

Report

Challenges Related to Positional Uncertainty

for Measurement While Drilling (MWD) in the Barents Sea

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Challenges Related to Positional Uncertainty for Measurement While Drilling (MWD) in the Barents Sea

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<p>ABSTRACT:</p> <p>The objective of this study is to present challenges related to positional uncertainties for directional drilling using MWD in the Barents Sea, specifically for deviated wellbores. The study summarizes relevant previous work and characterizes the expected random and systematic errors encountered in surveying by standard MWD in the Barents Sea. The study then assesses the availability of suitable aeromagnetic surveys to correct for crustal magnetic anomalies by In-Field Referencing (IFR). To further correct for time-varying "space weather" disturbance fields, mitigation methods using the available ground magnetic monitoring stations were compared, including Nearest Observatory, Interpolated In-Field Referencing and the Disturbance Function method. The results of this study will be useful to both operators and regulators in the Barents Sea, as they provide metrics on how well various crustal and disturbance field mitigation methods perform in the region. More specifically, the study presents recommendations for different sub-regions in the Barents Sea, allowing an operator in a particular location to use the proper mitigation methods in order to allow the operator to perform safe operations. More broadly, the results of the study will be useful to the industry at large. Despite having focused on the Barents Sea region, the study's results will outline general trends with regards to the performance of different mitigation methods relative to one another, and should be applicable to oil fields worldwide.</p>
<p>KEY WORDS:</p> <p>Wellbore Surveying, Well Placement, Measurement While Drilling, MWD, Barents Sea, Positional Uncertainty, Geomagnetic Referencing, Geomagnetic Disturbance, Global Field Models, Crustal Anomaly, In-Field Referencing, IFR.</p>

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Executive Summary

This study by Magnetic Variation Services (MagVAR) and Add Energy estimates the expected positional uncertainties for wells in the Barents Sea off the Northeast coast of Norway. Methods of reducing these uncertainties are discussed and evaluated.

Current directional drilling technology uses a Measurement While Drilling (MWD) instrument to measure the gravity vector and the magnetic vector at survey stations in the wellbore. From these measurements the inclination from vertical and the azimuth from magnetic north are determined. The along-hole depth, inclination, and azimuth, are used to estimate the wellbore trajectory using the minimum curvature method. Uncertainties in the measurements are propagated from survey station to survey station and are represented by an Ellipse of Uncertainty (EoU) at each survey station.

The magnetic vector has both a horizontal and a vertical component. The horizontal component may be thought of as a compass needle which points to magnetic north. At high latitudes this horizontal component is quite small, amplifying the relative effects of measurement errors and variations in the magnetic environment.

The earth's magnetic field is not constant. There are slow variations predictable over a period of months, and sudden variations due to charged particles from solar flares being deflected by the earth's magnetic field. These sudden variations are more intense at high latitudes; the aurora borealis is one manifestation of these variations. There are also local static variations due to magnetic minerals in the earth's crust.

In a downhole drilling assembly, the measured magnetic field is also influenced by the steel parts of the drillstring. The MWD instrument is contained in a non-magnetic section. Steel parts above and below the instrument cause magnetic interference which corrupt the compass reading. Drillstring magnetic interference can be mathematically corrected in most situations provided the expected magnitude of the horizontal and vertical components are well known and the instrument is properly calibrated.

The key challenge at high latitudes is to have accurate knowledge of the earth's magnetic field at the time and place the measurement is taken. It is also important to control the magnetic properties of the drillstring by using proper non-magnetic spacing of the MWD instrument from the steel components and by demagnetizing any steel components adjacent to the MWD instrument.

An estimate of the geomagnetic vector at a particular location and date can be made using a worldwide geomagnetic model. A better estimate can be made using a local geomagnetic model created from high-resolution aeromagnetic or marine magnetic surveys. This technique is called "In-Field Referencing" Type 1, or IFR1.

The study summarizes relevant previous work and characterizes the expected random and systematic errors encountered in MWD surveying in the Barents Sea. This includes modeled magnetic declination variation, solar disturbances, and drillstring magnetic interference.

The availability of suitable magnetic data for IFR1 models is assessed. The full spectrum of spatial wavelengths is needed, including the long wavelengths captured by satellite measurements which account for the crustal field, main field, secular variation and steady external field; and shorter wavelengths captured by local magnetic surveys which are the source of local crustal field anomalies. Suitable existing aeromagnetic data was only located for the western portion of the Barents. New data could be acquired if further research does not find suitable previous aeromagnetic or marine magnetic data in the eastern area.

At high latitudes it is important to subtract from the measured magnetic vector the time-dependent variations due to geomagnetic storms. Geomagnetic or solar storms are caused by ionospheric currents as charged particles from the sun are deflected by the earth's magnetosphere. The subtraction is most effective when the variations are measured with a local observatory within a few km of the drilling site. This is called "In-Field Referencing, Type 2" or IFR2 and is used in addition to the IFR1 method. The available geomagnetic ground stations were assessed.

A local observatory with a real-time data link is not always practical. Alternative methods to correct for the time-varying disturbance field discussed and evaluated include Nearest Observatory, Interpolated In-Field Referencing (IIFR), and the Disturbance Function method. These methods were compared in locations where other observatory data exists to provide comparison of the local time-dependent variations of the magnetic field.

Of these three alternative methods for determining the time-dependent variations, the Disturbance Function achieved the best estimate of the local magnetic values, especially far (up to 250 km) from the nearest real-time observatory. Nearest observatory and IIFR methods may be sufficient for drilling sites close (up to 50 km) to the nearest magnetic observatory.

The combination of IFR1 models, IFR2 disturbance field monitoring, and attention to the magnetic properties of the drilling assembly combined with standard good drilling practices can reduce the positional errors to acceptable levels even in this difficult location.

1. Introduction

1.1 Background

Advanced drilling technologies make it possible to drill and directionally steer a wellbore with high accuracy. Critical to directional drilling is a measurement-while-drilling tool (MWD). The MWD provides constant feedback on the attitude of the wellbore and the orientation of the bend in the motor, enabling steering control. The technology is based on gravity and magnetic field measurements to infer the orientation of the Bottom Hole Assembly (BHA) and the direction of the wellbore.

During the drilling operation, most wellbore surveys are conducted by MWD tools using a directional sensor with 3 perpendicular accelerometers and 3 perpendicular magnetometers, as shown in Figure 1.1 (Maus, 2017). The triaxial accelerometers allow for measurement of the total gravitational field, which can be used to determine the instrument's inclination from vertical and the gravity tool face. The magnetometers additionally provide magnetic azimuth and magnetic tool face. In addition, the system measures the strength of the gravity acceleration (G_{total}), the strength of the magnetic field (B_{total}) and the angle of the magnetic field with respect to the horizontal plane (Dip angle). These measurements can then be compared to a reference value (indicative of the actual gravity and magnetic vectors at that point in space and time) in order to determine true orientation.

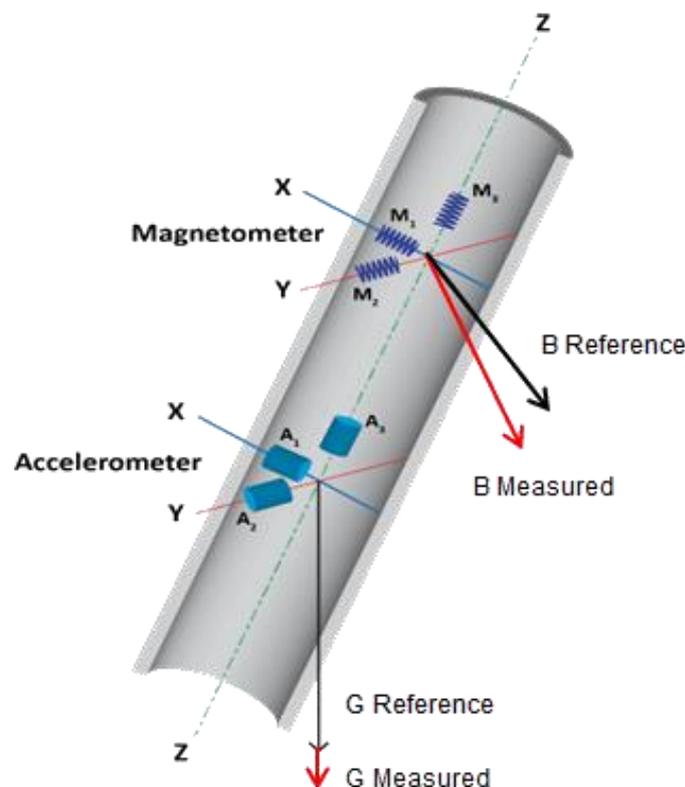


Figure 1.1: Typical Bottom Hole Assembly (BHA)

At the high latitudes of the Barents Sea, the horizontal component of the geomagnetic field is reduced. This is because the earth is a magnetic dipole, and field lines are nearly perpendicular to the surface near the poles leading to small horizontal components, as shown in Figure 1.2. This increases the effect of internal interference from the drill string and external interference from crustal magnetic anomalies and ionospheric disturbance fields, as the same interferences become much more significant when the entire horizontal component becomes smaller.

Key challenges for drilling at high latitudes are the active management of magnetic interference from the BHA and drill string components as well as the accurate specification of the natural geomagnetic field as a reference to convert magnetic azimuth to true azimuth, shown in Figure 1.3. MWD errors are particularly problematic for horizontal wells, warranting particular attention to all aspects of geomagnetic referencing.

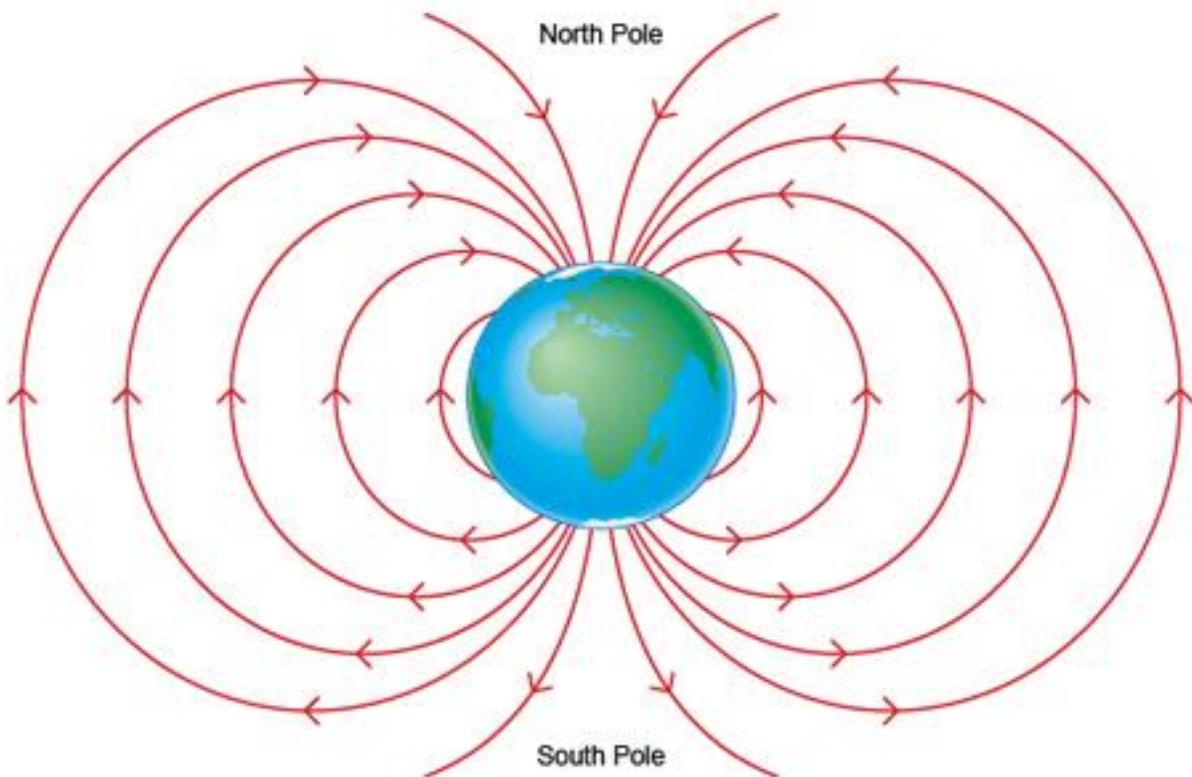


Figure 1.2: Earth's magnetic field, illustrating field lines nearly perpendicular to surface at Northern latitudes

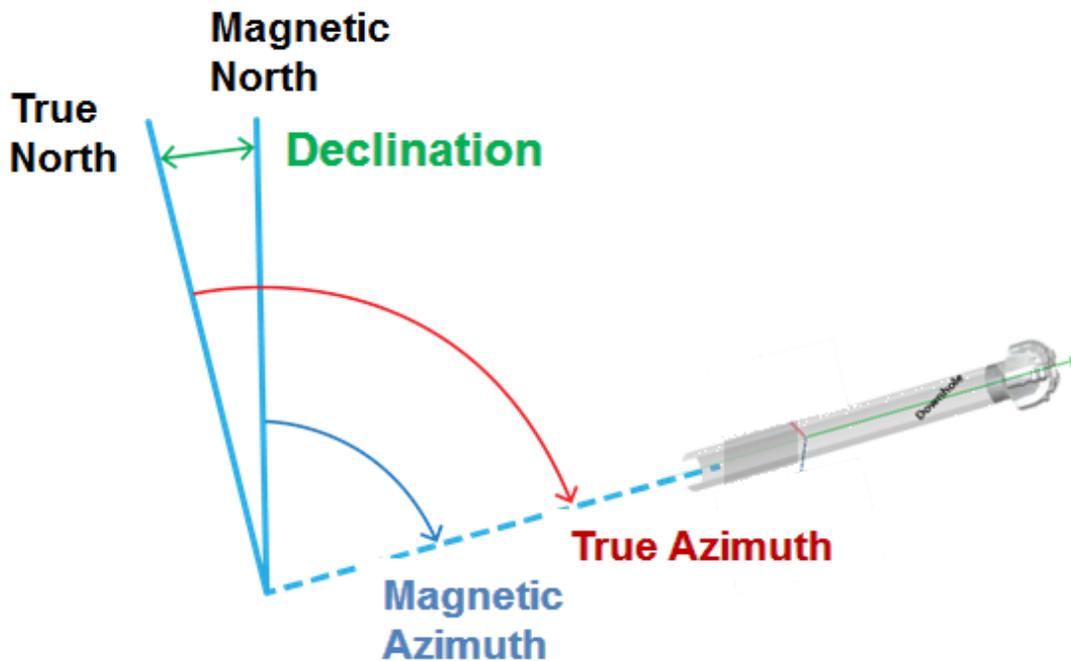


Figure 1.3: True North and magnetic North azimuths, visualized

With the advent of modern drilling technologies, there has been a rise in the frequency and type of directional drilling operations being performed. Intentional deviation of a wellbore can be used to achieve a wide variety of aims that would otherwise be uneconomical, or not feasible from an engineering perspective. Some applications of directional drilling include:

- Drilling to a target located under an inaccessible surface location
- Drilling to several targets from the same surface location
- Drilling to multiple targets with the same wellbore
- Maximizing reservoir contact area in a horizontal wellbore
- Performing sidetrack operations
- Drilling relief wells

1.2 Problem Definition

There are several limitations to surveys performed by magnetic MWD instruments. First and foremost is that the Earth's Magnetic Field is neither temporally static, homogeneously distributed, nor perfectly aligned with the axis of rotation. An MWD survey measurement provides the orientation of the tool relative to the local magnetic field. However, wellbore positioning applications must relate this to a map system of some kind.

This requires correcting the MWD survey using geomagnetic reference values of the magnetic declination, dip and total field. The declination is of particular importance. It cannot be internally verified, so care must be taken to ensure that an accurate spatial magnetic model is being used in the appropriate manner.

The geomagnetic reference values are modeled in a process called in-field referencing, described in 4.2.1, and presented as a three dimensional model. This model, a visual cutout of which is shown in

Figure 1.4, references locations in the subsurface, and for each x/y/z, the magnetic declination, inclination, and total field strength are given.

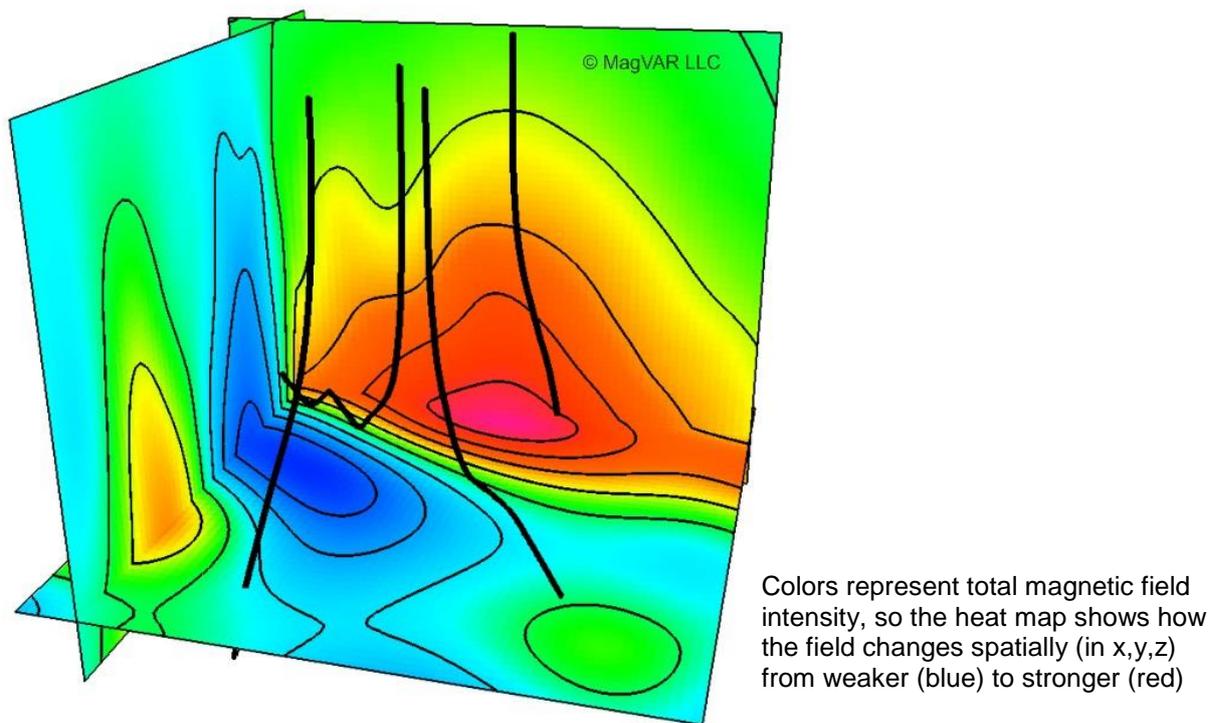


Figure 1.4: Cross sectional visual representation of an IFR model offshore of Brazil.

By applying measured values to reference values, drillers can determine the tool's true orientation in the subsurface, and integrate those orientations to determine position underground. Of course, there is some amount of error possible in both the reference model and the measurements, as well as the integration method (as measurements are not made continuously). This leads to quantifiable positional error, which is encapsulated in positional error models. These are sets of formulas for given error-mitigation methods mapping drilling data to potential difference between calculated and actual location downhole. They are often visually represented as ellipses of uncertainty, where the ellipse represents the full range of possible locations based on a calculated location in the middle.

Additionally, temporal variations must be monitored to ensure that the magnetic reference values are temporally correct. The high geomagnetic latitude of the Barents Sea means that the horizontal magnetic field is weaker than in many other areas where drilling typically takes place, which makes the declination more susceptible to large changes over time, and more likely to be impacted by local geologic anomalies. The location of the Barents Sea within the auroral electrojet region also means that care must be taken to account for temporal variations.

The magnetic disturbance field in this region is due to a combination of effects caused by the magnetospheric ring current, auroral electrojets, and secondary induced fields.

Magnetospheric Currents

The magnetospheric current systems are fed by charged particles originating in the solar wind. The strongest contribution is from the ring current, shown in red in Figure 1.5. The ring current increases in strength during magnetic storms, which are caused by coronal mass ejections from the sun. The field-aligned currents (shown in yellow in Figure 1.5) also have an important effect, since they predominantly affect the declination of the magnetic field, leading to errors in the MWD azimuth, if not corrected for.

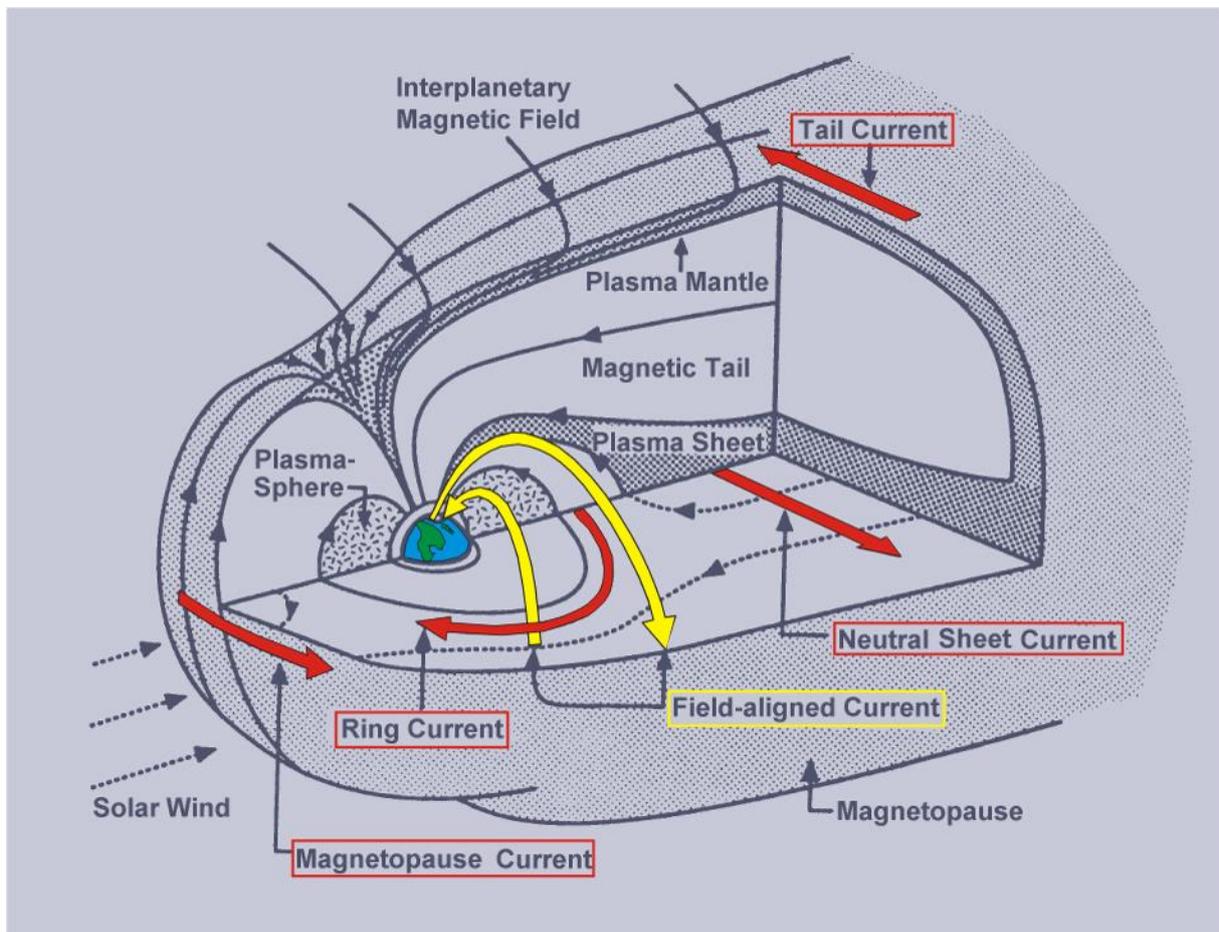


Figure 1.5: Magnetospheric current systems contributing to the geomagnetic disturbance field at high latitudes

Auroral Electrojets

The ionosphere is a region approximately 80 km to 1000 km above the Earth's surface. It is much closer to the Earth than the magnetosphere. Currents in the ionosphere are present even during quiet times and are caused by tides of the atmosphere. During magnetic storms, a strong electric field is imposed through field-aligned currents, see yellow lines in Figure 1.6, onto the polar ionosphere. This electric field drives strong east/west currents in the auroral region, called auroral electrojets. The auroral electrojets cause large magnetic disturbances at high latitudes. The sketch on the right shows the different currents in the ionosphere. Of these, the auroral electrojets (in blue) generate by far the largest magnetic field disturbances at high latitudes

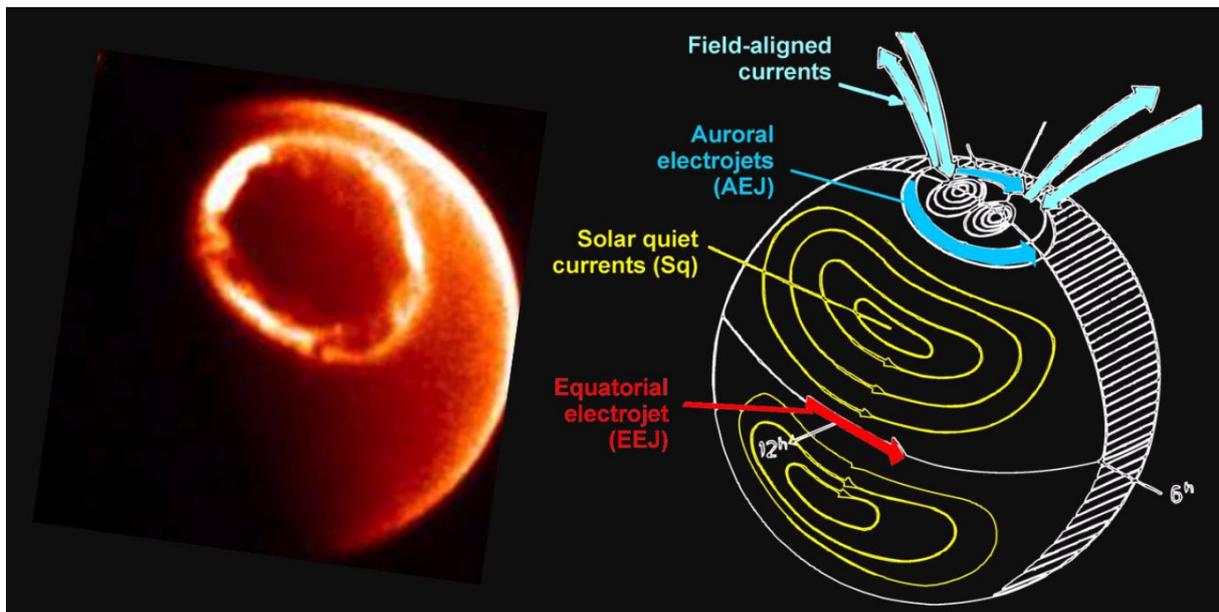


Figure 1.6: NASA ultraviolet image of the auroral zone in which the electrojets flow.

Secondary Induced Magnetic Fields

Finally, any time-varying disturbances in the magnetic field induce electric fields in the Earth and oceans. These electric fields generate electric currents and secondary magnetic fields. Such "induced magnetic fields" make up approximately one-third of the disturbance field. Conductivity inhomogeneity's within the Earth, as well as the contrast between the solid Earth and oceans, gives rise to complicated spatio-temporal structures of the disturbance field, necessitating real-time measurements in the vicinity of the drillsite.

1.3 Regulations and Standards for Directional Drilling

There are several standards, rules and regulations for directional drilling. The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) developed a framework for quantifying positional errors through ellipses of uncertainty (EOU). The ISCWSA's work resulted in an error model which is described in detail by Williamson (2000).

The Operator's Wellbore Survey Group (OWSG), a sub-committee of the ISCWSA, continued development on the original error model and publishes a set of Instrument Performance Models that enable the computation of ellipses of uncertainty, discussed in more depth in Chapter 2.5, for specific surveying methods. This consolidated set is referred to as the OWSG set of tool codes. As better surveying methods are used, ellipses of uncertainty shrink, as shown in Figure 1.7 (Deverse, 2016). The figures show expected wellbores in middle, surrounded by pink ellipses of uncertainty representing a good surveying method, surrounded by blue ellipses of uncertainty representing a poor surveying method.

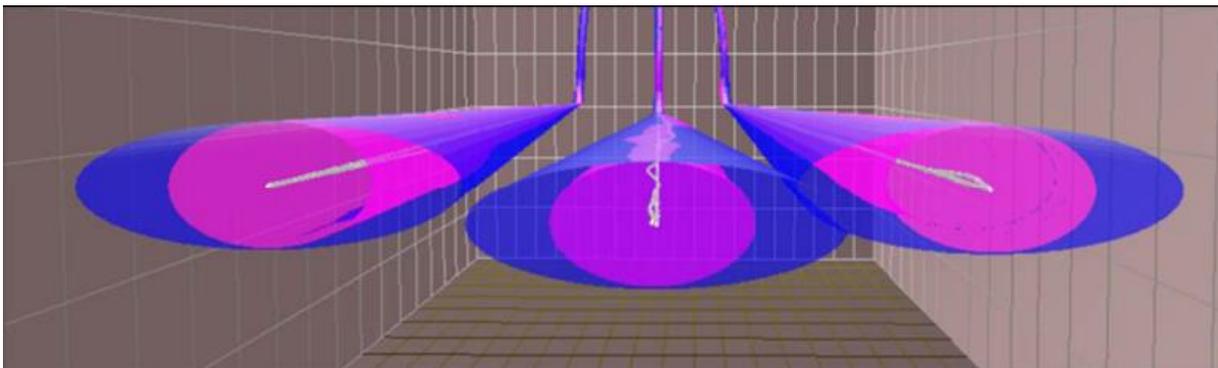


Figure 1.7: Simulated ellipses of positional uncertainty

The American Petroleum Institute (API) is working on a document of recommended practices (RP 78) for wellbore surveying.

On the Norwegian Continental Shelf (NCS) the Activity Regulations apply and the NORSOK standard includes guidelines on how to ensure a proper directional survey of a wellbore.

1.3.1 The Activities Regulations

The Activities Regulations apply to offshore petroleum activities and are issued and enforced by the Petroleum Safety Authority, the Norwegian Environment Agency and the health authorities. Section 82 "Well location and Wellbore" in the Activities Regulations states that "The well location and wellbore shall be known at all times and selected based on well parameters of significance for a safe drilling and well activity".

1.3.2 NORSOK D-010

The NORSOK D-010 is a standard defining the requirements and guidelines to well integrity in drilling and well activities. In the standard, it is stated that a precise determination of the well path is important to:

- avoid penetrating another well,
- facilitate intersection of the wellbore with a relief well (blowout),
- facilitate geological modelling,
- facilitate anti-collision assessments for new wells.

It is further specified that:

- The position of the wellbore being drilled (reference well) and the distance to adjacent wells shall be known at all times. The minimum angle of curvature method or other equivalent models should be used.
- A survey program should be established to minimize ellipses of uncertainty.
- Procedures for quality control of survey data shall be in place. The ellipses of uncertainty shall be based on survey tool error models which reflect the level of quality control applied.

1.4 Scope of Work

The objective of this study is to present challenges related to positional uncertainties for directional drilling using MWD in the Barents Sea, especially for horizontal wellbores. Mitigating solutions to these challenges are presented.

The study first summarizes the relevant literature and characterizes the expected random and systematic errors encountered in surveying by standard MWD in the Barents Sea. It then assesses the availability of suitable aeromagnetic data for In-Field Referencing (IFR) crustal anomaly corrections. Turning to the disturbance field, the available geomagnetic ground stations are assessed and mitigation methods compared, including Interpolated In-Field Referencing (Williamson et al., 1998), the Disturbance Function method (Maus and Poedjono, 2015) and the deployment of an ocean bottom magnetometer at the drill site. An example comparing these methods for a pair of geomagnetic observatories in Alaska is shown in Figure 8.4 in Appendix. The impact of these methods as a function of distance from the drill site are analyzed using triplets of geomagnetic station measurements around the Barents Sea. Finally, the impact on wellbore placement accuracy is compared for the different methods in relation to the uncorrected MWD surveys.

The results of this study will be useful to both operators and regulators in the Barents Sea, as they provide metrics on how well various crustal and disturbance field mitigation methods perform in the region. More specifically, the study presents recommendations for different sub-regions in the Barents Sea, allowing an operator in a particular location to use the proper mitigation methods in order to ensure safe operation.

More broadly, the results of the study will be useful to the industry at large. Despite having focused on the Barents Sea region, the study's results will outline general trends with regards to the performance of different mitigation methods relative to one another, and be roughly applicable anywhere.

2. Measurement While Drilling

2.1 General

Well placement by MWD uses magnetic field measurements to infer the orientation of the BHA and the direction of the wellbore. MWD is a critical component of directional drilling and collisional avoidance as well as reaching geologic targets. MWD provides constant feedback on the location of the bend in the motor enabling steering control and, at intervals, updates on the direction the wellbore is pointed. At high latitudes, the horizontal component of the geomagnetic field is reduced, which increases the effect of internal interference from the drill string and external interference from crustal magnetic anomalies and ionospheric disturbance fields. MWD errors are particularly problematic for horizontal wells, warranting attention to these technical components.

Technologies such as In-Field Referencing (IFR), Multi-station Analysis (MSA), and disturbance field monitoring can improve MWD outcomes. IFR greatly improves the accuracy of geomagnetic reference declination, which can reduce positional uncertainty more than 30 percent. Reliable geomagnetic reference values given by IFR further provide the basis for MSA, the most cost-effective solution for correcting standard MWD surveying and substantially improving the wellbore accuracy (Maus et al. 2017) that has consistently challenged drill operators in recent decades (Grindrod et al. 2016). MSA survey quality control is highly effective at identifying gross errors and reducing systematic errors. This can further reduce uncertainty, achieving total reductions by as much as 60 percent compared with standard MWD surveying. In addition, disturbance field monitoring can be used to successfully account and correct for temporal variations of the geomagnetic reference field.

2.2 Directional Drilling

With the advent of modern drilling technologies, there has been a rise in the frequency and type of non-vertical drilling operations performed. Intentional deviation of a wellbore can be used to achieve a wide variety of aims that would otherwise be uneconomical, or not feasible from an engineering perspective. Some applications of directional drilling include:

- Drilling to a target located under an inaccessible surface location
- Drilling to several targets from the same surface location
- Drilling to multiple targets with the same wellbore
- Maximizing reservoir contact area in a horizontal wellbore
- Performing sidetrack operations
- Drilling relief wells

Many methods are currently in use to perform intentional deviation of a wellbore. Techniques such as jetting (using fluid to asymmetrically wash out the wellbore) and whipstocks (metal wedges installed in a wellbore used to deflect the drillstring) have been in use since the mid-1900s, however their use is typically limited to only the initial deviation of the well, after which rotary drilling was still performed. It was only with the advent of bent-housing mud motors and rotary steerable systems that complex directional control could be performed continuously throughout the drilling process.

Drilling motors operate by using hydraulic pressure from the drilling fluid to rotate the bit. This enables it to steer while the drill string is rotating. This drilling mode is referred to as "sliding". The addition of a bent housing in conjunction with the motor means that there will be an inherent bias in the direction drilled when the motor is in this sliding mode. As long as the slide is continued, the path of the well will build in the direction of the bend making a smooth arc. Once the desired angle is reached, the motor can be rotated similar to a classic drilling scenario, and the bias tendency is equally balanced among all directions. By switching between the sliding and rotating modes, the directional driller can use the bent motor to actively steer the well as needed to keep the wellpath on the plan. Critical to this operation is an MWD tool, which provides not only the current orientation of the bottom hole assembly (BHA) but also the rotational angle in which the bend is oriented (tool face angle).

Mud motors provide the advantage of having high dogleg capabilities (strong curvature of the well bore) and being mechanically robust. One drawback to the motor system is that while sliding is being performed there is no rotation of the drillstring, limiting the effectiveness of hole-cleaning efforts and at times making it challenging to transfer weight all the way to the bit.

A modern alternative to mud motor drilling is the rotary-steerable system (RSS). RSS tools combine a directional package similar to that of an MWD with an automated control unit capable of deflecting the bit downhole. Unlike a motor, where a directional driller must be actively steering the well, the RSS directly integrates the sensor and steering modules in a closed loop system. The ability of the RSS to respond dynamically to motion in the bottom hole assembly enables it to continue steering even while the drill string is rotating. Based on commands transmitted to the downhole computer through mud flow, the RSS can be set to either steer, drill straight, or perform a more complicated action such as hold a heading. The constant rotation of the drill string means that there are fewer concerns with weight transfer and hole-cleaning. However, the mechanical complexity of RSS systems tends to add expenses relative to mud motors, and there can often be operational limitations to the drilling environment (such as flow rate, temperature and pressure) that limits their use.

2.3 Well Placement

In order to steer a well to a target, it is necessary to plot the trajectory of the wellbore as it is being drilled. Placing wellbores accurately to begin with will have a positive impact on field development and increase the feasibility of future infill drilling programs. An online simulator of recovery losses due to inaccurate wellbore positioning (Maus and DeVerse, 2016) can be used to assess the economic benefits of accurate drilling and compare the effects of different surveying methods.

Modern surface surveying techniques such as differential GPS are ineffective in subsurface applications, and instead a variation on the surveyor's traverse is employed. Measurements known as "survey stations" are taken at periodic intervals along the wellbore (typically 10 m -30 m). These survey stations consist of an along-hole depth measurement, a measurement of deviation from the vertical, called inclination, and a measurement of the borehole's direction relative to a north reference, known as azimuth. In between consecutive survey stations, change in position is

calculated using the minimum curvature method, where it is assumed that any angular change between consecutive stations happened in an equally distributed manner along the intervening length. This method allows a well path to be constructed in a piecewise fashion from a known well reference point (tie-in point).

The additive nature of the minimum curvature traverse means that any error in the starting point will be carried through each additional iteration. Furthermore, any errors in the subsequent measurements will continue to be inherited by all future measurements. In surveying terms this is what is known as an “open traverse” meaning that there is no tie-off to verify the amount of error at the end of the process. The net result is that each survey station in a wellbore survey is associated with an amount of positional uncertainty that grows as the well is drilled deeper. These uncertainties can be mathematically described through a positional covariance matrix, but more often represented as ellipses of uncertainty.

2.4 Magnetic Surveying Instruments

During the drilling process, most wellbore surveys are conducted by MWD tools using a directional sensor with 3 perpendicular accelerometers and 3 perpendicular magnetometers. The triaxial accelerometers allow for measurement of the total gravitational field, which can be used to determine the instrument’s inclination from vertical and gravity tool face. The accelerometers and magnetometers together are capable of measuring the horizontal component of the Earth’s magnetic field, which can be used to produce a compass direction for azimuth. These technologies are easy to ruggedize and are able to acquire survey measurements in less than a minute, making them well suited for drilling applications.

There are several limitations to surveys performed by magnetic MWD instruments. First and foremost, is that the Earth’s Magnetic Field is neither static, nor perfectly aligned with the axis of rotation. An MWD survey measurement provides the orientation of the tool relative to the local magnetic field, however wellbore positioning applications must relate this to a map system of some kind. This requires correcting the MWD survey for a reference magnetic declination. This declination correction cannot be internally verified, so care must be taken to ensure the appropriate magnetic model is being used in the appropriate manner. The high geomagnetic latitude of the Barents Sea means that the horizontal magnetic field is weaker than in many other areas where drilling is typically undertaken. This makes the declination more susceptible to large changes over time, and more likely to be impacted by local geologic anomalies. The local declination can have its accuracy greatly improved by mapping the local spatial and temporal variations and incorporating them into a high-resolution real-time model.

A component of the Earth’s magnetic field that cannot be accurately modelled in advance is that from solar disturbance. Space weather can cause short term variations in local fields with minimal warning time, particularly in areas near the magnetic poles. Just as with other magnetic model errors, any change in the magnetic declination will cause an undetectable error in the MWD sensor’s azimuth measurement. Proper accounting for these types of errors can only be done by constantly monitoring the magnetic field and applying the appropriate corrections to the survey measurements.

In addition to potential magnetic modelling error, the presence of magnetic interference can adversely affect the accuracy of MWD surveying. Any interference in the horizontal-East/West direction relative to the reference model will result in corruption of the survey azimuth. One major source of such corruption is ferromagnetic material in the drilling BHA. This is of particular concern as the steel components are located near the directional sensor for the entire duration of the drilling process. The largest component of interference from the drill string is aligned with the borehole direction. Hence, the closer to horizontal and the closer to magnetic East/West the drilling will be, the greater the potential for corruption of the survey azimuth and the more non-magnetic spacing that will be required.

In terms of disturbance field variation, the collection of long-term electromagnetic data is critical to these variations over time. Unlike an aeromagnetic survey that is bound by a finite moment in time, remote observatories on land and the seafloor can provide datasets extending over long periods, allowing for the identification of time-bound anomalies that affect wellbore positioning and MWD operations.

Placing, maintaining, and receiving data from a Sea Floor Electro-Magnetic Station (SFEMS) adds complexity to sub ocean directional magnetic MWD operations, yet the benefits of properly-placed wellbores are numerous (Maus et al. 2017). To more reliably predict the disturbance field at a drill site using in-situ measurements on the seafloor, three ocean bottom vector magnetometers (OBMs) must be deployed near the drill site to monitor the disturbance field over a period of 3-6 months (Maus et al. 2015). This enables the computation of a disturbance function relating the measurements of multiple neighboring variometers.

A recent development in robotic autonomous marine vehicles is the Wave Glider by Liquid Robotics (Monk et al. 2014), which also shows promising results for disturbance field monitoring. It can either directly measure variations in the total magnetic field, or it can act as a real-time satellite relay by using acoustic signals transponded to the vehicle from a seafloor magnetometer to the ocean-surface, and then sent by satellite to the desired location, allowing for real-time data collection (Poedjono, B., et al. 2014). The Waveglider and SFEMS are described in more detail in Appendix Section 8.7.

2.5 Ellipses of Uncertainty

In seeking to quantify the wellbore positioning accuracy, the important thing is the potential spatial error from each error source, including the accuracy of the BHA tool, the magnetic interference from drill string components, and the accuracy of the IFR (or other magnetic) model, among others. Each error source contributes in some form to the magnitude of uncertainty that propagates along the computed wellbore trajectory. For example, a dip uncertainty may be in degrees ($^{\circ}$), which must be transformed into spatial (feet or meters) uncertainty downhole.

This spatial uncertainty, resulting from directional uncertainty, is quantified as an Ellipse of Uncertainty (EOU). This refers to a shape, elliptical in cross-section, surrounding the wellbore and showing the range of locations the BHA could actually be, based on the accuracy of methods used. These shapes are elliptical due to differences in propagation between z errors (along hole) and x/y errors (perpendicular

to the hole). They also grow larger downhole due to compounding uncertainty. EOU's of neighboring wells must never touch, as this could result in a blowout if both wells' actual positions were in the intersecting zone and higher pressure in one wellbore were transferred into the other. By using advanced wellbore placement techniques and thereby reducing the EOU's, one can place the wells with higher confidence. Additionally, in the event of a blowout, it is necessary to drill a relief well with confidence of being able to intersect the blowing well.

The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) has developed a framework for quantifying the magnitude of uncertainty. The Operator's Wellbore Survey Group (OWSG), an ISCWSA subcommittee, continued development on the original error model and published a set of instrument performance models that enables the computation of EOU for specific surveying methods (Appendix Section 8.7). This consolidated set is referred to as the OWSG set of tool codes.

Figure 2.1 (Maus, SPE 175539) illustrates the difference between EOUs for standard MWD versus advanced corrections using MWD with IFR and corrections for sag (MWD+IFR1+SAG). Because the BHA is not perfectly rigid, and is slightly smaller than the borehole, gravity can pull down on various parts of the BHA and induce bending, bringing the accelerometer out of alignment with the inclination of the wellbore trajectory, as shown in Figure 2.2 (Studer et al. 2006). This effect is referred to as sag, and can be corrected for, which is encapsulated in the MWD+IFR1+SAG toolcode. The actual drilled wellbore trajectory is with 95 % confidence within the EOU of the selected surveying method. Generally, one can see that the large uncertainty of standard MWD can be reduced by 11 to 38 % by use of IFR, while further applying multistation analysis (MSA) can reduce the uncertainty by 50 to 61 %. Vertical uncertainty can also be reduced by advanced survey correction methods.

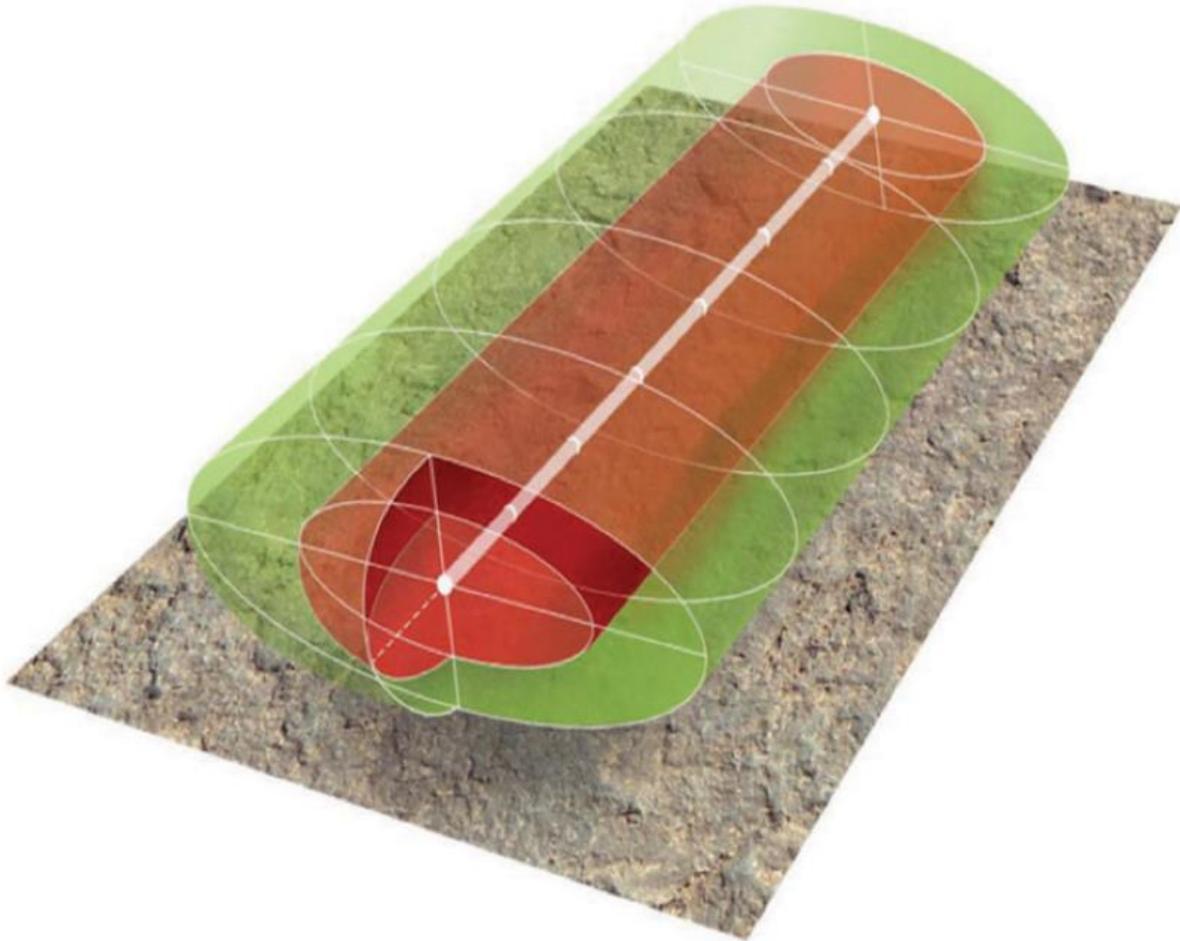


Figure 2.1: Comparison of the EOU at a standard deviation of 2.79 for 95 % confidence for the tool codes MWD (green) and MWD+IFR+SAG (red)

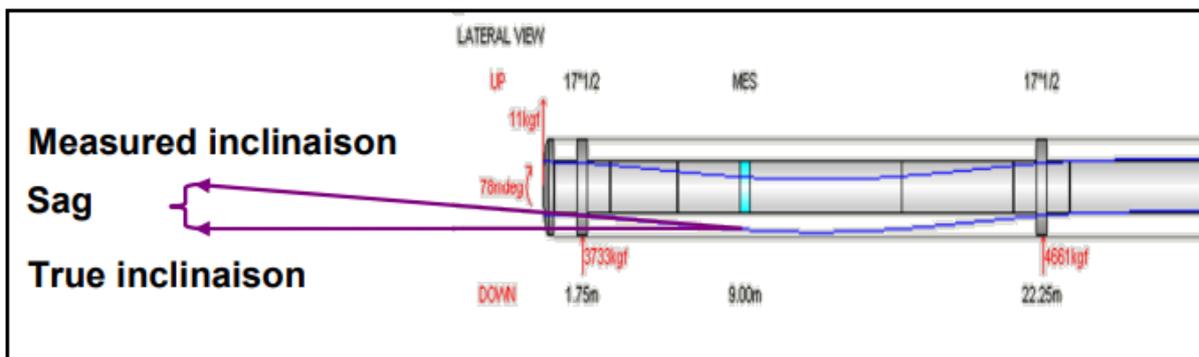


Figure 2.2: Sag, the difference between measured and true inclination due to sagging of the BHA in the borehole, as borehole and BHA are not of exact same diameter

2.6 Collision Avoidance

Increasing directional complexity of the wells being drilled, along with a greater number of wells being drilled from a single location, increases the risk that a well being drilled may intersect an existing well. The consequences of a collision have the potential to be severe, with possible negative outcomes including uncontrolled release of hazardous materials or loss of well control. Mitigating these risks requires putting in place a comprehensive collision avoidance risk management system. A key component in any such system includes proper handling of both wellbore positioning data and its associated uncertainties.

The most common tool used across industry to manage collision risk is the separation factor (SF), which is often incorporated to a minimum allowable separation distance (MASD) rule. Calculating a separation factor involves comparing the distance separating the two wellbores to the amount of uncertainty in their relative positions. These distances are typically normalized based on the acceptable level of risk so that anything less than a ratio of 1 (where uncertainty is greater than separation) is deemed unacceptable. The greater the level of accuracy in the surveying process (i.e. lower uncertainty between the position of the well and its offset), the more likely it is that the drilling process can proceed safely. Implicit in the entire risk management system is that the survey measurements used to calculate the borehole position meet the assumptions that were made when performing the positional uncertainty calculations.

There are numerous error sources associated with MWD survey measurements and each error source contributes in some form to the magnitude of uncertainty that propagates along the computed wellbore trajectory. The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) framework mentioned in chapter 2.4 can be used to quantify the magnitude of uncertainty. A fuller description of the ISCWSA's work can be found in the Appendix.

2.7 Geological Targets

The final endpoint of a well path is defined by a geological objective that, if penetrated, will allow the operator to economically produce hydrocarbons from the wellbore. This target is defined in advance by geological considerations and used when designing the well plan to be drilled. To assure that the well penetrates this target, the effective target size for considering deviation from plan must be reduced by the expected amount of positional uncertainty when the wellbore reaches total depth so that after accounting for survey uncertainty, the geological objectives are still met. This process is known as "Driller's target erosion".

The higher the level of surveying accuracy employed during the drilling process, the less target erosion occurs, and the greater flexibility there is in the drilling process. In some cases, standard surveying methods may produce a positional uncertainty that is larger than the initial geological target specified. Under this condition it may be technically impossible to meet the geological objectives through the geometric drilling process. In those cases, either a higher accuracy surveying method must be used or additional navigational information, such as from Logging While Drilling (geosteering), must be incorporated into the steering process.

2.8 Relief Well Drilling

In some extreme cases, such as loss of well control or damage to the surface location of the wellsite, it may be necessary to drill a relief well. A relief well is a secondary well drilled to intercept the initial wellbore so that remedial actions may be performed. In the prototypical case, a relief well establishes communication with a well that is blowing out so that drilling fluid may be pumped restoring control of the initial well. As a large number of risk factors are all present simultaneously, relief well drilling can be one of the most complex operations performed in the oil field.

Due to safety considerations, relief wells must be started at some distance from the primary wellbore and the uncertainty accumulated in the approach will typically not allow for direct drilling of an intercept. Instead, the relief well is drilled to the likely location of the blowing out well, and then ranging operations are performed to determine the relative positions of the two wells. From that point, directional drilling can be guided with these relative locations until an intercept is achieved.

Survey accuracy is of particular importance when performing relief well operations. The detection radius for ranging tools can be limited, and to maximize the possibility of success the uncertainty in both the initial well and the relief well should be minimized using high accuracy surveying techniques. Ranging instruments also rely on detecting small disturbances in the magnetic field to identify the location of the well casing. External disturbances can mask this signal if not corrected for, reducing the effectiveness of the ranging equipment. Inability to locate the blowout well using ranging techniques, or locating the well in a position that is far from the surveyed location may require multiple sidetracks to be drilled, adding days or weeks to the relief well operation. Given that surveying operations generally cannot be performed on a subject well after the blowout has occurred, it is important to already have high accuracy surveys while drilling to be prepared for the event that intersection by a relief well becomes necessary.

2.9 Global Field Models

Global models of the geomagnetic field vary in accuracy and are produced by different organizations. The main difference between the models is how often they are updated (yearly or every 5 years) and their spatial resolution. However, they do all operate on the same basic foundation, namely a spherical (or ellipsoidal) harmonic expansion of the magnetic potential of a magnetic field originating in the interior of the Earth. The degree (N) of this expansion determines the resolution of the model. A spherical harmonic expansion in its typical form is given by:

$$V(\lambda, \psi, r) = a \sum_{n=1}^N \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} (g_n^m \cos m\lambda + h_n^m \sin m\lambda) P_n^m(\sin \psi),$$

where V is the magnetic potential, λ is longitude, ψ is geocentric latitude, r is the distance from the Earth center, $a=6371.2$ km is the geomagnetic reference radius, n is degree, m is the order, g_n^m and h_n^m are the Gauss coefficients and P_n^m are associated Legendre functions.

The World Magnetic Model (WMM), produced in collaboration between the US National Geospatial-Intelligence Agency (NGA) and the UK Defence Geographic Centre (DGC) is a global main field model that is used as a world-wide standard for navigation and defense applications. It is updated every 5 years and the current model, WMM 2015, is valid until December 31st, 2019. WMM is a spherical harmonic expansion to degree 12. This free model is widely used in directional drilling by smaller directional drilling companies. It fulfills the requirements of the OWSG tool code MWD+IGRF, as explained below.

The International Geomagnetic Reference Field (IGRF) is a main field model comparable to the WMM. It is produced by scientists under the auspices of the International Association of Geomagnetism and Aeronomy (IAGA). Also updated every 5 years, this main field model covers spherical harmonics to degree 13. As a free model, it is also widely used in directional drilling by smaller contractors. It fulfills the requirements of the OWSG tool code MWD+IGRF.

Increasing accuracy slightly from these models are the standard definition (SD) models which fulfill the requirements of the MWD tool code. These are more accurate than IGRF and WMM through yearly updates and higher spherical harmonic degree. Examples of this type of model are the BGGM produced by the British Geological Survey (BGS) and the MVSD produced by Magnetic Variation Services (MagVAR). Both of these models include a steady external ring current field and parts of the long wavelength crustal magnetic field. The resolution of the BGGM depends on the calendar year, ranging from degree 8 to degree 133. Consequently, the BGGM represents different parts of the geomagnetic field depending on the date entered. The MVSD avoids this confusion by maintaining a constant degree 133 resolution for all dates ranging back to 1960.

Finally, the most accurate global field models utilize an ellipsoidal harmonic expansion to more accurately represent the geometry of the Earth. These high definition (HD) models also increase the degree of expansion significantly. They fulfill the more stringent requirements of the MWD+HRGM tool code, as presented below. The first generation HDGM to degree 720 was developed at the National Geophysical Data Center (Maus et al., 2010) and is still being produced by its follow-on organization National Centers for Environmental Information (NCEI). A newer follow-on model MVHD to degree 1000 is based on improved ellipsoidal harmonic inversion techniques and is produced by MagVAR. The degree of a model can be compared with the pixel resolution of a camera. The WMM corresponds to a 12 x 12 pixel image, the BGGM to a 133x133 pixel image and the MVHD to a 1 Mega-Pixel image of the magnetic field of the Earth, with corresponding improvements in the resolution and accuracy.

The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA) produces a set of industry-standard error models under their Operator Wellbore Survey Group (OWSG) sub-committee. These error models, commonly called "tool codes", represent the expected uncertainties when using various technologies and methods. WMM and IGRF main field models fall under the MWD+IGRF tool code. Standard definition models with yearly updates qualify for use with the MWD tool code. Finally, high resolution models with ellipsoidal harmonic degree of 720 and higher are represented by the MWD+HRGM tool code. HDGM and MVHD satisfy or exceed this tool code.

Figure 2.3 shows the power spectrum of the internal geomagnetic field. Increasing degree (lower X axis) corresponds to the resolution of shorter wavelengths (upper X axis) of these common global models. Shaded areas represent models with changing degree and resolution. The latest BGGM extends to degree 133. The red shaded area corresponds to the part that is missing from the field model and is referred to as the omission error.

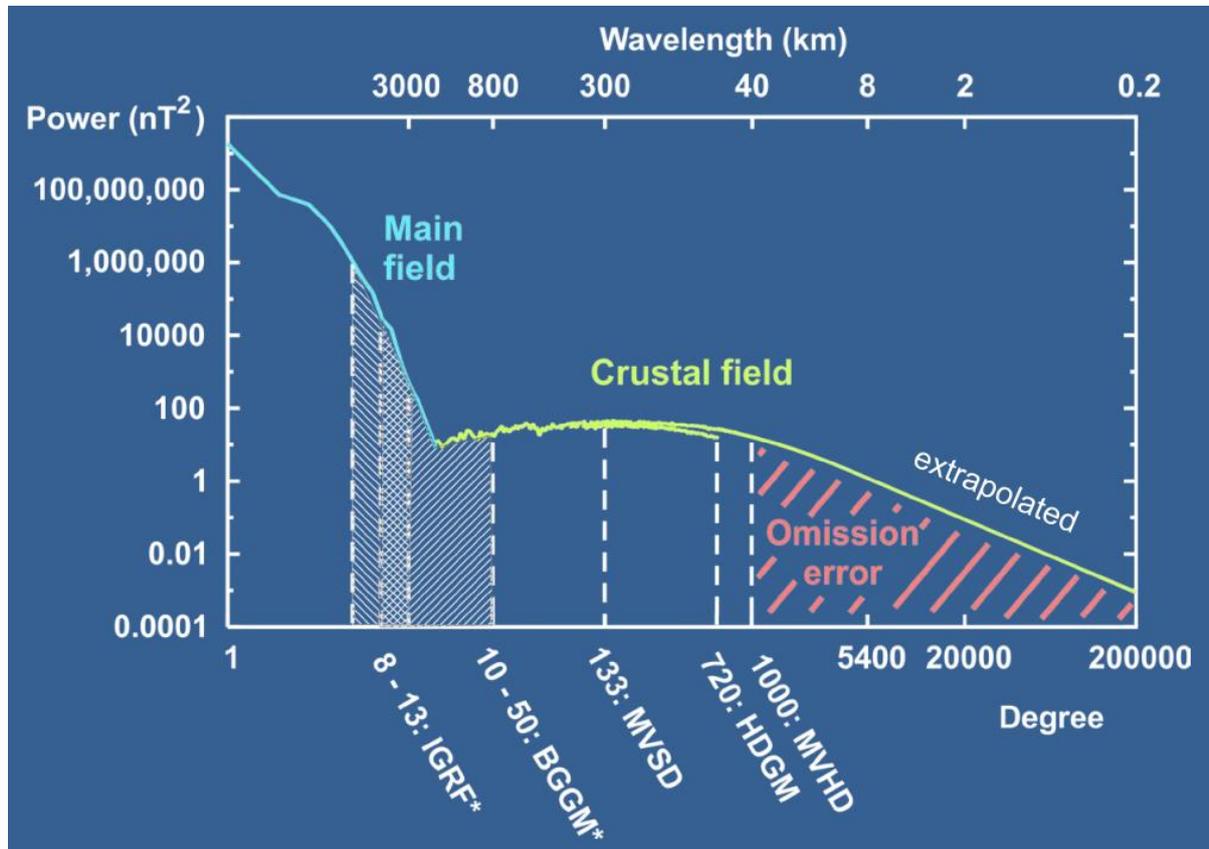


Figure 2.3: Global power geomagnetic power spectrum

To illustrate the different accuracy of various main field models, Table 2.1 gives 3-sigma uncertainties for each OWSG tool code classified above. The declination values scale inversely with the strength of the horizontal component of the geomagnetic field. The smaller the horizontal component, the larger the uncertainty in declination. The values in the table have been calculated for a horizontal magnetic component characteristic of the Barents Sea.

Table 2.1: A representation of 3-sigma uncertainties for each OWSG tool code

	MWD+IGRF (WMM & IGRF)	MWD (BGGM & MVSD)	MWD+HRGM (HDGM & MVHD)
Declination (degrees)	2.579	2.144	1.771
Inclination (degrees)	0.72	0.6	0.48
Total field (nanoTesla)	471	390	321

2.10 Crustal Anomaly Mitigation

In-Field Referencing (IFR) is a catch-all for techniques measuring the geomagnetic field at the drilling location and creating a reference model (IFR model) from those local measurements. There are two types of IFR models. The first type is based on measurements of the direction and strength of the field, for example by a magnetic theodolite. The second technique is based on a total field magnetic survey covering at least 80 km x 80 km surrounding the drill site and transforming the total measurements into a 3D directional magnetic field model.

IFR accounts for three of the four contributing factors of the magnetic field: main field (generated by Earth's core), crustal field (magnetic minerals in Earth's crust), shown in Figure 2.4 (Maus, 2017), and steady external field (generated by charged particles flowing in the earth's atmosphere). The remaining contribution to the magnetic field is the magnetic disturbance field generated by electric currents in near-Earth space, described in the following section (Maus et al. 2017). IFR itself is presented in more depth later in this report.

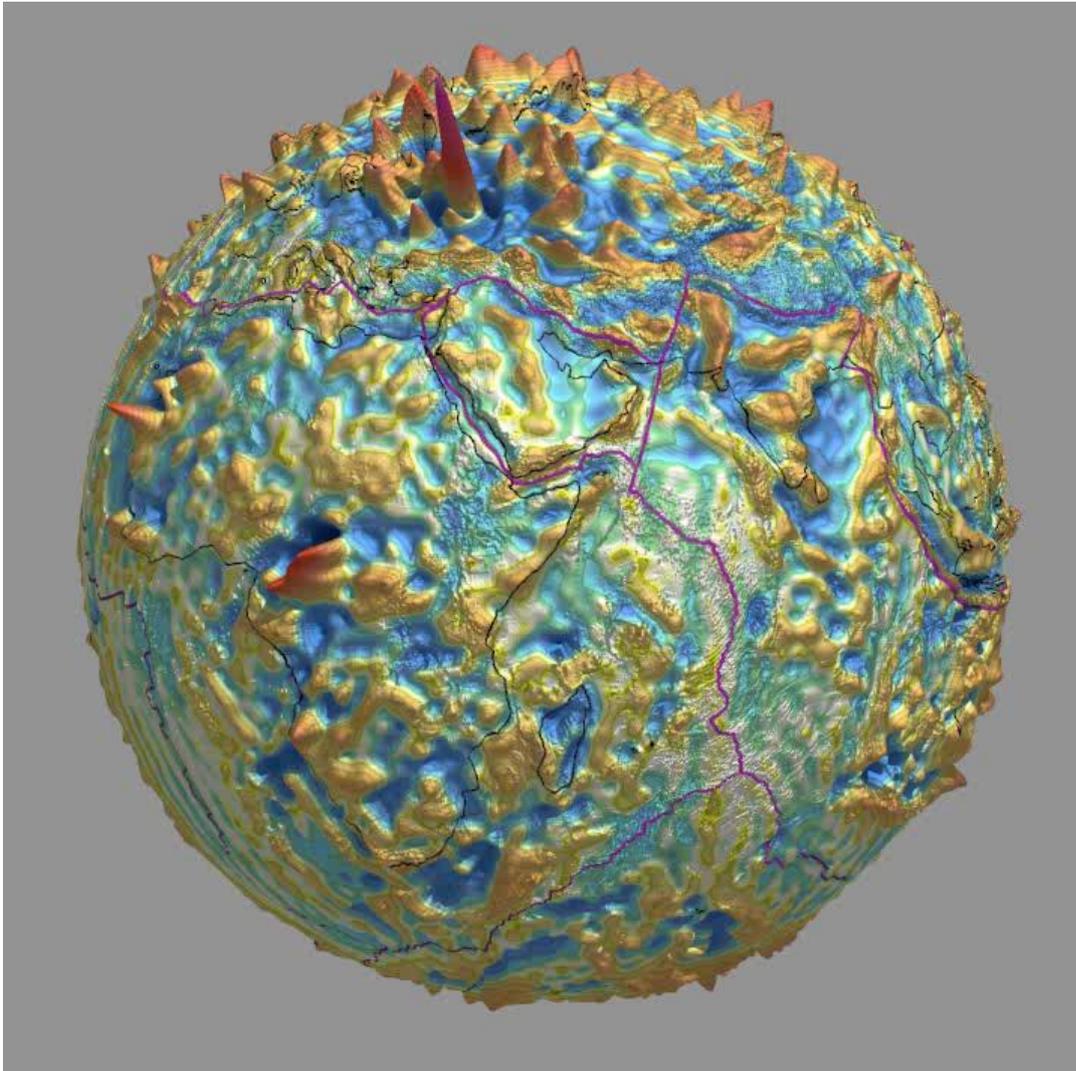


Figure 2.4: Earth's magnetic crustal anomalies, represented as a raised 3D heatmap

2.11 Disturbance Field Mitigation

The main motivation for disturbance field mitigation methods is to generate time-varying geomagnetic field corrections for the local geomagnetic reference field by remotely monitoring variations of the earth's magnetic field for specific time periods (Shiells et al. 2000, Edvardson et al. 2013). That is, in contrast to an IFR model which creates a spatial representation of the crustal magnetic anomaly for a certain area, disturbance field mitigation methods provide a source of reference for time-dependent variations of the magnetic field. This is a particularly relevant method to mitigate the disturbance field factors at higher latitudes, where time-dependent current fluctuations in the Earth's ionosphere cause inaccuracies in wellbore directional surveying (Edvardson et al. 2013).

Interpolated In-Field Referencing (IIFR) is a method in which absolute local geomagnetic field data is obtained by location-specific measurement of the earth's magnetic field (Shiells et al. 2000). The data must be generated from a location sufficiently close and must be indicative of the earth's magnetic field at the drilling site. However, it must also be sufficiently remote from the drilling site that the measurement data is unaffected by magnetic interference from the drilling site itself and other man-made installations (i.e. the drilling rig).

A downhole magnetic field data is obtained by monitoring magnetic field variations in the vicinity of the borehole as well as at a series of locations along the borehole. The orientation of the borehole is determined from the downhole magnetic field data and the time-varying geomagnetic field data. Integrating these data sets through this survey method accounts for short-term variations in the geomagnetic field, which are caused by electrical currents in the ionosphere and magnetosphere, and the corresponding mirror currents induced in the Earth.

For sub-ocean and offshore drilling operations where sheer distance from the shore-based observatory previously limited drillers' capability of maintaining directional accuracy (Williamson et al. 1998) the integration of IIFR methodology as well as the use of data generated from remote observatories has proven especially valuable (Macmillan et al. 2009). An implementation of IIFR was employed in the Norwegian Sea over a two-year period and is detailed in the Appendix.

The disturbance field function (DF) is an alternative method to IIFR and addresses issues with the traditional methods through on-site deployment and non-real time collecting requirements. These prediction methods: (1) a simple linear interpolation between the surrounding stations using the traditional method of IIFR, versus (2) the DF method (Maus et al. 2015) will be described and systematically compared later in this report.

3. Challenges with MWD measurements in the Barents Sea

Historically, most drilling has been carried out at lower latitudes. At high latitudes, such as those of the Barents Sea region, the horizontal component of the geomagnetic field is reduced, which increases the effect of internal interference from the drill string and external interference from crustal magnetic anomalies and ionospheric disturbance fields. Key challenges for drilling at high latitudes are the active management of magnetic interference from the BHA and drill string components as well as the accurate specification of the natural geomagnetic field as a reference to convert magnetic azimuth to true azimuth.

MWD errors are particularly problematic for horizontal wells at these latitudes. In any area, the risks of horizontal drilling are numerous, warranting the development of unique technologies and calculation systems to increase directional accuracy and mitigate associated risk, including wellbore collisions, blowouts, and lease-line violations, while maximizing hydrocarbon extraction. However, the challenges of surveying at northern offshore sites like the Barents Sea are greater than elsewhere, as the opening of the Arctic Ocean to drilling operations has shown (Edvardson et al. 2013).

Wellbore surveying by MWD leverages the direction of Earth's gravity and magnetic field as a natural reference frame to acquire these critical measurements (Poedjono et al. 2013). The horizontal component of the geomagnetic field is a particularly critical reference point when using magnetic north to identify azimuthal orientation of the borehole. The previously mentioned reduction in this component at arctic latitudes exacerbates any error sources collected during the survey. Based on the smaller horizontal geomagnetic component, there is an increased impact from axial and cross-axial interference from the drill string and/or mud effects (ibid). Quite simply, BHAs that are magnetically acceptable in areas of lower latitude can lead to significant inaccuracies in the Arctic environments.

Knowledge of the crustal field and real-time magnetic disturbance field is also critical to achieve an accurate wellbore position when drilling in the Arctic. In the region, fluctuations in the geomagnetic field make the application of geomagnetic referencing more challenging and the correct implementation of geomagnetic referencing is particularly critical during the increased magnetic activity during the maximum of the 11-year solar cycle (Poedjono et al. 2013). To combat this challenge, precise crustal mapping and the monitoring of real-time variations by nearby magnetic observatories is crucial to achieving the required geomagnetic referencing accuracy.

Geographically, the Barents Sea is in the auroral zone, subject to solar winds as shown in Figure 3.1, an illustration of the Dungey cycle in the Earth's noon/midnight meridian plane. The IMF (interplanetary magnetic field) field reconnects to the earth's dipole field at 1, and the opened field lines are peeled back (2 through 4), and reconnected in the magnetotail (5). Closed flux is returned to the dayside (6 and 7). The magnetopause is indicated by a black dashed line. The northern and southern polar caps are north and south of red lines indicating open/closed field boundaries. The resultant two-cell ionospheric convection is shown in the lower subfigure, where blue dots correspond to numbered field lines in the main illustration. The auroral oval is represented by the green band and the open/closed field boundary by the red dotted line (Edvardsen et

al, 2013). These electric currents in the ionosphere of the auroral zone cause magnetic disturbances with more frequency and with larger amplitude than at any other latitude. Thus, the external-magnetic-field variations in the Norwegian Sea and Barents Sea areas were studied with special attention given to the declination (Edvardsen et al, 2013). The findings were that declination offset at disturbed days for the Barents Sea observatories SOR and BJN were approximately 0.5° . Calculating the effect on wellbore positioning, if the 4000 m long horizontal section is drilled during a period where 6 hours of the day are disturbed, approximately one-fourth of the horizontal section is affected by a 0.5° error in the declination, if not corrected. The lateral displacement caused by this declination offset is approximately 9 meters, which is enough to cause concern warranting special attention by survey correction analysts (Edvardsen et al. 2013).

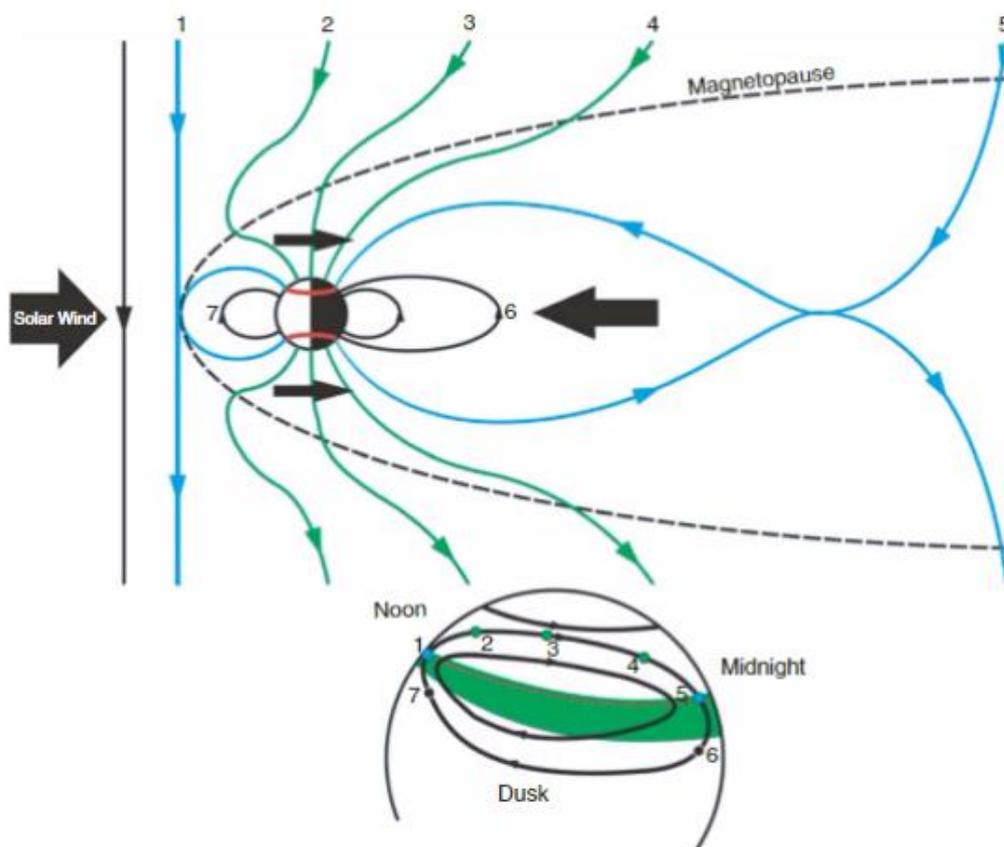


Figure 3.1: Solar wind and the Dungey cycle

Given these challenges unique to the region, the approaches presented in the sections that follow provide critical corrections to operations in the Barents Sea and corresponding risk mitigation. Employment of appropriate mitigation methods can provide the most useful resource in increasing directional accuracy and mitigating the disruptive effects of disturbance field anomalies on time-bound data. IFR and disturbance field mitigation methodology contributes to safer and more productive offshore operations at high latitudes (ibid), confronting the challenges of the Barents Sea.

4. Mitigation Methods

4.1 General

The anomalies in the earth's magnetic field fall into two distinct types, each involving different techniques for detection and mitigation. Crustal anomalies are spatial, while disturbance field anomalies are temporal.

4.2 Crustal Anomalies and Mitigation

4.2.1 In-Field Referencing

Standard MWD assumes the use of a global geomagnetic reference field which does not include local crustal magnetic anomalies. Long wavelength crustal anomalies are accounted for in global High Resolution Geomagnetic Models (HRGM). The technique of IFR further accounts for short wavelength crustal anomalies. In order to use IFR, high quality marine or airborne total field magnetic measurements have to be available for the region surrounding the drilling location. The case of the Barents Sea is no different, and MWD efforts must account for crustal anomalies originating in the oceanic crust.

It should be noted that (in theory) it is also possible to create a 3D IFR model from vector magnetic measurements. However, taking oriented vector measurements at the ocean surface is very challenging. A large number of such measurements would have to be taken to trace the field lines into the subsurface and resolve the depth dependence of the magnetic field. We are not aware of any attempts to create a 3D IFR model from vector measurements. What is more common is to take single spot measurements of the magnetic field vector at the surface and assume that the field has no depth dependence. Such ground shots are also useful to validate or calibrate a 3D IFR model derived from total field survey data.

When producing a 3D IFR model from marine or aeromagnetic survey data, it is important to be aware that the input data set only specifies the total intensity of the magnetic field (B_{total}), which can be thought of as the length of the magnetic field vector. Its direction has to be separately estimated by geomagnetic modeling. For a single location, the direction of the magnetic field cannot be inferred from the strength of the field alone. However, if the field is known in a sufficiently large area with complete 2D coverage, the solution of Laplace's differential equation for that area provides an estimate of the full vector of the geomagnetic field. To solve Laplace's equation, the magnetic field vector is first represented as the negative gradient of a scalar magnetic potential

$$\mathbf{B} = -\nabla V$$

Subsequently, Laplace's differential equation:

$$\Delta V = 0$$

is solved for the magnetic potential V .

A complication arising here that is frequently overlooked is that such a differential equation only has a unique solution if suitable boundary conditions are specified at the edges of the magnetic survey.

The popular flat-Earth methods using Fourier transforms (e.g. Dean 1985; Russel Shiells and Kerridge, SPE 30452, 1995) or the equivalent source method (Dampney 1969; Macmillan & Billingham, ISCWSA-40, 2014) implicitly assume that the potential is zero on the edges of the survey. Another way to phrase it is that they assume that all magnetic anomalies are completely contained within the local grid. Since the crustal field extends to very long wavelengths, and the peak of the spectrum is at about 300 km wavelength (see Figure 4.1), this assumption, while convenient, is entirely unrealistic. This can be demonstrated by a simple synthetic example (Maus, ISCWSA, London).

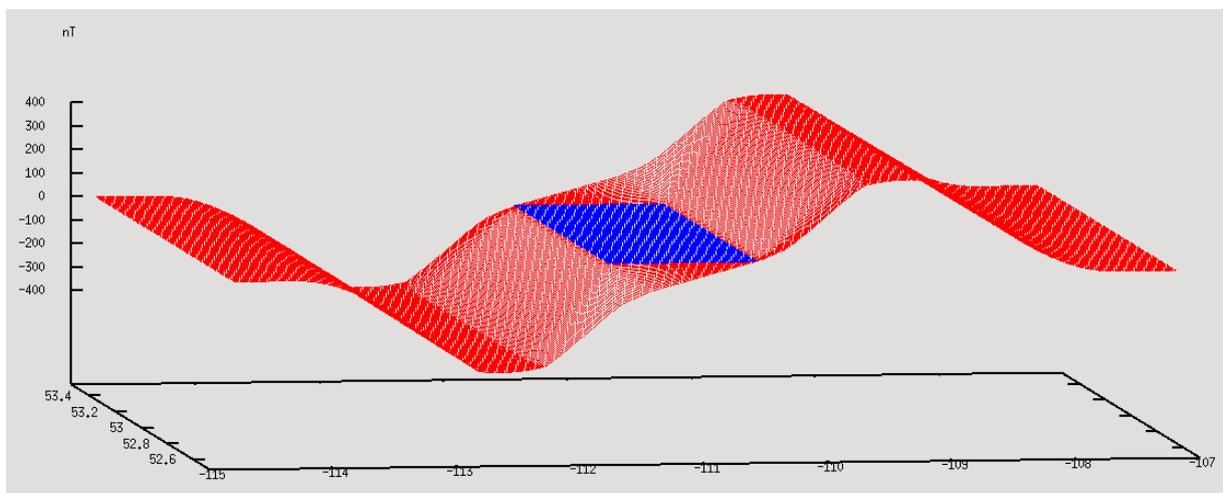


Figure 4.1: Synthetic input data illustrating the effect of long wavelength magnetic anomalies on the local declination

A 80 km x 80 km grid is usually considered a standard magnetic survey size for producing IFR models. To make it simple, assume the total field anomaly is zero throughout the grid (shown in Figure 4.1 in blue). Outside of the grid area, we assume a typical long wavelength crustal anomaly with 400 nT amplitude (red in Figure 4.1). Note that instead of assuming all of the anomalies to be inside the grid, this setup provides a counter-example, illustrating what happens if the anomalies are instead outside of the grid. Applying any of the commonly used flat Earth FFT or equivalent source methods to the grid will result in zero declination anomaly throughout the blue area because there is no information in that grid providing anything to the contrary, and the potential on the boundary is unknown and set to zero. If the differential equation is now solved accurately for the whole Earth ellipsoid using the technique described later, one can see in in Figure 4.2 that the magnetic potential (green) on the boundary is actually far from zero. This means that the implicit boundary condition of $V=0$ in practice leads to completely incorrect results.

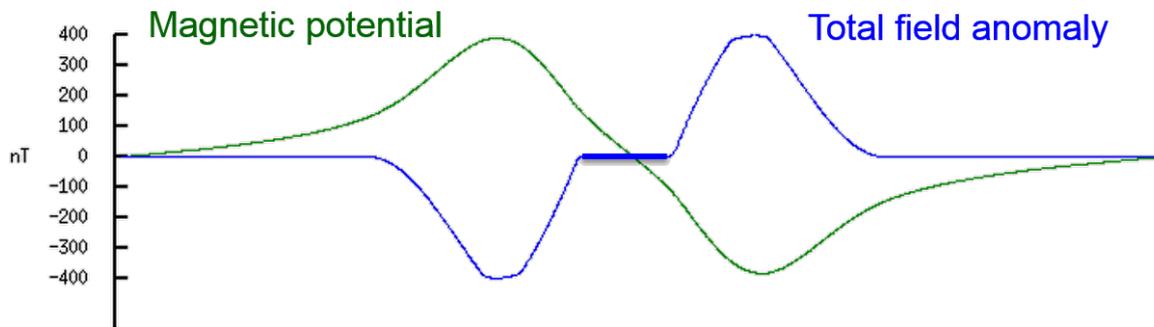


Figure 4.2: Magnetic potential (green) for a synthetic example of total field anomaly data (blue)

Figure 4.3 illustrates the corresponding declination anomaly in the area of the synthetic grid. While the flat Earth methods would predict a zero declination anomaly (blue), the true declination anomaly due to the long wavelength crustal field is over 1° in this example. It is well known that differential equations can only be solved with appropriate boundary conditions. This synthetic example illustrates that all of the flat Earth IFR methods commonly used to solve Laplace's equation for the magnetic field without specifying boundary conditions will provide incorrect results.

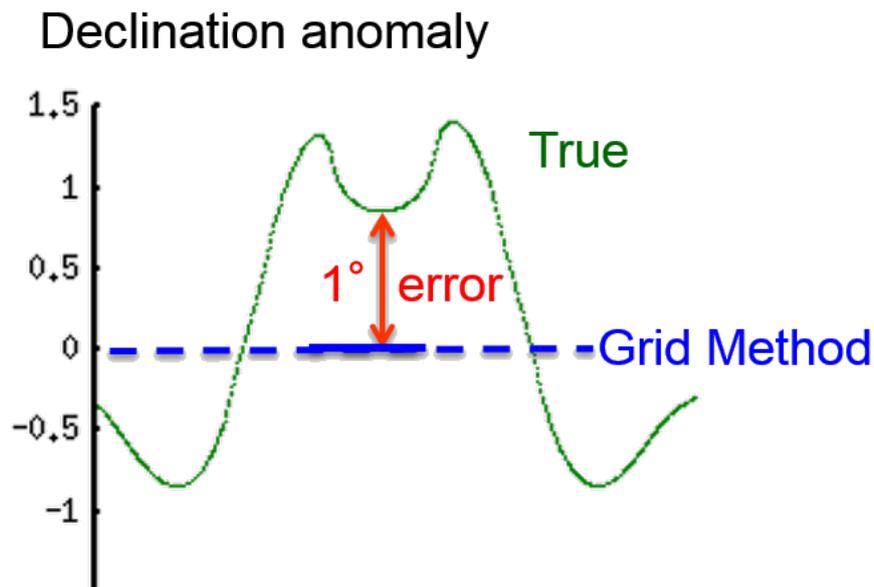


Figure 4.3: True declination anomaly (green) versus declination anomaly of zero provided by flat Earth methods (blue)

The problem of unknown boundary conditions for the potential can be solved by eliminating the boundary and wrapping the grid around the Earth. That means we have to use regional magnetic data to extend the local survey into a global grid, while being aware that we only have the high-resolution data locally. The regional data are usually of lower quality, but still sufficiently specify the long wavelengths. To use an analogy from weather models: The commonly used flat Earth methods correspond to creating a local weather model assuming that no wind blows through the boundaries of the

model. A correct solution instead uses a global atmospheric weather model with locally enhanced resolution.

To tie the local magnetic survey into the global crustal magnetic field, the first step in a more accurate method is to bridge the gap between the long-wavelength main field contribution and the short-wavelength aeromagnetic survey data with larger regional and satellite datasets. Integrating these regional data sets then means that a local flat Earth approximation is no longer appropriate. The only accurate solution is to use ellipsoidal harmonic functions. These enjoy widespread use in geodesy, where the global potential model EGM2008 is an ellipsoidal harmonic model.

Since the Earth shape is best approximated by an ellipsoid of rotation, ellipsoidal harmonics are the most suitable functions to represent the geomagnetic field. These functions are defined (Maus, 2010) as

$$V(\lambda, \beta, u) = R \sum_{n=1}^N \sum_{m=0}^n \frac{Q_n^m \left(i \frac{u}{E} \right)}{Q_n^m \left(i \frac{b}{E} \right)} (g_n^m \cos m\lambda + h_n^m \sin m\lambda) P_n^m(\sin \beta)$$

where λ is longitude, β is reduced latitude, u is the semi-minor axis of the confocal ellipsoid at this location, R is the traditional geomagnetic reference radius, N is the degree of the expansion, and Q_n^m and P_n^m are fully normalized associated Legendre functions of the first and second kind, respectively. E and b are the focus and semi-major axis of the WGS84 reference ellipsoid. Finally, g_n^m and h_n^m are the ellipsoidal harmonic model coefficients of the expansion, estimated by least squares from the input data for the area.

The method of expanding a global magnetic grid into ellipsoidal harmonics gets rid of the problem of the boundary condition, so we can compute the IFR model as a global model with very high resolution locally in the area of interest. The advantage of this approach is to have only one model. Instead of adding local crustal anomaly corrections to global models, an ellipsoidal model extends to a very high degree and fills the entire spectrum without gaps.

A detailed validation study of the ellipsoidal harmonic IFR algorithm was published by Poedjono et al (2012). Comparisons were further made between a large number of ground measurements with both the flat Earth and ellipsoidal harmonic solutions. Figure 4.4 shows that the ellipsoidal harmonic solution agrees significantly better with the ground measurements, reducing IFR errors by over 50 %. The ellipsoidal harmonic method gives significantly lower residuals. Also shown is the 1-sigma error model threshold for the ISCWSA MWD+IFR tool code the corresponding mean errors are shown in Table 4.1. The IFR values computed by the flat Earth method are about twice as large and fail the assumptions of the ISCW.

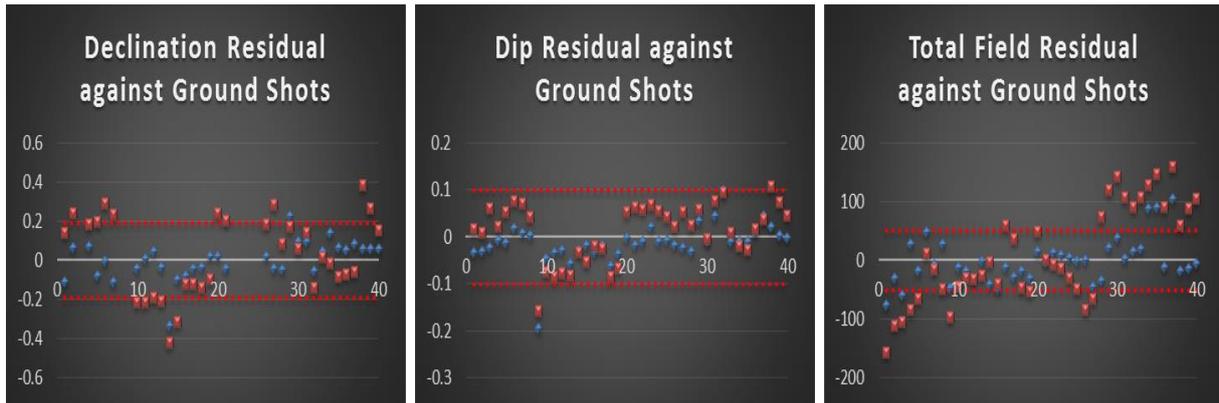


Figure 4.4: Validation of the Ellipsoidal harmonic method (blue) and Flat Earth method (red) against ground shots.

Table 4.1: Root means square residuals between 40 ground measurements versus predictions from the Ellipsoidal harmonic method and the flat Earth method

	Ellipsoidal harmonic Declination	Flat Earth Declination	Ellipsoidal harmonic Dip	Flat Earth Dip	Ellipsoidal harmonic Total Field	Flat Earth Total Field
Actual Error (1 σ)	0.096 °	0.202 °	0.043 °	0.061 °	38.4 nT	82.0 nT
Error model (1 σ)	0.19 °		0.1 °		50 nT	

4.2.2 Aeromagnetic Surveys Available for IFR in the Barents Sea

The previous section described modeling methodology to produce accurate IFR models in the Barents Sea. In order to create the IFR model, however, one must start with input data of sufficient quality. Until recently, available aeromagnetic data for the Barents Sea consisted of surveys flown from 1970 to 1991, largely by the Geological Survey of Norway (NGU) and various others (Figure 4.5). The line spacing of these surveys ranged from 4 to 12 km. A tight line spacing is critically important to the accuracy of an IFR model to be built from the specified survey. This is because the line spacing directly affects the lower bound of the range of wavelengths that can be captured by the survey. In order to provide the same quality of IFR model as other regions use, aeromagnetic surveys with 1 - 2 km line spacing should be used.

More recent surveys of the south Barents Sea were conducted by NGU at 2 km line spacing (Table 4.2). The BASAR surveys (06, 08, 09, 14; corresponding to year of survey) cover a large area off the coast of northern Norway. They replace the lower quality NGU-69, BAMS-85, and NGU-70 surveys that previously covered this area. The 2 km line spacing is optimal for creating the highest quality IFR models for MWD operations.

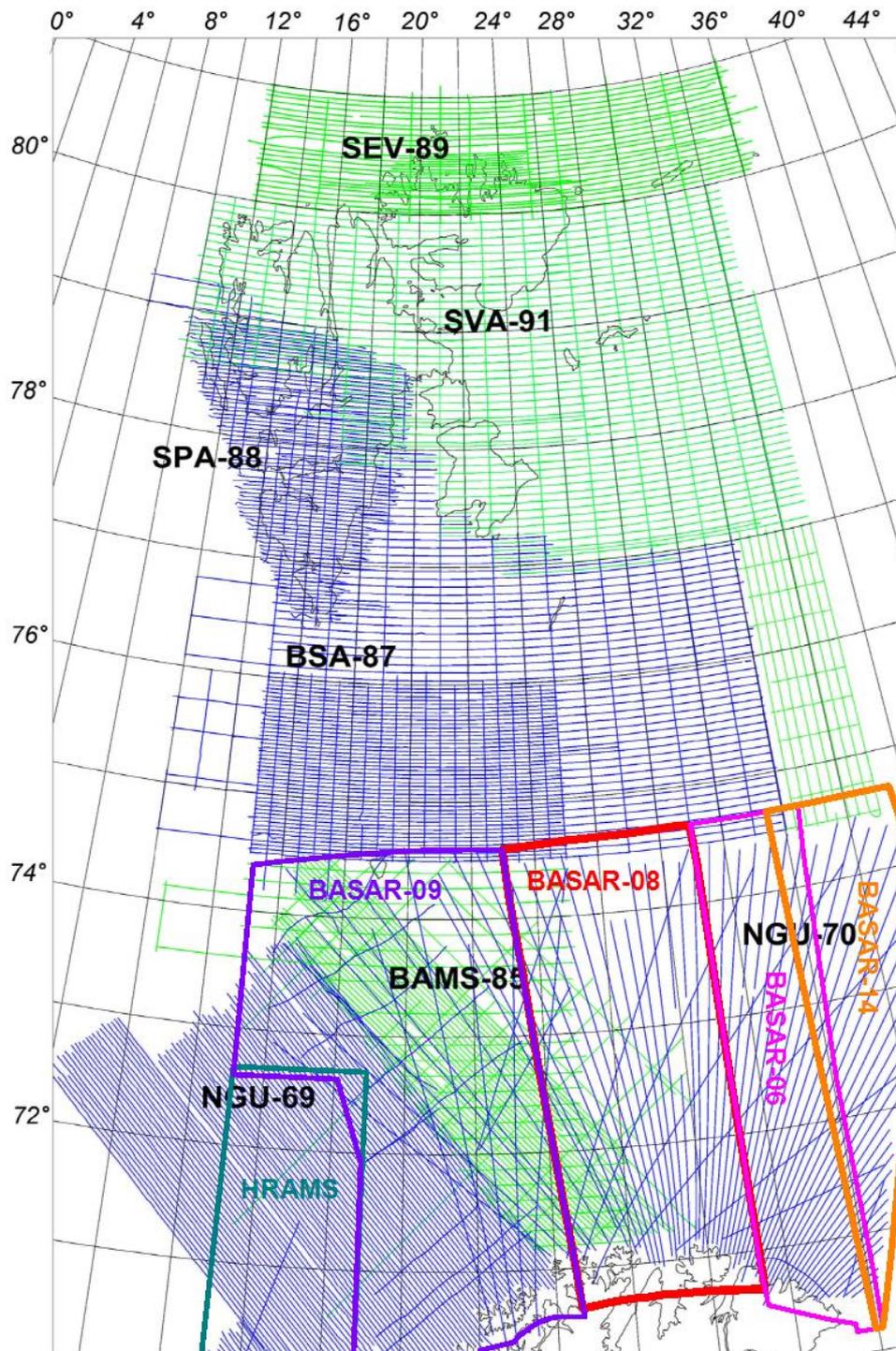


Figure 4.5: Barents Sea available Aeromagnetic Surveys (Base image credit: Geological Survey of Norway)

Table 4.2: Aeromagnetic survey details for Barents Sea

Year	Area	Operator, reference	Survey Name	Survey Height (m)	Line Spacing (km)	Length (km)
1989	Northern Svalbard	N/A	SEV-89	N/A	N/A	N/A
1991	Svalbard	Amarok/TGS	SVA-91	900	7.5	27,800
1988	Spitsbergen	NGU	SPA-8	1550	5.5	13,300
1987	NW Barents Sea	NGU	BSA-87	250	4 - 8	34,000
1970	SE Barents Sea	NGU	NGU-70	200	4 - 8	22,800
1985	SW Barents Sea	CGG	BAMS-85	200	4	16,900
1969	SW Barents Sea	NGU	NGU-69	200	4	26,200
2009	Western Barents Sea	NGU	BASAR-09	230	2	77,000
2008	Southern Barents Sea	NGU	BASAR-08	230	2	57,600
2006	Southeastern Barents Sea	NGU	BASAR-06	230	2	30,000
2014	Southeastern Barents Sea	NGU	BASAR-14	230	2	44,000
1997/1998	Andfjorden and Harstad	StatoilHydro	HRAMS-97/98	150	1	7,000

Aeromagnetic data are not available east of approximately 32 ° East longitude. However, the available data does cover most active oil and gas locations in the Barents Sea. IFR models can be provided in all areas covered by the BASAR surveys with a high degree of confidence. Additionally, areas uniformly covered by 4 km line spacing (for example, SW corner of BSA-87) could be included in an IFR model as well. A buffer of at least 10 km from the edge of the input data should be included to avoid edge effects. For reference, Figure 4.5 and Table 4.2 show coverage areas and line spacing for the surveys presented.

4.2.3 Barents Sea Study

For the purposes of this study, a location in the Barents Sea was evaluated assuming mediocre input data from older NGU surveys (4 km line spacing, 200 m survey height). Below are the 3 sigma uncertainties at varying depths. The parameters relevant to the estimates of uncertainty are given in Table 4.3. Uncertainties in the declination, inclination, and total field are then summarized in Table 4.4 to Table 4.6.

Table 4.3: Parameters relevant to the assessment of uncertainties

Parameter	Value	Relevant for uncertainty contribution of
Horizontal field strength	8,119 nT	Main, crustal and disturbance field
Vertical field strength	54,867 nT	Main, crustal and disturbance field
Aeromagnetic survey altitude	200 m above MSL	Crustal field
Nonmagnetic layer thickness*	4000 m	Crustal field
Water depth**	188 m	Crustal field
Aeromagnetic data resolution	4 km	Crustal Field
Corrected geomagnetic latitude	71.5°	Disturbance field
Absolute measurement available	Yes	Crustal Field

*Note: It is assumed here that the layer down to a depth below sea level of 4000 m is non-magnetic. An average TVD for Barents Sea of 3500 m was combined with a 500 m margin for this estimation.

**Note: Water depth was determined with the NGDC ETOPO1 model at our test location.

Table 4.4: Declination uncertainty (3 sigma)

Depth (m)	Main field (°)	Crustal field (°)	Disturbance field (°)	Total (°)
0	0.24	0.36	1.2	1.29
500	0.24	0.36	1.2	1.29
1000	0.24	0.36	1.2	1.29
1500	0.24	0.36	1.2	1.29
2000	0.24	0.39	1.2	1.29
2500	0.24	0.42	1.2	1.29
3000	0.24	0.48	1.2	1.32
3500	0.24	0.6	1.2	1.38

Table 4.5: Dip Angle uncertainty (3 sigma)

Depth (m)	Main field (°)	Crustal field (°)	Disturbance field (°)	Total (°)
0	0.09	0.09	0.33	0.33
500	0.09	0.09	0.33	0.36
1000	0.09	0.09	0.33	0.36
1500	0.09	0.09	0.33	0.36
2000	0.09	0.09	0.33	0.36
2500	0.09	0.12	0.33	0.36
3000	0.09	0.15	0.33	0.36
3500	0.09	0.18	0.33	0.39

Table 4.6: Total field uncertainty (3 sigma)

Depth (m)	Main field (nT)	Crustal field (nT)	Disturbance field (nT)	Total (nT)
0	55.5	60	242.7	255.9
500	55.5	60.6	242.7	256.2
1000	55.5	61.8	242.7	256.5
1500	55.5	64.8	242.7	257.1
2000	55.5	69.9	242.7	258.6
2500	55.5	78.9	242.7	261
3000	55.5	94.8	242.7	266.4
3500	55.5	122.4	242.7	277.5

To further understand the magnitude of the above uncertainties, one must compare them to other crustal mitigation methods. The ISCWSA/OWSG tool codes of interest to crustal mitigation are MWD and MWD+IFR1. These two tool codes and their associated global uncertainty values are shown in Table 4.7, as given by OWSG. The MWD tool code assumes the use of a standard-definition main field model with yearly updates. Therefore, BGGM qualifies for use under the MWD tool code.

The MWD+IFR1 tool code makes no assumptions on the IFR modeling methods or resolution. It simply defines the uncertainties that the model is expected to achieve. Any number of IFR solutions could therefore qualify for this tool code under ideal conditions. However, with the unique challenges that the Barents Sea presents, inferior methods that utilize plane grid assumptions or spherical harmonics will likely exceed the MWD+IFR1 tool code.

The ellipsoidal harmonics method described in this section has been evaluated at the Barents Sea location and uncertainty estimates are shown above. Combining (adding in quadrature) the main field and crustal field values at depth gives the values in the final column of Table 4.8. These values depend on the sediment thickness and ultimately the depth to magnetic basement, which is estimated here at 4000 m. They are well within the MWD+IFR1 tool code, despite the high-latitude Barents Sea location and the less dense 4 km line spacing.

It was suggested earlier that a tighter 1-2 km line spacing be flown over any areas where wellbore placement is critically important. Areas of the Norwegian Sea are surveyed in this detail and a tighter spacing could further improve the uncertainties shown using the ellipsoidal harmonics method. It is also important to note that the ellipsoidal harmonics method exceeds the MWD+IFR1 tool code at all depths, not only at surface. Care should be taken when selecting IFR providers that the tool code is met everywhere. Some may only consider surface uncertainties when comparing against tool code.

Table 4.7: OWSG error model global values (1-sigma)

	MWD	MWD+IFR1
Declination - Global (degrees)	0.36	0.15
BH-Dependent Declination - Global (degrees*nT)	5000	1500
Magnetic Dip - Global (degrees)	0.2	0.1
Total Magnetic Field - Global (nT)	130	50

$$3\sigma_{dec} = 3 * \sqrt{\sigma_{dec}^2 + \left(\frac{\sigma_{BH-dep dec}}{BH}\right)^2}$$

Table 4.8: Comparison of crustal mitigation methods (3-sigma uncertainties)

	OWSG MWD	OWSG MWD+IFR	EH Method (4 km line spacing)
Dec (degrees)	2.143771	0.714942	0.64622
Dip (degrees)	0.6	0.3	0.201
Btotal (nT)	390	150	134

4.3 Geomagnetic Disturbance Field Mitigation Study

The geomagnetic disturbance field is a major source of directional error. It also affects the ability to quality-control MWD survey data. An effective disturbance field correction is therefore required for accurate and reliable wellbore placement. Such a capability is of particular importance in case a relief well has to be drilled in response to a well control event.

4.3.1 Global Climatological Models of Magnetic Disturbance

Global climatological models of the geomagnetic field were first developed by Sabaka et al (2002, 2004, 2015) at NASA. The idea is to use an extensive data set of satellite and ground observatory magnetic measurements over many decades and compile a model that then predicts the magnetic field at any given location and time. To account for temporal variations of external fields originating in the magnetosphere and ionosphere, the model is driven by time-varying indices, such as the Disturbance Storm-Time (DST), solar flux (F10.7) and interplanetary magnetic field (IMF Bx, By, Bz). The NASA Comprehensive model is available as software from NASA/GSFC.

Similar models are also available from other organizations. While these climatological models offer a reasonable approximation of the disturbance field at mid latitudes during magnetically quiet periods, they are known to perform poorly during disturbed periods, in particular at higher latitudes. In order to evaluate the utility of such climatological models for directional drilling, the performance of NASA's CM4 model was compared against a global data set of geomagnetic observatory measurements from 1995 to 2012. The results are shown in Figure 4.6 for magnetically quiet conditions. While the corrections offer some benefit at low latitudes, their effect is almost negligible at high latitudes where the disturbances have the largest impact.

In Figure 4.7 the results are seen for magnetically disturbed conditions, as given by a planetary magnetic disturbance index (Kp) of greater than or equal to 6. During such magnetic storms the declination improvement becomes even smaller, while the correction offers a substantial benefit for predicting the dip and total field disturbances at low latitudes. As can be seen, such a climatological model only provides a disturbance field reduction of the order of 10 %, which makes it unsuitable for use in directional drilling. The IFR2 error model tool code for disturbance field corrected data assumes that the mitigation method removes about 75 % of the disturbance field, which is unrealistic using global climatological models, but can indeed be achieved by the local methods described below.

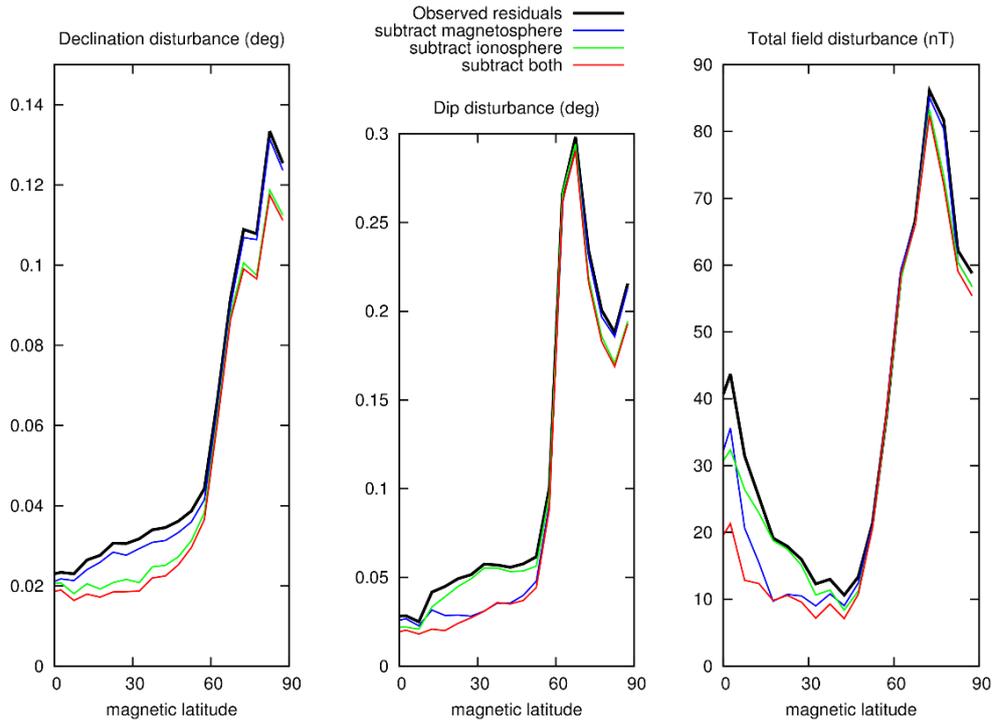


Figure 4.6: Magnitude of the global magnetic disturbance field (1 sigma) shown as the uncorrected residuals (black), after correcting for the magnetosphere (blue), the ionosphere (green) and both (red).

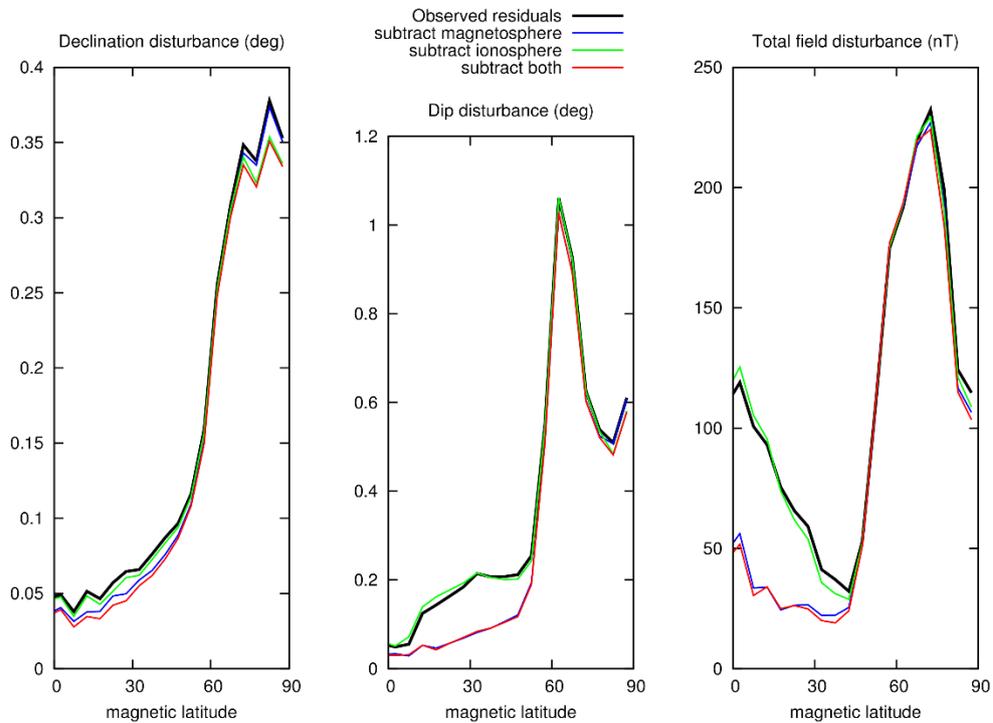


Figure 4.7: Same as Figure 4.6, but limited to disturbed times with planetary Kp index > 6

4.3.2 Prior Work - Nearest Observatory

A study presented in 2014 at the Offshore Technology Conference (OTC) (Poedjono et al., 2014) characterized the geomagnetic disturbance fields at high latitudes by analyzing more than a decade of geomagnetic ground station measurements. Apart from estimating the magnitude of the disturbances, the study also derived the expected remaining errors after correcting for disturbance fields using the nearest geomagnetic observatory. Generally speaking, to reduce the disturbance field by 75 % (in other words, to get to 25 % error remaining) requires an observatory within about 60 km of the drill site, as illustrated in Figure 4.8 below. The accuracy of this method is low, as no interpolation is performed, and the disturbances at the observatory location may differ substantially from those at the location of interest. However, the nearest observatory method is often used because it is simple to implement and offers improvement over using no disturbance mitigation at all.

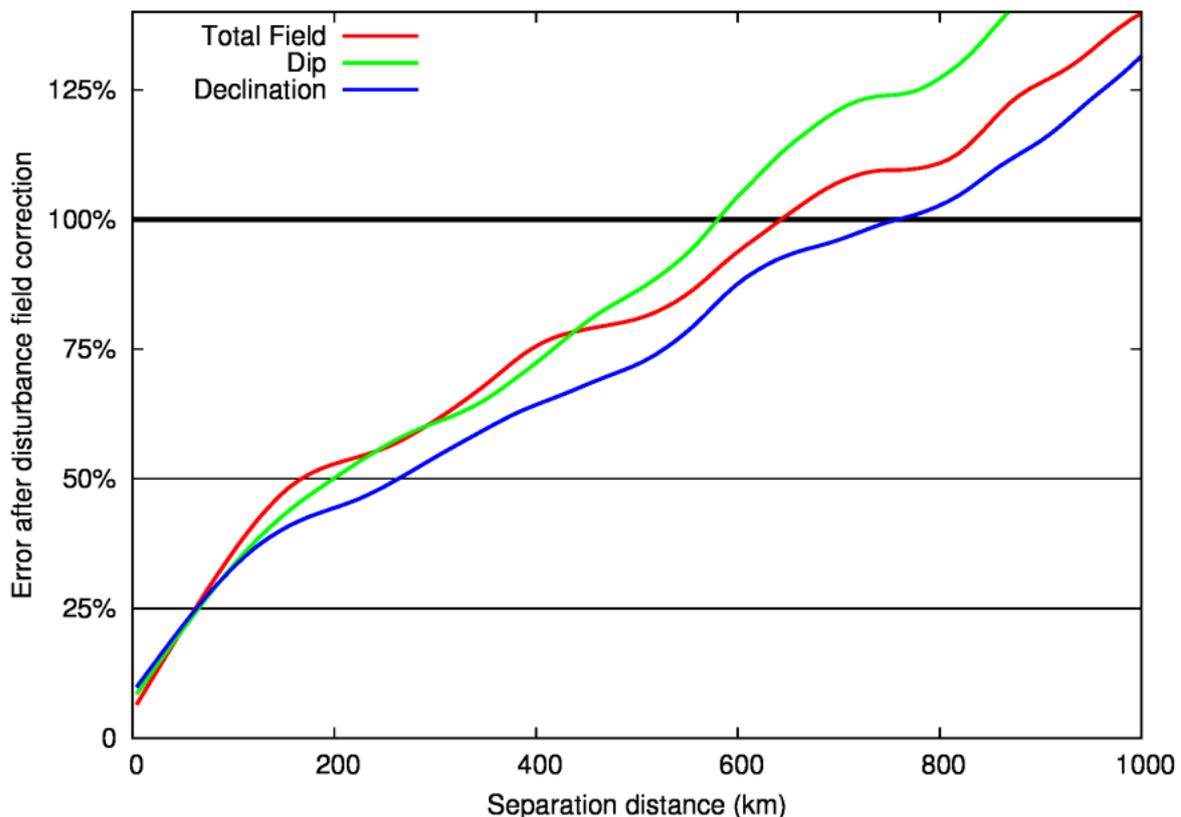


Figure 4.8: Remaining error in the total field, dip and declination after subtracting the disturbance field, plotted against the distance of the observatory from the drill site

The earlier study assumed that the data from the nearby observatory would be used without any extrapolation to the drill site or any interpolation between several observatories. In this study, interpolation methods are examined, and this previous analysis is extended to include advanced disturbance field correction methods, showing much longer-range efficacy.

The other disturbance error mitigation methods that will be presented are Real-time Local Observatory, IIFR, and DF. The local observatory requires physical equipment with a real-time link, IIFR builds on the non-extrapolated, single-observatory method by adding data from a second available observatory and performing extrapolations, and DF uses a second observatory as well as past local data in order to come up with extrapolated real-time local data.

4.3.3 Real-Time Local Observatory

The real-time local observatory method involves placing a physical magnetometer within a few km of the drill site. This has been successfully done offshore in Japan as an ocean-bottom deployment for scientific studies, as well as in Canada and Texas as surface deployments. Essentially, a magnetometer is set up with power connection and real-time data transmission and placed as close to the drill site as possible without picking up interference from the steel infrastructure involved in drilling. Because it is placed locally, there is no extrapolation needed, and as long as the device is properly set up and calibrated, the data can be understood to perfectly predict the disturbance field at the drill site. This is the ideal disturbance mitigation method, but often it is not feasible due to cost, logistics, time constraints, magnetic interference from passing vessels, the difficulty involved in seafloor deployments, or the like.

Although a local magnetometer is required for both the local observatory and disturbance function methods, a disturbance function implementation is far less expensive. To use a local magnetometer by itself, a real-time link must be somehow established. This can be in the form of a wave-glider that picks up sonar pulses from the magnetometer, a hard-wired cable to the rig, or a cable to an above-water satellite uplink. These are difficult and expensive to implement in ocean-bottom situations. The disturbance function, however, does not require a real-time link, so one can simply leave the magnetometer on the ocean bottom for a couple months, retrieve it, process the data, and move on to creating the function. Compared to establishing and maintaining a real-time link, this can be more cost-effective by an order of magnitude.

4.3.4 Interpolated In-Field Referencing

Interpolated In-Field Referencing (IIFR) is a method that can be implemented using existing observatory infrastructure and may be used quite effectively anytime there are two available magnetometers or variometers within approximately 300 km on both sides of the drill site. If there is no observatory on an opposite side, then IIFR essentially defaults to using the nearest observatory, which provides a relatively poor correction. As previously shown, non-interpolated values from nearby single observatories are already used in many oil fields. If there is a second observatory within reasonable distance on the opposite side of the drill site, implementing interpolation by IIFR can be an attractive option.

For each downhole survey time stamp, the values for B_x , B_y , and B_z are gathered from each of the two or more proximate observatories and the disturbance field is separated from the main and crustal field. These residual disturbance field measurements are then transformed into declination, dip, and total field disturbances. To synthesize

values for those three quantities at the location of concern, a weighted average is performed.

For each remote observatory used, the disturbances are split into low- and high-frequency parts with low- and high-pass filters, and each is multiplied by a weighting function. The low-frequency part is further phase-shifted to account for longitudinal differences between the remote observatory and the location of concern. These weighting functions and pass filters depend on the region of earth as well as the geometry of the stations. The weighted values for each remote observatory are then summed to provide a synthesized local magnetic vector (Shiells et al. 1997).

4.3.5 Disturbance Function

The Disturbance Function (DF) method addresses some major short comings of the IIFR method. The IIFR method assumes that the magnetic disturbances can be estimated by a simple spatial interpolation between surrounding observatories. This leads to two problems:

1. The surrounding observatories may not be ideally situated on both sides of the drill site.
2. The disturbance field varies with the conductivity of the sub-surface. Observatories placed on resistive land masses record variations that can differ significantly from the disturbances on the sea bed, surrounded by conducting sea water, sediments and oceanic crust. This is even a problem on land, where observatories located on geological units with different electrical conductivity display different disturbance fields. In fact, these variations in the disturbance field are used in the method of geomagnetic depth sounding to map the conductivity of the sub-surface.

The DF addresses both issues by using by first deploying a mobile observatory at the land or ocean bottom location in the vicinity of the drill site. The disturbance field at the drill site is then recorded for about 3 months and is then used as a "learning data set" to compute the disturbance function parameters between any surrounding observatories and the drill site. The DF parameters can be computed for any possible permutation of input observatories, providing maximum flexibility in case of outages of any of the surrounding stations. Since the data of the mobile observatory is not required in real-time, it can be placed on the sea floor and record the data to memory only. This significantly reduces the cost and logistical difficulties of such a deployment. Indeed, such mobile observatories are readily available for both land and sea floor deployments.

The equations for estimating and applying the DF method are provided in the patent by Maus and Poedjono (2014). The general outline of the process is as follows: Beginning with a period of data for both the location of concern and the remote observatories, a Fourier transform is performed. This takes the data from the time domain to the frequency domain, revealing the occurrence of various-wavelength magnetic disturbances in the data. Complex weighting coefficients are then found for each wavelength to get the ultimate combination to closely approximate the phase and amplitude of the disturbances at the location of concern. This is similar to IIFR in that

it weights the data available from other observatories in order to attempt to interpolate the values at the location of concern, but goes much further. The geometry of the situation is considered, as well as the conductivity of the subsurface, as different conductivity profiles lead to higher or lower damping of different frequencies. Ultimately, a solution is sought which best matches waveform amplitudes and phase shifts at the location of concern. This method also works very well if only one input observatory is available. Any modulations in the amplitude and phase of the disturbances between the observatory and drill site are then optimally accounted for.

Once the DF parameters have been estimated in the form of a set of complex coefficients to correspond with each frequency, the DF method can then be used at any past and future time to approximate the disturbance field at the location of concern. In an operational implementation, the DF method uses data feeds from the surrounding observatories to predict the disturbance field at the drill site in real-time.

4.3.6 Barents Sea Simulation Study

A large amount of magnetic data from both observatories and variometers is publicly available for a variety of scientific and technical applications. Unfortunately, many of these data have significant issues, such as unreliable baselines and baseline jumps. Significant effort was therefore spent to derive a corrected and validated data set of all available global 1-minute data from 1995 through 2012. These were used here in a large-scale simulation study to characterize and compare the performance of the nearest observatory, IIFR and disturbance function methods. The locations of all observatories and variometers in the data set are shown in Figure 4.9.

Recently, some observatories and variometers have also started reporting 1-second data. However, this leads to very large data sets which are beyond the scope of this study. Furthermore, depending on the data transmission method used, downhole surveys can usually only be timed accurately to within about 1 minute, so that minute-averages are considered an appropriate choice of temporal sampling.

Because the study was carried out on observatory data from 1995 through 2012, some of these stations are no longer available for use, and some new stations have been added. Figure 4.10 below shows all Barents Sea region observatories that should be available for use going forward.¹

¹ Data are available from <http://flux.phys.uit.no/map/>, <http://geomag.gcras.ru/obs.html>, and <http://www.ava.fmi.fi/image/realtime/UT/>

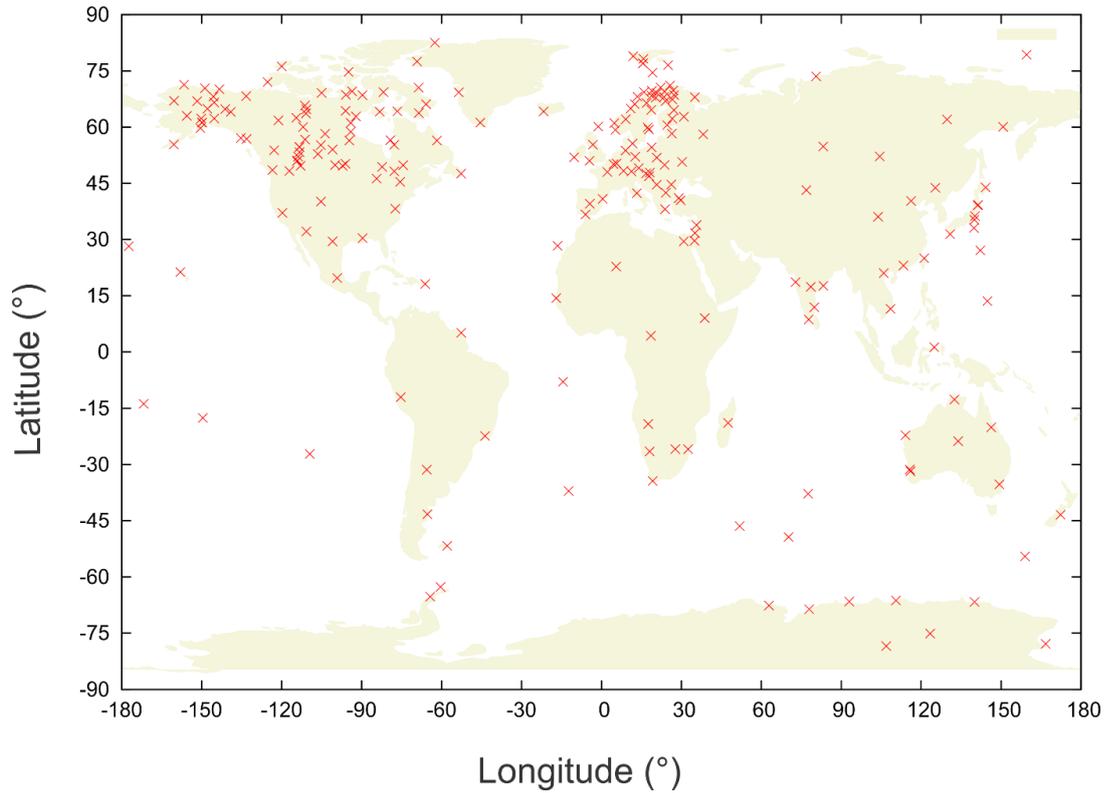


Figure 4.9: Locations of magnetic observatories with publicly available data

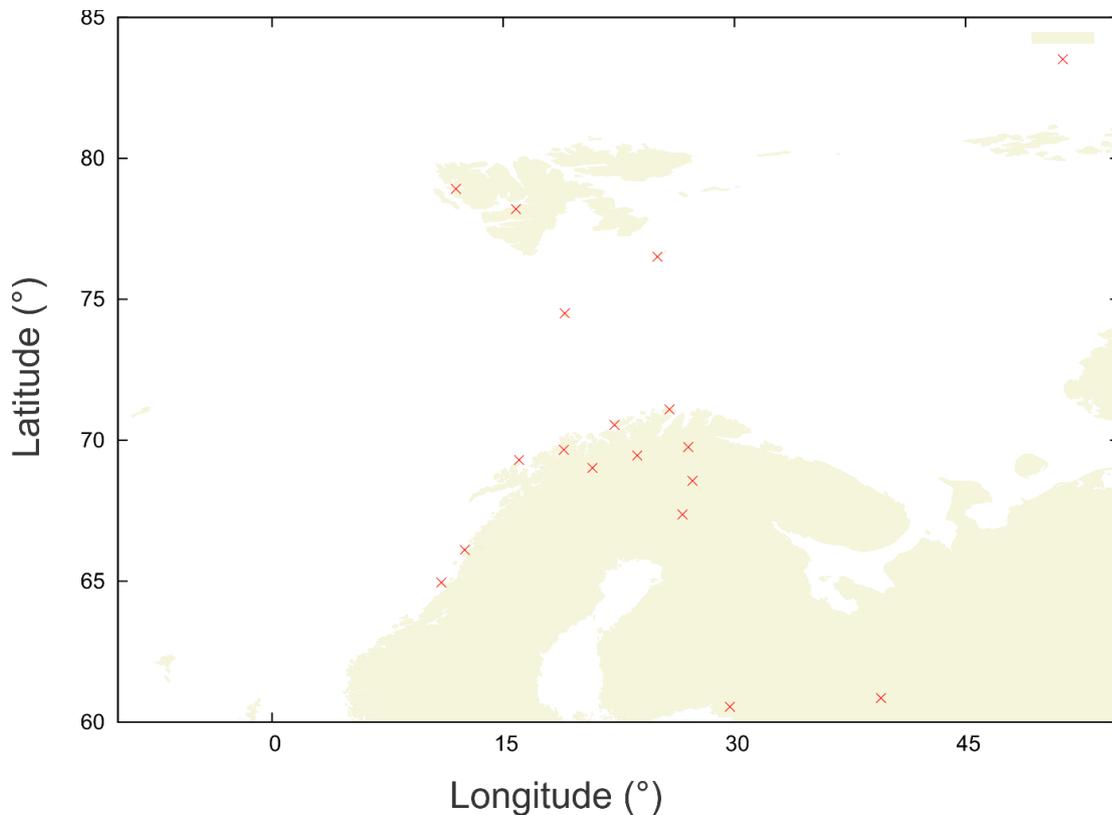


Figure 4.10: Magnetic observatories applicable to the Barents Sea

In order to characterize the extent by which the disturbance function and IIFR methods reduce the disturbance error, all station triplets above 50° latitude among whom no two were farther apart than 600 km were identified. This subset of stations is shown in Figure 4.11. The list of selected stations is given in the Acknowledgements section, with acknowledgement of the organizations running these stations.

The Nearest Observatory, IIFR and DF correction methods were then applied to each triplet of stations. 600 km was chosen for a couple of reasons. First, as can be seen in Figure 4.10, that is the approximate distance at which it is no longer beneficial to use uninterpolated single-observatory disturbance data, which is the simplest default method. Second, this is approximately the distance from mainland Norway to the Svalbard archipelago, as well as the radius of the Barents Sea, so it is a good representative distance for this region. The triplets can be seen in Figure 4.11 as connected triangles.

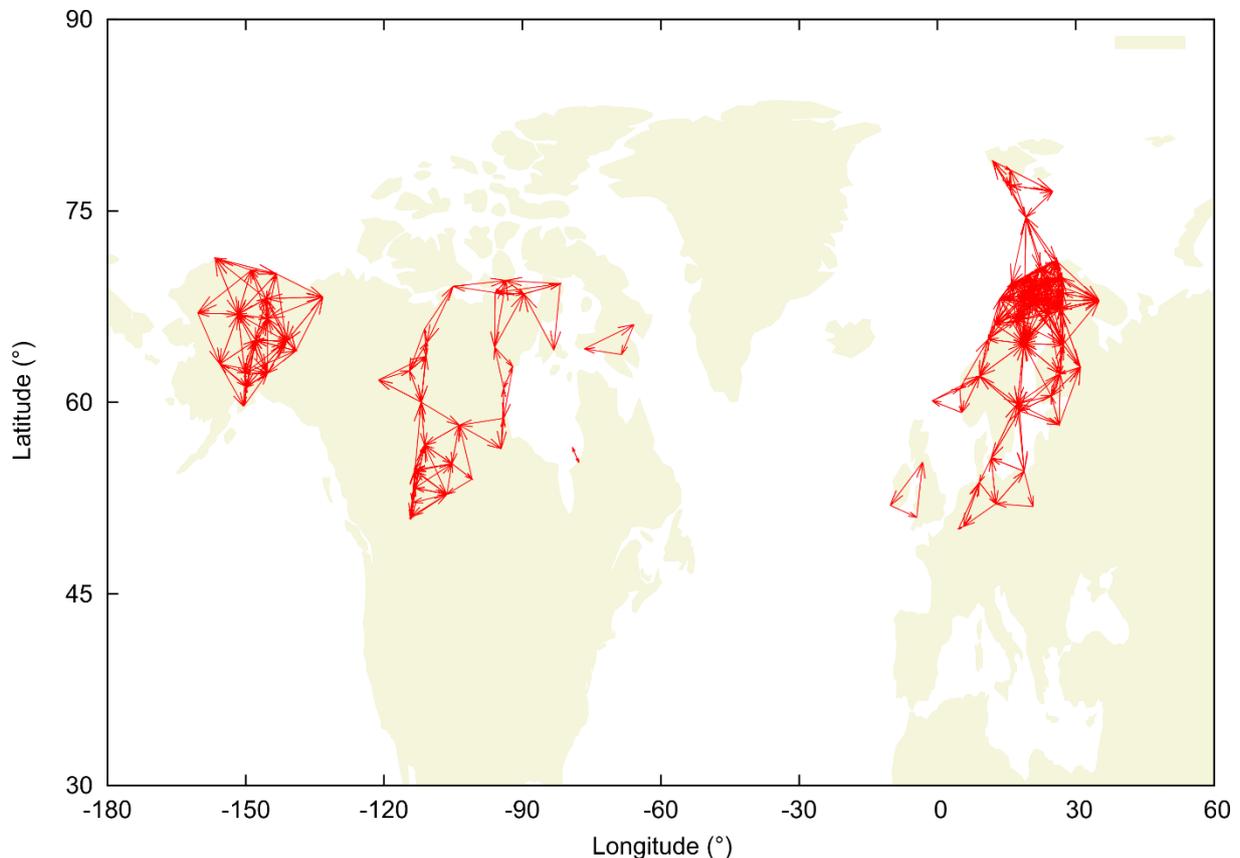


Figure 4.11: Triplets of stations (depicted as triangles) within 600km of each other upon which a disturbance simulation was performed.

For any selected "target" observatory, mimicking the drill site, the other two observatories were used to synthesize disturbance values at that target location using the nearest observatory, IIFR and DF methods.

After synthesis, residuals were taken by subtracting the synthesized value off the actual value, and then these residuals were split into systematic and random parts. The industry is concerned with both long-period ("systematic") and short-period ("random")

disturbance field variations. Here, we defined the systematic disturbance field contribution as the 3-day average residual, which may be considered representative for the time taken for a single downhole BHA run. The random variation is then defined as the per-minute deviation from that running mean.

Statistics were performed on the absolute values of these residuals in order to determine the confidence intervals expectable through each method. It is important to note that while a 3-sigma value is generally used to calculate 99.7 percent confidence intervals, the distribution of actual geomagnetic disturbances does not follow a Gaussian normal distribution. In fact, the 99.7 percentile on geomagnetic disturbances is generally closer to the 6-sigma value. In order to more accurately predict these 99.7th percentile values in this scenario, the residuals were binned to determine the actual value of the 99.7 percentile.

The goal of the simulation study was to assess the level by which downhole data would be affected by the disturbance field, before and after applying corrections. Specifically, we were interested to compare how much of the disturbance field could be reduced with the different available mitigation methods. Without applying a disturbance field mitigation method, the remaining disturbance is simply the actual disturbance. Thus, the same 99.7th percentile value finding method described above was also used on the raw, uncorrected disturbance values measured at the observatory representing the drill site.

The plots in Figure 4.12 through Figure 4.17 below show the systematic and random disturbance field contributions as a function of geomagnetic latitude, all of which have been fitted with a smoothed Bezier spline for more clarity. As expected, the uncorrected 99.7th percentile value (shown in red) is always higher than the IIFR value (shown in yellow), which is in turn higher than the disturbance function value (shown in green). This confirms that the disturbance function method achieves the most significant reduction in the disturbance field, followed by the less-accurate, though relatively simple, IIFR method, and that using no disturbance mitigation method at all can lead to large uncorrected errors.

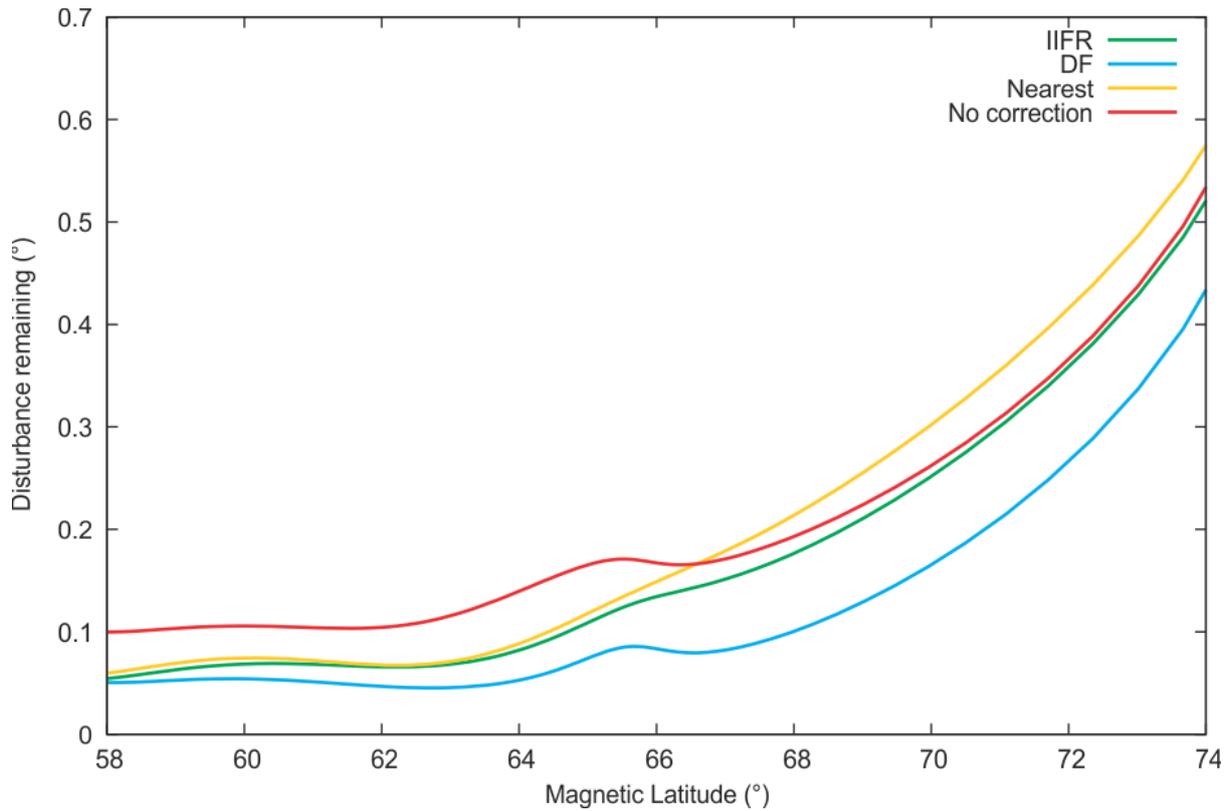


Figure 4.12: 99.7 % error percentiles for systematic declination disturbance remaining after corrections

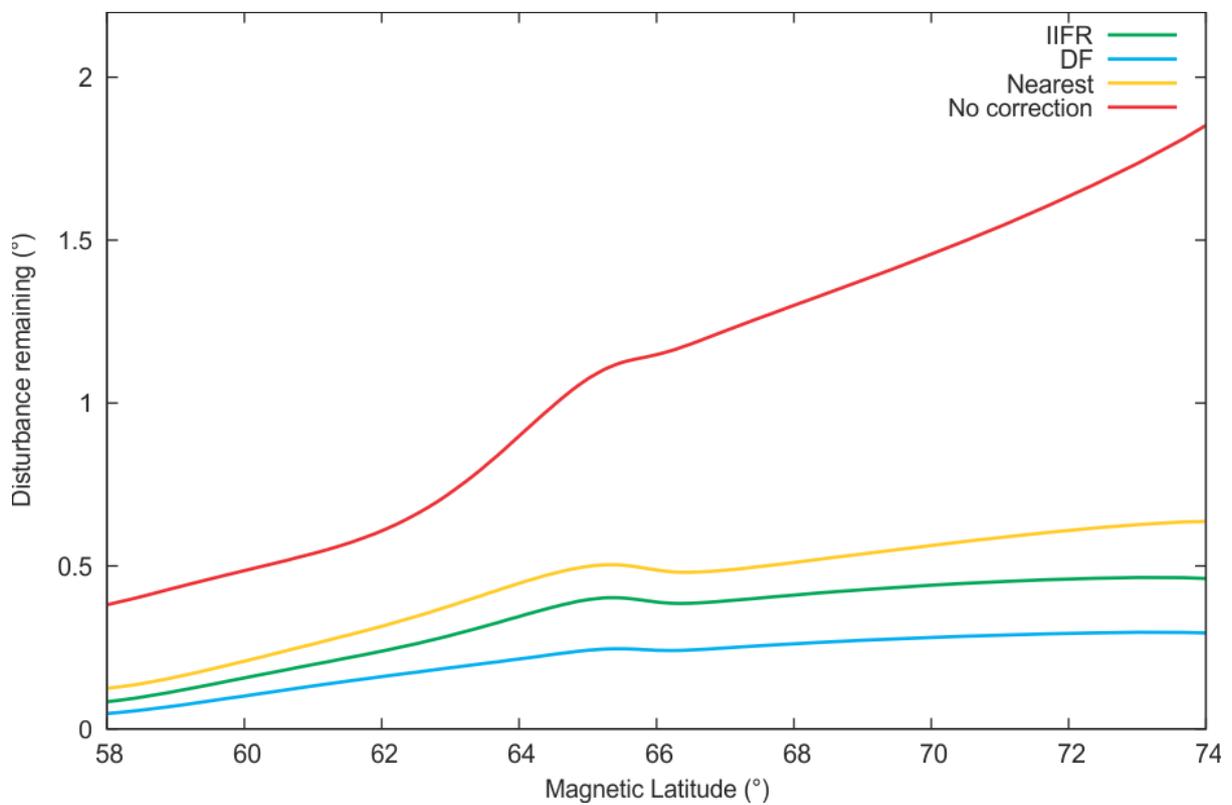


Figure 4.13: 99.7 % error percentiles for random declination disturbance remaining without (red) and after corrections

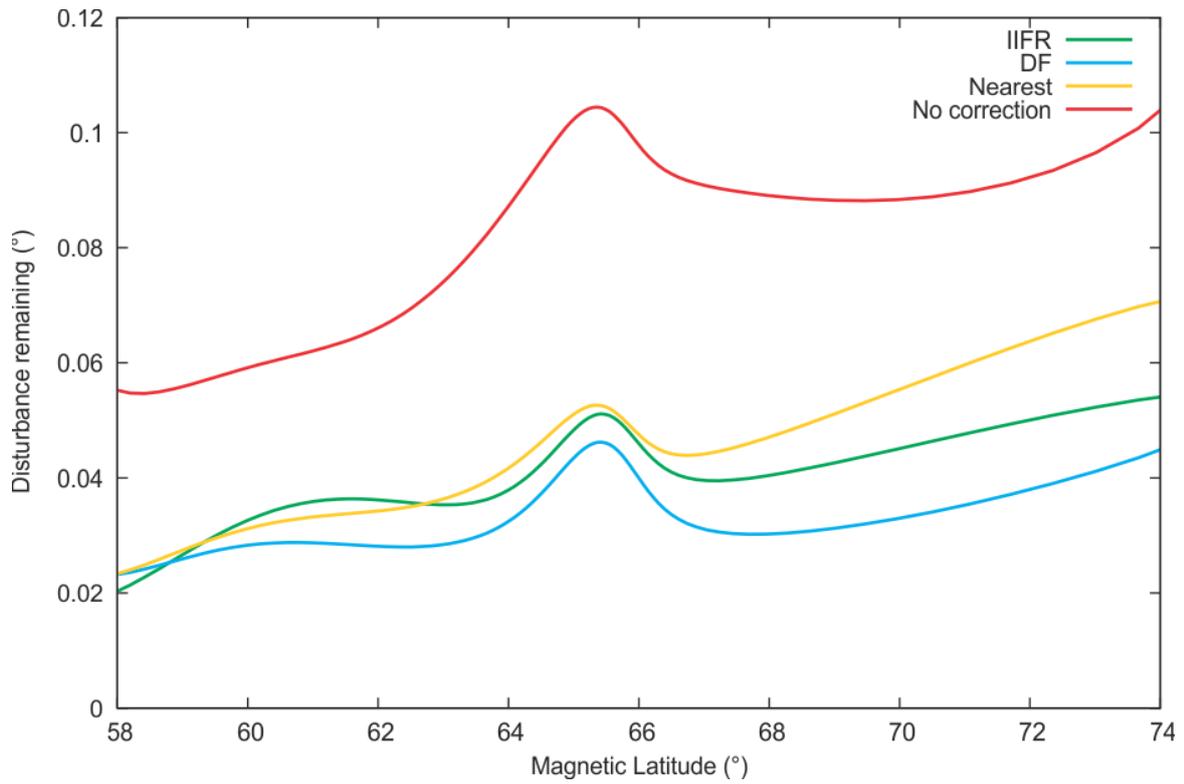


Figure 4.14: 99.7% error percentiles for systematic dip disturbance remaining after corrections

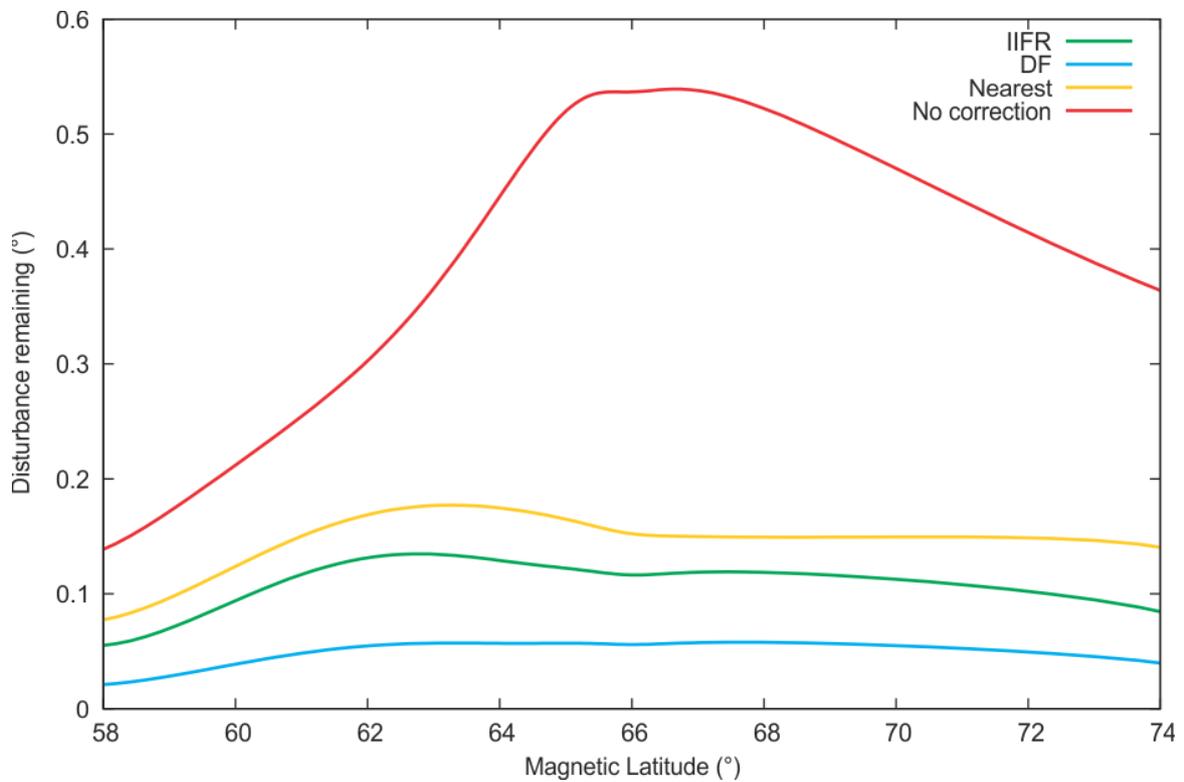


Figure 4.15: 99.7% error percentiles for random dip disturbance remaining after corrections

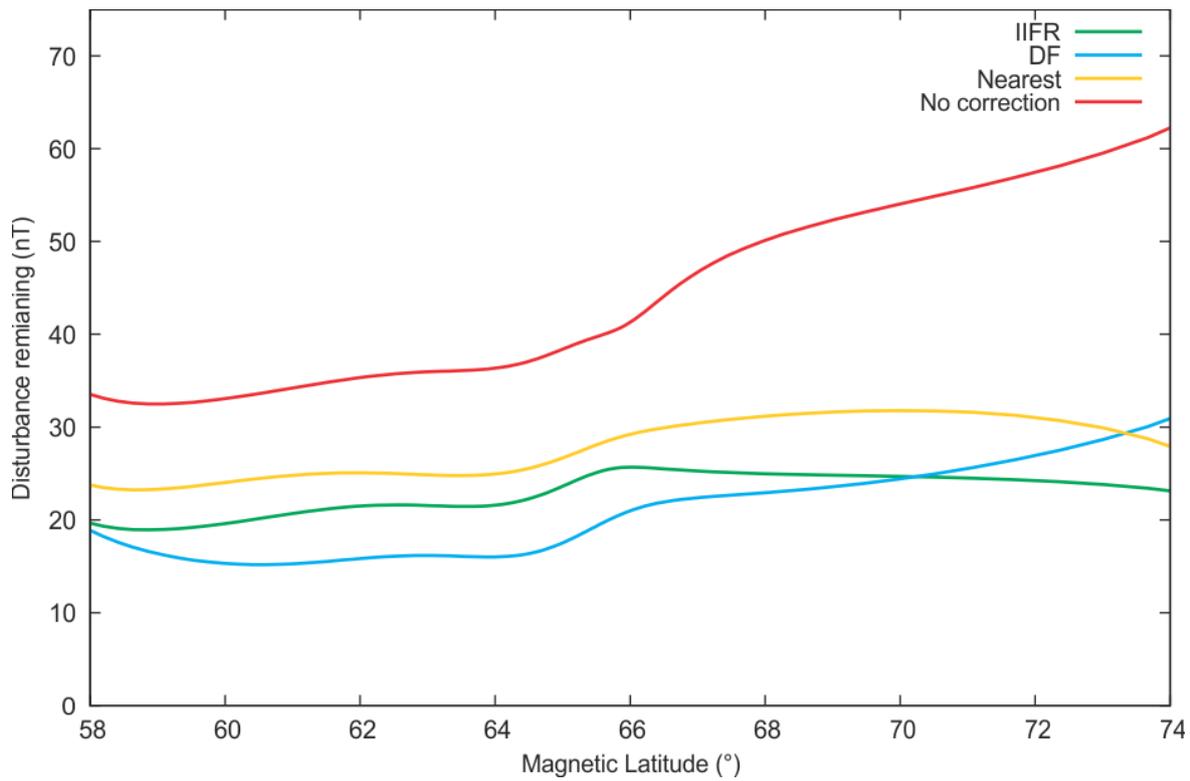


Figure 4.16: 99.7% error percentiles for systematic B_{total} disturbance remaining after corrections

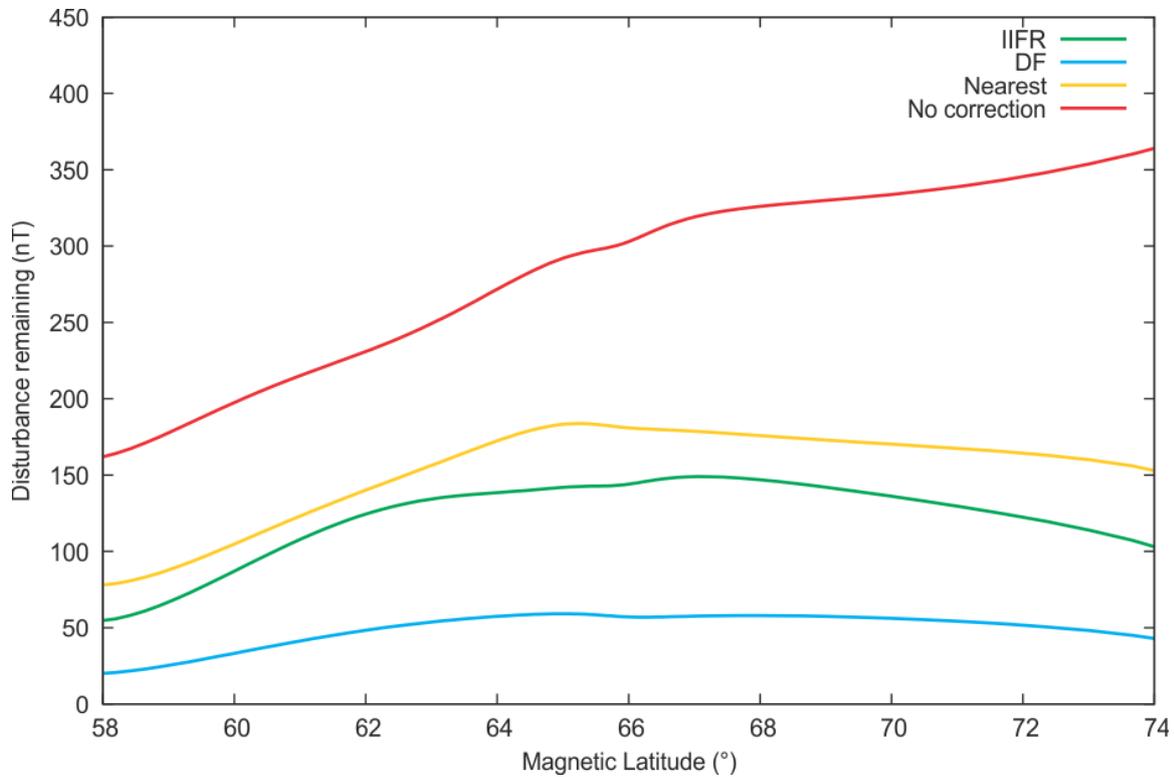


Figure 4.17: 99.7% error percentiles for random B_{total} disturbance remaining after corrections

It is of note that there are auroral electrojet effects visible in the above plots. As the electrojet current traverses east-west, it has different effects on the declination, dip, and total field. Declination disturbance is mostly caused by other effects, thus the bump visible in the uncorrected plot (red) at 65° in Figure 4.13 is fairly small. The largest effect on dip is at the crest of the current, with smaller effects to each side, thus the uncorrected disturbances are quite large around 65 ° in Figure 4.15. For total field, the largest effect is north of the current’s crest, with medium effect south and small effect at the crest. This is illustrated in Figure 4.17 by the larger bumps to either side of the crest.

4.3.7 General Findings

To arrive at representative mean values to be used in specific error models representative for the situation in the Barents Sea, each 99.7th percentile after correction was divided by the corresponding uncorrected 99.7th percentile value and averaged across all triplets involved in the study. Table 4.9 shows the results, along with average RMS values for each metric, which are representative of typical actual measured disturbances. It then multiplies these together to show the worst-case actual disturbance.

Table 4.9: 99.7th percentile error remaining after corrections

		Uncorrected		Nearest Observatory		IIFR		DF	
Error type	Element	99.7p	%	99.7p	%	99.7p	%	99.7p	%
Systematic	Declination	0.166	100	0.126	75.9%	0.112	67.5%	0.071	42.8%
	Dip	0.090	100	0.042	46.7%	0.039	43.3%	0.031	34.4%
	Total Field	38.36	100	26.47	69.0%	22.17	57.8%	17.16	44.7%
Random	Declination	1.042	100	0.463	44.4%	0.364	34.9%	0.221	21.2%
	Dip	0.479	100	0.158	33.0%	0.115	24.0%	0.053	11.1%
	Total Field	284.0	100	172.65	60.8%	130.89	46.1%	54.80	19.3%

This means, for example, that the 99.7th percentile systematic error for declination disturbances after correcting by IIFR is 67.5 % of the corresponding uncorrected error. In other words, compared to no correction, IIFR on average delivers 32.5 % reduction in systematic declination disturbance at the 99.7th percentile.

Because the study was limited to triplets above 50 ° geomagnetic latitude, and due to the density of observatories in Canada, Alaska, and Scandinavia, most station/variometer triplets close enough to be used in this study fall in the same latitude ranges as the Barents Sea, so these averages can be readily applied to the Barents Sea as a whole.

As the results of this study will ultimately be used to make determinations on which disturbance mitigation method to use in particular situations within the Barents Sea, plots are provided illustrating the diminishing effects of each method with distance from the observatories used. Figure 4.18, Figure 4.19, and Figure 4.20 (as in Figure 4.8 at the beginning of this section illustrating the effectiveness of the un-interpolated method on observatory pairs worldwide), represent the percentage of error remaining after application of disturbance function mitigation method.

$$e_r = \frac{d_u}{d_r} * 100\%$$

The percentage of error remaining after correction is e_r , d_u is the uncorrected disturbance at the 99.7 percentile, and d_r is the disturbance remaining after correction, again at the 99.7 percentile. Linear fits are also provided, so that these charts may be used for quick reference for specific locations in the Barents Sea

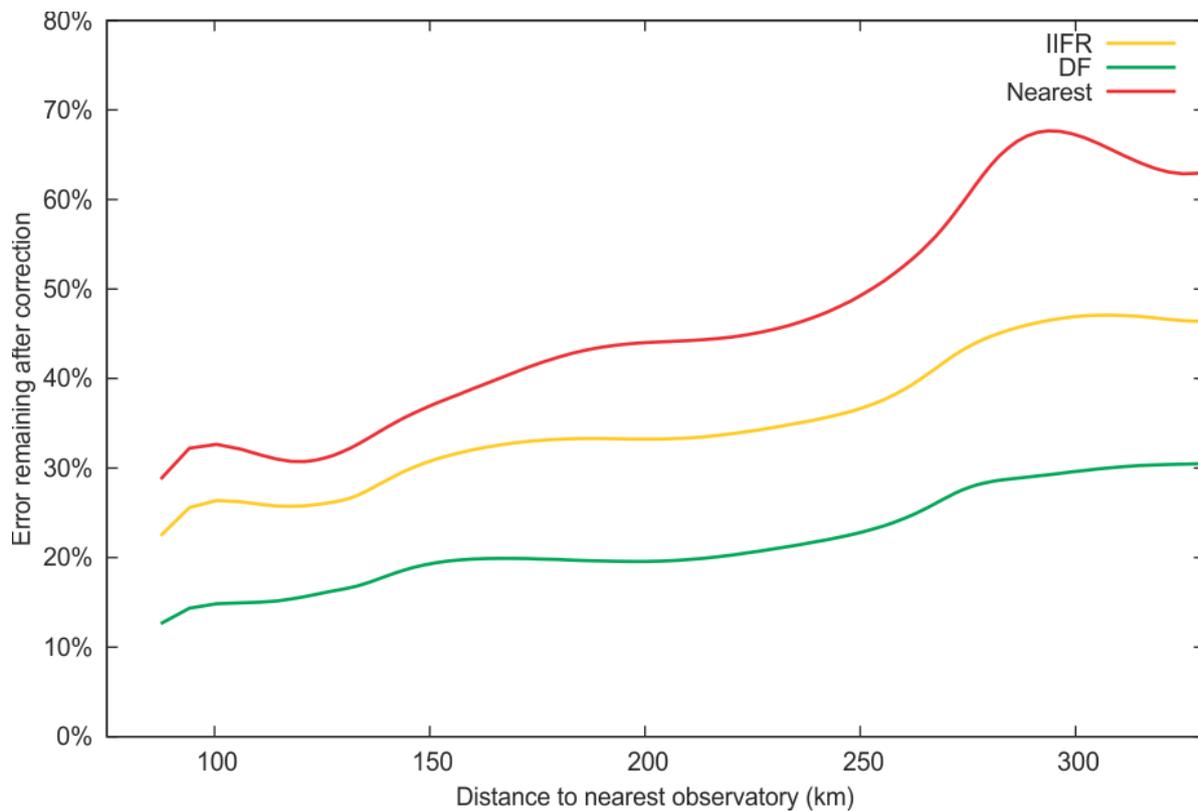


Figure 4.18: Percentage of declination error remaining after correction by both DF and IIFR for varying distances to nearest observatory

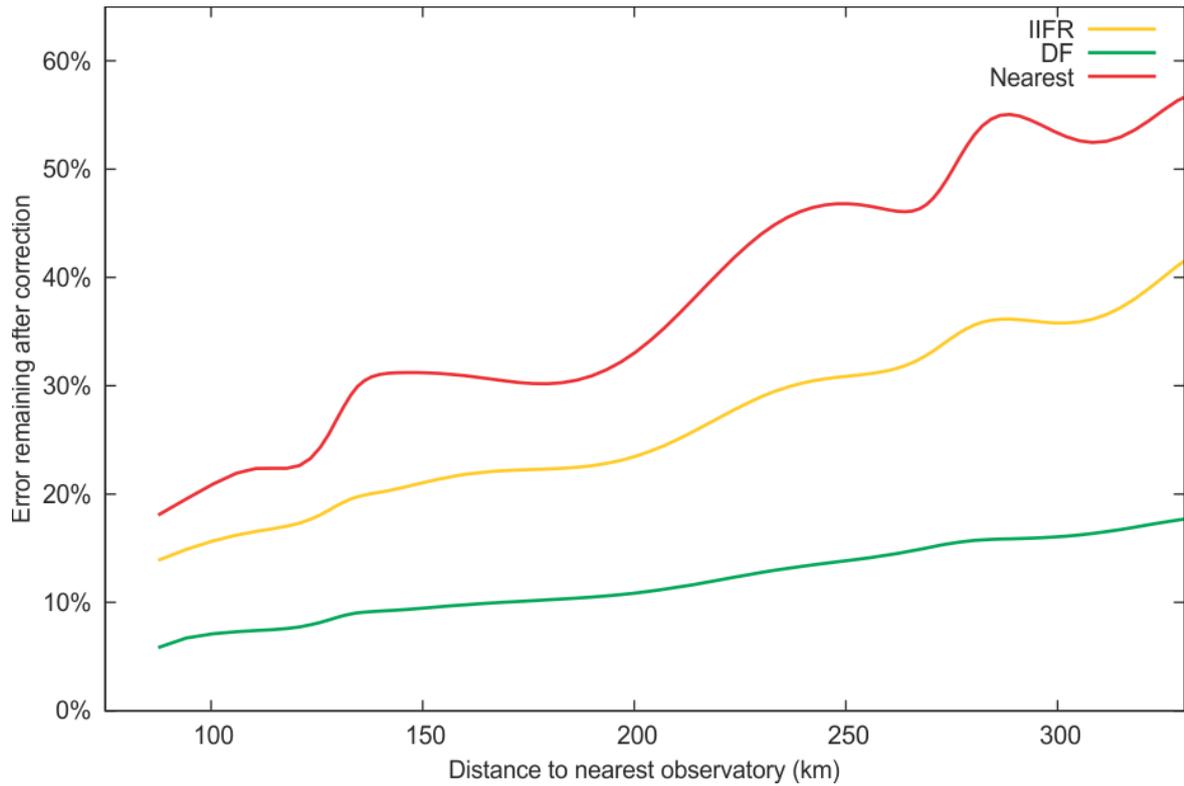


Figure 4.19: Percentage of dip error remaining after correction by both DF and IIFR for varying distances to nearest observatory

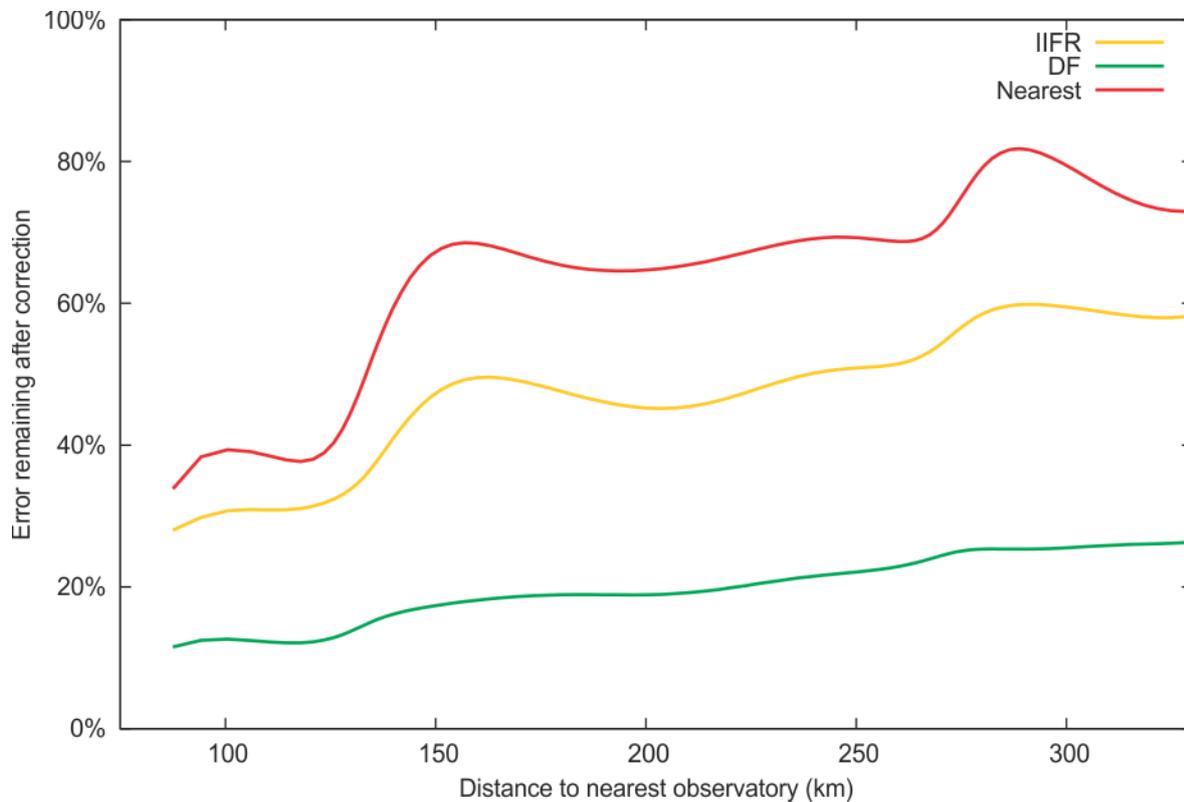


Figure 4.20: Percentage of Btotal error remaining after correction by both DF and IIFR for varying distances to nearest observatory

A heat map of distances to the nearest observatory is provided below in Figure 4.21. For a given drill site location, one can quickly determine the rough distance to the nearest available observatory, and referencing the above plots can give a good idea of the error reduction in each metric for each method at that location.

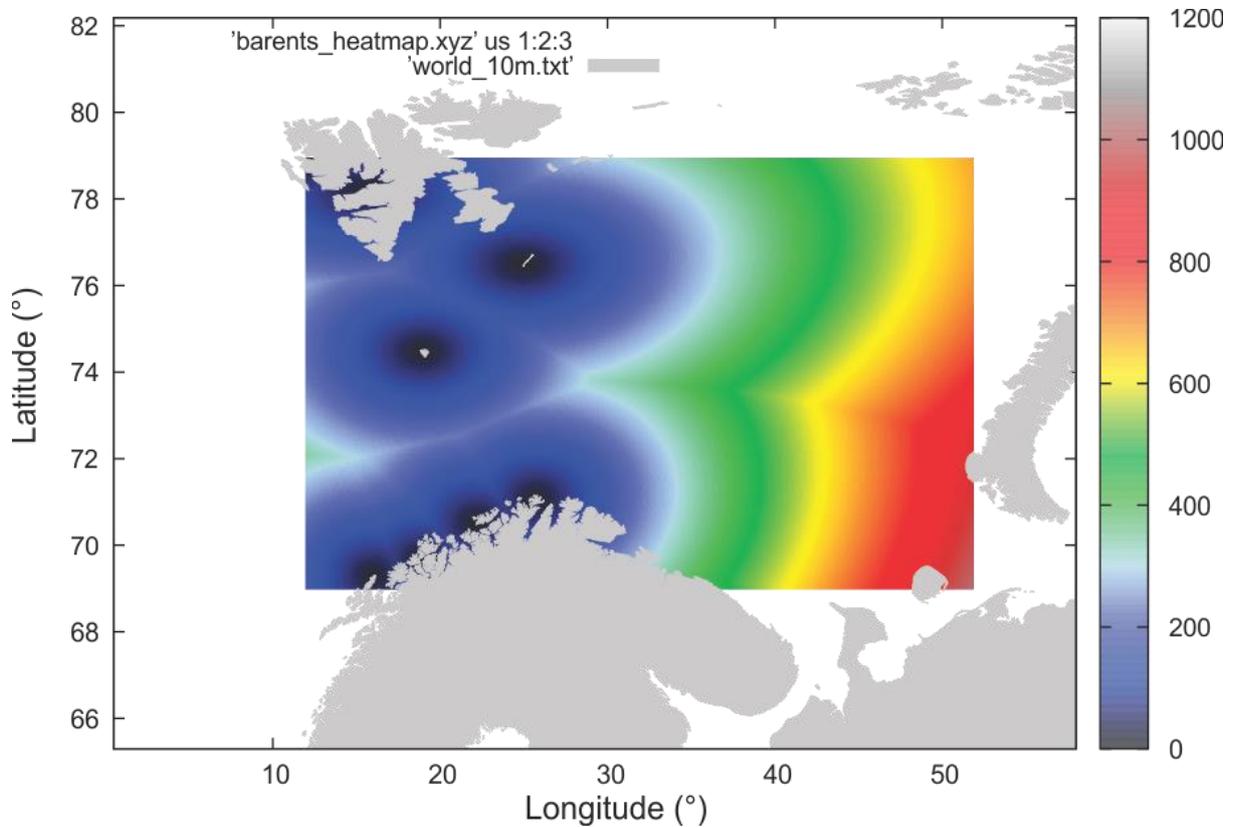


Figure 4.21: Distances to the nearest currently active observatory for locations in the Barents Sea

5. Results and Discussion

5.1 Wellbore Uncertainty in the Barents Sea

Applying the results of the mitigation studies to Barents Sea drilling, wells similar to those typically found in the region are studied. Well position uncertainties, both in the vertical and horizontal directions, calculated based on the results of the studies are shown for such wells with varying levels of surveying performed.

5.1.1 Prototype Well

The amount of uncertainty present in a bottom hole location will depend on both the well profile and the method of surveying used to determine the position. For this study, a set of prototype wells were used matching the profile outlined as ISCWSA NO. 1 in *Williamson 2000*. The well profile consists of a build to 60 degrees, holding a tangent section for 3000 m, a build to horizontal, then an extended reach lateral. This profile is advantageous for this type of study because:

- It is a representative prototype for wells that have been drilled offshore in Norway
- It has been well studied in the context of positional uncertainty evaluation
- It demonstrates a full range of reasonable inclinations for quality control purposes
- It is easily broken into segments if wells of other types want to be studied (e.g. low angle build and hold, or build to horizontal directly from vertical).

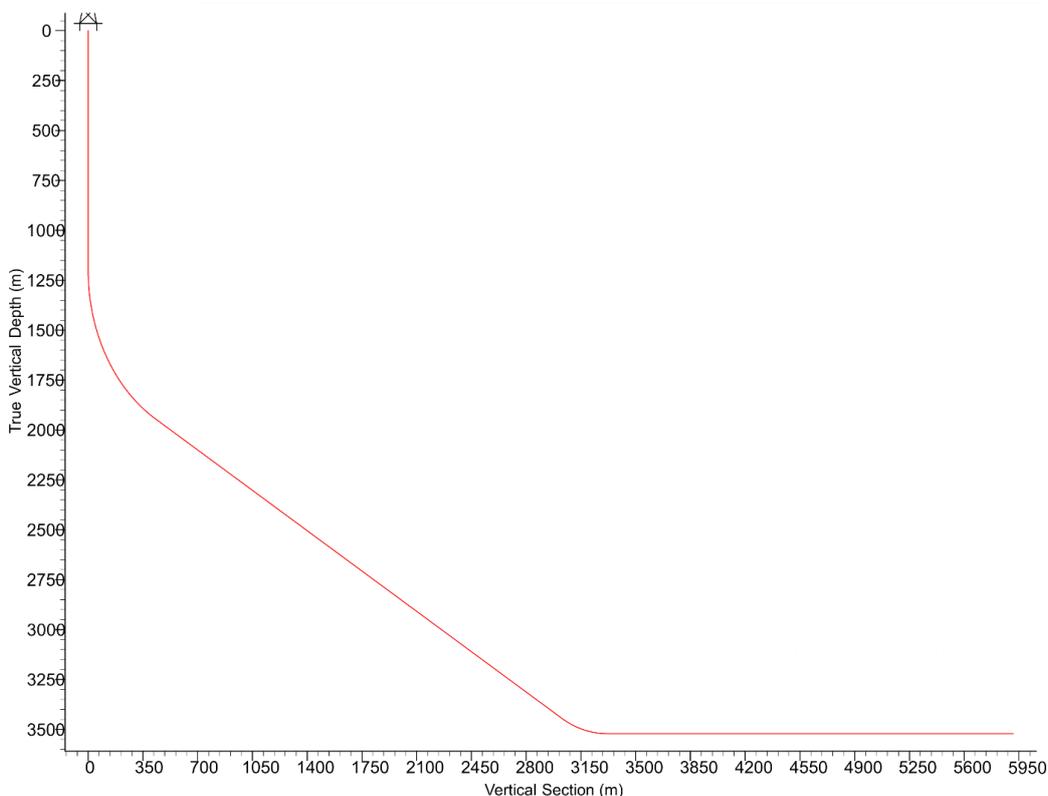


Figure 5.1: Profile of the test wells used in the study

Two alterations were made to the well proposed in *Williamson* to reflect the purposes of this study. These changes were:

- Changing the magnetic reference values used to correspond with those expected in the Barents Sea. This is so that positional uncertainty calculations will reflect the higher magnetic latitude of the proposed Barents Sea drilling. The magnetic reference values used for uncertainty modelling were 55,000 nT Total Magnetic Field Strength, 80 ° Magnetic Dip Angle, and 15 ° Magnetic Declination.
- Plotting several wells over a range of azimuths rather than a single well at a single azimuth. This enables the azimuthal dependence of positional uncertainty to be readily illustrated. For this study, well azimuths ranging in equal intervals from 15 to 135 true azimuth were used for analysis. It should be noted that the azimuth dependency of positional uncertainty will mirror about magnetic East/West, that is a well drilled at 135 ° true azimuth (30 ° south of magnetic east) will have the same lateral uncertainty as a well drilled at 75° true azimuth (30° north of magnetic east). The well at 135 ° true azimuth was included in the study so that this point could be illustrated, and wells with a more southerly trajectory were omitted to avoid redundancy.

5.1.2 Vertical Uncertainty

The calculated true vertical depth of a well is strictly a function of the measured survey depth (length of pipe downhole) and the measured inclinations. A minimum curvature calculation is performed between each pair of surveys. For two given inclinations with a known curve length between them, a constant-radius curve can be fit, and the change in vertical depth can be found. Because measured depth does not have error associated (an operator knows exactly how much pipe has been fed downhole), the only way vertical uncertainty may arise is through inaccurate inclination. The inclination measurement coming solely from the accelerometers in the MWD sensor has far fewer potential sources of error than the azimuth measurement, which employs both the accelerometers and magnetometers.

Assuming proper procedure is followed and a well-calibrated instrument is used, the measurement of tool deflection from vertical should be robust and accurate. The dominant errors when determining inclination come from the physical misalignment of the surveying instrument with the borehole. Sagging of the bottom hole assembly due to gravity can cause large systematic misalignments between the MWD sensor and the well path, as shown above in Figure 2.2. These misalignments are expected to grow as more inclination is built in the hole.

Table 5.1: Vertical uncertainty with and without sag correction (calculated at 3-sigma)

Well Section	Measured Depth	Standard Vertical Uncertainty	Sag Corrected Vertical Uncertainty
First Kick Off Point	1200 m	± 2.4m	± 2.4m
End of Build (60° inc)	2100 m	± 5.6m	± 4.8m
End of Tangent	5100 m	± 32.4m	± 21.6m
Landing Point	5400 m	± 35.6m	± 23.4m
Well TD	8000 m	± 64.9m	± 39.2m

For an extended reach lateral well, sag is the single largest source of vertical uncertainty. This is true of wells surveyed with MWD regardless of geographic location and is not a problem unique to the Barents Sea. This error can be significantly reduced by performing analysis on the bottom hole assembly and compensating for expected misalignments between the sensor package and the borehole. The difference between the expected uncertainties before and after compensating for sag can be found in Table 5.1. The vertical uncertainties described in Table 5.1 are independent of azimuth and will be the same for all test wells in this study. Given that the analysis required for sag compensation does not require any special equipment or additional drilling time, there is virtually no downside to including sag corrections in the wellbore positioning process.

5.1.3 Lateral Uncertainty

In general, deviated wellbores surveyed with magnetic MWD survey sensors will have a larger uncertainty in the lateral direction than the vertical direction. This is because there are multiple large errors that can affect a magnetic survey that exist outside of the surveying sensor itself. Error in the magnetic reference and axial magnetic interference from the drillstring are the two largest contributors of lateral uncertainty and given that they are not sensor-related, they cannot be removed through sensor calibration or by replacing the MWD with more accurate instrument.

Declination is a value that is added to the magnetic reading to correct the azimuth from a magnetic north direction to a true north direction. There is no way to internally measure this value downhole with an MWD instrument, instead it must be calculated from a reference model. Any error in that reference model will therefore contribute directly to azimuth error in a 1-to-1 fashion. To reduce the uncertainty from magnetic declination error, a more accurate model must be used for calculating the reference values. There are a range of considerations that must be accounted for when choosing a magnetic model. Some models of the global main are freely available and updated every 5 years (IGRF and WMM), however it should be noted that these models are not designed with directional drilling and wellbore positioning in mind.

Annually updated models of the main field (Standard Definition Models) and long wavelength crustal field (High Resolution Models) are available for use with directional drilling and reduce both the errors due to both secular variation and crustal fields. Much like sag corrections, applying these higher accuracy models requires no additional

equipment or rig time which has led to their wide adoption across the industry. Hence, for the base case in this study wells are modelled using the MWD+HRGM+SAG tool code, representative of a well drilled using an MWD sensor and an annually updated global high-resolution geomagnetic model. Lateral Uncertainties for the test trajectories using the high-resolution geomagnetic reference model can be found in Table 5.2.

Further reduction of the error in declination can be achieved by taking local magnetic measurements and building a high-accuracy model of the crustal field in the area drilling will take place. This process known as In-Field Referencing type 1 (IFR1) can greatly reduce the lateral uncertainty in the wellbore, particularly in the North/South direction. The improvements from IFR1 are less apparent when drilling East/West, not because the corrections are less valid, but instead because axial interference contributes a greater portion of the overall error. Table 5.3 shows the lateral uncertainties for the test well trajectories if a crustal field model meeting industry standard accuracy levels is used to compute the reference declination. A spider plot showing the top-down view of both sets of trajectories is shown in Figure 5.2.

Table 5.2: Lateral uncertainty with MWD+HRGM+SAG (calculated at 3-sigma)

Well Section	Measured Depth	Lateral Uncertainty for each well direction				
		15° azi	45° azi	75° azi	105° azi	135° azi
Kick Off Point	1200 m	± 6.4m	± 6.4m	± 6.4m	± 6.4m	± 6.4m
End of Build	2100 m	± 18.6m	± 21.1m	± 24.9m	± 27.1m	± 24.9m
End of Tangent	5100 m	± 115.13m	± 151.9m	± 190.2m	± 212.1m	± 190.2m
Landing Point	5400 m	± 126.1m	± 160.8m	± 209.3m	± 233.5m	± 209.3m
Well TD	8000 m	± 226.6m	± 293.0m	± 385.4m	± 431.5m	± 385.4m

Table 5.3: Lateral uncertainty with MWD+IFR1+SAG (calculated at 3-sigma)

Well Section	Measured Depth	Lateral Uncertainty for each well direction				
		15° azi	45° azi	75° azi	105° azi	135° azi
Kick Off Point	1200 m	± 6.4m	± 6.4m	± 6.4m	± 6.4m	± 6.4m
End of Build	2100 m	± 15.2m	± 18.2m	± 22.9m	± 24.9m	± 22.9m
End of Tangent	5100 m	± 86.6m	± 125.3m	± 178.1m	± 198.1m	± 178.1m
Landing Point	5400 m	± 94.9m	± 137.8m	± 196.4m	± 218.2m	± 196.4m
Well TD	8000 m	± 171.5m	± 252.8m	± 362.9m	± 405.2m	± 362.9m

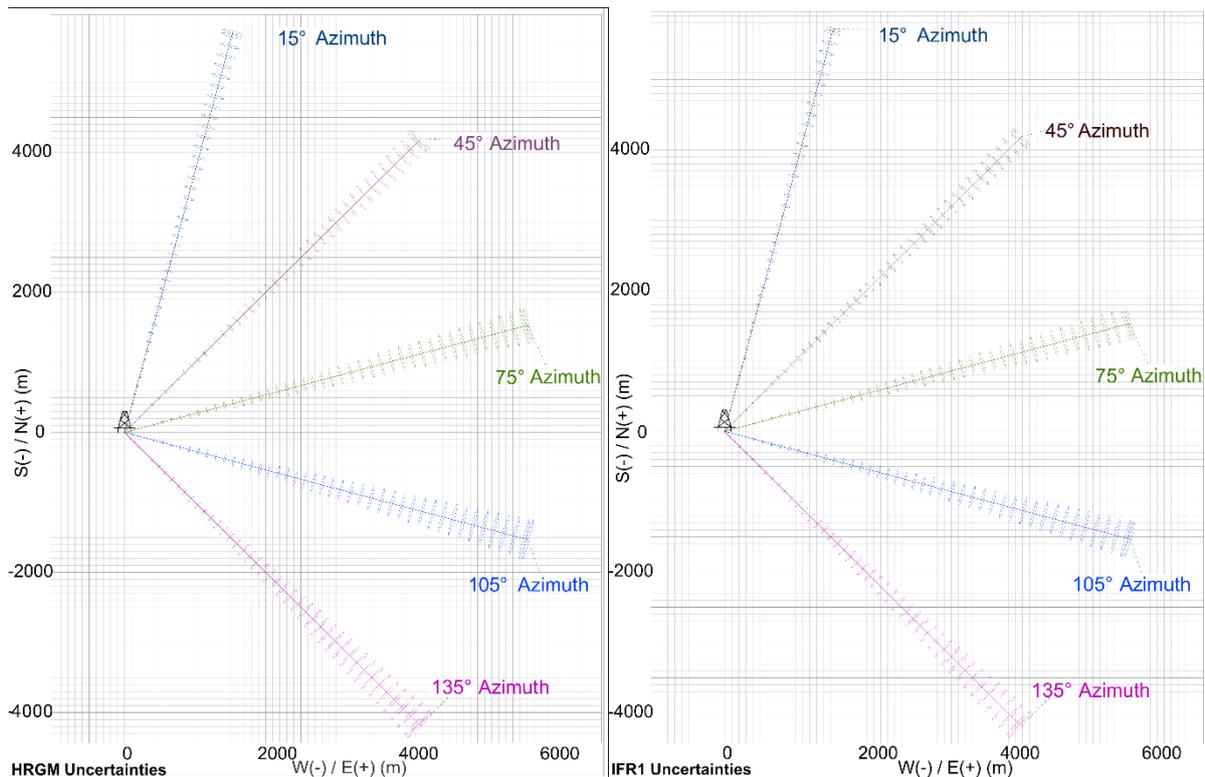


Figure 5.2: Plan view depiction of test wells with uncertainties from a High-resolution geomagnetic model and type 1 In-field referencing (calculated at 3-sigma)

The presence of magnetic components in the bottom hole assembly will create an effective bias on the axial magnetometer in the MWD sensor. The amount of azimuth error this causes is directly related to the inclination and azimuth of the wellbore. In particular, the closer to horizontal East/West a well is being drilled, the greater the impact of the axial bias on the azimuth.

If there is sufficient change in the wellbore orientation, there are methods to estimate this axial bias and correct for it while the well is being drilled. This process, known as multi-station analysis, can yield a significant reduction in wellbore uncertainty if properly applied. A prerequisite for applying a multi-station solution is having an accurate magnetic reference for the total magnetic field strength and the magnetic dip angle. For drilling operations at low latitudes, it is typically sufficient to have a crustal field model (IFR1) to use multi-station analysis techniques. At the high latitudes like those proposed in the Barents Sea, the magnetic disturbance field is a confounding factor when attempting to apply multi-station analysis. The details of why this is so are presented in greater detail in the next section.

For the purposes of analyzing possible uncertainty reductions, the multi-station analysis solution was modelled only if a real-time disturbance field correction was also being performed (In-Field Referencing type 2, or IFR2). Table 5.4 outlines the uncertainty reductions that can be achieved given that both IFR2 and multi-station analysis are performed on the dataset. Figure 5.3 shows a graphical comparison of these uncertainties relative to those provided by only an IFR1 correction. As would be

expected from how axial bias impacts surveys, the greatest benefit from multi-station analysis comes when drilling closer to magnetic East/West.

Table 5.4: Lateral uncertainty with MWD+IFR2+MS+SAG (calculated at 3-sigma)

Well Section	Measured Depth	Lateral Uncertainty for each well direction				
		15° azi	45° azi	75° azi	105° azi	135° azi
Kick Off Point	1200 m	± 6.4m	± 6.4m	± 6.4m	± 6.4m	± 6.4m
End of Build	2100 m	± 12.4m	± 13.3m	± 14.9m	± 15.8m	± 14.9m
End of Tangent	5100 m	± 57.3m	± 71.1m	± 90.7m	± 100.7m	± 90.7m
Landing Point	5400 m	± 62.5m	± 77.8m	± 99.4m	± 110.5m	± 99.4m
Well TD	8000 m	± 111.1m	± 139.5m	± 179.6m	± 200.1m	± 179.6m

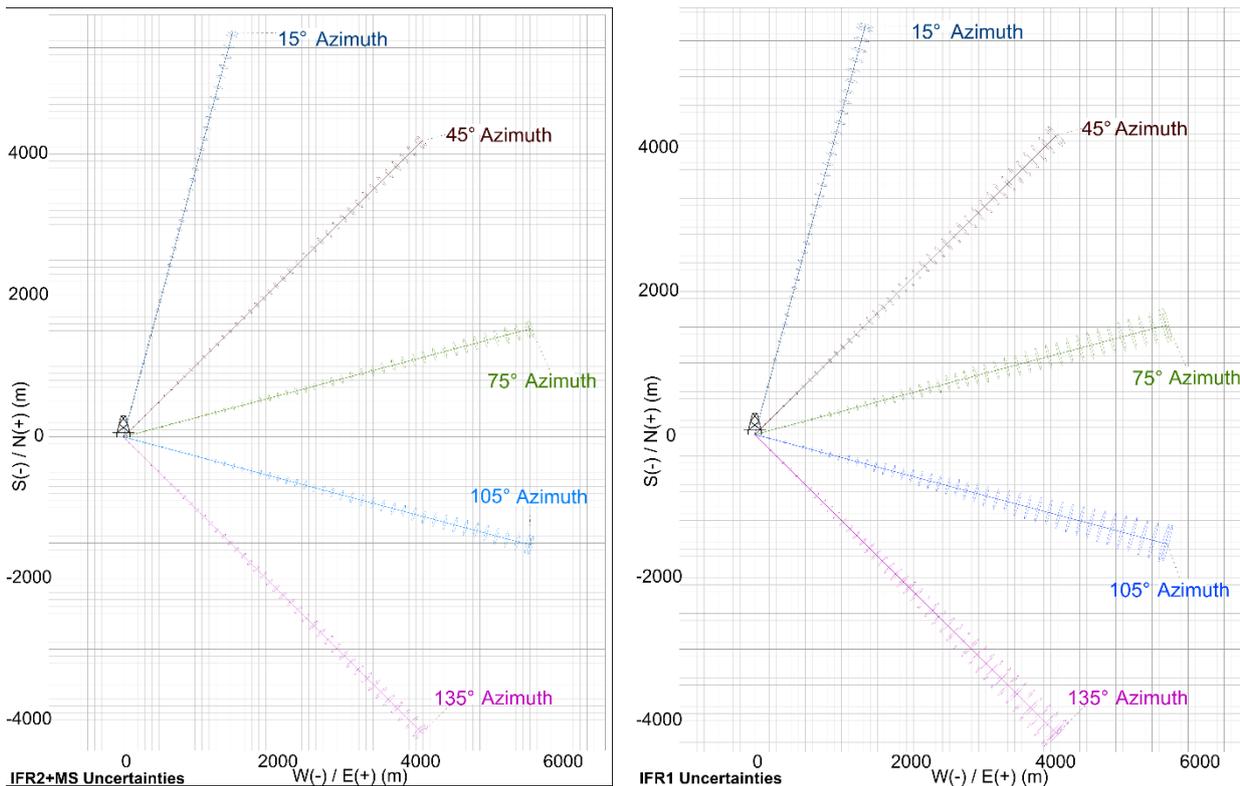


Figure 5.3: Plan view depiction of test wells with uncertainties from a type 1 In-field referencing and type 2 In-field referencing with multi-station analysis (calculated at 3-sigma)

5.1.4 Uncertainty Reduction Considerations

The required level of uncertainty reduction is often driven by many factors. Some of these are economically motivated, such as the amount of production that will be lost if a geologic target is missed, or the ability to accurately drill numerous wells in proximity to maximize the amount of hydrocarbon that can be produced from an asset. These decisions are subject to any number of business considerations that will be operator specific and will not be touched upon further in this document. Other uncertainty reduction considerations are safety related, in particular the ability to successfully drill a relief well in the event there is a loss of well control. This worst case scenario has several aspects that must be considered regardless of the other reasons one may want to improve the accuracy of the well position.

When drilling a relief well, a new hole is spudded in a safe distance away from the original surface location which is then directed toward the original well path. Once the relief well is close enough to the original hole, well-to-well ranging technologies are used to precisely determine their positions relative to each other. By directing the new well into the old well path, communication of drilling fluids can be established, and a high-density mud can be pumped into the old hole regaining control of the well. The success of this operation depends on several key factors:

- How deep the original hole is cased (to identify via ranging)
- The accuracy of the original hole position (to drill at with the relief well)
- The accuracy of the relief well position (to enable accurate steering)

For the purposes of this study, it will be assumed that the relief well is of a similar style and trajectory as the original well, and therefore has a similar positional uncertainty associated with it. This is a reasonable assumption, as well intercept trajectories strive to be near parallel to the original wellbore at the point of interception, thus maximizing the length across which the intercept may occur. Given that the interception must occur above the most recent casing point, it is assumed that this would take place somewhere along the tangent section (2100-5100m) in the test trajectories. Finally, when dealing with the uncertainty in the relative position of two wells, it is necessary to add their respective uncertainties in quadrature, effectively increasing the uncertainty by 40 % over the original amount. Using those assumptions, Table 5.5 shows the average combined uncertainties expected along the tangent section of the test trajectories for each of the magnetic surveying methods mentioned.

Table 5.5: Estimated average relative uncertainties between a relief well and a target well drilled parallel along the tangent (calculated at 3-sigma)

Survey Type	Average combined uncertainty along tangent				
	15° azi	45° azi	75° azi	105° azi	135° azi
HRGM	± 94.6m	± 122.3m	± 152.1m	± 169.1m	± 152.1m
IFR1	± 72.0m	± 101.5m	± 142.1m	± 157.7m	± 142.1m
IFR2+MS	± 49.3m	± 59.7m	± 74.7m	± 82.4m	± 74.7m

Magnetic ranging methods are divided into two types – active and passive systems. Active magnetic systems require pulling the drill string from the hole so that a wireline instrument may be lowered into the well and used to detect the offset casing. Passive systems use measurements taken from the MWD system to estimate the distance of an offset well. The trade-off between the two systems is time vs. capability. Performing surveys for a passive ranging run may only require an hour of off-bottom time for a drilling operation, while a full active ranging run may require multiple days. The stated capabilities of both passive and active ranging will vary depending on conditions and provided, but typical detection ranges are on the order of 25 m for passive systems and 50 m for active systems.

It should be noted that these ranges are generally lower than the estimated relative uncertainties modelled in the ranging scenario above. There are several techniques that may be employed to augment the capabilities of the ranging tools in the relief well scenario. The first is known as a “fly-by” drilling pass. In this scenario, a relief well is initially drilled at a high angle of incidence toward the target well at a point much earlier than intended intercept point. The uncertainty of the wells is low enough to establish ranging contact and reduce the relative uncertainty in the wells to a manageable level. After establishing ranging contact, the original well is then sidetracked so that the interception operations can continue. This technique is time-consuming, however may be necessary in cases where the relative uncertainty at the intercept location is significantly greater than the ranging distance. In these cases, such as the uncertainties modelled for the HRGM method and for the IFR1 scenarios near magnetic East/West, there is a high probability that a direct intercept will not succeed.

A second method known as “sweeping” involves drilling the relief well at a slightly higher angle of incidence to the target until ranging contact is made. This technique takes advantage of the fact that uncertainty is concentrated primarily along one axis, so a side-to-side “sweep” of that axis increases the probability that ranging contact is made at some point in the operation, rather than at a single specific point. This technique is inherently limited by the ability to steer the relief well relative to the target across the intercept window while maintaining a trajectory that can still successfully intercept the target well. As a result, it is generally only used once the relative uncertainty between the two wellbores is already at an acceptably low level. In practice, a combination of both techniques may be used on a relief well intercept operation.

5.2 Effects of Inaccurate Geomagnetic Referencing

Real-time quality control of MWD surveys is an important step in ensuring that pre-job risk assumptions related to wellbore positioning are met. This is crucial for maximizing the potential for economic viability (hitting the geological target), minimizing the possibility of wellbore collision, and deployment of mitigating actions (drilling a relief well) in the event of a loss of well control. The orientation measurements (inclination and azimuth) from any surveying instrument can only be verified directly by running an additional surveying instrument and comparing the results.

In most drilling applications, this type of verification is unnecessarily burdensome and may expose the operation to additional risk (rigging up a wireline, limiting the rig’s ability to circulate or rotate the drillstring, etc.). Instead, for magnetic measurement while

drilling tools, it is possible to perform an interval validation of the instrument by analyzing a secondary set of orientation-independent measurements. This typically involves a direct measurement of the local magnetic field strength, the local gravitational acceleration, and the magnetic field dip angle. These readings can be produced at every survey station along with an inclination and azimuth and as long as these readings match the theoretical expectations to within a tolerance, there is no reason to believe that the surveying instrument is operating outside of the expectations made prior to commencing drilling. The quality of this verification process will correspond directly to the extent with which the reference field values are known, and the extent to which the dominant error sources on inclination and azimuth are observable in the survey data. Survey Quality Tolerances can be calculated based on the assumptions made in the error model chosen prior to beginning drilling.

5.2.1 Dominant Errors and Directional Dependence in MWD Surveying

Industry standard instrument performance models for MWD surveying tools list more than twenty different error sources that are expected to impact a survey even assuming all standard practices are correctly applied. Despite the large number of potential error sources, for a particular survey set the majority of the survey error (both in terms of positional uncertainty and with respect to survey quality control) will come from only a handful of the error terms. The most common large survey errors are:

- Error in the geomagnetic reference model
- Axial magnetometer bias from drillstring interference
- Alignment error between the bottom hole assembly and the wellbore (sag)

Of these three error sources, only the first two can be detected through internal quality control measures. Geomagnetic reference error is caused by source external to the surveying assembly, and therefore has no directional dependence in how it impacts either survey azimuth or survey quality control. On the other hand, drillstring interference is aligned with the bottom hole assembly and will exhibit a strong directional dependency both in how it manifests in survey acceptance criteria and in how it will corrupt the measured azimuth. Due to this, proper quality control of an MWD survey must consider the wellbore orientation, and the expected effects of drillstring interference to assure that the assumptions made in the positional uncertainty model have been met (Ekseth et al., 2006a, 2006b).

Drillstring interference behaves in a fashion identical to a sensor bias in the axial MWD magnetometer. When evaluating how an MWD survey deviates from the reference magnetic model, this means that magnetic field errors are expected to be larger in the direction being drilled. This directional dependency creates a covariance between acceptable level of errors in total magnetic field and dip. For example, when drilling vertically, drillstring interference will create a positive correlation between field strength and dip, because any vertical addition to the field magnitude would also deflect the field vector downward, increasing the dip angle. A survey exhibiting a higher than reference field strength coupled with a higher than reference dip is more likely to be an acceptable survey than one that shows an inverse relationship, because vertical interference (aligned with the drilling direction) is expected to be stronger than horizontal interference (perpendicular to the drillstring). Similar relationships for other error

sources can be derived, but in practice the impact of drillstring interference creates the largest directional dependence. The charts in Figure 5.4 show a model of how drillstring interference at the 1-sigma level for the MWD standard error model (220 nT) is expected to impact the total magnetic field and dip measurements for each of the example wells.

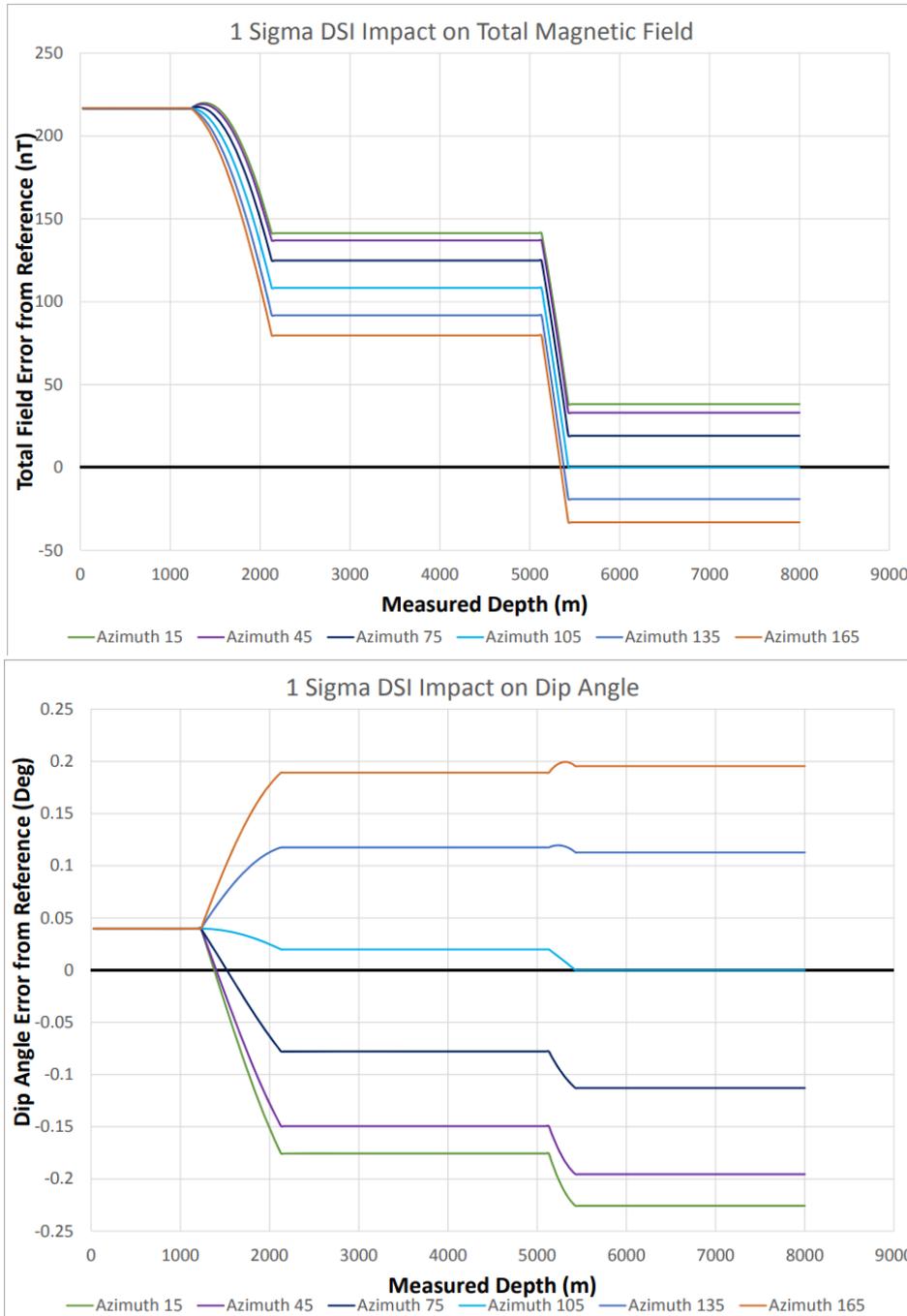


Figure 5.4: Errors in measured magnetic field strength and dip angle caused by 220 nT of axial magnetic interference

From a practical perspective this creates three "zones" of survey quality depending on how well the survey values correspond to the reference: "green" surveys are of such high quality that there is no need to assess the covariance between quality parameters to validate the positional uncertainty model; "red" surveys have one or more parameters that are so far removed from reference that they will not meet model assumptions; in between those are "orange" surveys, where it is necessary to look at the correlations between errors to determine whether or not a survey is meeting expectations. Quality control plots are shown below demonstrating these various zones at a 3-sigma level of total field strength and dip for two of the example wells, one at a 15 ° azimuth and one at a 75 ° azimuth.

The trends in these field acceptance criteria closely follow those of the modelled drillstring interference from Figure 5.5. In the case of the 15 ° azimuth well, a large shift in dip may be observed as the drillstring orientation changed from being aligned with the vertical magnetic field to being in line with the horizontal magnetic field. For the 75 ° azimuth well this effect is much smaller because the interference will not be aligned with the magnetic field. When drilling closer to magnetic East/West the error from drillstring interference contributes to azimuth rather than magnetic dip angle.

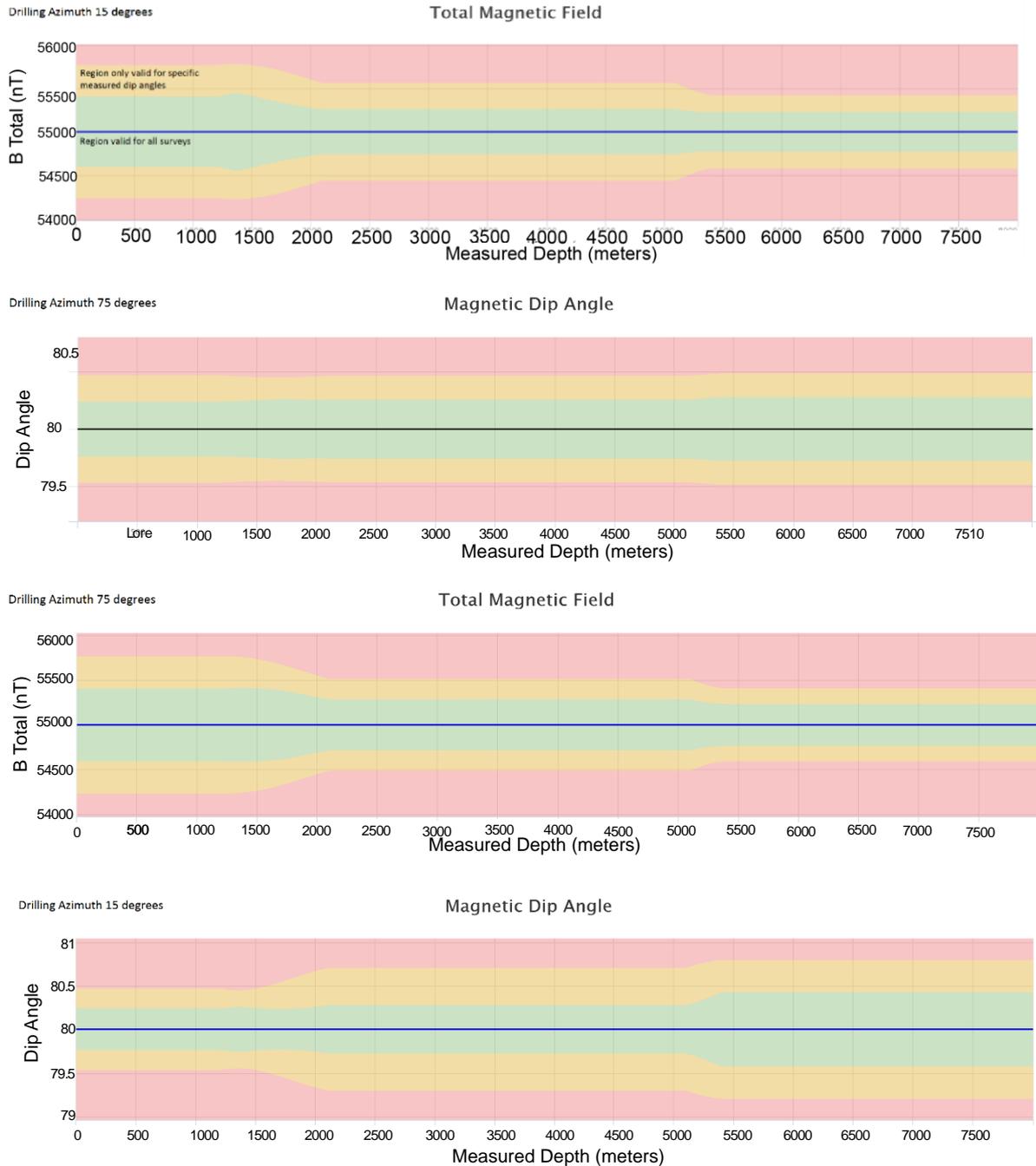


Figure 5.5: Field acceptance criteria for total magnetic field and dip angle on two example wells

A public web API (<http://fac-api.magvar.com>) and calculator (<http://fac.magvar.com>) are being provided by MagVAR, which implements dynamic quality control for the ISCWSA OWSG Rev-2 error model tool codes. Users can upload MWD surveys and receive the relevant QC information for the selected tool code. Apart from the sigma-distance indicating pass or failure of the survey, the API also returns the random and systematic uncertainties in the measured inclination and azimuth taking the location and wellbore orientation into account. The API enables single queries via a web interface, as well as programmatic access by user software. This API and calculator

was presented at the 46th General Meeting of the ISCWSA in San Antonio (Maus et al., 2017).

The use of 3 "zones" in qualifying an MWD survey leads to potential ambiguities that are generally considered undesirable. Instead a mathematical transform can be performed that directly incorporates the covariances of the quality control parameters and assigns each survey a relative error (known as the Mahalanobis distance) from the expected reference.

The Mahalanobis distance can be thought of similar to the sigma level used in pre-drill planning operations, and as such is often referred to as a "sigma" qualifier for a given survey. Computing a sigma for each survey removes the ambiguous area where it is unclear if a certain quality control parameter is inside or outside of specification. Additionally, the pass/fail criterion for sigma is completely independent of wellbore orientation, positional uncertainty model, and geographic location. The downside of using a sigma distance is that the mathematical process for reproducing it by hand is arduous, but in the modern age of ubiquitous microprocessors this is rarely an issue. An example of a sigma quality control plot is shown in Figure 5.6, and would be identical for all of the test wells used in this study.

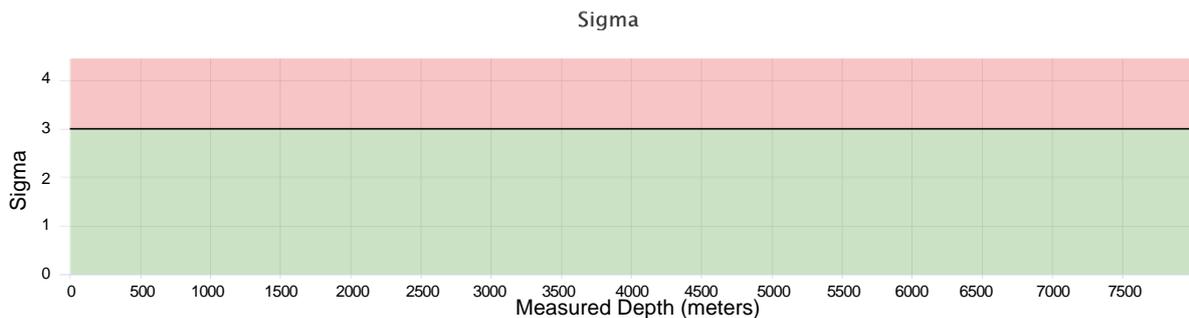


Figure 5.6: Field acceptance criteria for total magnetic field and dip angle on two example wells

Using the single sigma criterion for qualifying a survey allows for the statistical qualification of any survey set using an identical metric that can be computed using a standard chi-squared table. For the case of evaluating whether a survey fails the assumptions of an error model, a probability can be derived using 3 degrees of freedom (Total Gravity, Total Magnetic Field, and Dip Angle) a 3-sigma confidence level (critical value of $32 = 9$). Solving for this gives a cumulative chi-squared probability of 0.97, meaning that a survey set should be rejected if more than 3 % of the surveys fall outside of a sigma distance 3 from reference. This type of survey qualification removes any ambiguity that may arise from orientation change, reference model quality, or survey corrections that have been applied.

5.2.2 Drillstring Interference Observability and Survey Corrections

As drillstring interference is one of the largest contributors toward positional uncertainty for wellbores surveys with MWD instruments, the ability to observe its magnitude is vital toward proper quality control of the bottom hole position. Once the level of drillstring interference has been estimated, it is only natural to attempt to correct the

survey by removing that effect. This process forms the basis for both single station and multi-station survey corrections.

Drillstring interference can be identified through several means. The first, and simplest, method involves estimating the interference by looking at the error of a survey station from the reference values. This has appeal because it can be done on a dataset as small as one point, and this forms the basis of single-station axial magnetic interference corrections (also known as short-collar corrections). The quality of this estimation, and in turn the correction, will be heavily dependent on wellbore orientation. As shown in Figure 5.4 for some wellbore orientations, there are certain combinations of inclination and azimuth where this is only a minimum level of error in both total magnetic field and dip angle.

In particular, when drilling in the horizontal East/West direction, where azimuth error from drillstring interference is the most, this method may over- or under-estimate the amount of error present in a survey. The presence of any errors not aligned with the borehole axis (such as cross-axis sensor biases or geomagnetic reference field errors) will violate the assumptions of the corrections and add errors to the survey azimuth. As a result, this single-point method is not recommended in cases where more sophisticated techniques can be readily applied.

The most powerful method of identifying drillstring interference from downhole survey data comes from analyzing a set of data for both deviation from reference values and also change in reference values with respect to changing instrument orientation. This technique, known as multi-station analysis, is capable of identifying a wide range of sensor errors including drillstring interference. Referring back to Figure 5.4, there are distinct transitions in measurement error level across each of the build sections in each test wellbore. When analyzing a survey set, these transition intervals are especially useful for estimating survey errors due to drillstring interference. Achieving a stable multi-station solution may require upwards of 10 to 20 surveys to be taken at a range of orientations. For magnetic surveying applications where accuracy is of high-importance, multi-station analysis has become a de facto standard when processing downhole data.

5.2.3 Ensuring the Quality of Multi-Station Analysis

Multi-station analysis can be a powerful tool for ensuring MWD survey quality, however achieving a high-accuracy correction requires certain fundamental criteria be met:

- Errors in the MWD sensors must be constant or near constant throughout the run
- Orientation change in the survey set should be maximized to the greatest extent practicable
- Error in the geomagnetic reference should be minimized to the greatest extent practicable

The first criterion can be met by choosing a survey provider with appropriate standard operating procedures in place to ensure survey quality. These procedures should cover

tool calibration requirements, pre- and post-job instrument verification, and proper monitoring of shock and vibration during the drilling process. Real-time monitoring of shock and vibration, along with rigorous calibration and tool qualification procedures are practices that have been widely adopted by virtually all major MWD surveying providers.

One of the biggest potential limitations for multi-station analysis is that its solutions may be limited by a lack of orientation change in a wellbore. For the extreme case of drilling a straight section, the drillstring interference estimate may not be much better than that of a single station correction. This limitation can be mitigated with proper planning and the addition of checkshot surveys. Checkshot surveys are additional measurements taken higher in the wellbore than the current drilling section, ideally at a known inclination and azimuth.

In the case of the example trajectories used in this study, surveys from the vertical and initial build section could be used to improve the quality of the corrections in the tangent interval and surveys from the tangent and second build should be used to augment the correction for the extended reach lateral. Checkshots must be taken in a portion of the wellbore that is free from external magnetic interference, so the presence of a casing shoe will limit the possible locations for checkshots. If possible, consideration should be given to casing points and build sections so that there is a significant variation in the open hole that is available for taking checkshots prior to drilling straight sections. This is of particular importance in East/West laterals where there is little to no magnetic observability of drillstring interference.

Geomagnetic reference error primarily comes from two different sources: crustal anomalies in the local geology where drilling is taking place, and solar disturbances that occur during the drilling process. How each of these errors impacts the survey qualification and correction process is different, but both can have significant impacts if not accounted for. Crustal anomalies will cause systematic offsets in the magnetic measurements relative to the modelled reference values, not unlike the effect of drillstring interference when drilling a straight section of the wellbore. This can lead to the improper estimation of drillstring interference when using either single or multi-station analysis techniques. These errors in drillstring interference estimation may in turn cause correction-induced systematic azimuth error in the survey set.

The solar disturbance field is unpredictable over the long term and has the overall effect of adding systematic and random noise to the survey measurements. Any disturbance field features that persist over several days, such as those due to the magnetospheric ring current, will create systematic errors in uncorrected survey data. Here we considered periods of 3 days and longer as systematic and all shorter period disturbances as random errors. The systematic solar disturbances cause wellbore positioning errors which do not average out to zero over the period of drilling. The detrimental effect of such systematic errors was already mentioned in a study of Edvardson, 2013.

In addition, the random variation of the magnetic field can have a number of indirect effects that complicate standard wellbore surveying workflows. At high magnetic latitudes, the random fluctuations in total magnetic field strength and magnetic dip

angle can be as large or larger as the deviations induced by other surveying error sources such as drillstring interference. The presence of this external noise can lead to the statistical rejection of a survey set that otherwise should have passed.

5.2.4 Reference Error Simulations

To demonstrate the impact of reference errors, a set of 5 example wells were modelled with 250 nT of drillstring interference applied to the 45 ° azimuth test trajectory. To provide the greatest amount of orientation change possible these trajectories were treated as though they had been drilling in a single run, even though in practice this would not be the case. These simulated wells had offsets and noise added to them corresponding to the expected distributions for the crustal anomalies and solar disturbance expected in the Barents Sea, as derived from observatory magnetic measurements in the prior section.

The resulting survey sets were then corrected using multi-station analysis, then had both the raw and corrected surveys evaluated against the sigma criterion to see whether they would statistically be accepted or rejected. An example of the raw survey quality control measurements along with the post-correction quality control is shown in Figure 5.7 and Figure 5.8. Recall that the rejection criteria of at the 3-sigma level is 3 % of surveys. Using that metric only one of the raw survey sets and one of the corrected survey sets would have been accepted as valid, even though these surveys were internally largely free of errors (the drillstring interference is near the 1-sigma level).

Even more concerning, the validity of the modelled survey sets bears little correlation with the true accuracy of the bottom hole position. Each of the raw surveys would have been equally accurate, having been corrupted with the same amount of drillstring interference. The accuracy of the corrected surveys is directly related to the quality of the drillstring interference estimation. In this case, the least accurate drillstring interference estimation turned out to be the only survey that would not have been rejected by statistical test established earlier. In this case the error induced by the inaccuracy of standard referencing is capable of completely overwhelming the validity of typical survey corrections.

Table 5.6: Modelled Quality Control of Wells with Standard Referencing

Well	Percentage of Raw Surveys Failing 3-Sigma	Percentage of Corrected Surveys Failing 3-Sigma	Estimated Drillstring Interference (nT)	Error in Drillstring Estimate (%)
Well 1	9.0	6.3	229	8.4
Well 2	39.5	2.2	458	83.2
Well 3	14.2	12.7	208	16.8
Well 4	19.4	11.9	245	2.0
Well 5	2.6	4.9	162	35.2



Figure 5.7: Well #3 simulated quality control values for drilling at a 45 degree azimuth with standard referencing



Figure 5.8: Well #3 simulated quality control values after multi-station analysis

5.3 Discussion

For the purposes of modelling the positional uncertainty of wellbores in the Barents Sea, a set of test trajectories were constructed mapping the extreme end of what an extended reach lateral may entail at a range of drilling azimuths. The positional uncertainties were modelled using industry accepted error models from the Operator's Wellbore Survey Group Standard Sets. These models included correcting for crustal anomalies (In Field Referencing Type 1, or IFR1), correcting for magnetic disturbances (In Field Referencing Type 2, or IFR2), and correcting for axial magnetic bias (MSA).

For all wells modelled there was at least some combination of standard corrections capable of reducing the uncertainty to a level where a relief well has a strong chance of success using conventional ranging operations (25-50 m detection range). For wells that are predominantly north/south, significant uncertainty reduction may be achieved using a high-accuracy crustal field model (IFR1). To see the same reductions of uncertainty in an east/west well, it is also necessary to use multi-station analysis techniques to reduce the uncertainty caused by axial magnetic bias in the drillstring.

The OWSG error models are the product of a group of wellbore positioning subject matter experts, have been subject to extensive peer review, and are widely implemented in industry standard software. While they are largely derived from aggregated data from wells surveys at much more moderate latitudes than the Barents Sea, they have the benefit of being performance-based, rather than procedure-based. In other words, rather than specifying a process required to use the error model, instead there is a specified level of accuracy that an operator may achieve through a variety of means. This means that their applicability to the Barents Sea can be demonstrated by validating the means of survey corrections, rather than relying on assumptions from low-latitude surveying that may not hold true further North. To this end both the IFR1 and IFR2 corrections were tested against the performance criteria outlined in the published error models.

5.3.1 Crustal Mitigation Results

For the purposes of crustal corrections through IFR1, two methods were evaluated in chapter 4.2.3. These are the flat earth method and the ellipsoidal harmonic method. Of these two methods, the ellipsoidal harmonic method was found to be likely to meet the requirements of the OWSG MWD+IFR1 error model, so long as aeromagnetic data of at most a 4 km line-spacing is available. Data with 1-2 km line spacing is much more desirable. A data search was conducted that found aeromagnetic data of this quality was present for the western portion of the Barents Sea (west of 32 °E longitude). To determine line spacing of data available for a particular sub-region of the Barents Sea, one may reference Figure 4.5 and Table 4.2. The present data search found data, but not of sufficient quality for an OWSG IFR1 compliant model covering the eastern portion of the Barents Sea as well.

5.3.2 Disturbance Mitigation Results

Three methods of correcting the magnetic disturbance field were explored: correction using the nearest magnetic observatory, correction using an interpolated value between two observatories, and correction using a disturbance function derived from nearby observatory data. Additionally, the concept of installing a local observatory was considered. Of these three methods evaluated, the disturbance function method achieved the best prediction of the local magnetic values, particularly as the distance to the nearest magnetic observatory increases.

The results of chapter 4.2.3 can be used to determine distances at which each method meets OWSG IFR2 tool code requirements. Since the error equations for dip and total field do not have any latitude-dependence, the OWSG IFR2 requirement for declination was considered: 0.279 ° remaining after corrections. Because geomagnetic latitudes in the Barents Sea are in the mid to high sixties, 68 ° is chosen as representative.

Referencing Figure 4.13, the 99.7th percentile for uncorrected disturbance expectable in the Barents Sea is 1.4 °. Because only 0.279 ° is allowable by the OWSG requirement, a mitigation method must be chosen which reduces the remaining error to 20 %. Referencing Figure 4.19, the Nearest Observatory and IIFR methods have more than 20 % error remaining at all distances. It is of note, however, that the study only addressed observatories at a distance of >50 km, so it is likely that either of those

methods would be sufficient at <50 km. The DF, on the other hand, reduces error to the 20 % threshold out to approximately 250 km. For the purposes of this study, installation of a real-time local observatory (ocean-bottom or other) is assumed to always meet these requirements.

5.3.3 MWD Note

The effect of the crustal and disturbance fields on the ability to quality control MWD data was studied. Of primary concern is the impact of the disturbance field on raw quality control measurements for MWD data. It was found that errors caused by the disturbance field on MWD surveys would likely be of a similar size as those expected by other typical MWD errors. As a result, there is a high likelihood that MWD survey sets using error-model derived quality acceptance criteria would be rejected as poor surveys even if a properly functioning instrument was used to conduct the survey. These disturbance field errors, if not corrected for, would also preclude the use of multi-station analysis to remove the axial magnetic bias from ferromagnetic components in the drillstring.

6. Recommendations

6.1 General Recommendations

Wellbore positioning on drilling projects in the Barents Sea has several unique issues that must be mitigated to have a successful drilling operation. That said, this should not be taken as license to neglect the due diligence that must be performed for standard wellbore positioning challenges that impact all wells. Bottom hole assemblies should be analyzed for possible sag errors, and the level of magnetic interference on the MWD should be estimated prior to running in hole. Corrections for sag should be applied, and sufficient non-magnetic spacing should be used to ensure that excessive axial bias will not be present in the MWD surveys. These processes add little to no time to the drilling process and failure to perform them will greatly increase the possibility of large, unmodeled errors in the ultimate wellbore position.

During the drilling operation, MWD surveys should have G_{total} , B_{total} and Dip measurements compared against accurate real-time reference values and validated using the appropriate field acceptance criteria. These field acceptance criteria should be derived from the relevant error model used in the design of the wellbore. More stringent error models producing smaller ellipses of uncertainty will require tighter acceptance criteria than the standard MWD error model. If the wellbore trajectory permits, multi-station analysis should be used to estimate and correct for the observed axial and cross-axial biases caused by drillstring and other interference. Instruments should have calibrations validated before and after being used to perform surveys to ensure no gross errors are present. Again, these errors are not unique to the Barents Sea, but their importance in the overall wellbore positioning process should not be underestimated. If there is a failure in the standard processes needed to position a wellbore, then procedures specific to the Barents Sea will prove fruitless.

6.2 Specific Recommendations Resulting from this Study

Standard uncertainty models published and reviewed by industry subject matter experts for In-Field Referencing (IFR) and multi-station analysis (MSA) should provide a sufficient framework for accurately locating wells and, if need be, drilling a relief well. For these models to be applied, extra actions will be required above and beyond a typical drilling operation. Current data availability restricts the geographic area where these models can be soundly applied. The use of an IFR error model will require the use of aeromagnetic data to generate a local magnetic field model. This study was only able to locate data of sufficient quality for a portion of the Barents Sea.

The extent to which additional correction will be necessary will depend on how deep the well is to be drilled, the amount of step out in the well, and the expected drilling azimuth for the step out. The greater the extent of horizontal deviation in the wellbore and the closer the drilling azimuth is to horizontal East/West, the more likely it will be that advanced corrections are required to meet the appropriate levels of positional uncertainty. For wells drilled in a northerly or southerly direction, the application of IFR will provide the greatest amount of uncertainty reduction. Wells predominantly in an easterly or westerly direction will likely require both IFR and MSA as a minimum surveying standard.

The use of MSA in these applications will likely require that additional checkshots be taken for some sections of the well to ensure that adequate variation in survey orientation is achieved. Application of MSA will necessitate real-time compensation of the magnetic disturbance field in order to accurately model survey measurement deviation from reference values. The disturbance field error magnitudes observed in the Barents Sea can be as large or larger than those produced by MWD surveying errors and attempting to perform MSA on data that has not removed these errors may result in the application of an erroneous survey correction, potentially adding additional uncertainty to the bottom hole location. These issues may be exacerbated further in situations where there is limited orientation change across a drilling run.

There are many publicly available magnetic observatories in the vicinity of the Barents Sea, and use of any disturbance mitigation method (Nearest Observatory, IIFR, or DF) results in decreased remaining disturbance error. To meet OWSG IFR2 requirements as stated above, the Disturbance Function (DF) will need to be applied beyond ~50 km. Anything beyond ~250 km from the nearest observatory will require a real-time local observatory. There was not sufficient data available to determine the effectiveness of disturbance mitigation methods at distances closer than 50 km.

In general, the errors are expected to be lower for all mitigation methods. This implies that the DF method will still be suitable, however it is possible that IIFR and nearest station methods may also have their errors drop to acceptable levels. For drilling activities expected to be within 50 km of a magnetic observatory additional study may be required if IIFR or nearest stations are to be used in order to determine if those mitigation methods will meet the requirements of the OWSG IFR2 error model.

Recommendations are as follows:

1. In the western part of the Barents Sea (West of 32° E longitude), IFR1 can be readily implemented with available data to meet the MWD+IFR1 tool code requirements. Results for this are in 5.3.1 Crustal Mitigation Results.
2. In the eastern part of the Barents Sea (East of 32° E longitude), higher resolution magnetic data (a maximum of 4 km line spacing, ideally 1-2 km) will be required to meet MWD+IFR1 requirements. This may already be available for discovery or purchase, or a new high-resolution aeromagnetic survey may need to be flown. If a new survey is flown, it should be acquired at 1km line spacing. Results in 5.3.1 Crustal Mitigation Results.
3. Seafloor magnetometers should be employed for any operation where cost is not a factor and the utmost accuracy is required. While expensive, they cut the disturbance uncertainty to essentially zero.
4. In regions of the Barents Sea within ~50 km of a magnetic observatory (near-shore, for example), the Disturbance Function method may be used to meet IFR2 tool code requirements. It is possible that either the Nearest Observatory method or IIFR may also be able to be used, however if they are to be employed a local study should be performed prior to drilling in order to confirm that uncertainties are within the IFR2 tool code. Of the latter two methods, IIFR will provide better results, as shown in Figure 4.19, Figure 4.20, and Figure 4.21, but is slightly more complicated to implement. Results in 5.3.2 Disturbance Mitigation Results.
5. In regions of the Barents Sea between ~50 and ~250 km from the nearest magnetic observatory, the Disturbance Function method must be used to meet IFR2 tool code requirements. Figure 4.21 provides a heat map of distances to the nearest observatory for locations in the Barents Sea. Results in 5.3.2 Disturbance Mitigation Results.
6. In remote regions of the Barents Sea beyond ~250km from the nearest magnetic observatory, a local magnetometer (seafloor or otherwise) with real-time data link must be deployed to meet IFR2 requirements. Results in 5.3.2 Disturbance Mitigation Results.

7. References

Buchanan, A., C. A. Finn, J. J. Love, E. W. Worthington, F. Lawson, S. Maus, S. Okewunmi, and B. Poedjono. "Geomagnetic Referencing—The Real-Time Compass for Directional Drillers." *Oilfield Review* 25, no. 3 (2013): 32-47. https://geomag.usgs.gov/downloads/publications/3_geomagnetic.pdf

Abstract: To pinpoint the location and direction of a wellbore, directional driller rely on measurements from accelerometers, magnetometer 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.

Dampney, C. N. G. "The equivalent source technique." *Geophysics* 34, no. 1 (1969): 39-53. <http://library.seg.org/doi/abs/10.1190/1.1439996>

Abstract: The inherent ambiguity of potential field interpretation can be put to advantage. Bouguer anomaly measurements on an irregular grid and at a variety of elevations can be synthesized by an equivalent source of discrete point masses on a plane of arbitrary depth below the surface. By keeping the depth of the plane within certain limits relative to the station spacing, we can ensure that the synthesized field closely approximates the true gravity field in the region close to and above the terrain. Once the equivalent source is obtained, the projection of the Bouguer anomaly onto a regularly gridded horizontal plane is easily done. In addition, the equivalent source can then be economically used to carry out vertical continuation. The technique is illustrated by a hypothetical example and a case history of a local gravity survey in precipitous topography.

Dean, W. C. "Frequency analysis for gravity and magnetic interpretation." *Geophysics* 23, no. 1 (1958): 97-127. <http://library.seg.org/doi/abs/10.1190/1.1438457>

Abstract: The operations of second derivative, analytic continuation, smoothing, the removing of residuals or regionals, and others in gravity and magnetic interpretation are analogous mathematically to the filtering action of electric circuits. The main difference between the two is that electrical filters act on functions of one variable (time), whereas the geophysical filters must act on functions of the two space variables (x and y). This paper develops linear filter theory for gravity and magnetic interpretation. As an application of the theory, downward continuation is discussed in some detail. The frequency response of upward continuation is an exponential function decreasing with increasing frequency. The inverse process of downward continuation has a frequency response which is the reciprocal of the upward continuation response. This paper discusses a method of matching frequency responses by coefficient sets and shows by examples some of the inherent difficulties in downward continuation. A final example calculated analytically shows how good a downward continuation can be expected from a finite coefficient set.

DeVerse, S., and S. Maus. "Optimizing Lateral Well Spacing by Improving Directional Survey Accuracy." In *SPE Liquids-Rich Basins Conference-North America*. Society of Petroleum Engineers, 2016. <https://www.onepetro.org/conference-paper/SPE-181772-MS>

Abstract: Optimizing lateral well spacing is a challenging problem that has significant economic consequences. The intent is to drill the fewest number of horizontal wells that will effectively maximize reservoir drainage. Successful field development requires spacing horizontal wellbores at an optimum distance that minimizes overlapping drainage areas without stranding reserves. There are many variables that must be considered when determining lateral spacing such as hydraulic fracture geometry and reservoir properties. However, a variable that is often overlooked is wellbore positional uncertainty. It is common to ignore the contribution that inaccurate directional surveying has on lateral wellbore spacing. The purpose of this paper is to demonstrate how inaccuracy in standard directional surveying methods impacts wellbore position and to recommend practices to improve surveying accuracy for greater confidence in lateral spacing.

Edvardsen, I., T. L. Hansen, M. Gjertsen, and H. Wilson. "Improving the accuracy of directional wellbore surveying in the Norwegian Sea." *SPE Drilling & Completion* 28, no. 02 (2013): 158-167. <https://www.onepetro.org/journal-paper/SPE-159679-PA>

Abstract: Time-dependent current fluctuations in the Earth's ionosphere cause inaccuracies in wellbore directional surveying. These inaccuracies increase at higher latitudes, and although monitoring and correction are possible, they become less valid as the distance between the monitoring site and the rig site increases, which is a particular problem for offshore drillsites. The characteristics of the ionosphere currents indicate that the most favorable location for monitoring stations is on the same geomagnetic latitude as the drillsite. Such an arrangement has been used to monitor and correct directional surveys at the Haltenbanken area of the Norwegian Sea over a period of approximately 2 years. Haltenbanken is approximately 200 km west of the Norwegian coast at latitude 65°N, where magnetic-storm activity can have a significant effect on directional surveying. A monitoring station was set up on the coast at the same geomagnetic latitude as Haltenbanken. To test the idea that magnetic disturbances are similar along constant magnetic latitude, an additional monitoring station was established 200 km east of the main station. The data broadly confirmed the hypothesis, although isolated events were observed when this was not the case. The challenges of surveying at offshore sites north of 62°N latitude are probably greater than the oil and gas industry is accustomed to—but such challenges will become more significant if the Arctic Ocean is opened to drilling operations. The technique described in this paper may contribute to safer and more-productive offshore operations at high latitudes.

Edvardsen, I., E. Nyernes, M. G. Johnsen, T. Lynne Hansen, U. P. Løvhaug, and J. Matzka. "Improving the accuracy and reliability of MWD/magnetic-wellbore-directional surveying in the Barents Sea." *SPE Drilling & Completion* 29, no. 02 (2014): 215-225. <https://www.onepetro.org/journal-paper/SPE-166226-PA>

Abstract: The years ahead will see increased petroleum-related activity in the Barents Sea, with operations far off the coast of Norway. The region is at high geomagnetic latitude in the auroral zone, and therefore, directional drilling by use of magnetic reference will experience enlarged azimuth uncertainty compared with operations in the Norwegian and North Seas. Two main contributors to azimuth uncertainty are magnetic disturbances from electric currents in the ionosphere and axial magnetic interference from the drillstring. The former is more frequent in the Barents Sea than farther south, and the effect of the latter is increased because of diminished value of the magnetic horizontal component. Wellbore directional surveying for operations on the continental shelf in the North Sea and the Norwegian Sea rely on well-established procedures for near-real-time magnetic monitoring by use of onshore magnetic-reference stations. The different land and sea configuration, distant offshore oil and gas fields, higher geomagnetic latitude, and different behavior of the magnetic field require the procedures to be reassessed before being applied to the Barents Sea. To reduce drilling delays, procedures must be implemented to enable efficient management of magnetic disturbances. In some areas of the Barents Sea, the management requires new equipment to be developed and tested before drilling, such as seabed magnetometer stations. One simple way to reduce drillstring interference is increasing the amount of nonmagnetic steel in the bottomhole assembly (BHA). To maintain azimuth uncertainty at an acceptable level in northern areas, it is crucial that wellbore-directional-surveying requirements are given high priority and considered early during well planning. During the development phase of an oil and gas field, the planned wells must be assigned adequate positional-uncertainty models and, if possible, be designed in a direction that minimizes the wellbore directional uncertainty.

Forsyth, D. W., and A. D. Chave. "Experiment investigates magma in the mantle beneath mid-ocean ridges." *Eos, Transactions American Geophysical Union* 75, no. 46 (1994): 537-540. <http://onlinelibrary.wiley.com/doi/10.1029/94EO02023/full>

Abstract: Observations of oceanic ridges from the Mantle Electromagnetic and Tomography Experiment (MELT), the largest coordinated marine geophysical field program ever attempted, promise to distinguish between two competing models of magma generation. Funded by the National Science Foundation as part of the Ridge Interdisciplinary Global Experiments (RIDGE) program, the experiment will increase current understanding of where melt is formed and how it is transported to the ridge crest to form a new crust of seafloor. The lack of direct, subsurface observations of the melt production region has led to the development of two classes of models

that describe the nature of upwelling and melting beneath spreading centers (Figure 1). In passive flow models, viscous drag from the separating plates induces a broad zone of upwelling, with melt produced over a region that may be 100 km or more across. From this melt area, the magma migrates horizontally to a narrow zone at the ridge axis. In models of dynamic flow, in contrast, the buoyancy from retained melt within the mantle matrix, depletion of the mantle, and lower viscosity within the upwelling zone combine to focus upwelling and melting into a narrow zone perhaps only a few kilometers across. In dynamic models, melt transport is primarily vertical, without the horizontal component required by passive models.

Geng-Xiong, C., W-Y. Xu, Z-G. Wei, B-H. Ahn, Y. Yamide. "Auroral electrojet oval." *Earth, planets and space* 55.5 (2003): 255-261. https://www.jstage.jst.go.jp/article/eps1998/55/5/55_5_255/_article

Abstract: The auroral electrojet is enhanced in the polar ionosphere associated with charged particle precipitation and field aligned currents during substorms. In this paper the geometry of the electrojet is determined by using the ionospheric equivalent current systems for every 5 minutes during March 18 and 19, 1978. The latitudinal and local time shifts of the oval are examined. Possible relationship of the electrojet oval with expansion of the auroral oval and the field aligned current belts during substorms are discussed. The electrojet oval in the polar region consists of westward and eastward electrojets, varying with AE index. As the magnetic activity increases, the westward electrojet has distinct latitudinal shifts in different local time sectors: it shifts poleward around the midnight (23: 00-03: 00 MLT), while moves equatorward in the morning sector (03: 00-10: 00 MLT) and afternoon sector (20: 00-23: 00 MLT). The eastward electrojet includes two insulated parts: a higher-latitude part around 80. latitude in the nighttime sector (21: 00-03: 00 MLT) and a lower-latitude part between 60°- 70°latitudes in other local time sectors. As AE index increases, the higher-latitude part of the eastward electrojet expands eastward from 03: 00 to 08: 00 MLT, while the lower-latitude part shows a equatorward shift in the afternoon sector, which is more or less similar to the westward electrojet.

Grindrod, S. J., P. J. Clark, J. D. Lightfoot, N. Bergstrom, and L. S. Grant. "OWSG Standard Survey Tool Error Model Set for Improved Quality and Implementation in Directional Survey Management." In *IADC/SPE Drilling Conference and Exhibition*. Society of Petroleum Engineers, 2016. <https://www.onepetro.org/conference-paper/SPE-178843-MS>

Abstract: Understanding wellbore position and the associated uncertainty is fundamental to all drilling operations and reservoir management. Without consistency in predicting to known uncertainties, activities involving positional uncertainty, such as risk mitigations for collision avoidance, cannot be performed reliably with known confidence. For the first time, industry has a common controlled set of uncertainty models thus allowing for transparency in error estimation. Reservoir targeting and subsurface hazard avoidance can be compromised resulting in unrealized stranded reserves and/or intersection of faulted, undesirable formation. Overly optimistic estimations can result in wellbore collisions where the risk of collision is assumed to be very low or can result in a missed well intersection during relief well first ranging point operation. Conversely, overly conservative estimations can result in excessive targeting constraints or directional control requirements. An analysis of industry survey of error codes being utilized across companies was performed, both vast inconsistencies and significant gaps were realized. A case for action was determined and a collaborative work group was formed under the Operator Wellbore Survey Group (OWSG). OWSG is a subcommittee of the SPE Wellbore Positioning Technical Section (SPE-WPTS). The SPE-WPTS originated as the Industry Steering Committee on Wellbore Surveying Accuracy (ISCWSA), which affiliated to the SPE and became a Technical Section. It was determined that many of the error codes being utilized in industry were based on survey tool error models established in SPE 67616 and SPE 90408, but there were uncontrolled changes, miss matched versions, and alterations in error assumptions (that were not vetted) being unknowingly utilized. Inspection revealed that the error models, although loosely based on ISCWSA, were varied across both service and operator companies and in some cases were varied internal to individual companies. The collaborative work group was established to develop a Standard Survey Tool Error Model Set based on the SPE 67616 and SPE 90408 publications, the current work of the ISCWSA error model subcommittee and with contributions from industry's leading subject matter experts. The result of the work is a series of 5 sets of OWSG Survey Tool Error Models. The sets have a Model Selection guide with a Standardized naming structure. The Standard Survey Tool Error Model Set has been released into the public domain to improve Survey Management Quality and has

been adopted by numerous companies (both services and operators). The OWSG error model set facilitates easy implementation in all common directional well planning software platforms; hence reducing risk of incorrect models leading to poor understanding of wellbore position and improving consistency of error estimation. The Standard Survey Model set has been compiled with contributions from industry's leading subject matter experts. The most recent second revision (Rev2) of sets A and B of the series were publicly released during the month of June of 2015.

Jegen, M., and R.N. Edwards: The electrical properties of a 2D conductive zone under the Juan de Fuca ridge. *GRL*, 1998, vol. 25 (19), pp. 3647-3650.
https://oceanrep.geomar.de/19653/1/1998_JegenEdwards_98GL52807.pdf

Abstract: Vertical gradient electromagnetic sounding (VGS) on the Endeavour segment of Juan de Fuca mid-ocean ridge reveals the presence of a 2D ridge-parallel, conductivity anomaly. If the anomaly is caused mainly by melt in a conventional upper mantle upwelling zone alone, then the conductivity of the zone is about 0.6 S/m. The corresponding Archie's law melt fraction exceeds 0.10. A significantly lower melt fraction requires a sheet-like, well interconnected melt. Upwelling zone conductivity can be reduced by a third if the anomaly is broadened and a crustal conductor is added to the model.

Lanzerotti, L. J., L. V. Medford, C. G. MacLennan, D. J. Thomson, A. Meloni, and G. P. Gregori. "Measurements of the large-scale direct-current Earth potential and possible implications for the geomagnetic dynamo." *Science* 229 (1985): 47-50.
<http://onlinelibrary.wiley.com/doi/10.1029/JA093iA07p07578/abstract>

Abstract: It is suggested that the existence of a sporadic multiple X line reconnection (MXR) process at the dayside magnetopause could be a source of energy to produce ULF hydromagnetic waves ($f \sim 1-10$ mHz) in the dayside magnetopause cusp region. The MXR process is characterized by the repeated formation and convection of magnetic islands and elongated plasma clouds, which compress and distort the adjacent closed geomagnetic field lines. This leads in a natural way to the generation of ULF waves with frequencies in the range 1-10 mHz along cusp geomagnetic field lines. These waves are expected to be approximately linearly polarized, dominated by variations in the radial magnetic field component near the dayside magnetopause and by variations in the azimuthal magnetic field component near the resonant closed field lines in the magnetosphere. In addition, the field-aligned currents associated with the MXR process may generate the impulsive magnetic field variations often observed to accompany the continuous variations in the ULF band. Hence the reconnection process may be an additional mechanism, together with the Kelvin-Helmholtz instability and direct penetration of upstream waves, for the production of hydromagnetic energy in the dayside magnetosphere.

Lejosne, S., S. Maus, and F. S. Mozer. "Model-observation comparison for the geographic variability of the plasma electric drift in the Earth's innermost magnetosphere." *Geophysical Research Letters* (2017).
<http://onlinelibrary.wiley.com/doi/10.1002/2017GL074862/full>

Abstract: Plasmaspheric rotation is known to lag behind Earth rotation. The causes for this corotation lag are not yet fully understood. We have used more than 2 years of Van Allen Probe observations to compare the electric drift measured below $L \sim 2$ with the predictions of a general model. In the first step, a rigid corotation of the ionosphere with the solid Earth was assumed in the model. The results of the model-observation comparison are twofold: (1) radially, the model explains the average observed geographic variability of the electric drift; (2) azimuthally, the model fails to explain the full amplitude of the observed corotation lag. In the second step, ionospheric corotation was modulated in the model by thermospheric winds, as given by the latest version of the horizontal wind model. Accounting for the thermospheric corotation lag at ionospheric E region altitudes results in significantly better agreement between the model and the observations.

Macmillan, S., A. McKay, and S. J. Grindrod. "Confidence limits associated with values of the earth's magnetic field used for directional drilling." In *SPE/IADC Drilling Conference and Exhibition*. Society of Petroleum Engineers, 2009. <https://www.onepetro.org/conference-paper/SPE-119851-MS>

Abstract: This paper describes updated uncertainties for use with predicted geomagnetic parameters within magnetic Measurement-While-Drilling (MWD) survey tool error models.

These models are used to define positional error ellipsoids along the wellbore which assist in hitting geological targets and missing existing wellbores. The declination, dip angle and total field strength of the Earth's magnetic field are used with magnetic survey tools for surveying the wellbore. These values are often obtained from mathematical models such as the British Geological Survey Global Geomagnetic Model (BGGM). As the Earth's magnetic field is continually varying with time the BGGM is updated annually to maintain accuracy. However a global predictive model cannot capture all sources of the Earth's magnetic field which results in uncertainties of the predicted parameters. The Industry Steering Committee on Wellbore Surveying Accuracy (ISCWSA) published a MWD error model in 2000 (Williamson, 2000). The geomagnetic field uncertainties that are part of this model were derived from work done by the BGS in the early 1990s. Since then more accurate data from magnetic survey satellites have been introduced into the BGGM and the uncertainty of the predicted geomagnetic field parameters has been reduced. The original approach to deriving the uncertainties involved separating the various error sources in the magnetic field and assessing them individually. This paper uses a simpler approach where clean orientated magnetic down-hole data are simulated using geomagnetic observatory data. Spot absolute measurements of the magnetic field made at observatories around the world are adjusted for the crustal magnetic field to make them more representative of hydrocarbon geology. The adjusted observatory data are then compared with the predicted values from the BGGM to assess the uncertainty. The uncertainties do not fit a 'normal' distribution so they are expressed as limits for various confidence levels. They vary with time and with location and, in their derivation, do not assume any underlying empirical error distribution. Options to further reduce the uncertainties using data from local magnetic surveys (In-Field Referencing) and observatories (Interpolation In-Field Referencing) are also described. The use of the revised geomagnetic uncertainty values in the MWD error model will reduce wellbore position uncertainty to reflect the increased accuracy from recent improvements in geomagnetic modelling.

Maus, S. "A corotation electric field model of the Earth derived from Swarm satellite magnetic field measurements." *Journal of Geophysical Research: Space Physics*. 2017. <http://onlinelibrary.wiley.com/doi/10.1002/2017JA024221/full>

Abstract: Rotation of the Earth in its own geomagnetic field sets up a primary corotation electric field, compensated by a secondary electric field of induced electrical charges. For the geomagnetic field measured by the Swarm constellation of satellites, a derivation of the global corotation electric field inside and outside of the corotation region is provided here, in both inertial and corotating reference frames. The Earth is assumed an electrical conductor, the lower atmosphere an insulator, followed by the corotating ionospheric E region again as a conductor. Outside of the Earth's core, the induced charge is immediately accessible from the spherical harmonic Gauss coefficients of the geomagnetic field. The charge density is positive at high northern and southern latitudes, negative at midlatitudes, and increases strongly toward the Earth's center. Small vertical electric fields of about 0.3 mV/m in the insulating atmospheric gap are caused by the corotation charges located in the ionosphere above and the Earth below. The corotation charges also extend outward into the region of closed magnetic field lines, forcing the plasmasphere to corotate. However, the nonaxially symmetric contributions of the geomagnetic field are found to slow down the corotation of the plasmasphere, particular in the South Atlantic. The electric field of the corotation charges also extends outside of the corotating regions, contributing radial outward electric fields of about 10 mV/m in the northern and southern polar caps. Depending on how the magnetosphere responds to these fields, the Earth may carry a net electric charge.

Maus, S., "Managing Main and Crustal Magnetic Fields and New Developments in Global Magnetic Modeling." ISCWSA-40, 2014. <http://www.iscwsa.net/download/8e5f8442-b64b-11e6-afa6-d13244c2a34f/>

Abstract: not applicable for this slideshow.

Maus, S., "Using Geomagnetic In-Field Referencing and Real-time Survey Management for Improved Wellbore Placement Accuracy." 2017.

Abstract: not applicable for this slideshow.

Maus, S., U. Barckhausen, H. Berkenbosch, N. Bournas, J. Brozena, V. Childers, F. Dostaler, J. D. Fairhead, C. Finn, R. R. B. von Frese, C. Gaina, S. Golynsky, R. Kucks, H. Lühr, P. Milligan, S. Mogren, D. Müller, O. Olesen, M. Pilkington, R. Saltus, B. Schreckenberger, E. Thébault, and F. Caratori Tontini, EMAG2: A 2-arc-minute resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne and marine magnetic measurements, *Geochem. Geophys. Geosyst.*, under review, 2015. <http://www.geomag.org/models/emag2.html>

Abstract: Magnetic anomaly maps provide insight into the subsurface structure and composition of the Earth's crust. Anomalies trending parallel to the isochrons (lines of equal age) in the oceans reveal the temporal evolution of oceanic crust. Magnetic maps are widely used in the geological sciences and in resource exploration. Furthermore, the global magnetic map is useful in science education to illustrate various aspects of Earth evolution such as plate tectonics and crustal interaction with the deep mantle. Distinct patterns and magnetic signatures can be attributed to the formation (seafloor spreading) and destruction (subduction zones) of oceanic crust, the formation of continental crust by accretion of various terranes to cratonic areas and large scale volcanism (both on continents and oceans).

Maus, S., and J. S. DeVerse. "Magnetic Referencing and Real-Time Survey Processing Enables Tighter Spacing of Long-Reach Wells." In *SPE Liquids-Rich Basins Conference—North America*. Society of Petroleum Engineers, 2015. <https://www.onepetro.org/conference-paper/SPE-175539-MS>

Abstract: Positional uncertainty in wellbores is caused by numerous error sources and propagates in magnitude along the measured depth of the wellbore. This can be problematic when planning or drilling closely spaced long-reach wells while still satisfying collision avoidance policies. The ellipses of uncertainty associated with surveys acquired by standard Measurement While Drilling (MWD) tools are often too large to enable adequate separation factors between wells. MWD tools are instruments mounted inside the bottom hole assembly (BHA) and use an accelerometer and magnetometer sensor package to determine the inclination and magnetic azimuth while drilling. The magnetic azimuth is used to calculate a true (geographic) azimuth by adding the declination angle from a geomagnetic reference model. The largest sources of error in standard MWD survey are inaccuracies in the global geomagnetic reference model and magnetic interference from the BHA. These error sources can be reduced significantly by using a local geomagnetic In-Field Referencing (IFR) model and by subsequently applying multi-station analysis (MSA) corrections to the raw survey measurements.

Maus S., and J.S. DeVerse. "Simulation of Recovery of Losses Due to Positional Errors in Wellbore Placement," URTeC : 2458814, Unconventional Resources Technology Conference in San Antonio, Texas, USA, 1-3 August, 2016.

<http://library.seg.org/doi/abs/10.15530/urtec-2016-2458814>

Abstract: In unconventional resources, horizontal wells are drilled in parallel at a spacing distance designed to maximize drainage of the reservoir. Lateral well spacing should be such that the drainage radiuses meet, but do not overlap. If drainage envelopes do not meet, then oil and gas are left stranded in the reservoir. However, due to the limited accuracy of downhole surveying methods, positional errors in wellbore placement often lead to deviations by hundreds of feet from the optimal wellbore position. The purpose of this study is to quantify the impact of such wellbore placement errors on reservoir recovery for different surveying methods. A recovery simulator web application was developed to approximate the effect of wellbore positional error on reservoir drainage. The application requires input parameters to define the drilling scenario being evaluated. These include lateral wellbore length, lateral well spacing and recovery percentage as a function of the drainage radius. A user selects surveying methods to be compared in the simulation. Using the latest error models of the Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA), the application simulates a large number of wellbores drilled with random errors corresponding to the selected surveying methods. The simulation assesses the expected amount of oil or gas left in the field due to inaccurate wellbore placement. It also provides statistics on the likelihood of wellbore cross-overs and lease line infractions. Initial results indicate that random errors in wellbore placement lead to hundreds of thousands of dollars in unclaimed hydrocarbons for a typical multi-well pad when using standard Measurement While Drilling (MWD). However, this loss is reduced significantly when applying advanced surveying methods with higher accuracy, such as In-Field Referencing (IFR) and Multi-Station Analysis (MSA). The likelihood of wellbore crossovers and lease line infractions is then also reduced significantly. Wellbore placement inaccuracy in unconventional plays has not

been a major concern until in recent years, when drillers began placing horizontal wells closely spaced together. Modeling positional uncertainty and improving survey accuracy has been driven mostly by drilling professionals in order to mitigate anti-collision risk and keep wellbores within lease lines. However, this study shows that improved wellbore placement has further significant economic benefits by increasing reservoir drainage and providing more accurate data for spacing tests and reservoir models.

Maus, S., & Croke, R., "Field Acceptance Criteria Based on ISCWSA Tool Error Models" 2014
<http://www.iscwsa.net/download/f7086db8-bce9-11e6-8ad6-1360ea316344/>
Abstract: not applicable for this slideshow.

Stefan Maus, Shawn DeVerse, Marc Willerth, David Sweeney, Shawn Waldrop and Prabhas Nayak (2017) A Public Web API to Provide Dynamic Quality Control for the ISCWSA Error Models, ISCWSA 46th General Meeting, San Antonio, TX, USA
Abstract: not applicable for this product.

Maus, S., and M. Nair (NOAA/NGDC) S. Okewunmi (Chevron), "Quantifying the uncertainty in global geomagnetic models." 2010.
<http://www.iscwsa.net/download/485f5970-bded-11e6-98dd-5586628dffff/>
Abstract: not applicable for this slideshow.

Maus, S., M. Nair, B. Carande (MagVAR), S. Pham (ConocoPhillips) and B. Poedjono (Schlumberger). "Systematic and Random Contributions to the Disturbance Field (IFR 2)." 2014.
<http://www.iscwsa.net/download/a2ee56b8-b64d-11e6-99bb-e117362139ff/>

Maus, S., and B. Poedjono. "Method To Predict Local Geomagnetic Disturbance Field And Its Practical Application." U.S. Patent Application 14/906,750, filed July 24, 2014.
<https://www.google.com/patents/WO2015013499A1?cl=en>
Abstract: A method for correcting geomagnetic reference field includes measuring Earth magnetic field elements at least one known geodetic position. Earth magnetic field elements are measured at a position proximate the location. A disturbance function is determined from the Earth magnetic field measurements made at the at least one known geodetic position. A magnetic disturbance field measurement transfer function is estimated between the at the at least one known geodetic and proximate positions to estimate a disturbance function at the proximate position. The estimated magnetic disturbance function is used to correct geomagnetic reference field or measurements made at the location.

Poedjono, B., S. Maus, and C. Manoj. "Effective Monitoring of Auroral Electrojet Disturbances to Enable Accurate Wellbore Placement in the Arctic." In OTC Arctic Technology Conference. Offshore Technology Conference, 2014. <https://www.onepetro.org/conference-paper/OTC-24583-MS>

Abstract: In measurement while drilling (MWD), wellbore azimuth is determined relative to the direction of the geomagnetic field. Converting this magnetic azimuth to a true azimuth requires accurate knowledge of the direction of the geomagnetic field at the point of measurement downhole. In the Arctic, MWD processing must include corrections for rapid changes in the geomagnetic field caused by auroral electrojet currents. The auroral zone, those latitudes at which the aurora borealis (or the northern lights) occurs, is a region where the electric field of the magnetosphere precipitates along magnetic field lines into the ionosphere. At 100 km above the surface, this electric field drives auroral electrojet currents in the east/west direction, generating the strongest magnetic field disturbances on the planet. The direction of the geomagnetic field in the auroral zone can change by several degrees in less than an hour. Data from geomagnetic observatory and variometer stations can be analyzed to characterize the auroral electrojets and compensate for the disturbance. Knowledge of the spatial structure of the electrojets' magnetic signature is essential for deploying a ground network of monitoring stations in the Arctic. This network provides the real-time geomagnetic infrastructure essential to support MWD operations, making it the most cost-effective technology available to achieve accurate wellbore placement in horizontal, relief well, and extended reach drilling, as well as in collision-avoidance applications. In one case study using historical data from two nearby observatories from 1995 to the present, the disturbance field was characterized and a time

series of maximum disturbances was derived and extrapolated to the year 2020. Maximum disturbance in the magnetic field was found to lag the maximum of solar activity by approximately two years, predicting the next maximum in 2015-2019.

Poedjono, B., N. Beck, A. Buchanan, L. Borri, S. Maus, C. A. Finn, E. W. Worthington, and T. White. "Improved Geomagnetic Referencing in the Arctic Environment (Russian)." In SPE Arctic and Extreme Environments Technical Conference and Exhibition. Society of Petroleum Engineers, 2013. <https://www.onepetro.org/conference-paper/SPE-166850-RU>

Abstract: Geomagnetic referencing uses the Earth's magnetic field to determine accurate wellbore positioning essential for success in today's complex drilling programs, either as an alternative or a complement to north-seeking gyroscopic referencing. However, fluctuations in the geomagnetic field, especially at high latitudes, make the application of geomagnetic referencing in those areas more challenging. Precise crustal mapping and the monitoring of real-time variations by nearby magnetic observatories is crucial to achieving the required geomagnetic referencing accuracy. The Deadhorse Magnetic Observatory (DED), located at Prudhoe Bay, Alaska, has already played a vital role in the success of several commercial ventures in the area, providing essential, accurate, real-time data to the oilfield drilling industry. Geomagnetic referencing is enhanced with real-time data from DED and other observatories, and has been successfully used for accurate wellbore positioning. The availability of real-time geomagnetic measurements leads to significant cost and time savings in wellbore surveying, improving accuracy and alleviating the need for more expensive surveying techniques. The correct implementation of geomagnetic referencing is particularly critical as we approach the increased activity associated with the upcoming maximum of the 11-year solar cycle. The DED observatory further provides an important service to scientific communities engaged in studies of ionospheric, magnetospheric and space weather phenomena.

Poedjono, B., and X. Li. "Validation and application of magnetic anomalies for directional drilling." International Workshop on Gravity, Electrical & Magnetic Methods and Their Applications 2011: International Workshop on Gravity, Electrical & Magnetic Methods and Their Applications, Beijing, China, October 10–13, 2011. Society of Exploration Geophysicists, 2011. <http://library.seg.org/doi/abs/10.1190/1.3659132>

Abstract: Accurate real-time wellbore positioning is essential for today's complex drilling programs. Geomagnetism as an alternative to gyroscopic surveys for directional drilling may require use of all three components of the Earth's magnetic field: the main, crustal and disturbance fields. This work concerns the crustal field. We have developed a technique for computation of the vector crustal magnetic field at depths from the scalar TMI (Total Magnetic Intensity) anomaly observed on or above the surface of the Earth. We validate our technique by comparing to gyroscopic readings in the White Rose field offshore eastern Canada, and then show its application to the Jubilee field offshore Ghana.

Poedjono, B., I. B. Olalere, I. Shevchenko, F. I. Lawson, S. Crozier, and X. Li. "Improved Drilling Economics and Enhanced Target Acquisition through the Application of Effective Geomagnetic Referencing." In SPE EUROPEC/EAGE Annual Conference and Exhibition. Society of Petroleum Engineers, 2011. <https://www.onepetro.org/conference-paper/SPE-140436-MS>

Abstract: For a deepwater operator facing the challenges of directional drilling and wellbore stability, surveying with high spread costs in excess of USD 1 million per day, any approach which promises to reduce or eliminate cost and risk has great potential benefit. This paper showcases how careful planning, a fit-for-purpose survey program, and, most importantly, an effective, real-time geomagnetic referencing service (GRS) can significantly improve the operator's ability to hit both geological and financial targets. The authors describe recent breakthrough improvements in the accuracy of GRS techniques and present a case study to illustrate the benefits of this approach for the industry, especially in deepwater operations.

Poedjono, B., N. Beck, A. Buchanan, J. Brink, J. Longo, C. A. Finn, and E. W. Worthington. "Geomagnetic referencing in the arctic environment." In OTC Arctic Technology Conference. Offshore Technology Conference, 2012. <https://www.onepetro.org/conference-paper/OTC-23729-MS>

Abstract: Geomagnetic referencing is becoming an increasingly attractive alternative to north-seeking gyroscopic surveys to achieve the precise wellbore positioning essential for success in

today's complex drilling programs. However, the greater magnitude of variations in the geomagnetic environment at higher latitudes makes the application of geomagnetic referencing in those areas more challenging. Precise, real-time data on those variations from relatively nearby magnetic observatories can be crucial to achieving the required accuracy, but constructing and operating an observatory in these often harsh environments poses a number of significant challenges. Operational since March 2010, the Deadhorse Magnetic Observatory (DED), located in Deadhorse, Alaska, was created through collaboration between the United States Geological Survey (USGS) and a leading oilfield services supply company. DED was designed to produce real-time geomagnetic data at the required level of accuracy, and to do so reliably under the extreme temperatures and harsh weather conditions often experienced in the area. The observatory will serve a number of key scientific communities as well as the oilfield drilling industry, and has already played a vital role in the success of several commercial ventures in the area, providing essential, accurate data while offering significant cost and time savings, compared with traditional surveying techniques.

Poedjono, B., S. A. Rawlins, C. K. Singam, A. Tweel, A. Dubinsky, R. Rakhmangulov, and S. Maus. "Addressing Wellbore Position Challenges in Ultra-Extended-Reach Drilling in Russia's Far East." In SPE Paper 160784-PP presented at Russian Oil and Gas Exploration & Production Technical Conference and Exhibition, Moscow, Russia, pp. 16-18. 2012. http://ebooks.wdcb.ru/2013/2013BS012/SESSION_5/Singam.pdf

Abstract: Drilling in Russia's Far East has always been associated with industry-defining ultra-extended-reach drilling. With the emergence of more powerful drilling rigs and advances in measurement and logging-while-drilling (MWD and LWD) tools, these wellbores can be designed to reach farther. Therefore, accurately penetrating and exploiting distant reservoirs have resulted in critical dependence on high-accuracy surveying techniques. Successful target penetration and meeting anticollision requirements without the need for shutting production in nearby wells are key proponents for a geomagnetic referencing service (GRS). Geomagnetic referencing is the technique to minimize the lateral position uncertainties when using MWD. This is particularly important for wellbores that extend the boundary of the drilling envelope with stepouts greater than 13 km. The wellbore azimuth accuracy is highly dependent on the quality of the magnetic data used to produce the geomagnetic reference model. This model characterizes the absolute magnitude and vector direction of the natural magnetic field for every point along the wellbore. Representation of the local crustal magnetic contribution is key to the process since it constitutes a significant error in the lateral wellbore position. Since 2011, a new, highly accurate geomagnetic referencing methodology has been used in Russia's Far East. Global contributions are accounted for by a high-definition geomagnetic model (HDGM). In addition, the local crustal magnetic anomaly is represented by 3D ellipsoidal harmonic functions tracking the shape and depth of the Earth, thereby providing seamless integration with HDGM and avoiding distortions faced by conventional plane-Earth approximations. A comparison with the previous industry standard shows improvements of 0.5° in azimuth determination. This high-degree geomagnetic technique will serve well for a number of upcoming developments in Russia's Far East, continuing to push the drilling envelope and providing essential, accurate wellbore positioning, while offering significant time and cost savings.

Roger Ekseth, Torgeir Torkildsen, Andrew G. Brooks, John Lionel Weston, Erik Nytnes, Henry Ferguson Wilson and Kazimir Kovalenko, "High integrity wellbore surveys: methods for eliminating gross errors." In SPE/IADC Drilling Conference, 20-22 February, Amsterdam, The Netherlands. Society of Petroleum Engineers. 2007. <https://www.onepetro.org/conference-paper/SPE-105558-MS>

Abstract: An earlier paper by the same authors, SPE 1037341, pointed out the potential safety and commercial costs of unreliable directional survey data. It described how a significant degree of reliability can be achieved with the application of quality control checks internal to the directional data, but it also identified the fact that such checks fall short of providing comprehensive reliability assurance. This paper documents weaknesses in conventional directional survey quality control (QC) procedures through theoretical considerations, statistical analyses of real survey data, and real examples of failed surveys that have made it through conventional QC procedures without detection. The paper defines principles for survey programme design and implementation to eliminate these weaknesses. It proposes a new set of minimum requirements for survey validation, which, in general, incorporate the need for an overlapping verification survey or other independent observation. This requirement is not

generally acknowledged in most of today's directional surveying QC procedures, which may be too weak to ensure the validity of a given error model and thus the integrity of the final well survey. This paper also discusses how analysis of a sufficiently large quantity of data, with the recommended QC methods applied, allows validation and refinement of the error model. This paper is the product of a collaborative work in the SPE Wellbore Positioning Technical Section (WPTS).

Roger Ekseth , Torgeir Torkildsen, Andrew G. Brooks, John Lionel Weston, Erik Nyrnes, Henry Ferguson Wilson and Kazimir Kovalenko, "The reliability problem related to directional survey data." In IACDC/SPE Asia Pacific Drilling Technology and Exhibition, 13-15 November, Bangkok, Thailand. Society of Petroleum Engineers, 2007 <https://www.onepetro.org/conference-paper/SPE-103734-MS>

Abstract: The validity of error model predictions of wellbore position accuracy is highly dependent on the application of rigorous quality control procedures to the survey data. Concern has been expressed within the SPE Wellbore Positioning Technical Section (WPTS, formerly ISCWSA) that failure to apply the necessary operational procedures may be commonplace, raising questions about the reliability of the survey data so generated. Directional survey data that does not conform to its model's predictions represents a risk in terms of lost production, damage to infrastructure and loss of life. This paper lists all sources of error, describes internal data checks that are capable of identifying many of them, and highlights those that are missed and which will therefore require alternative QC measures. Real wellbore survey data are used to illustrate how the use of inadequate QC procedures can lead to invalid survey data being accepted as valid. The paper is the product of collaborative work within the SPE WPTS.

Russell, J. P., G. Shiells, and D. J. Kerridge. "Reduction of well-bore positional uncertainty through application of a new geomagnetic in-field referencing technique." In SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, 1995. <https://www.onepetro.org/conference-paper/SPE-30452-MS>

Abstract: A new In-Field Referencing (IFR) technique, for measuring local geomagnetic-field parameters at, or very close, to the well site is described. IFR is shown to enable reduction in the uncertainty associated with the estimates of geomagnetic field values, normally obtained from main-field geomagnetic models. This significantly reduces the magnitude of certain critical directional uncertainty error terms which are inputs to survey tool accuracy performance models, reducing positional uncertainty for well-planning purposes. Logistical problems and high unit-cost have precluded IFR development to date, but recent innovative thinking which has evolved from dialogue between oil and drilling-service companies and the scientific/academic community has refined the concept and greatly improved the feasibility.

Sabaka, T. J., Olsen, N. and Langel, R. A. "A comprehensive model of the quiet-time, near-Earth magnetic field" *Geophysical Journal International*, 151: 32–68. 2002. <http://onlinelibrary.wiley.com/doi/10.1046/j.1365-246X.2002.01774.x/abstract>

Abstract: The near-Earth magnetic field is caused by sources in the Earth's core, ionosphere, magnetosphere, lithosphere and from coupling currents between the ionosphere and the magnetosphere, and between hemispheres. Traditionally, the main field (low degree internal field) and magnetospheric field have been modelled simultaneously, with fields from other sources being modelled separately. Such a scheme, however, can introduce spurious features, especially when the spatial and temporal scales of the fields overlap. A new model, designated CM3 (Comprehensive Model: phase 3), is the third in a series of efforts to coestimate fields from all of these sources. This model has been derived from quiet-time Magsat and POGO satellite and observatory hourly means measurements for the period 1960–1985. It represents a significant advance in the treatment of the aforementioned field sources over previous attempts, and includes an accounting for main field influences on the magnetosphere, main field and solar activity influences on the ionosphere, seasonal influences on the coupling currents, a priori characterization of the influence of the ionosphere and the magnetosphere on Earth-induced fields, and an explicit parametrization and estimation of the lithospheric field. The result is a model that describes well the 591 432 data with 16 594 parameters, implying a data-to-parameter ratio of 36, which is larger than several popular field models.

Sabaka, T. J., Olsen, N. and Purucker, M. E., "Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data." *Geophysical Journal International*, 159: 521–547. 2004 <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-246X.2004.02421.x/abstract>

Abstract: A new model of the quiet-time, near-Earth magnetic field has been derived using a comprehensive approach, which includes not only POGO and Magsat satellite data, but also data from the Ørsted and CHAMP satellites. The resulting model shows great improvement over its predecessors in terms of completeness of sources, time span and noise reduction in parameters. With its well separated fields and extended time domain of 1960 to mid-2002, the model is able to detect the known sequence of geomagnetic jerks within this frame and gives evidence for an event of interest around 1997. Because all sources are coestimated in a comprehensive approach, intriguing north–south features typically filtered out with other methods are being discovered in the lithospheric representation of the model, such as the S Atlantic spreading ridge and Andean subduction zone lineations. In addition, this lithospheric field exhibits significantly less noise than previous models as a result of improved data selection. The F-region currents, through which the satellites pass, are now treated as lying within meridional planes, as opposed to being purely radial. Results are consistent with those found previously for Magsat, but an analysis at Ørsted altitude shows exciting evidence that the meridional currents associated with the equatorial electrojet likely close beneath the satellite. Besides the model, a new analysis technique has been developed to infer the portion of a model parameter state resolved by a particular data subset. This has proven very useful in diagnosing the cause of peculiar artefacts in the Magsat vector data, which seem to suggest the presence of a small misalignment bias in the vector magnetometer.

Sabaka, T., Olsen, N., Tyler, Robert. And Kuvshinov, Alexey; "CM5, a pre-Swarm comprehensive geomagnetic field model derived from over 12 yr of CHAMP, Ørsted, SAC-C and observatory data." *Geophysical Journal International*, Volume 200, Issue 3, 1596–1626. 2015. <https://academic.oup.com/gji/article-lookup/doi/10.1093/gji/ggu493>

Abstract: A comprehensive magnetic field model named CM5 has been derived from CHAMP, Ørsted and SAC-C satellite and observatory hourly-means data from 2000 August to 2013 January using the Swarm Level-2 Comprehensive Inversion (CI) algorithm. Swarm is a recently launched constellation of three satellites to map the Earth's magnetic field. The CI technique includes several interesting features such as the bias mitigation scheme known as Selective Infinite Variance Weighting (SIVW), a new treatment for attitude error in satellite vector measurements, and the inclusion of 3-D conductivity for ionospheric induction. SIVW has allowed for a much improved lithospheric field recovery over CM4 by exploiting CHAMP along-track difference data yielding resolution levels up to spherical harmonic degree 107, and has allowed for the successful extraction of the oceanic M2 tidal magnetic field from quiet, nightside data. The 3-D induction now captures anomalous Solar-quiet features in coastal observatory daily records. CM5 provides a satisfactory, continuous description of the major magnetic fields in the near-Earth region over this time span, and its lithospheric, ionospheric and oceanic M2 tidal constituents may be used as validation tools for future Swarm Level-2 products coming from the CI algorithm and other dedicated product algorithms.

Segawa, J., Y. Hamano, T. Yukutake, and H. Utada. "A new model of ocean bottom magnetometer." *Journal of geomagnetism and geoelectricity* 35, no. 11-12 (1983): 407-421. https://www.jstage.jst.go.jp/article/jgg1949/35/11-12/35_11-12_407/_article

Abstract: A triaxial fluxgate magnetometer for use on the sea floor has been built and tested. This magnetometer, which is small and easy to handle, is housed in a pressure-tight glass sphere. The instrument is equipped with a timed release which enables free-fall installation and automatic recovery. Maximum period of measurement is 60 days with 3-minute samplings and the accuracy of the measurement is ± 0.8 nT. This corresponds to the error of ± 1 least significant bit unavoidable in digital conversion using a 16-bit AD converter.

Shiells, G. M., and D. J. Kerridge. "Borehole surveying." U.S. Patent 6,021,577, issued February 8, 2000. <https://www.google.com/patents/US6021577>

Abstract: A borehole survey is conducted at a drilling site S by a so-called Interpolated In-Field Referencing (IIFR) method in which: (a) absolute local geomagnetic field data is obtained by spot measurement of the earth's magnetic field at a local measurement site R which is sufficiently close to the drilling site S that the measurement data is indicative of the earth's

magnetic field at the drilling site S but which is sufficiently remote from the drilling site S that the measurement data is unaffected by magnetic interference from the drilling site and other man-made installations; (b) time-varying geomagnetic field data is obtained by combining the absolute local geomagnetic field data with data indicative of variation of the geomagnetic field with respect to time obtained by monitoring variation of the earth's magnetic field with respect to time at a remote monitoring site P1, P2; (c) downhole magnetic field data is obtained by monitoring by means of a surveying instrument the magnetic field in the vicinity of the borehole at a series of locations along the borehole; and (d) the orientation of the borehole is determined from the downhole magnetic field data and the time-varying geomagnetic field data. Such a survey method takes into account short-term variations in the geomagnetic field caused by electrical currents in the ionosphere and is therefore more accurate than known survey methods.

Studer, R., Total, S.A., Macresy, L. "Improved BHA Sag Correction and Uncertainty Evaluation Brings Value to Wellbore Placement." 2006. SPE 102088

Abstract: Not applicable for this slideshow

Toh, H., T. Goto, and Y. Hamano. "A new seafloor electromagnetic station with an Overhauser magnetometer, a magnetotelluric variograph and an acoustic telemetry modem." *Earth, planets and space* 50, no. 11-12 (1998): 895-903. https://www.jstage.jst.go.jp/article/eps1998/50/11-12/50_11-12_895/_article

Abstract: A new type of Sea Floor Electro Magnetic Station (SFEMS) has been newly developed by adding a magnetotelluric (MT) variograph to its prototype built previously (Toh and Hamano, 1997). New SFEMS is able to conduct long-term electromagnetic (EM) observations at the seafloor, which is one of the principal goals of the Ocean Hemisphere Project (OHP). Long-term seafloor EM observations enable us to probe into the deep Earth (both the mantle and the core) by improving the spatial coverage of the existing EM observation network. The SFEMS has been tested in three sea experiments to yield 3 components of the geomagnetic field, 2 horizontal components of the geoelectric field and 2 components of tilts in addition to the absolute geomagnetic total force. The SFEMS is designed for measuring these EM signals at the seafloor continuously for as long as 2 yrs. The SFEMS mainly consists of the following three parts: (1) An Overhauser proton precession magnetometer for the absolute measurements of the geomagnetic total force with a possible bias of less than 10 nT. (2) An MT variograph that measures the rest of the EM components and tilt. (3) An Acoustic Telemetry Modem (ATM) that allows us to control/monitor the seafloor instrument as well as data transmission at the maximum rate of 1200 baud. Construction of seafloor EM observatories in regions where significant EM data have never been collected is now quite feasible by development of the SFEMS.

Williamson, H. S., P. A. Gurden, D. J. Kerridge, and G. Shiells. "Application of interpolation in-field referencing to remote offshore locations." In *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers, 1998. <https://www.onepetro.org/conference-paper/SPE-49061-MS>

Abstract: A method for modelling the crustal magnetic field vector from total intensity data has been used to determine the magnetic field snapshot required for Interpolation In-Field Referencing (IIFR). The method has been validated in a number of ways, including comparison of magnetic and gyroscopic survey data in three UK fields.

Williamson, H. S. "Accuracy prediction for directional measurement while drilling." *SPE Drilling & Completion* 15, no. 04 (2000): 221-233. <https://www.onepetro.org/journal-paper/SPE-67616-PA>

Abstract: In this paper a new method for predicting wellbore position uncertainty which responds to the current needs of the industry is described. An error model applicable to a basic directional measurement while drilling (MWD) service is presented and used for illustration. As far as possible within the limitations of space, the paper is a self-contained reference work, including all the necessary information to develop and test a software implementation of the method. The paper is the product of a collaboration between the many companies and individuals cited in the text.

Worzewski, T., M. Jegen, H. Kopp, H. Brasse, & W. Taylor: Magnetotelluric Image of the Fluid Cycle in the Costa Rican Subduction Zone. *Nature Geoscience*, 2011, vol. 4 (2), pp. 108-111. <http://adsabs.harvard.edu/abs/2011NatGe...4..108W>

Abstract: Fluids entering the subduction zone play a key role in the subduction process. They cause changes in the dynamics and thermal structure of the subduction zone¹, and trigger earthquakes when released from the subducting plate during metamorphism. Fluids are delivered to the subduction zone by the oceanic crust and also enter the oceanic plate as it bends downwards at the plate boundary. However, the amount of fluids entering subduction zones is not matched by that leaving through volcanic emissions or transfer to the deep mantle, implying possible storage of fluids in the crust. Here we use magnetotelluric data to map the entire hydration and dehydration cycle of the Costa Rican subduction zone to 120 km depth. Along the incoming plate bend, we detect a conductivity anomaly that we interpret as sea water penetrating down extensional faults and cracks into the upper mantle. Along the subducting plate interface we document the dehydration of sediments, the crust and mantle. We identify an accumulation of fluids at ~20–30 km depth at a distance of 30 km seaward from the volcanic arc. Comparison with other subduction zones indicates that such fluid accumulation is a global phenomenon. Although we are unable to test whether these fluid reservoirs grow with time, we suggest that they can account for some of the missing outflow of fluid at subduction zones.

8. Appendix - Technical Notes and Previous Work

8.1 General

In this section, we expand in more depth regarding existing work on IFR and disturbance field characterization and mitigation methods. Each is used to reduce the error of geomagnetic reference fields used during horizontal drilling operations.

8.2 Positional Error Models

There are numerous error sources associated with MWD survey measurements and each error source contributes in some form to the magnitude of uncertainty that propagates along the computed wellbore trajectory. The Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) developed a framework for quantifying the magnitude of uncertainty, described by Williamson (2000). The Operator's Wellbore Survey Group (OWSG), a sub-committee of the ISCWSA, continued development on the original error model and publishes a set of Instrument Performance Models that enable the computation of ellipses of uncertainty for specific surveying methods. This consolidated set is referred to as the OWSG set of tool codes. As of this study, this set of tool codes has been revised once, resulting in OWSG Rev-2. The standard MWD error model in OWSG Rev-2 has been made consistent with the standard MWD error model in ISCWSA Rev-4. Note that the OWSG set contains a much larger set of tool codes than ISCWSA Rev-4. The OWSG tool codes are described in detail in Grindrod et al., 2016.

One of the largest sources of positional error is the uncertainty in the geomagnetic reference field, in particular when using global geomagnetic reference models. Confidence limits for geomagnetic reference models were derived by (Macmillan, McKay & Grindrod, 2009). Characterizations of geomagnetic error sources were further provided for global geomagnetic field models by Maus et al., (2010). The disturbance field error model coefficients for OWSG-Rev2 were derived and presented by Maus et al. (2014).

8.3 Solving MWD Challenges With IFR

There are numerous cases which already demonstrate challenges of MWD and the mitigation of these challenges utilizing IFR. Jeanne d'Arc basin off the coast of Eastern Canada, where extensive faulting makes precise wellbore positioning especially challenging. The newer IFR methods for correcting errors accurately are required to enable drilling into multiple small geological targets and avoid costly collisions between adjacent wellbores (Poedjono et al. 2011). All together, these challenges require more accurate surveys, improved descriptions of positional uncertainty, and a reduction in error ellipse size. For drillers, this translates into the ability to hit smaller targets, greater drillability, and a potentially significant reduction in drilling time and cost. In addition, geologists and geophysicists benefit from having higher confidence in the ability to penetrate the geological targets successfully (ibid).

Accurate wellbore positioning is also a significant challenge in the Frade field, a deep-water heavy oil project offshore Brazil (Poedjono et al. 2012). This project has been

historically, technically, and economically challenging due to the inherent subsurface and surface complexities, which alone might have prevented the development of this asset, as the structure is a low-relief anticline with two main fault blocks, consisting of three stacked reservoirs, and spanning an area of 20 km². The unique challenge in magnetic surveying in this region is the wide discrepancy between downhole tool readings and the British Geological Survey (BGS) Global Geomagnetic Model (BGGM), which was previously used to provide the magnetic reference field at a coarse 400-km resolution. An improved understanding of natural variations in the local magnetic field is essential for a successful development of the field (ibid). In the project outlined in Successful Application of Geomagnetic Referencing for Accurate Wellbore Positioning in Deepwater Project Offshore Brazil (Poedjono et al. 2012), collaboration among operator, contractors and academic experts, and the development of the High-Definition Geomagnetic Model (HDGM) by the United States National Geophysical Data Center improved the spatial resolution to 30 km. Integration with the Bacia de Campos aeromagnetic survey (the methodology of aeromagnetic surveying is presented elsewhere) helped account for the entire spatial spectrum of the geomagnetic field, down to the kilometer scale (ibid). This integration allowed for higher accuracy wellbore positioning during drilling.

8.4 Creating An IFR Model

As previously noted, three of the four contributing factors of the magnetic field are accounted for by IFR. IFR makes use of linear filter theory, as detailed by William C. Dean (1958), which explains the process of distorting geophysical data in desirable ways, using analytic continuations, second derivative, and smoothing techniques to suppress some characteristics of the data while emphasizing others that were not evident on the original map. Objects like mountains alter aeromagnetic surveys through their detection of long wavelength anomalies, which must be managed through downward continuation mathematics. At the same time, short wavelength anomalies present in the ground beneath the mountains, such as a pipeline or mineral deposit, may be missed without amplification through this data filtration method.

Earlier IFR methods were based on flat-Earth approximations using Fourier transforms (e.g. Dean 1985; Russel Shiells and Kerridge, SPE 30452, 1995) or the equivalent source method (Dampney 1969; Macmillan & Billingham, ISCWSA-40, 2014). However, according to Maus et al. (2017), creating an IFR model requires capturing the full spectrum of spatial wavelengths of the geomagnetic field. Satellite measurements account for the long-wavelength (266-2,500 kilometer) crustal field as well as the main field, secular variation and steady external field. A local magnetic survey provides the shorter wavelengths by accurately mapping local crustal field anomalies. To provide a model that is continuous across the geomagnetic spectrum, the local magnetic survey is extended by merging it with a larger regional survey. The merged grid is then further extended to cover the longest wavelengths by merging with satellite measurements. The merging of these different datasets must be evaluated at the same altitude and must make seamless boundary transitions.

While there are often global surveys from which data can be drawn to create a three-dimensional IFR model -- one global model being the British Geological Survey (BGS) Global Geomagnetic Model (BGGM) (Poedjono et al.) -- some areas are particularly

difficult to account for due to weak or inaccurate data and, in some regions, there may be no data at all. In these instances, commissioning an aeromagnetic survey can allow directional drilling companies region-specific data tailored to lease agreement boundaries. Aeromagnetic surveys, however, present unique challenges due to topography and altitude that require retroactive data analysis before the surveys can be used for disturbance field detection and error modeling.

Local magnetic surveys only specifies the total strength of the magnetic field vector, and MWD requires accurate modeling of the direction of the magnetic field vector. It is possible to accurately determine the direction of the magnetic field by representing its vector as the gradient of a scalar potential using ellipsoidal harmonic basis functions.

Brazil's deep-water project offshore provides one example of aeromagnetic surveying, resulting in initial large discrepancies between downhole tool readings and the British Geological Survey (BGS) Global Geomagnetic Model (BGGM) (Poedjono et al.). A new method of mapping the natural variations was developed off the High-Definition Geomagnetic Model (HDGM) by the United States National Geophysical Data Center, which improved the spatial resolution to 30 km. By integrating this large-scale magnetic field study with the Bacia de Campos aeromagnetic survey, scientists accounted for the entire spatial spectrum of the geomagnetic field, down to the kilometer scale (ibid), thus resulting in improved directional accuracy and generally a more vivid representation of the drill's location three-dimensional space at a given moment in time.

The criticality of wavelength variety in creating an IFR model has led scientists and industry leaders to seek multiple sources of data to mitigate disturbance field anomalies and correct uncertainty values (Toh et al. 1998, Toh et al. 2010, Maus et al. 2015, Poedjono et al. 2014, Macmillan et al. 2009). For sub-ocean and offshore drilling operations, sheer distance from the shore previously limited drillers' capability of maintaining directional accuracy (Williamson et al. 1998), yet the integration of Interpolated IFR (IIFR) methodology as well as the use of data generated from remote observatories has proven especially valuable (Macmillan et al. 2009), later allowing analysts the capability of manipulating and combining data from a plethora of sources, thus strengthening the accuracy of an IFR model.

8.5 Case Study In Disturbance Field Mitigation

Disturbance field mitigation has been employed to monitor and correct directional surveys at the Haltenbanken area of the Norwegian Sea over a period of about 2 years with an increasing number of geophysical observation stations in Norway and Denmark, maintained by the Tromsø Geophysical Observatory (TGO) (Edvardson et al. 2013). Because the magnetometer cannot be mounted on the rig and seabed magnetometers are not easily available and tested in the water surrounding Norway, the TGO are forced to rely on magnetometers onshore, often as much as 100 km away, potentially compromising the accuracy of the data collected (Edvardson et al. 2013, Edvardson et al. 2014, Williamson 1998). Haltenbanken is located approximately 200 km west of the Norwegian coast at a latitude of 65°N, where magnetic-storm activity often has a significant effect on directional surveying. A monitoring station was set up on the coast at the same geomagnetic latitude as Haltenbanken and, to test the idea

that magnetic disturbances are similar along constant magnetic latitude, an additional monitoring station was established 200 km east of the main station

A main result of this case study by Edvardson et al. (2013) was positive confirmation of the following: the theory of similar and nearly simultaneous magnetic disturbances along the geomagnetic latitude of several hundreds of kilometers; the locations of monitoring stations relative to the drill site are important for effective monitoring of electro-jet currents (Poedjeno et al. 2014); placing the monitoring station on the same geomagnetic latitude as the drill site provides better correlation of total intensity and dip angle, and allows useful correlation of all three magnetic-field elements at distances up to 500 km from the rig site; disturbance field correction methodology can be usefully applied to distant off-shore drill sites at high latitudes, improving directional control and increasing wellbore-survey accuracy for MWD operations.

8.6 The Disturbance Function Method

While the IIFR methods performs a spatial interpolation between surrounding observatories without taking specific properties of the disturbance field variations at the drill site into account, the patent pending disturbance function (DF) method (Maus and Poedjono. 2015) relates the remote observatories to time series at the drill site from a temporarily deployed station. Such temporary deployments without real-time connection for a limited period of about 3 months are relatively easy to carry out and therefore cost effective. By making use of the “training” data set from the drill site, the method achieves significantly higher accuracy than IIFR, as was demonstrated in predicting the values at the Deadhorse Observatory from the Barrow observatory. In see Figure 8.1 the shaded areas represent models with changing degree and resolution. The latest BGGM extends to degree 133. The red shaded area corresponds to the part that is missing from the field model and is referred to as the omission error.

Given the proximity the Deadhorse Field to the arctic, the employment of disturbance function corrections results in the ability to combat these high-latitude challenges, which is presented in greater detail in the disturbance field characterization field section. What is critical is the collection of accurate data collection and analysis in these near-polar regions, where magnetic disturbances are particularly prominent.

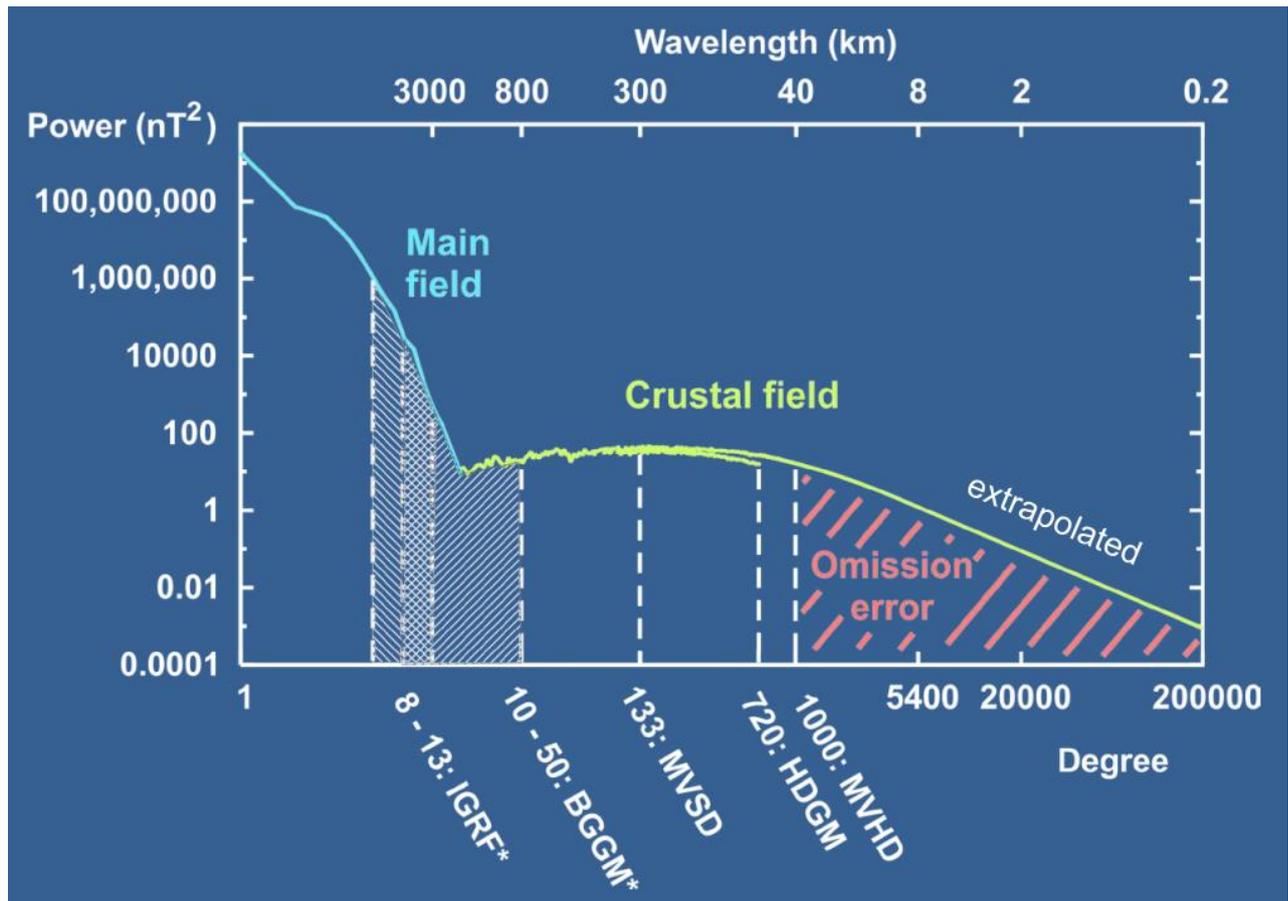


Figure 8.1: Global power geomagnetic power spectrum

8.7 Remote Observation Through Land & Seafloor Magnetometers

Since as early as the early 1980's, construction of seafloor electromagnetic (EM) observatories has been pursued for scientific studies offshore Japan (Segawa et al., 1983), especially in regions where significant EM data have never been collected. These techniques have become increasingly feasible due to the development of the Sea Floor Electro-Magnetic Station (SFEMS) (Toh et al. 1998, Toh et al. 2010). Two kinds of observations are now available: real-time monitoring of seafloor EM fields by deploying semi-permanent infrastructure and off-line measurements by long-life pop-up type instruments. Monitoring of Earth's geoelectric field by employing trans-ocean submarine cables (Lanzerotti et al., 1985) is a typical example of the former while the latter is accomplished by several international cooperative projects including the Mantle Electromagnetic and Tomography (MELT) experiment (Forsyth and Chave, 1994).

In Japan, the Ocean Hemisphere Project (OHP) has been in operation since 1996, which is also a seismic-EM joint project like MELT to probe into the deep Earth through the ocean window. Even more recently, similar studies on ocean-based seismology also utilize SFEMS, as these tools are capable of measuring both scalar and vector geomagnetic fields in addition to the seafloor instrument's precise attitudes. This makes it a valuable tool in detecting the so-called oceanic dynamo effect (Toh et al., 2016). These stations are able to conduct long term electromagnetic (EM) observations

at the seafloor over the course of multiple years, which is one of the principal goals of the OHP. Long-term seafloor EM observations enable stakeholders to probe into the deep Earth (both the mantle and the core) by improving the spatial coverage of the existing EM observation network, while generating historical data that can be used to mitigate disturbance (Toh et al. 1998, Toh et al. 2010).

Placing, maintaining, and receiving data from an SFEMS adds complexity to sub ocean directional magnetic MWD operations, yet, as shown previously, the benefits of properly-placed wellbores are numerous (Maus et al. 2017). To more reliably predict the disturbance field at a drill site using in-situ measurements on the seafloor, three ocean bottom vector magnetometers (OBMs) must be deployed near the drill site to monitor the disturbance field over a period of 6 months (Maus et al. 2015). This enables the computation of a disturbance function relating the measurements of multiple neighboring variometers. Two disturbance field prediction methods can be compared in such a study: (1) a simple linear interpolation between the surrounding stations using the traditional method of Interpolated In-Field Referencing (IIFR), versus (2) the disturbance field function (DFF) method (ibid). Such a study is described in the later sections of this report.

Deploying a seafloor observatory without real-time capability is relatively simple and can be very cost effective. Geomar has developed an ocean bottom magnetometer (OBM) featuring a triaxial fluxgate (Jegen & Edwards, 1998, Worzewski et al., 2011). This magnetometer, which is small and easy to handle, is housed in a pressure-tight glass sphere and is equipped with a timed release which enables free-fall installation and automatic recovery. The maximum period of measurement is 90 days with 3-minute samplings and the accuracy of the measurement is ± 0.8 nT. This corresponds to the error of ± 1 least significant bit unavoidable in digital conversion using a 16-bit AD converter. Geomar has developed a similar product in more recent years, which can perform two types of experiments: Magnetotelluric (MT) measurements and Controlled source electromagnetic (CSEM) measurements (Jegen-Kulczar 2014).

A more recent development in robotic autonomous marine vehicles is the Wave Glider by Liquid Robotics (Monk et al. 2014), which shows promising results for disturbance field monitoring. It can either directly measure variations in the total magnetic field, or it can act as a real-time satellite relay by using acoustic signals transponded to the vehicle from a seafloor magnetometer to the ocean-surface, and then sent by satellite to the desired location, allowing for real-time data collection (Poedjono, B., et al. 2014).

In a case study by Stefan Maus and Benny Poedjono (2014), the mean ocean depth where the measurements were taken as deep as 4837 meters. Working in tandem, two Wave Gliders collected electromagnetic data transmitted via satellite as the vehicle follows a rectangular pattern in the ocean. This movement accounts for the inability to keep the unit stationary. Differences in the crustal field along the rectangle result in the measurement of a crustal magnetic gradient. This gradient has to be subtracted from the data before treating the residuals as time variations of the total magnetic field. The data in the southwest corner of Figure 8.2 has lower magnitudes than that in the northeast corner. The second variation is an additional vertical scatter at all the grid points. The plane displayed above represents the post-deployment data analysis to

remove data leaks due to spatial gradient caused by UAV's movement through ocean, as drifting can cause data to become unviable.

The data in Figure 8.2 demonstrates the estimated crustal gradient after being removed from the measured data to recover time variations of the disturbance field. Red lines show original measurements, blue lines represent the corrected data from this procedure, and the green line shows the geomagnetic data at HON observatory. Once this crustal contamination is removed, the RMS error between the vehicle and HON observatory decreases from 11.2 nT to 1.9 nT (Poedjono, B., et al. 2014)

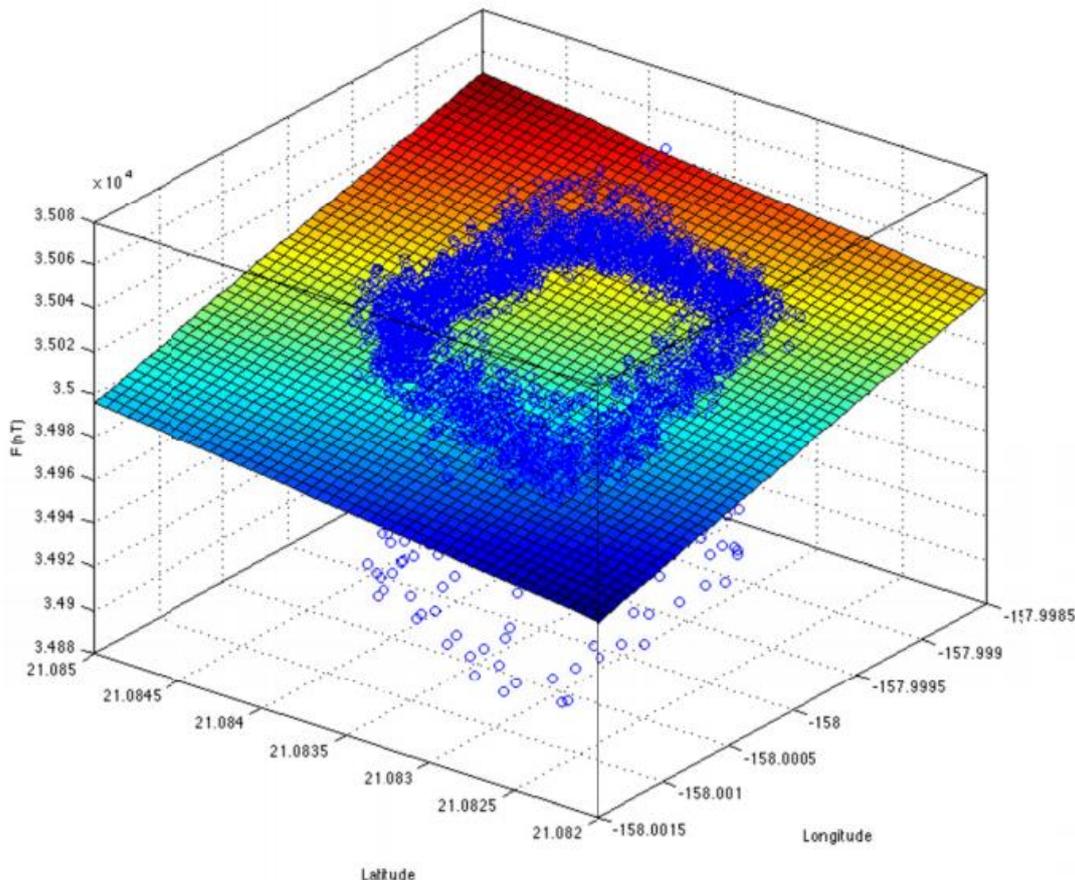


Figure 8.2: Estimated crustal gradient over region of Waveglider motion (Maus et al.) 2014

Oscillations in the original data as seen in Figure 8.3 are due to the vehicle sampling the crustal field on its rectangular paths. If the dimension of the vehicle's cruising rectangle is larger than the depth of the sources of the crustal field or any man-made metallic installations on the seafloor, the strong crustal gradient may be difficult to remove, even when magnetic disturbance field activity is moderate. In this case, data from another platform (for example, an observatory) may be used to first remove the time variations commonly present in both the data sets, before attempting to fit and remove the crustal field effects (Poedjono, B., et al. 2014).

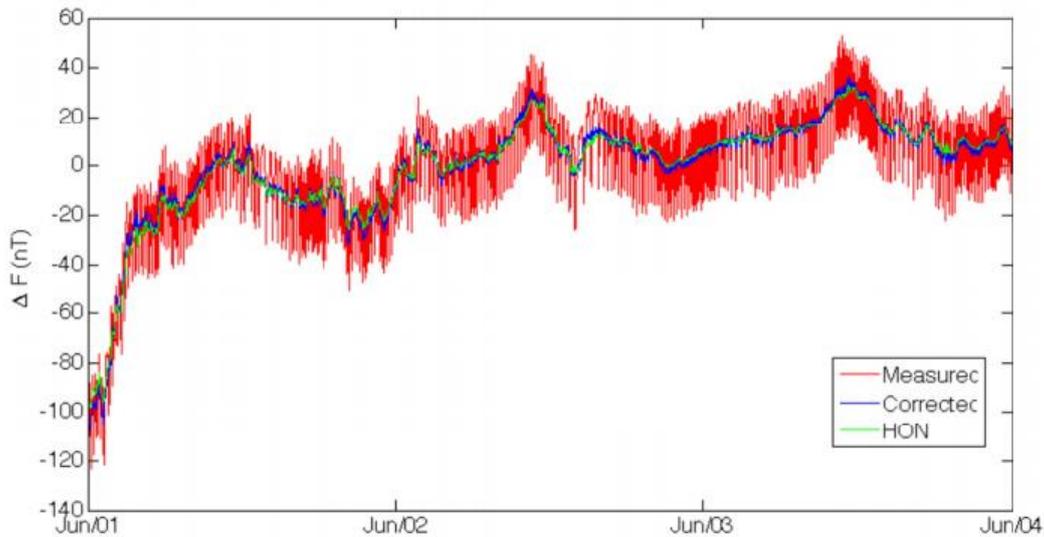


Figure 8.3: Disturbance measured by Waveglider (Maus et al. 2014)

Land based observatories in Alberta, Canada were found to provide special value when responding to electromagnetic storm disturbances for Meanook in March 2015 (Figure 8.4). Much like in the aforementioned Haltenbanken area of the Norwegian Sea (Evardsen et al. 3013), these time-dependent current fluctuations in the Earth's ionosphere cause inaccuracies in wellbore directional surveying, which only increases at higher latitudes. Although monitoring and correction are possible, they become less valid as the distance between the monitoring site and the rig site increases, which is a particular problem for offshore drill sites.

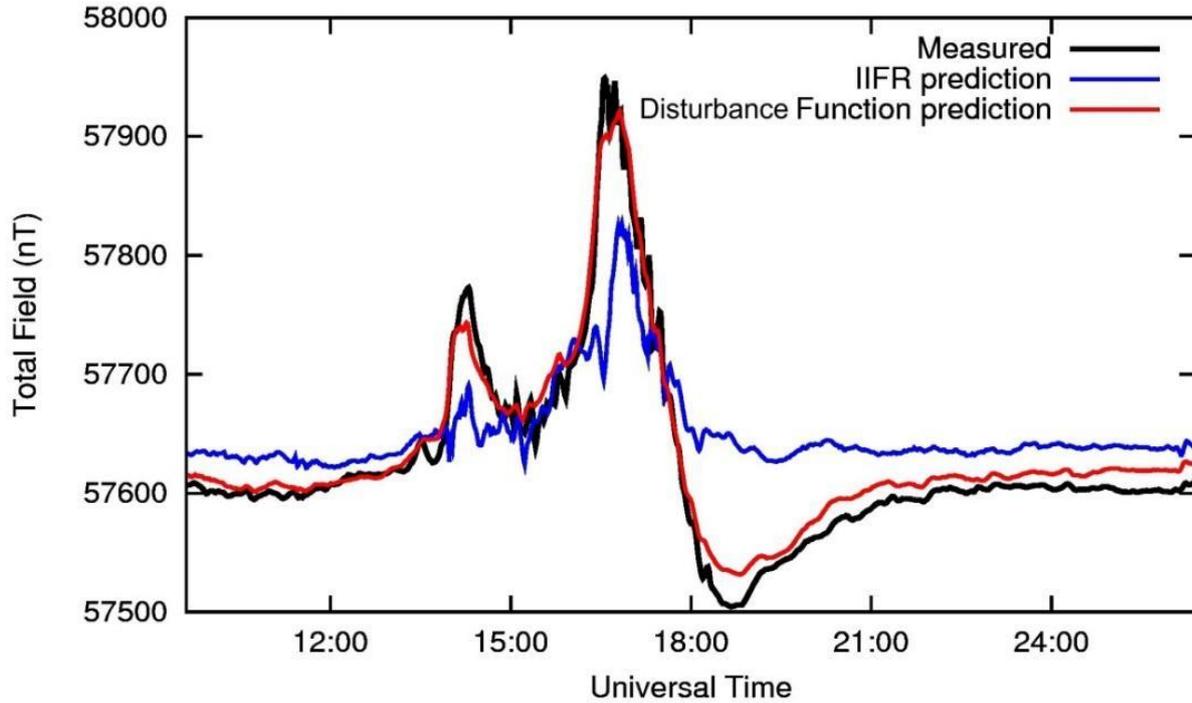


Figure 8.4: Measured disturbance field at Deadhorse (black) with IIFR (blue) and disturbance function (red) prediction from BRW, located 300 km to the west.

9. Acknowledgements

This study is based on magnetic data from the geometric observatories and variometers below. The authors are grateful to the organizations and individuals maintaining this essential infrastructure.

- Natural Resources Canada
- World Data Centre for Geomagnetism (Edinburgh)
- Institute of Geophysics, Polish Academy of Sciences (Poland)
- Geological Survey of Canada (Canada)
- U.S. Geological Survey: Geomagnetism (USA)
- International Service of Geomagnetic Indices (France)
- British Geological Survey (Great Britain)
- Halliburton
- Institute of Ionosphere, Republic Kazakhstan (Kazakhstan)
- Geophysical Observatory of Addis Ababa University (Ethiopia)
- Indian Institute of Geomagnetism (India)
- Geological Survey of Sweden (Sweden)
- National Antarctic Scientific Center (State Committee of Ukraine on Science, Innovation and Informatization) (Ukraine)
- Ecole et Observatoire des Sciences de la Terre (France)
- Ministry of Natural Resources & Environment - Meteorology Division (Western Samoa)
- Istituto Nazionale di Geofisica e Vulcanologia (Italy)
- Geophysical Institute, Academy of Sciences of the Czech Republic (Czech Republic)
- Institute of Geophysics Polish Academy of Sciences (Poland)
- DTU Space, National Space Institute, Technical University of Denmark (Denmark)
- Institute of Geology and Geophysics, Chinese Academy of Sciences (China)
- Institut de Recherche pour le Développement (France)
- United States Geological Survey (United States of America)
- Geophysical Center of the Russian Academy of Sciences (Russia)
- Institut de Physique du Globe de Paris (France)
- Geoscience Australia (Australia)
- China Earthquake Administration (China)
- Institute of Geophysics of the Vietnamese Academy of Science and Technology (Vietnam)
- Royal Meteorological Institute of Belgium (Belgium)
- Observatori de l'Ebre - Instituto Geografico Nacional (Spain)
- Ludwig Maximilians University Munich (Germany)
- Geophysical Institute of Grocka (Serbia)
- South African National Space Agency (South Africa)
- Geophysical Institute of Slovak Academy of Sciences (Slovakia)
- Instituto Geofísico del Perú (Peru)
- National Geophysical Research Institute (India)
- Dirección Meteorológica de Chile (Chile)

- Institute of Solar-Terrestrial Physics of Siberian Branch of the Russian Academy of Sciences (Russia)
- Earthquake Research Institute (Turkey)
- Japan Meteorological Agency (Japan)
- Institute of Geophysics of the National Academy of Sciences of Ukraine (Ukraine)
- South African National Space Agency (South Africa)
- Directorate General of Telecommunications
- Institute of Cosmophysical Researches and Radio Wave Propagation-RAS (Russia)
- Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences (Hungary)
- Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences (Germany)
- Finnish Meteorological Institute (Finland)
- Altay-Sayan Branch of Geophysical Survey of Siberian Branch of the Russian Academy of Sciences (Russia)
- Bulgarian Academy of Sciences (Bulgaria)
- Institute of Geology and Mineral Exploration (Greece)
- Institute of Geophysics of the Vietnamese
- Servicio Meteorológico Nacional (Argentina)
- National Centre for Geophysical Research (Lebanon)
- Institute of Geological and Nuclear Sciences Limited (New Zealand)
- Real Instituto y Observatorio de la Armada (Spain)
- Sodankyla Geophysical Observatory, University of Oulu (Finland)
- Geological Institute of Romania (Romania)
- Centre de Recherche en Astronomie (Algeria)
- Institut et Observatoire Géophysique d'Antananarivo (Madagascar)
- Instituto de Geofísica - Universidad Nacional Autónoma de México (Mexico)
- Geological and Geophysical Institute of Hungary (Hungary)
- Universidad Nacional de la Plata (Argentina)
- The Irish Meteorological Service (Ireland)
- Arctic and Antarctic Research Institute (Russia)
- Observatorio Nacional (Brazil)
- Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS (Russia)
- UiT, The Arctic University of Norway
- Various small airstrip operators