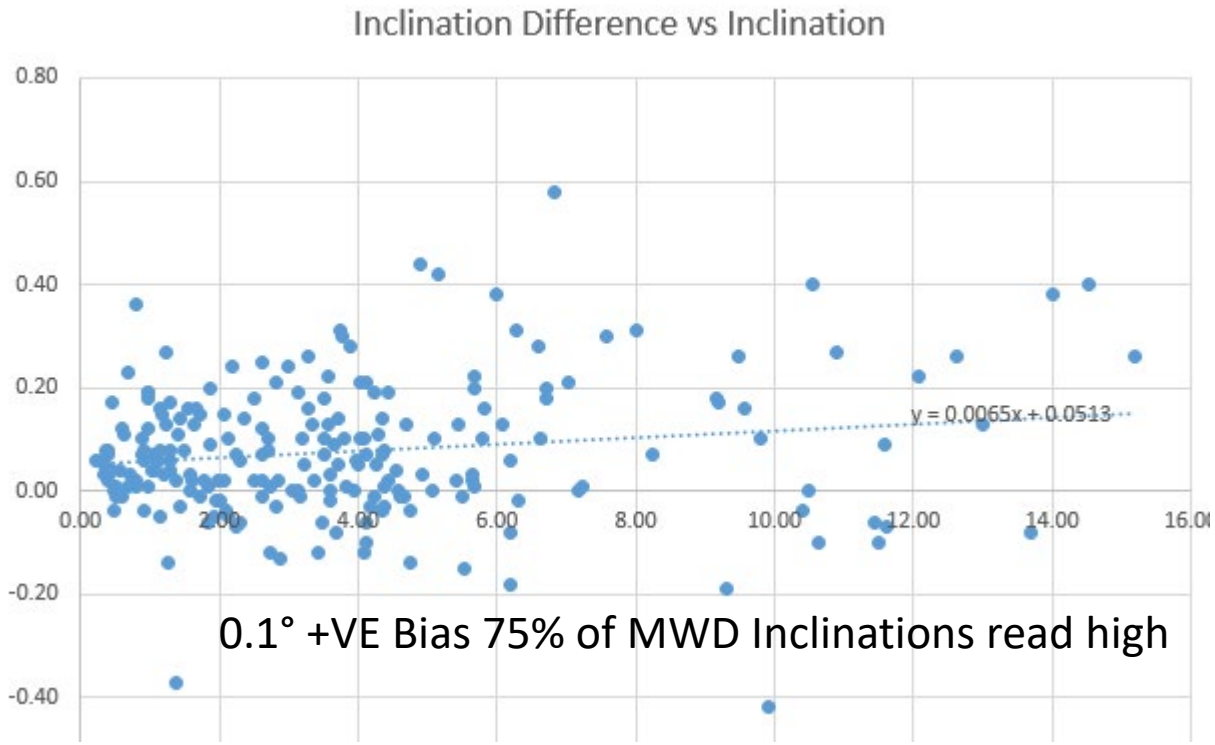


SAGE More Separation Data with Inclination up to 15°

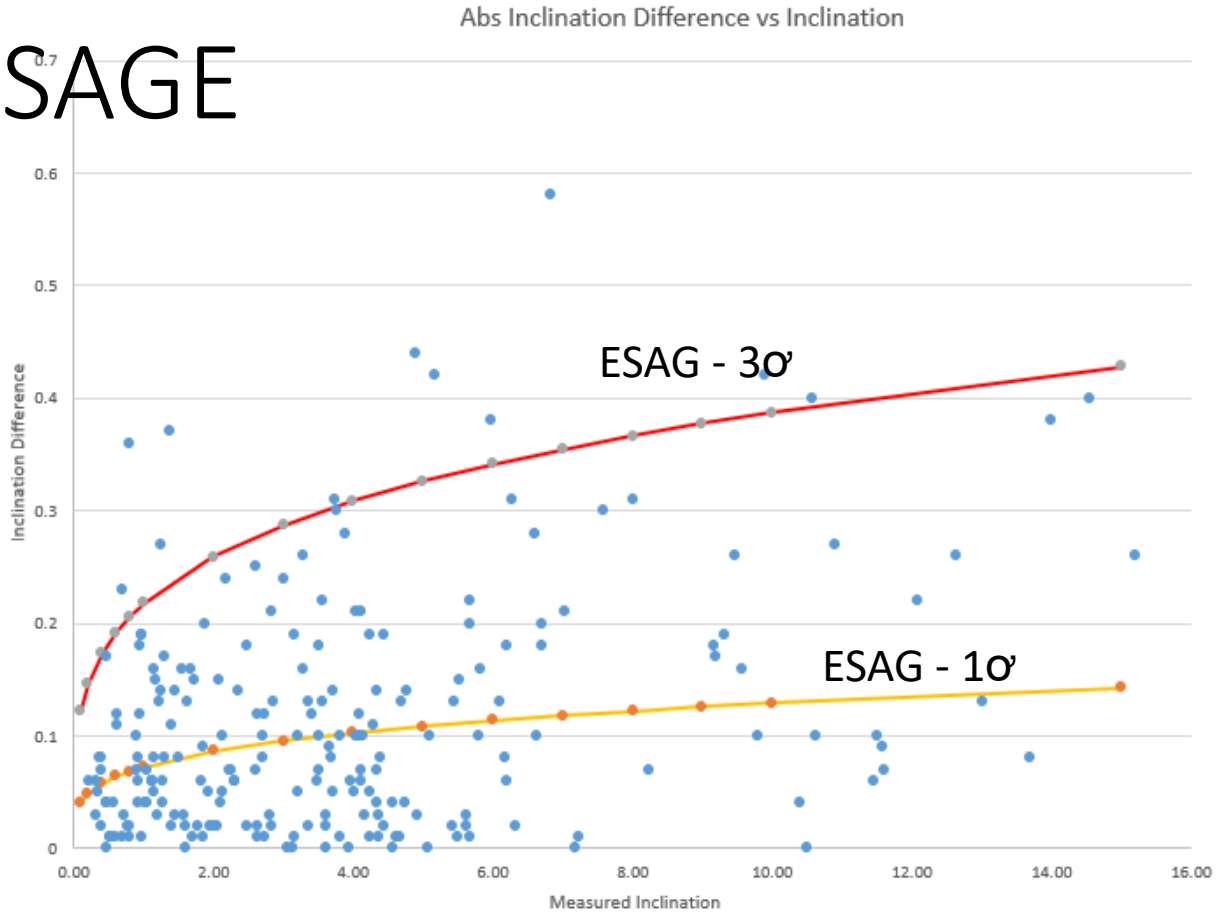


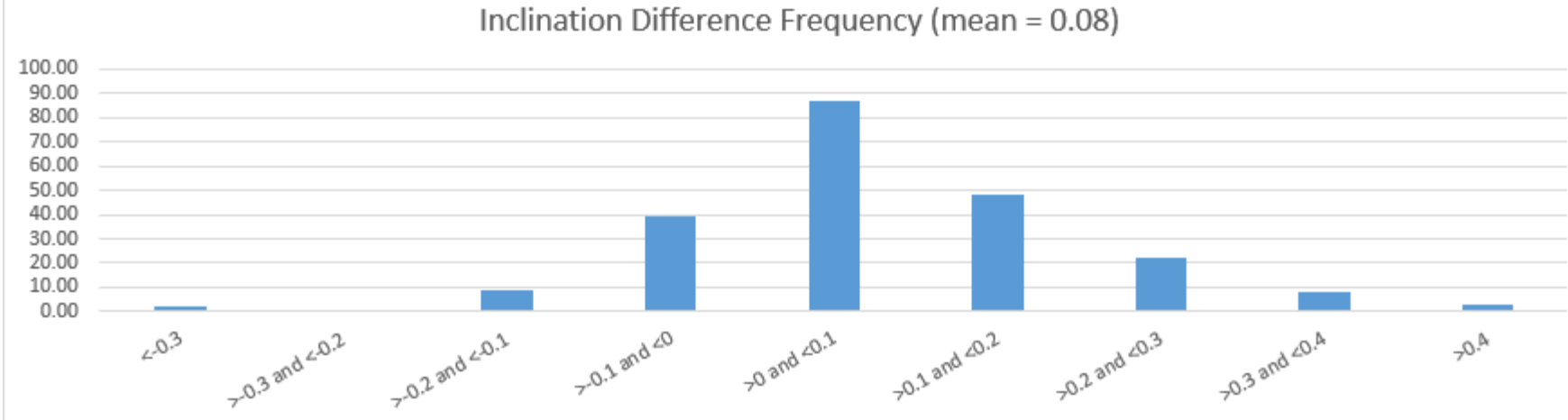


Inclination Differences – SAGE

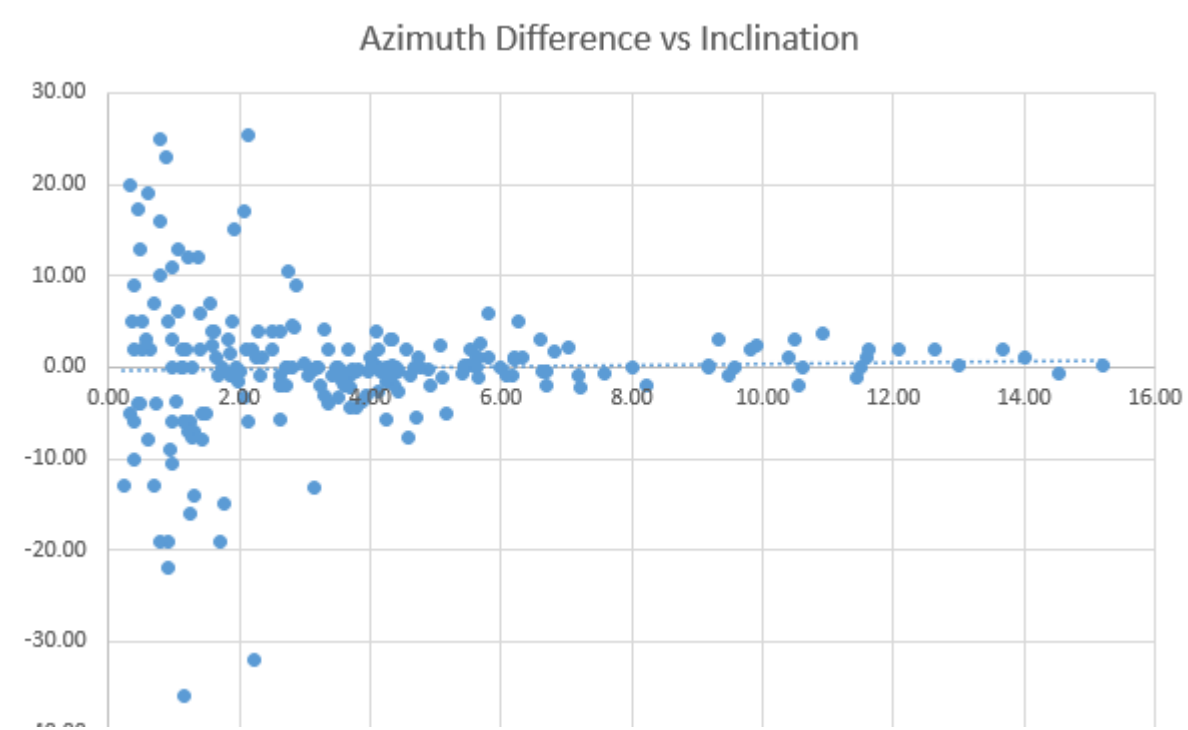


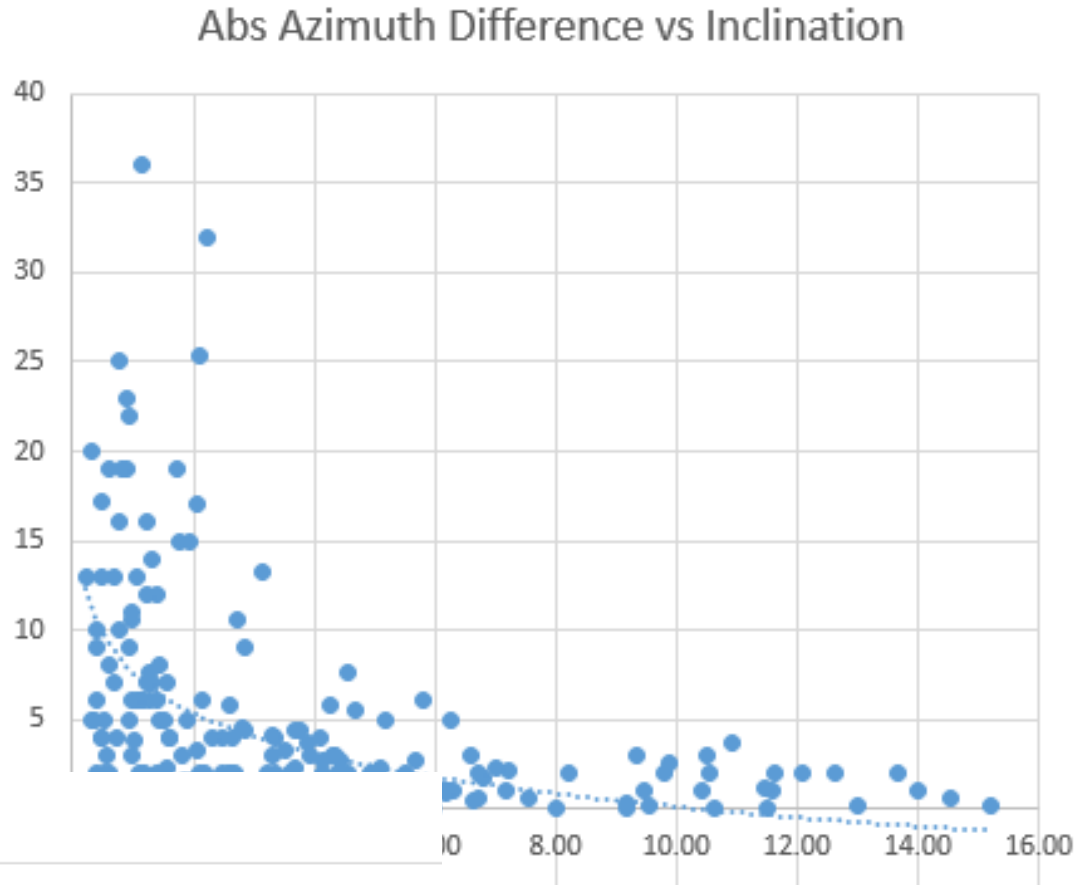
0.1° +VE Bias 75% of MWD Inclinations read high

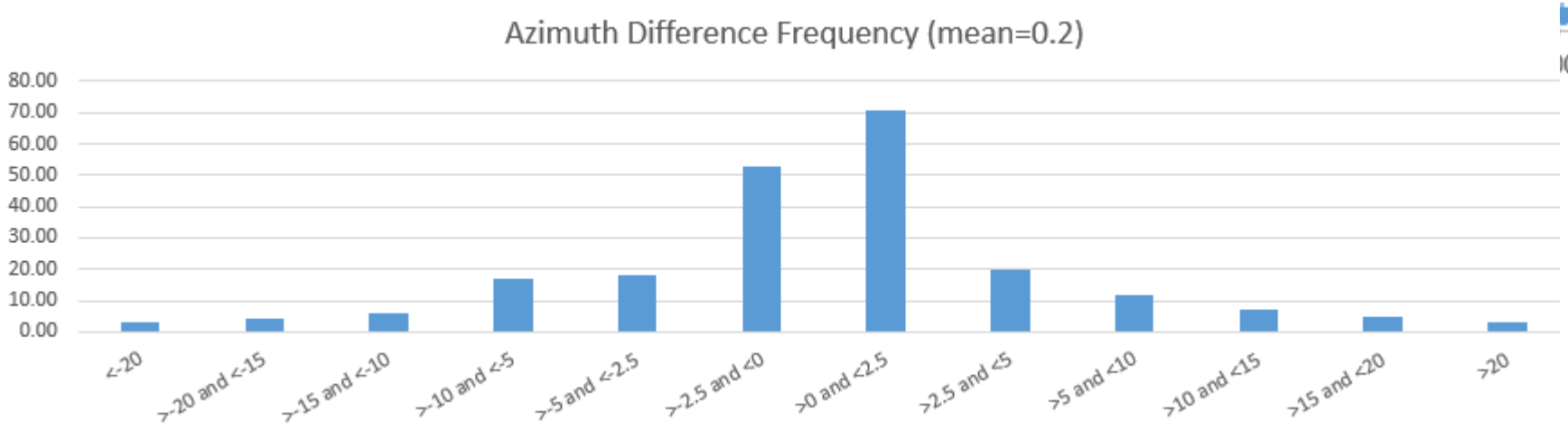




Azimuth Differences – XYM & Gross Errors

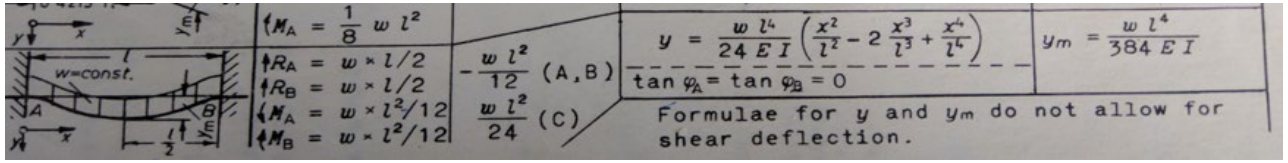






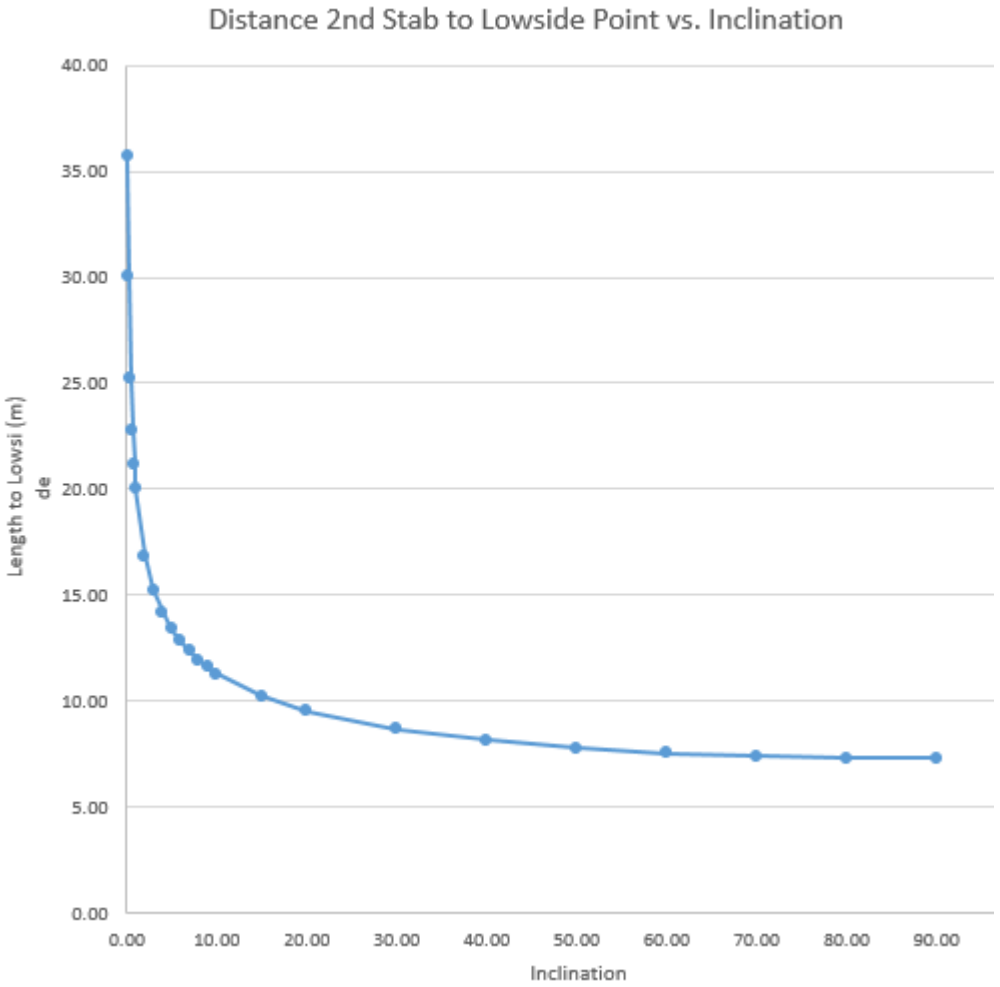
Low Angle SAGE Error

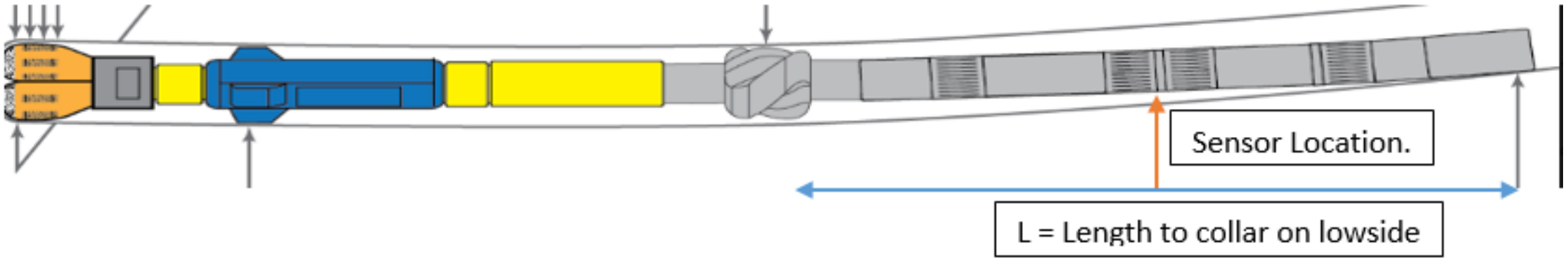
2 Stabilizer BHA, MWD above 2nd stab



$$Y_m = \frac{W \, \mathrm{Sin}(\mathrm{Inc}) L^4}{24 \, E \, I}$$

W = Weight per unit length of drill collar
Inc = Inclination
L = Length of collar from stabilizer to lowside point
E = Stiffness modulus (steel = 30×10^6psi)
I = Moment of Inertia. (=PI/64 * ($OD^4 - ID^4$)
Y_m = deflection to lowside = 0.5*(HoleOD-OD)



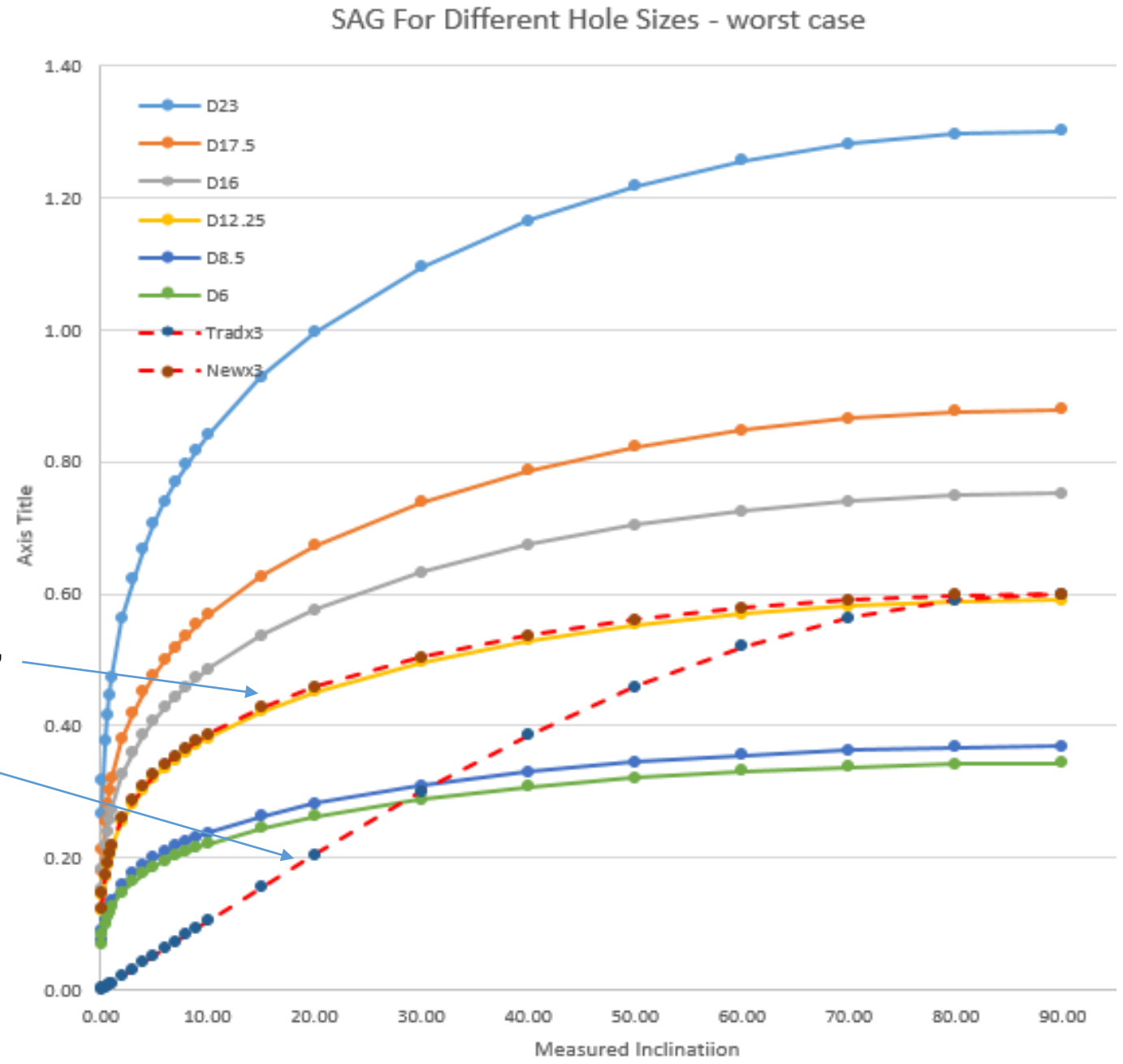


SAG – Worst Case

$$SAG\ (worst\ case) = 2Y_m \left(\frac{\mathrm{WSin(Inc)}}{Y_m 24\mathrm{EI}}\right)^{0.25}$$

New ESAG Weighting 3σ

Old SAG Weighting 3σ



Test Data
ISCWSA #1,#2,#3

XCL I&A
SAGE
XYM 3&4

Will add 300m & 1000’ for XCL

Test Data Well 1 – North Sea extended reach well. Results at 8000m for 1 sigma error for Highside, Lateral and Along Hole half-axis dimensions. Results for original ISCWSA Rev 5 are shown for 30m survey intervals.

	MWD – ISCWSA Rev 5			MWD NEW – 30M STATIONS			MWD NEW – 100M STATIONS		
TERM	HIGH	LAT	AH	HIGH30	LAT30	AH30	HIGH100	LAT100	AH100
XYM3	0.76	5.94	1.18	0.20	1.42	0.32	0.36	2.58	0.59
XYM4	2.85	1.59	4.40	0.74	0.38	1.20	1.35	0.69	2.20
SAGE	18.81	0.00	5.91	20.12	0.00	7.30	20.12	0.00	7.25
XCLI				1.48	0.54	0.95	9.10	3.30	5.65
XCLA				0.00	1.34	0.54	0.00	8.18	3.30
TOTAL	**21.64**	**95.65**	**10.57**	**22.66**	**95.48**	**10.59**	**24.40**	**95.92**	**12.51**

Test Data Well 2 - Gulf of Mexico – fish hook well. Results at 12500’ for 1 sigma error for Highside, Lateral and Along Hole half-axis dimensions. Results for original ISCWSA Rev 5 are shown for 100’ survey intervals.

	MWD – ISCWSA Rev 5			MWD NEW – 100’ STATIONS			MWD NEW – 300’ STATIONS		
TERM	HIGH	LAT	AH	HIGH30	LAT30	AH30	HIGH100	LAT100	AH100
XYM3	6.37	10.37	9.06	2.20	2.85	2.99	3.67	4.72	4.94
XYM4	5.11	12.84	8.21	1.62	3.53	2.61	2.71	5.86	4.30
SAGE	14.13	0.77	5.95	16.94	0.42	10.82	16.97	0.42	10.82
XCLI				2.86	2.04	2.55	14.18	9.87	12.58
XCLA				1.83	4.52	3.17	8.62	22.16	14.93
TOTAL	**19.12**	**31.67**	**16.52**	**20.12**	**27.84**	**15.41**	**26.15**	**37.17**	**25.11**

Test Data Well 3 – Bass Strait – designer well. Results at 4030m for 1 sigma error for Highside, Lateral and Along Hole half-axis dimensions. Results for original ISCWSA Rev 5 are shown for 30m survey intervals.

	MWD – ISCWSA Rev 5			MWD NEW – 30M STATIONS			MWD NEW – 100M STATIONS		
TERM	HIGH	LAT	AH	HIGH30	LAT30	AH30	HIGH100	LAT100	AH100
XYM3	2.37	1.00	3.30	0.81	0.29	1.05	1.49	0.52	1.90
XYM4	0.13	4.58	0.97	0.14	1.32	0.29	0.28	2.39	0.53
SAGE	6.57	0.67	0.86	8.09	1.18	2.14	8.05	1.10	2.06
XCLI				1.17	0.51	1.01	15.18	5.32	7.71
XCLA				0.24	1.06	0.67	2.93	11.84	8.05
TOTAL	**8.73**	**8.87**	**10.53**	**9.74**	**7.80**	**10.27**	**18.26**	**15.26**	**15.17**

That’s all..

Thanks & questions..

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Mag Field Errors – BGS

Using bggm code bggmerr_calc function included in bggm.c & h

D_Error is minutes at 1 sigma

H_Error is nT at 1 sigma

```
// get error values
DATE_STRUCT ds = DecimalDateHelpers::DecimalDateToDateStruct(options.date);
double err_d(0), err_s(0), err_h(0);
char error_msg[1048], filename[1048];
CString csModel = Compass::Install::GetConfigPath();
csModel += L"\\Geomagnetic Models\\err";
csModel += m_csModel;
csModel += L".dat";
if ( Compass::Path::FileExists(csModel) )
{
    strcpy(filename, CStringA(csModel).GetBuffer());
    int errmsg_max_len = 1048;
    if ( BGGM_SUCCESS == bggmerr_calc (filename, options.lat, options.lon,
                options.depth, ds.day, ds.month, ds.year,
                &err_d, &err_s, &err_h, error_msg, errmsg_max_len))
    {

    }
}
```

) › Landmark › EDT › COMPASS › Config › Geomagnetic Models

Name

- BGGM
- HDGM
- bggm2018.dat
- errbggm2018.dat
- example_output.txt
- hdgm_2014.exe
- hdgm_2018.exe
- hdgm_2019.exe
- hdgm_file.exe
- HDGM_file_sample_coords.txt
- IGRF90.GAM
- IGRF95.GAM
- igrf2000.gam
- igrf2005.dat
- IGRF2010.gam
- IGRF2015.gam
- igrf200510.gam
- WMM_95.GAM
- Wmm_2000.gam
- Wmm_2005.gam

errbggm2018.dat - Notepad

File Edit Format View Help

```
#---Scalable 1-sigma errors associat
#Update of work described in Macmill
#Confidence limits associated with values of the Earth's
#magnetic field used for directional drilling. SPE Drilling &
#Completion, 25 (2), 230-238, 10.2118/119851-PA. Any n
#comment lines here. Any number of time intervals and
#multiplicative factors. Grid resolution of 1 degree a
#+/- 85 deg lat is fixed.
1900.0 1990.0 1.05
1990.0 2018.5 0.99
2018.5 2020.0 1.00
#The grid spacing must be specified before the first g
# it is given as: GRID SPACING x y
# where x = distance between latitude points in degree
#       y = distance between longitude points in degre
GRID SPACING 1.0 1.0
#LAT LONG D(deg) I(deg)  F(nT)
 -85 -180   0.63   0.14  118
 -85 -179   0.63   0.14  118
 -85 -178   0.63   0.14  118
 -85 -177   0.63   0.14  118
 -85 -176   0.63   0.14  118
```

Magnetic Calculator

Input Location

Project Site Well User

Latitude: 56° 16' 35.328 N Longitude: 3° 23' 46.789 E ED50_NOR_S62

Input Model & Date

Magnetic Model: BGGM2018 Date: 06/03/2019

Vertical Depth: 0.0 ft below WELL @ 98.4ft (Original Well Elev)

Magnetic Field (nT) for Location + Error (output level)

Field Strength:	50200 nT	89.275	Horizontal:	16994 nT	North: 16992 nT
Dip Angle:	70.21°	0.11			East: 246 nT
Declination:	0.83°E	0.38	Mag North:	0.83° True	Vertical: 47236 nT

Mag Field Errors –HDGM

Using hdgm_file.exe with –e option
only works with 2017 and later versions
D_Error is minutes at 1 sigma
H_Error is nT at 1 sigma

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
	Date	MSL-Ellips	Depth	Latitude	Longitude	D_deg	D_min	I_deg	I_min	H_nT	X_nT	Y_nT	Z_nT	F_nT	dD_min	dI_mi	dH_nT	dX_n1	dY_n	dZ_r	dF_r	D_Error_min	I_Error_min	H_Error_nT	X_Error_n	Y_Error_n	Z_Error_n	F_Error_nT
49	1999.5	M	M0	0	120	1d	11m	-17d	19m	39321	39312.5	814.1	-12255.4	41186.6	-0.6	5.5	7.3	7.4	-6.3	67	-13							
50	2000	M	M0	80	0	-10d	10m	82d	54m	6736	6630.3	-1188.6	54022.7	54441.1	25.5	0.6	-5.4	3.5	50.2	40	39	41	10	155.2	153.4	82.9	107.5	106.6
51	2000.5	M	K3	0	120	1d	11m	-17d	15m	39366.9	39358.5	811.7	-12223.4	41220.9	0.5	3.2	-6.1	-6.2	5.6	42	-18	19	10	107.6	107.7	215	117	106.6
52	2001	M	M0	-80	-120	70d	16m	-73d	9m	16474.2	5560.2	15507.5	-54420.2	56859.1	-4.1	2.5	16.9	24.1	9.3	85	-77	23	10	158.8	117.4	154.1	112.4	106.6
53	2001.5	M	M5000	80	0	-9d	36m	82d	54m	6745.1	6650.8	-1124	54198.9	54617	24.9	0.6	-4.3	4	48.9	37	36	41	10	155.7	154.1	82.6	107.5	106.6
54	2002	M	M5000	0	120	1d	11m	-17d	11m	39389.6	39381.2	813.5	-12177	41228.9	-0.3	3	-5.2	-5.2	-3.9	40	-17	19	10	107.6	107.7	215.2	117.1	106.6
55	2002.5	M	M5000	-80	-120	70d	0m	-73d	9m	16502.4	5643.7	15507.3	-54501.9	56945.5	-3.6	2.1	11.3	20.1	4.7	81	-74	23	10	159	117.7	154.2	112.4	106.6
56	2003	M	M0	80	0	-8d	55m	82d	55m	6722.7	6641.6	-1041.1	54142.9	54558.6	22.5	0.5	-4.5	2.4	44.2	29	28	41	10	155.5	154.1	82.2	107.5	106.6
57	2003.5	E	M0	0	120	1d	11m	-17d	5m	39314.7	39306.3	808.6	-12076.9	41127.8	-1	3.8	5.2	5.4	-11	46	-8.6	19	10	107.6	107.7	214.8	116.8	106.6
58	2004	E	K5	-80	-120	69d	54m	-73d	6m	16518.8	5675	15513.4	-54370.2	56824.2	-3.9	2.1	9.9	21	2.8	87	-80	23	10	158.7	117.8	153.8	112.4	106.6
															0.3	21.4	0.5	-4.1	2.1	42.1	27	26	41	10	156	154.7	81.9	107.5	106.6
															9.4	-1.5	4.4	-1.6	-1.3	-17	56	-18	19	10	107.6	107.7	215.2	117	106.6
															3.5	-4.1	2.1	9.5	21.7	2.1	88	-81	23	10	158.3	117.9	153.5	112.4	106.6
															37	21.7	0.5	-4.6	1.2	42.6	27	27	41	10	155.8	154.7	81.5	107.5	106.6

HDGM Console Program

The HDGM console program is designed to be run with command line arguments through a command terminal, and is typically accessed through well planning software, such as Landmark Compass.

The file executable is invoked via: `hdgm2019_file.exe` [options]

where the command line options are given by:

```
-f input_filename   : specify input filename
-F output_filename  : specify output filename
-e                  : include 1-sigma errors in output file
-v                  : print version information
-h                  : print help
```

Magnetic Calculator

Input Location

Project Site Well User

Latitude: 56° 16' 35.328 N Longitude: 3° 23' 46.789 E ED50_NOR_S62

Input Model & Date

Magnetic Model: HDGM_2019 Date: 06/03/2019

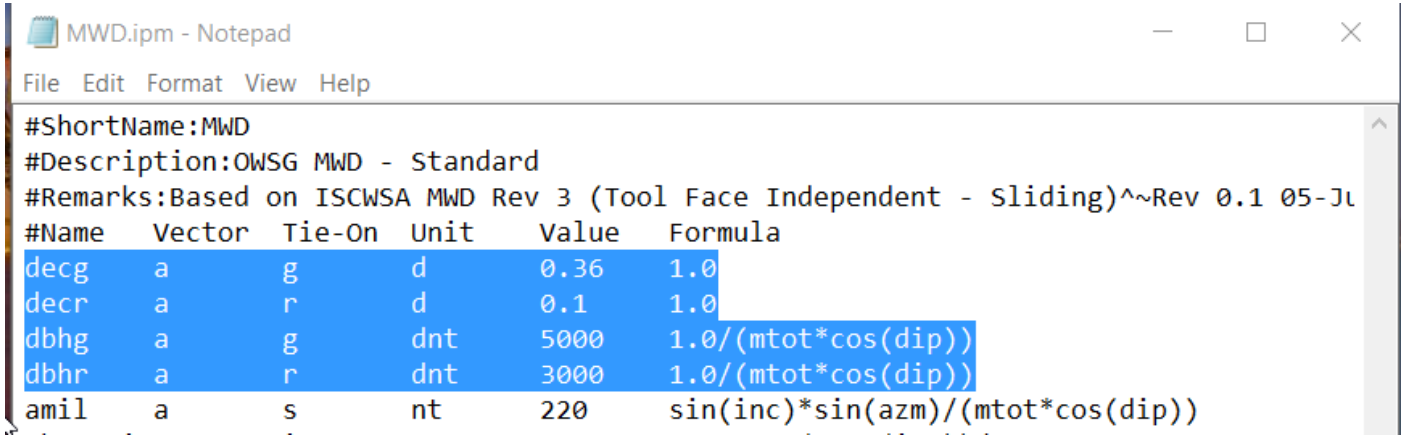
Vertical Depth: 0.0 ft below WELL @ 98.4ft (Original Well Elev)

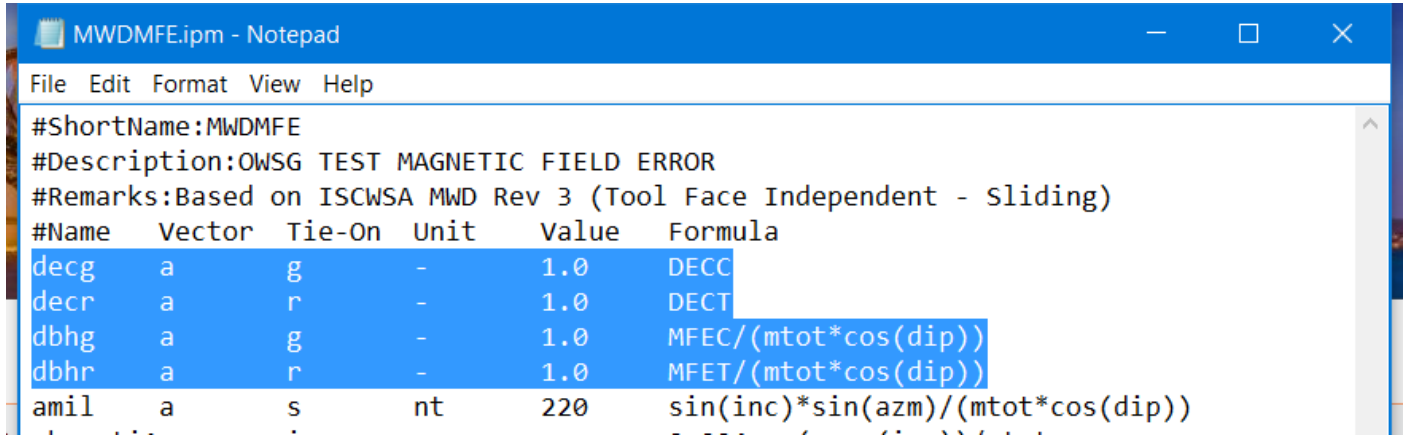
Magnetic Field (nT) for Location + Error (output level)

Field Strength:	50196 nT	139.90	Horizontal:	16976 nT	North: 16972 nT
Dip Angle:	70.23°	0.17			East: 220 nT
Declination:	0.75°E	0.38	Mag North:	0.75° True	Vertical: 47239 nT

KEYWORDS in formulas – using external values

DECC – Only this
DECT
MFEC
MFET

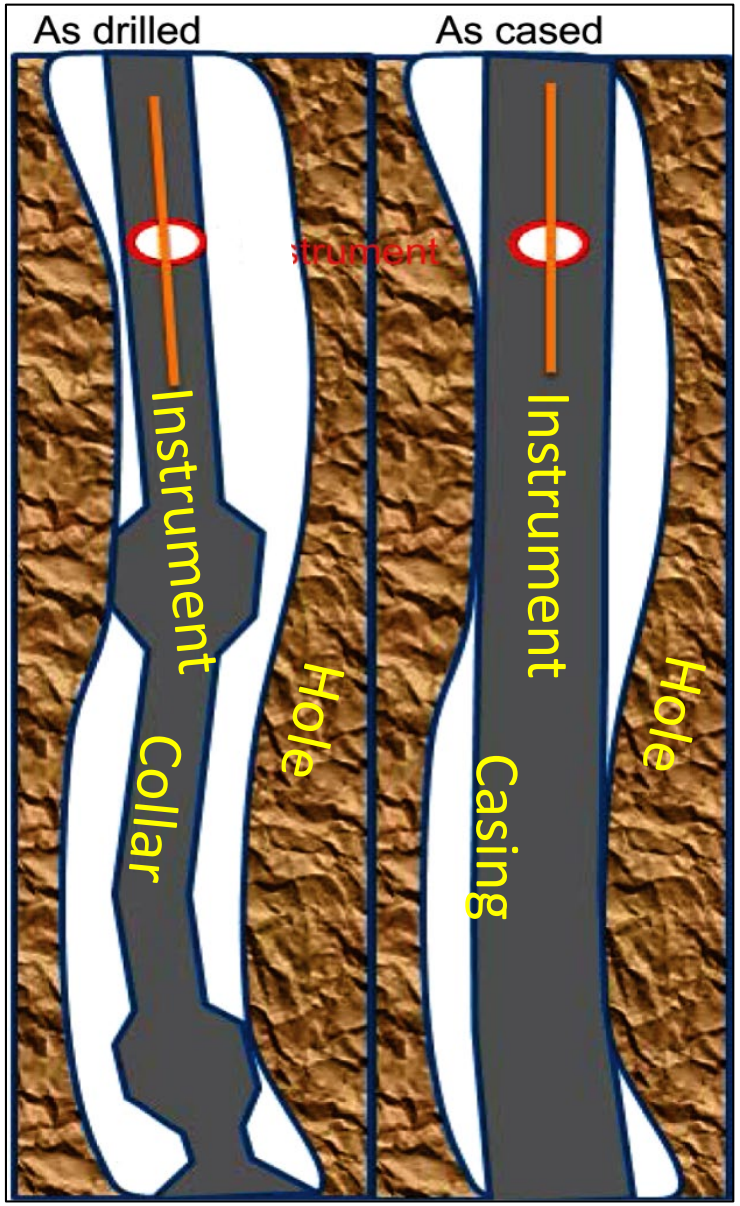




Worst Case: Vertical Misalignment

- MWD – Collar to hole size over 40 ft.
- Gyro – Casing Connector to hole over 40 ft.
- Table of maximum angle from misalignment…

Type	Hole Size (in.)	Casing Size (in.)	Gauge Conn. (in.)	Collar Size (in.)	Casing Len. (ft.)	Angle Gyro (°)	Angle MWD (°)
Casing	26	20	21	9.5	40	0.60	0.98
Casing	23	18.625	19.625	9.5	40	0.40	0.81
Casing	17.5	13.375	14.375	9.5	40	0.37	0.48
Casing	16	13.375	14.375	9.5	40	0.19	0.39
Casing	12.25	9.625	10.625	8	40	0.19	0.25
Casing	8.5	7	7.677	6.5	40	0.10	0.12
Tubing	6	2.875	3.668	—	40	0.28	—
Tubing	8.5	3.5	4.5	—	40	0.48	—



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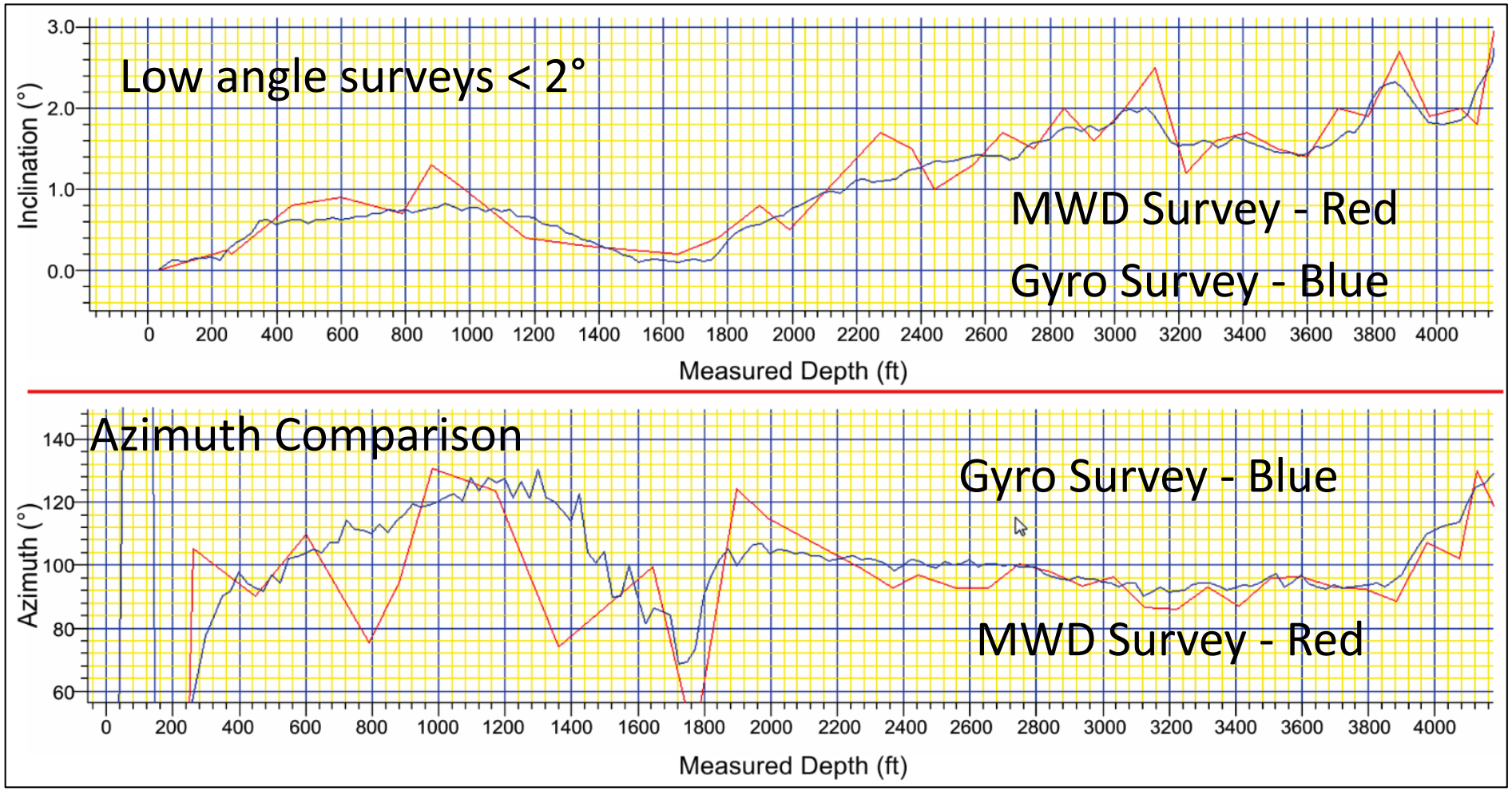
Evidence: Misalignment - Survey Comparisons Gyro vs. MWD



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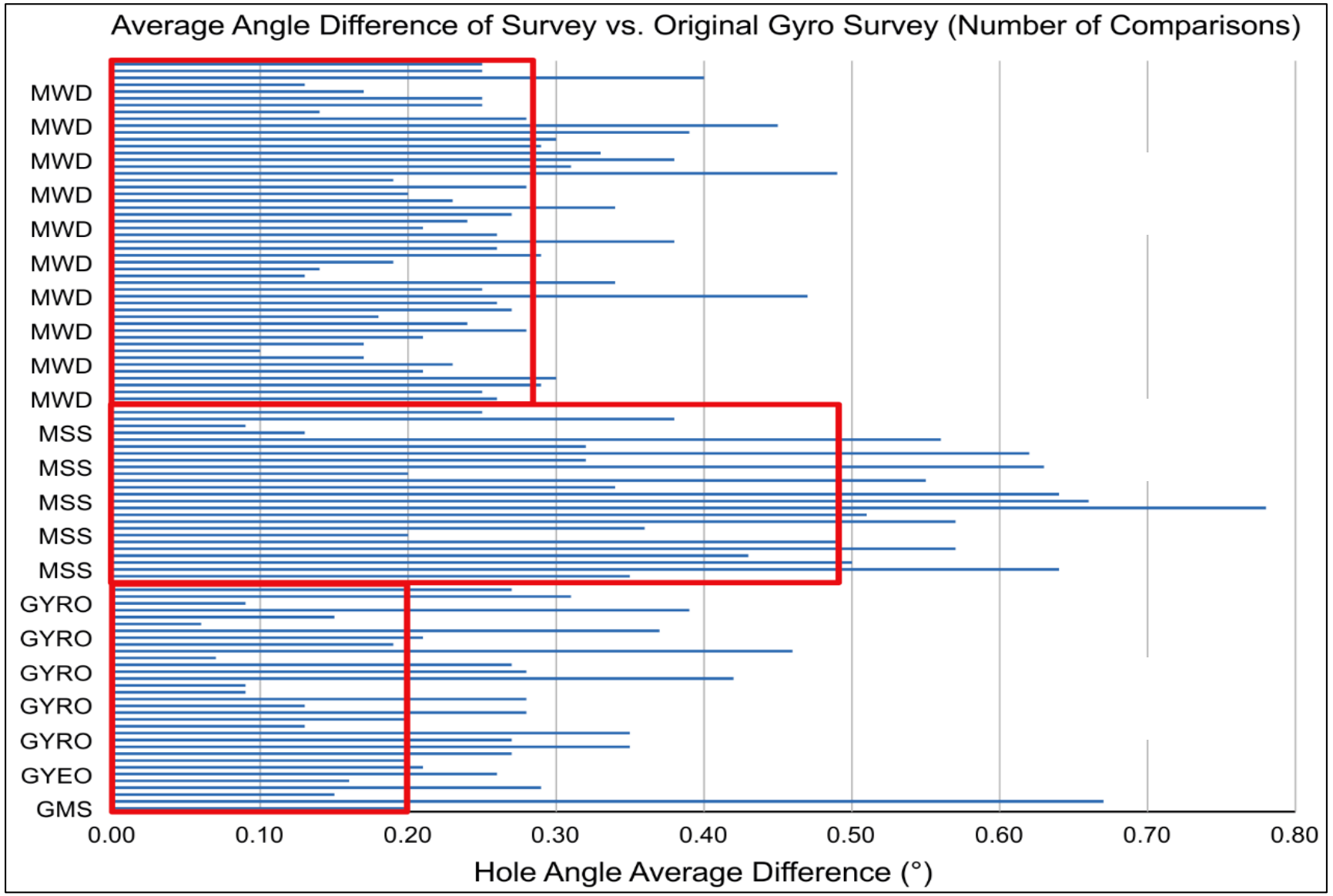
Evidence: Misalignment – Average Survey Comparisons



Gyro vs. MWD (53)
Average = 0.28°

Gyro vs. MSS (23)
Average = 0.49°

Gyro vs. Gyro (29)
Average = 0.20°

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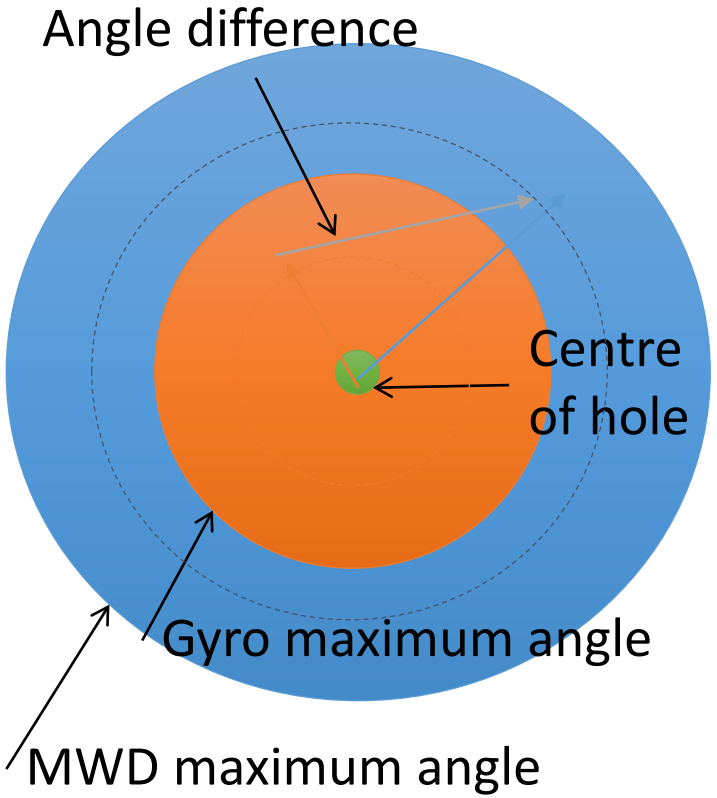
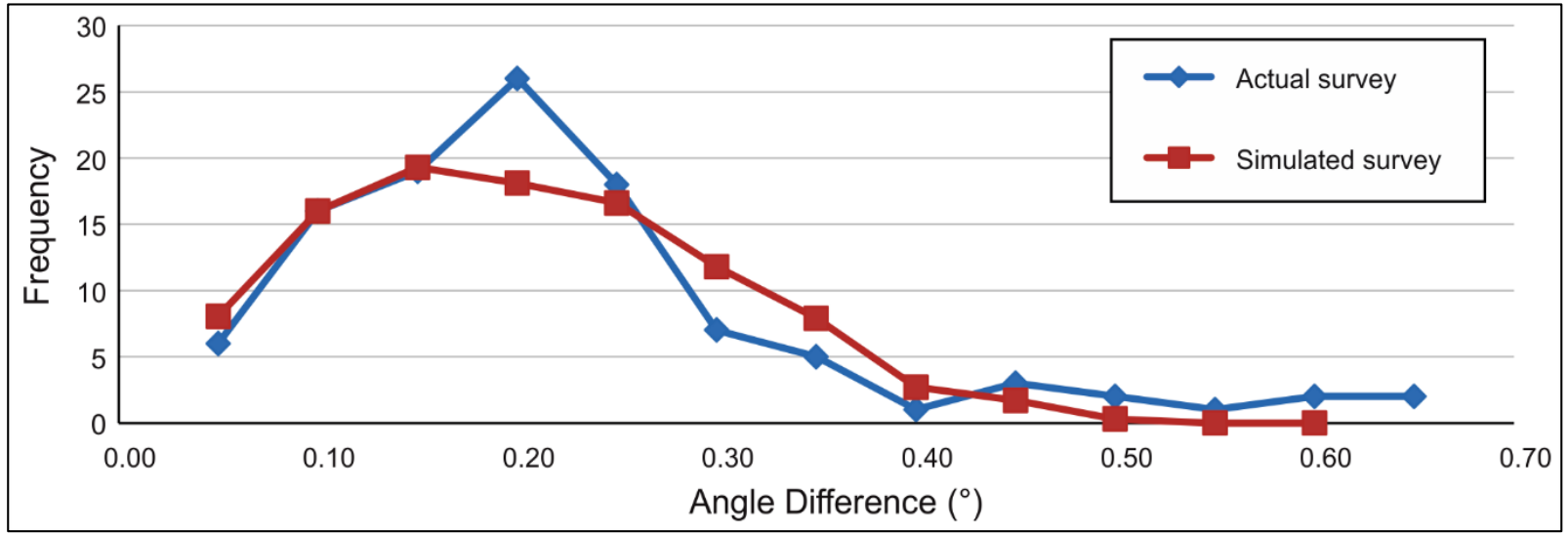
Analysis: RMIS Misalignment Behaviour

Polar Diagram Angle vs Rotation





Rate Gyro vs.	Average Difference°	Maximum Angle°	RSS Angle° 1σ
Gyro	0.20	0.28	0.16
MWD	0.28	0.52	**0.30**
MSS	0.49	0.94	0.54

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