**SPE 95611**

**Quantification of Depth Accuracy**

**Abstract**

Depth is a critical measurement in the economic development of a hydrocarbon asset. Almost all downhole activities, from making petrophysical measurements to setting packers, are performed remotely from surface.  The common reference for all such activities is depth. A depth error of as little as one foot vertically can have a financial impact counted in millions of dollars. However, despite the Industry’s heavy reliance on depth, its accuracy is poorly specified.

This paper describes an algorithm which allows proper quantification of along-hole depth uncertainty for all commonly used measurement systems.  Additionally, the algorithm includes correlation coefficients that allow quantification of the relative uncertainty between two competing measurements.

Although the physical measurement that is made at the rig site is normally along-hole depth, it is vertical depth that defines the relationship between sub-surface features. The quantification of along-hole measured depth uncertainty is therefore only a partial solution; it is also necessary to estimate vertical uncertainty.

The directional survey of the wellbore defines vertical depth for any along-hole depth, and directional surveys are routinely accompanied by an estimate of positional uncertainty. A method is described for combining the directional survey’s estimate of the wellpath’s vertical position uncertainty with the along-hole depth uncertainty associated with another downhole operation, resulting in a valid vertical uncertainty for that operation.

Adoption of the techniques described in this paper will result in valid estimates of depth uncertainty, which it is hoped will encourage better depth management practices, and result in more productive wells.

**Introduction**

There are frequent calls from the end users of formation evaluation (FE) logs for improved depth accuracy (1). Zones of interest within the wellbore identified from FE logs (e.g. zones targeted for production, injection, etc.) are subsequently exploited using tools and procedures that are also applied at specified depths. It is therefore desirable that improvements made to the measurement and management of FE depths are applied to all other depth measurements.

It has been proposed that rational improvement in depth measurement accuracy is not possible until current performance is better understood and properly quantified, and that the directional survey tool error models, commonly used in the Industry to predict wellbore position uncertainty, offer a useful starting point for modelling the performance of depth measurement systems(2). Survey tool error models quantify accuracy largely in terms of uncertainty or probability. Their outputs are position bias and position uncertainty, but these values are derived from estimates of the biases and uncertainties associated with the measured values of along-hole depth, inclination and azimuth. Along hole depth is more commonly referred to as measured depth (MD).

Several directional survey tool error models are described in the literature ( 3, 4, 5, 6, 7, 8). These models include MD terms, which can be extracted, revised and added to, to produce a dedicated MD error model. The most recent papers on the subject (7, 8) where written under the auspices of the Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA). The models described in these papers are now being widely adopted within the Industry, and are likely to become de facto standards. In 2004, the ISCWSA was assimilated into the SPE as its Wellbore Positioning Technical Section.

The new Technical Section saw the development of a comprehensive depth error model as a natural extension of the earlier error modelling work of the ISCWSA, and as something that might benefit the wider wellbore construction community. This paper is a first step in meeting the Section’s objective of providing a standard depth error model.

It should be noted that an error model is a necessary component of, and not a substitute for, good depth management practices.

**Basic principles of a survey tool error model**

The methodology applied to the modelling of survey tool accuracy is as follows.

1. All possible sources of error are identified.
2. The magnitude of each error source is determined; both its bias and standard deviation.
3. The magnitudes of most errors are partly dependent on the standard operating procedures (SOPs) used to calibrate and run the tools. This means that the model’s predictions are only valid as long as the SOPs are adhered to.
4. A weighting function is determined for each term. The function is designed to model, as closely as possible, how the term responds to its environment. Environmental variables might be the wellbore’s depth, attitude, temperature, pressure, etc. Variables used in a model’s weighting function must be included in the data that the model is to be applied to.
5. The propagation mode for both the bias and standard deviation component of each term is specified. This includes correlation station to station (measurement to measurement), log to log and well to well.
6. Typically propagation is limited to correlation coefficients of 1 and 0 (fully correlated and fully uncorrelated).
7. Different terms are normally assumed to be uncorrelated one to the other.
8. The models facilitate the reporting of absolute and relative accuracy.
9. The models are used to determine the minimum cost survey programme that will meet the well’s positional objectives.

All of the items above are relevant to a dedicated MD model.

A survey tool error model outputs position uncertainty in three dimensions. An MD model need only deal in one dimension, resulting in a scalar uncertainty acting along the wellbore’s trajectory at the measurement point.

It is possible to construct a general error model that includes sufficient terms to model all known depth measurement systems. By definition, the error term values in such a general model are unspecified. System specific error models are then defined by inserting appropriate values for selected terms.

The main focus of this paper is the general error model and its use. This model has been populated with representative error term values to provide illustrative examples of model results. However, quantification of term values is properly the responsibility of the companies providing depth measurements. The model proposed here offers a common framework for specifying depth accuracy.

**Error model verification**

An error model includes many assumptions relating to environmental conditions and SOPs. Its predictions are invalid if these assumptions are not true for any given application. Error models are used widely and routinely, and usually without specialist supervision. It is therefore necessary that robust quality control (QC) measures are used to assure consistency with error model assumptions. Since the QC measures are intended to assure compliance with the model, it follows that they should be derived from the model.

A directional survey station includes a measurement of inclination and azimuth, as well as MD. The inclination and azimuth are usually determined by measuring components of the earth’s gravity field and magnetic field or spin vector. These are all parameters for which we have reference values. The level of agreement between the tool’s measurement and the reference value is predicted by the error model, from which an acceptable maximum difference can be determined and used for QC purposes. The MD measurement lacks such a convenient external reference.

However, another standard QC measure used in directional surveying is comparison of two measurements of the same parameter. Whether the measurements are from the same tool, the same type of tool or different types of tool, their error models predict how well they should agree. Values for maximum acceptable disagreement can be determined and applied for QC purposes. This method of QC *can* be applied to MD. In fact, since MD is such a critical measurement, and since comparison of multiple measurements might be the only method of QC available, the acquisition, analysis and resolution of cross check measurements deserves careful attention.

The error models’ predictions are in terms of standard deviations, which can be converted to probabilities with the assumption of normal error distribution. The QC limits are quantified in the same terms, and are typically set at 2 or 3 standard deviations.

**The general error model**

Early survey error models (3) included only a single scale factor type depth uncertainty term. Williamson (7) described a set of 3 directional MWD measured depth error terms, categorized according to the relationship between the error magnitude and position along the wellbore (weighting function).

* Reference errors - constant magnitude
* Scale factor errors - constant unit strain error
* Stretch type errors - unit strain error proportional to vertical depth

The terms were defined as having a bias or a standard deviation, but not both.

Williamson recognised 4 modes of error propagation; Random, Systematic, Well by Well and Global. They are defined as:

* Random – uncorrelated from one measurement to the next
* Systematic – correlated from one measurement to the next within a continuous log
* Well by Well – correlated measurement to the next within a well
* Global – always correlated, including well to well

An example of a random reference error would be variable drill pipe stick up above rotary table. An example of a systematic scale factor error would be a calibration error of the tape used to measure the drill pipe. An example of a global stretch type error would be inexact compensation for thermal expansion of the drillstring.

Torkildsen (8) et al defined similar terms for wireline depth (logger’s depth) measurements, and introduced a fourth term; a systematic version of the reference error term, an example of which is wireline zero reference error.

In order to calculate relative uncertainty between drillpipe and wireline depths, we have found it necessary to add a fifth and sixth term. These are a Well by Well version of the scale factor type term and a Systematic version of the stretch type term. The proposed general error model therefore contains the following terms:

Reference errors – systematic

(e. g. reference to survey datum, wind on block height line, weather, tides/ballast, cable sag)

Reference errors – random

(e. g. waves, weather, tides/ballast, pipe stick-up, log picks)

Scale factor errors – systematic

(e.g. measurement temperature, weight-on-bit, pump-off, differential pressure, annulus viscous drag, nozzle thrust, rotary torque, wireline wheel wear, wheel slippage, wheel build-up, marking temperature, marking accuracy)

Scale factor errors – well by well

(e. g. tape measure)

Stretch type errors – systematic

(e. g. wireline inelastic stretch, elastic stretch, temperature, pressure, torsion)

Stretch type errors – global

(e. g. drillpipe elastic stretch, temperature, hydrostatic)

Approximate values for many of these terms can be found in the literature (3, 6, 7, 9, 10). These terms can be modified for coiled tubing or pipe-conveyed logging.

Where the sign of the error is known and the correction is not applied, the error takes on a bias in addition to uncertainty. For example, drillstring tension and thermal expansion may be expected to elongate a drillstring, therefore an uncompensated measurement will contain a positive bias, i.e. the most probable MD will be longer than the measured value. Each term may now be represented by a bias and a standard deviation.

Several of the values depend on operating conditions (e.g. floating rig versus fixed, drilling versus off-bottom) and on measurement corrections applied (e.g. basic depth correction(1, 2)). Each application, and combination of applications, represents a distinct error model. In order to apply the appropriate error model to a particular MD, it must therefore carry relevant acquisition details.

This is a simple categorization of depth errors, and more detailed analysis may reveal a need for additional terms in the future.

Since seismic horizons are often calibrated using well logs, their resulting true vertical depth (TVD) uncertainty may be related to the depth uncertainty associated with the corresponding logging tool.

**Tie-on of MD**

When one depth system is thought to be significantly more accurate than another, it may be advantageous to tie the two systems together at a common point. An example of this is tying drillpipe depth to that measured by a high-accuracy gyro at a casing point. When this is done, the combined uncertainties of the more accurate tool serve as the reference depth uncertainty for the second tool. Scale factor and stretch uncertainties for the second tool should then be reset to start from zero at the tie point and to be weighted by the incremental measured depth or TVD below this point. Biases from the two sources should be summed.

To the authors’ knowledge, handling of depth tie-on has not previously been described in the error model literature.

**System specific models**

 **Illustrative example 1**

As an example, we will consider the well profile described by ISCWSA Example Well number 1(7) at a measured depth of 5100m. At this point the well inclination is 60 degrees, and TVD is 3444m. We wish to estimate the depth uncertainty associated with a gas-oil contact which is assumed to appear at this depth on an LWD log, given that the LWD depth error magnitudes have been determined as follows:

Reference errors: Bias Std. Dev.

Systematic 0 0.1m

Random 0 1.3m

Scale factor errors:

Systematic -1.0m 3.1m

Stretch type errors:

Global +7.6m 2.5m

The resulting measured depth bias at the point of interest is the sum of the individual bias contributions, which is +6.5m. The measured depth uncertainty is the RSS of the independent components, ±4.1m at 1 σ. The best estimate of the MD of the feature is therefore 5106.5m, with a 68% confidence that it is within 4.1m of this depth.

**Calculation of relative MD uncertainty, log to log**

During the course of drilling a well, depth measurements may be made by several independent systems. An obvious example would be the use of drillpipe length measurements for MWD and LWD, with independent wireline depth measurements. When both systems measure the depth of the same point, if the biases and uncertainties associated with both measurements are known, this information can be used to validate the depth(2).

 **Illustrative example 2**

In the same example well, a wireline log might indicate the assumed gas-oil contact at an apparent depth of 5115m, 15m deeper than the feature appeared on LWD. Suppose that the wireline depth uncertainties are given as:

Reference errors: Bias Std. Dev.

Systematic -0.1m 0.1m

Random 0m 1.3m

Scale factor errors:

Systematic 0m 1.3m

Stretch type errors:

Systematic 0m 1.2m

The wireline depth measurement shows an overall bias of -0.1m and a standard deviation of 2.2m. After adjusting the depths for bias, the corrected LWD depth is 5106.5m and the corresponding wireline depth is 5114.9m, a difference of 8.4m. Since the LWD depth measurement has a 1-σ uncertainty of 4.1m and the corresponding wireline uncertainty is 2.2m, the relative uncertainty is √(4.12 + 2.22) = 4.7m at 1 σ. The 8.4m discrepancy between wireline and LWD is at 1.79 σ, which means that the error models predicted that there was a 7% probability that the two measurements would disagree by this much or more. Although this level of disagreement does not indicate a gross error in either measurement, it comes close to indicating marginal performance by one of the depth systems. Over multiple runs, the frequent occurrence of comparisons falling between 2 and 3 σ would be of concern.

**Calculation of vertical uncertainty**

It is frequently necessary to determine the TVD uncertainty of a log feature. This typically has two components; one resulting from logging depth uncertainty, and the other representing the TVD component of the positional uncertainty of the wellpath along which depth is measured. The former is simply calculated as measured depth uncertainty multiplied by the cosine of local inclination. The latter can be calculated from the covariance matrix describing uncertainty of the wellbore survey, taking care to compute the uncertainty at an assigned depth (4, 7). When these two uncertainties are derived from different tool runs, most of their components are independent and they should be combined as though uncorrelated. The wellpath uncertainty includes a component describing the uncertainty of the MD reference point (e.g. drill floor relative to mean sea level).

 **Illustrative example 3**

Using the same example from ISCWSA Well 1 at 5115m MD, the wireline MD uncertainty was calculated as 2.2m at 1σ. Since the hole is inclined at 60 degrees, the TVD uncertainty resulting from logging depth uncertainty is 2.2 ·cos60° = 1.1m. This is the TVD uncertainty of the wireline log pick with respect to the wellpath. Similarly the wireline MD bias of –0.1m corresponds to a TVD bias of -0.1m.

The wellpath has its own TVD uncertainty, which is derived from analysis of the survey data. In this case the absolute TVD uncertainty of the wellpath at a measured depth of 5115m might be 4.0m at 1σ (as calculated for an assigned depth of exactly 5115m). The absolute TVD uncertainty of the gas-oil contact as determined from the wireline pick is 4.1m, which is a combination of 1.1m from logging TVD uncertainty and 4.0m from wellpath TVD uncertainty, combined by RSS.

**Calculation of relative vertical uncertainty, well to well**

 **Illustrative example 4**

Now suppose that the gas-oil contact had appeared at a depth of 3455m in a nearby vertical well. We are interested in finding the relative uncertainty between the TVD of the GOC in the two wells. Wireline MD errors in the vertical well were:

Reference errors: Bias Std. Dev.

Systematic -0.1m 0.1m

Random 0m 1.3m

Scale factor errors:

Systematic 0m 0.9m

Stretch type errors:

Systematic 0m 0.8m

After correcting for bias, the GOC is identified at an MD of 3454.9m which, with an uncertainty estimated at 1.8m. This being a vertical well these values apply equally to TVD.

The inclined well found the same feature at a TVD of 3451.5m with a 1 σ uncertainty estimated at 4.1m. The relative TVD uncertainty is √(1.82 + 4.12), which is 4.5m 1 σ. The discrepancy of 3.5m is equivalent to 0.76 σ. In other words, the error models predicted that there was approximately a 55% probability of agreement to within 3.5m.

If the two wells had been drilled from the same drilling pad, offshore platform, etc. it is likely that the MD reference uncertainty component of the two wellpath survey uncertainties would be common (i.e. correlated) and therefore would be excluded from the calculation of relative TVD uncertainty.

**Conclusions**

A framework has been described for implementing a MD error model.

The correct handling of MD errors across tie-ons between different depth systems in the same well has been defined.

A method has been described for the conversion of MD uncertainty to absolute and relative TVD uncertainty.

Together, these methods contribute to the consistent treatment of all depths used in well operations.

The error model is not a solution in itself, but is a useful tool which facilitates good depth management practices.

It has been suggested that measurements that fall outside of their error model’s 3 σ uncertainty prediction can be assumed to indicate the presence of gross error.

Further effort is required to validate the error term values.

**Acknowledgements**

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