Geomagnetic Referencing—The Real-Time Compass for Directional Drillers

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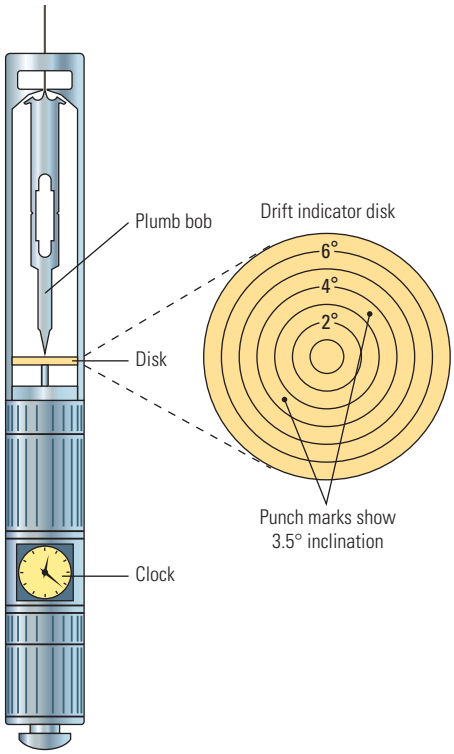
To pinpoint the location and direction of a wellbore, directional drillers rely on measurements from accelerometers, magnetometers and gyroscopes. In the past, high-accuracy guidance methods required a halt in drilling to obtain directional measurements. Advances in geomagnetic referencing now allow companies to use real-time data acquired during drilling to accurately position horizontal wells, decrease well spacing and drill multiple wells from limited surface locations.

For a variety of reasons, operating companies need to know where their wells are as they are being drilled. Many of today's deviated and horizontal wells no longer simply penetrate a reservoir zone but must navigate through it laterally to contact as much of the reservoir as possible. Precise positioning of well trajectories is required to optimize hydrocarbon recovery, determine where each well is relative to the reservoir and avoid collisions with other wells.

To accomplish these objectives, drillers require directional accuracy to within a fraction of a degree. To achieve this level of accuracy, they use measurement-while-drilling (MWD) tools that include accelerometers and magnetometers that detect the Earth's gravitational and magnetic fields; they also use sophisticated procedures to compensate for measurement perturbation. As drillers have found success with these tools and become more dependent on them for well guidance, the need for accurately quantified positional uncertainty that takes into account all measurement error has also increased. For some applications, the uncertainty is as important as the position itself.

This article reviews aspects of wellbore surveying, focusing on modern techniques for magnetic surveying with MWD tools. To understand the operation of and uncertainty associated with magnetic tools, we examine important aspects of the Earth's magnetic field and its measurement. Examples from the USA, Canada, offshore Brazil and offshore Ghana illustrate the application of new techniques that improve measurement accuracy and thus effect considerable reduction in magnetic tool survey error.



^ Mechanical drift indicator. This downhole device measures drift, or deviation from vertical, using a pendulum, or the "plumb bob," principle. The sharp-tipped pendulum is lowered onto a disk into which it punches two holes that mark an initial measurement then a verification measurement. In this example, the inclination is 3.5°. The technique gives no indication of azimuth but may be reliable for surface hole intervals and shallow vertical wells in which dogleg severity and inclination are not significant. [Adapted from Gatlin C: *Petroleum Engineering Drilling and Well Completions*. Englewood Cliffs, New Jersey, USA: Prentice-Hall, Inc. (1960): 143.]

Oilfield Review Autumn 2013: 25, no. 3.
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For help in preparation of this article, thanks to Essam Adly, Muscat, Oman; Goke Akinniranye, The Woodlands, Texas; James Ashbaugh and Robert Kuntz, Pennsylvania General Energy Company, LLC, Warren, Pennsylvania, USA; Nathan Beck, Anchorage; Luca Borri, Jason Brink and Joseph Longo, Eni US Operating Co. Inc., Anchorage; Daniel Cardozo, St. John's, Newfoundland, Canada; Pete Clark, Chevron Energy Technology Company, Houston; Steve Crozier, Tullow Ghana Ltd., Accra, Ghana; Mike Hollis, Chesapeake Energy, Oklahoma City, Oklahoma, USA; Christopher Jamerson, Apache Corporation, Tulsa; Xiong Li, CGG GravMag Solutions, Houston; Ross Lowdon, Aberdeen; Diana Montenegro Cuellar, Bogotá, Colombia; Ismail Bolaji Olalere, Shell Nigeria, Port Harcourt, Nigeria; Irina Shevchenko, Michael Terpening and John Zabaldano, Houston; Tim White, US Geological Survey, Denver; and the Government of Newfoundland and Labrador, Department of Natural Resources, St. John's, Newfoundland, Canada.

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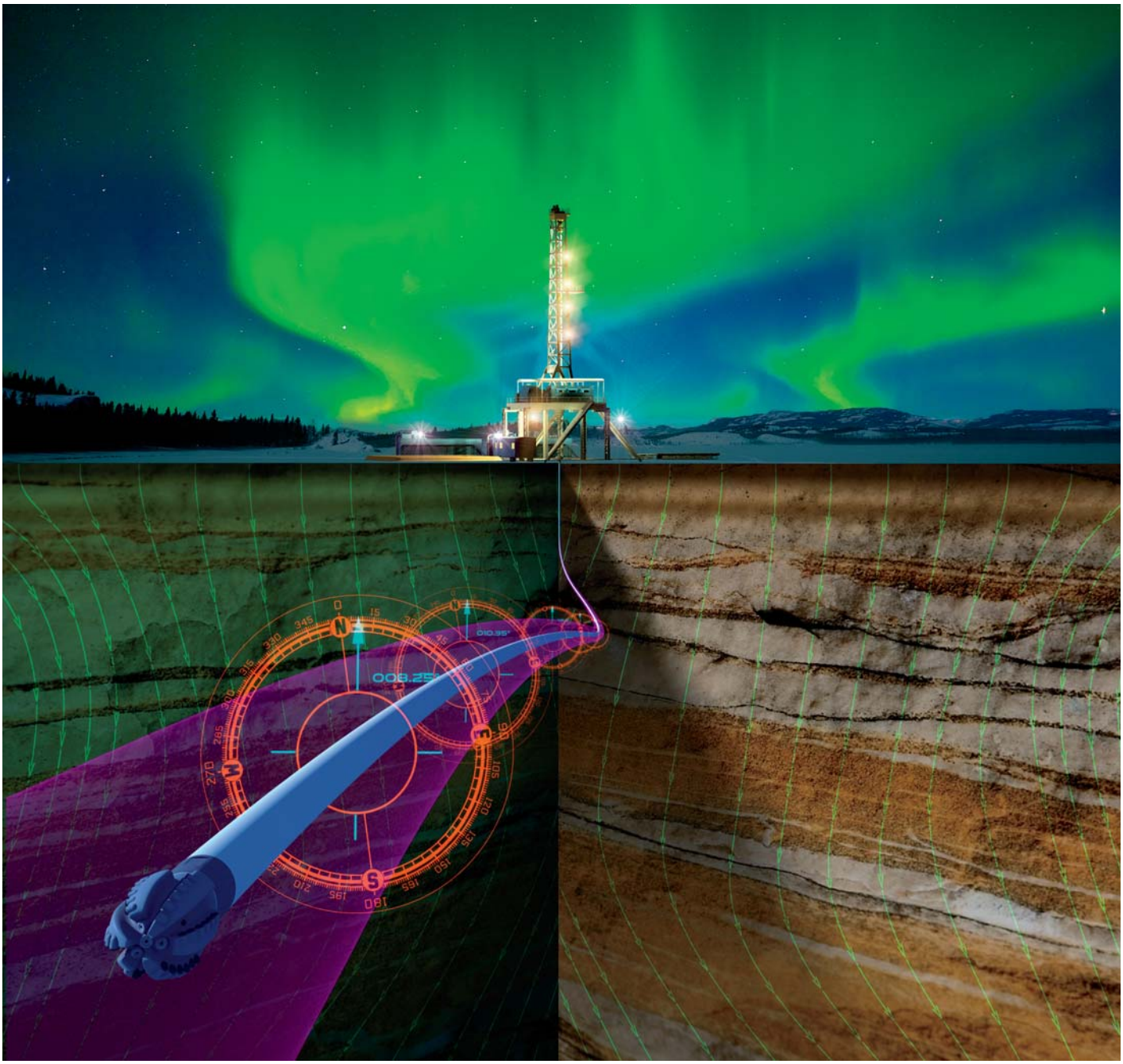
1. Borehole orientation may be described in terms of inclination and azimuth. Inclination refers to the vertical angle measured from the down direction—the down, horizontal and up directions have inclinations of 0°, 90° and 180°, respectively. Azimuth refers to the horizontal angle measured clockwise from true north—the north, east, south and west directions have azimuths of 0°, 90°, 180° and 270°, respectively. For more on borehole orientation: Jamieson AL: *Introduction to Wellbore Positioning*. Inverness, Scotland: University of the Highlands and Islands, 2012, http://www.uhi.ac.uk/en/research-enterprise/wellbore-positioning-download (accessed June 18, 2013).
2. Griswold EH: "Acid Bottle Method of Subsurface Well Survey and Its Application," *Transactions of the AIME* 82, no. 1 (December 1929): 41–49.



Historical Perspective

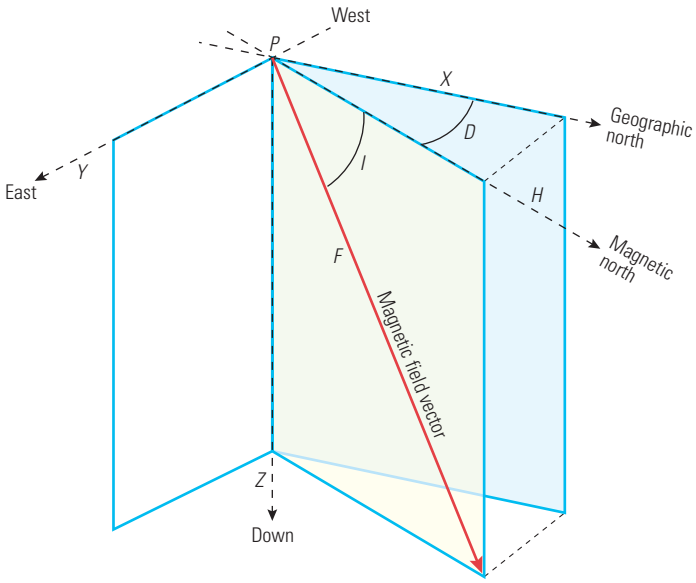
Traditionally, wellbores were drilled vertically and were widely spaced. Well spacing decreased as fields matured, regulations tightened and reservoirs were targeted in remote areas. Over time, drilling multiple horizontal wells from a single pad became common practice. Today, more than a dozen wells may fan out into the reservoir from a single offshore platform or onshore drilling pad.

Pad drilling—grouping wellheads together at one surface location—necessitates fewer rig moves, requires less surface area disturbance and makes it easier and less expensive to complete wells and produce hydrocarbons. However, the introduction of horizontal drilling and closer wellbore spacing has intensified the need for accurate wellbore positioning and for processes to prevent collisions between the bit and nearby wellbores.

Before the introduction of modern steerable downhole motors and advanced tools to measure hole inclination and azimuth, directional or horizontal drilling was much slower than vertical drilling because of the need to stop regularly and take time-consuming downhole surveys. The directional driller stopped drilling to measure wellbore inclination and azimuth.[1]

The oldest survey method entailed lowering a glass bottle of acid downhole and holding it stationary long enough for the acid to etch a horizontal ring in the bottle. The ring's position was interpreted for inclination once the device was retrieved.[2]

Another simple survey tool is the single shot mechanical drift indicator (previous page). Magnetic single shot (MSS) and multishot (MMS) surveys have also been used to record inclination and magnetic azimuth. For those surveys, the tool



^ Magnetic field orientation. At any point *P*, the magnetic field vector (red) is commonly described in terms of its direction, its total magnitude, *F*, in that direction and *H* and *Z*, the local horizontal and vertical components of *F*. The angles *D* and *I* describe the orientation of the magnetic field vector. The declination, *D*, is the angle in the horizontal plane between *H* and geographic north. The inclination, *I*, is the angle between the magnetic field vector and the horizontal plane containing *H*. Of these measurements, *D* and *I* are required to convert the compass orientation of a wellbore to its geographic orientation. The absolute magnitudes of *F*, *Z* or *H* are used for quality control and calibration.

took photographs, or shots, of compass cards downhole while the pipe was stationary in the slips. Photographs were taken every 27 m [90 ft] during active changes of angle or direction and every 60 to 90 m [200 to 300 ft] while drilling straight ahead. The introduction of downhole mud motors in the 1970s and the development of ruggedized sensors and mud pulse telemetry of MWD data enabled the use of continuously updated digital measurements for near real-time trajectory adjustments. Most wells are now drilled using survey measurements from modern MWD tools.

Well Survey Basics

Today, directional drillers rely primarily on real-time MWD measurements of gravitational and magnetic fields using ruggedized triaxial accelerometers and magnetometers. Other categories of survey tools include magnetic multishot tools, inclination-only tools and a family of tools based on the use of gyroscopes, or gyros.[3] Unlike MWD tools, many of these specialty tools are run as wireline services, thus requiring cessation of the drilling process. Increasingly, however, gyroscopic tools are also being incorporated into downhole steering and surveying instruments for use while drilling.

Triaxial accelerometers measure the local gravity field along three orthogonal axes. These measurements provide the inclination of the tool axis along the wellbore as well as the toolface relative to the high side of the tool.[4] Similarly, triaxial magnetometers measure the strength of the Earth's magnetic field along three orthogonal axes. From these measurements and the accelerometer measurements, the tool determines azimuthal orientation of the tool axis relative to magnetic north. Conversion of magnetic measurements to geographic orientation is at the heart of MWD wellbore surveying. The key measurements are magnetic dip (also called magnetic inclination), total magnetic field and magnetic declination (above).[5]

A variety of tools exploit gyroscopic principles. These systems are unaffected by ferromagnetic materials, giving them an advantage over magnetic tools in some drilling scenarios. Some tools take measurements at discrete intervals of measured depth (MD) along the well path when the survey tool is stationary; others operate in a continuous measurement mode. North-seeking gyrocompasses (NSGs) make use of gyroscopes and the rotation of the Earth to automatically find geographic north. Rate gyros provide an output proportional to the turning rate of the instrument and may be used to determine orientation as the survey tool continuously traverses the well path. Surveying engineers also use them in gyrocompassing mode, in which the stationary tool responds to the horizontal component of the Earth's rotation rate. The use of rate gyros has reduced errors—such as geographic reference errors and unaccountable measurement drift—that are associated with conventional gyros. Unfortunately, because they are taken while the tool is stationary, gyro surveys carry operational risk and rig time cost associated with wellbore conditioning when drilling is stopped.[6]

In some intervals, significant magnetic interference from offset wellbores makes accurate magnetic surveying impossible. To address this limitation, scientists developed gyro-while-drilling methods. Tool design engineers are extending the operational limits of some commercial gyro-while-drilling survey systems to the full range of wellbore inclinations.

For some situations, surveying engineers combine gyroscopic and magnetic surveying. One of the combined techniques—inhole referencing—makes use of highly accurate gyroscope measurements in shallow sections to align subsequent data obtained using magnetic surveys in deeper sections.[7] In highly deviated and extended-reach wells, this approach delivers levels of accuracy comparable to those acquired with wireline gyroscopic surveys without incurring the added time and costs. In these inhole referencing systems, gyroscopic measurements are used in shallow near-vertical wellbore sections in the vicinity of casing until MWD magnetic surveys can be obtained free of interference and in longer-reach sections in which inclinations increase. An additional benefit of using both gyro and MWD surveys is the detection of gross error sources in either tool.

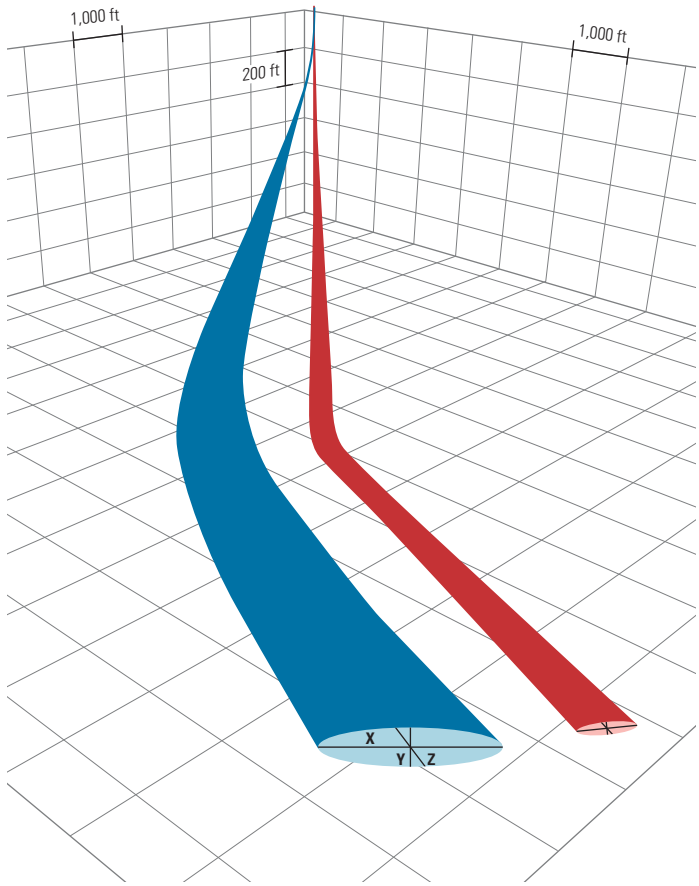
Positional Uncertainty

Drillers use positional uncertainty estimates to determine the probability of striking a geologic target and of intersecting other wellbores.[8] They base the estimates on tool error model predictions, which themselves depend on quality control (QC) of survey data. Survey tool quality checks help identify sources of error, often with redundant surveys as independent cross-checks.

For most survey tools, the outputs are azimuth, inclination and measured depth. Errors in each measurement may occur because of both the tool and the environment. Accuracies available from stationary measurements made with standard MWD tools are on the order of ±0.1° for inclination, ±0.5° for azimuth and ±1.0° for toolface.

A surveying engineer's ability to determine borehole trajectory depends on the accumulation of errors from wellhead to total depth. Rather than specifying a point in space, surveying engineers consider wellbore position to be within an ellipsoid of uncertainty (EOU). Typically, the uncertainty in the lateral direction is larger than in the vertical or along-hole directions. When displayed continuously along the wellbore, the EOU presents a volume shaped like a flattened cone surrounding the estimated borehole trajectory (right). The combined effects of accumulated error may reach values of 1% of measured well depth, which could be unacceptably large for long wellbores.[9]

The Industry Steering Committee for Wellbore Survey Accuracy, ISCWSA—now the SPE Wellbore Positioning Technical Section, WPTS—has promoted development of a rigorous mathematical procedure for combining various error sources into one 3D uncertainty ellipse.[10] External effects on accuracy include axial misalignment, BHA deflection, unmodeled geomagnetic field variations and drillstring-induced interference. The latter two factors dominate the performance of magnetic tools and their error models; such models depend on the resolution of the geomagnetic reference model in use.[11]



^ Planned well trajectories showing slices of the ellipsoids of uncertainty (EOUs) obtained from standard MWD (blue) and from higher accuracy MWD (red) surveys. The azimuthal and inclination uncertainties are in the XY plane perpendicular to the borehole. The depth uncertainty is along the Z-axis of the borehole. When shown at a dense series of points along the well trajectory, they form a "cone of uncertainty." The high-accuracy method delivers a wellbore with smaller positional uncertainty. (Adapted from Poedjono et al, reference 32.)

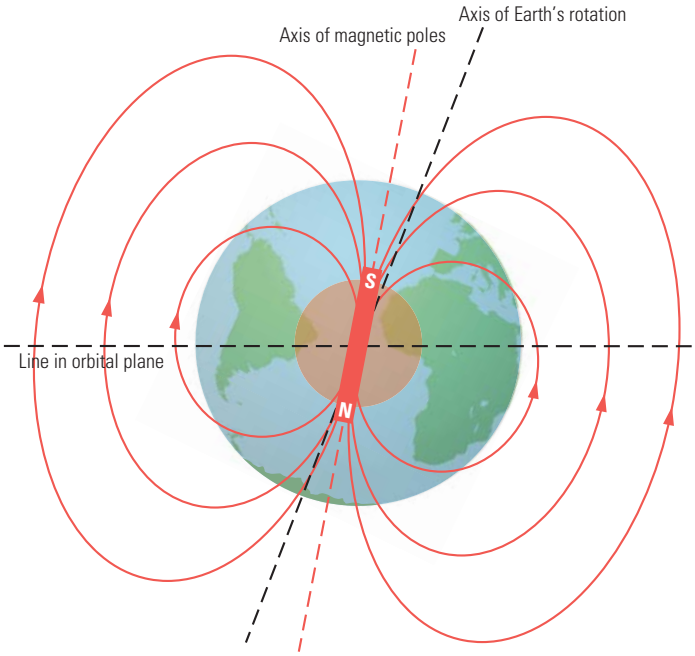
The Geomagnetic Field

To make use of magnetic measurements for finding direction, it is necessary to take into account the complexity of the geomagnetic field. The geomagnetic field surrounds the Earth and extends into nearby space.[12] The total magnetic field measured near the Earth's surface is the superposition of magnetic fields arising from a number of time-

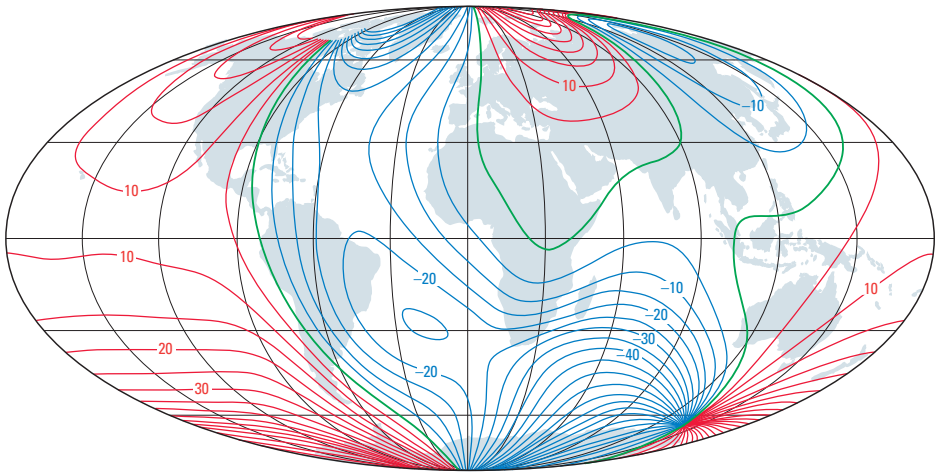
3. This family includes conventional gyros, rate gyros, north-seeking gyros, mechanical inertial gyros and ring laser inertial gyros. For more on gyros: Jamieson AL: "Understanding Borehole Surveying Accuracy," *Expanded Abstracts*, 75th SEG Annual International Meeting and Exposition, Houston (November 6–11, 2005): 2339–2340.

   Jamieson, reference 1.
4. Gravity, or high side, toolface is the orientation of the survey instrument in the borehole relative to up. Magnetic toolface is the orientation of the survey instrument relative to magnetic north, corrected to a chosen reference of either grid north or true north. Most MWD systems switch from a magnetic toolface to a high side toolface once the inclination exceeds a preset threshold typically set between 3° and 8°. For more on instrument orientation: Jamieson, reference 1.
5. By international agreement, magnetic field orientation may be described in terms of dip (also referred to as inclination) and declination. Dip is measured positively downward from the horizontal direction—the down, horizontal and up directions have dips (inclinations) of 90°, 0° and –90°, respectively. Declination is defined similarly to hole azimuth. For more on magnetic field orientation: Campbell WH: *Introduction to Geomagnetic Fields*, 2nd ed. Cambridge, England: Cambridge University Press, 2003.
6. Gyro surveys conducted on wireline in openhole sections carry the risk of stuck survey tools. Surveys made through drillpipe when the drilling is stopped carry the risk of stuck drillpipe. Additionally, operators usually perform a hole conditioning cleanup cycle after drilling is stopped. These combined operations may require many hours of rig time.
7. Thorogood JL and Knott DR: "Surveying Techniques with a Solid-State Magnetic Multishot Device," *SPE Drilling Engineering* 5, no. 3 (September 1990): 209–214.
8. Ekseth R, Torkildsen T, Brooks A, Weston J, Nyrnes E, Wilson H and Kovalenko K: "High-Integrity Wellbore Surveying," *SPE Drilling & Completion* 25, no. 4 (December 2010): 438–447.
9. For typical well depths and step-out, or horizontal reach, the dimensions of the uncertainty envelope may be on the order of 100 ft [30 m] or more unless action is taken to correct error sources and run high-accuracy surveys. This may exceed the size of the target and increase the risk of unsuccessful wellbore steering. For more on the calculation, extent and causes of positional uncertainty: Jamieson, references 1 and 3.
10. For more on tool error model selection and the accepted industry standard ISCWSA error models for magnetic tools: Williamson HS: "Accuracy Prediction for Directional Measurement While Drilling," *SPE Drilling & Completion* 15, no. 4 (December 2000): 221–233.

    For more on error models for gyroscopic tools: Torkildsen T, Håvardstein ST, Weston JL and Ekseth R: "Prediction of Wellbore Position Accuracy When Surveyed with Gyroscopic Tools," paper SPE 90408, presented at the SPE Annual Technical Conference and Exhibition, Houston, September 26–29, 2004.
11. Williamson, reference 10.
12. Love JJ: "Magnetic Monitoring of Earth and Space," *Physics Today* 61, no. 2 (February 2008): 31–37.



^ Simplified geomagnetic field. The Earth's main geomagnetic field is portrayed as the ideal magnetic field of a geocentric tilted dipole with poles at the core of the Earth (brown shading). Lines of magnetic flux (red) emanate outward through the surface of the Earth near the geographic south pole and reenter near the geographic north pole. Those positions along the axis of the dipole are the magnetic south and north poles, although the polarity of the internal dipole is the opposite. The geographic north and south poles lie on the Earth's axis of rotation. Both axes are tilted relative to the plane of the Earth's rotational orbit.



^ Values of declination along lines of equal declination (isogonic lines) of the Earth's magnetic field. In the areas surrounded by red lines, or the lines of equal positive declination, a compass points to the east of true north. Lines of equal negative declination, for which the compass points to the west of true north, are blue. Along the green, agonic lines, for which declination equals zero, the directions to magnetic north and true north are identical. The field shown is the International Geomagnetic Reference Field for the year 2010. [Adapted from "Historical Main Field Change and Declination," *CIRES Geomagnetism*, http://geomag.org/info/declination.html (accessed June 24, 2013).]

varying physical processes that are grouped into four general components: the main magnetic field, the crustal field, the external disturbance field and local magnetic interference.[13] The significance of these contributions to direction, strength and stability of the total magnetic field varies with geographic region and with magnetic survey direction. The importance of accounting for each component in the measurement depends on the purpose and required accuracy of the survey.

Physicists have determined that the Earth's main magnetic field is generated in the Earth's fluid outer core by a self-exciting dynamo process. Approximately 95% of the total magnetic field measured at Earth's surface comes from this main field, a significant portion of which may be described as the field of a dipole placed at the Earth's center and tilted approximately 11° from the Earth's rotational axis (left). The magnitude of the main magnetic field is nearly 60,000 nT near the poles and about 30,000 nT near the equator.[14] However, there are significant nondipole contributions to the main magnetic field that complicate its mathematical and graphical representation (below left). As an additional complication, the main field varies slowly

13. Akasofu S-I and Lanzerotti LJ: "The Earth's Magnetosphere," *Physics Today* 28, no. 12 (December 1975): 28–34.

    Jacobs JA (ed): *Geomagnetism*, Volume 1. Orlando, Florida, USA: Academic Press, 1987.

    Jacobs JA (ed): *Geomagnetism*, Volume 3. San Diego, California, USA: Academic Press, 1989.

    Merrill RT, McElhinny MW and McFadden PL: *The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle*. San Diego, California: Academic Press, International Geophysics Series, Volume 63, 1996.

    Campbell, reference 5.

    Lanza R and Meloni A: *The Earth's Magnetism: An Introduction for Geologists*. Berlin: Springer, 2006.

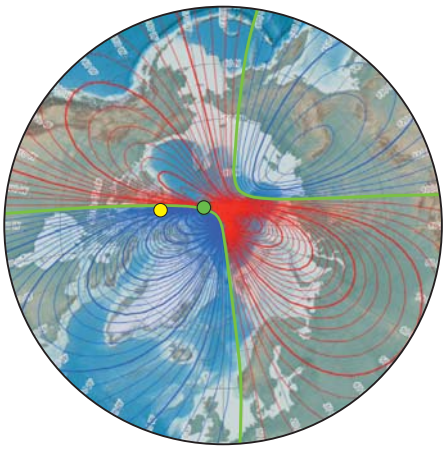
    Auster H-U: "How to Measure Earth's Magnetic Field," *Physics Today* 61, no. 2 (February 2008): 76–77.

    Love, reference 12.

14. The symbol *B* is often used for magnetic induction, the quantity that is sensed by magnetometers. The SI unit for *B* is the Tesla (T), and the centimeter-gram-second (cgs) unit is the Gauss (G); the common unit is the gamma, which is 10^{-9} T = 1 nT.

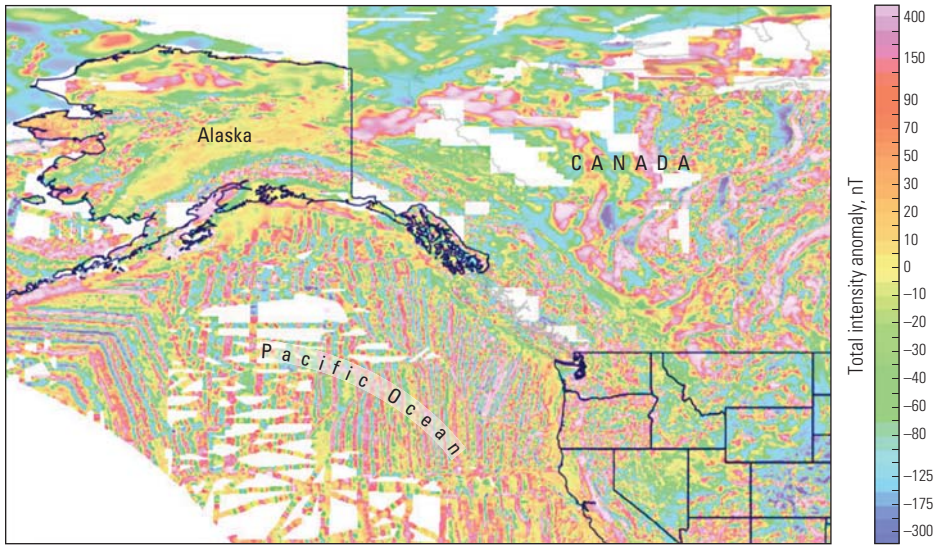
15. Time variations, called secular variations, necessitate periodic updating of magnetic field maps and models. These variations are caused by two types of processes in the Earth's core. The first is related to the main dipole field and operates on time scales of hundreds or thousands of years. The second is related to nondipole field variations at time scales on the order of tens of years. For more on secular variations: Lanza and Meloni, reference 13.

16. Remanent magnetism of rocks results from exposure of magnetic materials in the rocks to the Earth's magnetic field when the rocks were formed. Igneous rocks retain thermoremanent magnetization as they cool. In some rocks, remanent magnetization arises when magnetic grains are formed during chemical reactions. Sedimentary rocks retain remanent magnetization when magnetic grains align with the magnetic field during sediment deposition. Remanent magnetism also occurs in ferromagnetic materials, such as the steel in casing or drillpipe, as a result of exposure to the Earth's magnetic field or industrial magnetic field sources.



Year 2010

^ Variation of the position of the northern magnetic pole between 1990 and 2010. Magnetic declination (red and blue lines) from the International Geomagnetic Reference Field model is shown for 2010. The green dot represents the position of the magnetic dip pole in 2010; the yellow dot represents the position of that pole in 1990. The agonic lines, for which declination equals zero in 2010, are highlighted in green. If a compass at any location points to the right of true north, declination is positive, or east (red contours), and if it points to the left of true north, declination is negative, or west (blue contours). [Adapted from "Historical Magnetic Declination," *NOAA National Geophysical Data Center*, http://maps.ngdc.noaa.gov/viewers/historical_declination/ (accessed June 24, 2013).]

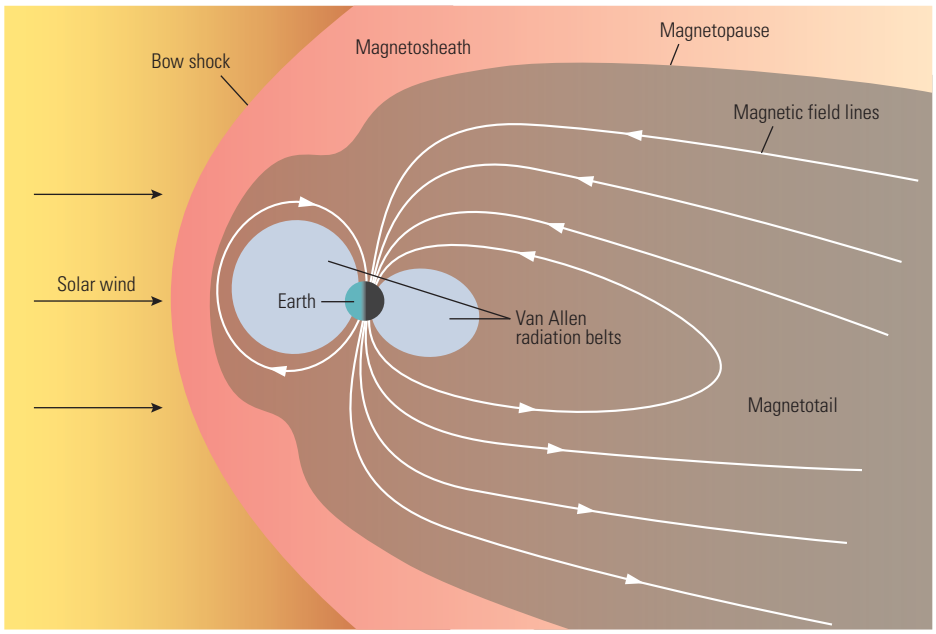


^ Geomagnetic crustal field. Airborne measurements of the strength of the magnetic field provide data that are used to determine the anomalous contribution from earth crustal materials. The total intensity anomaly (TIA) is the difference between the magnitude of the total field and that of the main magnetic field. The TIA field over western Canada; Alaska, USA; and the northwest continental US varies from –300 nT (blue) to +400 nT (pink). The mean total field strength is about 55,000 nT in this region. The crustal field shows local intensity ridges, with variation on a much finer spatial scale than that of the main magnetic field. [Adapted from "Magnetic Anomaly Map of North America," *USGS*, http://mrdata.usgs.gov/geophysics/aeromag-na.html (accessed July 23, 2013).]

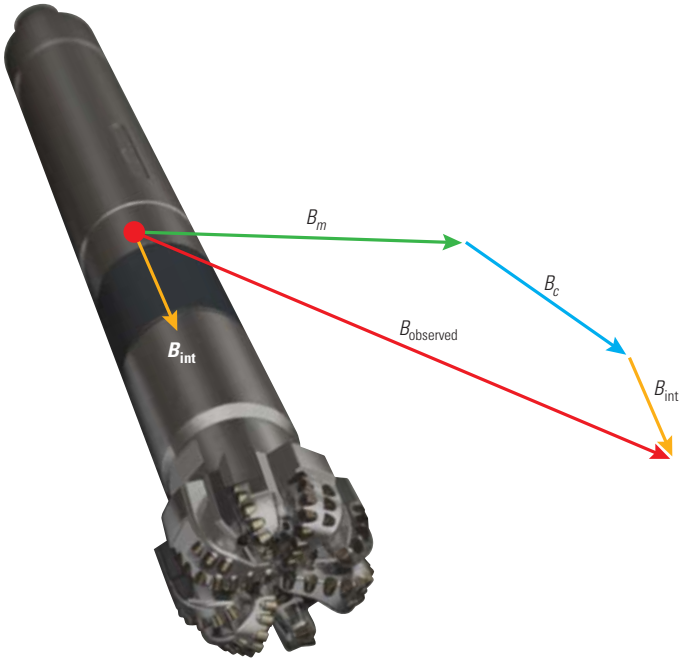
because of changes within the Earth's core. The relative strengths of nondipole components change, and the magnetic dipole axis pole position itself wanders over time (above).[15]

The magnetic field associated with the Earth's crust arises from induced and remanent magnetism.[16] The crustal field—also referred to as the anomaly field—varies in direction and strength when measured over the Earth's surface (above right). It is relatively strong in the vicinity of ferrous and magnetic materials, such as in the oceanic crust and near concentrations of metal ores, and is the focus of geophysical mineral exploration.

The disturbance field is an external magnetic field arising from electric currents flowing in the ionosphere and magnetosphere and "mirror-currents" induced in the Earth and oceans by the external magnetic field time variations. The disturbance field is associated with diurnal field variations and magnetic storms (see "Blowing in the Solar Wind: Sun Spots, Solar Cycles and Life on Earth," *page 48*). This field is affected by solar activity (solar wind), the interplanetary magnetic field and the Earth's magnetic field (right).



^ Distortion of the Earth's magnetosphere from the solar wind. The sun emits a flux of particles, called the solar wind, which consists of electrons, protons, helium [He] nuclei and heavier elements. The Earth's magnetic field is confined by the low-density plasma of the solar wind and the interplanetary magnetic field (IMF) that accompanies it. These distort the Earth's magnetic field away from its dipolar shape in the magnetosphere, the extensive region of space bounding the Earth. The field becomes compacted on the sunward side and elongated on the opposite side. The solar wind produces a variety of effects, including the magnetopause, radiation belts and the magnetotail. Time-varying interactions of the magnetosphere with the solar wind produce magnetic storms and the external disturbance field.



^ Contributions to the total observed magnetic field. During periods of solar quiet, the discrepancy between the observed field, $B_{observed}$ (red), and the main magnetic field, B_m (green), is largely due to the local crustal field B_c (blue) and the drillstring interference, B_{int} (yellow). At other times, the external disturbance field also makes a contribution. (Adapted from Poedjono et al, reference 30.)

The external magnetic field exhibits variations on several time scales, which may affect the applicability of magnetic reference models.[17] Very long-period variations are related to the solar cycle of about 11 years. Short-term variations arise from daily sunlight variation, atmospheric tides and diurnal conductivity variations. Irregular time variations are influenced by the solar wind. Perturbed magnetic states, called magnetic storms, arise and show impulsive and unpredictable rapid time variations.

On the local scale, nearby structures such as rigs and wells may induce magnetic interference. Drillstring remanent magnetization and magnetic permeability contribute to perturbations of the measured magnetic field (above). Operators may use nonmagnetic drill collars to reduce these effects along with software techniques to compensate for them.

Model	Organization	Order	Resolution, km	Update Interval
WMM	NOAA, NGDC and BGS	12	3,334	5 years
IGRF	IAGA	13	3,077	5 years
BGGM	BGS	50	800	1 year
EMM and HDGM	NOAA and NGDC	720	56	5 years and 1 year

^ Magnetic field reference models. Several groups and organizations have developed reference models of differing resolution; the models are updated at various intervals. In the Order column, order increases with the complexity of the model and in this case refers to spherical harmonic models. These models construct the global magnetic field as a sum of terms of varying order and degree. Terms of order "*n*" have a total of *n* circular nodal lines on the sphere at which the magnetic field contribution is zero. The orientation of the lines depends on the combination of order and degree. Resolution corresponds to the wavelength of the highest order term.

Magnetic Field Measurements, Instrumentation and Models

Physicists have developed a variety of sophisticated instruments for measuring magnetic fields.[18] Of particular interest for geomagnetic referencing are the instruments that scientists use within magnetic observatories on the Earth's surface and those that surveying engineers use in the oil field for downhole MWD surveying.

Proton precession and Overhauser magnetometers, which measure the Earth's magnetic field, are based on the phenomenon of nuclear paramagnetism and the tendency of atomic nuclei with a magnetic spin to orient along the dominant magnetic field. During this process, a current-induced magnetic field is applied and removed intermittently, and then the frequency of precession is measured as protons in the sensor fluid precess under the influence of the Earth's magnetic field. The Overhauser magnetometer makes use of additional free electrons in the sensing fluid and the application of a strong radio frequency polarizing field to enable continuous measurement of the precession frequency. The 14 US-based US Geological Survey (USGS) magnetic observatories use Overhauser magnetometers to provide absolute measurements of magnetic field intensity.[19] These magnetometers achieve absolute accuracy on the order of 0.1 nT.

Fluxgate magnetometers operate by driving the cores of magnetic circuits into saturation and measuring slight asymmetries that arise from the additional contribution of the Earth's magnetic field. These instruments give nonabsolute magnetic measurements along a particular direction, with resolution as fine as 0.01 nT.[20] The instruments are used in surface observatories and in ruggedized downhole MWD equipment, although some instruments are temperature sensitive and require stabilization through mechanical design.

Magnetic field models provide values for magnetic declination, magnetic inclination and total magnetic field at points on the surface of the Earth; scientists use these models to transform magnetic measurements to directions in the geographic coordinate system. Various organizations have developed geomagnetic reference models using global magnetic field measurements taken from satellite, aircraft and ships. These organizations include the US National Oceanic and Atmospheric Administration (NOAA), the NOAA National Geophysical Data Center (NGDC), the British Geological Survey (BGS) and the International Association of Geomagnetism and Aeronomy (IAGA). The models differ in their resolution in space and time (left).

The World Magnetic Model (WMM) characterizes the long-wavelength portion of the magnetic field that is generated in the Earth's core; it does not represent the portions that arise either in the crust and upper mantle or from the disturbance field generated in the ionosphere and magnetosphere.[21] Consequently, magnetic measurements may show discrepancies when referenced to the WMM alone. Local and regional magnetic declination anomalies occasionally exceed 10°, and declination anomalies on the order of 4° are not uncommon but are usually of small spatial extent. To account for secular variation, the WMM is updated every five years. An international task force formed by the IAGA has released International Geomagnetic Reference Field IGRF-11, a series of mathematical models of the Earth's main magnetic field and its rate of change. These models have resolution that is comparable to that of the WMM.[22]

Directional drilling requires higher resolution models than WMM or IGRF alone. The BGS Global Geomagnetic Model (BGGM), widely used in the drilling industry, provides the main magnetic field at 800-km [500-mi] resolution and is updated annually.[23] The Enhanced Magnetic Model (EMM) improves greatly on this spatial resolution. The EMM and a successor, the High-Definition Geomagnetic Model (HDGM), resolve anomalies down to 56 km [35 mi], an order of magnitude improvement over previous models. By accounting for a larger waveband of the geomagnetic spectrum, the HDGM improves the accuracy of the reference field, which in turn improves the reliability of wellbore azimuth determination and enables high-accuracy drillstring interference correction.[24]

Improving Well Position Accuracy

To place wellbores accurately when using magnetic guidance, surveying engineers must account for or eliminate two important sources of survey error: interference caused by magnetized elements in the drillstring and local variations between magnetic north and true, or geographic, north. Analysis of data from multiple wellbore survey stations, or multistation analysis (MSA), has become the key to addressing drillstring interference. Surveying engineers use geomagnetic referencing, which accounts for the influence of the crustal field and the time-varying disturbance field as well as secular variations in the main magnetic field.

Multistation analysis—MSA is a technique that helps compensate for drillstring magnetic interference, which can affect downhole magnetic surveys.[25] Drillstring components generate local disturbances to the Earth's magnetic field because of their magnetic permeability and remanent magnetization. Using tools manufactured with nonmagnetic materials to isolate directional sensors from magnetized drillstring components is beneficial, but the use of such tools may be imperfect or impractical because they may impact the cost or performance of the BHA. An alternative is to characterize the magnitude of the disturbance associated with the BHA so that its influence is predictable.

The MSA technique assesses the magnetic signature of the BHA by comparing the Earth's main magnetic field with magnetic data acquired at multiple survey stations. The magnitude of the perturbation depends on the orientation of the tool relative to the magnetic field direction. With sufficient data, the method determines a robust correction of the BHA disturbance to be applied for each particular well orientation.

Multistation analysis is an improvement over the earlier technique of single station analysis in which compensation is estimated and applied to each survey station independently. Now commonly used in the industry, MSA generally reduces directional uncertainty and aids in penetration of smaller reservoir targets than were previously achievable. The technique can eliminate some gyrocompass runs, thus reducing operational costs. Service companies have developed data requirements and acceptance criteria that have to be fulfilled when applying MSA, and an industry standard has been proposed.[26]

Geomagnetic referencing—Another technique for improving wellbore position accuracy, geomagnetic referencing provides the mapping between magnetic north and true north that is necessary to convert magnetically determined orientations to geographic ones on a local scale. The mapping must account for secular variations in the main magnetic field model and include an accurate crustal model. Furthermore, it must incorporate the time-varying disturbance field when it is significant. The Schlumberger geomagnetic referencing method builds a custom model of the geomagnetic field, with all its magnetic field components, to minimize the error in the mapping between magnetic and true north.[27]

Annually updated magnetic field models such as the BGGM or HDGM accurately track secular variations of the main magnetic field. Surveying engineers employ such models as the foundation for a custom model. They use various techniques

17. During quiet periods of solar activity, daily field variations, called diurnal variations, can have magnitudes of about 20 nT at midlatitudes and up to about 200 nT in equatorial regions. During periods of heightened solar activity, magnetic storms may persist for several hours or several days with deviations in magnetic intensity components on the order of several tens to hundreds of nT at midlatitudes. In auroral regions, the disturbances occasionally reach 1,000 nT, and the declination angle can vary by several degrees or more. For more on magnetic reference models: Lanza and Meloni, reference 13 and Campbell, reference 5.
18. Campbell, reference 5.

    Lanza and Meloni, reference 13.

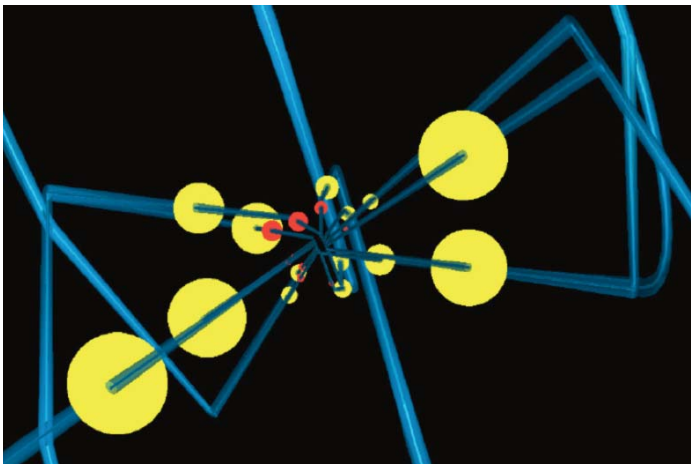
    Auster, reference 13.
19. Love JJ and Finn CA: "The USGS Geomagnetism Program and Its Role in Space Weather Monitoring," *Space Weather* 9, no. 7 (July 2011): S07001-1–S07001-5.
20. Auster, reference 13.
21. For more on the World Magnetic Model (WMM): Maus S, Macmillan S, McLean S, Hamilton B, Thomson A, Nair M and Rollins C: "The US/UK World Magnetic Model for 2010–2015," Boulder, Colorado, USA: US NOAA technical report, National Environmental Satellite, Data, and Information Service/National Geophysical Data Center, 2010.
22. For more on the International Geomagnetic Reference Field (IGRF) model: Glassmeier K-H, Soffel H and Negendank JFW (eds): *Geomagnetic Field Variations*. Berlin: Springer-Verlag, 2009, http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html (accessed July 21, 2013).
23. For more on the BGS Global Geomagnetic Model (BGGM): "BGS Global Geomagnetic Model," *British Geological Survey*, http://www.geomag.bgs.ac.uk/data_service/directionaldrilling/bggm.html (accessed July 16, 2013).

    Macmillan S, McKay A and Grindrod S: "Confidence Limits Associated with Values of the Earth's Magnetic Field Used for Directional Drilling," paper SPE/IADC 119851, presented at the SPE/IADC Drilling Conference and Exhibition, Amsterdam, March 17–19, 2009.
24. For more on the Enhanced Magnetic Model (EMM): Maus S: "An Ellipsoidal Harmonic Representation of Earth's Lithospheric Magnetic Field to Degree and Order 720," *Geochemistry Geophysics Geosystems* 11, no. 6 (June 2010): Q06015-1–Q06015-12.

    For more on the High-Definition Geomagnetic Model (HDGM): Maus S, Nair MC, Poedjono B, Okewunmi S, Fairhead D, Barckhausen U, Milligan PR and Matzka J: "High Definition Geomagnetic Models: A New Perspective for Improved Wellbore Positioning," paper IADC/SPE 151436, presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, California, March 6–8, 2012.
25. Brooks AG, Gurden PA and Noy KA: "Practical Application of a Multiple-Survey Magnetic Correction Algorithm," paper SPE 49060, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, September 27–30, 1998.

    Lowdon RM and Chia CR: "Multistation Analysis and Geomagnetic Referencing Significantly Improve Magnetic Survey Results," paper SPE/IADC 79820, presented at the SPE/IADC Drilling Conference, Amsterdam, February 19–21, 2003.

    Chia CR and de Lima DC: "MWD Survey Accuracy Improvements Using Multistation Analysis," paper IADC/SPE 87977, presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Kuala Lumpur, September 13–15, 2004.
26. Nyrnes E, Torkildsen T and Wilson H: "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 and Exhibition, Manama, Bahrain, October 26–28, 2009.
27. For a detailed description of crustal magnetic modeling, including construction of the vector crustal magnetic field using downward continuation and trilinear interpolation: Poedjono B, Adly E, Terpening M and Li X: "Geomagnetic Referencing Service—A Viable Alternative for Accurate Wellbore Surveying," paper IADC/SPE 127753, presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, February 2–4, 2010.



^ Plan view of wellbore trajectories, looking down. PGE used a multiwell pad design for 14 wells drilled into the Marcellus Shale from a single pad. The plan shows initial uncertainty disks at true vertical depths of 2,500 ft (red) and 5,000 ft (yellow). As expected, uncertainty grows larger with increasing distance from the surface location and can impact the drilling program. None of the red disks intersect each other, nor do the yellow disks, indicating that the wellbores (blue) are clear of each other at those depths. (Copyright 2010, SPE Eastern Regional Meeting. Reproduced with permission of SPE. Further reproduction prohibited without permission.)

for local crustal magnetic mapping, including land, marine or aeromagnetic surveys. Fortunately, the crustal magnetic field needs to be characterized only once in the life of the reservoir. The disturbance field, however, varies rapidly over time. Because data are available from magnetic observatories, surveying engineers are able to incorporate disturbances caused by diurnal solar activity and magnetic storms into survey data processing.

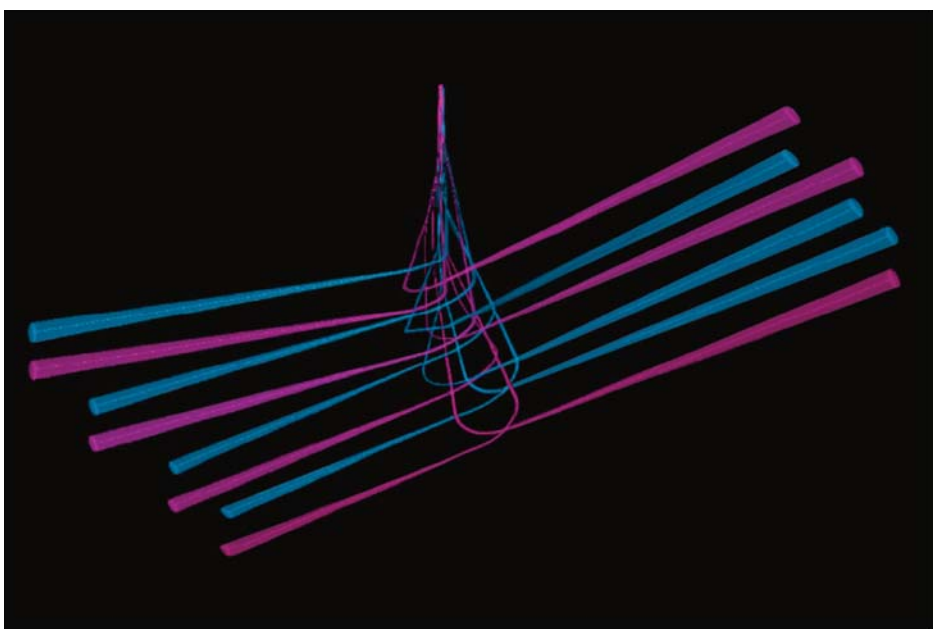
The technique of infield referencing (IFR) makes use of data from local magnetic surveys near a wellsite to characterize the crustal magnetic field. Service companies have developed extensions of this technique, incorporating remote observatory data to account for time variations. Surveying engineers use these techniques to extend the main magnetic field model and provide the best estimate of the local magnetic field, which is critical for geomagnetic referencing and multistation drillstring compensation. These techniques allow magnetic surveying even at high latitudes, where the local magnetic field exhibits extreme variations.

Schlumberger has introduced the geomagnetic referencing service (GRS) as a cost-effective alternative to conducting gyroscopic surveys in real-time drilling applications.[28] GRS provides accurate data on wellbore position and enables timely corrections to wellbore trajectory. Surveying engineers use a proprietary algorithm, a 3D crustal model and a time- and depth-varying geomagnetic reference to correct MWD measurements for magnetic drillstring interference, calculate tool orientation from the corrected measurements and advise the directional driller on course adjustments. Coordination between the operator, directional drilling contractor, MWD survey provider, geomagnetic observatory and survey engineer is essential for managing this survey technique. Examples from the USA, Canada, offshore Brazil and offshore Ghana illustrate a range of geomagnetic referencing applications.

Avoiding Collision in the Marcellus Shale

Pennsylvania General Energy (PGE) has undertaken field development in the Marcellus Shale that illustrates the benefits of multiwell planning and the need for quantifying positional uncertainty and assuring collision avoidance. PGE and its service providers sought to optimize pad design for multiwell drilling.[29] Historically, operators have developed the Marcellus Shale and other resources in the Appalachian basin using inexpensive vertical wells with minimal quality control on well surveys conducted by gyro and steering tools. Currently, however, more operators are turning to multiwell pads and horizontal drilling to improve logistics and economic and environmental impact during the development of shale gas reservoirs.

Operators now are drilling up to 14 wells per pad on 7-ft [2-m] centers by constructing deviated wells. First, a 17½-in. surface hole is air drilled to a depth of about 1,000 ft [300 m] and then surveyed. A 12¼-in. section for a water protection string is then air drilled to a true vertical depth (TVD) of 2,500 ft [760 m] using gyro-while-drilling tools to guide the separation of wells on the pad. The directional driller uses

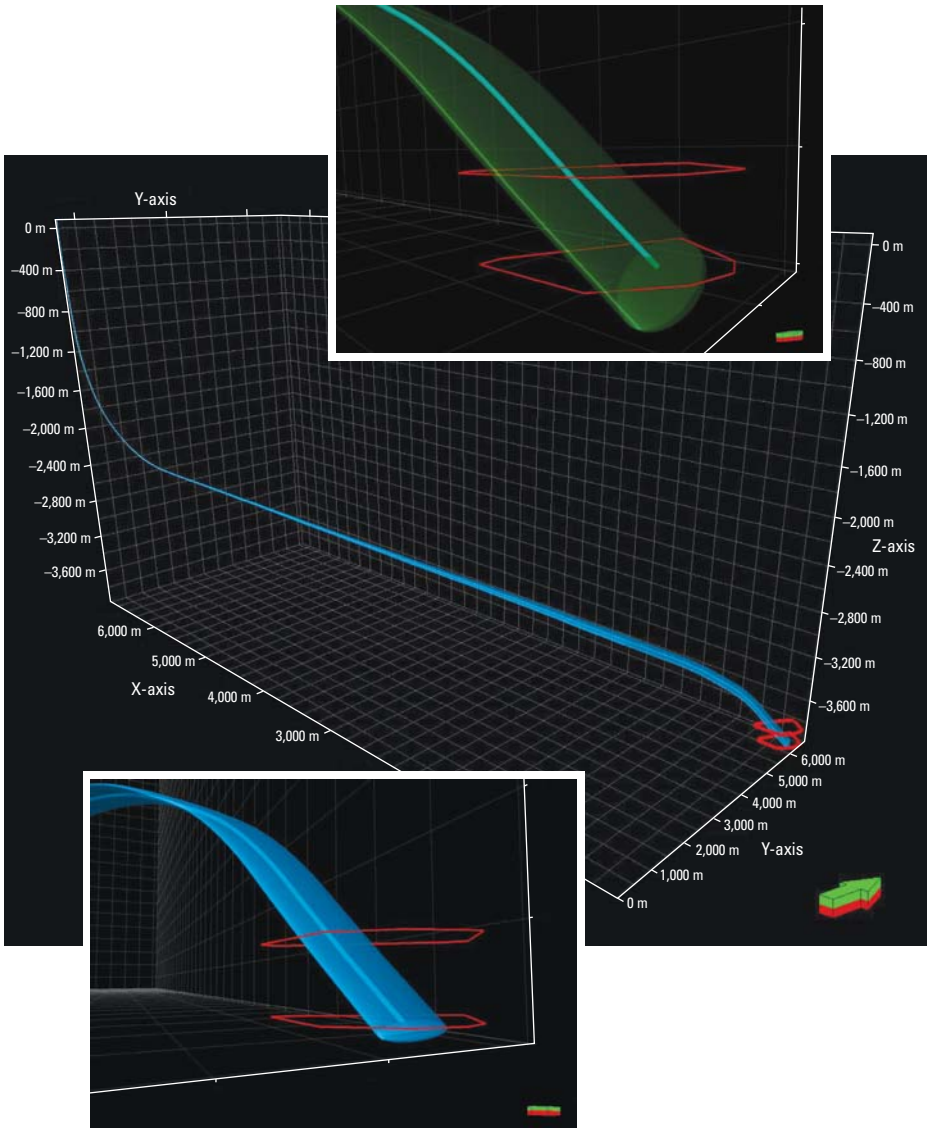


^ Pad design and well trajectories. PGE drilled 14 wells into two reservoirs during Phases 1 (magenta) and 2 (blue) of the drilling campaign. The graphical size of each wellbore corresponds to the size of the EOUs as defined in the survey program. The drilling team confirmed the anticollision condition. At the reservoir entry point, each well needed to have a minimum 200-ft [60-m] separation from its counterpart drilled in the opposite direction. (Copyright 2010, SPE Eastern Regional Meeting. Reproduced with permission of SPE. Further reproduction prohibited without permission.)

a north-seeking gyro until the well reaches a depth that is free of external magnetic interference from nearby wellbores. The deeper, deviated 8¾-in. section is simultaneously drilled and surveyed to total depth (TD) with a rotary steerable system (RSS) and MWD.

Because accurate surveying and anticollision monitoring are imperative, PGE took a proactive approach to the multiwell pad design and drilling by using a recently proposed anticollision standard.[30] Following this procedure, the operator defined uncertainty areas at three TVDs: 1,000 ft, 2,500 ft and 5,000 ft [1,500 m]. Well planners performed anticollision analysis of trajectories to ensure wellbores were properly separated at these depths. Visualization of wellbore trajectories, with uncertainty areas plotted at intermediate and deeper depths, confirmed that the drilling plan was unlikely to lead to wellbore collision (previous page, top).

The selection of slots in the multiwell pad was an important aspect of the PGE pad design because of the constraints on surface hole locations and target coordinates. PGE drilled seven wells into each of two stacked reservoirs. The drilling engineer completed the final pad design after surface holes were drilled and surveyed; then they replanned all wells, recalculated uncertainty areas and reassessed anticollision conditions (previous page, bottom). As a result, the plan reduced the risk of wellbore collision and its associated costs.



^ Hitting distant targets with an extended-reach well in the Jeanne d'Arc basin, offshore Canada. This well trajectory (*center*) extends approximately 7,000 m [23,000 ft] before dropping to hit two targets (red) at about 4,000 m [13,000 ft]. Insets (*top* and *bottom*) show close-up views of the targets and the ellipsoids of uncertainty (EOUs) for two survey methods. The positional uncertainty (green) of the magnetic surveys without GRS (*top*) is so large that the well may be outside the targets. With GRS (*bottom*), the positional uncertainty (blue) is well within the size of the targets. (Adapted from Poedjono et al, reference 27. The images in this figure are copyright 2010, IADC/SPE Drilling Conference and Exhibition. Reproduced with permission of SPE. Further reproduction prohibited without permission.)

Reaching Difficult Targets Offshore Canada

Geomagnetic referencing techniques have helped an operator efficiently and safely reach its objectives in the Jeanne d'Arc basin offshore eastern Canada.[31] Weather conditions are often severe in this remote area of the North Atlantic, leading operators to develop strategies for minimizing the extent of their offshore installations. The construction of multiple extended-reach wells drilled from slots on gravity-based platforms leverages the use of infrastructure but creates a crowded subsurface, placing a premium on collision avoidance and precise wellbore positioning.

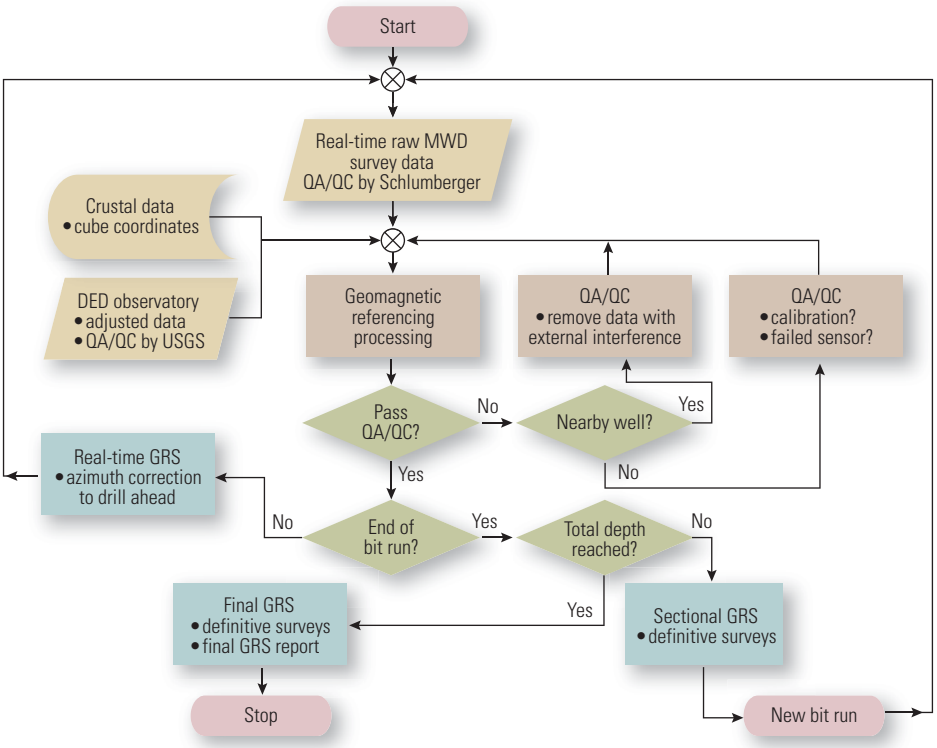
As a further challenge, the geology of the area is complex. The sedimentary basin consists of thick, layered sandstones separated by shales and subdivided by faults into large compartments or blocks. The reservoir is in a fault-bounded sector in which the target zones are smaller than the seismic resolution. The operator needed to employ sophisticated drilling and surveying techniques to hit these small targets while maintaining tight restrictions on wellbore trajectory designs.

For a successful drilling program, the operator required an accurate description of positional uncertainty and a small error ellipsoid. The GRS guided drilling program met these requirements and provided extended drillability, reduced drilling time and improved chances of hitting the geologic target (above).

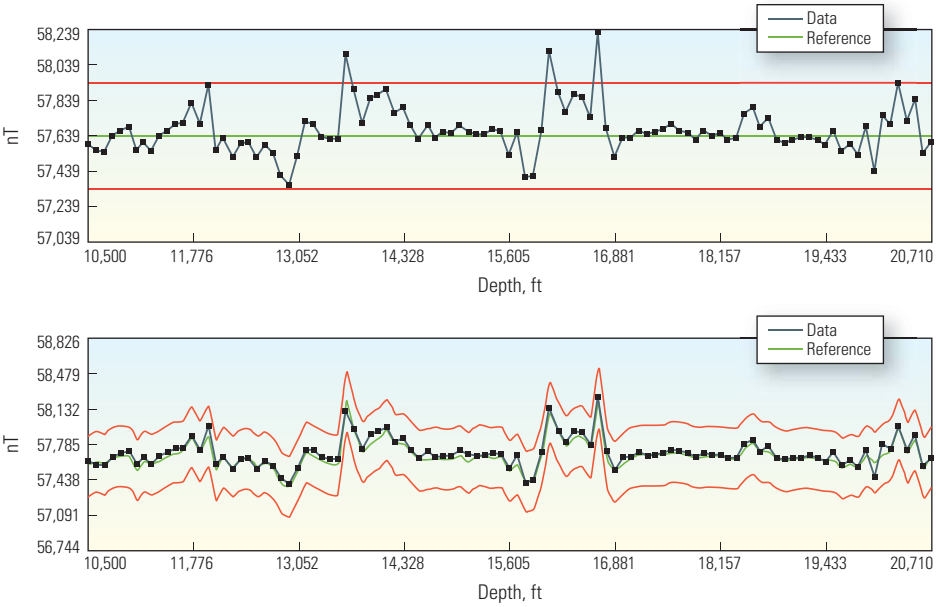
High Precision in High Latitudes

Geomagnetic referencing brings significant advantages but encounters its greatest challenge when applied at high latitude, where the magnitude of geomagnetic disturbance field variations

28. Lowdon and Chia, reference 25.
29. Poedjono B, Zabaldano J, Shevchenko I, Jamerson C, Kuntz R and Ashbaugh J: "Case Studies in the Application of Pad Design Drilling in the Marcellus Shale," paper SPE 139045, presented at the SPE Eastern Regional Meeting, Morgantown, West Virginia, USA, October 12–14, 2010.
    Kuntz R, Ashbaugh J, Poedjono B, Zabaldano J, Shevchenko I and Jamerson C: "Pad Design Key for Marcellus Drilling," *The American Oil & Gas Reporter*, 54, no. 4 (April 2011): 111–114.
30. Poedjono B, Lombardo GJ and Phillips W: "Anti-Collision Risk Management Standard for Well Placement," paper SPE 121040, presented at the SPE Americas E&P Environmental and Safety Conference, San Antonio, Texas, USA, March 23–25, 2009.
31. Poedjono et al, reference 27.
    Kuntz et al, reference 29.



^ Geomagnetic referencing workflow. The workflow starts with raw MWD and magnetic observatory data streams (shown here as from the DED observatory) and combines them with crustal magnetic field data then progresses through geomagnetic processing, data adjustment and quality control. Processing continuously generates directional drilling corrections and provides definitive surveys at the end of bit runs. (Adapted from Poedjono et al, reference 32.)



^ Time-varying reference data. Raw magnetic MWD survey data (*top*, blue) initially exceeded the data quality acceptance limits (red) at several depths, but the data passed when referenced to DED observatory data (*bottom*). Initial acceptance limits were based on a static reference value (*top*, green) for the local magnetic field strength, whereas the DED data provided actual time-varying values (*bottom*, green) to which the limits could be referenced. (Adapted from Poedjono et al, reference 32.)

is large. The Eni US Operating Co. Inc. Nikaitchuq field in the Beaufort Sea off the North Slope of Alaska, USA, is one such location. Continuity of the reservoir is broken by several faults, and drillers need to consider local reservoir compartmentalization in well planning.[32] Wellbore positioning must be precise and accurate.

At these high latitudes, the external disturbance field varies dramatically over time.[33] This disturbance represents the major source of noise in magnetic data used for well guidance. Amplitude variations are as large as 1,000 nT, and measured declination angles may vary by several degrees during magnetic storms. To account for these perturbations, GRS applies time-varying reference data from a nearby observatory to MWD measurements.

In 2009, the USGS launched a joint public-private partnership with Schlumberger to begin planning for installation and maintenance of a new observatory, called Deadhorse Geomagnetic Observatory (DED), at the town of Deadhorse, on the North Slope of Alaska. The newest of the 14 observatories, DED is now operated by Schlumberger under USGS guidance and follows Intermagnet standards.[34]

Instrumentation at the observatory includes a triaxial fluxgate magnetometer for vector field measurements, an Overhauser magnetometer for total field intensity measurements and a single-axis fluxgate declination-inclination magnetometer (DIM) on a nonmagnetic theodolite. Specialists use DIM and Overhauser data to calibrate the fluxgate variational data weekly. USGS scientists have developed specialized data processing algorithms to produce adjusted and definitive versions of real-time data streams received remotely at the USGS Geomagnetism Program headquarters in Golden, Colorado, USA.[35]

The workflow for geomagnetic referencing includes simultaneous acquisition and quality control of two data streams—MWD survey data at the rig site and real-time magnetic data at the observatory (above left).[36] Schlumberger wellsite engineers perform QC of the raw MWD data. USGS experts execute automated QC and daily inspection of data from the DED observatory and apply sensor calibration factors to produce adjusted observatory data representing the time-varying disturbance field correction. GRS processing combines the time-stamped disturbance field data, crustal field data and main magnetic field model data. The algorithm applies the combined magnetic field data to the raw MWD sensor data at each survey depth and performs multistation processing and geomagnetic referencing,

yielding geographic hole orientation. During additional processing stages, the algorithm implements data acceptance logic and computes a correction to drilling direction. The directional driller applies the drill-ahead correction until a new set of surveys is completed and a new drill-ahead correction is available. At the completion of each BHA run, surveying engineers apply BHA deflection corrections and compile the final definitive survey for that run.

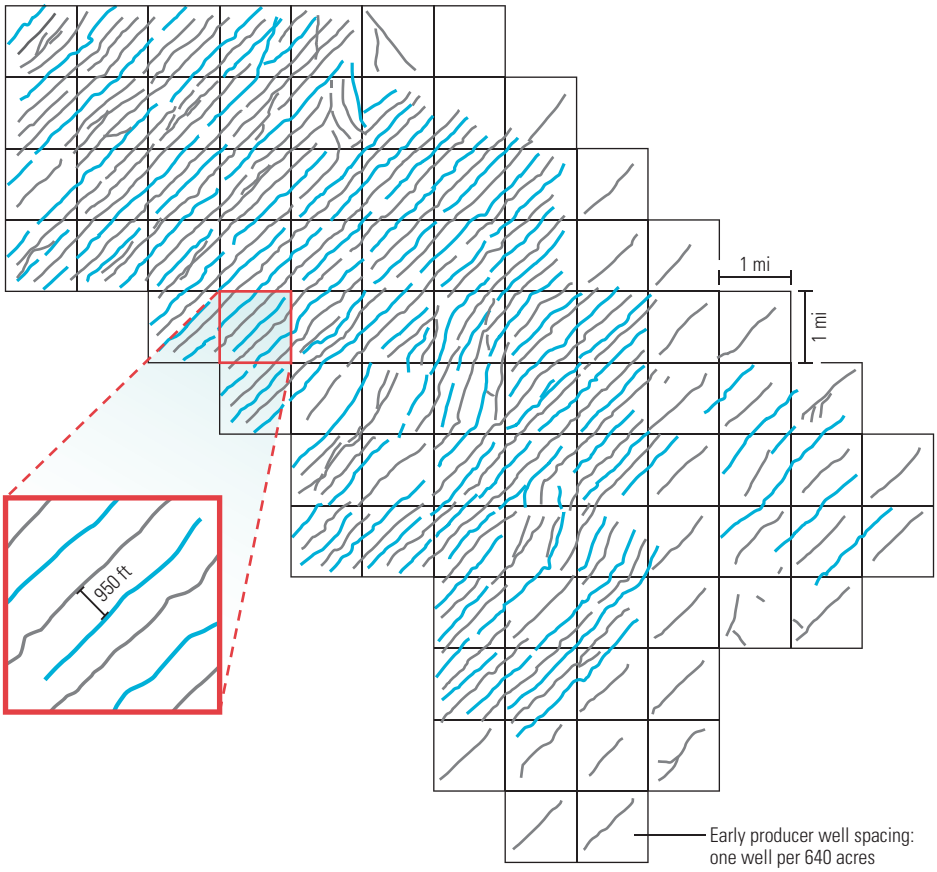
The use of time-varying reference data was essential for drilling engineers to plan and execute drilling in the Nikaitchuq field. Magnetic MWD survey raw data initially failed the data quality acceptance limits at several depths but improved to an acceptable range when referenced to DED observatory data (previous page, bottom). Because the company used GRS, drilling activities continued without the need for dedicated and costly surveying operations beyond the standard MWD survey stations.

High-Density Wells in the Williston Basin

ConocoPhillips Company has demonstrated that improved wellbore survey accuracy contributes to increased oil production. Better survey accuracy enables closer well separation and longer horizontal wells essential for boosting the efficiency of water injection programs designed to enhance oil recovery. Operating in two fields near the Cedar Creek anticline along the border between Montana and North Dakota, USA, the company has systematically studied the accuracy of existing wellbore survey data and examined the causes of MWD errors. By developing improved methodologies for magnetic data collection and reducing those errors, the company reduced positional uncertainty and contributed to both the safety and viability of the horizontal drilling program.[37]

Initially, the operators in these fields placed horizontal wells on a 640-acre [2.6-km^2] spacing. They subsequently reduced well spacing to 320 acres [1.3 km^2] and reconfigured the well pattern for a line-drive waterflood, in which rows of injection wells alternated with rows of producers (above right). Reservoir modeling suggested that reducing well spacing to 160 acres [0.65 km^2] would be beneficial. However, before proceeding, the operator needed to assess the accuracy of wellbore placement, because inadvertent convergence of boreholes could adversely affect waterflood sweep efficiency, reducing hydrocarbon production and increasing lifting and disposal costs.

Williston Basin

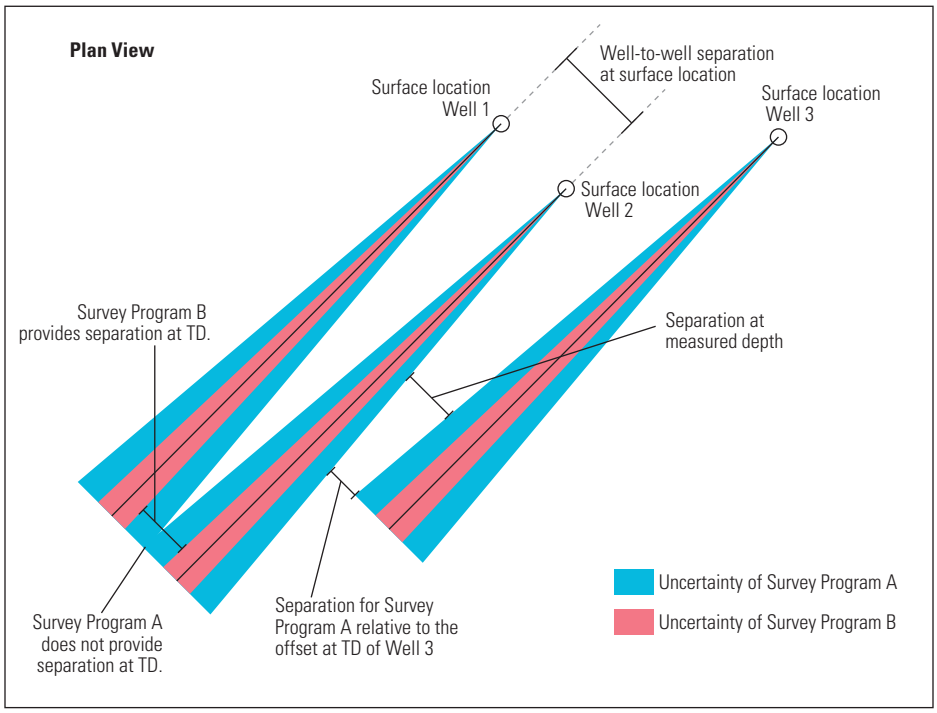


^ Field development plan. In a field in Montana and North Dakota, USA, operators started field development with one well per 1-mi^2 [640-acre, 2.6-km^2] parcel. Alternate rows of injector (blue) and producer wells (gray) show planned down-spacing to an interwell spacing of 950 ft [290 m] (red box). Positional uncertainty needs to be minimized to keep the well trajectories parallel and reduce the risk of premature breakthrough of water from the injectors. (Adapted from Landry et al, reference 37.)

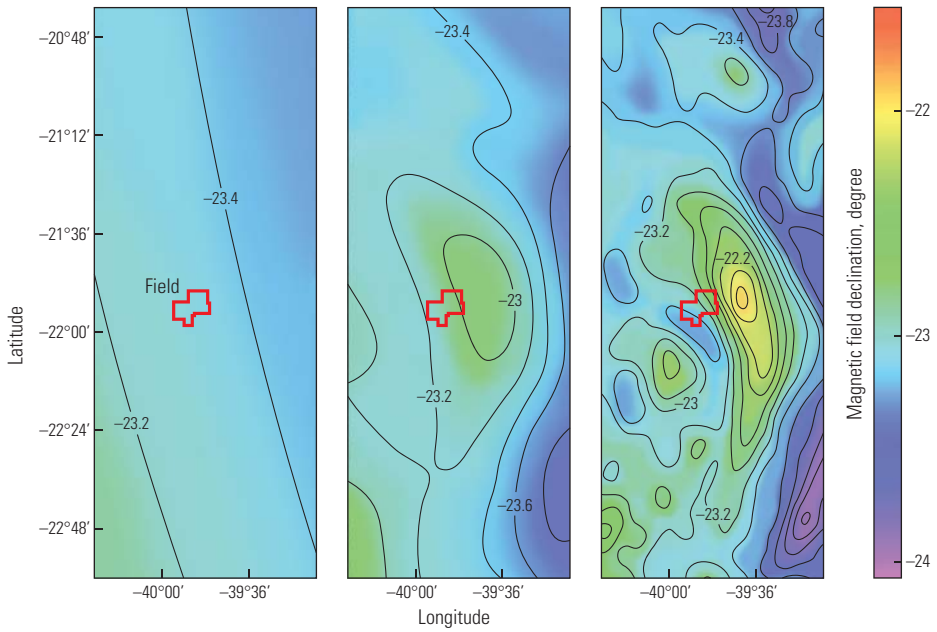
To assess the accuracy of MWD surveys, the operator conducted several statistical surveys in which the positions of wells drilled using MWD were compared with positions determined from postdrilling gyro surveys. Results showed that while the average azimuth deviation between the MWD and gyro data was about 1°, the differences were larger for a significant number of wells. After evaluating the data, surveying engineers determined that the principal cause of azimuthal error was BHA-induced magnetic interference. Other factors included local magnetic field variations and drillstring sag.

Understanding and minimizing BHA-induced magnetic interference proved to be the key to improving survey accuracy. Surveying engineers used specialized software to estimate the contribution of drillstring interference to azimuth error

32. Poedjono B, Beck N, Buchanan A, Brink J, Longo J, Finn CA and Worthington EW: "Geomagnetic Referencing in the Arctic Environment," paper SPE 149629, presented at the SPE Arctic and Extreme Environments Conference and Exhibition, Moscow, October 18–20, 2011.
33. Merrill et al, reference 13.
34. For more on Intermagnet: "*Inter*national *R*eal-time *Mag*netic Observatory *Net*work," *INTERMAGNET*, http://www.intermagnet.org/index-eng.php (accessed October 16, 2013).
35. Love and Finn, reference 19.
36. For more on the workflow at the DED observatory and on the geomagnetic referencing: Poedjono et al, reference 32.
37. Landry B, Poedjono B, Akinniranye G and Hollis M: "Survey Accuracy Extends Well Displacement at Minimum Cost," paper SPE 105669, presented at the 15th SPE Middle East Oil and Gas Show and Conference, Bahrain, March 11–14, 2007.



^ Strategies for ensuring optimal spacing to prevent water breakthrough. Survey Program B (pink) delivers higher accuracy than Survey Program A (blue). Had Wells 1 and 2 been drilled from adjacent surface locations using Survey Program A, the wells may have collided at TD. Survey Program B, with compensation for magnetic interference, ensures noncollision and allows the wells to be extended to planned total depth. By staggering one wellhead to the surface location of Well 3, the operator could increase well separation at total depth, drill wells with the desired orientation and spacing and prevent early water breakthrough. The operator chose to use both Survey Program B and wellhead staggering. (Adapted from Landry et al, reference 37.)



^ Magnetic field declination maps offshore Brazil. The standard model (*left*) shows smooth, large-scale variations in magnetic field declination in the vicinity of the hydrocarbon field (red polygon). The higher resolution HDGM (*center*) includes more detail. The combined HDGM and aeromagnetic survey model (*right*) contains the highest resolution information of all three models. All maps show declination at mean sea level. Differences of nearly 1° in declination are observed between the standard and highest resolution models near the field. (Adapted from Poedjono et al, reference 38.)

and evaluate the benefits and tradeoffs of placing nonmagnetic material between the magnetometers and the rest of the BHA. Because separating sensors from the bit can compromise real-time steering, the operators minimized nonmagnetic components and instead employed single station and multistation processing techniques to correct the surveys in real time. Postdrilling comparisons of MWD drilled trajectories with gyro surveys confirmed that discrepancies had been reduced statistically, including for instances in which the real-time magnetic interference corrections were large. Taking the reduced EOUs into account, drilling engineers were able to stagger wellhead positions and optimize wellhead spacing to prevent water breakthrough (left).

Crustal Variations

In some situations, the main concern is not the time-varying field but the crustal correction. Such was the case for one operator in a deepwater heavy-oil field offshore Brazil.[38] The project lies in 1,100 m [3,600 ft] of water in the northern Campos basin. The operator had drilled several wells using MWD and had observed discrepancies between downhole tool readings and those expected from the BGGM. To improve magnetic surveying here, it was necessary to develop a better model of the local magnetic field so that wellbore trajectories would attain their targets. The company needed to employ a highly accurate geomagnetic model to avoid field acceptance criteria failures in real-time drilling. Such failures may lead to unnecessary tool retrieval operations because of suspected tool failure.

To resolve the survey discrepancies, a research team composed of representatives from the operator, Schlumberger, other contractors and academia developed a method for mapping the magnetic variations using the High-Definition Geomagnetic Model (HDGM2011), which had recently been developed at the US NGDC. The team integrated this large-scale magnetic field model with data from a local aeromagnetic survey to extend the spatial spectrum of the magnetic field from regional scales down to the kilometer scale (left).

The team used two independent methods to analyze the crustal magnetic model.[39] Method 1 combined the BGGM with aeromagnetic survey data and employed an equivalent source method for downward continuation of the field to reservoir depth. Method 2 combined the aeromagnetic

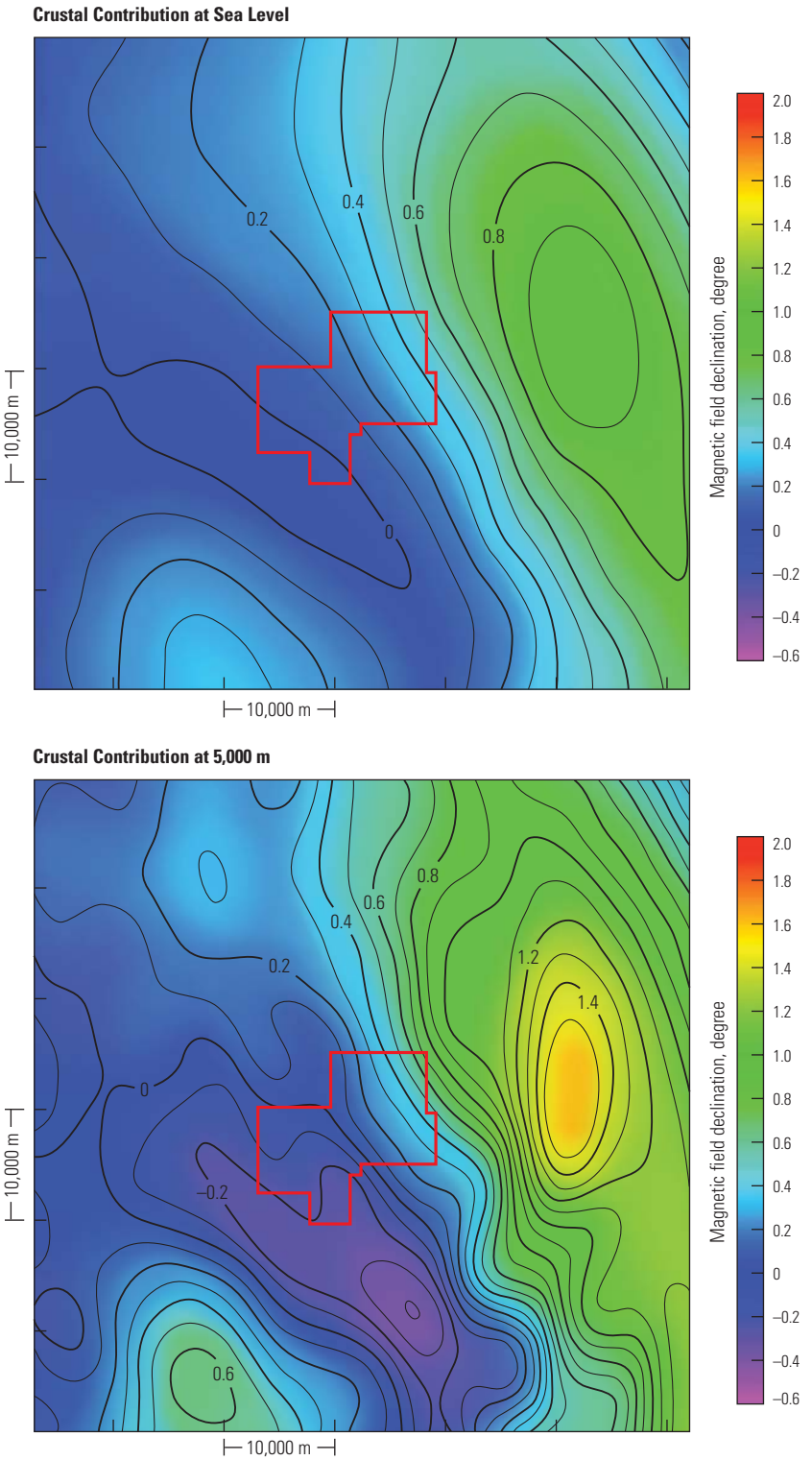
survey with a long-wavelength crustal field model provided by the German CHAMP satellite survey and created a 3D magnetic model for the lease area. The team established the validity of Method 2 by comparing the results with marine magnetic profiles taken from the US NOAA/NGDC archive. Magnetic field model attributes computed with these two methods closely agreed with each other when compared at mean sea level and at the 5,000-m [16,400-ft] reservoir depth (right).

The team discovered that intermediate-wavelength anomalies caused by large-scale magnetization of the oceanic crust had a significant impact on local magnetic declination. The higher-resolution geomagnetic reference models enabled more-refined multistation compensation for drillstring interference. By comparing predictions of horizontal and vertical magnetic field components with those from MWD tool readings, the team established validity of the broadband models. Data points affected by drillstring interference were outside quality control acceptance bands when processed with the BGGM but were consistent with the other data when processed with a high-resolution model.

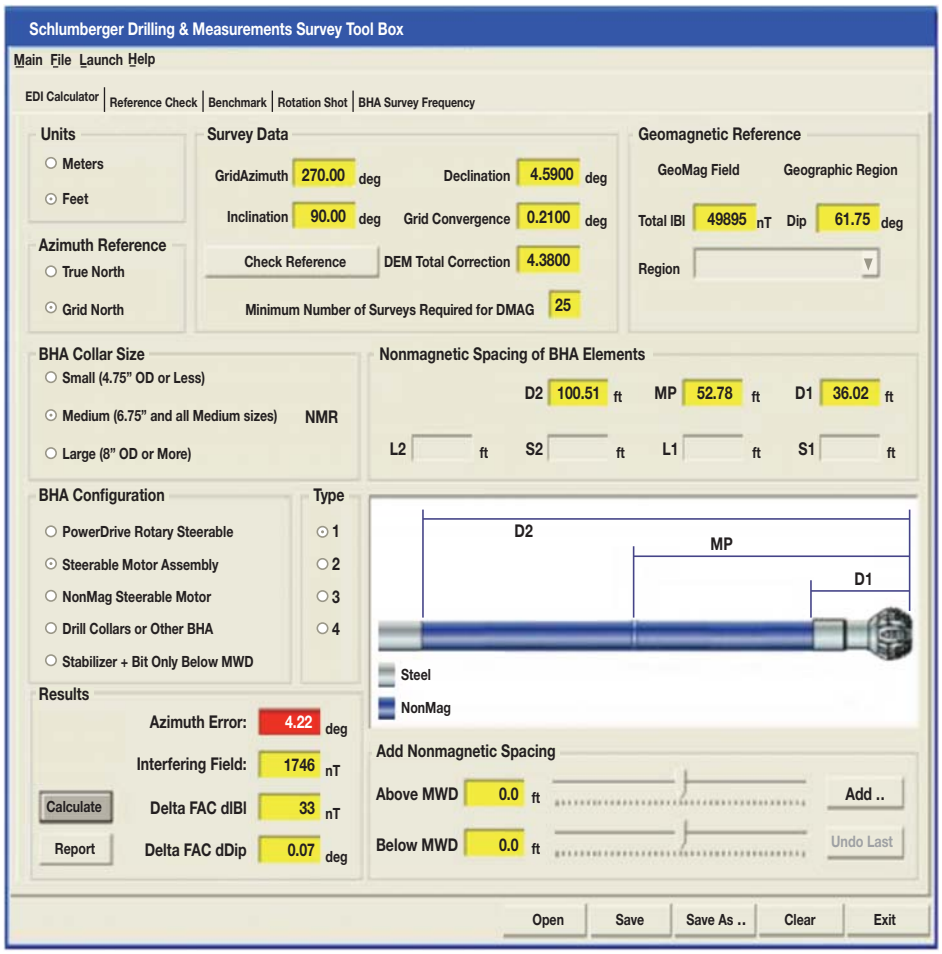
The team evaluated the importance of the time-varying disturbance field using data from the nearby Vassouras Magnetic Observatory in Brazil. Results showed small variations in declination, dip and total field intensity. Diurnal variations were insignificant at the wellbore positions during times of low solar activity, and data from the high-resolution static models were sufficient for these times. Operator representatives concluded that multistation analysis improved when they used the high-resolution geomagnetic models compared with the BGGM magnetic field predictions. Significant localization improvements occurred when they used GRS to correct MWD raw readings. Estimated wellbore bottomhole locations shifted significantly, and the sizes of the ellipsoids of uncertainty and the TVD uncertainty consistently decreased.

38. Poedjono B, Montenegro D, Clark P, Okewunmi S, Maus S and Li X: "Successful Application of Geomagnetic Referencing for Accurate Wellbore Positioning in a Deepwater Project Offshore Brazil," paper IADC/SPE 150107, presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, California, March 6–8, 2012.

39. Two proprietary processing methods developed for analyzing the crustal field are discussed in Poedjono et al, reference 38. Method 1 was developed by Fugro Gravity & Magnetic Services Inc, now part of CGG. Method 2 was developed by Magnetic Variation Services LLC.



^ Crustal contribution to the magnetic field declination at two depths in the vicinity of a field offshore Brazil. The crustal field contribution to the magnetic declination is shown in plan view at mean sea level (*top*) and at a depth of 5,000 m (*bottom*). Values were calculated using a method that combined an aeromagnetic survey with a long-wavelength crustal field model provided by the German CHAMP satellite survey; the method then created a 3D magnetic model for the lease area. The 3D magnetic field changes with depth, in large part because of the magnetic properties of the Earth's crust underlying the sediments offshore Brazil. (Adapted from Poedjono et al, reference 38.)



^ Quantifying magnetic measurement sensitivity to toolstring interference. Modeling codes are used to simulate the extent of magnetic interference for various survey orientations and BHA designs. This simulation, taken from the Schlumberger Drilling & Measurements Survey Tool Box, shows the large azimuthal error (red) that would occur at this particular wellbore grid azimuth of 270° and inclination of 90° if the driller did not add nonmagnetic spacing material to the BHA in addition to that included in the initial design (blue). Drilling engineers use these simulations to determine the length of nonmagnetic material above or below the MWD measure point necessary to reduce the error sufficiently.

Deepwater Success

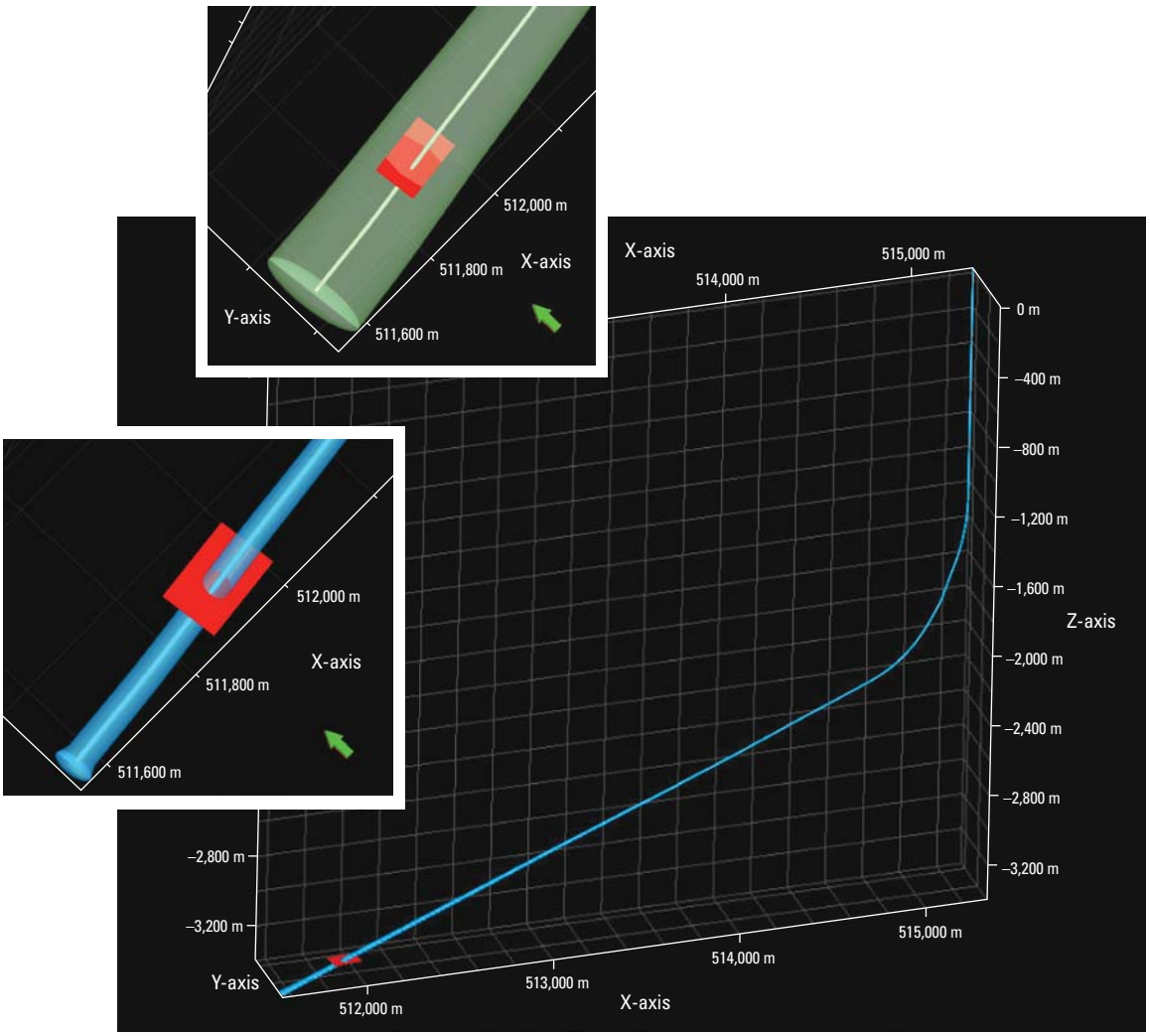
Accurate real-time magnetic surveys allow directional drillers to stay on path and to reduce the number of required confirmatory gyro surveys. Tullow Ghana Ltd. used geomagnetic referencing to achieve its objectives to hit distant geologic targets accurately and within budget while developing the Jubilee field offshore Ghana.[40]

The operator wanted to drill all wells safely and successfully in the shortest possible time because rig spread costs are exceptionally high in this area. To enable accurate GRS, Schlumberger surveying experts conducted numerical simulations, which quantified the sensitivity of the magnetic measurement to wellbore trajectory and to the inclusion of nonmagnetic collars for BHA variations (above).

An aeromagnetic survey provided the basis for the custom-built geomagnetic model. This 80-km × 80-km [50-mi × 50-mi] survey was centered at the Jubilee field at an altitude of 80 m [260 ft] and included presurvey test flights for calibration and use of a base station as reference for time-varying changes in the magnetic field. Analysts computed a total magnetic intensity (TMI) anomaly grid using the total magnetic field measured in the aeromagnetic survey combined with the 2010 BGGM main magnetic field model.[41] Crustal magnetic field processing yielded an updated magnetic field from sea level to a depth of 4,500 m [14,800 ft] using downward continuation of the scalar TMI anomaly. Subsequent processing determined the east, north and vertical components of the magnetic field and transformed them into declination and inclination perturbations relative to the main magnetic field.

40. Poedjono B, Olalere IB, Shevchenko I, Lawson F, Crozier S and Li X: "Improved Drilling Economics and Enhanced Target Acquisition Through the Application of Effective Geomagnetic Referencing," paper SPE 140436, presented at the SPE EUROPEC/EAGE Annual Conference and Exhibition, Vienna, Austria, May 23–26, 2011.

41. For more on the processing workflow: Poedjono et al, reference 32.



^ An extended-reach well in the Jubilee field offshore Ghana. The Tullow Ghana Ltd. Well 4 has a long step-out and tangent profile to hit the target (red). The EOU from standard MWD (*top left,* green) is larger than the rectangular geologic target. Because of the smaller EOU from GRS (*center left,* blue), the operator was able to drill the well with high confidence that the wellbore would penetrate the target. (Adapted from Poedjono et al, reference 40. The images in this figure are copyright 2011, SPE EUROPEC/EAGE Annual Conference and Exhibition. Reproduced with permission of SPE. Further reproduction prohibited without permission.)

For the initial wells in the Jubilee field, standard MWD surveys yielded small enough EOUs to hit the geologic targets with confidence. These initial well paths had relatively shallow inclination angles. For more-distant targets with higher inclination angles and longer tangent sections, the uncertainty associated with standard MWD surveys was unacceptably large. However, uncertainty was considerably smaller for GRS processed magnetic data, and drillers reached their objectives with high confidence. Using GRS, the operator was able to drill the well with guaranteed placement of the wellbore inside the target (above).

Reaching the Target

These examples illustrate a range of new and exacting requirements for wellbore guidance and the geomagnetic measurement technology that has been developed to satisfy those requirements. Challenges have included avoiding wellbore collision, reducing drillstring magnetic interference and accounting for geomagnetic field variations associated with crustal magnetism and temporal magnetic field variations.

Directional drillers now place wellbores within increasingly demanding targets by relying on real-time wellbore surveys and small EOUs. High-resolution geomagnetic reference models aid processing for drillstring interference compensation and enhance measurement quality control by employing customized acceptance criteria. Geomagnetic referencing improves well placement accuracy, reduces positional uncertainty and mitigates the danger of collision with existing wellbores. When used in real-time wellbore navigation, GRS saves rig time, reduces drilling costs and helps drillers reach their targets. —HDL