High Definition Geomagnetic Models: A New Perspective for Improved Wellbore Positioning

Stefan Maus and Manoj C Nair, NOAA’s National Geophysical Data Center and CIRES, University of Colorado; Benny Poedjono, SPE, Schlumberger; Shola Okewunmi, SPE, Chevron Corporation; Derek Fairhead, GETECH; Udo Barckhausen, German Federal Institute for Geosciences and Natural Resources; Peter R. Milligan, Geoscience Australia, and Jürgen Matzka, Technical University of Denmark.

Abstract

Earth's gravity and magnetic fields are used as natural reference frames in directional drilling. The azimuth of the bottomhole assembly is inferred by comparing the magnetic field measured-while-drilling (MWD) with a geomagnetic reference model.

To provide a reference of sufficient quality for accurate well placement, the US National Geophysical Data Center (NGDC), in partnership with industry, has developed high-definition geomagnetic models (HDGM), updated regularly using the latest satellite, airborne and marine measurements of the Earth's magnetic field. Standard geomagnetic reference models represent the main magnetic field originating in the Earth's liquid core, but the new models additionally account for crustal magnetic anomalies, which constitute a significant source of error in directional drilling. NGDC maintains a public archive of global ship and airborne magnetic field measurements. These are compiled into a global magnetic anomaly grid and expanded into ellipsoidal harmonics. The harmonic expansion coefficients are then included in the high-definition models to accurately represent the direction and strength of the local geomagnetic field. The latest global model to degree and order 720 resolves magnetic anomalies down to 28 km half-wavelength, achieving more than an order-of-magnitude improvement over previous models.

A side-by-side comparison of different on- and off-shore regions shows the high level of local detail represented in the new model. Accounting for a larger waveband of the geomagnetic spectrum significantly improves the accuracy of the reference field. This directly benefits the reliability of the well azimuth determination. We further demonstrate that model accuracy is a prerequisite for applying drill string interference corrections. Finally, an accurate reference model facilitates the validation of MWD surveys by keeping the field acceptance criteria centered on the true downhole magnetic field. Together, these factors improve well placement, prevent and mitigate the danger of collision with existing wellbores and enable real-time steering to save rig-time and reduce drilling costs.

Introduction

Magnetic field sensors are widely used in navigation systems and in determining the orientation of devices such as satellites, solar panels and antennas. Such electronic compasses play a particular important part below the sea and earth surface where the global positioning system (GPS) is unavailable. Measurement while drilling (MWD) employs a combination of gravity and magnetic field sensors to determine the inclination and azimuth of the bottom hole assembly (BHA). Conversion from magnetic azimuth to true azimuth requires knowledge of the direction and strength of the ambient magnetic field, which is provided by a geomagnetic reference model. Such a model specifies the declination angle (measured in degrees positive east of true north), the dip angle (measured positive downward), and the total field strength (measured in nT).

Geomagnetic reference models are empirical models produced from global magnetic field measurements by satellite, aircraft and ships. The US National Geophysical Data Center (NGDC) has a long term commitment to collect, archive and
disseminate geomagnetic data and reference models for use by academia, industry and the general public. Here, we first provide some background on the three data types and then describe how they are blended into a global reference model. The final section shows the benefits of using High Definition Geomagnetic Models (HDGM) in directional drilling.

**Satellite magnetic measurements**

Uniform global coverage of the geomagnetic field is provided by polar-orbiting satellites. They are particularly suited for monitoring the secular variation of the main field originating in the Earth’s liquid outer core. Low-orbiting satellites further enable mapping the long-wavelength portion of the crustal magnetic field, caused by ferrous minerals such as magnetite. The smallest wavelengths resolved by a satellite roughly correspond to its orbital altitude.

The recently completed German **CHAMP mission** (CHAllenging Microsatellite Payload, Reigber, 2002) was launched in July 2000 into an orbit at an initial altitude of 450 km, which gradually decayed to 250 km before re-entry in September 2010. Due to its low altitude and advanced instrumentation, CHAMP was the primary satellite data source for global geomagnetic reference models, such as the World Magnetic Model (Maus et al., 2010), the International Geomagnetic Reference Field (Finlay et al., 2010) and NGDC’s HDGM (http://www.ngdc.noaa.gov/geomag/hdgm.shtml). CHAMP further enabled the production of a series of crustal magnetic field models. The latest being MF7 (http://geomag.org/models/MF7.html) with a full wavelength resolution of 300 km. The corresponding grid resolution or half-wavelength resolution is 150 km. A snapshot of MF7 is shown in **Fig.1**.

The only dedicated magnetic satellite presently in orbit is the Danish **Ørsted satellite**. It was launched before CHAMP in February 1999 into a higher-altitude orbit at 850 km. After the star cameras failed in 2003, it now only provides measurements of the strength of the magnetic field. Furthermore, due to the weakness of the batteries, the data coverage has become somewhat sparse. These measurements do not completely determine the global magnetic field. However, they are nevertheless sufficient to extend geomagnetic field models for a few years, bridging the present gap in satellite magnetic coverage.

The next geomagnetic satellite mission, scheduled for launch in the second half of 2012, is the European Space Agency’s **Swarm constellation mission**. It consists of three identical satellites in low altitude orbits, which will monitor the geomagnetic field over a mission life time of at least four years. Swarm’s accurate magnetometers and its design to measure gradients between side-by-side flying satellites will offer unprecedented opportunities to improve the specification of the long wavelength crustal magnetic field.

![Fig. 1–Vertical component of the Earth’s magnetic field as seen by the CHAMP satellite. The large anomaly on the upper right is due to the iron ore deposits at Kursk, Russia. Snapshot of animation by Maus and Rother, 2011.](image-url)
Aeromagnetic compilations

Due to their high altitude, satellites can only be used to infer the long wavelengths (> 300 km) of the geomagnetic field. Over land, the most effective means of surveying smaller-scale features is by using aircraft. Such surveys have been conducted for more than 60 years. They typically cover areas with sidelengths of the order of tens to hundreds of kilometers. Significant efforts are being made to stitch these surveys together into continental-scale magnetic compilations (Fairhead et al., 1997, Minty et al., 2003). The primary challenge in producing continental scale compilations is to accurately represent the intermediate to long wavelengths. The global satellite magnetic missions have contributed significantly to overcoming these difficulties. Nevertheless, there is still considerable uncertainty in the intermediate wavelengths of about 50 km to 300 km.

To address this issue, Geoscience Australia flew a mesh of long-range aeromagnetic profiles which were used to correct the long wavelengths for the 5th edition of the Australian magnetic anomaly map (Milligan et al., 2010). A similar correction of long wavelengths by long-range aeromagnetic profiles was carried out for North America (Ravat, 2009). For NGDC’s global magnetic reference field models, the continental scale compilations, together with some isolated smaller surveys, were merged into a common global grid, displayed in Fig. 2.

Marine and airborne magnetic trackline data

The second source of near-surface geomagnetic survey information is from ship and aircraft trackline data. Areas far from the shore are usually surveyed by ships on marine scientific cruises. The US Naval Research Laboratory has further flown extensive aeromagnetic surveys under the Project Magnet program, which was conducted for several decades. NGDC maintains a global Geophysical Data System (GEODAS) archive of marine trackline data. This archive will be augmented with the available aeromagnetic trackline data. Both trackline data types are shown in Fig. 3.
Earth magnetic anomaly grid

The continental-scale compilations were merged with the ship and airborne trackline data into a common Earth Magnetic Anomaly Grid (EMAG2), with a grid cell size of 2 arc minutes (Maus et al., 2009). The trackline data were first line leveled onto the combined continental-scale compilations. Then, the data were merged using least-squares collocation, also sometimes referred to as kriging. In order to better represent linear sea-floor spreading anomalies, an anisotropic covariance model was employed over the oceans. The direction of strike was inferred from isochrones of the age of the oceanic crust by Müller et al. (2008). This directional gridding technique proved particularly successful in filling data gaps in the southern oceans by interpolation and extrapolation. After merging the near-surface data, the long wavelengths were substituted with the MF6 model (Maus et al., 2009) from CHAMP satellite measurements.

High Definition Geomagnetic Model

The EMAG2 data set discussed in the previous section only specifies the anomaly in the strength of the magnetic field, which can be thought of as the anomalous length of the magnetic field vector. To find the orientation of the BHA in directional drilling one further needs to know the direction of the geomagnetic field vector. For a single location, the direction of the magnetic field cannot be inferred from the strength of the field alone. However, if the field is known in a sufficiently large area, the solution of Laplace’s differential equation provides an estimate of the full vector of the geomagnetic field.

Since the Earth’s shape is well approximated by an ellipsoid, the appropriate basis functions for solving Laplace’s equation for the global magnetic field are ellipsoidal harmonics. The procedure of estimating the ellipsoidal harmonic coefficients from the EMAG2 model is described in detail in Maus, 2010. A companion paper (Poedjono et al., 2012) describes how a local magnetic model represented in ellipsoidal harmonics was produced from an aeromagnetic survey of a deepwater field off-shore Brazil. For a global geomagnetic reference, however, it is advantageous to transform the ellipsoidal harmonic expansion into a corresponding spherical harmonic expansion, in order to make it easier for the user to evaluate the model using standard software for spherical harmonic geomagnetic models. The spherical harmonic expansion of the crustal anomaly field (essentially the transform of EMAG2) is then combined with a satellite-derived time varying main field model, accounting for the magnetic field contribution from the Earth’s core. Finally, an external field contribution accounting for the steady contribution of the magnetospheric ring current is added to the model.

NGDC’s HDGM thus represents the main field, crustal field and external field in the following way: The magnetic field vector $B$ is written as the negative spatial gradient of a scalar potential $V$. In geocentric spherical coordinates, where $(\lambda, \varphi, r, t)$ stands for longitude, latitude, radius and date, this gives

$$B(\lambda, \varphi, r, t) = -\nabla V(\lambda, \varphi, r, t)$$

(1)

The potential $V$ is then expanded in terms of spherical harmonics:

$$V(\lambda, \varphi, r, t) = a \sum_{n=1}^{N_i} \left( \frac{r}{a} \right)^n \left[ \sum_{m=0}^{n+1} \left( g_n^m(t) \cos m\lambda + h_n^m(t) \sin m\lambda \right) \tilde{P}_n^m(\sin \varphi) \right]$$

$$+ a \sum_{n=1}^{N_e} \left( \frac{r}{a} \right)^n \left[ \sum_{m=0}^{n} \left( g_n^m(t) \cos m\lambda + h_n^m(t) \sin m\lambda \right) \tilde{P}_n^m(\sin \varphi) \right]$$

(2)

where $N_i$ and $N_e$ are the truncation degrees of internal and external expansion, respectively, $a$ (6 371 200 m) is the
geomagnetic reference radius, $i g_n^m(t)$ and $i h_n^m(t)$ are the internal and $e g_n^m(t)$ and $e h_n^m(t)$ the external time-dependent Gauss coefficients of degree $n$ and order $m$, and $\tilde{P}_n^m(\mu)$ are Schmidt semi-normalized associated Legendre functions.

HDGM is a step-wise linear model. For every linear interval with start date $t_0$, the Gauss coefficients $i g_n^m(t)$, $i h_n^m(t)$, $e g_n^m(t)$ and $e h_n^m(t)$ are determined for the desired date $t$ from the model coefficients $i g_n^m(t_0)$, $i h_n^m(t_0)$, $e g_n^m(t_0)$ and $e h_n^m(t_0)$, and the linear secular variation model coefficients $i \dot{g}_n^m(t_0)$, $i \dot{h}_n^m(t_0)$, $e \dot{g}_n^m(t_0)$ and $e \dot{h}_n^m(t_0)$, at epoch $t_0$ as

$$
\begin{align*}
  i g_n^m(t) &= i g_n^m(t_0) + (t - t_0) \dot{i} g_n^m(t_0) \\
  i h_n^m(t) &= i h_n^m(t_0) + (t - t_0) \dot{i} h_n^m(t_0) \\
  e g_n^m(t) &= e g_n^m(t_0) + (t - t_0) \dot{e} g_n^m(t_0) \\
  e h_n^m(t) &= e h_n^m(t_0) + (t - t_0) \dot{e} h_n^m(t_0)
\end{align*}
$$

(3)

The present model revision HDGM2012 has internal coefficients $i g_n^m(t)$ and $i h_n^m(t)$ to degree and order 720, representing the internal magnetic field down to wavelengths of about 56 km. The time variations of the core field are represented by the coefficients $i \dot{g}_n^m(t_0)$ and $i \dot{h}_n^m(t_0)$ to degree and order 15. The external field and its secular variation is represented by the coefficients $e g_n^m(t)$, $e h_n^m(t)$, $e \dot{g}_n^m(t_0)$ and $e \dot{h}_n^m(t_0)$ to degree and order 1.

Global geomagnetic power spectrum

The improvement in the representation of the geomagnetic field can be illustrated in terms of the global geomagnetic power spectrum. At long wavelengths (left side in Fig. 5 and Fig. 6) the spectrum is dominated by the main field originating in the Earth’s liquid iron outer core. At degree 16 and higher, corresponding to wavelengths shorter than 2500 km, the spectrum is dominated by the crustal magnetic field. The area under the spectral curve is proportional to the global average of the square of the geomagnetic field vector. For a geomagnetic reference model to degree $N$, the area under the spectral curve for degrees larger than the model degree $N$ represents the omission error of the model.

In contrast to the main field, the spectrum of the crustal field is very flat. Consequently, a magnetic field model has to extend to very high degrees in order to significantly reduce the omission error. The British Geological Survey’s Geomagnetic Model (BGGM), which is widely used in directional drilling, extends only to degree 50, missing most of the crustal field, resulting in a large omission error (Fig. 5). In contrast, NGDC’s HDGM extends to degree 720, past the crustal peak in the geomagnetic power spectrum, thereby significantly reducing the omission error of unmodeled crustal field contributions (Fig. 6).
Fig. 5–Global geomagnetic power spectrum illustrating the waveband covered by the BGGM and the associated error of omission.

Fig. 6–Extending to degree 720, the HDGM covers a larger waveband of the geomagnetic field, thereby reducing the error of omission.

**Level of crustal detail**

Extending to spherical harmonic degree 720, employing about 500,000 model coefficients, HDGM represents features down to 28 km half wavelength. This compares with BGGM extending to degree 50, employing about 2500 coefficients and representing half-wavelengths down to 400 km. A sample map of a shale gas region in Canada illustrates the difference in resolution of the two models (Fig. 7). The higher spatial resolution of HDGM typically results in corrections of about 0.5° in declination. However, as seen in the example of Figure 7, the declination corrections provided by HDGM can reach much larger values, particularly at high northern and southern latitudes.
Fig. 7–Comparison of BGGM and HDGM for a drill site in the Helmet area of north-eastern British Columbia. By accounting for local crustal magnetic anomalies, the HDGM provides a correction in the declination of 1.6° at this site.

Model Validation

The improved resolution of HDGM over previous models should lead to significantly reduced reference errors, if the additional level of detail is genuine. Of course, this depends on the reliability and coverage of the underlying data sets. While the satellite coverage is global, the ship and airborne data coverage is variable, both in data coverage and quality. It is therefore to be expected that the full advantage of a degree-720 expansion is only partly achieved in practice. In order to quantitatively assess the gain in accuracy, the BGGM and HDGM were compared with recent ship and airborne measurements of the magnetic field. Only recent data, which were not included in the global models, were used in the validation. The objective in selecting the data was to achieve a reasonable global coverage, preferably by long-range profiles.

The selection included 16 marine profiles provided by the German Federal Institute for Geosciences and Natural Resources, 6 long-range aeromagnetic profiles from Geoscience Australia, one Arctic aeromagnetic profile from Technical University of Denmark (Matzka et al, 2010) and one Alaskan aeromagnetic profile from USGS. The locations of the 24 profiles are illustrated in Fig. 8. Once selected, all profiles were used in the statistical analysis, irrespective of their misfit with the models.

It is important to note that there is a large difference between the predictive and the retrospective period of a model. For example, the HDGM2011 was released in December 2010. For the period before December 2010 (retrospective), the model is directly based on satellite, ship and airborne magnetic field measurements, and it is therefore more accurate than for the period from January 2011 (predictive), since the evolution of the geomagnetic field can only be predicted with limited accuracy. For this analysis, we therefore only chose models which were released prior to the measurements analyzed. For HDGM, we used our first degree-720 model, which was publicly released in June 2007 under the name Pomme-4 (http://geomag.org/models/pomme4.html). This model is referred to in the following as pre-HDGM. For BGGM, we used the
latest version prior to each survey, namely the BGGM versions of 2007 to 2009. Three typical sample profiles showing the measured data together with the BGGM and pre-HDGM predictions are shown in Figs. 9 to 11.

Fig. 8–Ship (blue) and airborne (red) magnetic profiles used in the validation of geomagnetic reference models.

Fig. 9–Sample total field aeromagnetic profile flown in the Arctic by the Danish Technical University in 2009.
Fig. 10–Sample total field aeromagnetic profile flown by Geoscience Australia in 2007. Shown here are the residuals against the International Geomagnetic Reference Field (IGRF-2005).

Fig. 11–Marine magnetic profile measured on a scientific cruise in the Pacific by the German Federal Institute for Geosciences and Natural Resources. Displayed are again the residuals against IGRF-2005.
In summary, a total of 24 ship and airborne magnetic profiles were compared with the BGGM and pre-HDGM models. For each profile, the root mean square (RMS) between the measurements and the reference models was computed (displayed as circles in Fig. 12). Subsequently, the RMS values were averaged. The resulting average is our best estimate of the global 1-sigma errors in the total field prediction of the models. These were found to be 136 nT for BGGM and 112 nT for HDGM and are displayed as red crosses in Fig. 12.

Error model

In well planning, one has to know the uncertainty of placing a well. These uncertainties are commonly illustrated by error ellipses. Wells are placed in such a way that the error ellipse lies within the target to be drilled. At the same time, collisions with existing wells are avoided by choosing a well path with an error ellipse that does not intersect the corresponding error ellipses of existing wells. The error ellipses combine all uncertainties encountered in placing a well. One of the dominant sources of uncertainty is the accuracy of the geomagnetic reference field. It is therefore important for the driller to have a realistic error model for the selected geomagnetic reference model.

In 2000, the Industry Steering Committee for Well Survey Accuracy (ISCWSA) adopted an error model proposed by Williamson (1999) for BGGM. The specifications of this error model are summarized in Table 1. The total field uncertainty of 130 nT given for BGGM by the ISCWSA error model agrees very well with the uncertainty of 136 nT found in our validation for the BGGM model. The angular quantities dip and declination could not be verified in our study, since ships and aircraft usually collect only total field measurements, due to the difficulties of accurately measuring the direction of the magnetic field on a moving platform. However, we can use the relative ratio of the HDGM/BGGM error, which is 112nT/136nT = 0.82 to scale the ISCWSA error model to HDGM. The result of scaling the ISCWSA error values gives the result displayed in Table 2.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Weighting Function</th>
<th>Magnitude</th>
<th>Propagation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declination (constant)</td>
<td>AZ</td>
<td>0.36°</td>
<td>G</td>
</tr>
<tr>
<td>Declination ($B_H$ dependent)</td>
<td>DBH</td>
<td>5000° nT</td>
<td>G</td>
</tr>
<tr>
<td>Dip angle</td>
<td>MFD</td>
<td>0.20°</td>
<td>G</td>
</tr>
<tr>
<td>Total field</td>
<td>MFI</td>
<td>130 nT</td>
<td></td>
</tr>
</tbody>
</table>

The total field uncertainty of 130 nT given for BGGM by the ISCWSA error model agrees very well with the uncertainty of 136 nT found in our validation for the BGGM model. The angular quantities dip and declination could not be verified in our study, since ships and aircraft usually collect only total field measurements, due to the difficulties of accurately measuring the direction of the magnetic field on a moving platform. However, we can use the relative ratio of the HDGM/BGGM error, which is 112nT/136nT = 0.82 to scale the ISCWSA error model to HDGM. The result of scaling the ISCWSA error values gives the result displayed in Table 2.

<table>
<thead>
<tr>
<th>MFI</th>
<th>MFD</th>
<th>AZ</th>
<th>DBH</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 nT</td>
<td>0.2°</td>
<td>0.36°</td>
<td>5000° nT</td>
</tr>
<tr>
<td>107 nT</td>
<td>0.16°</td>
<td>0.30°</td>
<td>4100° nT</td>
</tr>
</tbody>
</table>
Downhole MWD survey examples

The magnetic azimuth of the BHA is inferred from the vector component measurements of the MWD survey tool. To convert the magnetic azimuth into true azimuth, one needs the local declination angle provided by a geomagnetic reference model. The more accurate the reference model, the more accurate the true azimuth of the BHA.

In addition to providing declination, the geomagnetic reference model further provides information on the dip angle and strength of the ambient field. This information is not directly required for drilling, since the inclination of the well can be inferred from the accelerometer in the MWD tool. The dip and total field measurements provided by the MWD tool therefore constitute redundant information which can be used to meet two additional objectives: (1) Validation of the magnetic MWD tool readings and (2) correction for magnetic drill string interference.

(1) The MWD tool readings are validated by comparing the measured dip and total field with the values given by the geomagnetic reference field. The difference between the tool reading and the reference is referred to as the magnetic residual. If the magnetic residuals exceed the given threshold values, called field acceptance criteria (FAC) the MWD survey is discarded. This process is illustrated in Fig. 13 for a deepwater well offshore Brazil. In this case, the MWD surveys fail the field acceptance criteria when using BGGM as a geomagnetic reference model (red line). The first response of the driller is usually to assume that the MWD survey tool is defective, pull out the string, and replace the tool. In this case, however, the problem is not with the tool, but with the geomagnetic reference model. Replacing BGGM with HDGM shows that the tool readings are in fact completely within the acceptance criteria, shown for HDGM as a blue line in Fig. 13. A second example of this kind is shown for a well in the Marcellus Shale for the eastern US in Fig. 14. Again, the surveys fail the FAC when using BGGM but pass the criteria when using HDGM as a reference. This is because HDGM accounts for regional crustal magnetic anomalies, which contribute significantly to the downhole geomagnetic field.

(2) In the examples presented here, a non-magnetic BHA was used. Nevertheless, magnetic interference of the drill string and drilling mud cannot be completely avoided. It is therefore common practice to estimate drill string interference from the redundant measurements of the dip and total field and apply a correction to the magnetic azimuth. In order for this correction to work, one requires an accurate geomagnetic reference field. This procedure is illustrated in Fig. 15 for a second well in the Marcellus shale. The magnetic MWD surveys (yellow squares) lie far outside of the BGGM criteria (red line). After applying the drill string interference correction (green squares), some of the values still lie outside of the FAC, indicating that the problem is not due to drill string interference. In fact, the drill string interference correction using BGGM may have imposed a further error onto the magnetic azimuth. On the other hand, when using HDGM as the reference, most of the raw surveys fall within the FAC. After applying the drill string interference correction (blue diamonds), all surveys pass the FAC (blue line), indicating the validity of the drill string interference correction.

These additional considerations underline the importance of using an accurate geomagnetic reference model for directional drilling MWD survey.
Fig. 13—Sample downhole surveys of a deepwater project offshore Brazil. Lack of agreement between magnetically clean MWD readings and BGGM criteria in red. Horizontal axis represent normalized horizontal component and vertical axis represent normalized vertical component of Earth’s magnetic field. The blue rectangle represents the HDGM acceptance criteria.

Fig. 14—Downhole surveys for well in the Marcellus Shale, eastern United States.
Fig. 15—Second example of a well in the Marcellus Shale of the eastern United States. In this case, the data have been corrected for drill string interference. The values corrected using HDGM (blue diamonds) then fall within the HDGM FAC marked by the blue rectangle. When the values are corrected using BGGM (green triangles), many of them still fail the BGGM field acceptance criteria marked by the red rectangle.

Summary and conclusions

Traditional global geomagnetic reference models only account for the longest wavelengths of the geomagnetic field. They primarily represent the main magnetic field originating in the Earth’s core. The innovation of the work presented here is to include a significant portion of the crustal magnetic field in a global field model by extending the representation to spherical harmonic degree 720. This corresponds to an improvement in half-wavelength resolution to 28 km, down from 400 km for a standard degree-50 model.

Geomagnetic reference models are based on satellite, ship and airborne measurements of the magnetic field. The near-surface ship and airborne data were combined into a global grid. After adjusting the long wavelengths to the satellite-inferred reference level, the grid was transformed into a spherical harmonic expansion of the crustal magnetic potential. Finally, the main field, secular variation and external field were added to produce the HDGM. The reduction of model omission errors for this high-degree model was illustrated on the global magnetic power spectrum. A sample map showed the increased level of detail in the geomagnetic declination, typically resulting in azimuth corrections of the order of 0.5°.

The HDGM was validated against a global data set of ship and airborne magnetic profiles. Statistical analysis of the magnetic residuals indicates a global reduction in uncertainties by 18% over a traditional degree-50 model. It is recommended to apply this reduction in uncertainty to the geomagnetic reference field coefficients of the ISCWSA-2000 error model when using the HDGM for well planning.

Finally, we presented examples of downhole MWD survey residuals against a standard model and our HDGM for wells offshore Brazil and onshore US. These examples illustrate the practical benefits of using a geomagnetic reference model with increased accuracy, both in correcting for drill string interference and in passing field acceptance criteria.

In summary, the present study demonstrates the benefits of the new HDGM; its application in different hemispheres to improve well placement, prevent and mitigate the danger of collision with existing wellbores and enable precise relief well drilling; and its use with magnetic tools in real-time steering to save rig-time and reduce drilling costs.
Acknowledgements

The authors appreciate the permission of the National Geophysical Data Center, Chevron Corporation, Schlumberger, GETECH, Geoscience Australia, Technical University of Denmark and German Federal Institute for Geosciences and Natural Resources for their permission to publish the material contained in this paper. We are grateful to Richard Saltus (USGS) for providing aeromagnetic profiles for Alaska. We further thank the numerous organizations who provide satellite, ship and aeromagnetic measurements to NGDC’s public archives and models. These organizations are acknowledged at http://geomag.org/models/EMAG2/acknowledgments.html.

References


Williamson, H. S., Accuracy prediction for directional MWD (1999), SPE 56702