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Enhanced Wellbore Placement Accuracy Using Geomagnetic In-Field Referencing and Multi-Station Correction

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Summary

Reduced lateral spacing in congested oil and gas fields requires advanced techniques to prevent collisions while drilling. Anti-collision separation factors depend on the accuracy of the steering technology employed. Geomagnetic In-Field Referencing (IFR) with Multi-Station (MS) correction improves lateral steering accuracy by about 50% (See Table 1 and Table 2). This technique enables the drilling of straighter wellbores with fewer deviations and closer spacing.

Most horizontal wells are steered using measurement while drilling (MWD). The MWD tool in the bottom hole assembly (BHA) houses an accelerometer and a magnetometer to determine the inclination and magnetic azimuth of the drill bit. This magnetic azimuth is then converted into a true (geographic) azimuth using a global geomagnetic reference model. Inaccuracies in the global geomagnetic model and magnetic interference are the largest sources of error in wellbore positioning by MWD. Local crustal magnetic anomalies and interference from the drill string cause significant distortions in the strength and direction of the natural geomagnetic field. These distortions can be reduced significantly by using a local 3D geomagnetic IFR model and by subsequently applying an MS correction to the raw survey measurements.

IFR models are computed from high-resolution satellite and aeromagnetic measurements of the geomagnetic field. A new constellation of low-orbiting satellites provides accurate specification of the long-wavelength geomagnetic field. This information is complemented by local high-resolution airborne magnetic surveys. Once the natural geomagnetic field is accurately specified by IFR, magnetic interference from the drill string can be removed by the Multi-Station correction.

This paper highlights the benefits of IFR and MS corrections on specific examples from Texas and North Dakota. Azimuth corrections of 1 degree lead to changes in wellbore position of 200 feet and more at TD. Improved specification of the strength and dip of the geomagnetic field further enables tighter quality control of MWD surveys. The improved accuracy of the IFR+MS technique is quantified in the new set of Operator Wellbore Survey Group (OWSG) tool code MWD+IFR+MS. This tool code reduces ellipses of uncertainty by about 50%, thereby facilitating well planning and enabling closer spaced laterals and in-fill drilling.

Introduction

Well placement by Measurement While Drilling (MWD) uses the direction of Earth's gravity and magnetic field as a natural reference frame. This requires accurate knowledge of the magnetic field direction and strength in the wellbore. Local high-resolution In-Field Referencing (IFR) models have been produced for various unconventional resource plays, including Eagle Ford, Bakken, DJ and Permian Basins. Here we first report on the production of the IFR models for Eagle Ford and Bakken, and then show how these models can be used to improve the accuracy of wellbore placement and reduce ellipses of positional uncertainty.

Ellipses of uncertainty

The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) maintains an error model, which provides the framework for the computation of ellipses of uncertainty (EOU) of the wellbore trajectory. The error model is described in detail by Williamson (2000)**.** As a further input, it requires so-called *tool codes*, which quantify the errors of particular MWD tools and corrections applied to the survey data. The Operator Wellbore Survey Group (OWSG), a sub-committee of ISCWSA, has recently undertaken a large effort to consolidate the numerous tool codes used throughout the industry. This consolidated set is referred to as the OWSG set of tool codes. Table 1 and Table 2 summarize the resulting uncertainties at TD of typical L-shaped wells in Eagle Ford and Bakken for eastward, southeastward and southward wellbore orientations. It can be seen that the uncertainties in Bakken are somewhat larger, due to the lower strength of the Earth's horizontal magnetic field at higher latitudes.

Table 1: Lateral uncertainties at 2.79 sigma for L-shaped wells at TD in Eagle Ford

Well Orientation	Lateral Length	MWD	MWD+IFR1	MWD+IFR1+MS
	(ft)	(ft)	(ft)	(ft)
Eastward	11000	± 439	± 390 (-11%)	± 173 (-61%)*
Southeastward	11000	± 387	± 329 (-15%)	± 160 (-59%)
Southward	11000	± 259	± 161 (-38%)	± 129 (-50%)

*With limitations

Table 2: Lateral uncertainties at 2.79 sigma for L-shaped wells at TD in Bakken, ND

Well Orientation	Lateral Length	MWD	MWD+IFR1	MWD+IFR1+MS
	(ft)	(ft)	(ft)	(ft)
Eastward	11000	± 615	± 569 (-7%)	± 229 (-63%)*
Southeastward	11000	± 532	± 478 (-10%)	± 207 (-61%)
Southward	11000	± 318	± 217 (-32%)	± 154 (-51%)

*With limitations

Generally, one can see that the large uncertainty of plain MWD can be reduced by about 15-30% using IFR, while further applying Multi-Station Analysis can reduce the uncertainty by over 50%.

In-Field Referencing (IFR)

The objective of In-Field Referencing is to use local magnetic field measurements to produce an accurate 3-dimensional magnetic reference model for the drilled volume. The most cost-effective method is to use aeromagnetic surveys, which have been employed for over 50 years to map geology and tectonic features. Earlier IFR methods used Fast Fourier Transforms (Dean, W.C. 1958, Russell, J.P. et al. 1995) or Equivalent Source techniques (Dampney, N.G. 1969) on plane 2D grids. A recent analysis showed that these grid methods can have significant errors because they assume that the crustal magnetic anomalies are entirely contained within the grid. A superior approach is to tie the grid into the global crustal field inferred from satellite measurements and represent the solution in terms of high-degree ellipsoidal harmonic functions (Buchanana, A. et al. 2013, Maus, S. 2015, Poedjono, B. et al. 2012a, 2012b)

In the Bakken, a suitable airborne survey of the Williston Basin was already available (Figure 1), while for Eagle Ford a new survey had to be flown (Figure 2). In order to arrive at a complete representation of the geomagnetic field, this crustal anomaly survey then has to be combined with main and disturbance field models as follow:
The natural geomagnetic field can be divided into four contributions:

1. The main field generated by the geodynamo in the Earth's core. For practical purposes, the main field is defined as the internal field of spherical harmonic degree 1-15, excluding time varying fields with periods shorter than about 2 years. The change of the main field over time is referred to as the secular variation.
2. The crustal field caused by magnetic minerals in the Earth's crust. In practice, the crustal field is defined as the static internal field of spherical harmonic degree 16 and higher. Its change over time is negligibly small.
3. The steady external field of the magnetospheric ring current – a current caused by charged particles circulating the Earth at a distance of a few ten thousand kilometers. The contribution of this current during

magnetically quiet times, slowly changing with the 11-year solar cycle, is included in global geomagnetic reference models.

4. Magnetic disturbance fields caused by electric currents in near-Earth space, and corresponding "mirror-currents" induced in the Earth and oceans. These fields are not covered by the model. However, they are accounted for in the assessment of geomagnetic reference field uncertainties.

Our IFR method first produces an accurate "baseline" magnetic field for a given reference date. The baseline accounts for contributions (1) to (3), namely the main, crustal and steady external field. This baseline for the reference date is supplied as an IFR model together with an IFR Calculator to the drilling engineer. The baseline can then be extrapolated to any desired drilling date using the main field model embedded into the IFR calculator.

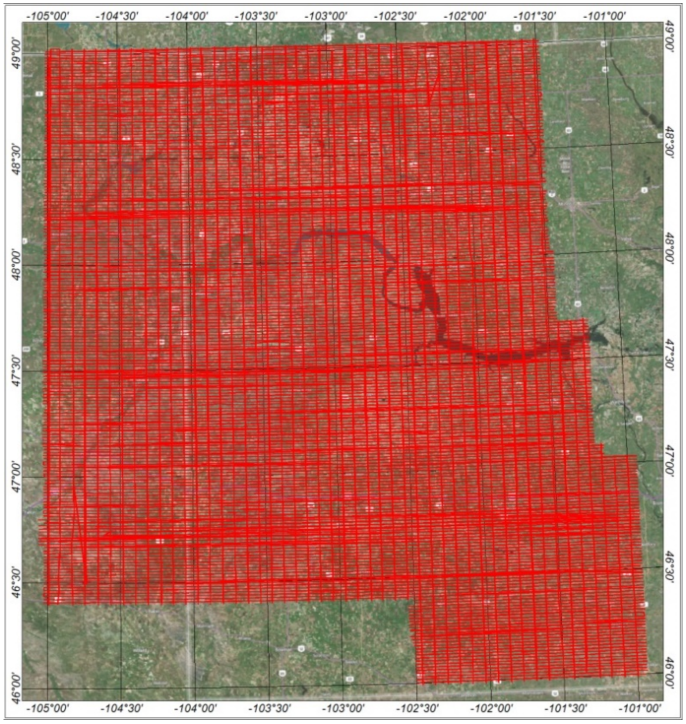

Figure 1: Flight lines of the Williston Basin aeromagnetic survey

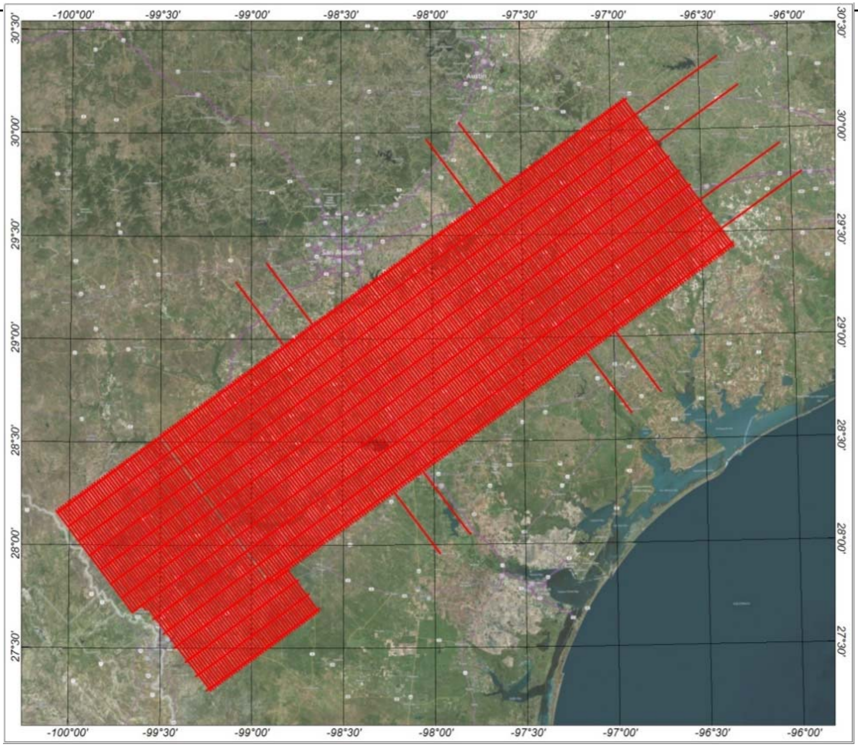

Figure 2: Flight lines of the Eagle Ford aeromagnetic survey

Figure 3 and Figure 4 show the baseline declinations at the typical TVD of the lateral sections for Bakken and Eagle Ford. The left side shows the main field only, while the complete baseline given by our IFR model is shown on the right. The IFR model includes the crustal field, which makes a significant contribution to the declination in the project area. The local declination anomaly is the difference between the two maps, computed by subtracting the main field to degree 15 (left in Figure 3 and Figure 4) from the complete field given by the baseline IFR model (right in Figure 3 and Figure 4).

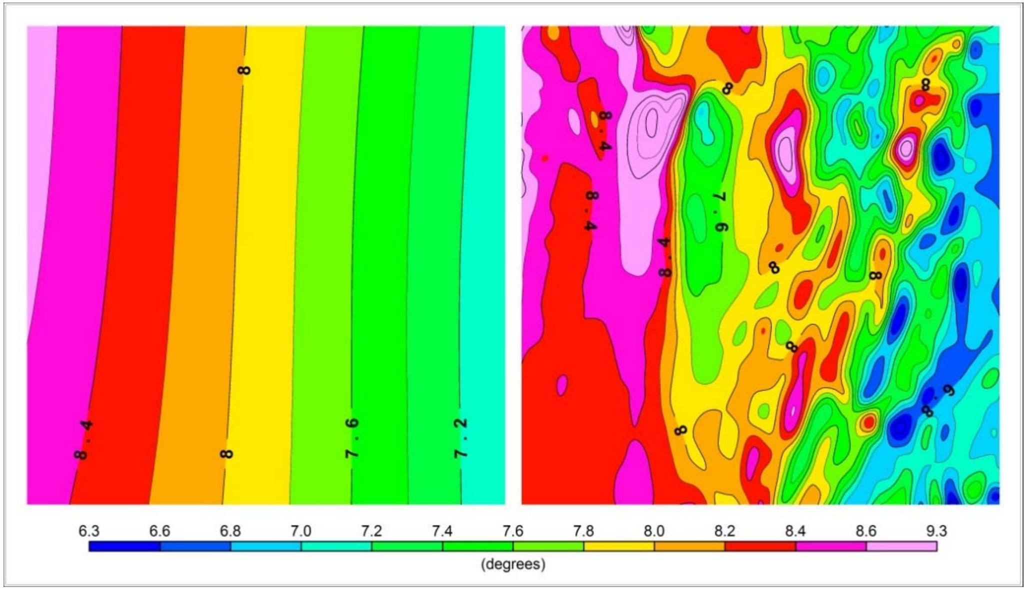

Figure 3: Geomagnetic declination at a depth of 10,000 ft, as given by a global main field model (left) compared with the IFR model derived from the Williston Basin aeromagnetic survey (right). Declination differences exceed 1° in some areas.

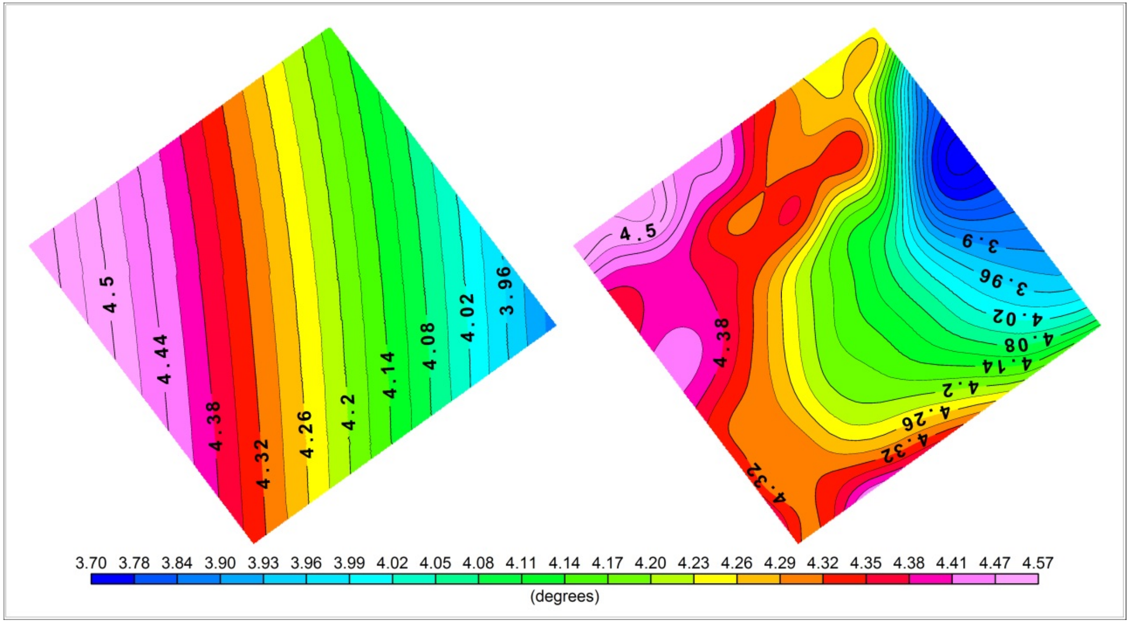

Figure 4: Geomagnetic declination in Eagle Ford at a depth of 14,000 ft, as given by a global main field model (left) compared with the IFR model derived from the Eagle Ford aeromagnetic survey (right).

As seen from the comparisons in Figure 3 and Figure 4, the differences in declination are usually of the order of 0.5° and can exceed 1° in some areas. Other unconventional resource plays, such as in the Permian Basin and in Alberta have even larger declination anomalies of several degrees.

Multi-Station analysis

Multi-Station Analysis (MSA) has been widely accepted in the drilling industry as a powerful and valid tool for enhancing the quality of MWD surveys (Nyrnes et al. 2009). When the background magnetic and acceleration reference fields are known with a high degree of accuracy, it is possible to correct MWD magnetic surveys using MSA. MSA is a mathematical method for reducing the effects of drillstring magnetic interference, poor calibration, and sensor errors of certain types which are typically expressed as bias or scale errors in MWD instruments. The combination of IFR and MSA offers the highest level of lateral accuracy and quality control for MWD surveys (Nyrnes et al. 2005, Maus, S. 2015).

It is possible to estimate the error from each accelerometer and magnetometer measurement acquired during an MWD survey by comparing those values against the expected unit vectors of the gravitational and magnetic reference fields. When these residual errors are determined over multiple surveys, the method of least squares can be used to estimate the bias and scale error of each sensor. Once these biases and scale factors are resolved, one can apply corrections to the raw sensor measurements and re-compute the azimuth, which minimizes the effects of the resolved error terms. The number and type of error terms that may be resolved is dependent on numerous factors such as wellbore direction, geometry, location, and number of surveys (Nyrnes and Torkildsen 2005). In order to avoid unrealistic corrections, it is critical that certain minimum requirements are satisfied when determining which error terms may be resolved (Nyrnes et al. 2009). Some of these requirements include sufficient tool face variation, adequate geometrical variation, and enough survey stations to reduce effects attributed to random noise.

One of the most common types of MWD survey errors that occurs when drilling is a result of drillstring magnetic interference. It is well known in the industry that the steel in drill pipe and the bottom hole assembly (BHA) may become magnetized and create a small disturbance to the background magnetic field. This is the reason MWD tools are mounted inside non-magnetic drill collars. However, depending on the length of the non-magnetic spacing and the pole strength of the BHA and drill pipe components, often times there is still enough magnetic interference to affect the MWD measurements. This is a particular concern because when the axial magnetic interference from the drillstring is oriented in any direction other than magnetic north or south, then the resulting measurement will introduce an azimuth error. Application of a single-station axial (or short collar) correction is a typical approach to reducing error from axial magnetic interference. However, the short collar correction approach is limited because it is based on a single survey. Therefore, it cannot distinguish differences between reference error, axial interference, cross-axial biases/scales, or sensor noise. MSA is a much more powerful method for determining these differences. Thus, MSA is considered the best approach for resolving these errors and generally provides a more realistic correction.

Figure 5 and Figure 6 show the azimuth measurements of two example horizontal wells from the Eagle Ford and Bakken drilled in the south-eastwardly direction. A multi-station analysis of the raw MWD survey data revealed an axial magnetic interference component of 445 nT for the first well and -257 nT for the second well. This order of magnitude for drillstring interference is commonly accepted when drilling, but due to the direction of the wellbore with respect to the Earth's magnetic field, the resulting azimuth error is approximately 0.65° for the first well and is -0.63° for the second well. This offset can be seen as the average difference between the raw azimuth and the MSA corrected azimuth in Figure 5 and Figure 6. Lateral wellbore sections commonly extend to 10,000' for a typical horizontal wellbore drilled in North Dakota and Texas. Therefore, a 0.65° error and a 0.63° error would result in a lateral displacement of 113' and 110' at total depth (TD), respectively. This lateral misplacement could have significant consequences on collision avoidance, reservoir recovery, and drilling permit regulations.

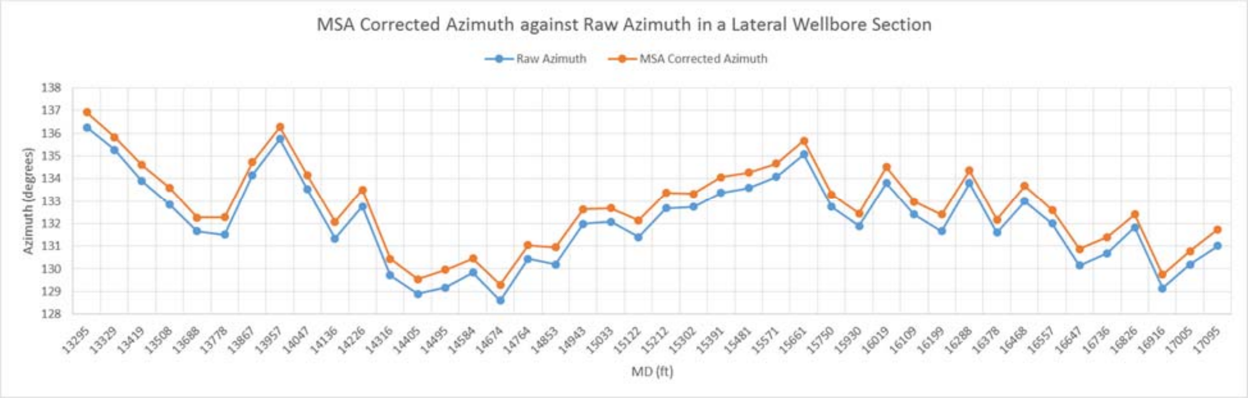

Figure 5: Comparison of raw azimuth and MSA corrected azimuth values from the lateral hole section of a horizontally drilled well in the Eagle Ford. The average azimuth correction is approximately 0.65 degrees which represents a lateral error of 113' at TD of a 10,000 ft hole section.

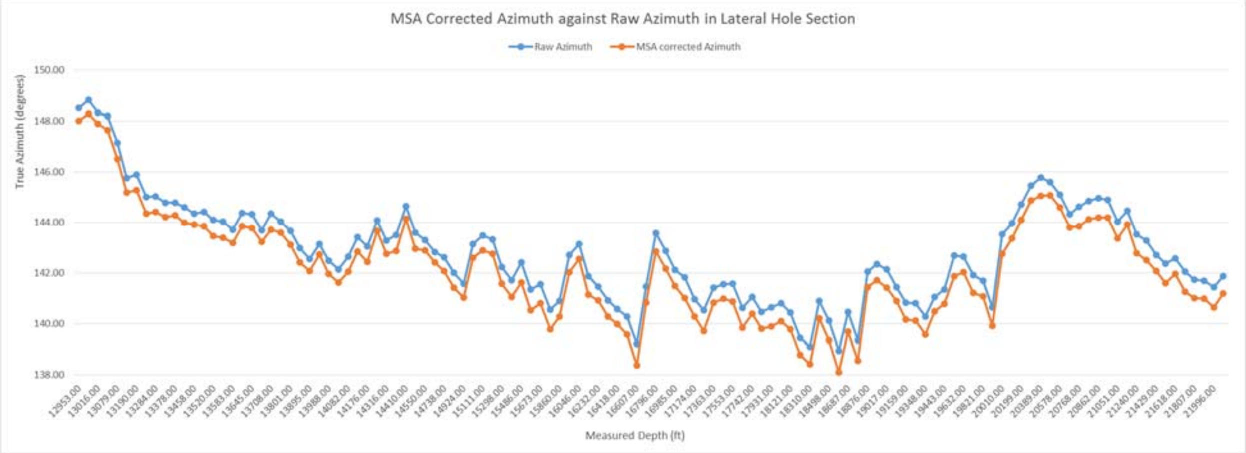

Figure 6: Comparison of raw azimuth and MSA corrected azimuth values from the lateral hole section of a horizontally drilled well in the Bakken. The average azimuth correction is approximately -0.63 degrees which represents a lateral error of 110' at TD of a 10,000 ft hole section.

It is interesting to note that the magnitude of azimuth error is relatively similar for both of these cases even though the magnitude of axial interference was about 73 percent higher in the Eagle Ford well. This is explained by the differences in the magnetic reference field at these two locations. In the Eagle Ford case, the dip angle was 57.6° and the declination was 4.4°. In contrast, the Bakken dip angle was 73° and the declination was 7.6°. These differences change how the axial interference of the drillstring impacts the resultant magnetic vector that the MWD tool measures. In the Bakken, the horizontal component of the reference field is smaller, so it is more easily influenced by the axial interference. Also, the angle between the reference declination and the direction of the Bakken well is closer to perpendicular than in the Eagle Ford well. As this angle approaches 90°, the effect on the measured azimuth is maximized. These examples show that the effect of axial interference in a horizontal well is highly dependent on the magnitude of the interference, the strength of the reference field horizontal component, and the angle between the reference field and the wellbore direction.

Figure 7 shows a comparison of the well path trajectories for the same wellbore computed from raw surveys and MSA corrected surveys. The vertical section of this wellbore is 4060' and the difference in lateral position is approximately 60' at TD. One can see that the corrected well path sets along the outer edge of the original well path's ellipses of uncertainty. However, now that the MSA correction has been applied, the new error ellipses associated with the MWD+IFR+MS tool code are further reduced.

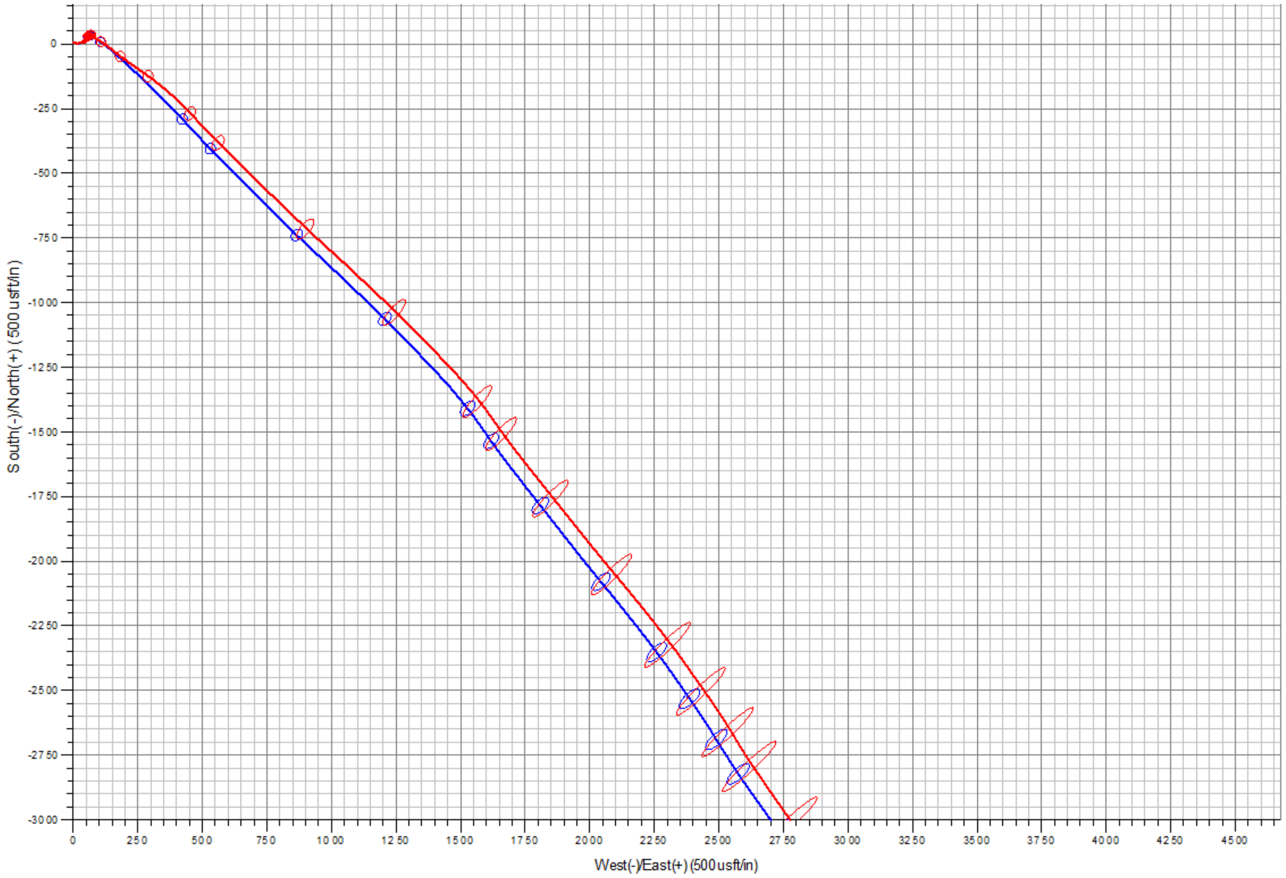

Figure 7: Plan view of a horizontally drilled well in the Bakken. The blue wellbore shows the path of the red wellbore after MSA corrections were applied to the raw surveys. The blue ellipses of uncertainty represent the MWD-IFR-MS tool code and the red ellipses of uncertainty represent the standard MWD tool code.

MSA also allows for better survey quality control. Looking at Figure 8, one can see the raw B total values and the MSA corrected B total values plotted against the IFR reference field and the IGRF reference field. If an MWD operator was using the IGRF reference model, they could wrongly assume that their B total values were off by an average 500 nT, when in reality, the true B total values are only off by an average of 375 nT compared to the more accurate IFR model. Since MSA demands the use of a high definition magnetic reference model, one can avoid applying incorrect axial corrections due to poor reference values. Once the MSA correction has been applied to the raw values, the corrected B totals fall much closer to the IFR reference field strength. This allows for tighter QC limits (field acceptance criteria), which provide a higher level of confidence that the surveys are free of significant errors and reduces the magnitude of lateral uncertainty.

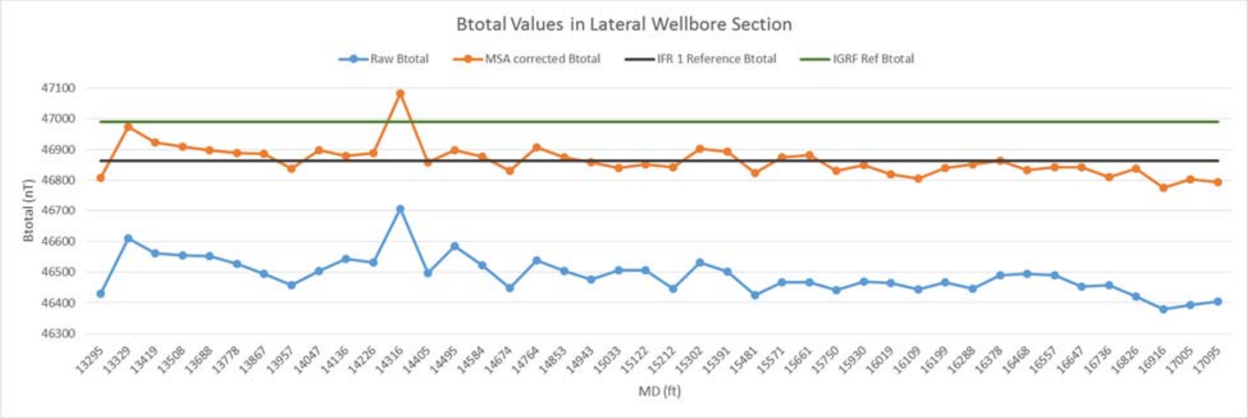

Figure 8: Comparison of raw Btotal and MSA corrected Btotal values from the lateral hole section of a horizontally drilled well in the Eagle Ford. The Total Field reference values are also shown for an IFR 1 model and the IGRF-12 model.

Figure 9 shows the Dip values correlated to the same data used in Figure 8. Again, one can see that the corrected Dip values fall much closer to the more accurate IFR model reference Dip than the original raw Dip values. Like before, this allows for tighter QC limits and higher confidence in the MWD survey accuracy.

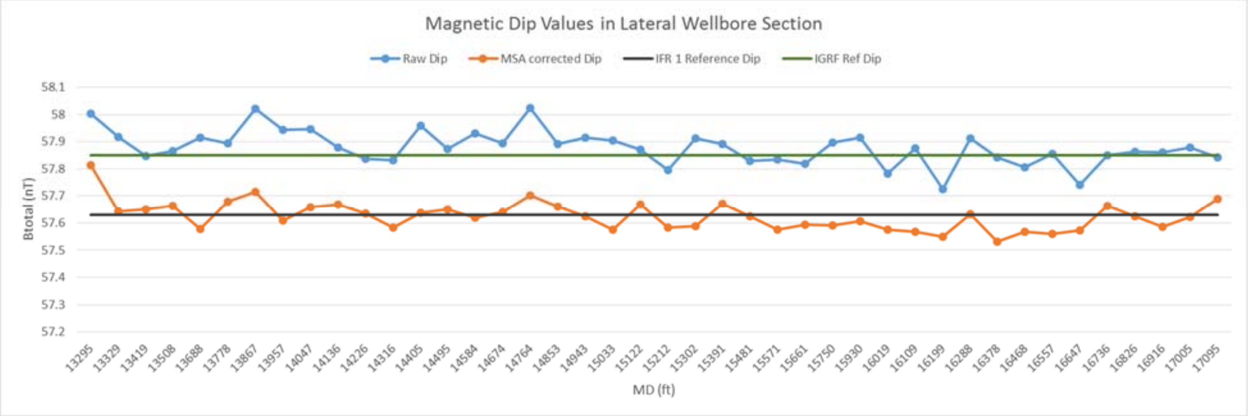

Figure 9: Comparison of raw Dip and MSA corrected Dip values from the lateral hole section of a horizontally drilled well in the Eagle Ford. The Dip reference values are also shown for an IFR 1 model and the IGRF-12 model.

Conclusions

Using IFR magnetic models for multi-well horizontal drilling offers many benefits to drillers that standard geomagnetic models are unable to provide. IFR models use high resolution magnetic data that capture crustal anomalies often found in oil fields. Since the magnetic field is the greatest source of lateral uncertainty in MWD surveys, IFR is an effective solution for significantly reducing this uncertainty. Highly accurate reference values result in more accurate azimuth measurements from MWD tool, and they also enable enhanced survey management such as MSA.

Once the reference field is known with a high degree of confidence, application of MSA can be very effective at identifying and correcting systematic errors attributed to drillstring magnetic interference, poorly calibrated MWD tools, and bias/scale errors in the raw accelerometer and magnetometer measurements. This creates a platform for higher level quality control of survey data, because we know with greater confidence what the raw MWD B total and Dip measurements should be.

Implementing IFR and MSA as part of the driller's standard survey management program are excellent for achieving the greatest MWD survey accuracy possible. Attaining this higher accuracy in wellbore placement is highly advantageous to drillers because it reduces collision risk with offset wells, minimizes legal risk associated with lease line boundaries and permit regulations, and maximizes wellbore value by optimizing reservoir drainage.

References

Buchanan, A., Finn C.A., Love, J.J., Worthington, E.W., Lawson, F., Maus, S., Okewunmi, S., Poedjono, B. 2013. Geomagnetic Referencing – The Real-Time Compass for Directional Drillers. *Oilfield Review* **25** (3): 32-47.

Dampney, N.G. 1969. The Equivalent Source Technique. *Geophysics* **34** (1): 39-53.

Dean, W.C. 1958. Frequency Analysis for Gravity and Magnetic Interpretation. *Geophysics* **23** (1): 97-127.

Maus, S. 2015. Managing Main and Crustal Magnetic Fields and New Developments in Global Magnetic Modeling. Presentation at the ISCWSA Meeting of the SPE/IADC Drilling Conference and Exhibition, London, 17-19 March

Nyrnes, E. et al. 2009. Minimum Requirements for Multi-Station Analysis of MWD Magnetic Directional Surveys. Paper SPE/IADC 125677 presented at the SPE/IADC Middle East Drilling Technology Conference & Exhibition, Manama, Bahrain, 26-28 October

Nyrnes E., Torkildsen, T. 2005. Analysis of the Accuracy and Reliability of Magnetic Directional Surveys. Paper SPE 96211 presented at the SPE/IADC Middle East Drilling Technology Conference and Exhibition, Dubai, UAE, 12-14 September 2005.

Poedjono, B. et al. 2012a. Successful Application of Geomagnetic Referencing for Accurate Wellbore Positioning in a Deepwater Project Offshore Brazil. Paper IADC/SPE-150107-PP presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, 6–8 March

Poedjono et al., 2012b, Addressing Wellbore Position Challenges in Ultra-Extended-Reach Drilling in Russia's Far East, Paper SPE-160784-PP, presented at the SPE Russian Oil & Gas Exploration & Production Technical Conference and Exhibition held in Moscow, Russia, 16–18 October 2012.

Russell, J.P. et al. 1995. Reduction of Well-Bore Positional Uncertainty through Application of a New Geomagnetic In-Field Referencing Technique. Paper SPE 30452 presented at the SPE Annual Technical Conference and Exhibition, Dallas, 22-25 October.

Williamson, H.S. 2000. Accuracy Prediction for Directional Measurement While Drilling. *SPEDC* **15** (4): 221-233.