XCL Terms and Low Angle Misalignments- Technical Supplement

MWD Error Model Rev5

Background

This document describes suggested changes to the MWD survey error model for measurements at low angles. They are derived from physical models and evidence from MWD vs Gyro survey comparisons. The changes are required for extended course length (XCL), random misalignment and revised SAG error weighting. These changes are shown in Table 1. The new terms and changes use the terminology of the previous error model papers (SPE 67616 and 90408).

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
XYM3E	Random	0.3	M abs(CosI) CosA	M -abs(cosI) sinA /sinI
XYM4E	Random	0.3	M abs(CosI) Sin A	M abs(cosI) cosA /sinI
SAGE	Systematic	0.2	$SinI^{0.25}$	0
XCLH	*Random	0.167	Max(abs(I_2-I_1),T (D_2-D_1))	0
XCLA	*Random	0.167	0	Max(sin(abs(A_2-A_1)), T (D_2-D_1)/SinI)
XCLL**	*Random	0.167	0	Max(sin(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.

T is default tortuosity term. For rev 5 a value of T = 1 deg/100ft has been chosen.

M = Max(1, sqrt(*MisalignmentMinCourseLength*/(D_2-D_1))) where for generic MWD *MisalignmentMinCourseLength is* 10m and D is in metres.

XCL Error Propagation

The XCL error is the survey position error derived from the wellpath not following the constant radius curve between stations that is expected with the minimum curvature survey calculation. They are a cumulative position error from the previous station to the current station, as such they are given as vectors perpendicular to the wellbore at the Current station.

Highside error.

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

Azimuth error

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

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

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

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Since implementors need to use a specific handling just for XCL terms, this later
equation is prefered as it avoids signularities in vertical hole.
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$e_{i,L,K}$ = 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 (=1deg/100')
(Units for T may need to be converted to match the units of D. e.g. T= 0.00018 rad/ft, or 0.0006 rad/metres)

This formulation splits the effect of highside and lateral XCL error. This is done for the following purposes…

1. It allows the definition of separate error characteristics for highside and lateral deviations.
2. A survey station can be considered accurate in inclination but not in azimuth (interference/fails QC).

It is necessary to treat the XCL as a position error generated over the current survey interval to correctly calculate errors for irregular survey stations. For example, due to magnetic interference it's not possible to get a good survey azimuth for 100m after a sidetrack. The additional long course length error at the end of the survey interval is correctly calculated for the MWD without the need to insert a BLIND error model for that station.

Implementation Considerations

XCL is a Random error source (see SPE 67616, Appendix A-11)

$e^*_{i,L,K}$ vectors are the same as $e_{i,L,K}$

Unlike the other weighting functions, XCL does not use the balanced tangential method.

This means that the definitions of above are for the full error vector, $e_{i,L,K}$. These values do not get multiplied by the $\frac{d\Delta \boldsymbol{r}_k}{d\boldsymbol{p}_k}$ matrices like other weighting functions.

When evaluating $\text{abs}(A_k - A_{k-1})$ ensure that the change in angle is calculated the shortest distance round the circle and doesn't wrongly give a large difference at north or south.

Similarly, when the builds are drops angle through vertical (i.e. I_k=0 or I_{k-1} =0) $\text{abs}(A_k - A_{k-1})$ should be zero.

XCLA is singular in vertical hole

Implementations of XCL will have to consider how they handle interpolated points.

For example, the user enters the points of inflection to define a plan and then produces an uncertainty report.

Does the user have to define the expected survey interval when the well is drilled – or is that just assumed to be the interpolation interval for the report?

In a survey output, if interpolated points are added for formation tops or casing depths, then like the anti-collision case, uncertainty should be calculated just from the true survey points.

Justification:

Codling, J. (2017, October 9). The Effect of Survey Station Interval on Wellbore Position Accuracy. Society of Petroleum Engineers. doi:10.2118/187249-MS

Compass IPM Definition

The following table shows the definition of these vector terms in Compass 5000.15 and later versions.

Name	Vec	Tie	Unit	Value	Formula
tort	n	n	-	0.00018	1.0
xcli	y	r	-	0.167	max(abs(din),tort*smd)
xcll	x	r	-	0.167	max(abs(daz)*sin(inc),tort*smd)

Application to Inclination Only Well

The XCL terms can be extremely useful for historic inclination only wells, which will often not have been surveyed at standard intervals. In this case, we have no azimuth change to drive the terms and we want the XCLL and XCLH terms to have a circular effect on uncertainty.

In this situation, the regular XCLH and XCLL terms are replaced by a specific inclination only version, XCLI:

$$XCLI1 \quad e_{i,L,K} = \sigma_{xcll}(D - D_{k-1})\, max\big(\mathrm{abs}(I_k - I_{k-1})\,, \mathrm{T}(D - D_{k-1})\big) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$XCLI2 \quad e_{i,L,K} = \sigma_{xcll}(D - D_{k-1})\, max\big(\mathrm{abs}(I_k - I_{k-1})\,, \mathrm{T}(D - D_{k-1})\big) \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

XYM3 and XYM4 Error Propagation

Misalignment for a single station is calculated as per Appendix C of SPE90408 – Alternative 3. This is the accepted method for misalignment applied to most survey instruments. The proposal is to change the low angle misalignment terms from systematic to random and increase the degree of error from 0.1° to 0.3°.

The net effect of this error is to increase the error radius in the range of 0 to 400m from vertical and therefore to increase the minimum separation distance in surface hole sections. For vertical wells with depths deeper than 400m the error will be smaller than currently predicted with systematic errors.

There is a requirement to limit the course length dependency of the misalignment randomization to 10m. The reason is that for MWD and Gyro surveys the degree of randomization is limited by the ending stiffness of the drill collar or casing that the survey is run inside. This is achieved by adding the following formula to the weighting of these functions. From SPE 90408 – Table B2 – Alternative 3.

$$w_{34} = abs(\cos I_k)\, max(1, \sqrt{MisalignmentMinCourseLength/(D - D_{k-1})}$$

Where 10m is generally used for *MisalignmentMinCourseLength* when D is in metres.

This formulation works well for regularly spaced surveys but can cause unwanted jumps when there is a step from a very short course length to a longer one. This is a situation when does not occur often in wellbore surveys, but problems are minimised by only applying the formula where 0.1 < $\boldsymbol{D - D_{k-1}} <$ $\boldsymbol{MisalignmentMinCourseLength}$**.**
Otherwise $w_{34} = abs(\cos I_k)$

Justification: SPE 187249

The same factor, $\sqrt{MisalignmentMinCourseLength/(D - D_{k-1})}$ must also be applied to the singular forms of XYM3E and XYM4E.

SAGE Error Weighting Function

In SPE67616 the SAG error was given as 0.2° (uncorrected) and 0.08° (corrected), with a weighting function of sin(inclination). It is recommended to change the weighting function to $\sin^{0.25}$ (inclination) {to the power of ¼}.

$$SAGE_h \qquad e_{i,l,k} = \sigma_{sag}((Dk_{k+1} - D_{k-1})/2)\, sin^{0.25}(I_k) \quad \begin{bmatrix} \cos I_k \cos A_k \\ \cos I_k \sin A_k \\ -\sin I_k \end{bmatrix}$$

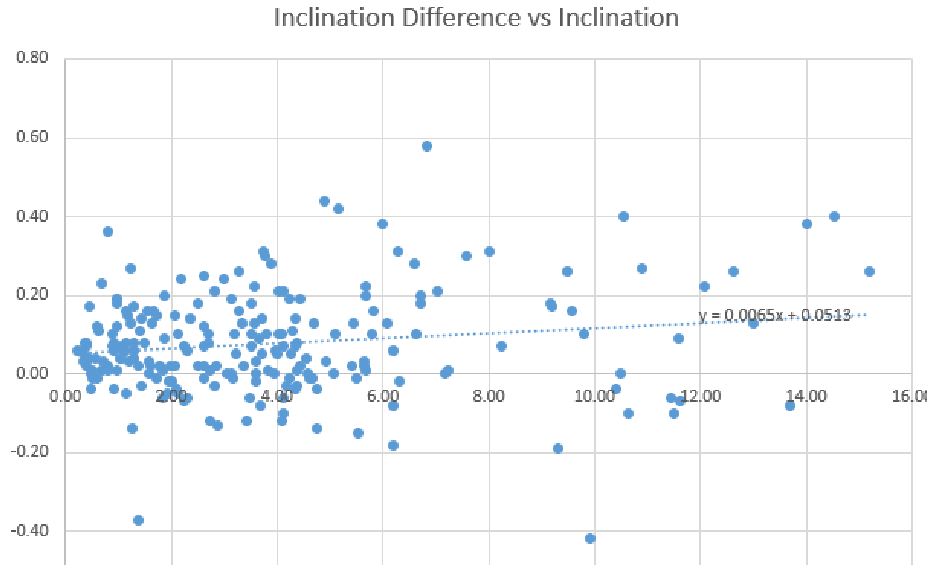
This formula is identical to existing SAG error, except weighting is $\sin^{0.25}(I_k)$

$e_{i,l,k}$ = Half Error at this station (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_{sag} = 0.2 (radians - uncorrected)
σ_{sag} = 0.08(radians – SAG corrected)
It is recommended that the designation of corrected SAG can also be given to BHAs where there is a stabilizer immediately above the MWD collar (and no correction applied).
Justification – see Appendix A

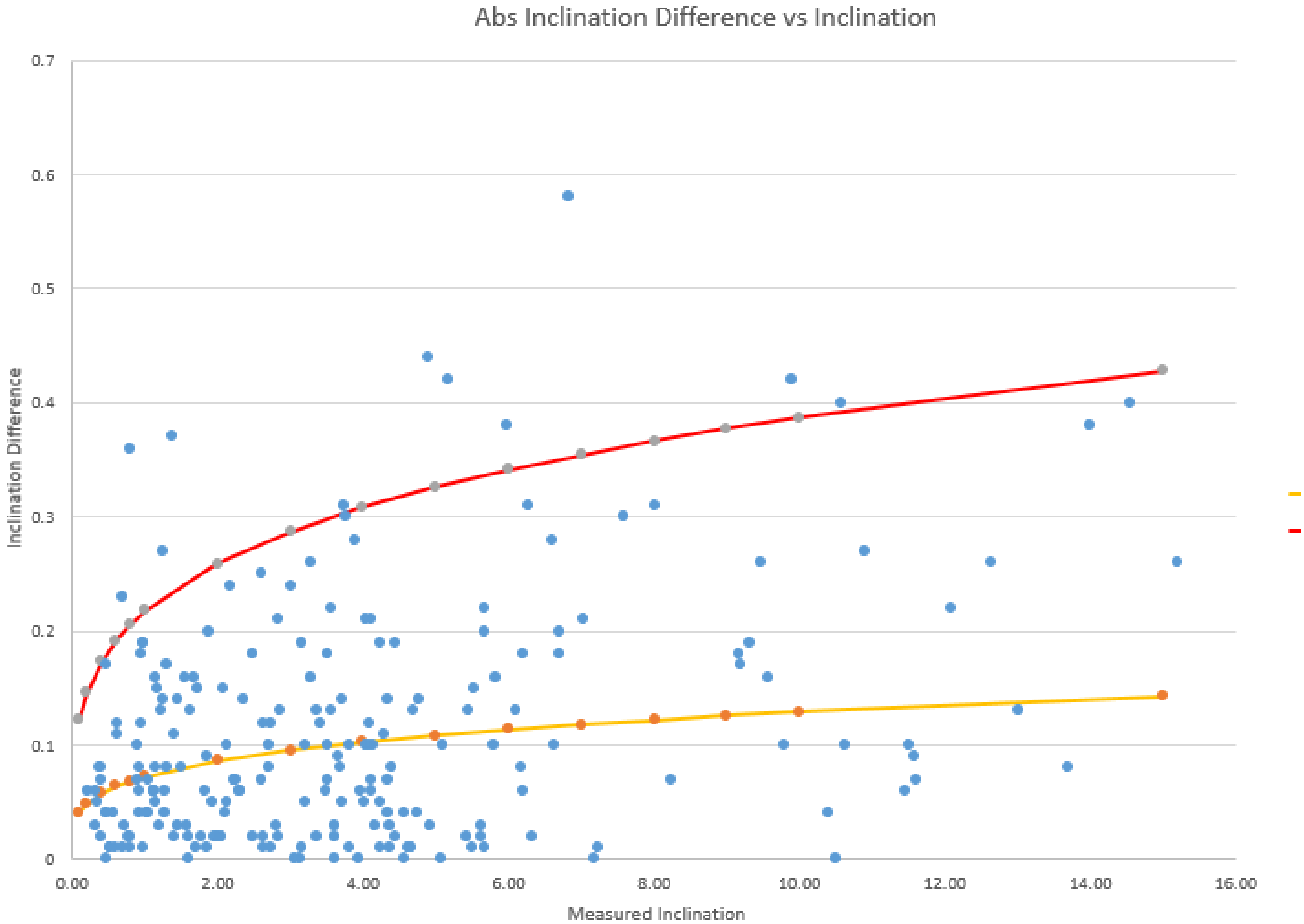
The net effect of this change in SAG error will be to increase the highside error at low hole angles. It is observed that the SAG magnitude and residual error is considerably smaller when a stabilizer is run above the MWD collar. The field comparison data shows that in most cases (75%) there is no stabilizer above the MWD sensor and that in these cases the MWD inclination is always higher than a gyro at the same depth.

Appendix A SAG Error Change

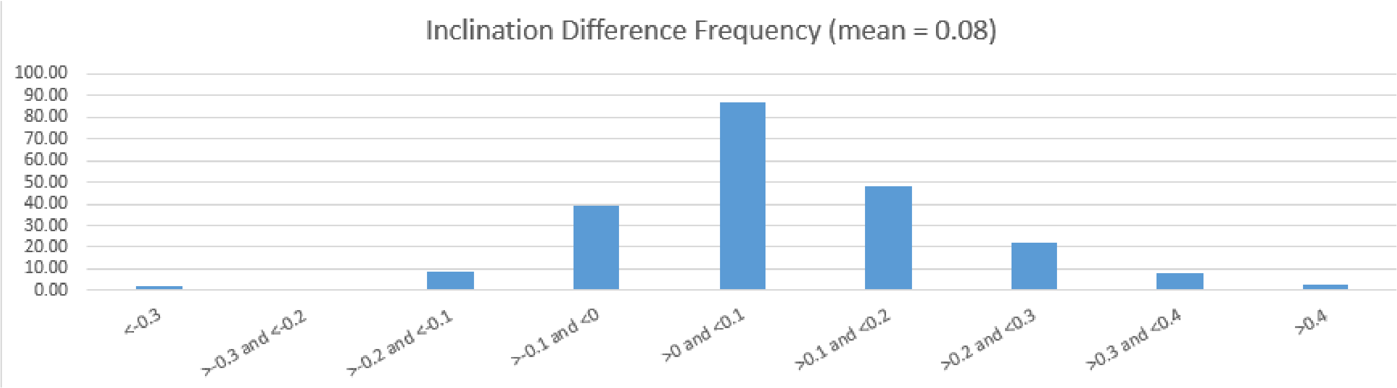
A number of gyro surveys were compared to MWD for Inclination difference vs measured Inclination. The results are shown below. Y axis is MWD Inclination – Gyro Inclination. X axis is the Gyro Inclination.



There is a systematic positive bias. That is the MWD Inclination is higher than the Gyro at the same depth. In the example 200 surveys were compared in the range 0-15 degrees and 75% of MWD surveys were higher. The plot below shows the absolute differences of inclination vs the Gyro inclination.

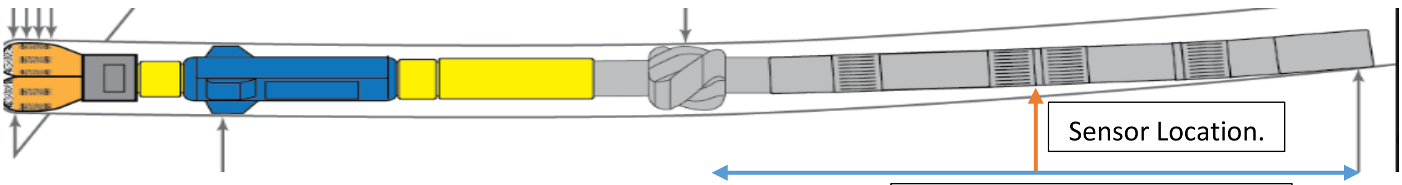


If this error is mostly due to SAG with the weighting function of SIN(Inclination), then the graph data points should be mostly linear in this range of inclination. The data suggests that it isn't, it appears to be an inverse power function. The orange line shows the weighting of Inc Error = 0.2 * $\sin^{0.25}$(inclination). The red line is the 3 sigma value.



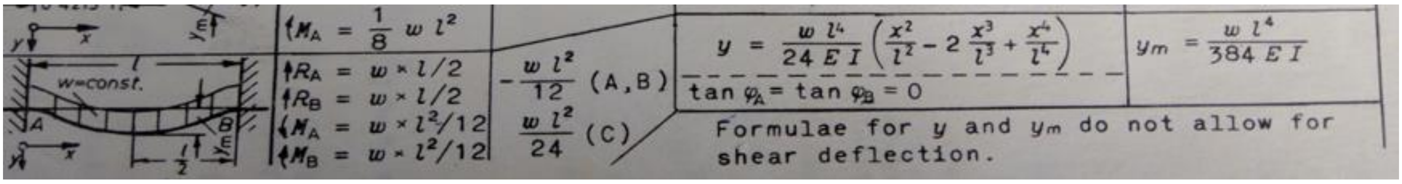
The sag error weighting function assumes that the instrument is located in drill collar suspended between 2 stabilisers, therefore the bending of the drill collar is proportional to the lowside weight on the collars (that is WL*sin(i)).

But that is not the case in most BHAs run in directional wells since 1985. These are mostly 2 stabiliser BHAs where the MWD sensor is run above the 2nd stabilizer.



This common location is the reason that most MWD surveys read higher in [illegible] depth. The degree of bending at the sensor position is also dependent on the length L which changes considerably with inclination.

This does not only apply to MWD sensors above the 2nd stabilizer, the bending below this position is also dominated by the bending above the stabilizer caused by the collar sagging to the low-side.



From Kurt Gieck – Engineering Formulas - stiffness of beams in deflection.

The formula shown above for the bending of the constrained beam to the deflection Y_m is shown as

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

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)

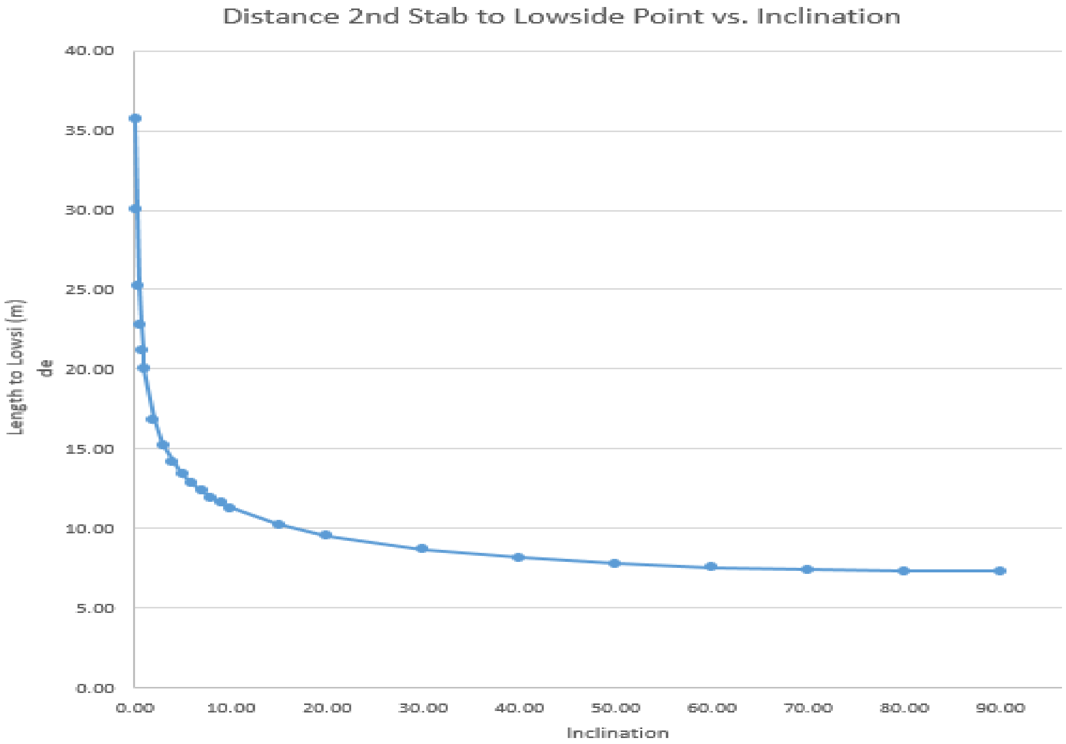
The inverse is used to determine L, length to lowside point.

$$L = \left(\frac{Y_m 24\ \mathrm{E\ I}}{\mathrm{W\ Sin(Inc)}}\right)^{0.25}$$

If the worst case SAG angle happens at the midpoint (0.5L) and is given

$$SAG = \frac{2 * \mathrm{Ym}}{L}$$

The graph below shows the relationship between L and inclination

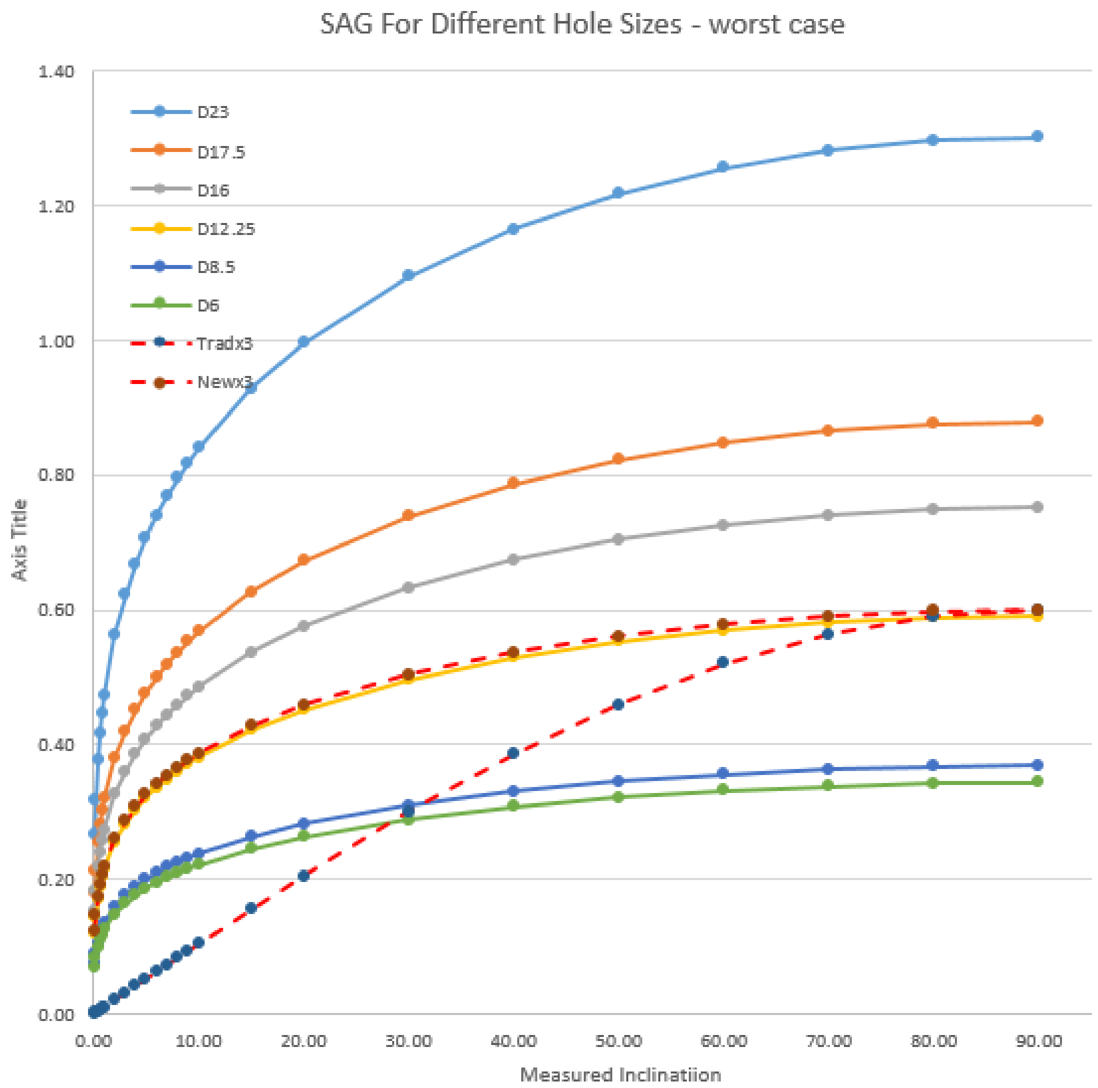


Substitute for L in the equation and solve for SAG angle…

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

Therefore, the inclination weighting function should be $\mathrm{Sin}^{0.25}$(Inclination)

the graph below shows worst case SAG value for different hole sizes. The model sag (red dashes – brown dots) matches the 3 sigma result for 12 ¼" hole size. The line is also shown with the original sag weighting (red dash – blue dots) at the 3 sigma level.


SAG For Different Hole Sizes - worst case
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Axis Title
D23
D17.5
D16
D12.25
D8.5
D6
Tradx3
Newx3
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
Measured Inclinatiion

Appendix B Results – from ISCWSA Test Wells

Test Data is provided for test ISCWSA test wells, with a single MWD survey from surface to TD. Interpolations are made at the given intervals with the plan change points retained from SPE67616 Table 2. Only the new or changed error terms are reported, the Total is for all error terms in ISCWSA MWD at Rev 4.

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**

It can be observed that on well 3 there is significant increase in course length error because of the uncertainty in the 15 deg/30m build to horizontal.