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Improved BHA Sag Correction and Uncertainty Evaluation Brings Value to Wellbore Placement.

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Abstract

Recent well positioning uncertainties evaluation per SPE published ISCWSA model for MWD survey tools suggests that 80% of the inclination measurement error budget is a consequence of BHA sag.

BHA sag is the misalignment of the directional sensor with the borehole direction due to deflection of the MWD drill collar under gravity and borehole curvature. The magnitude of the error depends on BHA type and geometry, sensor spacing, hole size and several other factors.

This paper presents a new methodology based on modern 3D BHA/Hole interacting modeling for BHA sag corrections and residual error evaluation at each MWD survey stations.

11 different typical 17½" and 12¼" rotary and steerable motor BHA's with variable gauge stabilizers were computed in multiple configurations (borehole geometry, BHA settings, friction...) following a Monte Carlo process which involved more than a million simulations. Results of this study show that the residual BHA sag uncertainty as proposed by the ISCWSA model can be further reduced by as much as 50%.

A simplified software automated process was developed in order that Operations Support Centres can easily integrate the proposed methodology as part of near real time Survey Management advanced processing routines.

A sound BHA sag correction method along with a thoroughly analysed residual sag error, readily fit for use within the ISCWSA MWD well positioning uncertainty model (today's industry standard), appears essential in a wide variety of directional drilling applications including extended reach and horizontal drilling.

The proposed process contributes to significantly improve wellbore placement through the pay zone while drilling. Reduced trajectory positional uncertainties contribute to the construction of sound geological models for rational well target design, positioning and development pattern fine tuning during the drilling campaign. In turn reservoir management including mature fields shall benefit from improved Wellbore Placement as a multidisciplinary task by locating more accurately layer tops and contacts.

Introduction

ISCWSA presentation

Objectives

Wellbore positioning uncertainties¹ should be neither underestimated because of collision avoidance issues, nor overestimated in terms of target hitting. Therefore, confidence levels on uncertainties should be set. To take up these challenges, companies joined their respective competences leading to the emergence of the ISCWSA: the Industry Steering Committee for Wellbore Survey Accuracy. The aim of this group is to "produce and maintain standards for the industry relating to wellbore survey accuracy". In 1999, H.S Williamson² highlighted the committee work and described a full MWD error model. With the gyro model³ completed, these two error models are today accepted as the new standard error models, continuously being maintained and improved⁴.

Error model

Wellbore survey stations are modeled as three-element measurement vectors, the elements being along-hole depth, D , inclination, I , and azimuth, A (D, I, A). The ellipsoid of uncertainty (E.O.U) is the result of numerous contributions of different error sources. Each error source is a physical phenomenon which leads in the model to an error term described by a name, a mean value, a magnitude and a weighting function: effect of the error on the measurement vector (D, I, A). Errors from different error sources are considered statistically independent and have their own mathematical propagation mode, either Random (R), Systematic (S), Well by well (W) or Global (G). The main physical error sources are derived from magnetic compass errors, gyrocompass errors, tool misalignment errors, magnetic field uncertainty and along-hole depth error. Among these error sources, it is commonly accepted that BHA sag is the

predominant parameter of the inclination measurement error budget.

Sag definition

We define also the borehole referenced frame (highside, lateral, along-hole, *subscript HLA*), the vertical plane *HA* and the lateral plane *LA*.

The BHA distortion is three dimensional. The consequence is a three dimensional misalignment of the BHA with the borehole direction. We define the BHA sag (fig.1) as being the projection of the BHA misalignment along the borehole, at the point of inclination measurement, on the vertical plan *HA*. We define the horizontal BHA misalignment (fig.2) as being the projection of the BHA misalignment along borehole, at the point of azimuth measurement, on the lateral plan *LA*. This horizontal BHA misalignment can be compared to the error term described by the collar distortion of the MWD outside the vertical plan in the ISCWSA error model.

Objective of the study

Reasons

The reasons that led to the performance of this study were generated by several facts including :

- The increasing concern by operators to define TVD's with reduced uncertainties.
- The recognised sag error predominance within the inclination measurement error budget.
- The difficulties experienced by some service companies :
 - to open their BHA sag correction models to the operator who was then left to consider these as "Black Boxes" (hypothesis based results not clearly defined),
 - to use 3D BHA models for sag correction services (2D BHA models being used instead),
 - to provide a sag residual error for each calculated sag correction value.
- Recognized limits of actual ISCWSA sag and horizontal misalignment modeling.

Solution

The development of new 3D BHA models^{5,6} has provided the opportunity to describe the distortion of the BHA in all configurations and to identify the BHA misalignment with the borehole direction at the measurement sensor on the MWD. If the wellbore E.O.U can be reduced using modern 3D BHA drillstring modelisation, giving accurate sag and horizontal misalignment correction, there is still a need to define correctly the residual error remaining after correction has been applied.

Paper structure

This paper presents a sag model correction & residual error evaluation based on a 3D BHA modelisation. After introducing the importance of sag on TVD evaluation and the definition of the ISCWSA model limits, the model is presented and tested over a large sensitivity analysis based on

numerous realistic BHA geometries. When sag correction is applied, a rigorous methodology to find out the correct residual error to be used will be described and tested on case studies.

Importance of BHA sag

Historic

At target or reservoir entry the cumulative TVD error resulting from BHA sag could be significant, particularly where few or only one bit run/BHA was managed successfully to drill the entire section. In such a case the sag error will be described as systematic. At target entry the cumulative TVD error will generally be of a magnitude that would jeopardize "best intended" well placement through the pay zone, if no sag corrections were made while drilling preceding drilling phases.

Examples are horizontal wells drilled in the 80^{ls} and up to the mid 90^{ls} in which no BHA sag correction was applied. At best some Directional Drilling experts had good intuition in suspecting inclination error measurement potential inherent to the relative position of the surveying tool measuring sensor with respect to the position of BHA string stabilisers. These experts, when and where possible, would design BHA that could mitigate that effect by making sure the survey tool was either maintained centralized in the well bore between evenly spaced out BHA string stabilisers or laying flat on the low side of the well bore away from any BHA string stabilisers. Sometimes rotational surveys at different tool face were also performed once per BHA to determine misalignment offsets to apply on inclination & azimuth surveys as a function of tool face.

Early water break through of a significant number of these horizontal wells have pushed the industry to analyse root causes for such events, and among those, well path mis-positioning due to uncorrected BHA sag was identified as the key issue. Resurveying of such horizontal wells would show in fact, for a significant amount of them and where horizontal position was intended, a near horizontal drain by tenth of degrees resulting in the drain being often placed within the water pool or close to it, depletion and active fluid contacts movement ending the drowning process of the drain to settle much faster than anticipated.

Impact

The applied standard MWD error model on well path examples given by Williamson¹ shows that 80% of the vertical error is a typical value for the sag contribution. The BHA sag term is directly related to the TVD error term and reducing TVD uncertainty opens the way to smaller geological targets and more accurate reservoir modelling. Table 1 is given to fully appreciate the order of TVD error magnitude in meters, induced by an inclination error measurement of 0.2° (typical BHA sag values) per 1000 m MD and for 10° to 90° hole inclinations.

Influencing factors

The BHA sag effect for the expert has for a long time been

purely the BHA deformation in the vertical plane resulting from the sole gravitational forces of its components. Recent 3D BHA models^{7,8} development shows that the final deformation of the BHA in the hole is 3D and depends on :

- BHA geometry & mechanical characteristics :
 - length
 - weight
 - rigidity
 - stabilisation
 - bent
 - connections
- Well geometry
 - inclination
 - curvature
 - diameter
- Operating parameters :
 - mud weight
 - friction
 - WOB
 - down-hole pressure

Objections and comments on current sag modelling

BHA sag

The ISCWSA suggests sag error, if no correction is applied, should be given a mean value of 0.2° with a weighting function $(0, \sin I, 0)$; in this formulation $\sin I$ intends to describe the gravity effect but :

- Should we accept that BHA distortion is due only to gravity ?
- Should we believe that a BHA with a bent device has nearly no sag on a well close to vertical ?
- Are we underestimating the BHA sag error term for wells with low inclination where anti-collision problems need to be addressed ?
- Are we overestimating the BHA sag error term for wells near horizontal where precision through target is needed ?

If a correction was applied, the ISCWSA model suggests a residual error mean value of 0.08° with the same weighting function but :

- The residual error should not be constant as it depends on the input parameters - i.e the global knowledge we have on the system.
- There is no reason why the residual error should obey the weighting function $(0, \sin I, 0)$.

Horizontal misalignment

As mentioned by Williamson¹, this error differs from the other tool misalignment errors in that it does not rotate with the tool and a typical value of 0.04° was identified. Because this value is small, it was included with the other sources of radially symmetric misalignment. As a consequence, the final term has a weighting function which depends on the toolface. If we randomized the toolface for the purpose of the computation ; we would then underestimate the collar distortion outside the

vertical plan for wells with significant azimuthal change intervals. In addition, we have highlighted some cases where this term was significant and should be fully considered.

Model presentation

Sag & horizontal misalignment correction

The correction evaluations were carried out with a 3D BHA model integrating the latest scientific work⁵ issued from a drilling laboratory research center ; this model integrates :

- a unique analytical rigid solution to support high volume computation
- a real drill-string & BHA / hole interaction contact calculation
- a 3D trajectory reconstruction based on minimum radius curvature or minimum torsion methods
- all types of BHAs (rotary, steerable motors, variable gauge stabilizers & rotary steerable systems)

To perform sag & horizontal misalignment evaluation with this model, the following assumptions were made :

- no weight on bit is applied as the survey is taken off bottom
- friction is not taken into account as the BHA is not rotating
- continuous rigidity throughout element connexions
- influence of temperature on element mechanical characteristics is neglected

Sag & horizontal misalignment error

The residual sag error is the uncertainty remaining once the sag error has been corrected. It is directly linked to our knowledge on the different input values of the system. The first step is to select the parameters of uncertainty to be used in the model ; each parameter λ_i is defined by :

- a mean value μ_i ,
- a magnitude σ_i always quoted as a 1 standard deviation value
- a weighting function F_{λ_i} to represent how the parameter impacts on the BHA sag.

The uncertainty σ_i of each single parameter i contributes to the global residual error. The contribution to the residual sag error of each parameter can be independent or correlated. We consider the parameters to be independent. In this case, each parameter has its own weighting function and the standard deviation of the magnitude σ of the residual sag error is given by :

$$s = \sqrt{\sum_{i=1}^{i=n} \sigma_i^2 * F_{\lambda_i}(m_i)^2} \quad (1)$$

$$F_{\lambda_i} = \frac{\partial Sag}{\partial \lambda_i} \quad (2)$$

The same approach is developed to treat horizontal misalignment.

Sensitivity analysis

Description of BHA chosen for simulation

17½" and 12¼" BHA's were selected because these drilling sections are usually significant in length and are therefore seen as major contributors to the potential cumulated inclination survey errors along the well path to the target, and induced by BHA sag & horizontal misalignment. The selected BHA are the ones commonly used today to drill directional wells ; they include Steerable Motor and Rotary BHA's (packed-hole, build-up, drop-off and Variable Gauge Stabiliser - VGS - assemblies). A full list of the BHA chosen for the simulation is given table 2.

Description of parameters retained for simulation

Different parameters were tested in order to find out their respective influence on the BHA sag & horizontal misalignment :

- Motor :
 - Bent angle
 - Bent housing position
 - Toolface
- VGS :
 - Active diameter
- MWD :
 - Equivalent ID
 - Sensor position
- Hole overgauge (inch)
- Mud weight
- Inclination
- Build/Drop & Turn rate (we consider the BHA in a single curvature)

Table 3 indicates the different mean values chosen for each parameter and table 4 indicates local variation applied for each parameter centered on all the respective mean values.

Correction

BHA sag

Table 5 gives the BHA sag correction at four different positions of the inclination sensor for all BHAs in the configuration given in table 6.

As observed, BHA sag affects all types of BHA's, but at different degrees as a result of hole size application, BHA design, and spacing of directional sensors. For the 12¼" BHA, we found that the sag is between 0.09° and 0.32° depending on the sensor position. For 17½" BHAs, the deflection can be more severe and sag values vary from -0.16° to 0.59°. These values are only indicative since the different BHAs have been set up in a particular configuration.

As indicated the BHA sag depends mainly on the distance between the measurement sensor and the bottom connection of the MWD. In general the MWD body located between an

upper and a lower stabiliser have a tendency to bend under gravity and to flex towards the bottom side of the wellbore. In some other cases bending moments generated by the two stabilisers induce a distortion of the MWD collar towards the high side of the wellbore the effect of which is stronger than gravity. In both cases, BHA sag may be either positive or negative depending on the relative location of the measurement sensor between the upper and lower stabiliser. For a low side deflection and a sensor closer to the lower stabiliser than the upper one, the measure will indicate a higher inclination than the real wellbore inclination, i.e a positive sag. When the sensor measurement is closer to the upper stabiliser than the lower one, the measure will indicate a lower inclination than the real wellbore inclination, i.e a negative sag.

The study revealed that the BHA sag of a well stabilised BHA with no bent in a slant in-gauge hole will be closely proportional to $\sin I$ (I being the inclination), therefore agreeing with the ISCWSA model, which suggests a predominant effect of gravity. However, in presence of a bent, wash out, dogleg/curvature, high bending moments or if the MWD collar is laying flat on the borehole, the BHA sag evolution is not linked to the inclination. To illustrate this, fig.3 gives the evolution of the sag for different inclinations for a 17½" BHA with a bent. Further more, sag exists for a BHA with a bent in low inclination wells in contradiction with the weighting function ($0, \sin I, 0$).

All parameters listed in this study have a direct impact on the sag correction computed. For example, fig.4 shows how the BHA sag varies with the bent angle of the motor and fig.5 illustrates how it is affected by the hole overgauge.

Horizontal misalignment

Table 7 shows that the horizontal misalignment value is generally around 0 but can become significant with the presence of a bent oriented laterally and/or when the well path turn rate is more than 1°/30m. In these cases, all the other parameters will have an impact on the collar distortion outside the vertical plan. The study did show typical values for horizontal BHA misalignment of $\pm 0.1^\circ$.

Residual error

BHA sag

For each specific configuration of the system, weighting functions of the different parameters were computed using the local variation as indicated in table 4. Table 8 summarises the impact on sag of the different parameters for a 12¼" BHA with a motor in the configuration given in table 6. For this BHA, the residual sag error to be considered in the ISCWSA model error would be 0.004°.

The residual sag error is computed for a given set of parameters errors and is not linked to the inclination. It may then change from one survey to another and reflects, in each survey how well the system has been informed.

For example, looking at fig.5, if we have no idea of the hole overgauge, the residual sag error will be higher, since we have considered the system with a higher overgauge uncertainty.

But if we have a good understanding of the hole overgauge, we are able to reduce the input uncertainty, which would lead to a lower residual sag error.

The same principle can be applied to all parameters. Because the residual sag error is issued from a root sum square formula, it is important to first inform the system with the parameters with the biggest impact on the sag.

Table 8 presents the contribution to the final residual error of each individual parameter - for standard deviation representative of the system knowledge commonly encountered - for a 12¼" BHA with a motor and VGS. For this BHA, sensor position, MWD ID & hole overgauge should be addressed carefully.

Horizontal misalignment

Table 8 gives a typical value of 0.004° for the horizontal misalignment residual error, to be included in the ISCWSA error model. As for the residual sag error, the residual horizontal misalignment error is computed for a given set of parameters and may vary from one survey to another.

Model limits

Correction & residual error presented above are obtained for parameters characterized by a mean value and a one s.d. Equation 1 applies for local parameters variation only.

In case of poor information on the system, it is still possible to have a representative correction & residual error to be applied. Indeed, with numerous simulations, one can draw correction values of a BHA for all possible drilling configurations and find out the best law to model sag & horizontal misalignment. This method, which integrates a large sensibility analysis over all parameters, can be compared to a randomised Monte Carlo process.

Fig.6 and fig.7 describe respectively the sag & horizontal misalignment distribution for a 17½" BHA with a bent and a VGS, at 60° inclination and for the measurement sensor position at 2m (all other parameters unknown). The results show that :

- the sag of this BHA can be modeled by a normal law with a mean value of 0.54° (the sag correction) and a one σ deviation of 0.03° (the residual sag error).
- the horizontal misalignment of this BHA can be modeled by a normal law with a mean value of 0° (the horizontal misalignment correction) and a one σ deviation of 0.04° (the residual horizontal misalignment error). This result seems to validate the magnitude of the error term - collar distortion outside the vertical plan - given by the ISCWSA, except that the weighting function should not be treated as inclination and TF dependent.

This methodology helps to improve efficiently the sag & horizontal misalignment corrections & uncertainties. Fig.8 compares the normal law used to modelise the sag for :

- the basic ISCWSA error model when no corrections have been applied
- the basic ISCWSA error model when sag corrections have

been applied

- the sag modelisation issued from the above described method.

Implementation in ISCWSA error model

The proposed model delivers BHA sag & horizontal misalignment corrections, for each survey. To illustrate representative drilling conditions, the ISCWSA error model can be applied with corrected survey using both the BHA sag to correct the inclination, and the horizontal BHA misalignment to correct the azimuth. The sag correction and the horizontal misalignment correction will have a significant direct impact on the 3D well placement.

For each survey, the model also delivers two sources of error: the sag & horizontal misalignment residual errors. The two sources of error should be used in the ISCWSA model in order to compute the E.O.U. When these two sources of error are used, the ISCWSA error model should be adapted :

- implementing the new sag weighting function : $(0, 1, 0)$
- implementing the new horizontal misalignment weighting function : $(0, 0, 1)$
- considering the two sources of error as systematic (S).
- changing the magnitude of the tool misalignment error terms MX and MY which included the collar distortion outside the vertical plan, from 0.06° to 0.046°.
- integrating individual magnitude of sag & horizontal misalignment errors by survey.

Application

Operational applications

Pre engineering

At the pre-engineering stage, the trajectory is cut into sections and BHA designs are proposed by the directional drilling contractor ; the model proposed in this study will be used to :

- design BHA with reduced sag effect,
- evaluate the level of system description required (BHA description, BHA settings at survey points...) to match the desired well positioning scope,
- anticipate the potential TVD uncertainty for target sizing.

While drilling

During the well construction phase, corrections & uncertainties will be applied in a near to real time fashion to improve target hitting and reservoir navigation.

Post analysis

After a well is drilled, different data are available : sliding sheet of the settings of the different BHA runs, toolface logs, calliper logs and definitive surveys. When necessary, a full analysis will be performed in order to properly define the well position and reduce associated uncertainties. The construction of a robust earth model during a field development campaign

will therefore be greatly improved.

Mature fields would also benefit from the application of the model (improved TVD calculation & uncertainty) to help diagnose causes of specific production issues such as early water break through and to put value on workovers designed to target unswept oil pockets.

Operational implementation

The advanced model was integrated in a directional drilling BHA management software developed through a collaboration between the operator and the drilling engineering company. The data required to conduct a full evaluation are :

- surveys
- BHA designs
- operating parameters (mud weight)
- active diameter position
- toolface orientation
- borehole caliper

According to the precision of the system description and the level of information really available, a list of uncertainties was defined and classified in four groups :

- BHA design
- BHA settings
- drilling parameter (mud weight)
- well geometry

For each of the uncertainties defined in the four groups, a standard deviation is automatically produced and can be changed manually. Table 9 summarises all parameters used and their associated uncertainties.

In case the toolface is unknown, an average sag & horizontal misalignment are evaluated for 4 positions of the toolface (up, down, left, right). The *one* σ s.d. of the residual error is computed so that 99.7% - for 3 σ - of the results are between the maximum and minimum correction computation.

When evaluating the effect of other parameters with unknown toolface orientation, a sensibility analysis is performed for the four main positions of the toolface and the maximum individual weighting function is memorized in order not to underestimate the error.

At the end of the computation, a definitive patrimonial well survey data is delivered by the software which includes the raw surveys, corrections & residual errors to apply.

Case study 1 - Pre engineering

A large sensitivity analysis was performed on a rotary steerable system BHA, which was meant to drill a long 8½" slant section at 90° inclination. At this inclination, the sag is more than predominant in the TVD uncertainty error budget. With no other information than the BHA description and the inclination, it was decided to drive a complete sensibility analysis on all parameters : a sag distribution was obtained (fig.9). The application of this result to the ISCWSA sag

corrected model enabled to reduce by a factor of 3 the position uncertainty and showed that geometrical position of the well - versus geosteering technics - was sufficient for the application.

Case study 2 - Post analysis

A full trajectory evaluation was performed on a 4 800 m well drilled mainly with steerable motors and VGS. The trajectory (fig.10 & fig.11) is composed of a kick off at 300m to reach 30° inclination, a long slant section in 12¼" and a final build in 8½" to near horizontal. The well path and drilling tools deployed on this case are representative of today's directional drilling applications. Table 10 presents all BHAs used. The calculations were performed with and without toolface data.

Fig.12 presents the evolution of the BHA sag correction along the trajectory (using toolface data). A 3 σ deviation of the basic ISCWSA sag error model, which should include 99.7% of the results, is also represented on the graphic. Results show that a standard sag error model largely underestimates sag at low inclination. The computed sag at 3000mMD is 0.5° with a residual error of 0.03°, at *one* σ s.d. . At the corresponding inclination 30°, the basic ISCWSA error model diagnoses a 0.1° (0.2° *sin I*) error - 0.3° for 3 σ deviation - underestimating the sag effect. As a result, there is a potential risk that the E.O.U does not contain the true well position.

Fig.13 and table 11 present respectively the evolution of the residual sag error (*one* σ deviation) and the different well positioning and uncertainty evaluation for :

- the basic ISCWSA error model
- the advanced sag model without toolface data
- the advanced sag model with toolface data

Results show (fig.13) that the basic ISCWSA sag model underestimates the sag error at low inclination. As a consequence, the size of the E.O.U can be too optimistic for wells close to vertical.

Results in table 11 have been displayed depending on whether we consider only one MWD tool along the trajectory, or whether we consider twelve legs associated to twelve different MWD tools. It is important to notice that considering twelve MWD tools instead of one does not affect the wellbore position but does reduce the TVD uncertainty by 59%, according to the ISCWSA error model. If it is true that there is no correlation between error values at survey stations in different legs in the same well, this assumption should be reconsidered for other error values - like sag - in order not to underestimate the E.O.U. As a consequence, if no sag correction has been applied, the basic MWD ISCWSA error model should be computed considering only one MWD tool.

At TD, correcting the surveys allowed a correction of the TVD of 5.3m, from 3684.1m to 3689.4m. In case Toolface data were available, the TVD uncertainty was reduced by 58%, from a *one* σ uncertainty (1/2 highside axis) of 7.55m to a *one* σ uncertainty of 3.20m. A 2 σ confidence level would give the TVD between 3683m to 3695.8m against a previous range from 3669m to 3699.2m.

At landing point (4160mMD) the TVD correction was corrected from 3614.3 to 3618.2 and the TVD uncertainty was reduced by 48% from a *one* σ uncertainty of 4.88m to a *one* σ uncertainty of 2.82m. Such a reduction opens ways for better drain placement in the pay zone.

Conclusion & Perspectives

Conclusion

This paper shows the potential of the application of 3D BHA models to address the sag & horizontal misalignment correction and error evaluation and the limits of ISCWSA sag modelisation. The new model is innovative while providing a residual error evaluation based on the system level of description. Effort was made to render this new model available for operational purposes. Case studies show a significant well path TVD re-positioning associated with a 50% range improvement of the TVD uncertainty.

The methodology presented in this paper can be easily extended. The list of parameters described by a mean value and a *one* σ standard deviation is detailed but not exhaustive. Connexion rigidity, hydrostatic parameters and intermediate doglegs, may be part of this list. The methodology can also be applied to continuous survey measurements. In this case, assumptions will change as surveys are taken while drilling on bottom ; drilling parameter such as WOB, friction or bit description are to be used to extend the input list of parameters.

Perspectives

BHA sag correction is a unique Advanced Surveying Process allowing significant refining of the TVD definition and uncertainty. With due consideration given to the production penalties associated with an off-target well bore, sag correction appears instrumental for effective wellbore placement definition in the reservoir. More specifically benefits foreseen for a near to real time sag correction process is the increase of precision of well placement during the landing phase of horizontal wells. On its own or combined with Geosteering techniques, sag correction helps to position the wells relative to fluid contacts improving thereof the net to gross through pay zone draining intervals.

Furthermore advanced sag correction is valuable to the overall well positioning process from the well engineering stage to the well execution phases and for the benefit of the construction of sound earth models and their pertinent use in reservoir management.

Safety of operations will also benefit from better borehole position knowledge and particular applications in HPHT drilling and design of related relief well contingency plans are well known.

This paper provides the ISCWSA group with an opportunity to progress on constant development of well positioning error models, in particular with regards to BHA misalignment error terms.

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Nomenclature

| | |
|----------|-----------------------------------|
| D | along-hole depth, m, ft |
| I | wellbore inclination, deg |
| A | wellbore azimuth, deg |
| HLA | borehole referenced frame |
| μ | mean of error value |
| σ | standard deviation of error value |
| ρ | correlation coefficient |
| i | indice of the parameter |

| Inc° / MD m | 1000 | 2000 | 3000 | 4000 | 5000 |
|-------------|------|------|------|------|------|
| 10 | 0.6 | 1.2 | 1.8 | 2.4 | 3.0 |
| 20 | 1.2 | 2.4 | 3.6 | 4.8 | 6.0 |
| 30 | 1.7 | 3.5 | 5.2 | 7.0 | 8.7 |
| 40 | 2.2 | 4.5 | 6.7 | 9.0 | 11.2 |
| 50 | 2.7 | 5.3 | 8.0 | 10.7 | 13.4 |
| 60 | 3.0 | 6.0 | 9.1 | 12.1 | 15.1 |
| 70 | 3.3 | 6.6 | 9.8 | 13.1 | 16.4 |
| 80 | 3.4 | 6.9 | 10.3 | 13.8 | 17.2 |
| 90 | 3.5 | 7.0 | 10.5 | 14.0 | 17.5 |

Table 1 : Degrees of inclination systematic error & impact on TVD (in metres) calculation for 0.2° sag error.

| A | Size | Type |
|----|------|-------------|
| 1 | 17½" | MOTOR + VGS |
| 2 | 17½" | MOTOR + VGS |
| 3 | 17½" | ROT |
| 4 | 17½" | ROT |
| 5 | 17½" | ROT |
| 6 | 12¼" | MOTOR + VGS |
| 7 | 12¼" | MOTOR |
| 8 | 12¼" | ROT + VGS |
| 9 | 12¼" | ROT |
| 10 | 12¼" | ROT |
| 11 | 12¼" | ROT |

Table 2 : List of BHAs for sensibility analysis.

| Parameters | Min | Max | Step | |
|---------------------------------|-------|------|------|--------|
| VGS Diameter (inch) | 16.25 | 17 | 0.25 | 4 |
| TFO (°) | 0 | 270 | 90 | 4 |
| Bent Angle (°) | 0.6 | 1.8 | 0.6 | 3 |
| Inclination (°) | 30 | 90 | 10 | 7 |
| Build/Drop (°/30m) | -5 | 5 | 5 | 3 |
| Turn (°/30m) | -5 | 5 | 5 | 3 |
| OVG (inch) | 0.25 | 0.75 | 0.25 | 3 |
| Sensor position (m) | 1 | 4 | 1 | 4 |
| Mud Weight (SG) | 1.2 | 1.6 | 0.4 | 2 |
| ID MWD/LWD (inch) | 2 | 3 | 1 | 2 |
| BHA configuration possibilities | | | | 145152 |

Table 3 : Configurations for 17½" BHAs.

| Parameters | Min | Max | Step |
|--------------------|-------|------|--------|
| Bent Angle (°) | -0.2 | +0.2 | 0.05 |
| Bent Position (m) | -0.2 | +0.2 | 0.05 |
| TFO (°) | -5 | 5 | 1 |
| OVG (inch) | -0.25 | 0.25 | 0.0625 |
| Inclination (°) | -5 | 5 | 1 |
| Build/Drop (°/30m) | -1 | 1 | 0.2 |
| Turn (°/30m) | -1 | 1 | 0.2 |
| Sensor Position(m) | -0.2 | +0.2 | 0.1 |
| Mud Weight (SG) | -0.2 | 0.2 | 0.05 |
| ID MWD/LWD (inch) | -1 | 1 | 0.5 |

Table 4 : Local variations around configurations.

| Sensor position (m) | | | | |
|---------------------|--------|--------|--------|--------|
| BHA | 2.0 | 3.0 | 4.0 | 5.0 |
| 1 | 0.517 | 0.470 | 0.413 | 0.348 |
| 2 | 0.530 | 0.551 | 0.547 | 0.524 |
| 3 | -0.077 | -0.112 | -0.139 | -0.155 |
| 4 | 0.370 | 0.283 | 0.187 | 0.084 |
| 5 | 0.585 | 0.511 | 0.422 | 0.322 |
| 6 | 0.338 | 0.291 | 0.235 | 0.176 |
| 7 | 0.316 | 0.268 | 0.213 | 0.155 |
| 8 | 0.342 | 0.268 | 0.182 | 0.089 |
| 9 | 0.297 | 0.270 | 0.222 | 0.159 |
| 10 | 0.345 | 0.271 | 0.185 | 0.093 |
| 11 | 0.296 | 0.273 | 0.229 | 0.169 |

Table 5 : Sag correction results for different sensor position on MWD.

| Parameters | Choice |
|---------------------|-------------|
| VGS Diameter (inch) | 17" or 12¼" |
| TFO (°) | 0 |
| Bent Angle (°) | 1.2 |
| Inclination (°) | 60 |
| Build/Drop (°/30m) | 0 |
| Turn (°/30m) | 0 |
| OVG (inch) | 0.5 |
| Mud Weight (SG) | 1.6 |
| ID MWD/LWD (inch) | 3 |

Table 6 : Configuration chosen to compute tables 5 & 7.

| Sensor position (m) | | | | |
|---------------------|--------|--------|--------|--------|
| BHA | 2.0 | 3.0 | 4.0 | 5.0 |
| 1 | 0.089 | 0.083 | 0.077 | 0.071 |
| 2 | -0.096 | -0.080 | -0.066 | -0.054 |
| 3 | -0.093 | -0.107 | -0.117 | -0.123 |
| 4 | 0.049 | 0.003 | -0.038 | -0.074 |
| 5 | 0.108 | 0.064 | 0.024 | -0.013 |
| 6 | 0.040 | 0.028 | 0.017 | 0.009 |
| 7 | 0.007 | 0.015 | 0.021 | 0.027 |
| 8 | 0.021 | 0.015 | 0.010 | 0.006 |
| 9 | 0.050 | 0.038 | 0.028 | 0.016 |
| 10 | 0.020 | 0.021 | 0.022 | 0.022 |
| 11 | 0.051 | 0.037 | 0.025 | 0.013 |

Table 7 : Horizontal misalignment correction results for different sensor position on MWD.

| Parameters | σ input error (+/-) | Residual Sag error | Residual Hor.Mis. error |
|--------------------|----------------------------|--------------------|-------------------------|
| TFO (°) | 5.0 | 10^{-3} | 2.10^{-3} |
| Bent angle (°) | 0.10 | 10^{-3} | 4.10^{-4} |
| Bent pos. (in) | 1.0 | 10^{-5} | 10^{-5} |
| Sensor pos. (in) | 2.0 | 2.10^{-3} | 10^{-4} |
| ID MWD (inch) | 0.25 | 2.10^{-3} | 10^{-4} |
| OVG (inch) | 0.125 | 2.10^{-3} | 3.10^{-3} |
| Inclination (°) | 0.50 | 3.10^{-4} | 2.10^{-4} |
| Build/Drop (°/30m) | 0.25 | 10^{-4} | 2.10^{-4} |
| Turn (°/30m) | 0.25 | 10^{-4} | 10^{-3} |
| Mud Weight (SG) | 0.05 | 10^{-3} | 10^{-5} |
| Residual Error | | 0.0038 | 0.0035 |

Table 8 : Contribution of different parameters to the Sag Residual Error.

| Name | Group | Default value |
|-------------------|--------------------|---------------|
| Gauge diameter | BHA design | 1/32" |
| Midblade position | BHA design | 0.1m |
| Sensor position | BHA design | 0.1m |
| Bent position | BHA design | 0.1m |
| Equi ID | BHA design | 1/8" |
| Bent angle | BHA design | 0.1° |
| Toolface | BHA setting | 3° |
| Overgauge | Well geometry | 1/32" |
| Mud weight | Drilling parameter | 0.05 |

Table 9 : Definition of uncertainties.

| Dia. | BHA |
|------|------------------------------------|
| 24" | BIT-ST.DHM-FS-XO-MWD-SST-DC-DC |
| 16" | BIT-ST.DHM-FS-XO-SST-MWD-SST-DC-DC |
| 16" | BIT-ST.DHM-FS-XO-SST-MWD-SST-DC-DC |
| 16" | BIT-ST.DHM-FS-XO-SST-MWD-SST-DC-DC |
| 12¼" | BIT-ST.DHM-XO-FS-MWD-DC-DC |
| 12¼" | BIT-ST.DHM-FS-SST-MWD-SST-DC-DC |
| 12¼" | BIT-ST.DHM-FS-SST-MWD-DC-DC |
| 12¼" | BIT-ST.DHM-FS-MWD-DC-DC |
| 8½" | BIT-ST.DHM-FS-MWD-FLEX-HWDP |
| 8½" | BIT-ST.DHM-VGS-FS-MWD-FLEX-HWDP |
| 8½" | BIT-ST.DHM-FS-MWD-FLEX-HWDP |

Table 10 : List of BHA used for full trajectory.

| | ISCWSA Sag | Sag without TF log | Sag with TF log | ISCWSA Sag + Legs | Sag without TF log + Legs | Sag with TF Log + Legs |
|-------------|------------|--------------------|-----------------|-------------------|---------------------------|------------------------|
| MD | 4910.0 | 4910.0 | 4910.0 | 4910.0 | 4910.0 | 4910.0 |
| TVD | 3684.1 | 3689.4 | 3689.4 | 3684.1 | 3689.4 | 3689.4 |
| N | -986.5 | -984.0 | -985.1 | -986.6 | -984.0 | -985.1 |
| E | 2388.4 | 2382.9 | 2383.0 | 2388.4 | 2382.9 | 2383.0 |
| σ_H | 7.55 | 4.15 | 3.20 | 3.08 | 1.95 | 1.71 |
| σ_L | 32.17 | 31.96 | 30.41 | 11.69 | 11.62 | 11.07 |
| σ_A | 7.10 | 4.95 | 3.17 | 5.02 | 4.61 | 4.35 |
| ρ_{HL} | -0.02 | -0.05 | -0.04 | -0.02 | -0.04 | -0.03 |
| ρ_{HA} | 0.69 | 0.22 | -0.50 | 0.32 | 0.26 | 0.12 |
| ρ_{LA} | -0.23 | -0.33 | -0.31 | -0.08 | -0.09 | -0.05 |

Table 11 : Trajectory positions and uncertainties for ISCWSA & paper model various assumptions.

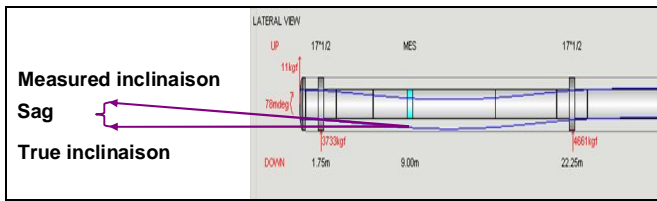


Fig.1 : Sag definition.

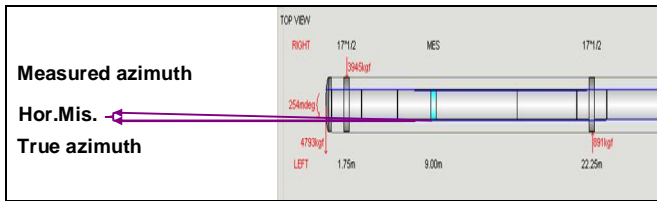


Fig.2 : Horizontal misalignment definition.

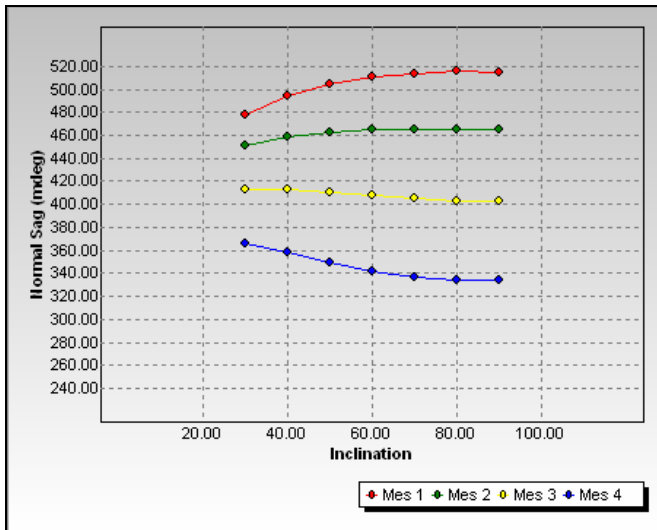


Fig.3 : Sag versus inclination for BHA 1.

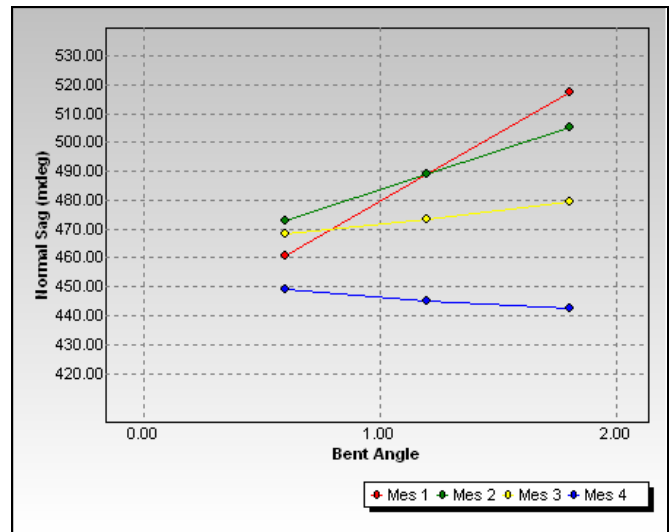


Fig.4 : Sag versus bent angle for BHA 1.

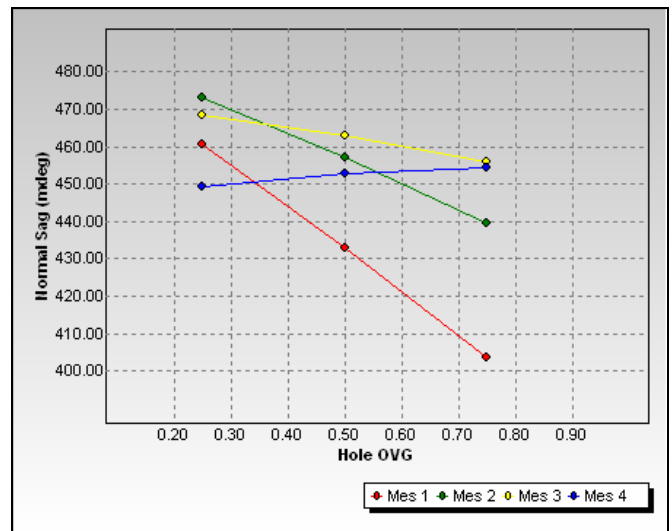


Fig.5 : Sag versus hole overgauge for BHA 1.

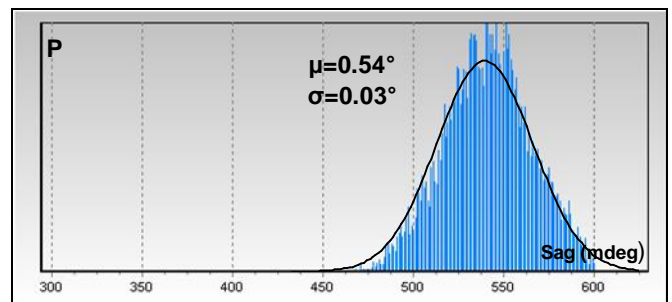


Fig.6 : Sag distribution for for a 17 1/2" BHA with a bent and a VGS, at 60° inclination and for the measurement sensor position at 2m (all other parameters unknown).

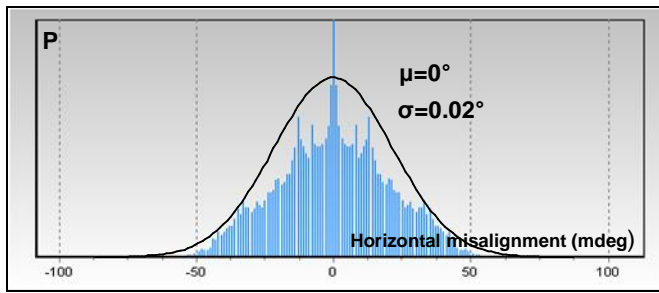


Fig.7 : Horizontal misalignment distribution for for a 17½" BHA with a bent and a VGS, at 60° inclination and for the measurement sensor position at 2m (all other parameters unknown).

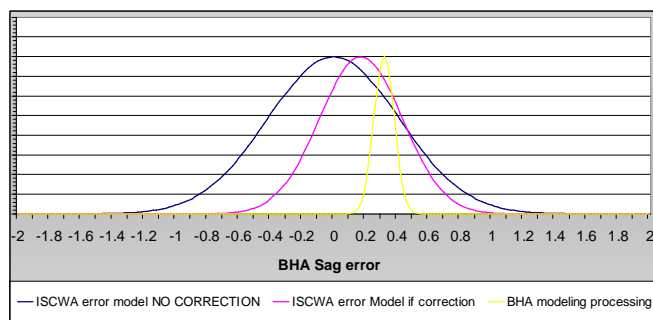


Fig.8 : Comparison between ISCWSA sag model and sag model issued from the Monte Carlo process.

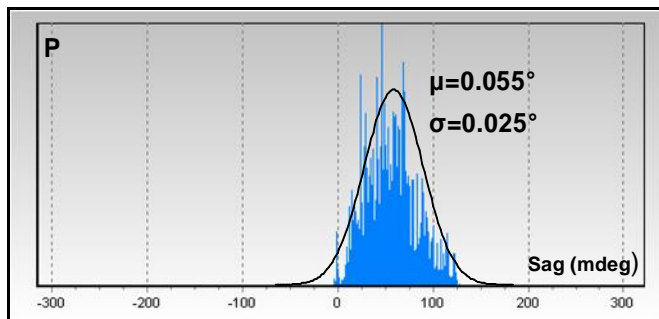


Fig.9 : Sag distribution of case study 1.

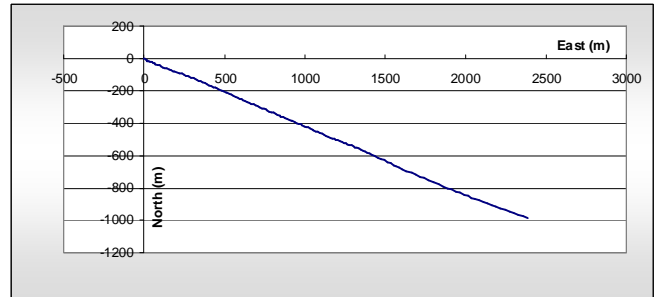


Fig.10 : Case study 2 trajectory - top view.

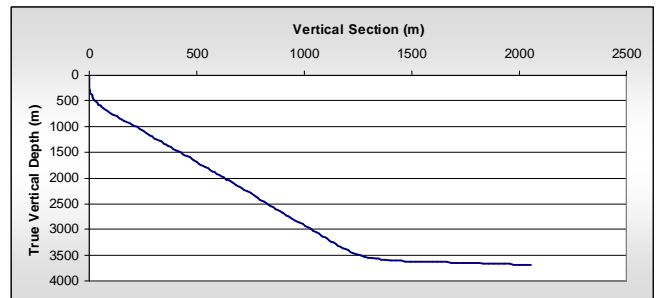


Fig.11 : Case study 2 trajectory - vertical section.

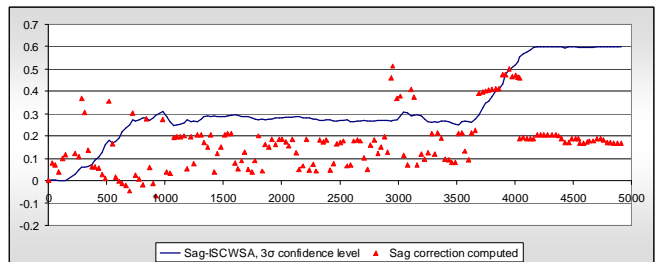


Fig.12 : Model sag correction & ISCWSA 3σ confidence level along trajectory for case study 2.

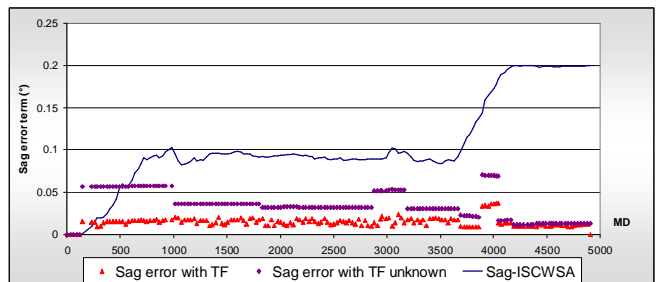


Fig.13 : Model (with & without TF log) & ISCWSA sag error along trajectory for case study 2.