Quantifying Global and Random Uncertainties in High Resolution Global Geomagnetic Field Models Used for Directional Drilling

C.D. Beggan, S. Macmillan, W.J. Brown, British Geological Survey; and **S.J. Grindrod,** Copsegrove Developments Ltd

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Abstract

Total field strength, declination and dip angle of the Earth's magnetic field, in conjunction with gravity, are used by magnetic-survey tools to determine a wellbore's location. Magnetic field values may be obtained from global models which, depending on the model, have a wide range of spatial resolution at the Earth's surface from large scale (3000 km) to small scale (28 km). The magnetic field varies continuously in both time and space, so no model can fully capture the complexity of all sources and hence there are uncertainties associated with the values provided. The SPE Wellbore Positioning Technical Section / Industry Steering Committee on Wellbore Surveying Accuracy (ISCWSA) published their original measurement-while-drilling (MWD) error model in 2000. Such models and uncertainties define positional error ellipsoids along the wellbore which assist the driller in achieving their geological target, in addition to aiding collision avoidance. With the recent update to Revision 5 of the ISCWSA error model, we have reassessed the uncertainties associated with our latest high-resolution global magnetic field model.

We describe the derivation of location-specific global and random uncertainties for use with predicted geomagnetic values from high resolution models within magnetic MWD survey-tool-error models. We propose a sophisticated approach to provide realistic values at different locations around the globe; for example, we determine separate errors for regions where the models have high spatial resolution from aeromagnetic data compared to regions where only satellite data are available.

The combined uncertainties are freely available via a web-service where the user can also see how they vary with time. The use of the revised uncertainty values in the MWD-error model, in most cases, reduces the positional error ellipsoids and allows better use of the increased accuracy from recent improvements in geomagnetic modelling. This is demonstrated using the new uncertainty values in the MWD-error model for three standard ISCWSA well profiles. A fourth theoretical well offshore Brazil where the vertical magnetic field is weak shows that, with drill-string interference correction relying on the more uncertain magnetic dip, the positional error ellipsoids can increase. This is clearly of concern for attaining geological targets and collision avoidance.

Introduction

The Earth's magnetic field can be considered as a four-dimensional vector quantity, varying in both space and time. For practical applications, it can be expressed as the instantaneous sum of contributions from three primary sources: the field generated in the Earth's core, the crustal field from local geology, and the external field created by the flow of electrical current systems in the ionosphere and magnetosphere (Langel and Hinze, 1998). The main field generated by the Earth's core accounts for approximately 98% of field strength at the Earth's surface between 23,000 and 65,000 nanoTesla (nT) depending on location. Its strength and direction vary relatively slowly with time; the rate of change of the field intensity is less than 150 nT per year and the direction changes a few arc-minutes per year across most of the globe away from the magnetic poles. The crustal field from local rocks is relatively weak in comparison (generally <1,000 nT) and may be regarded as static on geologic time scales, but electrical currents flowing in the upper atmosphere driven by the variable solar wind can cause large and rapid fluctuations on time scales of minutes to hours. During severe magnetic storms, the intensity of the electrical currents reach over 3,000 nT and can cause variations of several degrees in the geomagnetic-field vector direction, particularly at high latitudes close to the auroral regions (Beggan et al., 2018).

Directional drilling requires subsurface navigation to targets that are often distant from the drilling pad (Poedjono et al., 2018). To navigate underground surveyors collect magnetic and accelerometer data from survey tools which obtain measurements of geomagnetic-field strength and angle of dip at a drilling location (Kabirzadeh et al, 2018). These are compared against modelled estimates from a global model of the geomagnetic field and should match to within an expected tolerance (Jamieson, 2017). Ideally, magnetometers should be located at a drillsite to measure the geomagnetic field vector's local strength and direction but this is not realistic, so full account of the uncertainties must be made to create uncertainty ellipses for the wellbore location (Russell et al, 1995).

The global magnetic field models used in directional drilling are a combination of the internal core and crustal field, and the steady external field arising from ever-present magnetosphere (so-called ring current).

Hence, the value of the field at the Earth's surface for a given time and location from field models will differ from the true value because of inherent errors from (a) how the models are constructed, (b) the effect of small-scale local crustal fields not captured by the models, and (c) unpredictable time-varying external fields (Macmillan and Grindrod, 2010). Note, there are additional techniques for predicting the time-varying magnetic fields which can further reduce uncertainties from the external field effects (Edvardsen et al, 2019) but those of the main and crustal field remain (Williamson et al, 1998).

In this paper, we investigate the magnitude and the spatial variability of these three uncertainties to allow a more nuanced representation of the associated errors. We then use the updated uncertainties to analyze the changes seen in uncertainty ellipsoids for downhole drilling locations using a high resolution main field model (+HRGM) with axial correction (+AX) in conjunction with Revision 5 Error Model from the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) for Measure While Drilling (MWD) applications. We apply the uncertainties to four model wells to show their advantage over the generic error values provided with this Revision and provide illustrative tables to show the decomposition of magnetic uncertainties into their recommended correlated and uncorrelated contributions.

Magnetic field models

The vector components of the Earth's magnetic field for any location on, above or below the surface can be represented by the summation of a set of weighting coefficients, called Gauss coefficients, multiplied by set of spherical basis functions called the Legendre polynomials, which are equivalent to a Fourier series on a sphere. By adding more Gauss coefficients, smaller features of the magnetic field can be captured. To represent the field to a particular resolution requires the 'degree' (n) of the model to be considered. The horizontal spatial resolution of the model is computed as $\sim 2\pi r/\sqrt{(n(n+1))}$, where r is the Earth's reference radius (6371.2 km). For example, low degree models of n = 13 such as the World Magnetic Model (WMM) or International Geomagnetic Reference Field (IGRF) have a resolution of approximately 3000 km, whereas a high-resolution model incorporating data from satellites, observatories, and aeromagnetic and marine survey data from the past 70 years and with n = 1440 has a spatial resolution of around 28 km.

However, some sources like the external field can be more difficult to model. Smaller-scale asymmetries and ionospheric sources are far harder to parameterize, though the large-scale part of this (the so-called 'ring current') is generally well-behaved. These small spatial scales and complex time-varying behavior in regions such as the auroral ovals and equatorial electrojet are particularly challenging.

For this work we co-estimate external fields along with the core field by parameterizing the large-scale magnetospheric field in terms of slow and fast time variations, and periodic components, along with the associated internally induced counterparts. The remaining unmodelled or under-parameterized external fields are accounted for by our approach in section "External field uncertainty". The efficacy of our model design is shown by the low-weighted misfits to the input satellite data (e.g. mean of 1.23 nT root-mean-square for the vector field components at low-latitudes, 2013-2019) and ground observatory data (e.g. mean of 1.13 nT root-mean-square for the vector field components at low-latitudes, 2013-2019), though these misfits serve to remind us that a model will always be an approximation.

As noted, contemporary field models are created from multiple data sources including satellite, observatory, aeromagnetic and marine data. The largest scales are derived from measurements made by low-Earth-orbit satellite such as the European Space Agency's Swarm mission (Friis-Christensen, Lühr and Hulot 2006) and the former CHAMP satellite mission (Reigber, Lühr and Schwintzer 2002). As a rule of thumb, the minimum height of the satellite is the smallest spatial scale achievable. The CHAMP satellite orbited at 300 km at the end of its mission in 2010, so a degree-133 model is possible from its data. For short wavelength features from 300 to 28 km, we used the World Digital Magnetic Anomaly Map (Lesur, Hamoudi, et al. 2016) which collected together aeromagnetic and marine data, relevelling and stitching surveys from different countries and datasets into a single consistent data grid. However, some countries have not made datasets available; in these regions and a significant part of the ocean area the resolution defaults to that of the satellite. From this dataset, we used a damped gradient descent method to solve for the Gauss coefficients from degree 133 to degree 1440. This gives us a complete description of the magnetic field from large-scale to small-scale. Note the magnetic field has a time-dependence for degrees 1 to at least 15 which requires an annual update to maintain the required accuracy for directional drilling purposes, and we include a predictive element for up to 18 months from the time of release. Figure 1 shows the regions containing both near-surface anomaly and satellite data in the model (orange) and those containing only satellite data (green).

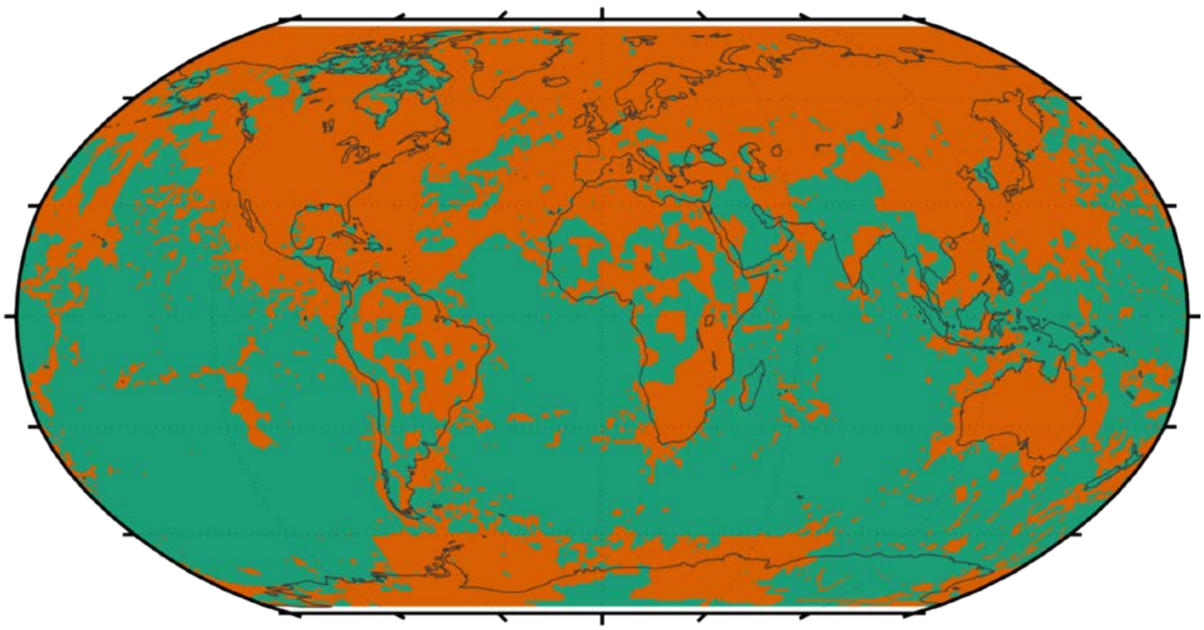

Figure 1: Distribution of near-surface anomaly data (orange) and satellite data (green) in the high degree (n=1440) model.

Uncertainty requirements

Directional drilling and survey management companies have a requirement for accurate geomagnetic field estimates and knowledge of the associated uncertainties when magnetic survey tools are used in the surveying of wellbores. Magnetic survey tools measure the direction of the wellbore relative to the direction of the local geomagnetic field. In addition, the magnetic dip angle and total intensity of the geomagnetic field are required to reduce the error caused by the additional magnetic field associated with drill-string interference. The uncertainties are used to compute positional error ellipsoids along the wellbore to help hit geological targets, increase extraction efficiency and avoid intersecting other local well bores.

The ISCWSA MWD error model is designed to quantify wellbore position uncertainty, and is widely used and accepted as the standard mathematical framework in the industry [see https://www.iscwsa.net/committees/error-model/ for details of revisions]. Whilst the magnetic field error magnitudes are part of the tool codes, the ISCWSA supplies a set of generic MWD models with pre-defined error magnitudes. Those associated with the geomagnetic field were derived by Williamson (2000) from the original study of Macmillan et al. (1993) and are invariant with location apart from a simple dependence on the horizontal field strength for the declination error. Within the present Revision 5, the usual global and random geomagnetic terms have been separated into multiple error sources to allow for correlations of these errors between wells e.g. in collision avoidance calculations.

For a Gaussian or normal distribution of errors, the one-standard deviation (1σ) error is equivalent to a 68.3% confidence that the estimated value is within that amount of the true value. Additionally, for a Gaussian distribution, 2σ is equivalent to being 95.4% confident, and 3σ is equivalent to being 99.7% confident. In the ISCWSA error model the estimated geomagnetic field errors are combined with other sources of well-path survey errors e.g. depth, which are assumed to be independent (that is, uncorrelated) and to follow a Gaussian distribution and all error magnitudes in the ISCWSA model are provided at one standard deviation (1σ). However, magnetic fields errors do not follow a Gaussian distribution; the distribution due to un-modeled external fields has long tails because of the occasional occurrence of extreme space weather events and similarly for the crustal field (see for example, Macmillan and Grindrod (2010)). To provide conservative standard deviations for the geomagnetic terms our approach is to estimate the 95.4% confidence limits and half them, which we term a one-sigma equivalent (*1σ equiv*). These can be combined with other error estimates in the ISCWSA error model and scaled up to the high levels of confidence required and for this reason we also use the term *scalable 1σ error estimates*.

Determining magnetic field model uncertainty

As described in the Introduction, magnetic models are constructed by assuming the field can be represented by the core, crust and external field. We use this method to analyze the individual uncertainty contributions from each part of the process and bring them together so the uncertainties are justified both in time and space. Although directional drillers are more familiar with the Declination, Magnetic Dip (geophysicists refer to this as magnetic Inclination) and Total Field (hence, DIF) manner of describing the field, this representation has a non-linear dependence on the Gauss coefficients. Instead, we computed the values in the orthogonal vector frame XYZ, where X is the strength of the northward pointing component, Y is the eastward component and Z is the vertical component pointing toward the center of the Earth. Using X, Y and Z makes it easier to linearly combine the uncertainties. Later, we convert XYZ to DIF which is directly useful for drillers. The uncertainties (denoted δ) in X, Y and Z can be converted to H (strength of the horizontal component), D, I and F using the following formulae based on the main field value at each location:

$$\delta H = \sqrt{[(\delta X)^2(\cos D)^2 + (\delta Y)^2(\sin D)^2]}$$

$$\delta D = \frac{\sqrt{[(\delta X)^2(\sin D)^2 + (\delta Y)^2(\cos D)^2]}}{H}$$

$$\delta I = \frac{\sqrt{[(\delta H)^2(\sin I)^2 + (\delta Z)^2(\cos D)^2]}}{F}$$

$$\delta F = \sqrt{[(\delta H)^2(\cos I)^2 + (\delta Z)^2(\sin I)^2]}$$

Equation 1: Conversion of X, Y and Z uncertainties to D, I and F.

This conversion also reveals the underlying structure of the main field.

Crustal field uncertainty

The crustal magnetic field can be assumed to be constant, though it does vary on geological timescales at mid-ocean ridges and in orogeny belts. To establish the uncertainty associated with the crustal field part of the model, we compared the high-resolution magnetic model field values to measurements from the thousands of spot values from the ground magnetic repeat station network and other one-off magnetic vector surveys. The ground station network is a global database of high-quality angle and total field measurements made at temporarily occupied sites on land over the past century. Many locations are repeatedly surveyed every few years, though only in a relatively small number of countries and most of the data are reduced to magnetic quiet night time levels when the external field signal is smallest.

The differences between the values from the degree 1440 model and the repeat station data allow us to estimate the globally average uncertainty for the X, Y and Z components. We point out that the repeat station data have not been included in the original construction of the degree 1440 model so are independent of it. However, there are some drawbacks to this approach, including the limited spatial extent of the database which does not cover a large percentage of the global land area, and the unknown quality of some of the older data. We limited the use of data prior to 1979, the beginning of the satellite vector magnetic survey era and when proton precession magnetometers began to be more widely used. We also removed gross outlier values which were greater than three standard deviations from the mean. Around 10,000 ground full-vector measurements were used to computed the differences with the high-resolution model. The means of the differences were approximately zero in each component. Next, the absolute differences were ranked from smallest to largest and we computed the 1, 2 and 3σ equivalent uncertainties. We took the 2σ values and divided them in half to give the 1σ equivalent of 90 nT for the X component, 91 nT for the Y component and 185 nT for the Z component.

Though relatively large, we emphasize these are global uncertainties from land-based measurements, which are conservative and overly-cautious as they encompass areas of the planet with volcanic or metamorphic geology. These areas have large crustal field magnitudes at small spatial scales (< 10 km) that the model cannot capture. In hydrocarbon regions, the crustal field tends to have larger spatial scales and weaker magnitudes in general so should be better captured by the high-resolution magnetic field model.

The next step of our analysis was to make a fairer estimate of the uncertainties of the unknown crustal field in oil-producing regions of the globe especially where aeromagnetic and marine data were available. Most but not all hydrocarbon fields are in these regions. We chose to examine three total field aeromagnetic datasets from the UK, US land and the World Digital Magnetic Anomaly Map grid. From these we computed hundreds of local estimates of the crustal field vector using Fourier transformations assuming planar geometry. The estimates were at locations of both ground-based stations and at hydrocarbon fields. The latter were drawn from locations where In-Field Referencing has been provided by BGS. Again, we ranked these separately for each type of location to compute their 1σ, 2σ and 3σ equivalent uncertainties and averaged the results from the three datasets. Finally, we used the ratios of the 2σ uncertainties from the hydrocarbon fields and the ground-based stations as scaling factors to reduce the results from the initial global analysis. We found scaling factors of 0.64, 0.68 and 0.81 for X, Y and Z, respectively (see Table 1), implying that the global uncertainties estimated from the repeat survey dataset are pessimistic for hydrocarbon regions.

	Scalable 1 sigma crust (global)	Aeromagnetic data scaling factor
Units	(nT)	-
X	90	0.64
Y	91	0.68
Z	185	0.81

Table 1: Uncertainties and scaling factors for scalable 1-sigma values

Finally, we also examined the scaling factors for locations of large oil fields. These locations were downloaded from the website of the American Association of Petroleum Geologists and date from 2011.

We repeated the analysis by computing crustal field values at these locations and comparing them to the global field values. From these differences we found an average scaling ratio of 0.55, again implying that the global uncertainties are conservative.

Based on the scalable 1-sigma values for X, Y and Z and the scaling factors for regions of both aeromagnetic and satellite data versus satellite data only (in Figure 1), we converted the X, Y and Z components of the uncertainties on a 1° x 1° grid in latitude and longitude to D, I and F using the formulae given in Equation 1. Figure 2 shows maps of these uncertainties. Note we only plot up to a latitude of +/- 85°.

For Declination, the uncertainties vary from around 0.1° in the regions covered by aeromagnetic data to 0.75° around the magnetic poles. The magnetic Inclination (dip) uncertainties reflect the strength of the magnetic field and are greatest (up to 0.4°) where it is weakest around the South Atlantic Anomaly. The total field values are small (around 50 nT) over regions covered by aeromagnetic data but largest in regions of satellite only data, particularly at the poles (> 200 nT).

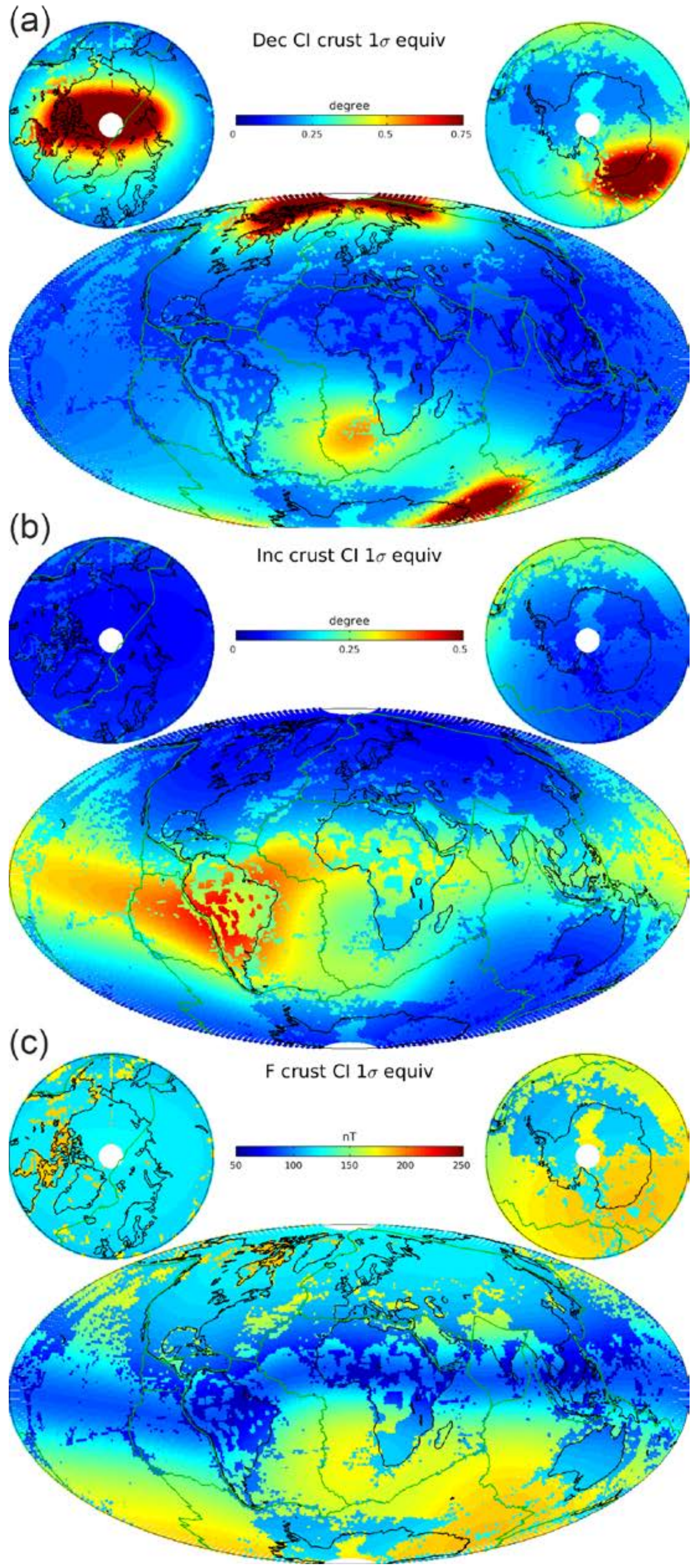

Figure 2: Crustal field error in the (a) Declination, (b) magnetic Inclination (or dip) and (c) Total Field components

External field uncertainty

The external (or disturbance) field has both regular and irregular signals. The regular signals such as the daily effect of the sun on the ionosphere are predictable and can be well captured by models at low latitudes. The irregular parts are driven by the unpredictable solar wind which creates electrical current systems in the ionosphere and magnetosphere that vary rapidly over seconds to days. There is also a longer-term variation on the approximately 11-year solar cycle.

Broadly speaking the external field is latitude-dependent (being largest in the high geomagnetic latitude auroral regions) and so it is possible to statistically examine the variation in this frame. To examine the external field uncertainty, we use long-term measurements from ground observatory data sets from a range of latitudes. This allows an estimate to be made of the distribution of the disturbance field globally.

Using the minute-mean values from between 70 to 120 observatories, depending on the year, from 1997 to 2018 (covering two solar cycles) we removed the main field contribution from each of the X, Y and Z components, and then further subtracted the average from these residuals to account for the local fixed crustal field. The remaining signal is assumed to be external in origin. These data were sorted by size and the 1, 2 and 3σ equivalent uncertainties were computed.

The observatory locations were then converted from geographic to magnetic quasi-dipole coordinates (i.e. a coordinate system orientated with respect to the magnetic poles and which takes account of the full harmonic structure of the core field, see Emmert et al., 2010). The halved 2σ equivalent uncertainties were plotted versus quasi-dipole latitude and splines are fitted through the values to get the scalable 1-sigma value at a given magnetic latitude. There is an element of judgement to the fitting of the spline knots to account for bad points and latitude gaps and to ensure the value at the magnetic poles (+/-90 degrees) are clamped.

The spline curves for each of the X, Y and Z components were then mapped from quasi-dipole coordinates back to geographic coordinates and transformed to D, I and F using the formulae in Equation 1. Figure 3 shows the resulting 1σ-equivalent uncertainties. The uncertainties broadly increase with latitude but note the Total Field also has an increased region of uncertainty values along the magnetic equator (where magnetic Inclination (dip) changes sign) related to the equatorial electrojet.

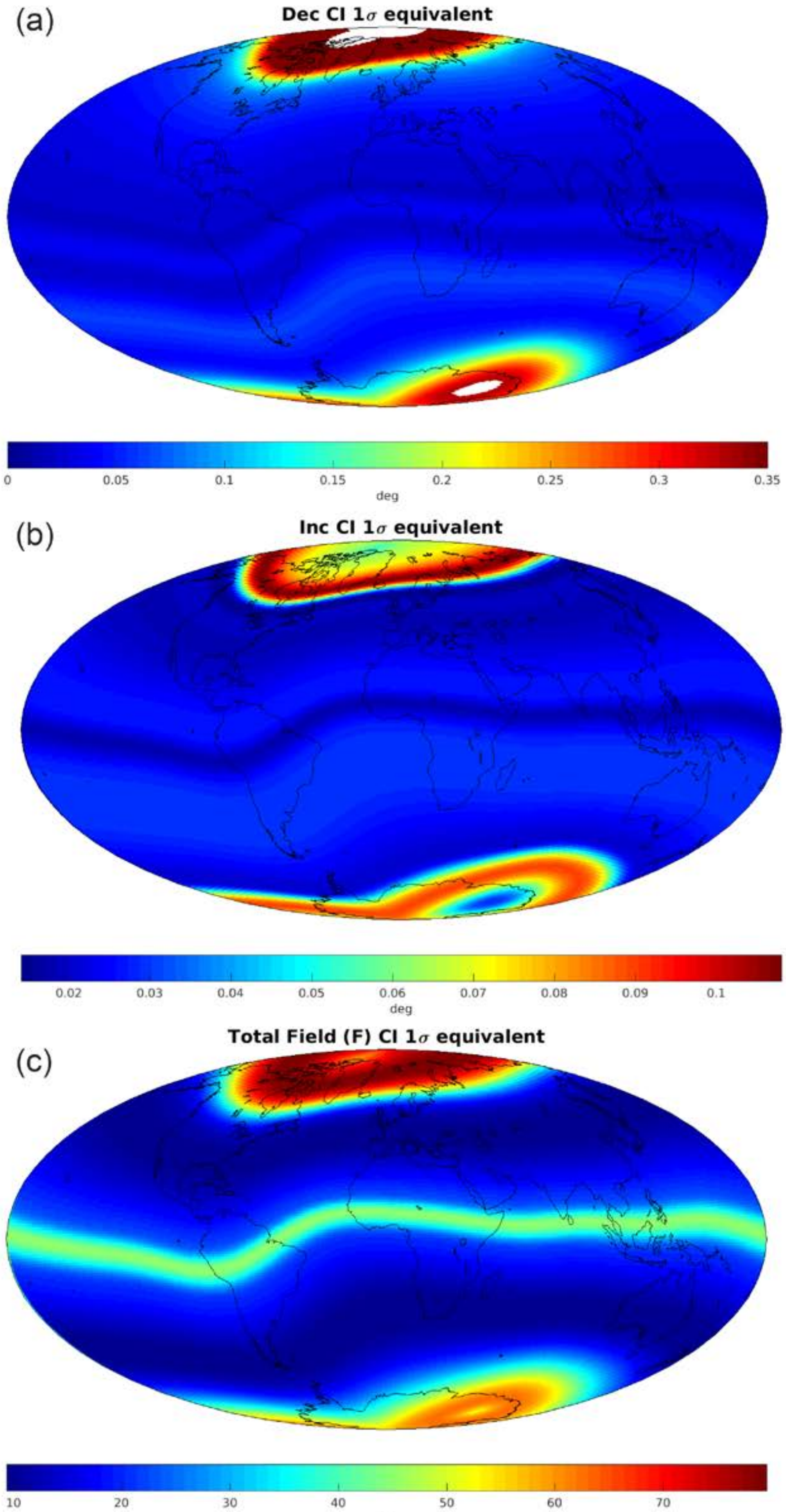

Figure 3: The 1σ-equivalent uncertainties from the external field in the (a) Declination, (b) magnetic Inclination (or dip) and (c) Total Field components.

Core field uncertainty

Finally, we estimate the uncertainty arising from the forecasting of secular variation up to eighteen months ahead of time. The error arising from the estimation of a core field model, particularly in the case of models used predictively e.g. for future well planning, is composed of two parts. First, errors arise from the field modelling process itself, while other errors arise from the prediction of core field secular variation (SV) to a future date. Errors arising from the modelling process encompass a wide range of factors, including measurement errors, incomplete parameterization and separation of field sources, and the more general issue of any model being only an estimated approximation of the true field.

Measurement errors are minimal thanks to modern ground or satellite instruments combined with very thorough quality control procedures. Lesur, et al. (2017) estimated the typical measurement precision (standard deviation) at a good quality ground observatory to be 400 pT (i.e. 0.4 nT), while Swarm satellite measurements have been shown to have an agreement within 200 pT between the scalar and vector instruments (Tøffner-Clausen, et al. 2016).

The core field is generally well fit in modern field models, through a combination of careful data selection for magnetically quiet and night (dark) times, and parameterization in space (typically to spherical harmonic degree 15 which is the point at which the crustal field begins to dominate over the main field) and time (typically using order 6 B-splines with 6 month spaced control knots).

Errors arising from the forecasting of SV to future dates can only be assessed retrospectively. While the SV can typically be described as a linear trend in time over short time scales, this is only an approximation, and one frequently broken by phenomena known as geomagnetic jerks – rapid acceleration of the field causing non-linear changes in the SV. As such forecasting the field is complex and poorly understood, and continues to be an active research topic in geomagnetism (Whaler and Beggan 2015, Fournier, et al. 2010).

We wish to quantify the uncertainties arising from SV and account for it using a single global value for each field component. We do this in the following manner: firstly, we took previous iterations of the BGS magnetic main field model, which used Swarm data and were fit with a degree 15 time-varying core field. From these we made estimates of the core field at each model's release point, and then its forecasts for one and 2 years ahead. Field values were estimated on a 1° x 1° grid at sea level on the WGS84 ellipsoid, up to |85°| latitude. Next, the field values were then differenced with those from a subsequent model release e.g. the 2016 model prediction at 2017.0 is subtracted from the definitive model for 2017 values at 2017.0. Finally, the field differences were weighted by cosine of latitude and a blackout zone was imposed to remove declination values near the magnetic dip poles where the horizontal field was less than 1000 nT. This procedure allows us to estimate the typical error arising by mis-prediction of SV, over the typical time span of model usage. While we assume our core models to be the "true core field" at points where they are retrospectively constrained by observations, these estimated SV error values may also account for a poorer estimation of the core field at the latter end of our models, when fewer ground data are available. Hence, they do represent a realistic use case uncertainty.

Using annual BGS main field model releases from 2016 to 2018, we estimated the SV prediction uncertainty (1-sigma scalable) in the main field values (after 1 year) to be 3 nT, 3 nT and 6 nT, in the X, Y and Z components respectively. The uncertainty after two years is typically twice the one-year value, though due to the non-linear nature of SV over longer timescales, we do not expect this trend to continue indefinitely but rather expect the errors to subsequently grow at a faster rate. It should be noted that this period contains geomagnetic jerks (the tail end of SV changes first reported by Torta, et al. (2015), and subsequent features noted by e.g. Kotzé (2019)), and so includes the type of field changes contributing most to the error in terms of mis-prediction of the SV.

Combining uncertainties

The crustal field and external field uncertainties can be combined in a root-sum-square sense to give the total uncertainty at any location on the globe or treated separately and propagated globally (G) or randomly (R) within the ISCWSA MWD error model. The new error model can be polled by passing in latitude, longitude and date and returned from it are G and R values of the declination (DEC) error, the magnetic dip (MDI) error and magnetic field intensity (MFI) error. Note in our implementation that the Declination-Horizontal terms (DBHG and DBHR) are set to zero as they are subsumed into the declination terms.

In collision-avoidance situations involving wells surveyed using different types of magnetic field referencing data, it has become apparent that the binary correlation options (fully or not correlated) for the covariance matrices incorporating the G and R terms is an over-simplification. For Revision 5 of the ISCWSA error model the G magnetic field terms were further separated into uncorrelated terms and several correlated terms determined by the type of magnetic referencing used. These new error terms are suffixed -U for Uncorrelated error, -CH for crustal error of Commission for HRGM referencing, -OH for crustal error of Omission for HRGM referencing and -OI for crustal error of omission for In-Field Referencing. The derivation of the generic values for these new terms takes account of partial correlations between different types of magnetic referencing. The derivation of the BGS location-specific values uses the same assumptions as in the computation of the Revision 5 generic values. In the next section we will demonstrate the application of the various location-dependent partially correlated terms as suggested in ISCWSA Revision 5.

Application to ISCWSA test wells

Within the ISCWSA error model framework, there are a number of options for describing errors associated with different types of magnetic field model from low resolution to standard and high-resolution models. For high-resolution global magnetic field models, the generic values for Declination, magnetic Dip and Total Field do not vary with location, though there is a location dependence on the DBH terms.

To illustrate the application of our new uncertainty terms, we derive location-dependent values for both Revision 4 and 5 magnetic field terms for the three ISCWSA (#1/2/3) test well locations. These are a North Sea extended reach well, a fish-hook well in the Gulf of Mexico and Bass Strait designer well. We also include a fourth well (extended reach) set in offshore Brazil to illustrate the effect of larger magnetic inclination (dip) uncertainties. The location-dependent values are given in Table 2.

	ISCWSA generic HRGM	ISCWSA#1 North Sea extended	ISCWSA#2 Gulf Mexico fish-hook	ISCWSA#3 Bass Strait designer	#4 Offshore Brazil extended
lat		60	28	-40	-23
long		2	-90	147	-41
mid-TVD (ft)		1760	4908	604	1760
HRGM DEC		-0.12	-1.02	13.72	-23.44
HRGM DIP		72.78	57.12	-70.32	-43.38
HRGM Btotal		51074	45556	60822	23292
DECG (rev 4)	0.30	0.23	0.14	0.17	0.20
DECR (rev 4 & 5)	0.10	0.07	0.04	0.05	0.06
DEC-U (rev 5)	0.16	0.14	0.02	0.08	0.10
DEC-CH (rev 5)	0.13	0.10	0.10	0.10	0.10
DEC-OH (rev 5)	0.21	0.05	0.05	0.05	0.05
DEC-OI (rev 5)	0.05	0.05	0.03	0.01	0.03
DBHG (rev 4)	4118	0	0	0	0
DBHR (rev 4 & 5)	3000	0	0	0	0
DBH-U (rev 5)	2359	0	0	0	0
DBH-CH (rev 5)	1789	0	0	0	0
DBH-OH (rev 5)	2840	0	0	0	0
DBH-OI (rev 5)	356	0	0	0	0
MDIG (rev 4)	0.16	0.08	0.10	0.07	0.24
MDIR (rev 4 & 5)	0.08	0.02	0.02	0.02	0.04
MDI-U (rev 5)	0.09	0.05	0.06	0.04	0.14
MDI-CH (rev 5)	0.07	0.03	0.05	0.03	0.11
MDI-OH (rev 5)	0.11	0.05	0.07	0.04	0.18
MDI-OI (rev 5)	0.03	0.01	0.02	0.01	0.07
MFIG (rev 4)	107	118	109	117	93
MFIR (rev 4 & 5)	60	19	12	13	18
MFI-U (rev 5)	61	68	62	67	55
MFI-CH (rev 5)	46	52	48	52	41
MFI-OH (rev 5)	73	84	76	82	65
MFI-OI (rev 5)	13	13	10	11	11

Table 2 Test wells and High Resolution Geomagnetic Model (HRGM) error values used

The well position uncertainties were computed using two different setups, with and without axial corrections while using the generic ISCWSA uncertainties compared to wells using these BGS location-specific values. Table 3 shows the 1-sigma comparisons for the semi-major axis uncertainties at Total Depth for each of the wells. All wells show a reduction in the average lateral size of the uncertainty ellipsoids of between 5% and 26%.

Well Name	TD	MWD+HRGM Semi-Major	MWD+HRGM-BGS-#1 Semi-Major	Reduction	Reduction
	m	m	m	m	%
ISCWSA#1	8000	91.0	83.6	7.4	8.2
ISCWSA#2	3810	8.5	7.9	0.7	7.8
ISCWSA#3	3000	8.9	6.7	2.2	24.9
PATH#4	8000	83.5	75.5	8.0	9.6
	TD	**MWD+HRGM+AX Semi-Major**	**MWD+HRGM+AX-BGS-#1 Semi-Major**	**Reduction**	**Reduction**
	m	m	m	m	%
ISCWSA#1	8000	172.6	138.2	34.5	20.0
ISCWSA#2	3810	8.1	7.0	1.1	13.6
ISCWSA#3	3000	8.8	6.5	2.3	26.0
PATH#4	8000	137.4	130.3	7.1	5.2

Table 3: Total Depth 1-Sigma Semi-Major Axis / Lateral Comparisons

Most directional survey tools have a complex accuracy performance dependent on geographic location and the well orientation. The Tool Performance Profiles are an attempt to show how the performance of a directional survey tool varies over the full range of inclinations and azimuths for a particular location. These 3-dimensional surface plots show how the position uncertainty (vertical axis) changes with inclination and azimuth (the two horizontal axes). These plots are produced by stepping through inclination and azimuth ranges and calculating the position uncertainty assuming a straight well segment (constant inclination and azimuth) 1,000 m long. The resulting data for the lateral uncertainty in m/1000 m is plotted as a surface against Inclination and Azimuth. By repeating the calculations using the same inclination and azimuth steps for a different survey tool error model the two uncertainties can be compared and a difference plot produced either in absolute terms (meters) or as a percentage. Plots can be produced for the Lateral, Radial and Vertical uncertainties.

In this study, only the lateral uncertainties have been compared because the Radial and Vertical are the same. Analyzing the wells by inclination and azimuth reveals that there is not always a reduction in the uncertainties. In particular, for well #4 (offshore Brazil), when drilling close to horizontal in an E-W direction with axial correction, the lateral 1-sigma uncertainties increase by up to 6.9 m representing, at worst, an increase of 24.0% (see Figure 4). This is related to the complicated interaction of the low magnetic dip angle with the low Total Field values in this region.

In other regions, with larger magnetic dips and stronger Total Field values the improvement is generally positive (i.e. error ellipses are smaller). Wells ISCWSA#1 (North Sea) and ISCWSA#3 (Bass Strait) show small improvements in uncertainties, whereas ISCWSA#2 (Gulf of Mexico) shows an improvement for all inclinations and azimuths, though again this is close to zero for the same horizontal E-W drilling. The profiles for each well are illustrated in Figures 5, 6 and 7.

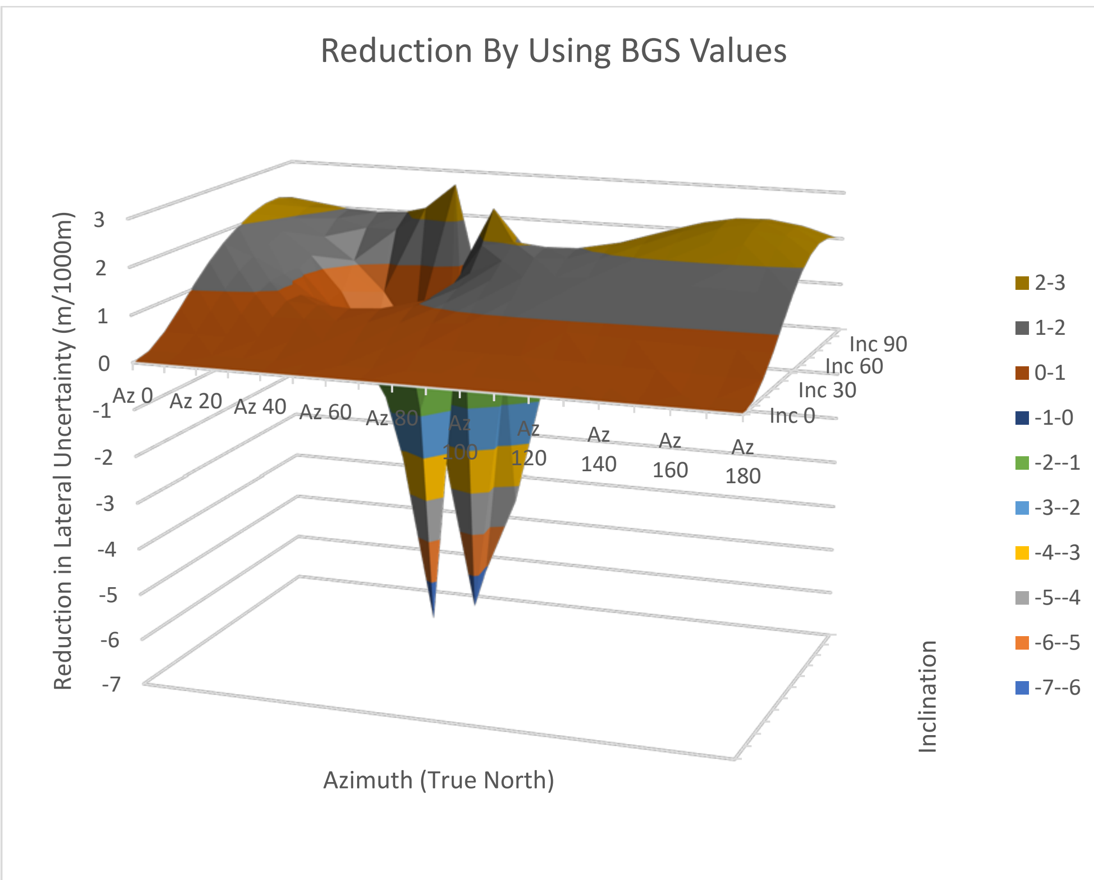

Figure 4 Reduction (+ve) in semi-major axis 1-sigma uncertainty for test extended-reach well #4 offshore Brazil

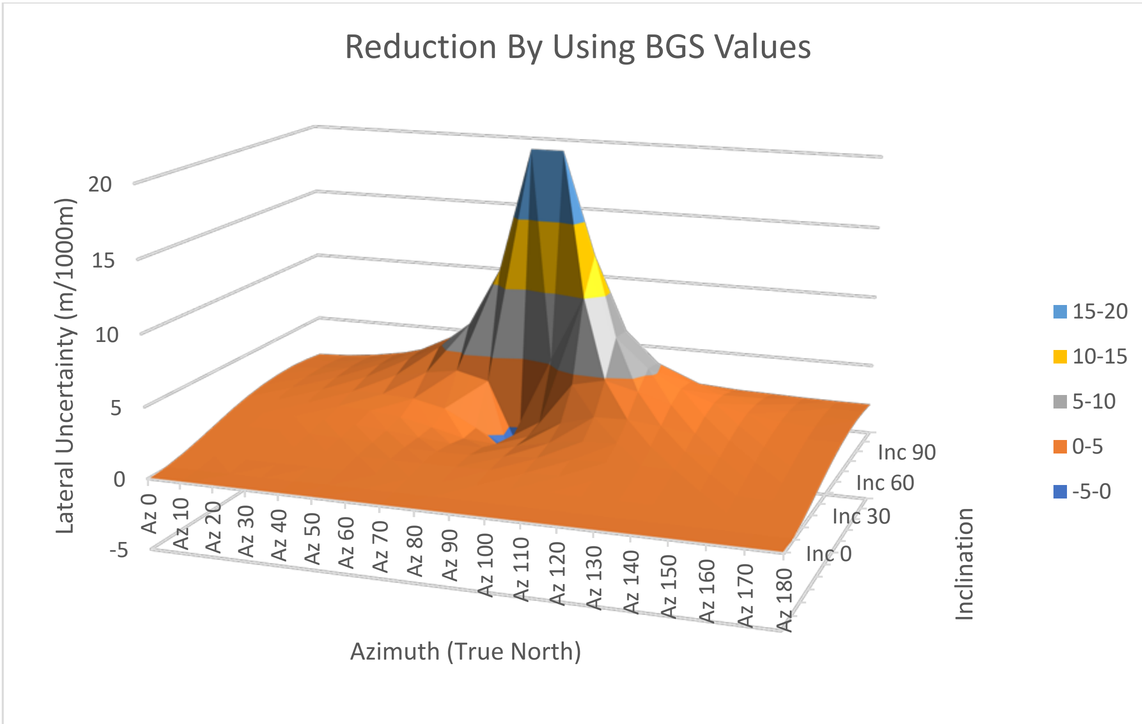

Figure 5 Reduction (+ve) in semi-major axis 1-sigma uncertainty for test extended-reach well ISCWSA#1, North Sea

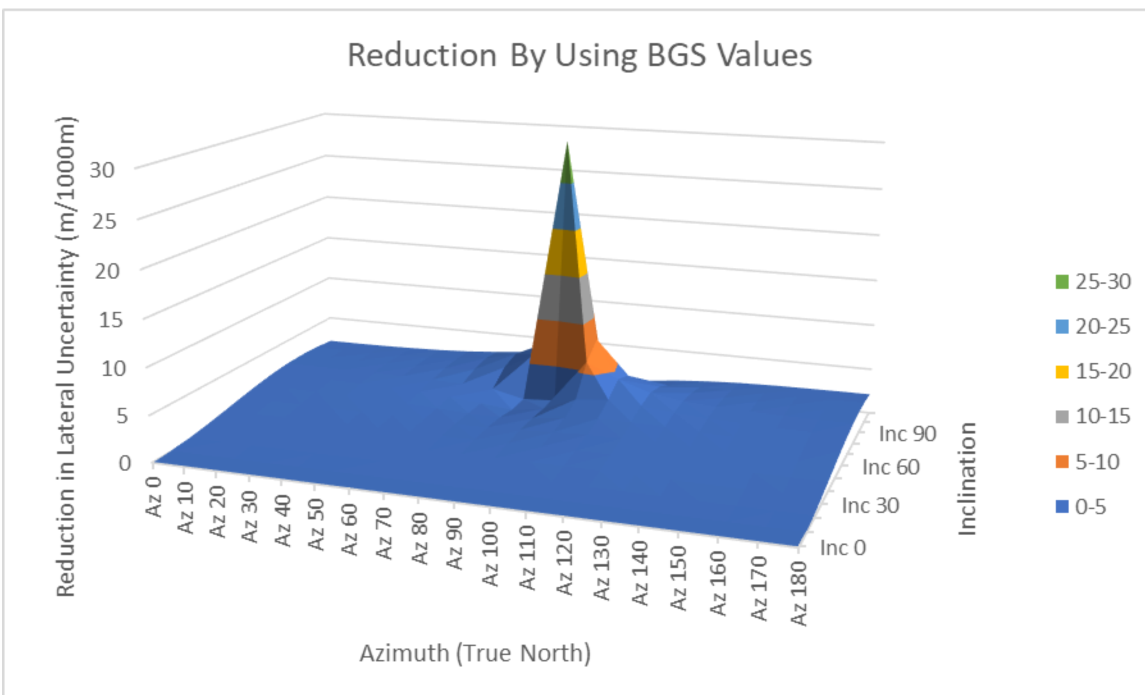

Figure 6 Reduction (+ve) in semi-major axis 1-sigma uncertainty for test well ISCWSA#2, Gulf of Mexico

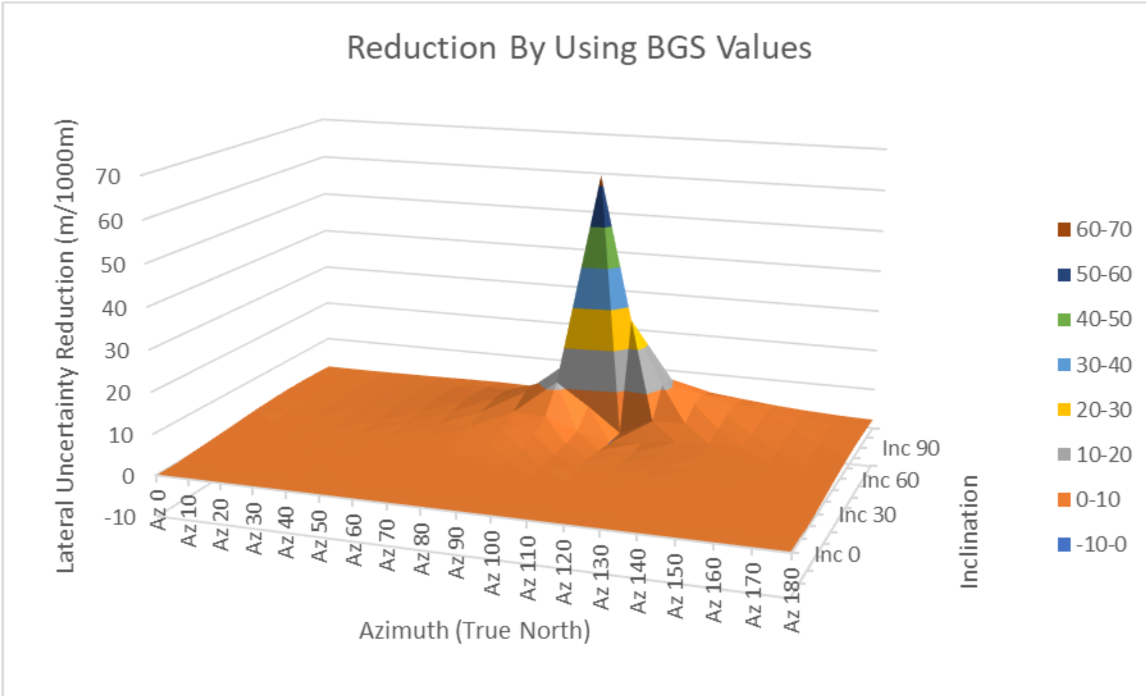

Figure 7 Reduction (+ve) in semi-major axis 1-sigma uncertainty for test well ISCWSA#3, Bass Strait

Discussion

To the best of our knowledge, this work represents the first application of the ISCWSA Revision 5 decomposition of magnetic field uncertainty into global correlated and uncorrelated parts in combination with location-specific crustal and external field variations. The uncertainties in this study strongly differentiate between regions where public aeromagnetic data are available as well as regions which lie in the mid to low latitudes. The influence of the main field strength is also important in determining the size of the uncertainties.

Historically, survey tool error models started as 'global' models applicable over wide geographic areas. The OWSG Survey Tool Error Model Sets (Grindrod et al, 2016) are an example of these generic models. However, these generic models are averages and tend to overestimate the uncertainty for some areas. To make more realistic uncertainty estimates, survey tool error models can now be produced for specific locations that reflect the particular drilling operations, using the techniques and information outlined in this study.

As the geomagnetic terms are also time varying, by using web server-based information mentioned in this paper, a more refined and realistic survey tool error model can be produced. In most cases, this will result in a further reduction of the uncertainty, though in certain regions the error ellipses can be larger than the generic models might suggest.

Conclusions

Using information from ground repeat stations, satellite, aeromagnetic and marine datasets, we have derived a new set of time and location-dependent one-sigma equivalent uncertainties for Magnetic Declination, Magnetic Dip and Total Field based on a new high-resolution model of the Earth's magnetic field. This gives more realistic values for the uncertainties as we account for the morphology of the magnetic field as well as the quality of the input data sources in the magnetic field model.

The improved uncertainties have been partitioned into their global and random contributions on a 1° x 1° grid and the global contributions have been further partitioned as recommended in the most recent revision (#5) of the ISWCSA error modelling group. This revision includes the effect of partial correlations between error terms from neighboring wells for collision avoidance calculations. In such calculations the 1-sigma positional uncertainties are typically multiplied up assuming all contributions follow a Gaussian distribution. The magnetic field uncertainties are not Gaussian but the 1-sigma equivalents presented here can be safely multiplied up to produce the high confidence levels required for positioning and collision avoidance.

We have analyzed the application of these new error terms to the magnitude of the uncertainty ellipsoids for the three standard ISCWSA test wells plus an extended reach well for offshore Brazil and found an average reduction of the semi-major axis of between 5% and 26%. However, there are orientation and location-dependent variations in the magnitude of the error ellipsoids which can produce complex behaviors resulting in enlarged ellipsoids for certain configurations of azimuth and inclination of a well bore. Hence, though the ellipsoids are not always smaller they are a correct representation of the uncertainty. A freely available web-service to allow access to these magnetic field uncertainty values has been produced.

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