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Abstract

Magnetic distortion of magnetometer readings affects the accuracy and efficiency of the wellbore positioning operations, which in turn degrades the industrial viability of the magnetic measurements while drilling survey instrument. Magnetic disturbances to the geomagnetic field reduces the wellbore positional accuracy and leads to uncertainties in the decision- making process. This master project provides an overview of the industrial limitations of magnetometers, highlights and maps the magnetic elements that affect the sensor readings. This leads to additional difficulties and uncertainties in the decision- making process, which is included.

The robustness and industrial capabilities of the interpolation in- field referencing method has been validated through presentation of case studies, mapping of its features and applications, comparison with other geomagnetic referencing techniques and analysis. This work concludes that the interpolation in- field referencing technique increases the accuracy of wellbore positioning and improves decision- making during drilling operations. However, limitations and shortfalls of the interpolation in- field referencing method were also recognized. These need to be addressed and corrected in order to reaffirm the industrial use of this survey method over competitive survey systems.

Acknowledgements

This thesis is the end product of a two- year master program on Petroleum technology with specialization in drilling and well technology. The last semester of the master studies has been allocated for this work. It has been a great experience but also a challenging one. I would like to express my greatest gratitude towards the major key players of this master project. These individuals have contributed in different forms to complete this thesis. The work would have been incomplete without the precious knowledge shared by these great people

The amount of enhanced knowledge has also been a major motivation. The topic of the thesis was introduced by Mr. Mike Herbert himself who always has been one of my main supporters. He has been a great influence and provided industrial knowledge and guidance throughout my academic journey. This thesis would have been incomplete without the precious inputs from him.

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This master project is dedicated to my beloved parents who have always supported me thru my whole life and their encouragement for this study.

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List of abbreviations and symbols

Abbreviation	Description
IGRF	International geomagnetic reference field
WMM	World magnetic model
MWD	Measurements while drilling
AC	Alternating current
DC	Direct current
BHA	Bottom hole assembly
NPT	Non-productive time
TF	Toolface angle
MDIP	Magnetic dip
WOB	Weight- on- bit
ISCWSA	Industry steering committee for wellbore surveying accuracy
LCM	Lost circulation material
3- D	Three-dimensional
HSE	Health, safety and environment
SPE	Society of petroleum engineers
NMDC	Non- magnetic drill collars
PSA	Petroleum safety authority
IFR	In- field referencing
IIFR	Interpolation in- field referencing
DFU	Defined hazard and accident situations
NPD	Norwegian petroleum directorate
BGS	British geological survey
UK	United Kingdom
NERC	Natural environmental research council
IAGA	International association of geomagnetism and aeronomy
IUGG	International union of geophysics and godesy
IGRF	International geomagnetic reference field

WDMAM	World digital magnetic anomaly map
SI	The International System of Units
BGGM	BGS global geomagnetic model
HDGM	High definition geomagnetic model
MD	Measured depth
RKB	Rotary Kelly bushing
MS	Multi- station analysis
SAG	Sag correction
RT	Real time
nT	Nanotesla

Symbol	**Description**
X	Northward intensity
Y	Eastward intensity
Z	Vertical intensity
∇x	Curl operator
H	Magnetic field
μ	Permeability
J	Density of the electrical current
$\frac{\partial D}{\partial t}$	Density of the electric displacement current
$\nabla \cdot$	Operator of divergence
B	Magnetic induction
V	Scalar magnetic potential
μ_0	Free space permeability
λ	Longitude
r	Radius
θ	90° minus the number of latitudes
p	Arbitrary point on the spherical coordinate system
a	Earth`s radius

g_l^m and h_l^m	Gauss coefficients
$P_l^m * \cos(\theta)$	Schmidts function

P and m coefficients announces the order

l	Harmonic degree
θ_{AZ}	Azimuth
γ	Inclination
m^2	Square meters
Km	Kilometres
K	Kelvin degrees
Kg	Kilograms
ε	Induced current
ΦB	Magnetic flux
dt	Rate of change
A	Area of an arbitrary object
ϑ	Angle between the area of the arbitrary object and the magnetic field though the object.
t	Time of interest
T_0	The epoch interval preceded time of interest or $T_0 \leq t \leq T_0 + 5.0$

$g_l^m(t)$ and $h_l^m(t)$ These two parameters characterizes the 5- year interval time derivation of the gauss coefficients. The unit of these two parameters are $\frac{nT}{year}$.

$B_{external}$	Magnetic contributions descending from electrical currents in the ionosphere and magnetosphere
$B_{magcrust}$	Magnetized crustal formations
$B_{geomangetic\ field}$	The earth’s magnetic field, which is generated in its core
ft	Feet

Chapter One: Introduction and problem statement

According to analysis and research [1] from the Norwegian continental shelf, more than half of the original oil reserves will remain in the reservoirs according to the plans for decommissioning drafted in 2011. From 2011 and until now, decommissioning plans and total recovery rates have been changed or improved. However, there is still an enormous potential in increased oil recovery for fields in production today. This potential is displayed by figure 1.1.

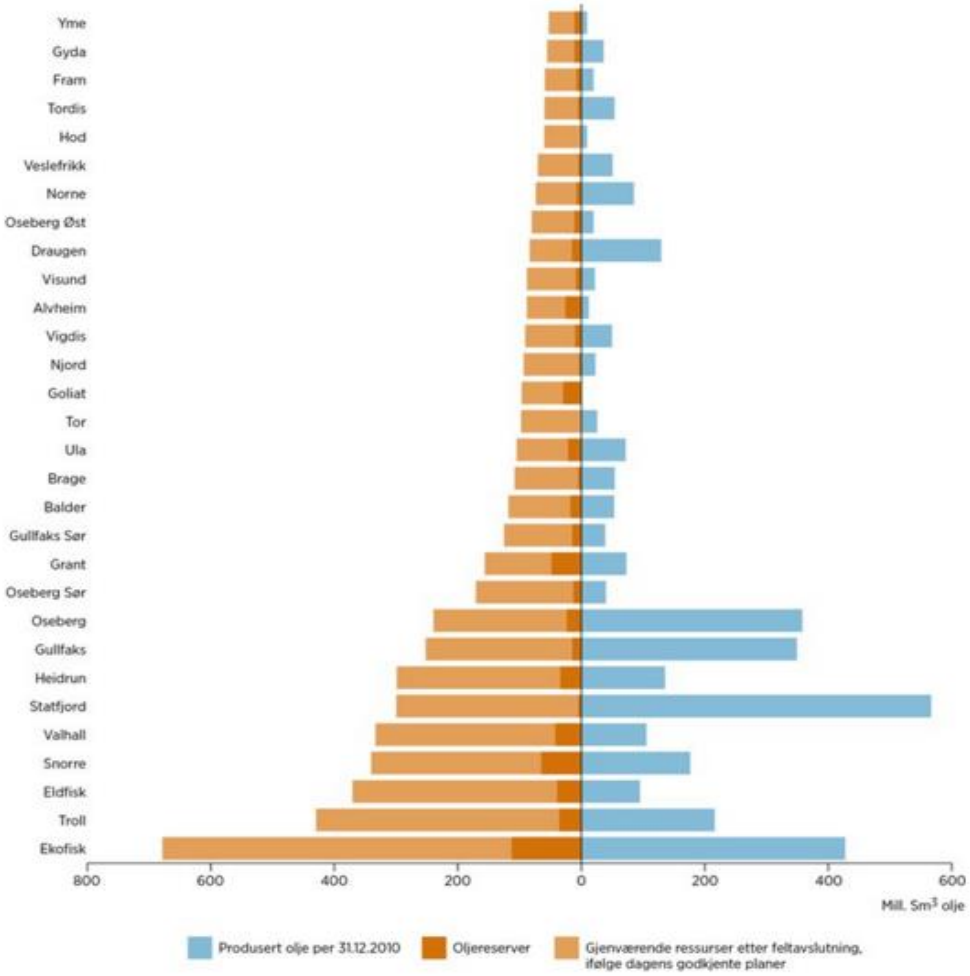


Figure 1.1: The relationship between already produced reserves, recoverable in- place reserves and in-place reserves after decommissioning [1]

In order to extract the vast quantities of immobile oil, it is important to perform research and conduct analysis on measures that improves the recovery rates. Another issue [1] that have been stressed by the NPD is the gradually reduction of hydrocarbon volumes extracted by already existing wells. Due to this deficit, operator companies operating on the Norwegian continental shelf finds it difficult to achieve annually pre-defined production targets. In order to fulfil this need, new and better positioned wells will be a prerequisite. Nevertheless, the staggering expenses related to drilling operations combined with low oil prices, extraction of the remaining oil volumes will not be economical viable. The solution will be an early decommissioning of the field, and lost revenues due to the unrecovered oil reserves in-place.

This issue have already been experienced on the Norwegian continental shelf [2]. Where production from the Varg field (located in the North Sea) is not economical viable due to low oil prices. However, the field still contains oil reserves to continue the production until 2021, but this will require new and improved positioned wells. Therefore, the final solution adopted by the operator company of this field is to decommission the field [2].

There has been a lot focus on injection of various chemical solutions, in order to enhance the recovery rates and cost reduction by various means. However, a potential solution to both of these two problems may be to improve the well positioning and navigation tools. By improving well positioning and placement apparatuses, enhanced oil recovery rates can be achieved alongside with wells that have an extended operating-period, which diminishes the need for early- new wells.

The service sector of the petroleum industry is saturated with systems and instruments for well positioning and navigation applications. These apparatuses differ from each other in terms of operating principles and functions. However, drilling operations requires precise descriptions of the wellbore depth, trajectory and direction for guiding the drillstring, both efficiently and safely. Therefore, the fundamental requirement is that: every well positioning instrument should be able to address and deliver accurate measurements of azimuth, inclination (drilling) and depth at all times. Currently, the gyroscopic survey instruments deliver the most accurate descriptions of the wellbore heading and direction [3]. However, this survey tool is associated with time- consuming operations, technical risks and high expenses.

An alternative to the gyroscopic instruments, are the magnetic MWD survey apparatuses. These instruments are comprised of a transmitter module and a sensors package, which includes tri-axial magnetometers and tri-axial accelerometers installed in three orthogonal orientations, fitted in a downhole probe. The accelerometers determine the toolface angles and borehole inclination (drilling) through measurements of the earth’s gravity, while the magnetometers determine the azimuth of the wellbore through measurements of the geomagnetic parameters.

The survey calculations extracted from the magnetic MWD survey instruments can contain errors descending from different factors: magnetic interference errors, calibration of sensors, inaccuracies in gravity models, bending, centralization errors, ballooning, thermal elements, misalignments and many more. However, the focus of this thesis is on the magnetic directional surveys of wellbores, since magnetic distortions to the magnetometer readings presents one of the major uncertainties in determination of the wellbore trajectory and direction.

In order to mitigate and minimize the survey uncertainties descending from magnetic sources, a technique named geomagnetic referencing is implemented. A common geomagnetic referencing method among survey crews has been to determine the geomagnetic parameters through estimations provided by a global geomagnetic model. However, this approach contains large uncertainties and errors, which in turn degrades the survey accuracy. Geomagnetic field models are programmed to provide estimations of the main core field only; such models are incapable to address contributions from magnetized crustal formations and external disturbances. Nevertheless, a geomagnetic referencing technique named IIFR holds the capabilities to address the contributions from the various magnetic sources. This technique incorporate measurements obtained from the magnetometers and magnetic observatories to provide accurate estimations of the magnetic field at the drilling site.

Fluctuations and disturbances in the geomagnetic field, threatens the accuracy and degrades the performance capabilities of the magnetic MWD survey instrument. Uncertainties and errors related to geomagnetic referencing is a global drilling survey challenge for the petroleum industry [4].

1.1 Thesis objectives

The main concern of this thesis is optimized wellbore positioning by utilization of the geomagnetic referencing technique named the IIFR method. Within this context, the project goals are as following:

- The primary goals of this master project is to map and identify applications and features within the geomagnetic referencing technique named interpolation in- field referencing (IIFR) with respect to:
    - Better well positioning.
    - Better decision making in directional drilling.
- Identify and point out limitations/shortfalls of the IIFR technique.

The main objective of this master project is to identify factors that affect the performance of IIFR.

The sub- goals of this thesis include:

- Describe and characterize the geomagnetic field.
- Point out applications of the geomagnetic field within the magnetic MWD survey tool.
- Present the principles, sensors configuration, functions and data integration of the magnetic MWD instrument. In other words, give an overview of this instrument from the drillbit to the surface.
- Highlight challenges and limitations of the magnetic MWD instrument, with respect to the magnetometers and data integration.
- Identify, map and address the various parameters and elements, which causes magnetic interference to the magnetometer readings and fluctuations to the geomagnetic field.
- Present the fundamental principles behind the survey process, and derive the central formulas for calculating important survey parameters that are utilized in directional drilling.
- Point out limitations and assumptions of the survey formulas used in directional drilling.
- Describe, introduce and highlight the benefits of geomagnetic referencing.
- Map the existing IIFR monitoring system of the geomagnetic field.
    - Put forward the developer`s story:
        - Study and present the functionality of this method.
        - Highlight features and applications developed for direction drilling.
        - Describe the operational sequence of this technique.
        - By implementation of this tool in the magnetic MWD instrument, which gaps will be filled?
- Identify and point out the industry challenges with respect to:
    - Well positioning from a survey viewpoint
    - Data integration, acquisition and processing

- Correlate the industry challenges to its needs and requirements.
- Assess and evaluate the practical performance of the IIFR method through:
    - Case studies/field cases
    - Conversations and meetings with subject matter experts
    - Comparisons with other geomagnetic correction models (IGRF) and survey tools.

1.2 Thesis outline

This master project is composed of five chapters. The 2nd chapter is intended to provide the background knowledge or necessary information, which is required for understanding the different themes and concepts discussed in the next two chapters. The main objective of this chapter is to function as a foundation, where the reader will be introduced to the main basics and industrial challenges. The 3rd chapter functions as an introduction to the solutions required to overcome the challenges presented in chapter 2. Chapter 3 will be used as a platform to present the IIFR technique as well as the global geomagnetic field model named IGRF. The functions and features of the IIFR method and IGRF model, which are used to monitor and correct the geomagnetic fluctuations at the drilling site and in well positioning, will be highlighted. The main objective of chapter 4 is to address the primary goals of this master project and provide an evaluation of the solutions presented in chapter 3. The applications and features of the IIFR method, which optimizes well positioning and decision-making will be highlighted in this chapter, alongside with its shortages and limitations. Chapter 4 provides an assessment of the advantages and limitations of the IIFR method through examination of case studies, comparison with other geomagnetic models and presentation of scientific analysis and research, involving the IIFR technique. The 5th and last chapter of this project provides a summary and concludes the main investigations of chapter 4. A recommendation is also included in chapter 5, which provides possible future studies and investigations based on the topics covered in this master project.

Chapter two: Fundamentals and theory

This segment contains a presentation of the geomagnetic field, in terms of characterization and structure. In order to obtain a holistic view of the magnetic MWD survey instrument, fundamentals of the geomagnetic field must be revised.

2.1 The geomagnetic dynamo effect

In order to explain the various processes and factors that gives rise to the geomagnetic field, a further investigation of the earth's inner and outer core is required. The inner core is the region that takes up the place at the centre of the earth. This compartment is mainly solidified and has a radius of around 1200 km. Iron and nickel is the most abundant elements in this area, but other metals can also be found in smaller quantities.

The temperature at this region is about 5400 °C, similar to the sun`s surface. Even though this portion of the earth holds such large temperatures, it will preserve its solidity. It will do so primarily due to the large pressures exerted by the gravity on this portion of the earth.

The outer core of the earth is in a complete divergent physical state than the inner core. The main reason behind this differentiation is the pressure and temperature differences. This territory consist of mainly liquefied iron – nickel alloy, with temperatures in the range of 4000 °C. This liquefied segment is in continuous motion, primary due to convection and the Coriolis effect.

The magnetic field exerted by the earth is a complex phenomenon, governed by several processes and reactions. For simplicity, it is a common practice to think of a permanent bar magnet that is located in the centre of the earth. This magnet has a north and south pole, which gives rise to a continuous magnetic field. Such an interpretation of the earth is a misconception, since the Curie temperature for iron is around 770 °C. The heat gradient in the inner core is a lot higher, which rends the solid inner core for magnetic properties. The Curie temperature of a material or element is defined as the critical point, where temperatures above this level will cause the material to lose its permanent magnetic characteristics. The permanent magnetic ability of a material will be replaced with induced magnetism, when exposed to temperatures above its Curie temperature.

The earth's magnetic field is generated through a process named the geomagnetic dynamo effect. This process is a multi- step reaction, which demands that the following elements and conditions are fulfilled:

1. A conductive liquid. This element will empower the induction process and assist currents to move effectively, without restrictions. This in turn will enhance the propagation of the magnetic fields.
2. Magnetic fields are generated by moving charges or by currents running through a conductive material. In other words, to produce such fields: a dynamic environment is required. This demand is met when the fluid has sufficient flow velocity and proper flow pattern.

3. A source of energy. Continuous input of energy will be necessary to sustain various dynamical processes and environments.
4. Electromagnetic induction.
5. An external magnetic field.

Most of these conditions and necessities are fulfilled in the earth`s outer core. This region consist of liquefied metal, which is an appropriate conductive material. Beside from that, two major effects that are generated in this compartment contributes to accomplish the requirements: the Coriolis effect and convection currents. These two processes are essential and plays a key role in generating the earth’s magnetic field.

The Coriolis effect is primarily a result of the earth spinning. Major contributions by this effect are as following:

1. All magnetic fields, which develops in every compartment (magnetic domains), must be aligned in order to give rise to a distinctive field. This effect combines all the minor fields generated in the earth’s outer core to one apparent field. Without this effect, all the small fields generated by the various domains would have balanced each other out. Beside from that no recognizable North-and South Pole would have existed without this effect.
2. Provides and maintains a dynamical environment in the liquefied metal core. This effect generates spherical/whirlpool type of flow regimes. These flow regimes assists the induction process and expands the magnetic fields throughout the outer core.

The convection process is empowered by continuously inputs of thermal energy from the solid inner core. This physical phenomenon will help the liquefied metal to distribute through the various magnetic fields generated in the outer core.

The sun provides the external magnetic field. As a compartment of liquefied metal moves through the external field, circulating electrical currents will be induced. This process is named electromagnetic induction. The circulating electrical currents will in turn produce its own magnetic field. This process combined with the dynamic fluid environment existing in the earth’s outer core, will bolster the original magnetic field.

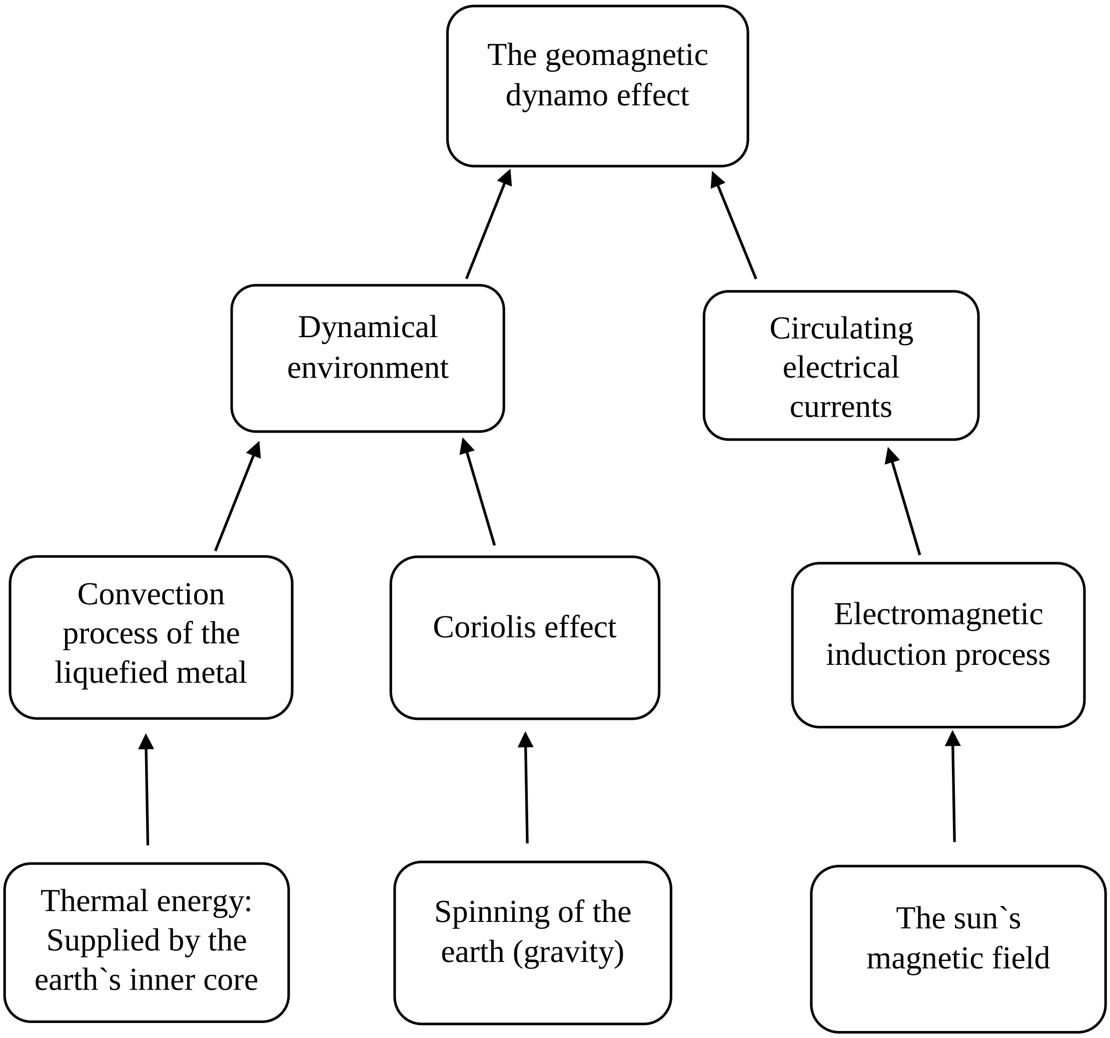


Figure 2.1: Summary of the geomagnetic dynamo effect

2.2 Basics and Characteristics of the earth’s magnetic field

2.2.1 Structure

The structure of the geomagnetic field can be related to a dipole field generated by an enormous magnetic bar located inside the earth. This magnetic dipole consists of two poles: the magnetic north pole and magnetic south pole. These two poles are positioned at their respective ends of the bar magnet. The geographical location of these two poles are defined where the magnetic field lines are completely vertical.

The magnetic north pole is positioned near the south geographical pole of the earth, and the south magnetic pole is located close to the north geographical pole. The geomagnetic field strength is highest at the magnetic poles, where the field lines converge together and forms a distinct magnetic field. The magnitude of the geomagnetic field is lowest at the equator, where the field lines diverge away from each other. Beside from that, magnetic field lines exerted by the earth, travels from the magnetic north pole to the magnetic south pole.

The magnetic axis of the earth is not aligned with its geographical axis. There is a slight divergence of around 11,5° from the geographical axis. The magnetic poles are not interlinked to each other; they drift independently and are not completely opposite each other. Beside from that, their field magnitude will also alter with position and time.

The magnetic field lines cover a broad area; from the earth's interior to thousands of kilometres out in the space. The section around the earth, which is dominated by its magnetic field, is called the magnetosphere. Under ideal conditions, this region would look like a bubble, surrounding the earth. However, due to constant bombardment of particles from the sun, it is usually deformed and compressed. The influence of the sun on the earth's magnetic field will be covered later in the thesis.

Some rocks hold the capabilities to store the magnitude of the earth's magnetic field existing during their depositional time. Core analyses from such rocks, indicates that the orientation of the earth's magnetic field used to be different from what we observe today. These studies suggest that the orientation of the dipole segments reverses. This reversal process occurs at irregular periods, without showing any fixed patterns. Nevertheless, analyses of rocks and studies of the suns magnetic field indicates that during a reversal, the field magnitude will experience a deficiency to zero, while the dipole orientation is fixed. After this stage, it regains its departed strength, but this time with an opposite orientation of the dipole. Geomagnetic reversals can be predicted through experiments and analyses. These phenomenons happens in the order of magnitude of several ten- thousands of years.

2.2.2 Characteristics

In terms of geographical positioning, the magnetic field can be described in several ways. The most common method is to quantify the field in terms of a geomagnetic vector ($\vec{B}$). This vector can be decomposed into seven components, which again can be organized into two groups:

Orthogonal parameters	**Directional parameters**
Total intensity (F)	Declination (D)
Northward intensity (X)	Inclination (I) or magnetic dip
Eastward intensity (Y)	
Horizontal intensity (H)	
Vertical intensity (Z)	

Table 2.1: Classification and components of the geomagnetic field

The declination is measured as an angle along the horizontal direction. This angle describes the difference between the magnetic north and the true geographical north. This component of the field is not a constant parameter; it is a function of time and geographical location.

The inclination is also referred to as the magnetic dip. This component is quantified as an angle between the horizontal plane of the earth and the magnetic field lines. The maximum and minimum values of this parameter can be found at the magnetic south (-90°) and magnetic north (90°) poles of the earth.

The total intensity expresses the magnitude of the magnetic field, when it is pointing towards the centre of the earth. This parameter is generally expressed in number of nanotesla (nT), and can be found within the following interval at the surface of the earth: 22 000 – 67 000 nT [5].

The rest of the orthogonal parameters simply represent the magnitude of the magnetic field in their respective directions, expressed in nT .Their directions are showcased by the figure below.

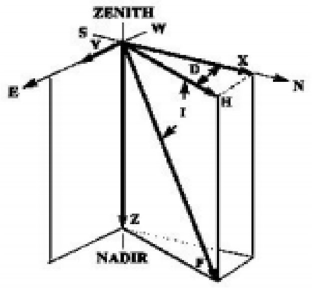


Figure 2.2: Orthogonal and directional parameters [6]

The mathematical relation between these parameters can be derived by utilizing simple geometrical correlations:

$$F = \sqrt{Z^2 + H^2} \tag{2.1}$$

$$H = \sqrt{Y^2 + X^2} \tag{2.2}$$

$$I = tan^{-1}\left(\frac{Z}{H}\right) \tag{2.3}$$

$$\mathrm{D} = tan^{-1}\left(\frac{Y}{X}\right) \tag{2.4}$$

2.2.3 Mathematical description

Even though the magnetic field of the earth is a complex phenomenon, dominated by continuous changes and disturbances: it is still possible to describe the field by utilizing an analytical approach. A mathematical description of the field can be derived by solving the Laplace`s equation with the help of spherical coordinates, which is also referred to as spherical harmonic expansion. This analytical expression is utilized as the main foundation for many programs and models that monitor the earth’s magnetic field, such as the IGRF and WMM [5]. Before deriving the solution of the Laplace`s equation, it is important to state the foundational assumptions, which the solution is based on:

- The earth is shaped as an ideal sphere, without any deformations.
- Contributions from external sources to the earth`s magnetic field is assumed to be negligible. This also includes electrical currents on the surface of the earth.
- The domain is dominated only by the main field, coming from the earth's interior.

Two of the Maxwell's equations linked to the magnetic field are:

$$\nabla x H = \mu\left(J + \frac{\partial D}{\partial t}\right) \qquad (2.5)$$

$$\nabla \cdot B = 0 \qquad (2.6)$$

By utilizing the assumptions, equation (2.5) is simplified into the following form:

$$\nabla x H = 0 \qquad (2.7)$$

Further on, H is now a conservative vector field. Therefore, a scalar magnetic potential (V) can be linked to equation (2.7):

$$H = -\nabla \mathrm{V} \qquad (2.8)$$

The magnetic induction on the surface of the earth can be formulated by the following equation:

$$B = \mu_o * \mathrm{H} \qquad (2.9)$$

By combining the equation (2.6) and (2.8), the Laplace`s equation in spherical coordinates is derived:

$$\nabla^2 V = \left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial V}{\partial r}\right)\right) + \left(\frac{1}{r^2\sin(\theta)\partial\theta}\left(\sin(\theta)\frac{\partial V}{\partial\theta}\right)\right) + \left(\frac{1}{r^2\sin^2(\theta)}\frac{\partial^2 V}{\partial\lambda^2}\right) \qquad (2.10)$$

The global magnetic field of the earth is mathematically characterized by the following solution of equation (2.10):

$$V = a\sum_{l=1}^{\infty}\sum_{m=0}^{l}\left(\frac{a}{r}\right)^{l+1} * (P_l^m * \cos(\theta))(g_l^m * \cos(m\lambda) + h_l^m * \sin(m\lambda)) \qquad (2.11)$$

The orthogonal parameters: X, Y and Z of the geomagnetic field can be attained by the following formulas:

$$X = \frac{1}{r} * \frac{\partial V}{\partial\theta} \qquad (2.12)$$

$$Y = -\frac{\partial V}{r * \sin(\theta)\partial\lambda} \qquad (2.13)$$

$$Z = \frac{\partial V}{\partial r} \qquad (2.14)$$

As mentioned earlier in this thesis, these equations plays a key role in determining the geomagnetic field and its components at different locations. Therefore, they are used in some of the most well known models and programs for magnetic field determination. Finally, two different maps are presented in figure 2.3 and 2.4. Highlighting the total intensity and declination at various places of the world in 2015, which has been calculated by using the presented equations above.

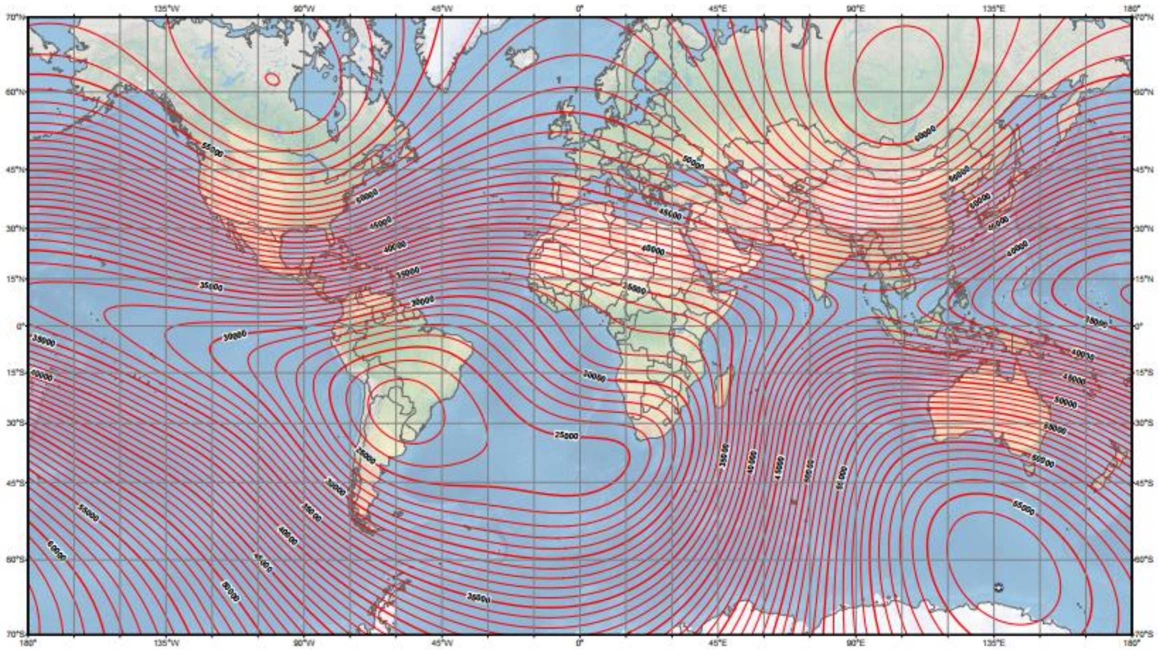


Figure 2.3: The total intensity (F) [7]

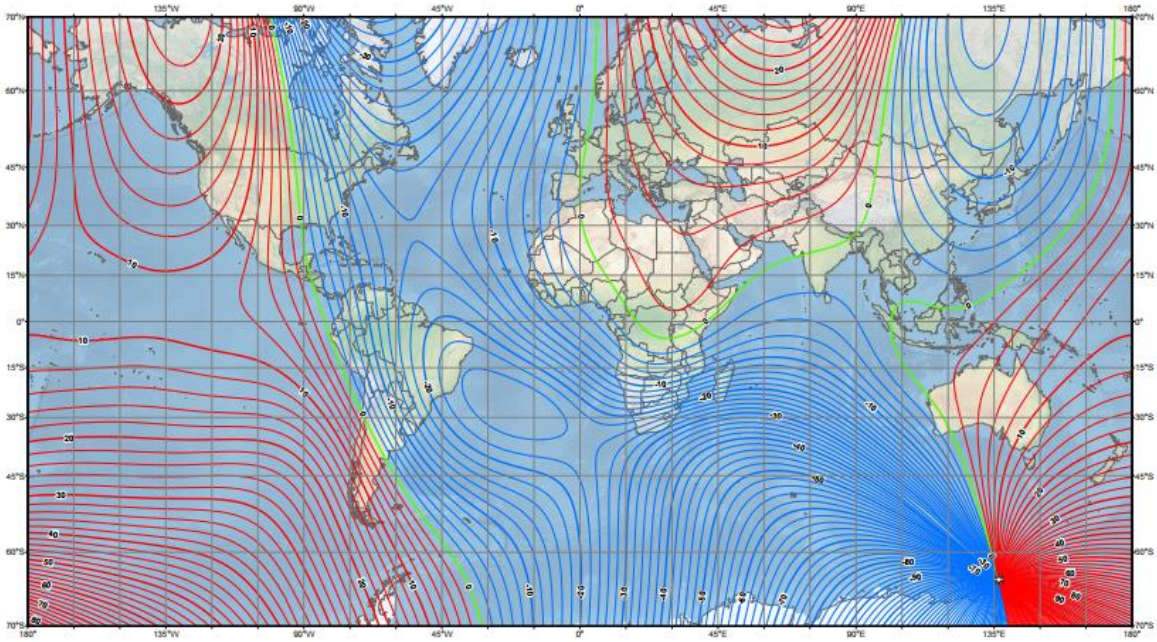


Figure 2.4: The declination (D) [8]

2.3 Applications of the earth`s magnetic field in directional drilling

The geomagnetic field has a large and wide scope within directional drilling for survey and wellbore positioning analysis. This segment will be concentrated around modern magnetic MWD approaches, using magnetic sensors for surveying and wellbore trajectory analysis. This segment will contain a presentation of the principles, sensor configuration, survey magnetometers and their limitations in the magnetic MWD survey instrument. Beside from that, important survey calculations will also be derived and presented.

2.3.1 Principles, functions and sensor configuration in magnetic MWD instruments

The MWD tool is usually made out of two elements: a wellbore survey package alongside with a telemetry module. The telemetry module makes it possible to transport downhole data up to the drilling crew, while the drilling activities and operations are being executed. The wellbore survey package consists of various sensors, which provide guidance in terms of wellbore trajectory and positioning. Usually, two types of sensors are included: three accelerometers and three magnetometers. These instruments are installed in such a manner that they are orientated orthogonal to each other, which is highlighted in figure 2.5.

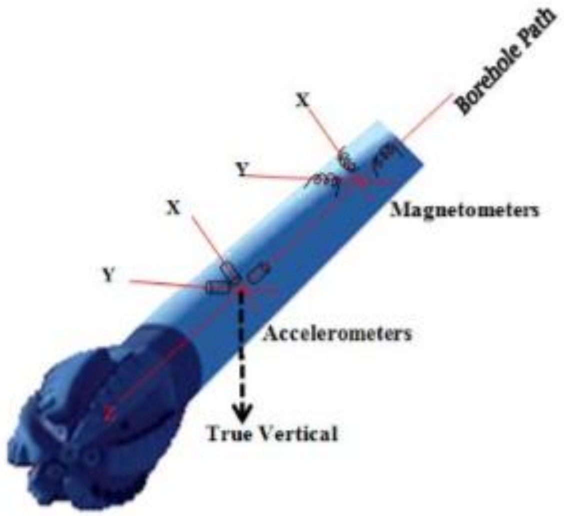


Figure 2.5: Sensor configuration in a magnetic MWD survey instrument [9]

Survey measurements are taken at regular depth intervals by the magnetic MWD instrument, at predetermined survey station points. These survey measurements are taken in a static condition, without circulating and drilling. A static condition while taking the MWD survey measurements are generally preferred due to the following reasons:

1. Rotation of the drillbit and circulation can disturbance the measurements obtained by the accelerometers and magnetometers. This can lead to miss- calibration of the individual orthogonal axis. Therefore, in order to achieve the individual null points of each individual axis, a stationary condition is favoured.
2. Acquire the necessary average values for each respective orthogonal axis, from the accelerometers and magnetometers. During the drilling and circulation process, several positional disturbances will be caused to the individual axis of the survey sensors. This leads to constant fluctuations in the X and Y- axis readings, while the readings obtained from the Z-axis will remain stable. X, Y and Z are the axes of the coordinate system, which belongs to the MWD instrument. There is also another coordinate or reference system, which is dedicated to the frame of the earth. This frame has the following axes: N, E and V. The various frames and their function in the survey process will be explained in details later in this thesis.

However, taking survey measurements while drilling can be preferential in some certain scenarios: For instance, while drilling through problematic geological environments, which could lead to borehole collapse or sticking of the drillstring. Other examples can be situations, where immediate bit positioning data is necessary for real- time borehole trajectory analysis.

Beside from that, the real- time measurements obtained from the MWD instrument provides the necessary downhole data and parameters, to safely guide and steer the drillstring through the projected trajectory towards the defined target.

2.3.2 Accelerometers

The three accelerometers provide strength measurements of the regional gravitational field along the direction of three orthogonal axes, which is displayed by figure 2.5. The measurements derived from these accelerometers provides the necessary information to calculate the wellbore inclination, alongside with the toolface angles of the bit.

2.3.3 Magnetometers

The three magnetometers provide measurements of the geomagnetic field at a certain region along the direction of three orthogonal axes. These measurements are used for magnetic surveying and wellbore positioning analysis. Beside from that, the magnetic azimuthal configuration of the MWD instrument axis is derived from the measurements obtained from the magnetometers and accelerometers. Initially, the magnetic north is used as the main reference point, when calculating the azimuth. Later on, the reference point is changed to true geographical north. The key parameters during the conversion are: the declination, magnetic dip and the total intensity of the geomagnetic field.

Fluxgate magnetometers

The most frequent used magnetometers for survey and well positioning analysis are the induction fluxgate sensors. These magnetometers are comprised of two key elements: primary and secondary coils. Every sensor is made out of two primary (inner) coils, surrounded by one secondary (sense) coil.

During measurements, each primary coil is subjected to an AC. This process produces oscillations of proportional voltages in the secondary coil, which is surrounding the primary coils. This mechanism is repeated every time an AC changes route. These events leads to the creation of buckling currents, which is produced by the magnetometers themselves. The main objective of these buckling currents is to force the oscillations voltages into their initial condition. The buckling currents have a strength, which is equal to the magnetic field of the earth, and their axis are coordinated with the sensors. Nevertheless, one important key requirement need to be fulfilled to ensure that the magnetometers will function properly: no external magnetic source must exist. If it does, it may disfigure the proportional oscillations.

A wide range of different versions of these magnetometers can be found in the market. However, one of the main reasons for their acceptance in the industry, as a reliable tool for measuring the magnetic field are the capabilities to withstand abrasive environments. These types of magnetometers hold the capabilities to endure shocks, dynamical loads and vibrations. They are highly robust instruments, which can provide measurements with a resolution down to 0,01 nT [10].

Range of operating temperature	0 °C – 215 °C
Shocks	Maximum 1,3 ms, 150G
Orthogonal offset amid axes	< 3 % maximum
Linear offsets	0,005 %
Time to settle	Delivers 99 % of the end value within 0,5 s

Table 2.2: Fluxgate magnetometer properties [11]

Proton precession magnetometers

These sophisticated instruments are constructed with respect to the physical principles of paramagnetism. It exploits the tendency among protons to coordinate themselves with the geomagnetic field. During this process, the protons will maintain a rotational movement, while they are coordinated on an axis coinciding with the geomagnetic field. However, if they are exposed to a dominant external magnetic field, the proton alignment will be distorted from the geomagnetic field, and the new orientation will be in the direction of the external magnetic field. Nevertheless, as the magnitude of the external field decreases, the protons will orient themselves towards the earth's magnetic field again.

During the measurement process, a wire is coiled around a container, like a solenoid. This container is filled by a fluid, which is enriched in hydrogen atoms. A DC is then sent through the wire, producing a dominant magnetic field. This forces the protons to be aligned according to the axis of this field. After some time, the DC is disconnected, causing the protons to be aligned with the earth's magnetic field again. During this process, the frequency emitted by the precession process is measured, which yields the magnitude of the magnetic field.

Overhauser magnetometers

These magnetometers are recognized for their high accuracy [12]. The functioning principle of these sensors are similar to the proton precession magnetometers. However, two fundamental differences exist. To begin with, additional available electrons are included in the fluid. Secondly, a radio frequency of high power is utilized to orient the available electrons. These two changes, causes the electrons to connect with the protons. These two adjustments result in greater sensitivity [13] and continuous measurements of the earth's magnetic field, with a greater accuracy.

2.3.4 Challenges related to MWD magnetometers

This segment will deal with various challenges and difficulties experienced while using MWD magnetometers in directional drilling operations. The limitations of magnetometers contributes to increased errors in the wellbore positional accuracies and reduces the viability of the magnetic MWD survey instrument.

Magnetic interference

The major challenge that needs to be addressed and analysed, is the magnetic distortion of magnetometer measurements. They measure what they see, so one has to understand the effects of magnetic interference, in order to be able to ultimately compute an accurate wellbore position. The various processes, sources and how they influence magnetic surveying is addressed later in this thesis. Any deformations caused to the magnetic field, will have a direct impact on the accuracy and precision of the well positioning operation, which is being conducted with a magnetic MWD survey instrument. Beside from that, the azimuth calculations of the BHA will also be highly affected by the disturbances. These factors pose a threat to the magnetometers, which decreases the operational reliability of the magnetic MWD survey tool. Other negative impacts of not fully understanding and calculating the effect of magnetic interference are as following:

- Well location and mapping challenges
- Reduced hydrocarbon recovery, due to inaccurate well positioning
- Collision with adjacent wells. This can lead to catastrophic fatalities if the collision happens to be with a live well, which can rapidly result in a fully blowout.
- Loss of operational revenues and time.
- Increased NPT and rig time.

- Loss of reputation in the market and society.
- Increased workload, stress and HSE issues.
- Excessive wear and damage to the drilling equipment.

Sagging of the BHA

A potential threat to accurate well placement and steering of the drillstring, is the phenomenon named BHA sagging. This challenge is defined as a misalignment between the MWD sensors, the BHA and the hole being drilled. Whilst drilling, most of the BHA will maintain its centralized position within the wellbore, while the MWD instrument will be decentralized from the wellbore itself. Throughout the course of wellbore survey history, experts have believed [14] that the major contributing factors to this challenge are wellbore arch and gravitational forces. However, current studies and models [15,16] suggests that this problem is more complex than previously anticipated. This phenomenon is a three-dimensional distortion of the BHA, with the following governing and contributing factors:

- Drilling parameters:
    - Weight of the drilling fluid.
    - WOB
    - Wellbore pressures
    - Torque and drag
- Size and shape of the wellbore:
    - Radius and diameter
    - Bending sections
    - Inclination of the borehole
- Design of the BHA, mechanical and physical properties:
    - Drill pipes and connections
    - Deformations like bends.
    - Centralisation and stabilizers
    - Load and length
    - Rigidity

The main concern related to the deformation of the BHA, is first of all reduced precision in wellbore placement due to inaccurate readings obtained from the MWD sensors. During BHA sag, the sensors will provide measurements of the earth's magnetic and gravitational field, which does not correlate with the position of the BHA. Recent survey analysis and studies performed by ISCWSA suggests that 80 % of the error contributions to the borehole inclination descends from this phenomenon [14].

Higher latitudes

It has been established that the magnetic azimuth is determined from measurements obtained from the magnetometers. In order to define the magnetic azimuth, the magnetic field sensing sensors measures the horizontal components of the geomagnetic field. One important aspects to highlight is that: At the north magnetic pole and south magnetic pole, most of the field lines are pointing vertically towards or out from the poles. In other words, the magnetic dip is either -90° (magnetic south pole) or 90° (magnetic north pole). Therefore, magnetic survey obtained from high latitude sites are highly prone to errors from magnetic interference, and the impact of magnetic error sources will be larger at those regions. This means that the accuracy of the magnetic survey is a function of geographical location. Through survey analysis, studies and scientific publications it has been established that magnetometer measurements of the magnetic azimuth includes substantial amount of errors, if obtained at high latitude sites or locations close to the magnetic poles [17].

This challenge is highly relevant for the petroleum industry today. In terms of exploration and analysing new drilling regions, the industry is moving further north towards the arctic. Special care has to be taken while conducting drilling operations in those remote areas. These areas are known for their environmental sensitivity, lack of infrastructure and accessibility. Due to these facts: operational locations, drilling pads and facilities have to be constructed with more compressed design, located close to each other. Therefore, errors in magnetic surveying and wellbore positioning will be more crucial in these regions.

Analysis and studies indicates [17] that the largest error propagation in magnetic surveying, relates from magnetic errors descending from magnetic interference. Therefore, in order to steer the drillstring accurately, sound error mitigation strategies will be crucial while drilling at higher latitude sites. Figure 2.6 highlights the error propagation as a function of latitude degrees.

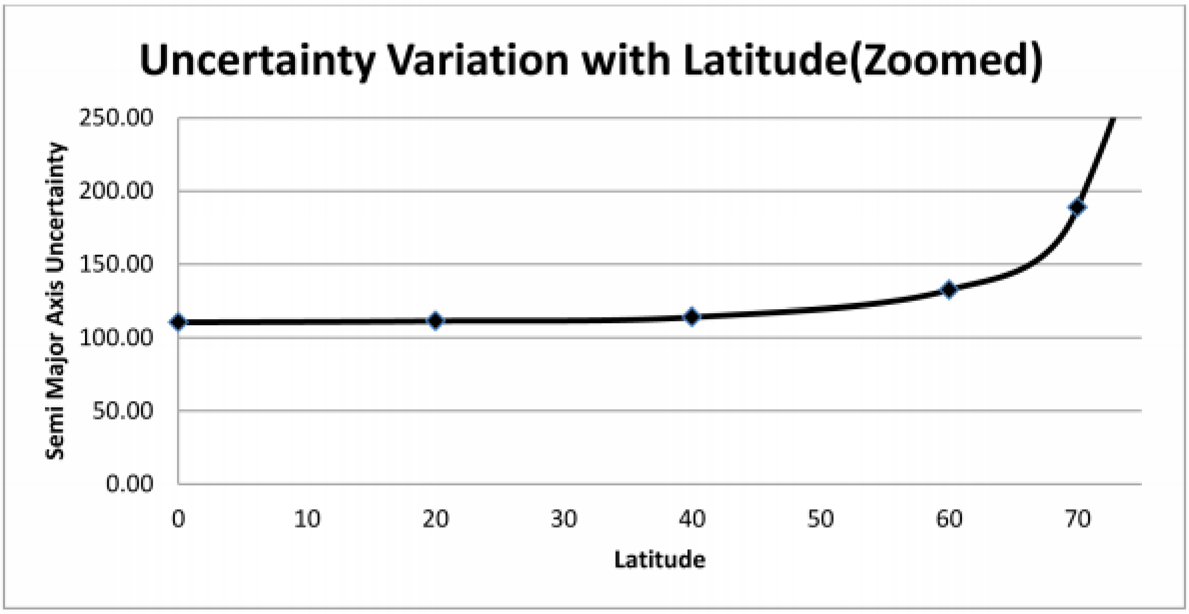


Figure 2.6: Relationship between latitude degrees and uncertainty [17]

Inconsistency

One of the most recognizable drawbacks of magnetometers is the inconsistency it maintains during the drilling phase. In order to obtain satisfactory measurements of the magnetic field, static conditions must be maintained. In other words, the magnetometers can only deliver proper readings, while circulation and drilling is stopped. The main reason behind this dysfunctionality is the positional sensitivity of the magnetometers aligned with the orthogonal axes. Small disturbances can lead to misalignments between the magnetometers and axes. The X and Y-axis are very sensitive to minor disturbances, which can cause large fluctuations in readings obtained from these two axes while drilling.

As mentioned, measurements are taken at predetermined survey points, for instance after 10 meters of drilling. For wellbores extending over thousands of meters, regularly halts in the drilling process can be very expensive and time consuming.

Instrumental errors and reliability

Every technological device with numerical applications, have inheritaged a term called error in its outputs. Error can be defined as a flaw, which causes the numerical outputs to diverge from the exact solution. Survey sensors used for directional drilling contain instrumental errors. These errors are comprised of several types of sub -errors, like systematic errors and gross errors. If these flaws accumulate in the survey data, they can cause significant inaccuracies to wellbore positioning and steering of the drillstring. In order to achieve satisfactory operational results, these errors must be mitigated within an acceptable threshold. Scientific publications [18] have proven that the magnetometers are prone to systematic sensor errors along each orthogonal axes (X,Y and Z), if the measurements are obtained without magnetic error corrections. These errors will propagate in the rest of the survey data and cause significant distortions to the declination, magnetic dip and total field strength measurements.

Another aspect that needs to be controlled is signal noises. This phenomenon is defined as undesired variations in electrical signals, due to instrumental malfunction. Noises in the sensor readings can also be enhanced by exposure to abrasive environmental conditions (temperature variations, shocks and impact forces) or transmission difficulties. In order to boost the reliability of magnetometers within direction drilling, errors and sensor noises must be mitigated and subdued.

Environmental exposure

During a drilling operation, the BHA is exposed to abrasive and harsh environments. Such surroundings are recognized by shocks, vibrations, impact forces, alternating temperatures, collisions, oscillations, high circulation velocities and much more. The magnetometers used in the survey analysis, are highly sensitive equipment. Minor positional disturbances can cause distortions in the sensor readings and temperature variations can also lead to sensor noise. Therefore, it is important to ensure that the sensors hold the capabilities to withstand such environments. Special attention needs to be allocated for the design and installation phase, with proper isolation from the dynamic environment. By doing so, time and expenses can be saved, and most importantly successful drilling operations can be achieved.

2.3.5 Survey formulas

Before deriving and elaborating on the survey formulas, it is important to pay special emphasis to the various coordinate systems that are used during directional drilling. As mentioned earlier in this thesis, two coordinate or frame systems exits: the earth`s frame and the MWD instrument frame.

The Earth`s frame is denoted with the following three axes: N, E and V. The N- axis is aligned with the horizontal intensity of the magnetic field of the earth. The horizontal intensity is directed towards the north magnetic pole. The V- axis is pointing towards the vector, which belongs to the earth’s gravity. Finally, E being in the direction of the Eastward intensity of the magnetic field. These three axes are perpendicular to each other.

The instrument frame is denoted with the following axes: X, Y and Z. The Z- axis is aligned with the direction of the drillbit, with an orientation that follows the longitudinal direction of the bit. While the remaining X and Y- axes are orientated in the cross axial surface of the BHA. These two frames are highlighted in figure 2.7, including the respective directions of each axis. Within the field of directional drilling, these two frames are interlinked to each other. The aspects that links these two frames together are the collection of angular revolutions of the following parameters: toolface angles, inclination (drilling) and azimuth. During wellbore survey analysis, the instrument frame is transformed into the earth`s frame. This conversion process will resolve the orientation of the wellbore. Another important factor to highlight, is the fact that the gravity and magnetic field sensing sensors are lined- up according to the frame of the instrument. In this frame, the orthogonal axes will be coordinated relative to the MWD instrument. This means that the positional alinement of the BHA with respective to the instrument is characterized by the orthogonal axes.

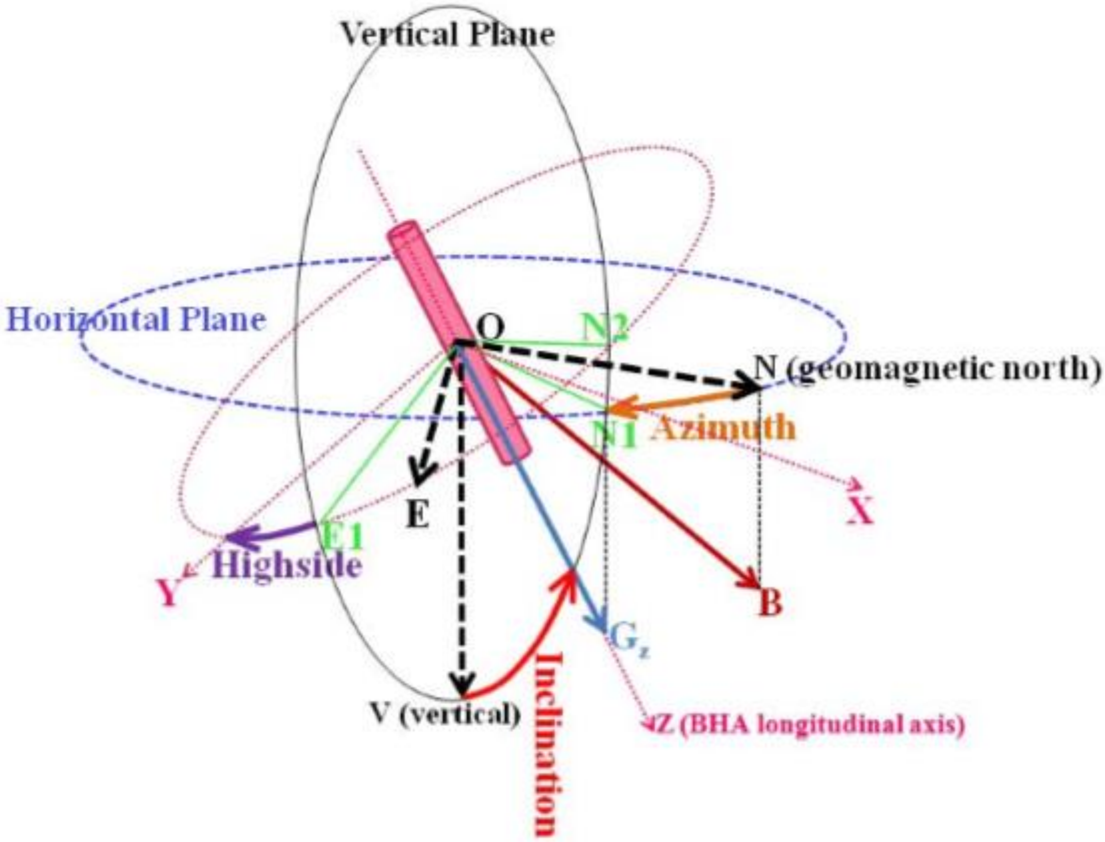


Figure 2.7: Survey frames, alongside their axis and orientation [9]

Assumptions and limitations

Before deriving the survey formulas, it is important to state the fundamental assumptions and limitations behind these equations. The following assumptions are applied:

1. The magnetic field and the gravitational field of the earth remains constant.
    a. The assumption of a constant gravitational field implies that the measurements obtained by the three accelerometers (G_x, G_y, G_z), in their respective orthogonal directions are identical to the earth's gravitational field at a predetermined location. This assumption is supported by two arguments:
        i. The earth's gravitational field is not prone to distortions or disturbances.
        ii. The survey measurements are taken in static conditions, which implies that the sensor instrument does not undergo any acceleration.
2. The gravitational field and total intensity of the magnetic field remains at two selected orientations must be the same.
3. The error propagation along the Z- axis (in the instrument frame) is only in the longitudinal direction of the bit, which is pointing straight down into the borehole (see figure 2.7).
4. Any fluctuations or errors caused to the earth's present magnetic field is only along the borehole orientation.

The following limitations exists:

1. The survey formulas cannot be utilized for wells that have been cased, due to the magnetic interference caused by the ferrous material in the casing.
2. Constant magnetic field is a valid assumption in a short time frame. However, the geomagnetic field is highly prone to disturbances and fluctuations in the longer time frame. Therefore, it does not remain constant over a longer periods.
3. Error propagation only along the Z- axis is also a slight ambitious assumption. In the presence of magnetic components in the mud or in the surround environment (for instance like barite, ilmenite or magnetite), error propagation will be distributed along the three orthogonal axes (X,Y and Z).
4. Positional dependency. The MWD instrument is mounted in the BHA segment, close to the bit. The gravity and magnetic field sensing sensors are highly sensitive to positional irregularities. Only a slight misalignment between the MWD instrument and the drillbit, will affect the survey positions derived from the formulas. Overall, the survey formulas lack compensating measures to take into account for slight imperfections in positioning between the BHA and the MWD instrument.

Derivation

First, a transformation of coordinate systems is required. In this transformation process, the unit vectors belonging to the instrument frame (X,Y and Z) is converted to the earth's frame (N,E and V). The conversion process is carried out by utilizing equation (2.15):

$$\overrightarrow{U_{NEV}} = [\theta_{AZ}]\ [\gamma]\ [\mathrm{TF}]\ \overrightarrow{U_{xyz}} \qquad (2.15)$$

If the opposite conversion step is wanted, the following equation can be utilized:

$$\overrightarrow{U_{xyz}} = [\theta_{AZ}]^T\ [\gamma]^T [\mathrm{TF}]^T\ \overrightarrow{U_{NEV}} \qquad (2.16)$$

In equation (2.15) the following elements $[\theta_{AZ}]$, $[\gamma]$, $[\mathrm{TF}]$ are defined as rotation matrices [14]:

$$[\theta_{AZ}] = \begin{bmatrix} \cos(\theta_{AZ}) & -\sin(\theta_{AZ}) & 0 \\ \sin(\theta_{AZ}) & \cos(\theta_{AZ}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[\gamma] = \begin{bmatrix} \cos(\gamma) & 0 & \sin(\gamma) \\ 0 & 1 & 0 \\ -\sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix}$$

$$[\mathrm{TF}] = \begin{bmatrix} \cos(\mathrm{TF}) & -\sin(\mathrm{TF}) & 0 \\ \sin(\mathrm{TF}) & \cos(\mathrm{TF}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The following parameters: $\overrightarrow{U_x}, \overrightarrow{U_y}$ and $\overrightarrow{U_z}$ are defined as unit vectors in the earths coordinate system, pointing in their respective directions (X, Y and Z). While in the coordinate system of the survey instrument, the following parameters are defined as unit vectors: $\overrightarrow{U_N}, \overrightarrow{U_E}$ and $\overrightarrow{U_V}$, pointing in their respective directions (N,E and V)

The next step is made out of the following operation: combine the measurements obtained from the accelerometers, which includes the gravity field components along orthogonal axes of the instrument frame (G_X, G_Y, G_Z) with equation (2.16). This step leads to the borehole inclination and toolface angle. The equation below is denoted as (2.17)

$$\begin{bmatrix} G_X \\ G_y \\ G_Z \end{bmatrix} = \begin{bmatrix} \cos(\mathrm{TF}) & \sin(\mathrm{TF}) & 0 \\ -\sin(\mathrm{TF}) & \cos(\mathrm{TF}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\gamma) & 0 & -\sin(\gamma) \\ 0 & 1 & 0 \\ \sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix} \begin{bmatrix} \cos(\theta_{AZ}) & \sin(\theta_{AZ}) & 0 \\ -\sin(\theta_{AZ}) & \cos(\theta_{AZ}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

In equation (2.17) the parameter denoted as g, is defined as the strength of the gravitational field. This parameter is derived from the vector of gravity, which is composed of the particular gravity measurements obtained from the accelerometers:

$$g * \overrightarrow{U_V} = \vec{g} = G_z * \overrightarrow{U_Z} + G_X * \overrightarrow{U_x} + G_Y * \overrightarrow{U_Y} \qquad (2.18)$$

The individual gravitational components are defined by the following equations:

$$G_Z = g * \cos(\gamma) \qquad (2.19)$$

$$G_Y = g * \sin(\gamma) * \sin(TF) \qquad (2.20)$$

$$G_x = -g * \cos(TF) * \sin(\gamma) \, (2.21)$$

One expression for the toolface angle (TF) can now be derived by combining the following two equations (2.20) and (2.21)

$$\frac{G_Y}{G_X} = \frac{g * \sin(\gamma) * \sin(TF)}{-g * \cos(TF) * \sin(\gamma)}$$

$$\mathrm{TF} = \tan^{-1}\left(\frac{G_Y}{-G_X}\right) \qquad (2.22)$$

The inclination (γ) of the wellbore can now be obtained by the following two equations:

$$\gamma = \cos^{-1}\left(\frac{G_Z}{\sqrt{G_Z^2+G_Y^2+G_X^2}}\right) \qquad (2.23)$$

$$\gamma = \tan^{-1}\left(\frac{\sqrt{G_Y^2+G_X^2}}{G_Z}\right) \qquad (2.24)$$

The only parameter left now is the azimuth of the wellbore. This component will be calculated by taking basis into the measurements of the magnetic field, obtained from the magnetometers. These orthogonally mounted sensors will measure each component of the geomagnetic field along the orthogonal axes of the earths frame (B_N, B_E, B_V) and the instrument frame(B_X, B_Y, B_Z). The following equation describes the earth`s magnetic field as a vector in the two coordinate systems:

$$\vec{B} = B_X * \overrightarrow{U_X} + B_Y * \overrightarrow{U_Y} + B_Z * \overrightarrow{U_Z} = B_N * \overrightarrow{U_N} + B_E * \overrightarrow{U_E} + B_V * \overrightarrow{U_V} \qquad (2.25)$$

The next step is comprised of combining equation (2.15) with equation (2.25). This process will result in the following mathematical expression:

$$\begin{bmatrix} B_N \\ B_E \\ B_V \end{bmatrix} = \begin{bmatrix} |\vec{B}| * \cos(MDIP) \\ 0 \\ |\vec{B}| * \sin(MDIP) \end{bmatrix} = \begin{bmatrix} \cos(\theta_{AZ}) & -\sin(\theta_{AZ}) & 0 \\ \sin(\theta_{AZ}) & \cos(\theta_{AZ}) & 0 \\ 0 & 0 & 1 \end{bmatrix} *$$
$$\begin{bmatrix} \cos(\gamma) & 0 & \sin(\gamma) \\ 0 & 1 & 0 \\ -\sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix} * \begin{bmatrix} \cos(TF) & -\sin(TF) & 0 \\ \sin(TF) & \cos(TF) & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} \qquad (2.26)$$

The magnitude of$|\vec{B}|$, in the equation above is calculated from the following term: $\sqrt{B_V^2 + B_N^2}$. By solving equation (2.26), the individual magnetic components in the earths frame (N, E and V) can be extracted:

$$B_V = -\sin(\gamma) * (B_X * \cos(TF) - B_Y * \sin(TF)) + B_Z * \cos(\gamma) \quad (2.27)$$

$$B_E = \sin(\theta_{AZ}) * (\cos(\gamma) * (B_X * \cos(TF) - B_Y * \sin(TF)) + B_Z * \sin(\gamma)) + \cos(\theta_{AZ}) * (B_X * \sin(TF) + B_Y * \cos(TF)) \qquad (2.28)$$

$$B_N = \cos(\theta_{AZ}) * (\cos(\gamma) * (B_X * \cos(TF) - B_Y * \sin(TF)) + B_Z * \sin(\gamma)) - \sin(\theta_{AZ}) * (B_X * \sin(TF) + B_Y * \cos(TF)) \qquad (2.29)$$

Before presenting the final equation, which yields the azimuth of the borehole. It is important to revise one important principle of wellbore surveying. The azimuth that is used as a reference point during the initial phases of drilling, is the magnetic azimuth or the north magnetic pole. If the measured magnetic field is purely the geomagnetic field of the earth, then any disturbance or distortions to the measurements can be ignored, this consideration allows the parameter: B_E in equation (2.28) to be set as zero. By doing so, the magnetic azimuth can be derived from equation (2.28):

$$\frac{\sin(\theta_{AZ})}{\cos(\theta_{AZ})} = \frac{-(B_X * \sin(TF) + B_Y * \cos(TF))}{\cos(\gamma) * (B_X * \cos(TF) - B_Y * \sin(TF)) + B_Z * \sin(\gamma)} \qquad (2.30)$$

Equation (2.30) can be expanded by incorporating already derived formulas for the wellbore inclination and toolface angle:

$$\theta_{AZ} = \tan^{-1}\left(\frac{(G_X * B_Y - G_Y * B_X) * \sqrt{G_Z^2 + G_Y^2 + G_X^2}}{B_Z(G_X^2 + G_Y^2) - (G_Z(G_X * B_X + G_Y * B_Y))}\right) \qquad (2.31)$$

One important factor to have in mind is that the various sensors in the MWD instrument can be installed at any preferred arrangement. This means that the accelerometers and magnetometers can be preferentially deployed with a coordinate system pointing at any of the three orthogonal axes. These equations are valid for a survey frame, with the Z- axis pointing in the direction of the bit, and X and Y- axis as the cross sectional axes. However, some sensor arrangements are installed in such a way, that the X-axis is pointing in the direction of the bit, and the two remaining axes are the cross sectional components. Different arrangements have their own formulas. Therefore, special attention should be paid while installing the sensors, and calculating the survey parameters during the drilling operation.

2.3.6 Magnetic error sources

This segment is dedicated to the magnetic error sources, which are responsible for degradation of magnetometer readings. An overview is given over the different sources, where these elements are described and presented in details.

The sun

Field reversals

The suns magnetic field is much more complex and dynamic than the earth's magnetic field. Both of these two fields change polarity, but this process is much more rapid and comprehensive on the sun. This process is accomplished every 11th year on the sun, which is also referred to as one solar cycle. Compared to the earth, such a process can take several ten-thousands of years to complete.

Many steps and events characterize the reversal process. Figure 2.8 displays the major occurrences during a magnetic field reversal on the sun. At the beginning of such an event, the suns magnetic field will experience a magnitude deficiency. This deficit will continue until the strength of the field reaches zero. After this nullification, the magnetic field strength will be boosted and recovered to initial magnitudes, with an exchanged polarity.

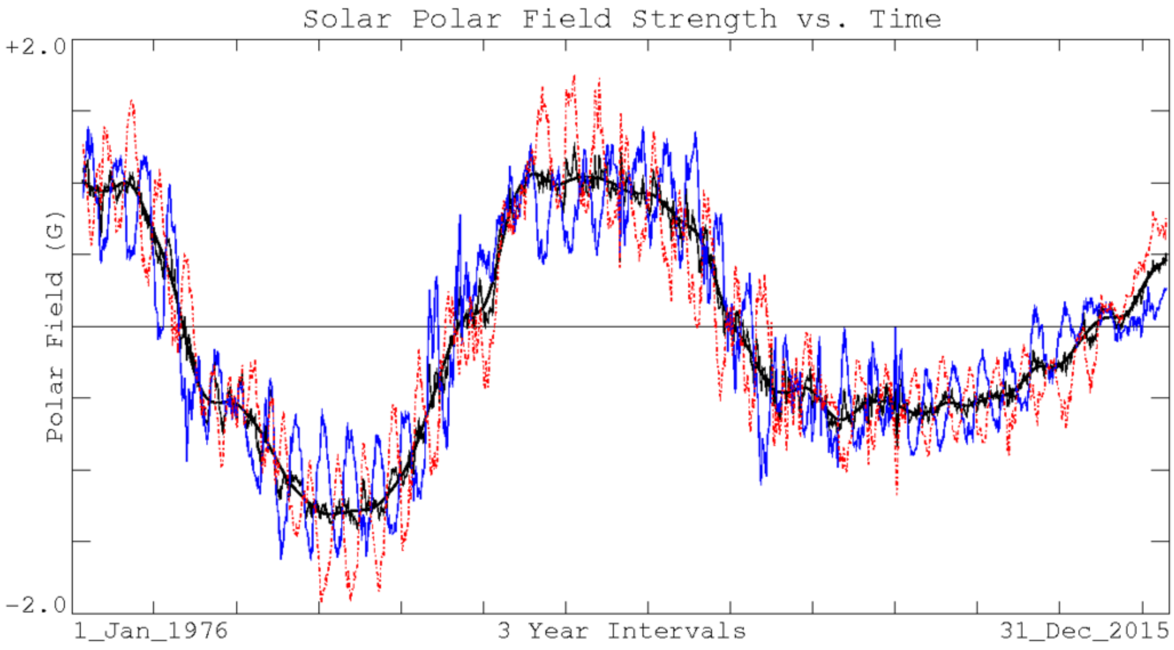


Figure 2.8: The magnetic field during reversals on the sun [36]

The alternating magnetic field produces electrical currents in the form of wavy current sheets, with the help of electromagnetic induction (the electromagnetic induction process will be presented in details later). These currents are being sent out in all directions from the suns equator. One important principle of magnetism is that: magnetic fields are produced and propagated in dynamic environments, which require the movements of charges. A current is comprised of flowing electric charges and due this fact, currents produce magnetic fields.

The wavy current sheets will produce its own magnetic fields, which will affect and influence the earth's magnetic field. The induced currents are very small in magnitude$\left(1 * 10^{-10}\,\frac{amps}{m^2}\right)$, but they are extensive in terms of quantity. That is the main explanation behind their influence on other magnetic active objects. Beside from that, the earth will continue to fall in and out of the current sheet, which causes fluctuations in the geomagnetic field.

Diurnal variations

Diurnal variations are also known as daily or regular fluctuations. The earth's magnetic field experiences minor fluctuations throughout the whole day. These fluctuations are very small in magnitude, for instance the total intensity experience variations in the range of tens of nT, while the magnetic dip is only disturbed by a $\frac{1}{10}$°. However, these variations must be corrected for during critical magnetic MWD operations, especially if drilling activities are conducted at higher latitudes. The diurnal variations from the Norwegian continental shelf are displayed in figure 2.9. These measurements were recorded by the magnetometers positioned at Karmøy.

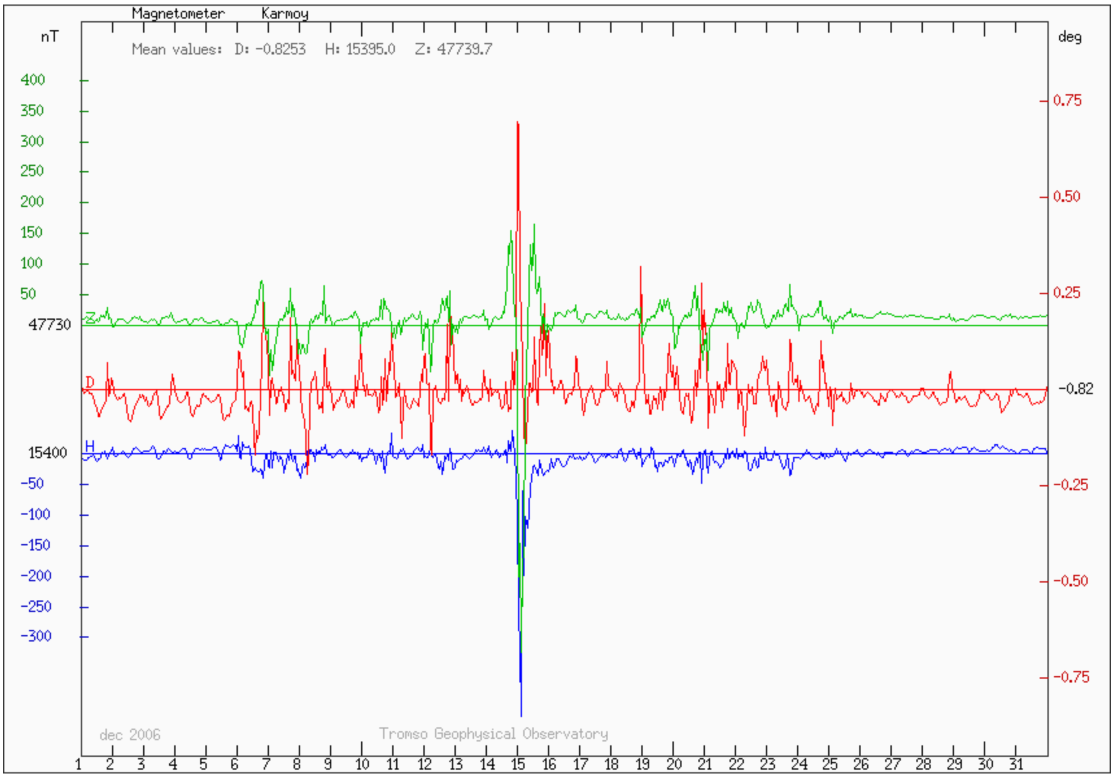


Figure 2.9: Regular variations [37]

Diurnal fluctuations are produced by electrical currents flowing in the ionosphere. This region is located approximately 100 km above the surface of the earth. However, in order to produce such currents, two essential conditions must be fulfilled:

1. A conductive environment
2. Winds

The sun accomplishes both of these two requirements. The sun emits X-rays and highly energetic ultra- violet rays. Both of these two elements contributes with the displacement of electrons from neutral charged molecules, located in the ionosphere. This process generates particles that are positive and negative charged. All of these events contributes to a conductive environment in the ionosphere. Usually, the sun is most active around the middle of the day and therefore the air in the ionosphere is most conductive around this period. Due to this fact, peaks of diurnal variations are observed around the midday. This is also displayed in figure 2.9.

The winds are produced by heating of the air in the ionosphere. The suns emitted rays carry out the heating process. These winds combined with tidal winds maintain and empowers the ionospheric dynamo. This dynamo effect in turn produces currents, when the conductive environment in the ionosphere passes through the magnetic field of the earth.

Irregular variations

Irregular fluctuations are large scale disturbances that are also known as magnetic storms. These variations are mainly a result of high energetic particles emitted by the sun, named solar winds. The stream of different particles is exerted with an extensive amount of pressure. During the collision between the stream and the earth’s magnetosphere, the pressure exerted by the sun and the impact itself causes a deformation of the magnetosphere. When the physical condition of the particle stream is alternating, the current environment of the magnetosphere is boosted, which results in large scale disturbances of the earth’s magnetic field.

Distortions of magnetic MWD surveys taken at high latitudes and auroral zones are larger. This is due to the fact that at each magnetic pole is surrounded by oval bands, which consist of enhanced currents. Magnetic MWD survey must be corrected for disturbances caused by irregular fluctuations. These perturbations results in large scale distortions and inaccuracies to the magnetometer measurements. The magnitude of the perturbations caused by magnetic storms are visualized in figure 2.10. This graph illustrates the impact of a magnetic storm on the horizontal intensity of the earth’s magnetic field. 2nd of September 06:00 1859, a magnetic storm hits the earth, which causes distortions to the horizontal intensity in range of several thousands of nT. Diurnal variations displayed in figure 2.9 resulted in only minor misalignments in the range of tens- hundreds of nT. Figure 2.10 also highlights the severity of magnetic storms and underlines the importance of correcting magnetic survey for solar winds.

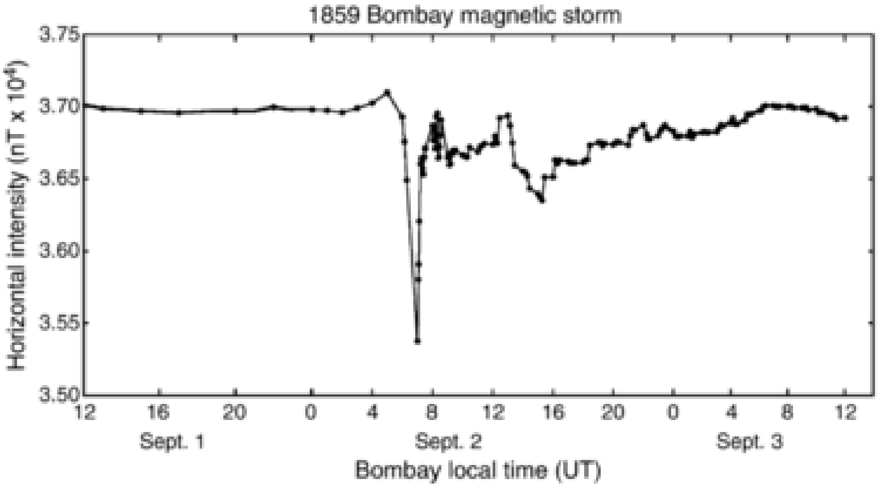


Figure 2.10: The horizontal intensity during a magnetic storm [38]

The earth

The earth's core, where the magnetic field is generated is alternating and changing continuously with time. These variations also effects the geomagnetic field itself. The changes in the geomagnetic field due to internal factors are named secular variations. The English mathematician Henry Gellibrand first recognized this term in 1634. He correlated observations of the declination made at London with former investigations. From these observations, Gellibrand discovered that the geomagnetic field is a function of time.

The rate of change in the geomagnetic field is not only a function of time, but it is also dependant on geographical location. Another important aspect related to secular variations is that all of the components of the geomagnetic field is changing; the alternation is not limited to certain components of the geomagnetic field. Analysis and investigations concludes that the vertical components of the geomagnetic field is experiencing annual changes of 45 nT every year. However, at some certain geographical locations changes in the secular variations can be up to 170 nT. Over a period of 160 years, a reduction in the total intensity has been experienced in Toronto. The total intensity have decreased from 64 000 nT to 55 000 nT, which is approximately 14 %. This deficiency is highlighted in figure 2.11.

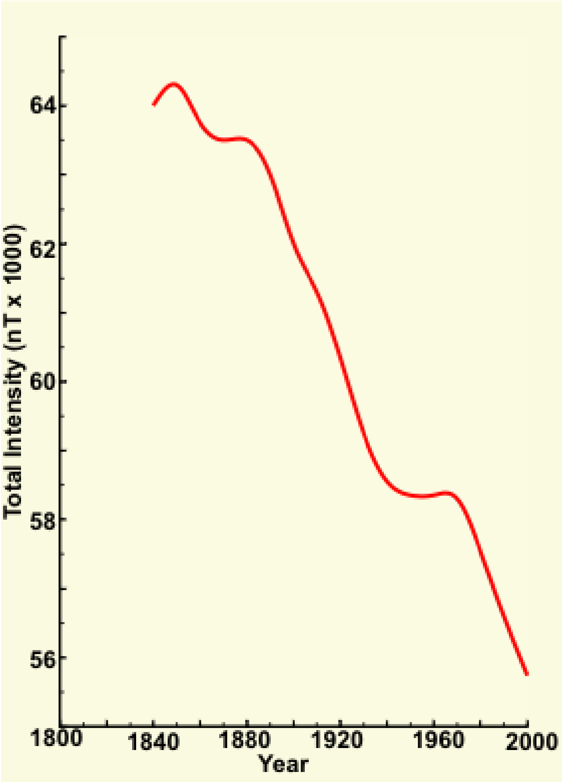


Figure 2.11: Secular variations [39]

Scientific research have concluded that secular variations are following three distinctive trends:

1. The geomagnetic field is decreasing.
2. The magnetic declination is moving to the west.
3. Fluctuations in the static part of the magnetic field. At some specific geographical locations the components of the geomagnetic field is increasing and decreasing at roughly the same location.

From a drilling point of view, secular variations can be modelled and predicted. These fluctuations are small in a drilling time scale, but significant in the longer run. Therefore, such disturbances are very minor to the survey readings and do not pose a significant threat to the drilling accuracy. However, one phenomenon related to secular variations that can cause distortions to the magnetic MWD surveys are geomagnetic jerks. This phenomenon is characterised by sudden and rapid changes in the geomagnetic field. Usually, these changes marks the end of an existing trend and beginning of a new in the magnetic field of the earth. Geomagnetic jerks are still a mystery for scientists, they have not yet been fully understood and prediction of this phenomenon is still a challenge. Figure 2.12 displays the characteristics of geomagnetic jerks and how it marks the end of an ongoing tendency with a maxima or minima in the geomagnetic field. On this graph, four major jerks can be observed in 1925, 1969, 1978 and 1992.

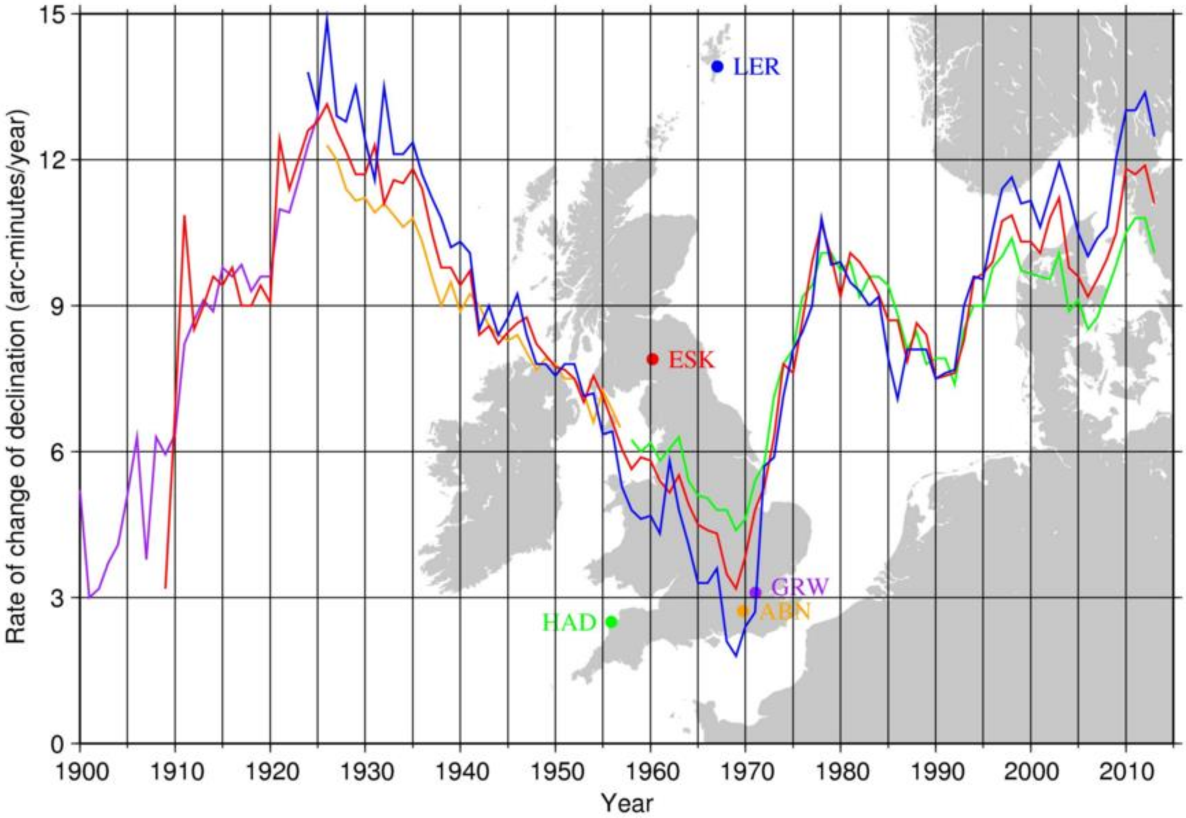


Figure 2.12: The rate of change in declination with time at Lerwich, Greenwich, Abinger, Hartland and Eskdalemuir observatories [40]

The drilling fluid

The magnetic properties of the drilling fluid additives and components can cause large-scale errors and deviations to the directional magnetic MWD survey. These errors contribute to the degradation of precision and accuracy of the measured azimuth, which in turn can lead to operational difficulties. According to analysis and research [42] azimuth distortions in the range of 5° and misalignments of up to 50 meters away from the pre-determined target section have been reported. The main contributor to these unsatisfactory results have been magnetic interference caused by magnetic properties of the drilling mud.

The magnetic distortions caused to the directional MWD survey due to the drilling fluid is referred to as magnetic shielding. This term has been dedicated to this phenomenon because the magnetic properties of the drilling fluid manipulates the geomagnetic field to look like a shield on a magnetic display unit. This phenomenon is recognized as a dampening effect, which weakens and reduces the measured geomagnetic field. The shielding phenomenon is visualized in figure 2.13, where the black line represents the original geomagnetic field and the red line represents the dampening effect of the drilling fluid on the geomagnetic field.

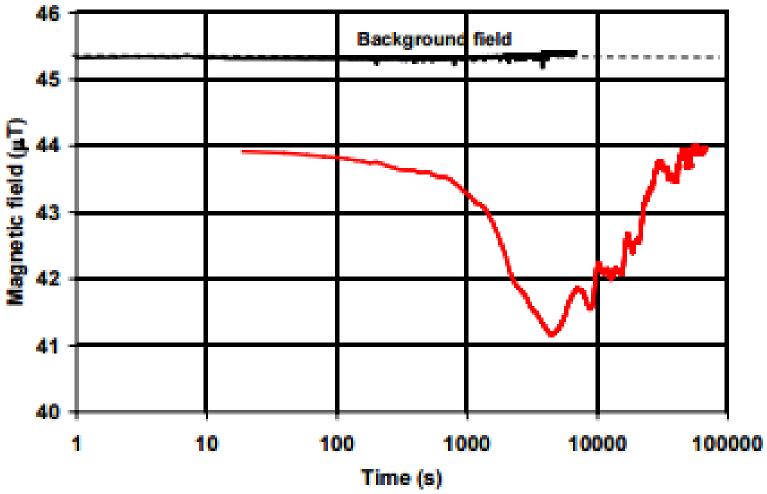


Figure 2.13: The magnetic field with and without the shielding effect [41]

The main parameter that is governing this effect is the magnetic susceptibility. This parameter is dimensionless and signify the effect of an external magnetic field on the magnetic properties of a material exposed to this field. Magnetic susceptibility is a material property that is also influenced by addition of other magnetic active components in a drilling mud, which in turn alters the magnetic properties of the drilling fluid. The susceptibility of a material defines whether it is of paramagnetic (positive value) or diamagnetic (negative value) attributes. Drilling fluids are generally characterized by paramagnetic properties with minor positive values of susceptibility. From a directional drilling point of view, susceptibility values above 0,01 can cause problems and challenges for the directional MWD survey process. In other words, the higher magnetic susceptibility of a drilling fluid the higher is the magnetic shielding. Magnetic susceptibility will be explained in more details later in this thesis, but from a geological perspective.

Magnetic shielding is a complex and dynamic effect. This phenomenon is governed and function of several parameters and processes. The next segment will be dedicated to the presentation of various parameters that affects and influences the magnitude of the shielding on the magnetometer measurements.

Weight material

The type of weight material used in drilling fluids affects the magnitude of the magnetic shielding. It has been established from experiments and field cases that ilmenite contributes with larger magnetic distortions than other weight materials, such as barite [42]. From the Norwegian continental shelf, ilmenite was used as a weight material in the Norne field [42]. Directional MWD survey measurements obtained from this field, displayed abnormal behaviour in the geomagnetic field. The root cause behind these abnormalities was identified to be ilmenite in the drilling mud. Another conclusion taken from this field case study was that: the dampening of the geomagnetic field was larger in wells with ilmenite and smaller in wells with barite. The results of this research is displayed in figure 2.14. The dampening of the cross- axial intensity caused by ilmenite was recorded as high as 2,7 %, which corresponds to an azimuth error of 5°.

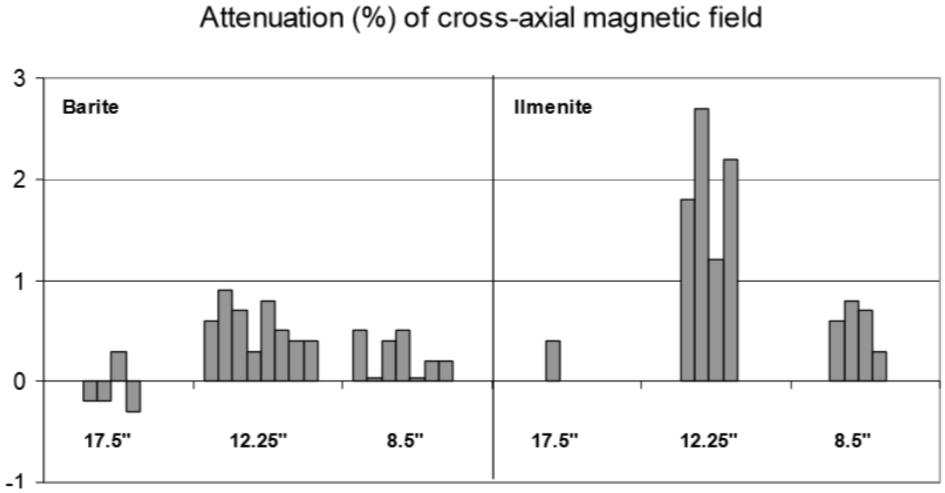


Figure 2.14: Dampening of the cross-axial intensity in different well sections [42]

The root cause behind the large differences between the dampening of the geomagnetic field between ilmenite and barite is identified to be magnetic susceptibility. Laboratory experiments [42] have recognized larger susceptibility values for mud systems containing ilmenite than barite. Beside from that, magnetic susceptibility of ilmenite in rocks are greater than barite. For ilmenite, the magnetic susceptibility is found [43] to be around $8042 * 10^{-6}$, while barite has a susceptibility of 0 [43]. In order to boost the accuracy of magnetic MWD surveys and mitigate the dampening effect, other weight materials in drilling fluids should replace ilmenite.

Temperature and pressure

The effect of temperature and pressure on the magnetic susceptibility of a material depends on a number of factors, such as presence of other magnetic materials, type of magnetic properties, grain size, distribution and many more. Generally, the magnetic properties of a materials decreases with increasing temperature and pressure. However, the impact of temperature is much larger than pressure. Laboratory analysis [44] concludes that abnormally large pressure is required in order to have significant effect on the magnetic susceptibility of a mineral. For instance, researchers [44] have found out that the magnetic susceptibility of magnetite decreases to half of its strength at pressures 120 000 to 160 000 times larger than the atmospheric pressure. However, in a drilling environment the pressure variations are too low, in order to have significant effects on the magnetic susceptibility. This means that the effect of pressure on the magnetic shielding is more or less negligible in a drilling environment.

Small temperature changes results in large variations in the susceptibility of a material. Figure 2.15 displays how the temperature influences the magnetic susceptibility of a paramagnetic material. From this graph, the susceptibility decreases with increasing temperatures. This means that the dampening effect (influenced purely by the temperature) will be larger at shallow depths, and it becomes more stable or mitigated as the vertical depth of the well increases.

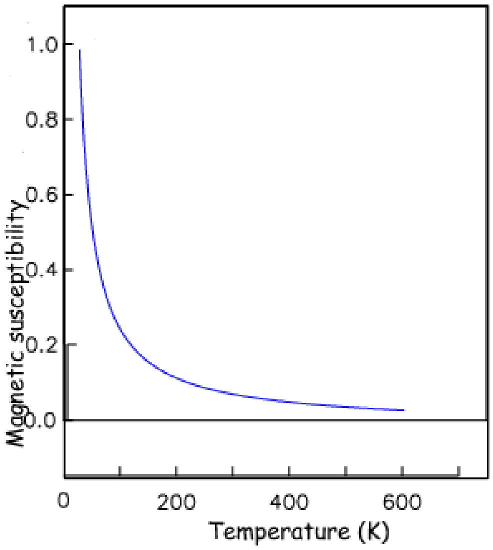


Figure 2.15: The relationship between the temperature and susceptibility [45]

Swarf and casing wear

The magnetic properties of a mud system is enhanced by adding steel or swarf particles, which in turn increases the magnetic shielding effect. The metal fragments can be introduced into the system in several ways: casing wear, equipment wear, small steel particles descending from the drillstring and so on. Casing wear develops when the rotating drillstring is in contact with the casing during a drilling operation. The amount of swarf generated from this process is largely enhanced when large contact forces are present between the casing and drillstring, bent casing sections and buckling of the casing due to considerable axial compressional forces. The amount of steel particles generated from a drilling operation varies and depends upon operational practices. Nevertheless, field case studies suggests that extensive amounts of swarf and steel fragments are generated from drilling operations that accumulates in the mud system. From one of the case studies [46], total 17,5 kg of steel particles were collected by the ditch magnets over a period of 13 days. This well contained 800 metres of casing and 2400 metres were drilled. Another study [47], highlights that approximately 5 % average of casing is lost due to wear over a drilling interval of several thousands of feets.

The effect of steel fragments on the geomagnetic field is visualized in figure 2.16. In this laboratory experiment [41], the impact of various mud systems on the geomagnetic field were evaluated. The drilling fluid containing swarf particles differentiated itself from the rest of the systems, by shielding the geomagnetic field.

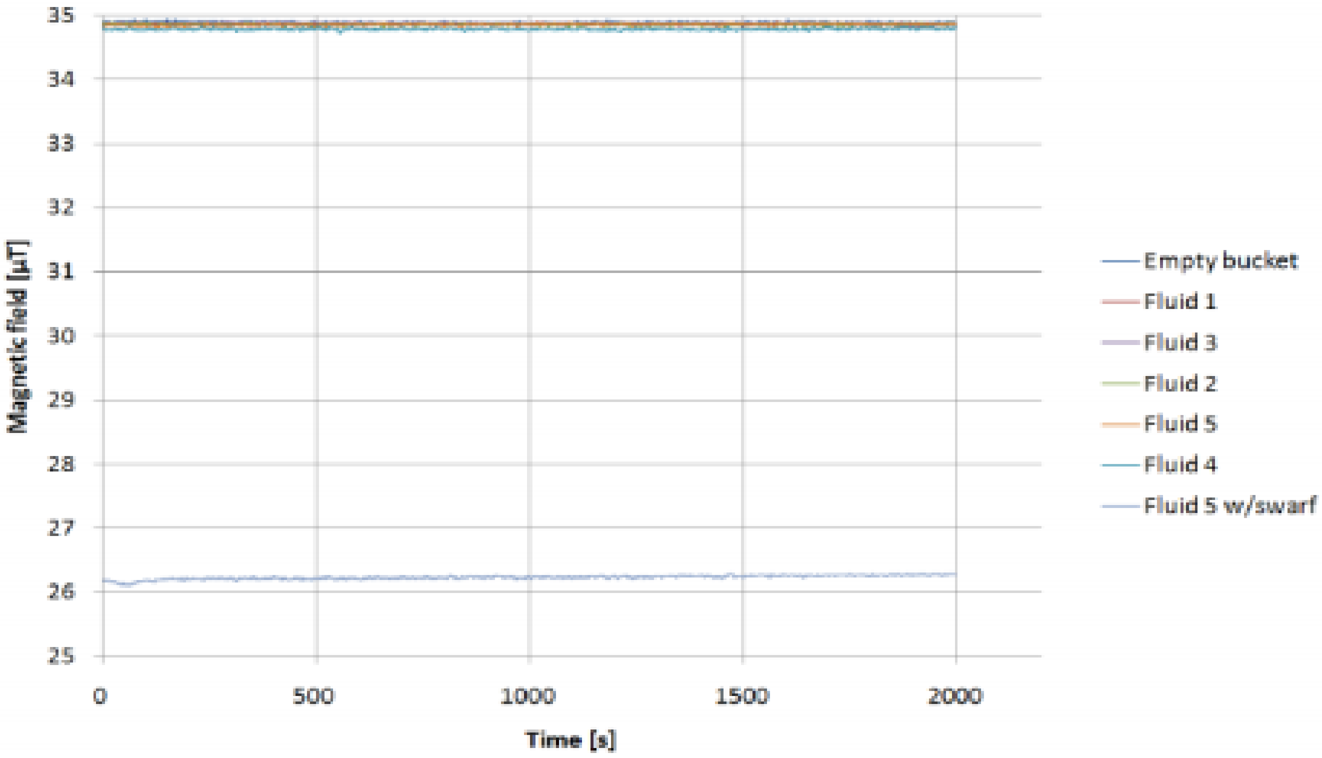


Figure 2.16: The geomagnetic field as a function of drilling fluids [41]

In order to enhance the accuracy of the magnetic MWD surveys, the amount of swarf particles generated during drilling operations must be mitigated. This can be accomplished by improving the drilling and operation practices, combined with proper pre-planning and execution.

Time effects, concentration, sagging, rheological properties, remix and grain size

The magnitude of the shielding effect varies with the timescale. The impact of the various magnetic sources (present in the mud system) on the directional MWD sensors will vary with time. Laboratory experiments [48] have concluded that the distortions of the geomagnetic field depends on when and how long the magnetic sources were present in the mud system. Figure 2.17 displays how the magnetic fragments influences the geomagnetic field through the timescale.

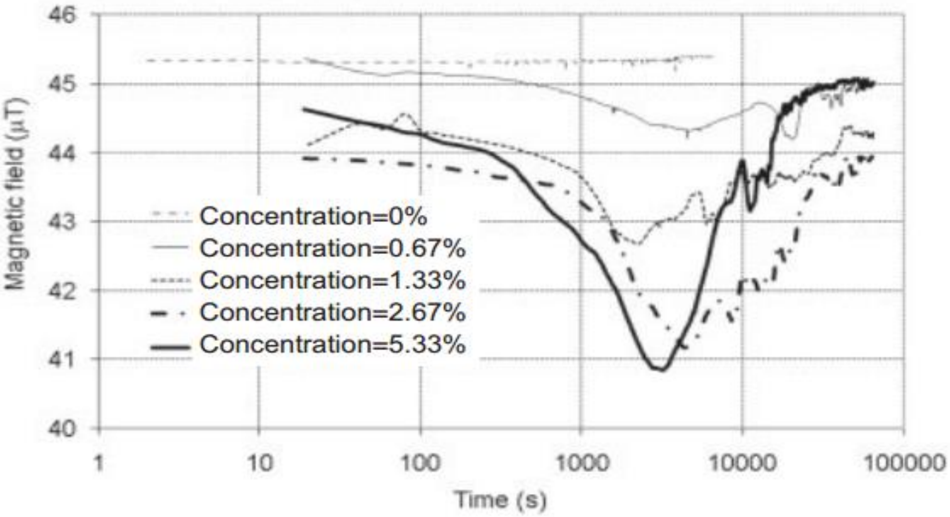


Figure 2.17: Effect of time and quantity of magnetic minerals on the geomagnetic field [48]

This graph highlights some important observations that must be emphasized:

1. The decay of the geomagnetic field starts instantaneously, right after the introduction of the magnetic particles. However, it takes some time before the decay rate is empowered. The main explanation behind this behaviour would be that the viscous forces in a mud system are much larger than the magnetic forces. Magnetic domains existing a magnetic fragment tends to align themselves oppositely to an external magnetic field. However, due to viscous forces the reorientation process of the various domains is impeded and hampered.
2. The absolute minima is reached rapidly, approximately after 4500 seconds.
3. After the minima, the dampening effect is gradually weakened and the geomagnetic field is boosted. Nevertheless, the distortion still present after 80000 seconds.

The increase in the geomagnetic field is caused by sagging. Under static conditions (without circulation and rotation of the drillstring), the rheological attributes of some drilling fluids tends to decrease, for example the viscosity. A deficiency of this parameter will decrease the suspension properties of the drilling fluid. This causes the heavy magnetic particles to settle themselves out of the mud system and thereby deposited at the bottom of the well. Another important aspect related to viscosity is that: viscous forces govern the orientation rate of the individual magnetic domains in a magnetic particle. A reduction in viscosity would also contribute with an enhanced alignment rate of the various domains and thereby increase the shielding effect. Beside from that, the magnetic domains in coarse-grained particles tend to align themselves faster than fine- grained fragments. This implies that the shielding effect is a function of rheological properties of the mud and grain size of the magnetic fragments.

4. The magnetic shielding also depends on the concentration of the magnetic fragments. The higher the concentration, the larger are the distortions of the geomagnetic field.
5. Minor reductions, around 1% in the cross- axial magnitude of the geomagnetic field can cause considerable inaccuracies to the magnetic MWD survey [48]. Concentration levels of just 0, 67 % causes bias in the geomagnetic field that exceeds this value.

This laboratory experiment also investigated whether there is a connection between the shielding effect and how many times the mud system is remixed. The result of this study is presented in figure 2.18. One important observation from this graph is that: for each remix the dampening effect is enhanced and the absolute geomagnetic field minima tends to occur earlier. This implies that old mud systems that are recycled and re-used several times, leads to larger distortions of the geomagnetic field, compared to fresh drilling mud. The main reason behind this difference is that the concentration and accumulation of magnetic fragments are much higher in recycled mud than for fresh drilling fluids.

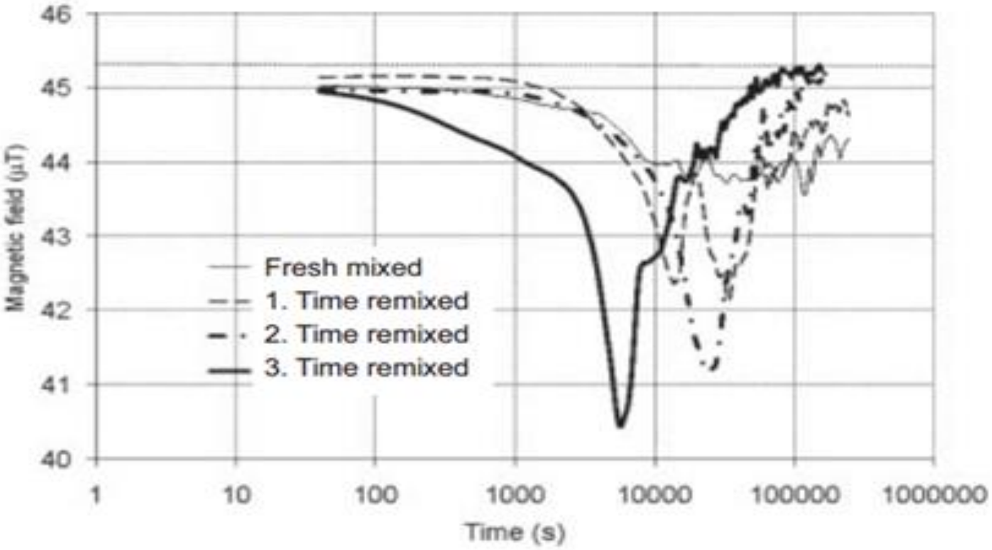


Figure 2.18: Effect of mud stirring on the geomagnetic field [48]

In order to enhance the accuracy of the directional survey measurements, the following recommendations should be considered:

- Recycled mud should be cleaned for magnetic particles before re-using it.
- Magnetic azimuth survey should be taken as fast as possible, preferentially just after stopping the circulation and rotation of the drillstring.
- Viscosity of the mud system should be monitored and kept below a certain threshold
- The suspension properties of the mud should not be overdue.

BHA Geometry and magnetometer positioning

The geometrical design of the BHA and position of the magnetometers inside the drillpipe, affects the dampening rate of the geomagnetic field. From research and analysis [49], it has been established that BHA`s with ideal axial geometries, the attenuation rate of the geomagnetic field is predictable. The dampening rate for such perfect symmetries is found out to be proportional to the square of the magnetic susceptibility of the drilling fluid. However, with more complex and non- symmetrical BHA designs, the attenuation rate shows a complex and non- predictable behaviour. For instance with a collar based BHA design, the magnetic shielding effects varies with the toolface angle and exhibits a compound nature. This nature consisted of both amplification and attenuation of the magnetic field strength.

Experiments and analysis [49] have investigated the effect of different BHA designs and magnetometer positions on the distortion rate of the geomagnetic field. These scientific investigations have studied the effect of two different tool geometries: a collar based and a sonde based design.

Collar based design

A $4\frac{3}{4}$`` collar based instrument was analysed in a $6\frac{1}{2}$`` hole. The magnetometers in this design were installed eccentrically relative to the tools centre axis. This model was design to resemble an operational sequence of drilling in a horizontal borehole. Therefore, two different magnetic permeabilities were introduced: 0,015 in the top segment of the well and 0,03 in the bottom. These differences simulates a situation where most of the magnetic fragments have sagged down to the bottom of the well. Beside from that, the tool is in contact with the borehole wall and the external magnetic field is 50 000 nT. The whole setup of this design and magnitude of the modelled magnetic field is displayed in figure 2.19 a, b. The coloured segment in figure 2.19a represents the drilling fluid.

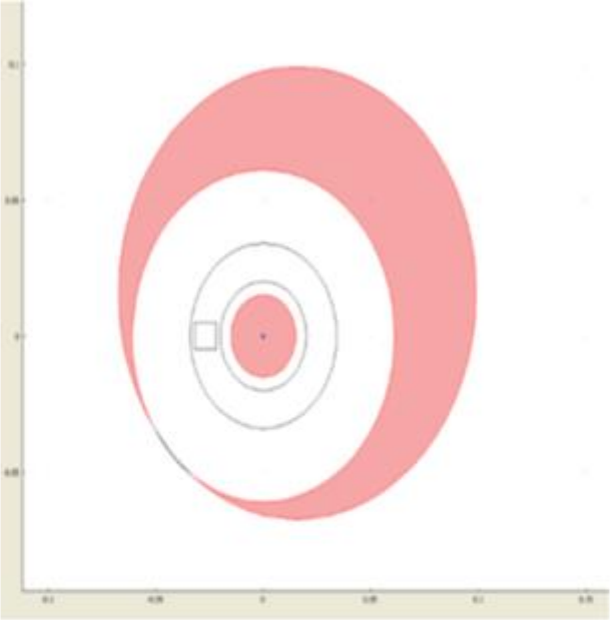


Figure 2.19a: The collar based tool setup [49]

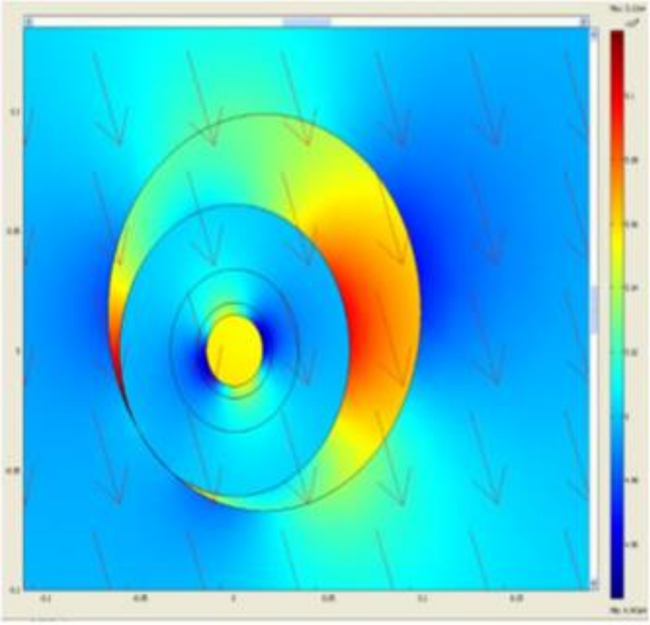


Figure 2.19b: The modelled magnetic field strength [49]

The results derived from this analysis indicated that the highest magnetic field strength was observed in the centre region, where the magnetometers were installed. The magnetic shielding effect is non-existent in regions where the collar based tool is in direct contact with the borehole wall.

Sonde based design

A 12 $\frac{1}{4}$`` borehole was used to run a 8`` collar, incorporated with a 2`` probe instrument. The magnetometers in this design is located in the probe tool, positioned near centre of the instrument. This design is more symmetrical compared to the collar based design. Beside from that, there is no contact between the borehole wall and the tool in this analysis and the magnetic susceptibility of the drilling fluid is 0,1. The whole configuration of this instrument and the modelled magnetic field in displayed in figure 2.20 a, b.

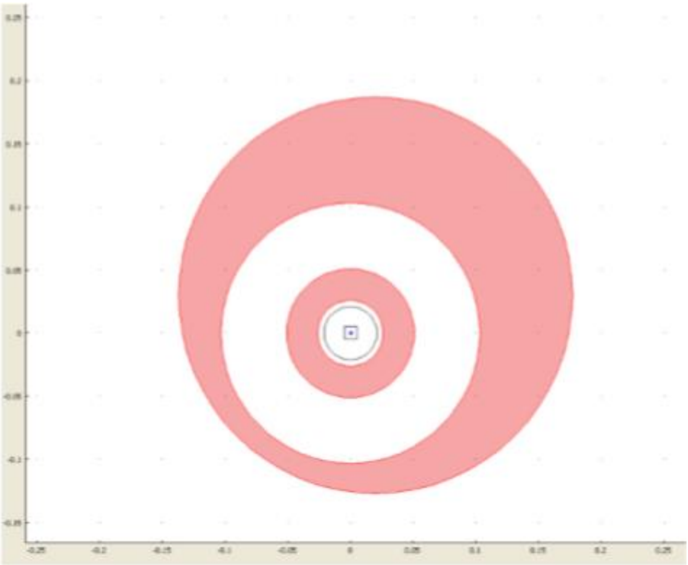


Figure 2.20a: The probe based instrument configuration [49]

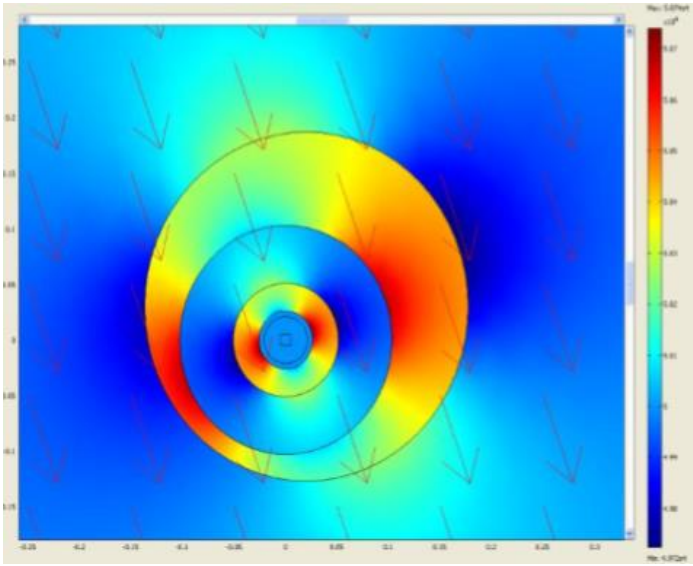


Figure 2.20b: The modelled magnetic field strength [49]

The results derived from this analysis, indicate that instruments with more symmetrical orientations are less prone to large fluctuations in the magnetic field.

Magnetic formations and minerals

The magnetic properties of formations are highly connected to its mineralogical content. Different minerals have differing magnetic properties and attributes. These fragments can influence the magnetic signature of geological formations through their physical and chemical properties, mineralogical characterization, behaviour in the presence of an external magnetic field, magnetic susceptibility and many more.

Anomaly fields

Distortions to the geomagnetic field caused by geological formations are exerted by the outer layer of the earth, which is characterized as a very thin layer. This region is approximately 30 – 60 km thick. Geological processes, tectonic setting, quantity and presence of magnetic active minerals in the formation govern the magnitude of the anomalies caused to the geomagnetic field. Magnetic minerals like hematite, magnetite and titano-magnetite are the most important fragments. The presence of these minerals in igneous and metamorphic rocks combined with temperatures below 600 °C and high magnetic susceptibility, makes these two rocks types potential crustal anomaly fields.

Usually, measurements obtained by magnetic examinations indicate that the fluctuations caused by minor anomaly fields never surpasses a few percentages of the geomagnetic field. However, in extreme scenarios fluctuations in the threshold range of 5- 8 % from the regional magnetic field intensity can be observed. In such areas and scenarios, the geomagnetic field is strongly attenuated or distorted. Distortions in the range of 2000- 4000 nT from the local geomagnetic field can be observed [50]. Magnetic active components and sources are considered as magnetic dipoles. Because of this, the magnitude of a magnetic field experiences a deficiency equal to the distance (factor) of: r^{-3}, r is the radius of the source. Due to this fact, the magnitude of the anomaly fields decreases rapidly. Figure 2.21 highlights the anomaly fields located on the geological setting of Norway, causing distortions to the geomagnetic field.

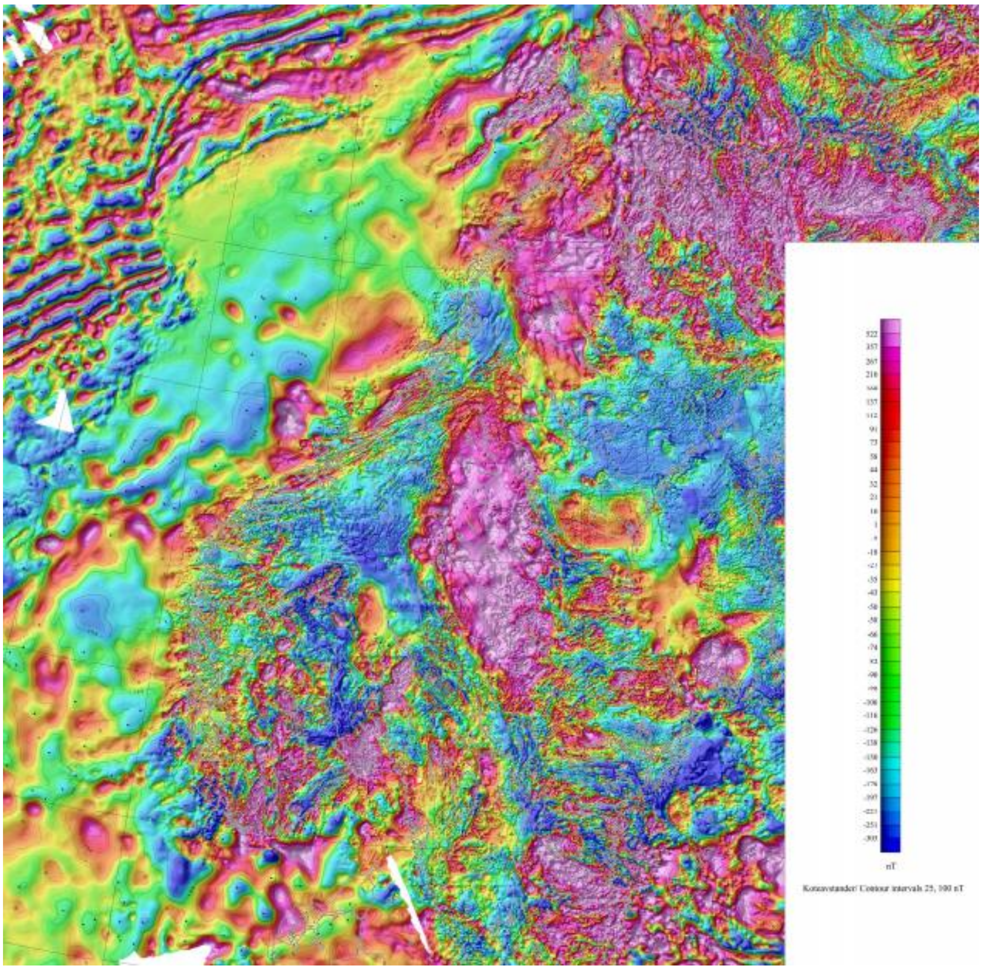
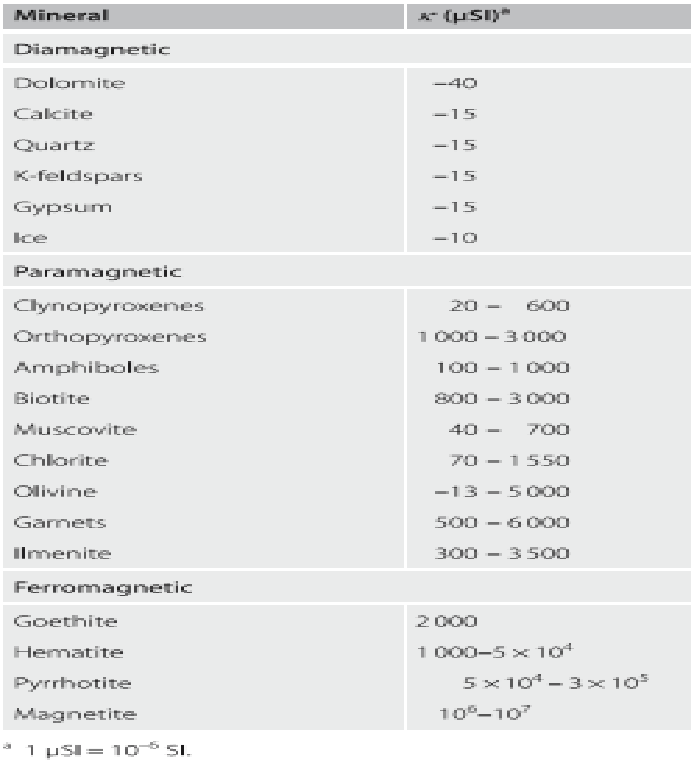


Figure 2.21: Anomaly fields of Norway [51]

Magnetic susceptibility

Magnetic susceptibility is one of the most important parameters when performing an assessment and evaluation of the magnetic characterizations of geological formations. This parameter is one of the most influential components in terms of causing irregularities to the geomagnetic field by rock formations. Another contribution of this parameters that it allows to categorize and classify minerals into three distinctive groups: ferro-, dia- and paramagnetic. Thereby, allowing magnetic evaluations of geological rocks. The value of the magnetic susceptibility of different minerals are displayed in figure 2.22 [50].



Mineral	κ (μSI)[a]
Diamagnetic	
Dolomite	−40
Calcite	−15
Quartz	−15
K-feldspars	−15
Gypsum	−15
Ice	−10
Paramagnetic	
Clynopyroxenes	20 − 600
Orthopyroxenes	1 000 − 3 000
Amphiboles	100 − 1 000
Biotite	800 − 3 000
Muscovite	40 − 700
Chlorite	70 − 1 550
Olivine	−13 − 5 000
Garnets	500 − 6 000
Ilmenite	300 − 3 500
Ferromagnetic	
Goethite	2 000
Hematite	$1\,000–5 \times 10^4$
Pyrrhotite	$5 \times 10^4 - 3 \times 10^5$
Magnetite	$10^6–10^7$

[a] 1 μSI = 10^{-6} SI.

Figure 2.22: The magnetic susceptibility and categorization of minerals [50]

- Diamagnetic minerals. Some of the most abundant minerals are found within this category, these minerals include: dolomite, calcite and quartz. Beside from that, ice is also found within this group. The magnetic susceptibility values of the diamagnetic minerals is found to be in the range of $-10 * 10^{-6}$ to $-40 * 10^{-6}$ SI.

- Paramagnetic minerals. In this category, some of the main constituents of geological rocks can be found. These minerals include: clay- minerals, micas, pyroxenes and many more. Beside from that, a number of silicates is also organized in this group. The susceptibility values of the various paramagnetic minerals are very widespread and does not display any strong correlation between themselves. From figure 2.22, values as low as $-13 * 10^{-6}$ SI and up to $6000 * 10^{-6}$ can be found in this group. One explanation of this irregularity is the variations in iron cations within the same rock mineral.

- Ferromagnetic minerals. Similar to the paramagnetic minerals, large variations in the susceptibility values can also be found within this group. For instance, Goethite is found to have a value as low as $2000 * 10^{-6}$ SI. While on the other hand, magnetite can have values as high as $10^7 * 10^{-6}$ SI. The most substantial and abundant ferromagnetic minerals are the iron- titanium oxides. These oxides includes the following minerals: magnetite, ilmenite, hematite, goethite and maghemite. The ferromagnetic minerals are only found in smaller quantities in rocks. However, their abnormal high magnetic susceptibility values can mask the contributions and effects of other magnetic minerals [50]. Due to this fact, the content of ferromagnetic minerals in rocks plays an essential role in disturbing the geomagnetic field. Figure 2.23 [50], highlights the impact of magnetite and other minerals on the magnetic susceptibility.

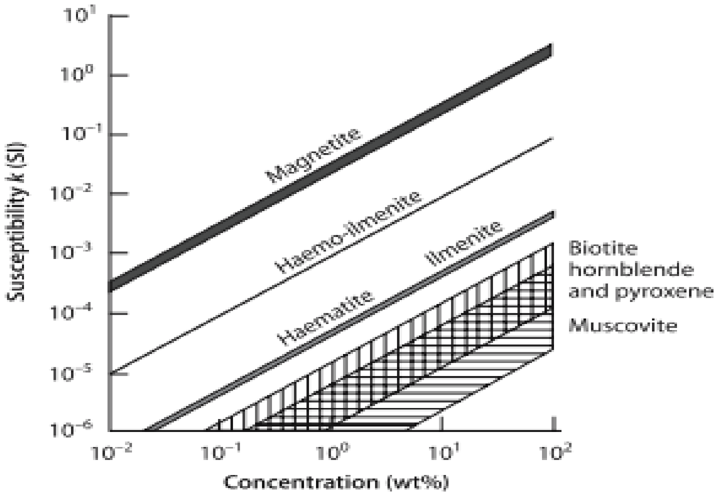


Figure 2.23: The impact of mineral quantity on the magnetic susceptibility [50]

Magnetic minerals

This segment will be dedicated to different minerals of main interest in rock magnetism. This portion will include a description and characterization of the magnetic properties of these minerals in rocks, alongside with their abundancy and occurrence. Beside from that, mineral attributes of importance to magnetic research and analysis will also be highlighted in this portion.

Iron

Pure iron in its native form is very difficult to find in some certain geological formations like terrestrial rocks. However, this mineral is one of the main contributors of magnetic capabilities in formations. Generally, iron is mostly discovered in its pure form or with differing amount of nickel. This element is mostly stable from the room temperature and up to approximately 910 °C. At this temperature threshold, the iron- element will maintain a body centered cubic structure. However, this structure is altered to a face centered cubic structure when exposed to temperatures above 910 °C. The critical Curie temperature of this element is around 770 °C. Iron is a ferromagnetic mineral, but its magnetic characteristics are altered to paramagnetic when exposed to temperatures above its Curie temperature.

Magnetite

Magnetite is a cubic fragment that is characterized by a contrary spinel arrangement. In this structure, the cations is positioned in two differing meshes. Which means that the Fe^{2+} and Fe^{3+} cations are located in the latter, while the Fe^{3+} is positioned in the former. This mineral has a density equal to $5200\,\frac{kg}{m^3}$. Like iron, magnetite is a ferromagnetic mineral with strong magnetic characteristics. However, it has a lower Curie temperature (around 578 °C). Due to this fact, temperatures above 578 °C will render magnetite for many of its magnetic properties.

Titano- magnetite

Titano- magnetite is a solid mineral that is composed of magnetite and ulvopsinel. This composition is only stable at temperatures above 600 °C, which results in a homogenous solid solution. With temperatures below 600 °C, the mixture of magnetite and ulvospinel is still immature, which results in an inhomogeneous solid solution with many small fragments. The Curie temperature of this mineral is a function of the mineralogical composition and distribution. With increasing amount of ulvopsinel, the Curie temperature of titano- magnetite decreases almost linearly. A Curie temperature of around 578 °C is recorded with no ulvospinel content, and -153 °C is established for titano- magnetites with no magnetite content. Other magnetic properties and characteristics of this mineral like the susceptibility, is also a function of the mineralogical composition. The level of oxidization in natural titano- magnetites are lower and contain a number of cations different from: Ti^{4+}, Fe^{3+} and Fe^{2+}. Examples of differing cations are aluminium and magnesium ions, the presence of these ions in the mineral structure will affect and influence the magnetic properties of the titano- magnetite.

Titano- maghemites

If titano- magnetite is exposed to extensive heating periods in air with low- medium temperatures (below or equal to 300 °C), titano- maghemites are generated. This process is also known as maghemitization. An example of this process is the generation of maghemite from magnetite, which involves a low temperature oxidation procedure. According to the mineralogical content, titano- maghemites displays a variety of magnetic properties. There is a challenge related to the establishment of the Curie temperature of this mineral. This parameter increases with oxidation and the transformation temperature of this mineral is around 300 °C. Above this temperature, a variety of products may be generated, for instance hematite. Beside from that, a self generated magnetization process is also reported and observed among titano- maghemites [50].

Ilmenite

Ilmenite is a paramagnetic mineral with a susceptibility value around $1{,}0 - 1{,}2 * 10^{-6}$ SI. This mineral have a melting point at 1470 °C and its density is approximately $4800\,\frac{kg}{m^3}$. Footprints of hematite and magnetite can be found in naturally occurring ilmenite. One of the most conspicuous properties of ilmenite is its weather resistivity. Due to this ability, this mineral often persists in rocks. Beside from that, ilmenite is very abundant in igneous rocks and lunar fragments.

Hematite

Hematite can be found in geological formations in two forms:

1. Black coloured polycrystalline particles.
2. Alternatively, as a glaze on other mineral fragments and in apertures in rocks. Hematite existing in this state is more finely divided than the first form.

This mineral can be found as an alternation product in igneous and metamorphic rocks. However, the magnetic properties and characteristics of these rocks are not influenced by the presence of hematite. The main reason behind this is usually the occurrence of titano-magnetite in metamorphic and igneous rocks. The titano- magnetite is much more influencing and stronger in terms of magnetic properties than the hematite fragment. The magnetic capabilities and properties of this mineral is very fluctuating. However, the mineral properties of hematite is a function of the following factors: grain size, temperature, impurities and many more. The critical Curie temperature of this mineral is 680 °C. A corundum structure with a rhombohedral symmetry characterizes this mineral. The density of this fragment is around $5300\,\frac{kg}{m^3}$. Beside from that, the melting temperature of this mineral is approximately 1750 °C. However, hematite is transformed into magnetite if exposed to temperatures around 1400 °C in air.

Pyrrhotite

Pyrrhotite is a mineral that belongs to the group of iron- sulphide minerals. These fragments are known for their brass shaped colour, which is enhanced by metallic lustre. Pyrrhotite can be found in basic metamorphic and igneous rocks. The Curie temperature of this iron-sulphide fragment is approximately around 320 °C. However, measurements of magnetic properties and characteristics of pyrrhotite may be difficult to obtain, due to high magnetocrystalline anisotropy.

Maghemite

The chemical arrangement and composition of maghemite is similar to hematite. However, this fragment is characterized by a cubic spinel arrangement with an imperfection. The defect is related to a lattice position, where an Fe^{3+} is unoccupied. At temperatures above 300 °C, maghemite is transformed into hematite. However, the exact transformation temperature will vary for each sample and eventual impurities in the lattice structure. Generation of the maghemite fragment is primarily a result of an oxidation process, which involves magnetite or a dehydration process related to the lepidocrocite mineral. Maghemite can also be generated as a product, descending from a weathering process in oceanic muds, red sandstones and some specific basalts. The density of this fragment is around $4900\frac{kg}{m^3}$. Like magnetite, this mineral is known for its strong magnetic properties. Due to low transformation temperatures, the absolute Curie point of this mineral is not fully known. However, research and studies indicate that the Curie temperature of this fragment is between 545 °C and 740 °C.

Titano- hematite

Two major components in titano- hematites are the ilmenite and hematite mineral. A homogenous and solid solution is stable at all compositional fractions and temperatures above 1000 °C. Titano- hematites are common in most volcanic rocks, metamorphic rocks, granites and gneisses. The magnetic properties of this fragments depends upon the fractions of ilmenite and hematite. Beside from that, the Curie temperature of this mineral is the range of 675 °C to - 200 °C.

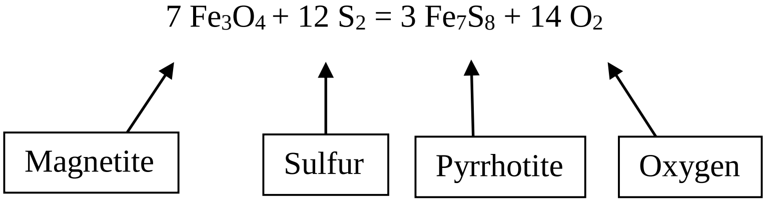
Ferromagnetic minerals in formations

From figure 2.23, the ferromagnetic minerals have a magnetic susceptibility that is extremely high. This property gives these minerals the capability to alter the contributions from para- and diamagnetic minerals in rocks. Beside from that, these minerals also causes largest anomaly fields on the earth’s crust compared to the other two groups. This segment will be dedicated to ferromagnetic minerals found in the three different rock types: sedimentary, metamorphic and igneous rocks.

Metamorphic rocks

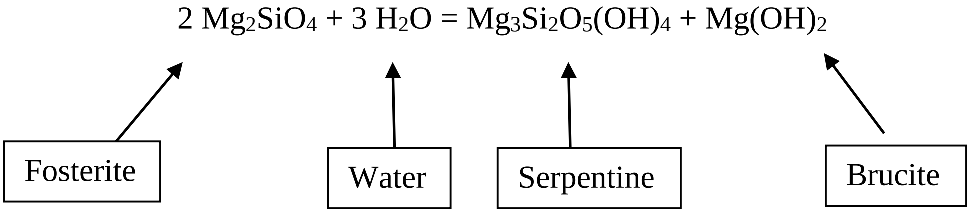
The quantity and formation of ferromagnetic minerals in metamorphic rocks depends on several factors and conditions: temperature and pressure, tectonic stresses, chemical and mineralogical arrangement of the protolith, alternation of pressure and temperature with time, type and existence of fluids and many more. However, the main processes are the generation of chlorides at the price of iron- titanium oxides in small metamorphic facies, generation of magnetite between the transition process from the amphibolitic and granulitic phases and the generation of sulphides. In these processes several parameters are involved and the processes itself are very sensitive, for instance two contrasting metamorphic rocks with different magnetic properties and characterization may be generated from two protoliths with similar magnetic properties. Examples of processes in metamorphic rocks, involving either generation or reduction of ferromagnetic minerals are described below:

1. The first example is observed and studied in the Himalayas and the western alps. These two geological regions have a limestone segment that is filled with magnetite. This geological formation is subjected and exposed to a sulfur rich fluid, which is continuously circulated during the process of metamorphism. All of these components are subjected to a low scale process of metamorphism, which involves temperatures in the range of 300- 350 °C. These factors combined converts the magnetite into pyrrhotite. The reaction is summarized below:



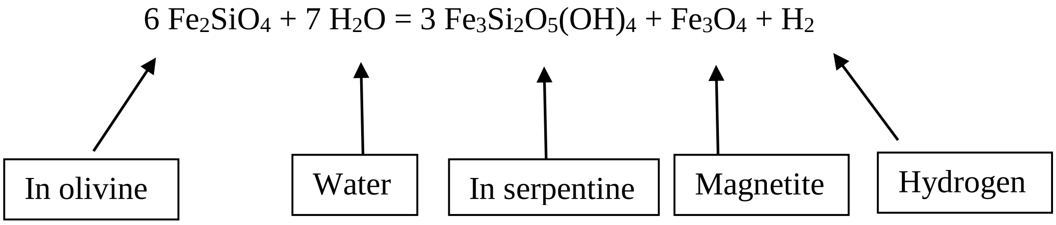
$$7\ Fe_3O_4 + 12\ S_2 = 3\ Fe_7S_8 + 14\ O_2$$

2. The second example involves large- scale metamorphism, which contains high temperatures. This reaction involves a conversion of peridotites to generate serpentinites. The following reaction describes the hydration of olivine at large temperatures:



$$2\ Mg_2SiO_4 + 3\ H_2O = Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$$

Iron can be found in olivine, which contributes to the formation of magnetite. This process is displayed in the reaction below:



$$6\ Fe_2SiO_4 + 7\ H_2O = 3\ Fe_3Si_2O_5(OH)_4 + Fe_3O_4 + H_2$$

This reaction generates a substantial amount of magnetite, thus increasing the magnetic susceptibility of the rock. Thereby causing larger anomalies in the geomagnetic field in the specific location of the rock.

Sedimentary rocks

Sedimentary rocks can contain ferromagnetic minerals of the following types: diagenic, authigenic and detrital. Two of the most abundant detrital fragments are the titano- hematites and titano- magnetites. The occurrence of these two minerals in rocks is largely dependent on their abundancy in the source rock. The total volume of iron- titanium oxides in sedimentary rocks, are largely dependent on the distance between the initial place or the original site of the fragments and the geological site where these fragments are deposited. The density [50] of the iron- titanium grains is approximately around $5000\,\frac{kg}{m^3}$. Due to this fact, these minerals are deposited and settled before the siliceous minerals.

The stability and content of ferromagnetic minerals in sedimentary rocks are also a function of the consolidation grade of the rock. For instance in unconsolidated and immature rocks, the state of the ferromagnetic minerals are very unstable and fragile. The presence of water and chemical reactions like: oxidation and reduction, may also contributes to even more instability among ferromagnetic fragments. Beside from that, processes like burial, diagenesis, presence and circulation of fluids, temperature and pressure variations can alter the magnetic properties and signature of sedimentary rocks. Examples are presented in the next paragraph, which highlights the impacts of these conditions on the magnetic characteristics of sedimentary rocks.

Continental environments, which are abundant with oxygen rich waters are generally associated with the formation of red beds. The colour of these beds are preserved through a component named: hematitic pigment, which impregnates the rock. Other geological environments like, marine and lacustrine basins that are rich in organic matter and characterized by still waters with low oxygen content: are associated with the formation of green and black clays. These geological rocks contains sulfides. The magnetic properties of the sulfides will vary with time, quantity and availability. With increasing content of sulfides, the iron- sulfur ratio will be changed. This modification leads to an evaluation process of the rock that follows the following steps: from pyrrhotite → greigite → pyrite. The end stage of this evolution leads to the formation of pyrite, which is common and non- ferromagnetic mineral. The remaining two, are ferromagnetic fragments but are very unstable. As the diagenesis process proceeds, the pyrrhotite and greigite are transformed into oxides. Beside from that, as the sedimentation process changes the possibility of forming a layered sedimentary rock increases with differing magnetic signature in each layer.

The content of ferromagnetic fragments are generally very low in carbonate rocks. The most abundant ferromagnetic minerals are titanium- hematite and titanium- magnetite. In some special circumstances, goethite can be developed and conserved. The presence of primary ferromagnetic components of detrital source in soils are mostly a result of disintegration of bedrocks. These minerals are found in substantial quantities in soils originating from red- sandstones and volcanic bedrocks. On the other hand, secondary ferromagnetic components are formed from advance biological and chemical reactions. These reactions are a function of several parameters such as: the weather, acidity and neutrality of the soil, moisture and organic elements, which governs the efficiency of these reactions.

Igneous rock

The stability, quantity and quality of ferromagnetic minerals in igneous rocks are governed by two factors:

1. The chemical configuration of the magma. This parameter governs the group of oxide-minerals that is formed and crystallized.
2. The history of the magma in terms of displacement and cooling. This parameter governs the stability of the minerals. Beside from that it also controls the thermal, mineralogical and chemical matureness of the mineral fragments.

The type of igneous rock is also essential in the process of formation and storage of ferromagnetic minerals. The amount of iron- titanium oxides in mafic rocks can reach up to 5 % of the total volume of the rock, the titanium content in mafic rocks is generally high as well. Felsic rocks on the other hand have a low titanium content, and the total amount of iron-titanium content is mere 1 % of the total volume of the rock.

The cooling process of the effusive rocks occurs very rapidly. This means that the crystals are not given proper time to mature and grow. Therefore, the grain size of the iron- titanium oxides in effusive rocks are generally very small. These oxides are usually found to be in the range of 0,1- 1 micrometres in effusive rocks. Beside from that, the physical and chemical conditions are alternating during the cooling and crystallization phase. This can lead to a swift transformation among the iron- titanium oxides. The cooling process of the intrusive rocks are very slow and time consuming. This gives the crystals proper time to grow and mature. Due to this fact, the size of the iron- titanium oxides in the intrusive rocks are relative large, fragments can be found to be in the range of 10- 100 micrometres. These oxides are also more stable and balanced in intrusive rocks.

The crystallization process of the iron- titanium oxides in igneous rocks starts at temperatures above 1000 °C. Large temperatures are required to make stable and solid solutions of the titano- hematites and titano- magnetites. The necessity for large temperatures is primarily for the integrity of iron- titanium oxides. At lower temperatures, the ferromagnetic minerals will no longer be a part of compound fragments and the miscibility will be incomplete. This will lead to a diffusion of every single element and thereby low integrity.

Electromagnetic induction and drilling equipment

Permanent magnetic sources are one of the main factors behind magnetic MWD survey errors, which distorts measurements obtained by the magnetometers. However, these permanent magnets may give rise to additional fluctuations in the magnetometer readings by contributing in the process named electromagnetic induction. The induction process is governed by the physical equation named as the Faraday`s law:

$$\varepsilon = -\frac{d\Phi B}{dt} \qquad (2.39)$$

$$\Phi B = H * A * cos(\vartheta) \qquad (2.40)$$

Faraday`s law states that an current will be induced in a conductive material if the magnetic flux (ΦB) changes in time. In other words, the induced current is equivalent to the rate of change in the magnetic flux through a conductive material. This implies that if a conductive material is exposed to an alternating magnetic field, a current will be induced in the system and give rise to an electric field. Which in turn will produce its own magnetic field. On the other side, an alternating electric field can give rise to a magnetic field. However, some fundamental requirement are needed in order to ensure an efficient induction process, magnitude of the electric and magnetic fields. The requirements are as following:

1. A magnetic field. This magnetic source can either be a permanent magnet, magnetic field exerted by an electric field or an induced current. Magnetic fields with high magnitude will induce an empowered electrical field.
2. A conductive material. An electric field or induced current can only propagate freely through conductive materials, for instance most metals are excellent conductors. However, alternating magnetic fields in the presence of only insulators will not induce any current in the environment.
3. A dynamic environment. The presence of a non- alternating magnetic field and non-moving conductive material will not induce any current in the material. Faraday`s law (equation 2.39), clearly states fundamental requirement of an dynamic environment: The faster the rate of change in the magnetic field, the larger will the induced current be.
4. Large surface area of the conductive material is not a fundamental requirement, but it will bolster the magnitude of the induced current.

In a drilling environment, all of these requirements are fulfilled. Therefore, a well is an ideal setting for the induction process. Listed below are the fundamental requirements alongside with examples from a wellbore setting:

1. A magnetic field: Magnetic weight materials in mud, formations, casings and the drillstring.
2. A conductive material: ions from seawater, formation-water, and water- based mud systems. Beside from that, other conductive materials and components in muds, drillcuttings, casings and drillstring.
3. A dynamic environment: friction forces, collision of particles, rotation of the drillstring, input of energy from the mud-pumps (circulation), viscous forces, flow regimes (turbulent, transitional and laminar), change in mud density or different mud gradients, installation of casing strings, tripping out, running the drillstring into the hole and shear forces.

Listed below is figure 2.24, which depicts and summarizes the electromagnetic induction process in wellbores.

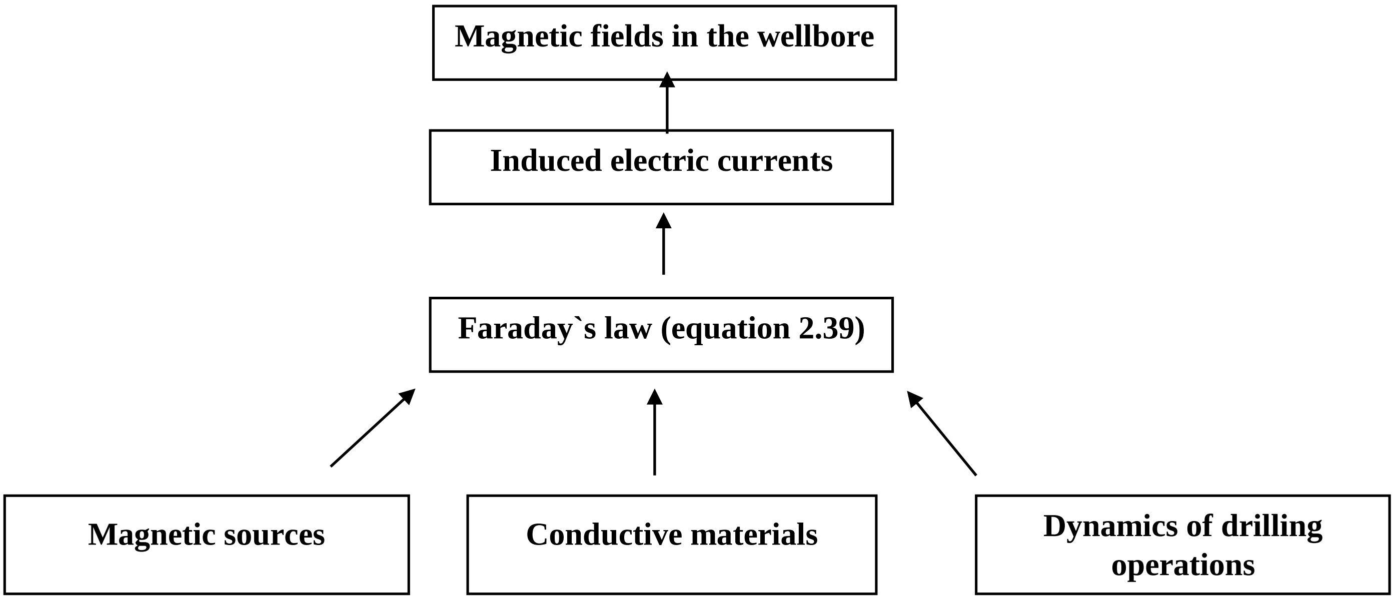


Figure 2.24: Summary of the electromagnetic induction process

The magnetometers that are utilized in a magnetic MWD survey apparatus are usually placed inside a non- magnetic drill collar segment, which surrounds the sensors and functions as a barrier against the external magnetic environment. This configuration is required, primarily for enhancing the quality of the directional survey, and isolation against magnetic interference exerted by nearby positioned drilling equipment.

The drillstring itself is a considerable error source to directional drilling surveys. This object is an enormous metallic cylinder, which can cause fluctuations to the geomagnetic field. The geometrical shape of this component alongside with drillstring rotation, can direct the magnetization to be positioned parallel to the borehole axis. The magnetic properties of the drillstring holds the capabilities to manipulate and disturb the local magnetic field, which in turn leads to error propagation in the directional survey. In order to minimize these errors, NMDCs are utilized in the drillstring. However, these components only dampen the magnetisation caused by the drillstring, but it does not eliminate the errors. A threshold for quality control of surveys was established by Wollf and De Wardt [53], which stated that the maximum magnetic azimuth error caused by the magnetized drillstring should be within the limit of 0,25 °. If the error was within this limit, the survey was recognized as a “good magnetic” survey. Beside from that, other drilling equipment that could give rise to errors are:

- The drilling rig
- Drillpipes and drillcollars
- Adjacent casingstrings
- Adjacent completed wells
- Sidetracked drilling assemblies

- Plugged and abandoned wells
- Hot spots. These are created by mechanical impacts between objects, which can create magnetized spots in a metallic non- magnetic component. Removal of magnetic field isolating films or wear, due to excessive flowrates or mechanical impacts can also create hot spots.

2.3.7 Data transfer and integration

In directional drilling, the recorded data by the sensors are of a huge importance. In order to benefit from this information, the obtained data must the transported in a safe, proper and efficient manner to the decision makers. The transportation operation in a magnetic MWD instruments is carried out by the process of data transmission. This part of the survey instrument is named as MWD telemetry. It enables the conversion of the data measured by the survey sensors, into an appropriate arrangement of transmission to the facilities at surface. The main objective of a telemetry system is to provide large amount of bandwidth with an extended reach to the decision makers.

There are a number of MWD telemetry systems available in the market. Some examples are wired- pipe telemetry, mud- pulse telemetry and electromagnetic telemetry. Each of these methods have different functioning principles, bandwidth capacity and reach. However, the mud- pulse telemetry system is currently the most used system for transporting downhole data to the surface, utilized on the Norwegian continental shelf [19]. This telemetry system have been adopted by the industry as the main transport system for real- time data obtained from the magnetic MWD instrument, due to the following reasons[20]:

- Durability
- Field-tested: Displaying high level of accomplishments under alternating borehole circumstances.
- Low complexity
- Offers the opportunity to accommodate different wellbore parameters during the drilling operation.

This segment will contain a system description of the various components of a telemetry system, from the MWD sensors to the surface facilities. A description of the principles behind the mud- pulse telemetry will be described, alongside with an explanation of the data flow from the sensor to the decision maker. Finally, challenges related to data acquisition and processing will be presented and highlighted.

Mud- pulse telemetry: system description

Before describing the fundamental functioning principles of the mud- pulse telemetry system, it is important to highlight the communication components and elements of this system. The elements of this transmitter module can be divided into two groups: The downhole elements and the surface elements.

The downhole elements consist of the following components:

- The transmission pathway
- A transport medium
- A source to provide power
- Transmitter and modulator
- Microprocessor

The transmission pathway of the mud – pulse system is the drill string itself. The mud filled inner bore of the drillstring, functions as the main conduit for transporting the downhole signals up to the decision makers at surface. However, a transport medium is required in order to carry the data. This process will be accomplished by the mud itself. The necessary downhole data will be transported across this flowing medium.

One of the most important elements of this transmission module is the microprocessor. This component has the responsibility to perform some of the most important key processes. The main objectives of this element are: ensure that the functions of the data module are coordinated, activation of the downhole sensors, collect measured data and guide it to the facilities at surface by energizing the transmitter. The primary function of the transmitter is to deliver the measured data to surface. The sensor data is sent in the form of pressure fluctuating pulses in the flowing mud (encoding the signal). This is accomplished by placing a controllable device that is regularly opened and closed, usually in the form of a valve inside a pulser. The pulser functions as a transmitter, while the adjustable valve operates as a modulator. In which sensor readings are modulated in the form of pressure pulses.

In order to ensure that the whole MWD instrument functions properly, a source of power is required. Three sources of power that can be utilized: batteries, turbine systems or a combination of these two solutions. The most common type of batteries used for MWD applications are the lithium chloride batteries. These batteries are known for its stability at relative high temperatures and high power[21]. The turbine system generates power with the help of flowing mud. In this method, the circulating mud will apply angular force to a turbine, which will be passed on to an alternator. This process will in turn generate an AC that will supply power to the MWD instrument. However, many MWD instruments are configured to utilize a combined solution. One of the biggest benefits of such systems is that the power supply is not limited by improper circulation rates of mud. All of the described sources have their own limitations and advantages; this aspect is summarized in the two tables presented below:

Lithium Cloride batteries	
Advantages	**Disadvantages**
➢ Operational at temperatures up to 150 °C. ➢ Does not rely on flow characteristics of the mud. ➢ Capable of supplying energy while tripping out. ➢ Reliable energy source ➢ Stable energy outputs throughout the service lifetime. ➢ Simple, does not require complex electronical environment.	➢ Not rechargeable. ➢ Strict disposal guidelines due to possible environmental impacts. ➢ Release of greenhouse gases due to transportation. ➢ Unstable at temperatures> 180 °C [21]. ➢ Not applicable for operations that require instantaneous energy demands. ➢ Inappropriate for operations with high electric energy requirements over longer periods. ➢ The energy output is limited by time.

Table 2.3: The disadvantages and advantages of the lithium chloride battery

Turbine system	
Advantages	**Disadvantages**
➢ Not limited by time ➢ No environmental or HSE impacts. ➢ Appropriate for operations that requires energy output over a longer period. ➢ Unlimited immediate energy supply as long as circulation is maintained.	➢ The turbine and its components must be designed to withstand debris and other materials. ➢ Operational at temperatures up to 125 °C. ➢ Energy supply is dependent on mud circulation. ➢ Unreliable, requires a certain amount of flow velocity in order to function properly. ➢ Must ensure flow rates above a certain threshold whenever energy output is required. ➢ Limited power supply during tripping out.

Table 2.4: The disadvantages and advantages of the turbine system

The surface components of the telemetry system includes the following elements:

- A receiver
- Data processing and acquisition device
- Real- time surface computers
- Display unit
- The decision maker

The receiver of this system is a pressure transducer, which is usually mounted on the standpipe. The primary objective of this element is to identify and detect pulses. After accomplishing this objective, the pulses are transformed into electrical signals. This component is usually comprised of pressure detection sensors, with a high sensitivity. The sensors are very prone to background noise originating from various sources: mud pumps, rig, drillstring, motors and other equipment. Therefore, proper correction methods should be applied in order to remove these disturbances.

A data processing and acquisition device decodes and corrects the received signal of disturbances and distortions. This device is integrated with filters, which eradicates or mitigates any interference caused to the electrical signals. Beside from that, this component demodulates the received information. In this process, the data is transformed into an accessible and readable form, so the real-time computers can interpret it. The surface and downhole components of the mud- pulse telemetry system is summarized in figure 2.25. An independent subchapter will be dedicated to the decision- maker, which will be presented later in this segment.

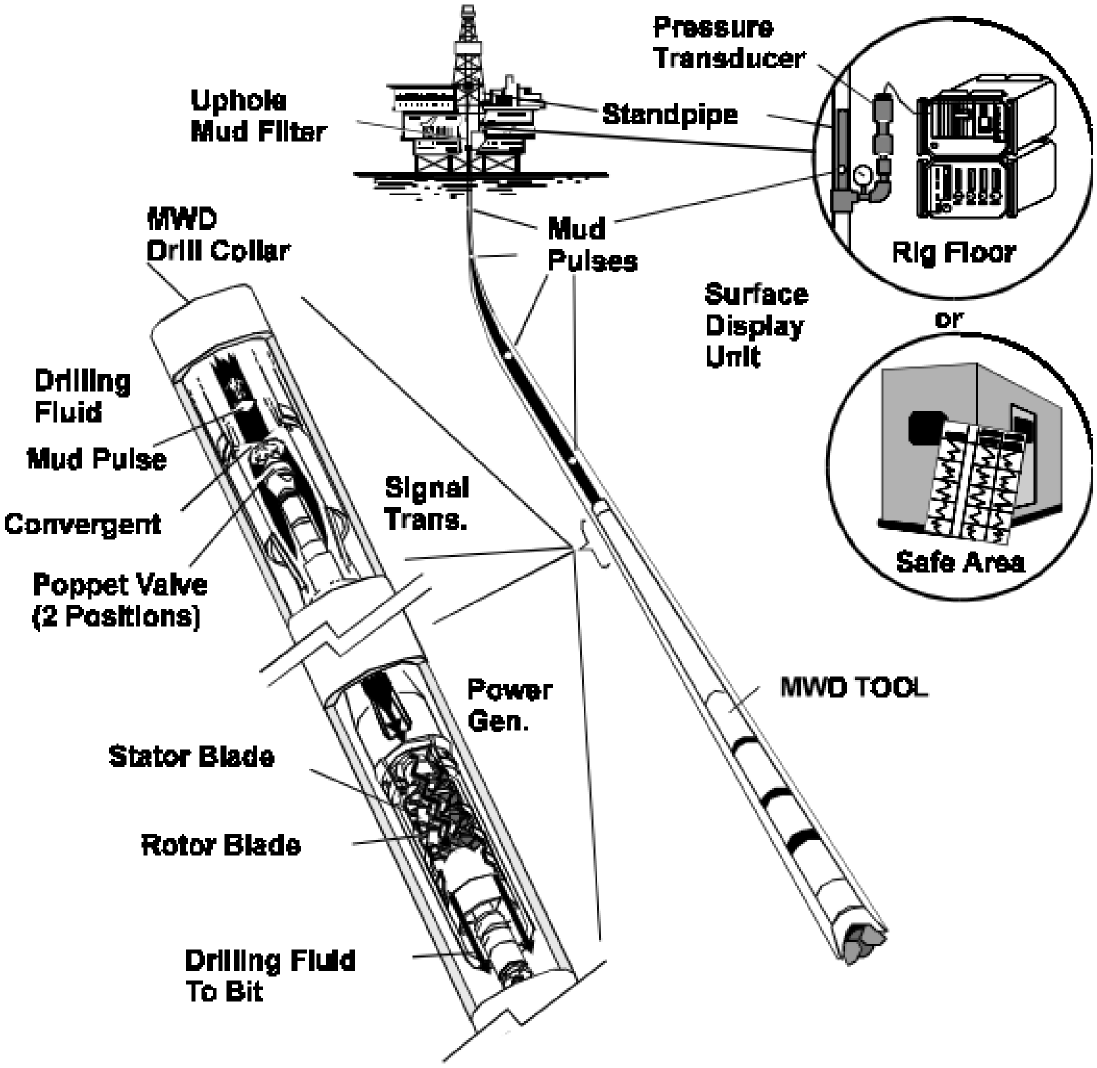


Figure 2.25: Components and elements of the mud- pulse telemetry system [22]

Data transfer

Until now, the individual components of the mud pulse telemetry technique have been presented, alongside with their functions and objectives. This segment will be dedicated to the data transfer process through each of the elements described above, alongside with a description of the various mud- pulse telemetry techniques.

How the data signal is transferred though each of the elements describes above, can be explained by the following points:

1. The directional MWD sensors measures the gravitational and geomagnetic field. After completing the measurement process, the recorded information is transferred to the microprocessor.

2. The microprocessor coordinates and activates the transmitter (pulser).
3. Through the drillstring: The pulser will then start to modulate the flow of the drilling mud by opening and closing a valve, which in turn produces pressure waves. The recorded data is transmitted to the receiver through these encoded mud waves.
4. At the surface, the sensors will detect the pressure variations and convert those into electrical signals. The signals is then sent to the data processing and acquisition unit.
5. This unit decodes and mitigates disturbances caused to signal. After that, the data is transformed into a readable format and sent to the real- time computers.
6. The information is then interpreted by the real- time computers and sent to a displaying unit.
7. This device will display the data to the driller and engineers. At the same time, the information will also be available to the supervision staff, present in an onshore drilling centre.
8. Finally, the data is evaluated and conclusive decisions are taken.

The decision maker

Until now, all the main technological elements of the mud- pulse telemetry system have been highlighted, including an explanation about how each component contribute to the data transportation process. However, the decision maker must be incorporated in the mud pulse telemetry system as an independent element. This is because in every technological or industrial process, the human plays a key role in the human – machine relation. The role of the human part can either be in the form of a decision maker, supervisor or as a monitoring unit.

The decision makers in a directional drilling operation is usually the driller and the drilling engineers. Based on the MWD sensor data, they have the responsibility to accomplish the challenging task of steering the drillstring, construct the wellbore and to hit the target. These assignments are associated with a large amount of complexity, risk and uncertainty. Any form of disturbance or disorientation can lead to fatal consequences like collisions with a nearby live wells, blowout or damage to assets. Therefore, drilling operations needs to be monitored and proper surveillance should be applied. Beside from that, the drilling crew should have a holistic view and proper knowledge about the drilling environment. These two elements should be incorporated in a human’s pre-emptive capabilities and used to anticipate possible future occurrences. This ability is also recognized as situation awareness, which affects and influences the performance of a process and decision-making.

Situation awareness is a property among humans that plays a critical role in ensuring safety, reducing errors and prevention of industrial fatalities. Situation awareness is defined as an employees capability to: extract essential information of the working environment, obtain a holistic view of the surroundings and to combine these two elements for anticipation of future occurrences. Reduced or limited situation awareness can lead to increased risk, higher probability of accidents and poor decision- making. Investigations [23] of several high profile accidents in the petroleum industry have identified inadequate situation awareness as one of the major contributors to the disasters. Inquiries and reports [24, 25, 26] have identified reduced situation awareness as one of the main root causes of the Deepwater Horizon and Montara drilling rig accident. Therefore, drillers and drilling engineers must have accurate and proper situation awareness of their surroundings and working environment.

Situation awareness is influenced and governed by several factors. These factors can be divided into the following groups: Internal, External, organizational and technological factors. The internal factors are related to the employee or individual. Important elements within this group are education, expertise, aims, practice and expectations. The organizational factors are linked to the operator. Essential aspects include operator experience, allocated resources, goals, standards, communication, monitoring, information management and company principles. The external factors are connected to the characteristics of the environment and the task itself. Important considerations within this group are workload, stress level, project progress, work time, characteristics and dynamics of the environment. The last group is linked to the technological elements surrounding the decision makers. Substantial elements include automation, displaying units, interface design and level of complexity. Safety and efficiency is promoted in drilling operations when all of these factors are combined together in the drilling environment, importance and influence of each element is assessed and finally possible future occurrences are predicted based on the acquired data.

In 2003, an analysis [27] of drilling related incidents due to situation awareness errors was performed. The data was collected from an international oil firm’s database. The survey was based on total 135 incidents, which occurred in the period January – October (2003). One of the major conclusions of this analysis was that: data related challenges were one of the major root causes of the various incidents, which led to situation awareness errors and high risk. 89 incidents out of total 135 were directly caused by data problems. The whole result of the survey is displayed in figure 2.26. The various data challenges will be presented later in this thesis.

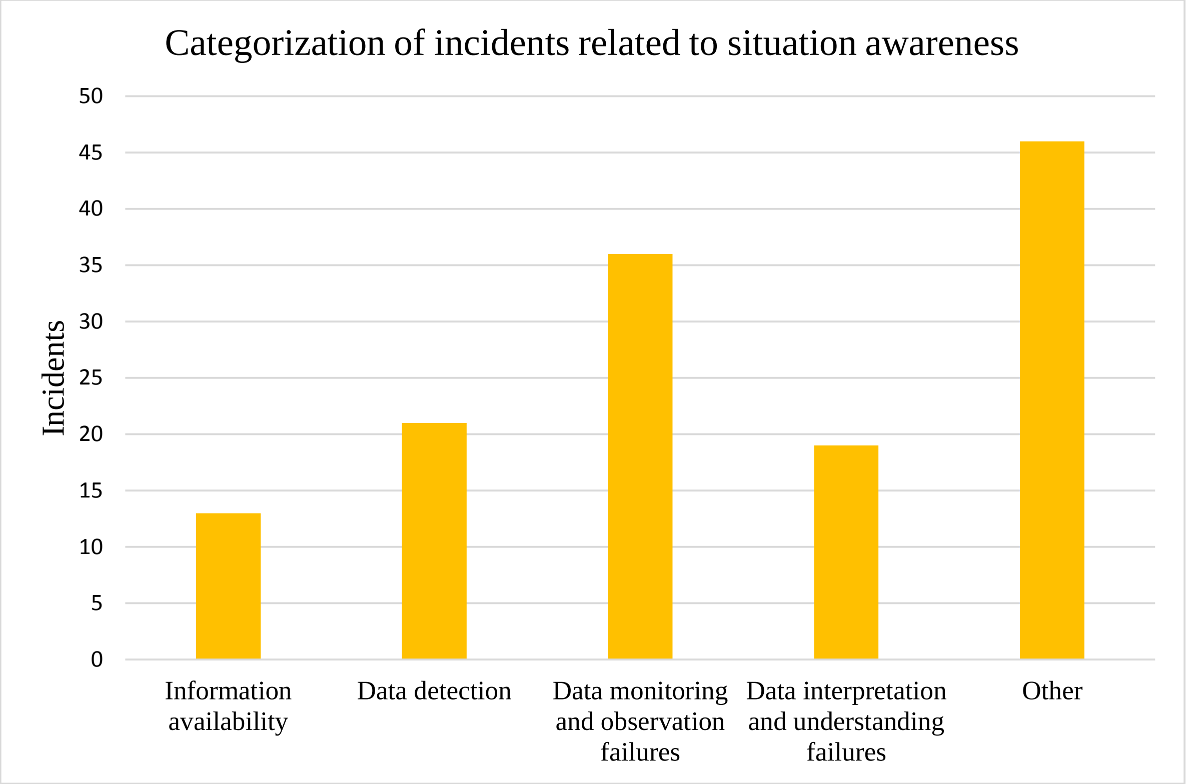


Figure 2.26: The root causes and severity of drilling related incidents

Techniques

Three different versions of the mud- pulse telemetry are available: positive mud- pulse telemetry, negative mud- pulse telemetry and continuous wave telemetry. The major difference between the various techniques is how they manipulate the pressure in the flowing mud column, in order to deliver the coded signal up to the surface.

Positive mud- pulse telemetry

This technique increases the pressure in the flowing mud column by producing positive pressure pulses. These pulses are generated by restricting the mud flow through the drillstring. Two elements are necessary in order to produce such pressure waves: an orifice and a positive pulser. The pulser element can be found in many versions and designs. However, the poppet valve is one of the most common types [19]. During a transmission operation, the poppet valve will be hydraulically activated to temporary hinder the mud flow through an orifice. This sequence will cause an increment in the hydraulic pressure, which will be captured by the standpipe mounted sensor receivers. There are some concerns related to this technique that must be assessed prior to the implementation:

- Scale accumulations.
- Mechanical and erosion damages.
- The positive pressure pulses can be a challenge while drilling in unstable, depleted or weak formations.
- The activation of the poppet valve requires considerable instantaneous energy outputs.

Currently, two versions of the poppet valve design exist. The main difference between these techniques is how the poppet valve is activated:

1. The first type is activated with the help of the mud pressure. High bandwidth and cost efficiency are the biggest benefits of this version.
2. The second type is activated purely by electrical energy, supplied by the energy source. This version is completely independent from the mud. However, there are some positive and negative aspects related to this version. This technique requires large energy inputs, which in turn decreases the bandwidth. One the other side, this type is more reliable and may mitigate noises [28].

Negative mud- pulse telemetry

This technique produces negative pressure waves with the help of a rotating valve. This device is used to momentarily vent some drilling mud from the inside of the drillstring into the annulus. The result of this venting operation is negative pulses, which is transmitted up the annulus and detected by the standpipe mounted receivers at surface. The valve utilized in this technique is manipulated by the means of electrical energy. Compared to the electric operated valve in the positive mud- pulse technique, this valve is more power efficient due to a lower energy consumption. This in turn enhances the bandwidth capacity of this approach. Beside from that, this type of valve is also less prone to plugging by scale, LCM, solids and other materials.

Continuous wave telemetry

One of the most unique attributes of this telemetry system is the design of its pulser. This component is comprised of two identical slotted disks, which is also known as a rotary valve. These two objects are placed parallel to each other and perpendicular to the flow of mud. During a transmission operation, the rotor will rotate while the stator will remain still. This sequence will confine the flowing mud in such a manner that alternating positive pulses will be generated. The rotary valve of this version holds the capability to produce regular positive pressure waves at a predetermined frequency level, by controlling the acceleration of the rotor. These pressure waves are then translated at the surface based on either their frequency level or phase. There are some versions of this technique, where the rotating valve is termed as a shear valve. For this design, the rotational movement of the rotor is in such a manner that the slots of the rotor and stator can be regulated. The shear valves holds the capability to produce both regular and discrete pressure waves, while the rotating valve can only generate regular waves.

2.3.8 Data acquisition and processing challenges

This section is comprised of an investigation of the challenges associated with data processing and acquisition. It is important to address and highlight the various data related challenges associated with the decision- making process. By doing so, an enhanced understanding of the potential obstacles and a holistic perspective may be developed.

Excessive amount of data

During a drilling operation, an extensive amount of data can be generated for the decision makers. This data can be related to various aspects of the ongoing project or activity. There is a slight misconception in the way of human thinking: that more information will lead to clearer alternatives and thereby better decisions. One of the roots behind this kind of mind-set is the thought that more information will reduce the uncertainty, which in turn will lead to better decision- making. However, this is not always correct. An appropriate amount of data is the main foundation behind any project or decision. In our desire to take right decisions at the right times, the data collections process can get out of hand and an extensive amount of data can be gathered. This comprehensive quantity of information can confuse the decision maker and thereby decrease the human capability to think and act independently.

Scientific research and analysis [29, 30, 31] have concluded that a human being will react positively to increased amount of data available, until a certain point. Distribution of data beyond this point will lead to significant declination of a person's performance. These analysis and studies also underlines that excessive data will not be incorporated in the decision- making process, lead to confusion, divert the individual`s attention, make essential data harder to remember, difficulties in establishing of priorities and much more. The relationship between amount of data and quality of the decision is highlighted by figure 2.27. In this figure, the quality of the decision increases with increasing data. However, at a certain maxima, the quality of the decision will decrease with increasing information.

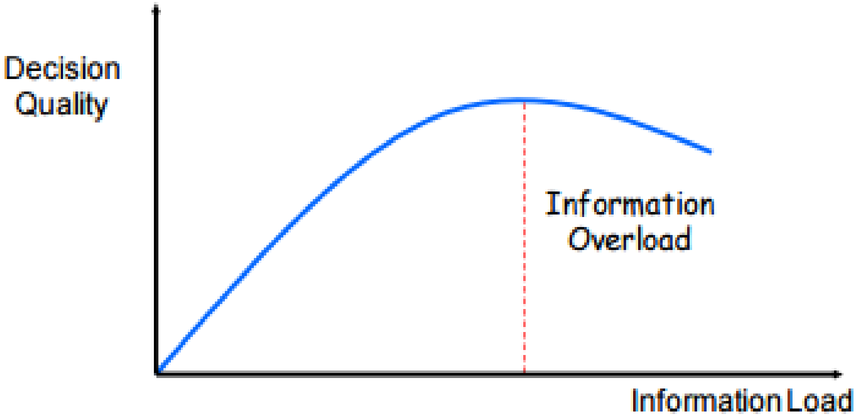


Figure 2.27: The relationship between amount of data and quality of the decision [32]

Data sharing and distribution

A drilling operation is multidisciplinary activity, which requires input of knowledge from various fields: geology, physics, mathematics, material technology and many more. In order to accomplish operations safely and efficiently, a sound knowledge sharing culture must be established. This culture must not be limited within the company and its employees; it should include sharing of data among other key players of the industry and collaborators as well. Some companies have adopted very strict and confidential routines related to data and knowledge sharing. Where the available information is only distributed among its employees and travels only in a closed loop within the firm itself. By limiting distribution of knowledge to certain groups or persons, a static mind-set will be spread within the industry, which in turn will hinder advancement, modification and exploration. Beside from that, inadequate access to data can result in increased risk, delay and potential obstacles in the decision- making process.

The importance of information distribution and sharing can be highlighted by analysing how the information travels in a loop within an organization. This loop is visualized by figure 2.28, where all the various stations of the information course are displayed.

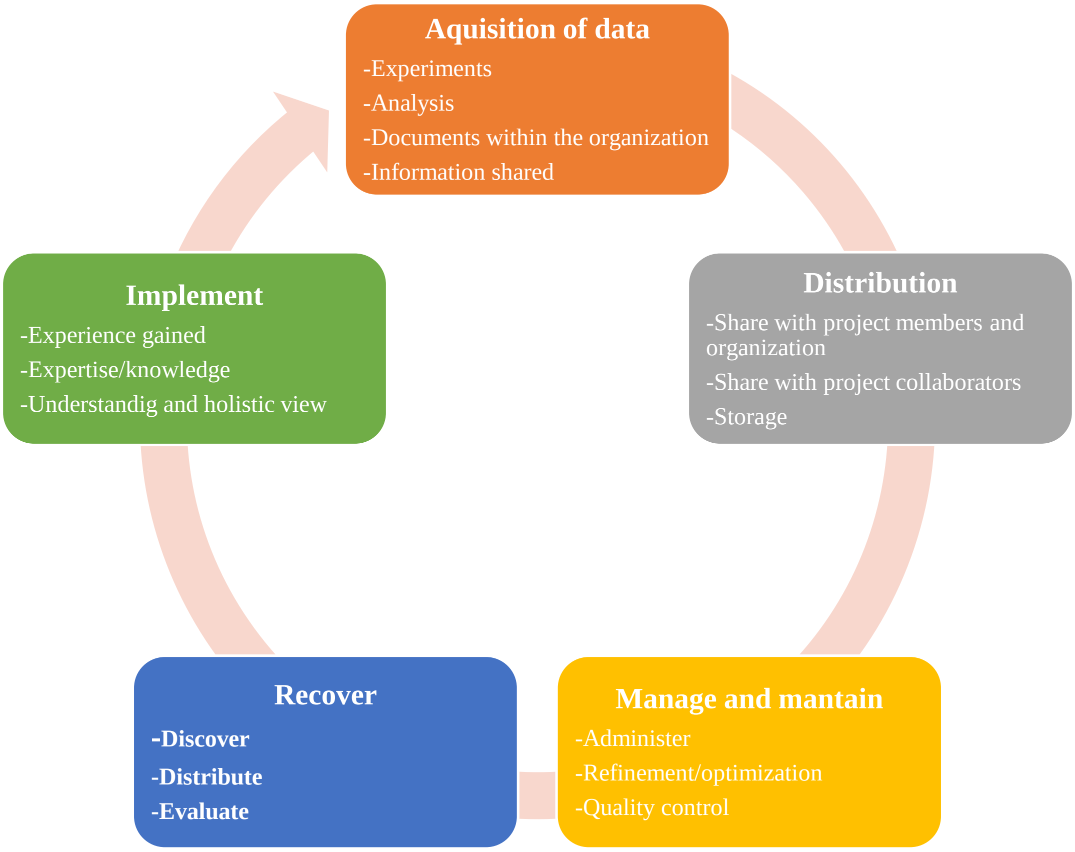


Figure 2.28: The information loop

The fundamental step and starting point of the information loop is the data acquisition process. The main objective of this station is to acquire raw information and transform it into applicable knowledge. Various information channels, like experiments, field- tests, co-workers, organization and many more can provide the raw data. This knowledge and information is then distributed within the organization, project group and project collaborators. By doing so, a new information loop begins for the new information holders. Finally, the data is safely stored.

The next step in the information loop is comprised of data management and maintenance. The vast amount of collected data must be tracked, systemized and structured. Beside from that, quality control and further optimization of the acquired data is completed in this segment. After that, there might be a need for retrieving and evaluating the maintained data, mainly to satisfy a data requirement.

Finally, the knowledge gained from the previous stations are implemented to accomplish a certain task or assignment. By completing the tasks with the help of the acquired wisdom, experience and expertise is gained. This understanding of an industrial process can again be shared among other employees and collaborators, which in turn starts a new information loop.

The information loop highlights how raw data and information can be transformed into applicable and practical knowledge. This wisdom also provides the capability to successfully complete projects and assignments. Therefore, sharing and distribution of information can prove to be an asset for the company, which in turn will provide a significant advantage for the organization. However, sharing and access to information is an essential process in the information loop. It is impossible to convert raw data into applicable knowledge without access to data. Therefore, data sharing is an excellent channel for providing access to information, which in turn will help the employees to function as catalysts for transforming data into knowledge-based assets.

Barriers like strict data sharing and distribution policies must be teared apart, in order to promote a cooperative approach among the various players of the petroleum industry. Work practices involving collaboration between different firms should be established. By implementation of a knowledge sharing culture within the organization, several benefits can be achieved:

- Optimization of drilling operations
- Integration of different departments
- Answers to problems with the help of involvement and collaboration
- Achieve an enlarged viewpoint
- Establishment of trust and confidence within employees
- Experience transfer
- Increased reputation in the society
- Establish best and cost effective industrial practices and technology
- Enhanced production and recovery rates
- Reduced expenditures
- Reduced risk

Data visualization

Visualization is a powerful instrument in terms of data presentation. It can be used to display real- time data in a more understandable and appealing format. Data can be visualized in many forms, like graphs, interactive 3- D visualization programs and many more. However, the objective of all the different forms of virtual displays are the same: to transform the numerical data into a more reachable, understandable and virtual form for the audience.

During a drilling operation, a considerable amount of real- time data can be produced. Making decisions based on the piles of spreadsheets filled with numbers can prove to be a challenge, which in turn can lead to confusion and disorientation. However, a virtual presentation of the same data on an interactive 3-D program can make the decision- making process easier. Such visualization instruments can also be used to combine data from other disciplines in order to obtain a 3-D presentation of the geological environment alongside with the borehole trajectory. Beside from that, dynamic sequences of a drilling operation can also be captured and presented.

The petroleum industry needs to widespread the use of data visualization as a tool for decision- making and data presentation. This can be accomplished by establishing virtual 3- D laboratories in the onshore drilling centres and on the drilling facilities. The utilization and display of real- time data on such instruments lead to the following benefits:

- Review, investigate and correlate real- time data without the need to disrupt the drilling operation.
- The engineers and physicists have the opportunity to evaluate and analyse the impact of various decision on the activity, prior to implementing them. This also enhances the pre-emptive aspect of the project.
- Optimization of the drilling process.
- Make decisions and their impact more predictable and clearer.
- Promotion of a cross functional cooperation.
- Save time and resources.
- Reduce risk and improve HSE.

Management and acquisition of good quality data

The exploration sector of the petroleum industry is moving further northwards in search of new hydrocarbon fields. These areas are known for their remoteness and challenging environmental conditions. In order to successfully assess and exploit the hydrocarbon potential of these areas, good quality data is required. Quality data is the main foundation of any successful activity, analysis and decisions. However, the management and acquisition of good quality data can be a challenge. The extraction and management process of quality real time data can be a challenge due to the following reasons: large quantity of information available and recovered, sophisticated data, large amount of data transfer between groups, information acquired from various technological devices resulting in poor data integration and many more. Beside from that, in every organization the data flow path is very complex and dynamic. The information travels from individuals to groups of many, and finally to large departments. Under such conditions, maintaining the quality of the information can be challenging and difficult.

According to research [33] performed in August 2009. Annual economic losses derived from poor quality data was estimated to be around 8 million dollars. A total of 140 companies was involved in this research and the loss total was calculated as an average among these companies. This survey highlights the negative economic consequences related to bad quality data. However, poor information can also lead to: loss of time and resources due to re-performing measurements or tests, poor decision making, increased rig-time, postponed project goals and deadlines, reduced success rate and increased uncertainty.

Another important aspect related to quality information are simulations. Simulators adds another dimension to the drilling process, by giving the operators the opportunity to perform a real- time drilling operation virtually. This element can be used to enhance the pre-emptive aspects of the operations, implement and test decisions, knowledge platform and sharing, analyse improvements and much more. However, in order to construct the well and successfully perform the simulations: good quality data needs to be feed to the simulator. Without this element, most simulations will be incorrect and invaluable.

Information accessibility

New and advanced technology have made it possible to generate a vast amount of data from the real- time drilling operations. The availability of this information have also been enhanced. The enormous amount of information collected from the operations and activities must be structured and stored. However, finding the right data for post- analysis among the enormous amount of information can be a considerable challenge. Accessibility to crucial data at critical periods can be the main difference between success and failure. Excessive time spent on collecting and searching for essential data can prove to be a fatal blow for the project progress and lead to several undesired consequences.

Scientific research [34] have concluded that employees use an excessive amount of their working hours to collect relevant data. According to analysis, engineers spends 60 – 80 % of their time on searching and preparing of information. This negative trend must be subdued; less resources needs to be spent on collecting and searching for already existing information, and more resources needs to be allocated for the integration of already existing information in the activities.

A survey [35] conducted in 1998 concludes that a majority of the industrial managers acknowledged the importance of information accessibility. These industrial leaders agreed that access to relevant and quality data is the foundation of any successful project. Beside from that, this element will also boost the decision- making capabilities of the employees, maintain resources, reduce repetitive activities within the organization and much more. The results of the survey is presented in figure 2.29.

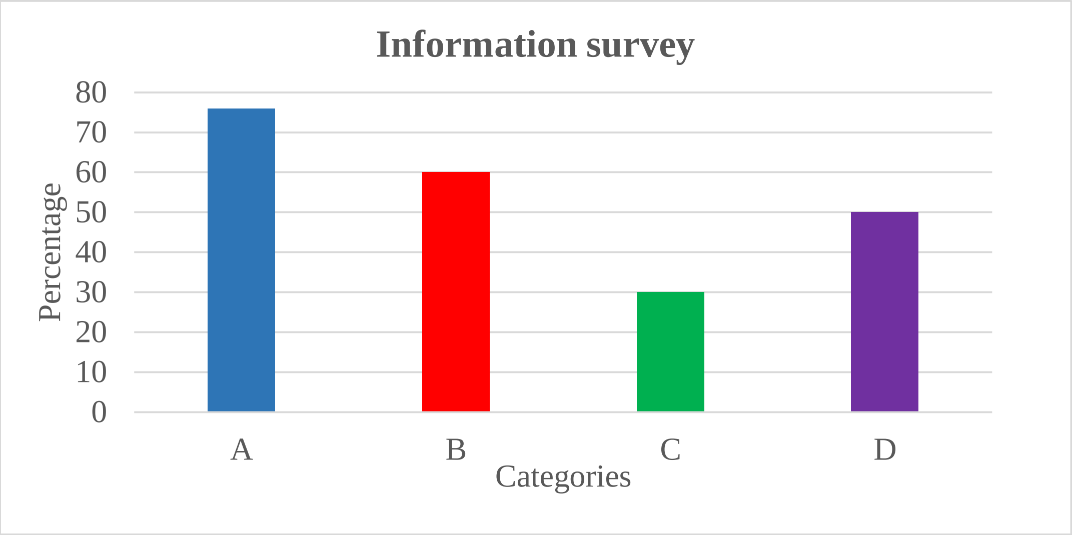


Figure 2.29: Information survey results

🟦 A : 76 % of the industrial managers believed that data is the most valuable resource of their organization and a crucial aspect.

🟥 B : 60 % of the leaders believed that time limitations and inadequate knowledge about how to search for data restricted their employees from acquiring the necessary information required for their task.

🟩 C : An employee spends around 2,5 hours daily in search for required information.

🟪 D : Around 35 – 50 % of the total available information at the organization lacks proper index.

Another important conclusion derived from the survey was that: Annually 2,5 $ millions worth of loss is taken by an organization consisting of 1000 employees, because of inability to acquire and locate relevant data.

According to estimates derived from the international data corporation [35], a staggering amount of 884,3 $ billions were spent by organizations on information technology in the year 2000. One essential question that must be raised is: why haven’t these resources mitigated the data location and acquisition problems. A potential answer to this question is that the information technology brought with it solutions that eradicated several problems for the employees. New and a vast amount of data became easily available and accessible for the worker. However, finding the appropriate data for the given task among the huge quantity of information available became more difficult.

In order to obtain a competitive advantage in the market, it is important to maintain and handle information just like an asset. Employees should receive proper training and information about how to find relevant information, provide accessibility to all the various information sources existing within the organization and given the opportunity to access and re-use data independent of location, position and format. By doing so, negative consequences like waste of time, loss of income, reduced efficiency and productivity, repetitive tasks and poor decisions can be mitigated.

The decision- making process in real- time operations

The decision- making process can prove to be considerable challenge for the drilling crew, stationed at the drilling rig. Based on the extensive amount of real- time data obtained from the telemetry system, the decision- making process can be difficult to execute properly and satisfactory. A proper awareness and clarity of the situation is necessary, in order to opt for the most optimal solution. This can be a challenge for the offshore crew, due to limited holistic view, compact time-schedule, numerous responsibilities and much more. The decision- making process is composed of many parameters and contains a considerable amount of complexity. Usually, the complexity of this process is characterized by two parameters:

1. Internal factors
2. External factors

The internal factors are related to the various aspects within the decision term itself. This includes number of possible outcomes, uncertainty and number of alternatives. The external factors addresses the exterior components, like number of interest groups, organizational issues, necessary communication and many more. Beside from these two elements, opting for a right decision at the right time based on real- time data can be challenging due to the following parameters:

- Excessive data
- Risk for undesired outcomes associated with each decision
- Numerous goals and targets
- Uncertainty related to the result
- Numerous or obscure options
- Cost
- Rate of success

2.3.9 Industry challenges- needs and requirements

Every successful industrial company and organization have pre-defined targets, which are meant to be accomplished within given deadlines. The impaired aims will generally be a function of industrial setting, environment, capacity, size of the organization and so on. Therefore, the determined targets will generally vary in size and scope. Nevertheless, the various targets defined by the different industrial key players often have a common goal. This could be to: minimize the operating costs, increase the market share, boost the profitability, enhance the productivity and efficient in a safe manner and bolster the reputation of the industrial organization (in the market and society). However, in the journey to achieve these targets, many obstacles and hinders are encountered by the organization. This segment is dedicate to the various industrial challenges that are faced by the Norwegian petroleum industry. The challenges that will be included are from the themes covered in this thesis. Beside from that, needs and requirements to get past these hinders are also presented.

Poor long-term decision-making

The PSA [56] Norway published a SPE paper in this year. In this publication, they have included statistics from the summary report of 2014 [57], which is also published by the PSA. The statistics is generally about trends in risk level experience on the Norwegian continental shelf. Some of the finding in this report [57] are displayed in the figures below.

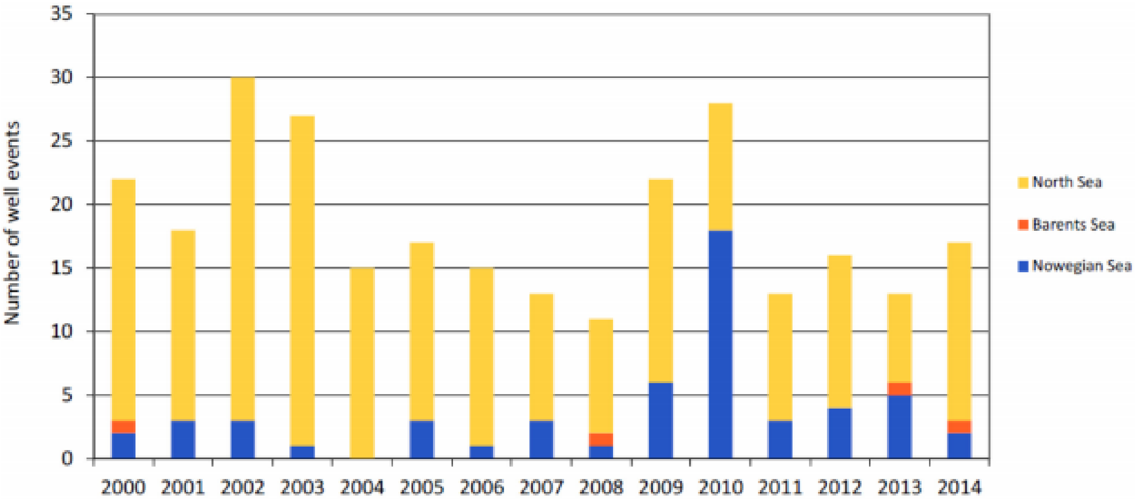


Figure 2.30: Well control incidents [57]

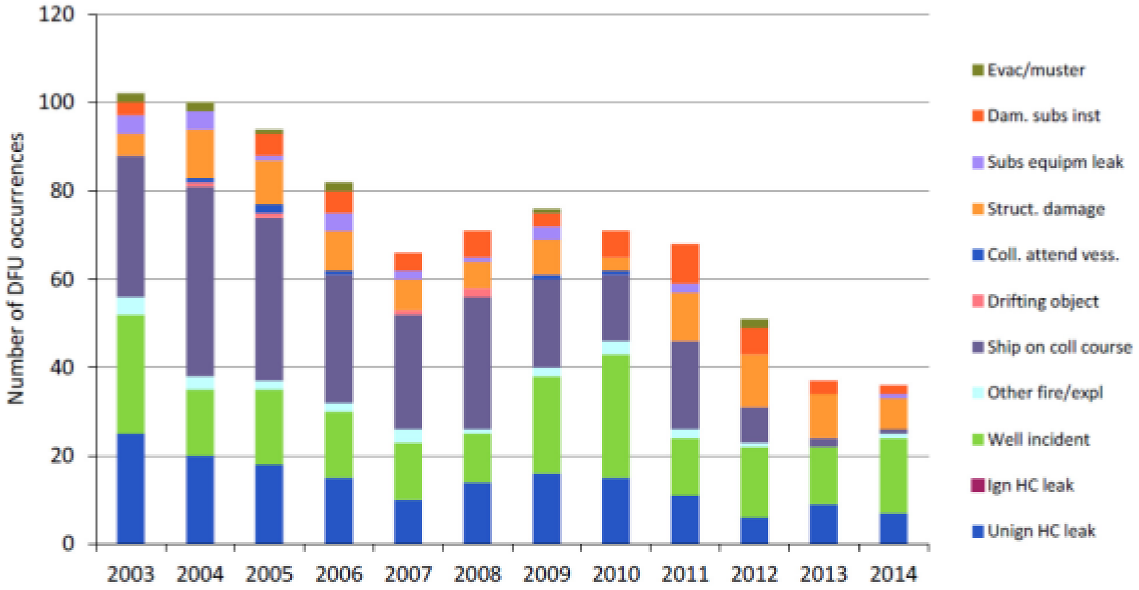


Figure 2.31: The total number of hazards and accidents [57]

From figure 2.31, it is clear that well control incidents and hydrocarbon leakages stands for the majority of major risk hazards recorded on the Norwegian continental shelf. There is a sinking trend among incidents related to hydrocarbon leakages over time. However, it can be observed that there is an opposite trend when it comes to well control accidents, especially in 2014. This trend is also underlined by figure 2.30. Where a substantial increase in total of well control accidents is recorded in 2014, especially in the North Sea region. Investigations and supervisions conducted by the PSA have identified lack of long-term decision- making as one of the key factors behind these unconformities. These two graphs underlines that decision-making is still a topic to master on the Norwegian continental shelf, which needs more attention.

Several remedial actions and organizational changes can be implemented to deal with poor decision-making. However, ensuring that workers with right education and competency are given this task. Alongside with this, it is also important to perform pre-emptive planning, research and conduct proper analysis. Beside from that, a holistic view of the industrial environment will be very helpful in the process of generating right decisions at the right times.

Drawdown of magnetometers

For some years ago, the petroleum industry in Norway made large investments on the Norwegian continental shelf. Those years were characterizes by staggering investments, high oil prices, stable operational costs, but stable to lowering production rates. This meant that the total amount of resources spent on producing oil increased with the time, while the production rates on the Norwegian continental shelf experienced a deficiency [58]. In other words, the petroleum industry has experienced a reduction in efficiency, especially in the drilling sector. Drilling operations takes much longer time to execute properly, than for 20 years ago [58]. This means increased operational costs, reduced productivity and larger discoveries are required in order to commercially develop the projects. Figure 2.32, displays the efficiency loss in the drilling segment. This graph highlights the fact that the total time it takes to complete a standard drilling operation is actually doubled, compared with equivalent drilling operations 20 years back. An exception are the two drilling operations in the beginning of the graph, which actually took shorter time to complete. The positive side of the y-axis represents the latency given in percents, while the opposite direction represents the rapidity of the project. The x-axis indicate the project alongside with the wellbore dimension.

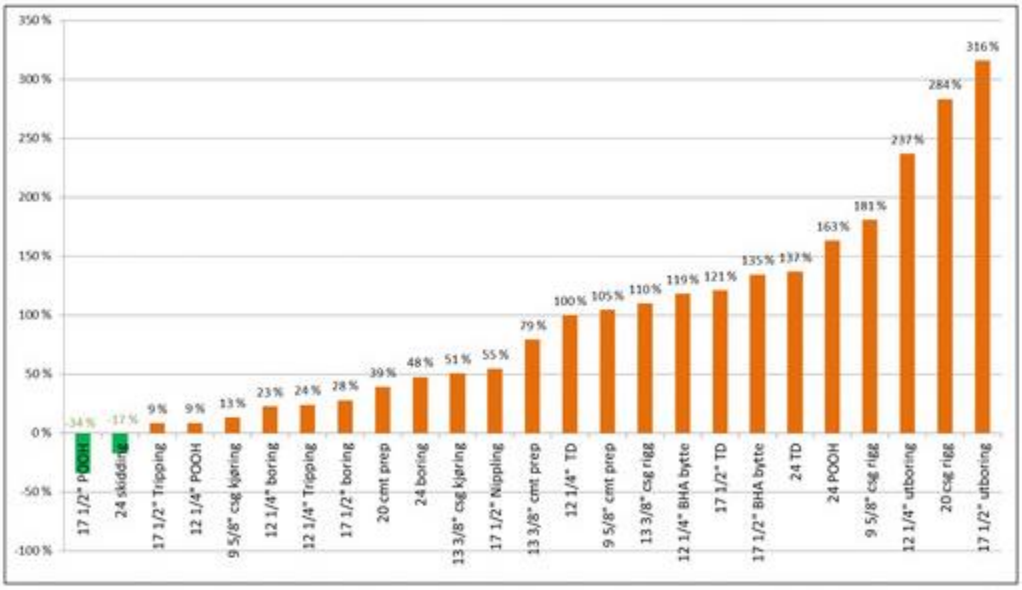


Figure 2.32: Loss of efficiency in drilling operations [58]

A potential solution to this inefficiency of drilling operations could be to improve the performance of magnetometers. It has been established from the previous sub-chapters that whenever survey measurements have to be taken, drilling and circulation needs to be stopped. This is due to the fragile physical condition of the magnetometers. A considerable amount of time and resources may be saved if the state of the magnetometers can be improved, upgraded or made more robust. By doing so, other drilling related problems can also be minimized, for instance drilling in geological formations that could results in stuck pipe.

Information sharing and data standardization

Every industrial process is comprised of several operations, interest groups, individuals with differing background, data from many departments and fields, collaboration with competitors and many more. All of these factors combined ads varies levels of complexity to the organizational tasks. One example that reflects this is from the process of survey management and drillstring navigation. The survey management process is comprised of the following groups with their different interests:

The operator	**The drilling contractor**	**Service company**	**The magnetic observatory**	**The navigation specialists and survey management party**
The main interest of this party member is to ensure that the surveys are as accurate as possible and obtained at a cost efficient level.	Main objective is to provide services of high quality to the operator company and ensure that the well placement goals are achieved.	Ensure that their instruments are capable of delivering high precision survey measurements, without any failure and at reasonable operating time.	Provide accurate real- time measurements of the magnetic crustal variations to the various groups.	Coordination of all of the group members. control and monitor the wellbore data. Provision of the corrected magnetic wellbore data.

Table 2.5: Involved parties in the survey process and objectives

In order to execute the well positioning operation successfully, collaboration and integration of every group's goals must be fulfilled. This can be achieved with the help of data sharing and standardization of industrial processes. However, these two elements have proved to be an issue for the upstream sector of the petroleum industry [59]. As the major key players in the industry becomes more saturated with technology and various solutions, the need for standardization and data sharing will be a prerequisite, in order to ensure that operations are executed efficiently and cost effective. Standardization and data sharing are powerful tools, which successfully allows the implementation of technology in the industry. Data accessibility and universal applicability to most of the available technologies will boost the ability of operator companies to utilize information from technological assets. Thereby, allowing service companies to concentrate on developing new technological solutions. The petroleum industry must get together and decide which standards to develop, and what information and principles should be included in these standards in order to boost the value of the core business. Alongside with this, data accessibility must be improved as well.

Chapter three: Solutions and services

3.1 Geomagnetic referencing

From the previous chapter, it has been established that the magnetic MWD survey tool is exposed to numerous error sources, which may degrade the accuracy of the directional survey. Thereby, contributing to a higher complexity and risk to the wellbore positioning and navigation operations. Leaving the magnetic distortion sources at side, the North Sea possesses several environmental challenges to wellbore surveying as well. The biggest environmental hinder to the drilling operations are the geographical location of the North Sea. This region is located in a geographical position, which is characterized by reasonable high latitudes. This means that the horizontal components of the geomagnetic field are very weak and measurements obtained by standard magnetic survey techniques are prone to irregularities.

A total necessity for any successful petroleum development is a high level of accuracy in the real- time wellbore positioning phase. Inadequate precision in wellbore positioning can lead to loss of financial means, loss of reputation (both socially and in the market), reduced oil recovery, HSE challenges, operational complexities, wrong well placement, complexity in the plugging and abandonment phase, excessive time spent on remedial actions, deviations from the pre-planned procedure, enlarged ellipses of uncertainty and many more. Due to all these challenges and hinders, a reliable, precise and cost-efficient solution is required to bolster the success rate of drilling operations in the Norths Sea and other challenging locations.

A solution to this problem is the survey method named: geomagnetic referring technique. This method addresses the stringent well positioning and placement necessities, alongside with the environmental survey challenges faced in the North Sea. Geomagnetic referencing is an industrial acknowledged solution [60], which have proved to enhance the success rates of accurate wellbore positioning in challenging survey environments. This technique holds the capabilities to resolve survey challenges faced in high latitude sites, compensate the magnetic distortions exerted by the drillstring and resolve disturbances to the geomagnetic field. A demonstration of one of the advantages related to the geomagnetic referencing is displayed in figure 3.1, where the ellipses of uncertainty have been reduced by utilizing this technique. The blue ellipses are achieved by using the magnetic MWD tool only, while the yellow ellipses are achieved by combining this tool with the geomagnetic referencing technique. Clearly, the uncertainty is largely dampened by utilization of the geomagnetic referencing technique.

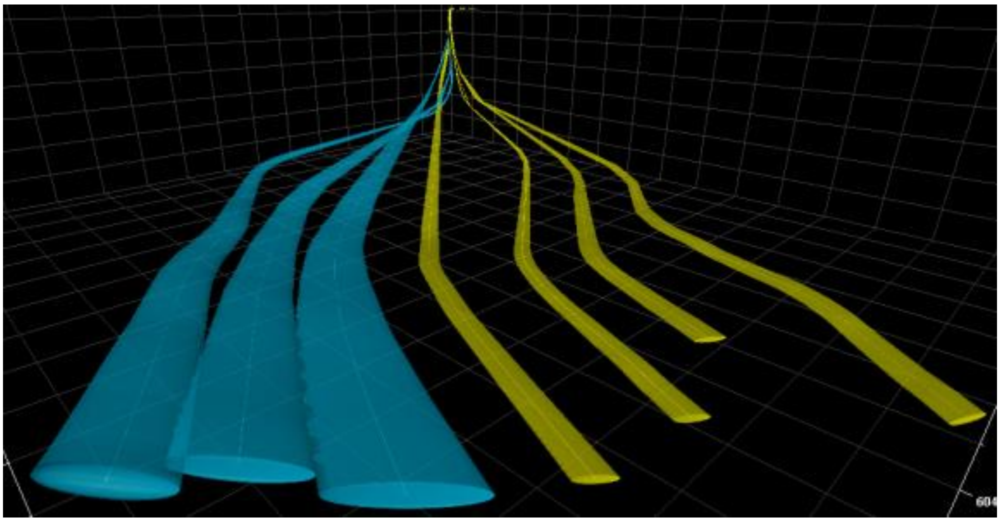


Figure 3.1: Ellipses of uncertainty [60]

Geomagnetic referencing models are utilized in directional drilling for navigational applications. These techniques is used to obtain accurate estimations of the magnetic field at a specific region, particularly for drilling applications accurate estimates of the declination are of a huge importance. This tool is primary comprised of mathematical models of the geomagnetic field, which includes periodic and locational variations. A number of versions of this technique is available, from mapping of the crustal contributions to the regional magnetic fields to the utilization of highly advanced inverted aeromagnetic survey inputs. Independent from the level of sophistication, availability of field data obtained from local magnetic observatories, airborne, ground, marine and satellite survey are the basic key requirements of these models. From the petroleum industries viewpoint, the purpose of utilizing this technique is to:

1. Correct the measurements towards the most precise projection of the declination.
2. Obtain the most accurate estimations of the local magnetic field variations at the wellsite. Thereby, apply the obtained values to the measurements obtained from the magnetic MWD survey tool.

Conducting drilling operations in low latitude regions, combined with low solar activity and non-magnetic formations, satisfactory survey quality can be maintained without the need for advanced geomagnetic survey models. In this case, a simple global geomagnetic field model will be sufficient to control the measurements obtained from the magnetometers. As mentioned, a wide range of geomagnetic models exist, these tools will be dealt with and explained in the next segment. However, drilling in harsh geomagnetic environment like high latitudes areas, with noisy sun periods and high magnetic crustal activity, there will be a need to acquire survey over the crustal magnetic variations of the wellsite. Acquisition of a permanent model of the crustal magnetic variations will also be a helpful tool in drilling future wells, since the magnetic survey will more or less be the same over the life cycle of the field development. However, at drilling locations with abnormally high magnetic activity, the need data from nearby magnetic observatories may be a prerequisite. If the data is obtained from a local or an observatory that is positioned close to the wellsite, then this technique is named as IFR. Another way of doing it is to install a virtual and simulated magnetic observatory at the site of drilling, this method is named as IIFR. The combination of local magnetic surveys and data from magnetic observatories provides the means of monitoring the geomagnetic field and its long-term variations on a drilling scale.

3.2 Service companies: products and services

The industry is saturated with numerous versions of the geomagnetic referencing technique, with varying levels of advancement, applications and features. This segment will be dedicated to some suppliers of geomagnetic services and surveys. The supplier will be highlighted, alongside with their objectives, geomagnetic services, their contribution within directional drilling will be displayed as well.

3.2.1 The British geological survey (BGS)

What is BGS?

The BGS is an UK based organization, which belongs to the public sector. This institution is one of the world’s most leading providers of geological surveys. The main area of focus is science, alongside with the implementation of research and analysis for a better understanding of the earth and its key mechanisms. Thereby, obtaining a holistic view of the earth and its components. The main objective of BGS is to spread awareness to the society about how to consume the natural resources of the earth, environmental development and threats. These objectives are achieved by providing and spreading accurate geoscientific information. Beside from that, BGS is also accountable for supplying assistance and provide advices to the government on themes that involves the earth and its environment. This service is also available for the academic society, public and industrial organizations. BGS is an organization that belongs to a council named: NERC, which is one of the leading agencies in the UK for providing financial support and management of analysis, coaching and information sharing in the field of environmental science. Alongside with the activities conducted in the UK, BGS is also involved in projects overseas. These projects includes implementation of research, analysis, survey, enhancing foreign institutions and monitoring. The main headquarter of BGS is located in Keyworth, close to Nottingham. Beside from that, BGS is also represented in the following cities: Cardiff, London, Wallingford and Edinburgh.

Fields of expertise and services

The main focus and area of expertise is geoscience. Examples of fields that are covered by this organization are as following: climate, energy, minerals, soil chemistry, groundwater, geomagnetism and many more. BGS provides monitoring, surveying, knowledge, data, research and analysis in many of the topics covered by the term geoscience. However, the main focus of this thesis is geomagnetism. Therefore, the next segments are going to be dedicated to the services and research provided by the BGS, which covers geomagnetism.

The geomagnetic team of BGS

The key objectives of the geomagnetic team is to mathematically model, measure, save and perform an interpretation of the fluctuations recorded in the geomagnetic field. This information, alongside with other services can also be provided to the industry, society and government. The Geomagnetic group is mainly located in Edinburgh, and the total staff is comprised of 24 workers [66]. The various geomagnetic services are provided with the help of magnetic observatories, which are located at different places of the world. These observatories contributes to the accomplished of a core function: perform long –term monitoring of the geomagnetic field, enhance our knowledge of the earth and its magnetic behaviour and processes. Beside from that, the main targets of this group is to be one of the leading global key players within:

- Supply accurate and precise geomagnetic information, services and products to the consumer.
- Spread awareness about the geomagnetic field to the various key players of the society.
- Improve the understanding of the geomagnetic field and its mechanism with the help of measurements, interpretations and recording.
- Understand the hazards related to geomagnetism.

The targets that are established with respect to the needs and requirements of the petroleum industry are as following:

- Provide support, products, data from geomagnetic observatories and assistance to the geophysical survey organizations, and directional drilling operations, with the geomagnetic referencing methods: IFR and IIFR.

The geomagnetic department of the BGS have played a significant role in the success of many drilling operations around the world. The various contributions of this group in the petroleum industry in year 2014 have been as following:

- IFR information have been delivered to 598 oil wells around the whole world.
- Installation of IFR services on 20 fields.
- 21 customer reports from the petroleum industry.
- IIFR information have been delivered to 75 oil wells around the whole world.

3.2.2 IAGA (The international association of geomagnetism and aeronomy)

What is IAGA?

IAGA is an international association that belongs to the union named IUGG. This organization is a part of the non- public sector of the society, and is financially supported through subscriptions delivered to IUGG. The economical resources are primarily given by countries that are members of IUGG. More than 70 countries are represented in this association, by a network of more than 8000 scientists. IAGA`s main objective is to enhance its knowledge, expertise and understanding of the magnetic and electrical characteristics of:

- The magnetosphere and ionosphere.
- Atmosphere, upper and middle part of it.
- The earth, especially: the core, crust and mantle.
- The sun and planets.

IAGA supports international scientific collaboration and sharing of information without any formalities or restrictions. Due to this, IAGA organises events, meetings and workshops for discussions and publication of results descending from various scientific analysis and research. This organization is also involved in charity programs, where scientists originating from developing countries are involved in activities and workshops.

Products and services

This organization provides several products and services, these includes many tools and standards within the field of geomagnetism. Some of the tools provided by IAGA are as following:

1. IGRF. This global model is utilized to determine the main geomagnetic field values at any location of the earth. This tool has many applications: it can be used for navigational applications (determination of declination), for instance in directional drilling. Beside from that, it can also be utilized in aeromagnetic surveys.
2. WDMAM. This is one of the first global and digital visualizations of the irregularities or fluctuations in the lithospheric magnetic field. This achievement is a joint effort, which included international collaborative work and contributions of many scientists. The first version of this map was realised in 2007.

3.2.3 The IIFR technique

Conducting drilling operations in high latitude and harsh magnetic environments, may lead to the need for advanced magnetic techniques for determining the direction of the wellbore. In these environments, the utilization of a global magnetic model may not be sufficient to ensure satisfactory well placement and navigation results. An explicit need for a survey technique that differentiates the geomagnetic core field, anomaly fields and external disturbances alongside with their rapid rate of change may become real.

Conventional survey approaches are based on the principle of determining the orientation of the borehole by knowing the direction of the earth's magnetic field, and thereby comparing it to the horizontal level and true geographical north. This is accomplished by conducting measurements of the borehole orientation comparative to the geomagnetic field. Beside from that, some survey instrument also require the magnitude of the geomagnetic field intensity for the calibration process. The various parameters required for both of these two processes can be obtained through global geomagnetic field models. Nevertheless, these conventional survey approaches neglects the short- term fluctuations in the geomagnetic field, which in turn degrades the accuracy of the directional survey. Reviewed from a theoretical viewpoint, degradation of the survey due to short- term fluctuations in the geomagnetic field can be eliminated, if sufficient measurements of the geomagnetic field is obtained at the drilling locations. Nevertheless, this is not practical, since the measurements will still contain magnetic perturbations descending from the drilling equipment.

In order to overcome these challenges and satisfy operational needs, the IIFR approach is utilized. This technique determines the borehole orientation by using the following three inputs:

1. Data containing spot measurements of the regional geomagnetic field, obtained from a local magnetic observatory. The location of this facility must be close enough to the drilling location, in order to ensure that the measurements of the local geomagnetic field is representative for the drilling site. However, the placement of the magnetic observatory should be remote enough to ensure that the data is not affected by the magnetic properties of the drilling facility or any other nearby installations.
2. Information on the secular variations in the geomagnetic field as a function of time. This data is stored and collected on a monitoring facility, which is located far away from the drilling location and the magnetic observatory providing the measurements over the geomagnetic field at the drilling locations.
3. The measurements conducted by the MWD magnetic tool, performed at the pre-determined survey stations.

The spot measurements of the geomagnetic field received from a local magnetic observatory (that is positioned near the drilling location), is then combined with continuous data of fluctuations experienced in the geomagnetic field over time. This element is obtained from a remote monitoring facility, which is located far away from the drilling site. These factors are then combined to produce instant and immediate values of the direction, orientation and intensity of the geomagnetic field at the drilling site. The data from the various monitoring and observation facilities are used to establish a "virtual observatory" at the drilling sites. Thereby, allowing the possibility to monitor the geomagnetic field in real-time and apply corrections due to secular variations. Rapid fluctuations in the geomagnetic field can occur in terms of minutes; therefore, it is crucial for the drilling operation that real-time IIFR data is supplied to the survey team in real- time. Thereby, allowing critical well-steering decisions and operations to be implemented efficiently and quickly. This survey technique also take into consideration the magnetic fluctuations descending from electrical currents in the ionosphere and magnetosphere, thus boosting the accuracy of the directional survey [67].

The IIFR technique takes into account three major magnetic field components to produce accurate estimates of the magnetic field at the drilling site. The following equation summarizes the principle of the IIFR for estimating the magnetic field at the operation site:

$$IIFR = B_{external} + B_{magcrust} + B_{geomagnetic\,field} \qquad (3.1)$$

The geomagnetic field is slowly deviating with time and estimations of this parameter are usually obtained from satellites. The magnetized crustal formations represents static magnetic anomalies, which is determined with the help of aeromagnetic surveys. The last parameter is the most dynamic in nature, and usually the most challenging to predict or accurately incorporate in the magnetic surveys. In order to successfully monitor this parameter, continuous measurements are taken on a magnetic monitoring observatory.

Usually, survey teams used to predict the magnetic field at the drilling site by estimating the direction and the geomagnetic field by using a global magnetic model. However, this method only considered $B_{geomagnetic\,field}$, while the rest of the parameter were left unassessed in the survey data. However, some global models are programmed to take into account magnetic anomalies of long wavelengths that is descending from magnetized crustal formations, alongside with steady variations in the geomagnetic field. Nevertheless, these disturbances are minor compared to the magnetic contributions that consist of smaller wavelengths [3], descending from electrical currents and magnetized formations. These magnetic components can cause large scale errors to the magnetic survey, especially if the drilling operations are conducted at high latitude sites. By utilizing the IIFR technique, measurements of $B_{external}$ obtained from magnetic observatories can be incorporated in the survey process, to produce accurate estimates of the magnetic field at the drilling site for real-time corrections.

Operational implementation

Prior to the implementation of the IIFR method to correct magnetic MWD data, one important prerequisite must be accomplished. Good quality and large quantity of data, representing the local magnetized crustal formations must be obtained and certified. Acquisition of such data will make it simpler to address and characterize the local geomagnetic field and identify possible crustal anomalies surrounding the operation site. After the data acquisition phase, the gathered information is incorporated in the process of constructing a new geomagnetic chart. This magnetic map visualizes the various crustal anomalies proportional to a global geomagnetic field model. The next step is comprised of interpolating the wellhead coordinates onto the new geomagnetic chart. The interpolation technique allows the service provider to characterize the crustal anomaly irregularities relative to the global geomagnetic field model. This in turn, allows to incorporate the secular variations into the IIFR correction sequence. One important factor that must be outlined is that: in order to simplify the derivation process, same calculated values of the magnetic field at the drilling site is utilized for the whole length of each individual well.

Restrictions and assumptions

Prior to the implementation of the IIFR technique, it is very important to review the various assumptions and restrictions related to this technique. To begin with, one of the most important and fundamental assumptions used in this program is that the measured geomagnetic field can be characterized as a gradient of the scalar potential, expressed in equation 2.8, page 12. This assumption is also utilized as the fundamental assumption in most geomagnetic field models. However, it is very important to remember that this assumption is only valid when there are no external disturbances or bias from for instance electrical currents in the ionosphere or nearby magnetized structures, while performing the aeromagnetic observations. Alongside with this assumption, it is also assumed that the gradient fulfils the Laplace’s equations.

The intensity of the magnetized crustal rocks is assumed to be the component of the crustal field vector, which is considered to be in the same direction of the local geomagnetic field vector. This is a valid assumption, because the magnitude of the magnetized crustal rocks are much less than the strength of the geomagnetic field. Alongside with this assumption, it is also assumed that the intensity of the anomaly fields also satisfies the Laplace`s equations.

The information and data received from the various observatories and monitoring facilities are situated on geological terrains that are horizontal, this also implies to aeromagnetic surveys. The IIFR technique also demands that the magnetic observations from the various input sources are accurate, which implies that the data collected must be from a magnetic region free from anomalies. In other words, the region where the surveys are performed must be dominated by the main geomagnetic field; the main field must also be constant in the survey region. Beside from that, a restriction related to this technique is that the monitoring observatories and facilities must be located close to the drilling site. The geomagnetic field is also assumed to be not a function of the depth. Which means that the magnetization is constant and no variations are experienced in the strength if this element with the depth.

3.2.4 The IGRF model

For directional drilling applications, data or measurements obtained from a local magnetic observatory alone are of little use. These data only represents the geomagnetic field at a certain point. However, the petroleum industry requires magnetic data from a vast area or region for better well positioning and efficient navigation through the downhole environment. In order to represents the geomagnetic field over the whole earth and its various regions, the global community of scientists within the field of geomagnetism, has opted to present the earth’s magnetic field with the help of geomagnetic reference fields. These reference fields are mathematical models of the geomagnetic field, which presents its locational and periodically fluctuations. These mathematical representations are constructed for instance with the help of power series in longitudes and latitudes, or by spherical harmonic polynomials. One such mathematical description of the geomagnetic field and its time variations is the IGRF model.

The IGRF is an internationally recognized mathematic model of the geomagnetic field, which characterizes a majority of the magnetic field generated in the earth's core [72]. The first edition of this model represented the geomagnetic field already in the epoch of 1900. Until now total 12 versions of these model have been released, each characterising an epoch of 5 years. After an epoch of 5 years, the IGRF model is updated and replaced with a new edition. The latest 12 generation of the IGRF model was implemented back in December 2014. This model is programmed to cover the geomagnetic field in the epoch interval of 2015- 2020. The model itself is a result of a joint effort, combining many international intellectuals, geomagnetic field modellers, institutions and observatories to provide magnetic field data from various locations of the world. This model is utilized in a wide range of applications, varying from academic research on the geomagnetic field, space weather, navigation and orientation information required by industrial organizations and much more.

Each generation of the IGRF model, is made out of three associated sub-models. The first constituent sub- model is named as the definitive geomagnetic reference field model. The word "definitive" is utilized to name this model, because further improvements in this model is more or less improbable. The second sub- model is termed as the IGRF model, which is not absolute. An absolute IGRF model will replace this model, after conducting future revisions. The last associated model is termed as the secular variation. This model is intended to describe and characterize the periodically fluctuations in the earth's magnetic field for the interval of 5 years. Irregularities, changes and fluctuations occurring the geomagnetic field, leads to the need of continuous updates and revisions of any reference model. The IGRF model is subjected to regular and frequent updates in order to maintain its precision, and to maintain its credibility as a reference model in various applications. Another factor, which enhances the credibility of the IGRF model, is the high number of participants involved in the development process of the latest edition of the IGRF. The amount of data collected, scientist and amount of institutions involved have never been so high for previous editions of the IGRF [73].

Mathematical description

The mathematical foundation of the IGRF model is based upon the equations presented in chapter 2, under the "mathematical description" segment. Therefore, in order to enhance the understanding of the founding equations of this model, it is recommended to revise this sub-chapter. However, the magnetic field on the surface of the earth is characterized with help of the scalar magnetic potential (equation: 2.8, page 12) and spherical coordinates (equation: 2.11, page 12). In this model, the Gauss coefficients are time dependant parameters, which is assumed linear during the 5-year epoch of the model. Any mathematical representation of the geomagnetic field requires time dependant coefficients; this is because the geomagnetic field itself alternates with time. These two coefficients are characterized by the following two equations:

$$g_l^m(t) = g_l^m(T_0) + g_l^m(T_0)(t - T_0) \qquad (3.2)$$

$$h_l^m(t) = h_l^m(T_0) + h_l^m(T_0)(t - T_0) \qquad (3.3)$$

During a models validity epoch (5 years), the following parameters: $h_l^m(t)$ and $g_l^m(t)$ of the predictive median are categorical provided. The number of harmonic degrees (l) and the precision of the coefficients varies between the various editions of the IGRF model. However, the latest 12th generation of this model contains a harmonic degree value of 13 and the accuracy of the coefficients are quoted to be 0,1 nT. The number of harmonic degrees included in the latest editions are programmed so that they do not include the crustal magnetic anomaly field inputs, which are dominating at higher harmonic degree values [73]. On the other hand, the secular variation model is developed with total 8 harmonic degrees and the time dependant coefficients have an accuracy of 0,1 $\frac{nT}{year}$. Beside from that, components of the magnetic field like the Z,X and Y are calculated by using the same equations presented in chapter 2, page 12 and equations: 2.12, 2.13 and 2.14.

Limitations

Prior to the utilization or implementation phase of the IGRF model, it is very important to recognize some limitations and restrictions related to this model. By doing so, the credibility of your results are maintained and safeguarded. To begin with, there is an uneven representation of the various regions and countries of the world by the IGRF model [72, 73]. This model represents some parts of the world more accurately and better, than other regions. The main reasons behind this irregularity, is the uneven geographical distribution and economical resources of countries. One of the key elements and foundations of the IGRF model is the input of data from the various magnetic observatories, located at their respective geographical positions. Some countries or regions may not have the economic resources to establish such magnetic observatories or economic viability to establish pronounced research upon the field of geomagnetism. Due to poor data availability, the errors in the recorded values will be larger for areas that are poorly represented, for instance the south pacific. On the other side, measurements obtained from regions that are well represented for instance Europe and America, will contain more accurate and precise values with low errors.

The IGRF model is programmed to predict the geomagnetic field at a certain location. Therefore, one should not expect a correlation between the magnetic field measured at one location and the IGRF prediction. The geomagnetic field measured by an external unit at a specific location, is comprised by magnetic contributions from several components. These components could include cars, building, magnetized crustal rocks, contributions from the sun and many more. Due to this fact, the IGRF model should not be used as a correlation tool to verify magnetic measurements obtained from a certain location.

A considerable part of the geomagnetic field, originates from electrical currents descending from the earth's core. Due to the extensive distance between the surface of the earth and its core, the observed geomagnetic field is mainly comprised of long wavelengths. However, contributions to the geomagnetic field is also made from magnetized crustal rocks, this contribution is dominated by shorter wavelengths. Based on the size of the different wavelengths, it is not possible to differentiate the crustal rock magnetization from the magnetic field descending from the earth's core. Nevertheless, the contributions from the magnetized crustal rocks are presented in the IGRF model, mainly at l = 10 and below. The shortest wavelengths that are represented by the IGRF model is mainly shortened by l = 10, which is around 4000 km. wavelengths that are shorter that this is ignored by this model, this is also valid for any short wavelengths descending from the earth's core. Mathematical techniques indicate that shorter wavelengths in the magnitude of 35 nT is being ignored [74]. However, the latest IGRF model is developed with l = 13, reducing the ignored value to 10 nT.

The IGRF model is comprised of several sub-models. The objective of one of these sub-models is to provide an estimation of the annual rate of change over 5- years experienced in the geomagnetic field, which is also referred to as secular variations. However, the behaviour of these irregularities are very un- predictive and difficult to estimate. Previous studies [3] indicates that the estimated values of the secular variations have been slightly of the mark, with around 20 $\frac{nT}{year}$. Beside from that, this sub- model is a very inappropriate tool to measure instantaneous rate of change in the geomagnetic field [74]. Nevertheless, more accurate and up to date models are currently being developed and constructed. These models are intended to provide precise estimations and monitoring of the geomagnetic field through data inputs from the swarm satellites.

IGRF-12 online calculator

The 12th edition of the IGRF model is available online, free to use and can be found on the following web- address: http://www.geomag.bgs.ac.uk/data_service/models_compass/igrf_form.shtml. However, in order to acquire values of the geomagnetic field and its components at a certain location, some input parameters are required by the online calculator. To begin with, the user of this calculator must specify and define the location, where the geomagnetic field value needs to be measured. This is accomplished by defining the altitude, latitude and longitude of the location. The longitude and latitude can either be supplied in terms of number of degrees, decimal degrees or minutes. On the other side, the latitude must be given in numbers of kms. Another element that must be specified is the moment; this is done by defining the date in decimal years. The online calculator will also request the user to supply geocentric or geodetic coordinates. The main difference between these two coordinates systems are that: In geodetic coordinates the shape of an ellipsoid characterizes the surface of the earth, and positions near the earth's surface is defined with the help of height, longitude and latitude. The geocentric coordinate system on the other hand, describe and locates positions with the help of the

Cartesian coordinate system. After supplying the calculator with all the input parameters required, it will calculate the geomagnetic field and its components at the pre-defined position and its alternation with time [76].

Chapter four: Evaluation and assessment

4.1 Advantages and capabilities of the IIFR technique

In this chapter, the primary goals of this master project are highlighted and investigated. An evaluation of the industrial capabilities of the IIFR method is performed. This assessment is carried out through mapping and identification of features and applications designed for improved well positioning and decision- making.

4.1.1 Accessibility to real- time data

The accessibility and availability to essential real- time data during critical phases of the well construction and steering processes, can prove to the decisive element between failure and success. Instant access to real- time data of the downhole environment may contribute to enhanced situation awareness, which in turn can be utilized as a pre-emptive tool to predict upcoming problems and potential hinders. Real- time data can also function as a catalyst to expedite and generate a continuous wave of right decisions at the right times, which in may result in lower risk, enhanced drilling efficiency, optimal placement and positioning of wells. Due to the various benefits of instant data delivery, the exploration and production sector of the petroleum industry is increasingly taking advantage of real- time data technologies and services [78].

The IIFR technique and its service providers have recognized the benefits of instant data delivery, and followed the development and increasing demands of real- time data services in the exploration and production sector of the petroleum industry. The various groups and departments involved in the navigation and directional survey process, are helped by the real-time capabilities of the IIFR program. This method delivers the geomagnetic field and its associated uncertainties at the drilling site in real- time. Real- time data from local magnetic observatories and distant monitoring facilities are integrated, and delivered instantly to help drillers to geosteer safely and make right decisions. The deliverability of monitored and corrected real- time data involving the geomagnetic field is very crucial for critical well placement and steering decision in a drilling environment, since the electrical currents in the ionosphere and external disturbances may result in magnetic irregularities that may vary significantly on a short time- period.

The various survey challenges associated with drilling operations conducted in dynamic conditions and harsh magnetic environments, are addressed in real- time by the IIFR program. Corrected and monitored estimates of the geomagnetic field at the drilling site is delivered to the interested party, which contributes to a reduction in the positional differences measured between then directional magnetic survey and increased survey accuracy. This limits and reduces the need for corrective actions, extensive steering operations, avoid subsurface collisions with nearby wells and optimal positioned wells.

4.1.2 Inclusion of external disturbances- optimization of the survey program

During a drilling operation, the magnetic MWD directional survey instrument is prone to magnetic distortions from various sources. These distortions may disturb magnetometer readings, which in turn must be corrected for in order to acquire the most accurate magnetic downhole readings for navigational and directional applications. Nevertheless, in order to obtain the most precise magnetic surveys, all contributing elements of magnetic distortions must be considered and included in the correction process. The contributing elements includes: the geomagnetic field, magnetized crustal formations and external disturbances.

Usually, correction and estimation processes among the directional survey crew involved the use of a global geomagnetic field model to determine the strength and direction of the geomagnetic field. However, major drawdowns behind such approaches is that global geomagnetic field models only takes into account the core field and longer wavelengths, descending from magnetized crustal formations. External disturbances to the magnetic field at the drilling site is not considered by these models. Beside from that, studies and research performed on uncertainties in global geomagnetic models by Maus Stefan et al. (2010) [77], concludes that: the geomagnetic models are precise during their initial release, but their accuracy deteriorate after that. This conclusion is visualized in figure 4.1, where the x- axis represents the time in years, while the y-axis represents the error in the total field strength. The black coloured curve that belongs to the IGRF model, is of main interest for this study.

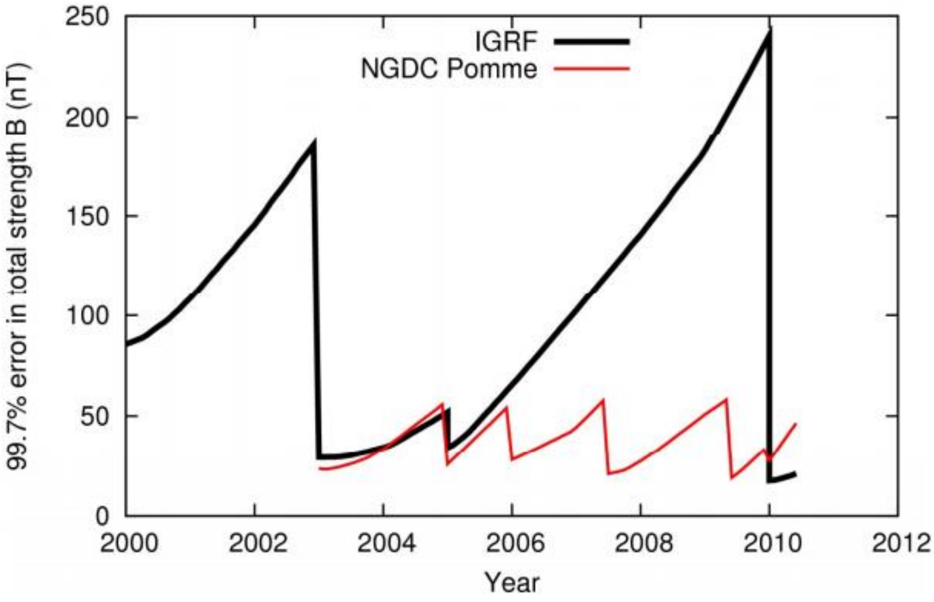


Figure 4.1: The accuracy of the IGRF model as a function of time [77]

The contributions from the external sources should be included in the correction process. By doing so, accurate estimations of the geomagnetic field can be extracted, which in turn will enhance the drilling efficiency. In analysis and research performed by Clarke and Turbitt (1994) [79], the data from observatories located in Lerwick (UK) was used to predict the external disturbances experienced in the North Sea. The predictions were most of the time achieved within industrial accuracy limits. In these analyses, the data from observatories based in Lerwick was compared with magnetic data of the North Sea from four other observatories: Hartland (UK), Eskdalemuir (UK), Dombås (Norway) and Brorfelde (Denmark). The conclusion of this study displayed that with accurate estimations of the contributions descending from the core field, magnetized crustal rocks and external disturbances, the confidence level in the North Sea is high as 99 %. However, during periods with abnormally high magnetic activity, the confidence level is below 95 %. Usually, the desired confidence level for well procedures in the petroleum industry is around 95,4 % [3]. The uncertainty and error related to the produced estimations of the main field and the anomaly fields were not considered. Nevertheless, precise prediction of the external disturbances can reduce the errors associated with the magnetic field at the drilling site.

The IIFR method takes into consideration the external disturbances alongside with the additions from the core field and anomaly fields. This is accomplished by incorporating the measurements obtained from observatories and the magnetometer data, which in turn produces the most accurate corrections for the magnetic field at the drilling site. The inclusion of the external disturbances by the IIFR method has proved to be beneficial for the upstream sector of the petroleum industry. Prior to the implementation of the IIFR technique, conducting drilling operations in harsh magnetic environments under a high level of external disturbances were very challenging, and in worst scenarios the magnetic MWD survey instrument could be left handicapped under periods of extensive external contributions. Under such conditions, the majority of the borehole must be re-surveyed when the irregular fluctuations have declined in strength.

In order to signify the importance and effect of including external variations in the correction process, a scientific study [3] was performed in which the IIFR method was compared to the IFR technique. The objective of this study was to compare the error reduction capabilities of the two different methods in differing environments and settings. The last method only takes into consideration the core field and the anomaly fields in the estimation process. In this study, three hypothetical wells were constructed in different latitude degrees: 50°, 55° and 60° north (North Sea) and exposed to varying magnetic and solar activities (minimum, maximum, ascending and descending). The error reduction measurements were also taken in three different seasons: summer (May, June, July and August), winter (November, December, January and February) and equinoctial (March, April, September and October). The results extracted from this activity indicated that the IIFR method is capable of reducing the well-course error with up to 20 % compared to IFR technique. This study also highlights the significant error reduction potential in correction procedures when the external disturbances are accounted for, even at low latitude degrees. Beside from that, the largest amount of errors were reduced during the period of maximum magnetic and solar activities, at highest latitudes and in the season period of equinoctial. The results of this research is visualized in the figures 4.2a,b and c.

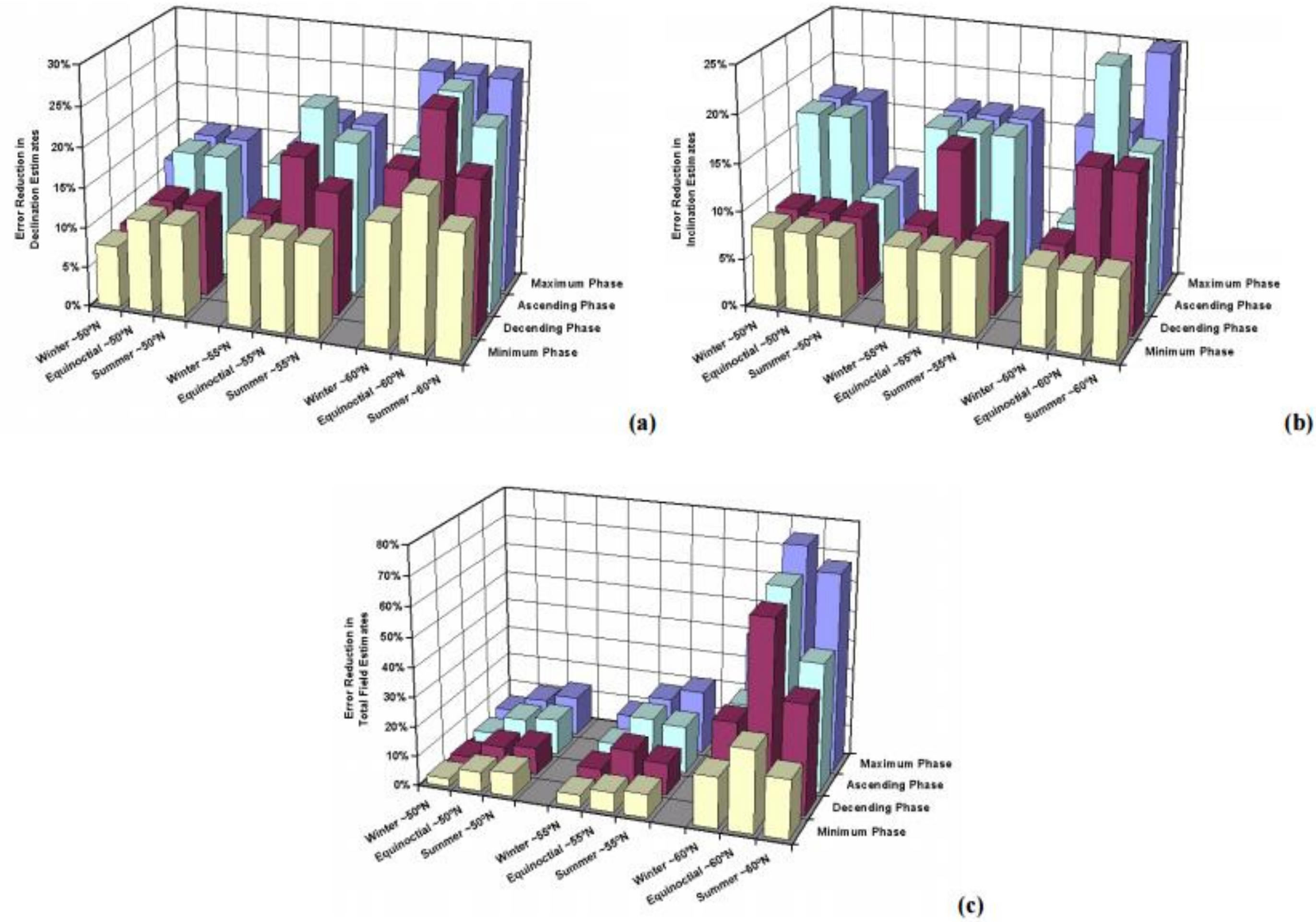


Figure 4.2: Percentage error reduction in the declination a), inclination b) and intensity c) [3]

4.1.3 An instrument for survey redundancy and quality control

Apart from the error reduction capabilities of the IIFR program, the instant delivery of geomagnetic real- time data also promotes the properties of this program to functions as a redundancy instrument. Instant delivery of information about the behaviour of geomagnetic field, enables independent confirmation of the performance delivered by the magnetic MWD survey instrument. Drilling in harsh survey environments or in abrasive conditions, may lead to the need for redundancy in the navigation and directional drilling applications. In such conditions, the operator organization must include at least two independent magnetic MWD survey instruments in the drilling operation in order to validate and verify the borehole survey measurements. However, this solution may prove to be very costly for the operator company and the survey measurements will still be highly unreliable during magnetic fluctuations.

In order to boost the reliability of the survey measurements and satisfy the need for validation in the navigation applications, the IIFR method can be incorporated with the utilization of a magnetic MWD survey instrument. An excellent correlation between the IIFR technique and the magnetic MWD survey instrument is sufficient to validate the performance of the downhole survey instruments, and confirm that the wellbore is navigated in the correct direction. This in turn may lead to improved well- positioning and better decision making among the survey crew. Nevertheless, a miscorrelation between these two methods may indicate operational limitation or a dispute in the magnetic MWD survey tool. In the case of a miscorrelation or a problem with the MWD tool, the use of excessive time and resources on re-surveying or tripping is eliminated, due to the utilization of the IIFR program. Which will still correct the geomagnetic field at the drilling site, by incorporating measurements obtained from various observatories. Overall, the IIFR method also hold the capabilities to function as a valuable asset for quality control, which eliminates the need for running expensive logging operations to verify the wellbore path. A comparison between the IIFR and magnetic MWD tool measurements is displayed in the figure below. Where the blue- coloured curve represents measurements of the MWD tool, while the orange curve highlights the IIFR measurements. The x-axis depicts the length of the well, while the y-axis represents the intensity given in nT. In this figure, the survey results indicates a good correlation between these two tools.

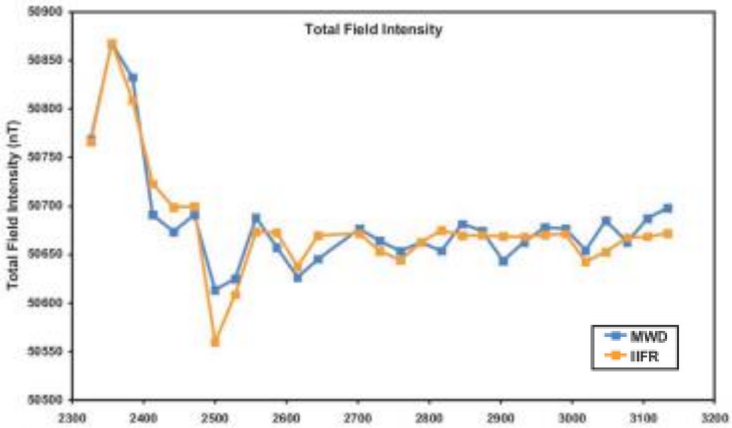


Figure 4.3: Comparison between the MWD tool and IIFR [3]

4.1.4 Successful in achieving industrial targets

The various key players and service providers of the petroleum industry have performed analysis and collected information. On the basis of this data, important industrial targets for desired uncertainty and accuracy have been established. In a technical report produced by the BGS [80], a study was performed on the magnitude of various effects, which caused estimations of a magnetic field to differ from predictions delivered by a global geomagnetic model. This study can be used to establish sound estimates of the uncertainties involved in global geomagnetic field models in the North Sea area. Beside from that, Russell et al (1995) [70] also established desired industrial targets for accuracy. The preferred accuracies and uncertainties established by both of the scientific publications for the magnetic MWD survey instrument are displayed in the table below:

Source	Declination	Inclination	Field strength	Element
BGS[80]	0,5 °	0,2 °	130 nT	Per magnetic field
Russell et al (1995) [70]	0,1 °	0,05 °	50 nT	Per survey

Table 4.1: Industrial limits and desired accuracies for geomagnetic parameters

The accuracy of the interpolation technique used in the IIFR method, have been tested in a number of scientific activities and analysis by using data from magnetic observatories [69]. The assessments of the precision capabilities of this technique have been carried out both during stable conditions and magnetic storms. Macmillan and Barraclough [81] carried out observations, where the main objective was to examine the possibility to regenerate magnetic fluctuations observed at the magnetic observatory of Eskdalemuir (55,3° North), by using information gathered from the magnetic observatories of Hartland (51° North) and Lerwick (60,1° North). The examination process lasted over a period of 3 years, in which 83 magnetic disturbed days were included. The various thresholds chosen for this study were as following: 0,083° for inclination and declination, 50 nT for the intensity. The results derived from this study indicated good correlations between the observed and interpolated values. An agreement of 94,3 %, 96,6 % and 93,9 % was found between the values. The conclusion of this research proves the capabilities of the interpolation technique, even during days of magnetic irregularities.

Other geological analysis and field cases also highlights the success of the interpolation technique [69]. A field case from the Liverpool bay displays that the standard deviation between the differences recorded from information interpolated at the Hartland and Eskdalemuir observatories and an on-site monitoring unit, were less than 10 nT in intensity and 0,01° for both declination and inclination. By combining the results of the various geological studies and research performed on the interpolation technique, the following uncertainties are associated with the IIFR method in the North Sea region [69]:

Parameter	**Per magnetic field**	**Per survey**
Declination	0,08 °	0,04 °
Intensity	0,025 °	0,04 °
Field strength	40 nT	25 nT

Table 4.2: The uncertainties related to the IIFR method

A comparison with the table 4.1, displays that the IIFR method is capable of delivering accuracy well above the industrial limits and expectations.

4.1.5 Alternative to gyroscopic instruments

A wide range of survey techniques and methods with differing functionalities, are available at the market to fulfil the survey requirements of a directional drilling operation. Generally, the most accurate descriptions of the wellbore in terms of direction is obtained by implementation of instruments named gyroscopic tools [3]. However, these survey instruments are associated with several undesired factors.

To begin with, the implementation of the gyroscopic tools in the directional drilling operations may prove to be time consuming and expensive for the operator company. The drilling sequence has to the interrupted for numerous hours while the survey instrument is being run. Beside from that, in order to extract the most precise survey measurements from some gyroscopic instruments: requires that the tools must be run in already completed wells segments, which contains cemented casings and liners. Running such accurate survey instruments in already completed and cemented well sections may prove unbeneficial. If any irregularities have been detected between the planned wellbore path and the current direction of the wellbore, corrective and remedial actions to correct the irregularities will be too late to implement. However, sidetracking to abandon the well section or milling operations to remove the cement may be regarded as remedial options to correct for the misalignment. Practically, these operations are too costly and time consuming to be considered. In order to protect the operation from these negative aspects, running intermediate gyroscopic surveys during the operation has become more regular. However, some of the accuracy of the gyroscopic instruments is sacrificed and the probability of some technical issues arises as well.

An alternative to the gyroscopic instruments is the magnetic MWD survey tool, which is combined with the IIFR method. By implementation of this survey technique, the negative consequences related to the gyroscopic tools are eliminated. Beside from that, the magnetic

MWD survey tool with the IIFR method saves operational time, less technical risks and saves survey resources. The accuracy is enhanced as well by implementing the IIFR technique, which is depicted by the figure below. In this figure, the green coloured ellipses represents the uncertainty related to the MWD methods, which only takes into consideration the core field. The red coloured ellipses represents the uncertainty related to the MWD technique, which is combined with the IIFR method. The blue coloured ellipses represents the uncertainty related to the gyroscopic instrument. The x-axis represents the eastward direction in meters, while the y-axis represents the northward direction in meters as well. The data used in this figure was collected over a period of 4 days during the year 2001.

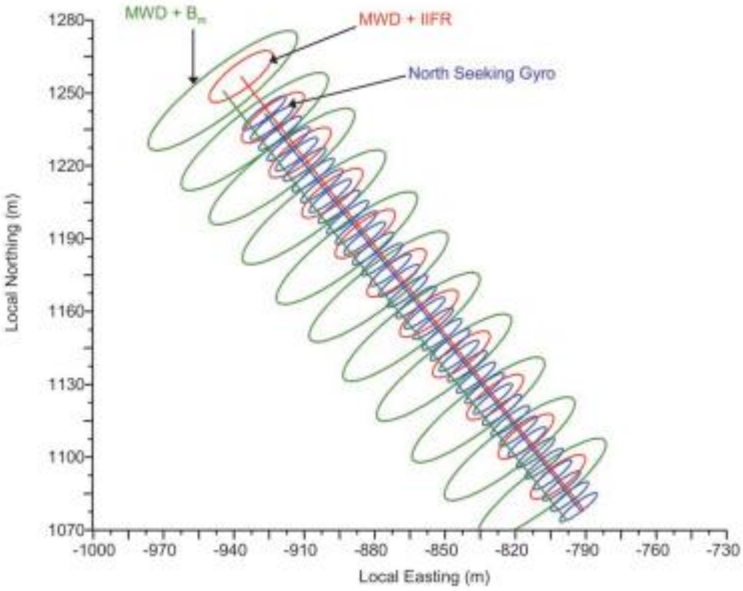


Figure 4.4: The ellipses of uncertainties associated with different survey techniques [3]

Figure 4.4 highlights that the most accurate survey method is the gyroscopic instrument. However, the accuracy of the MWD tool combined with IIFR is not far away from the gyroscopic tools. Beside from that, there are some technical, operational and economic benefits related to the MWD and IIFR method compared with the gyroscopic tools, which are in the favour of the MWD and IIFR survey technique.

This section highlighted the properties of the IIFR method, which enhances the well positional accuracy and improves decision making. Absorption of the advantages and benefits of this method were completed, which enhances the industrial viability of the magnetic MWD survey instrument.

4.2 Limitations and shortages of the IIFR technique

In this subchapter, the author of this thesis will investigate and address the major concerns, drawdowns and limitations of the IIFR technique. Major focus will be on the current shortages of this technique, but difficulties experienced in the past will also be highlighted. By doing so, a holistic perspective can be obtained of the IIFR technique and issues related to this method.

4.2.1 Dependency on monitoring facilities

The quality and accuracy of every geomagnetic model or technique is dependent on data acquisition. The data can be acquired through different means, for instance aeromagnetic surveys, magnetic observatories, satellites and many more. A common shortage of many magnetic models and techniques are the fact that: remote sites located in undeveloped regions and which lacks accessibility to data or magnetic observatories, are very poorly represented in these models. The predicted estimates of the magnetic field and its components at these sites are inaccurate and can contain considerable errors. This issue has been highlighted with the IGRF model. Likewise, the IIFR technique is also surrounded by similar technical limitations.

The performance and delivery of the IIFR method has been validated and approved at drilling sites in Alaska and other locations as well [82,83], where the accessibility of data is good due to short distances between the local magnetic observatories and drilling sites. Nevertheless, remote regions where the distance between the drilling site and magnetic observatories are far away from each other (>200 km) [82], the validity and performance of this technique is questionable. This is true especially, if the drilling site is close to the magnetic north.

Statistical research and analysis [84] of magnetometer and variometer data descending from magnetic monitoring observatories, located in Norway was assessed and investigated. Some of the major findings of this report were that: utilization of the IIFR method in high latitude areas, resulted in a reduced deviation of the declination. An improvement rate of 60 % was reported over a distance of 130 km, and further improvement of 30 % was reported over a distance of 540 km. One of the conclusions of this research was that there was a correlation between the improvement rate, and the distance between the drilling site and the magnetic observatory. The generally trend was that, a reduction in improvement rate with increasing distance between the magnetic observatory and the drilling site.

4.2.2 High latitude sites and electrical currents

It is well established that drilling operations conducted at high latitudes can lead to significant errors to the magnetic surveys. Distortions of even larger magnitude can also occur to the directional survey, if the magnetic measurements are exposed to time dependent currents occurring the ionosphere and magnetosphere. Research and analysis [85] indicates that there is a correlation between the magnitude of errors in directional surveys and number of latitude degrees. These scientific activities displays that magnetic surveys which are corrected with techniques of similar foundation as the IIFR program, the magnitude of errors becomes larger when drilling operations are conducted at higher latitudes. Therefore, the error increases with increasing latitude degrees.

The experiments and analysis [85] evaluated the accuracy of numerous gyroscopic and magnetic techniques, by investigating their performance in simulated representative wellbores. One of these assessed methods had the same foundation as the IIFR technique, which determined the magnetic field at the drilling site by considering the main geomagnetic field, magnetized crustal rocks and finally external fields. The wellbores were constructed in locations that were representative for the North Sea (60° north) and the Barents Sea (75° north).

The results of these scientific activities indicates that an increment in the horizontal goal element by a determinant of 2 is required when the drilling site is moved from 60° to 75° north. This change is necessary in order to maintain the probability of hitting the target. In other words, when the drilling site is moved further north, the lateral uncertainty increases close to a determinant of 2. Some of the results, involving the program that are similar to the IIFR are presented in the figures below (figure 4.5 and 4.6)

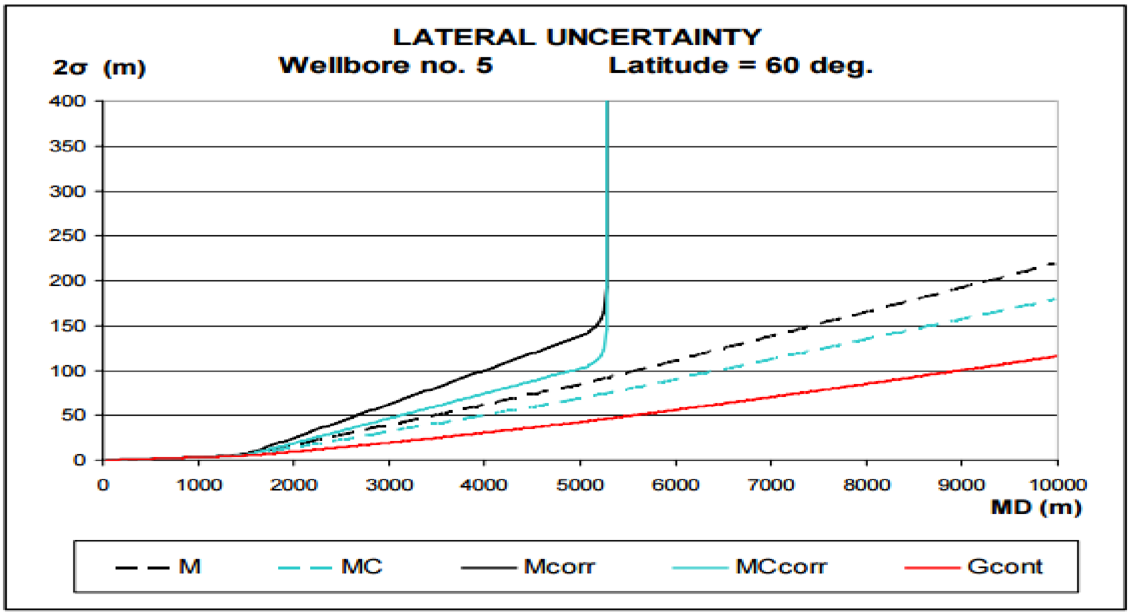


Figure 4.5: The different services and their associated deviation at 60° latitude [85]

In figure 4.5, the y- axis represents the standard deviation and the x-axis represents the measured depth. The MC method takes into account the main field and the crustal field, this method represents the program that have the same foundation as the IIFR program. The reason behind this representation is that: during the analysation of the results, the MC and the program similar to the IIFR showed similar results [85]. The results displayed on this graph are recorded for a deviated well with two kick off points.

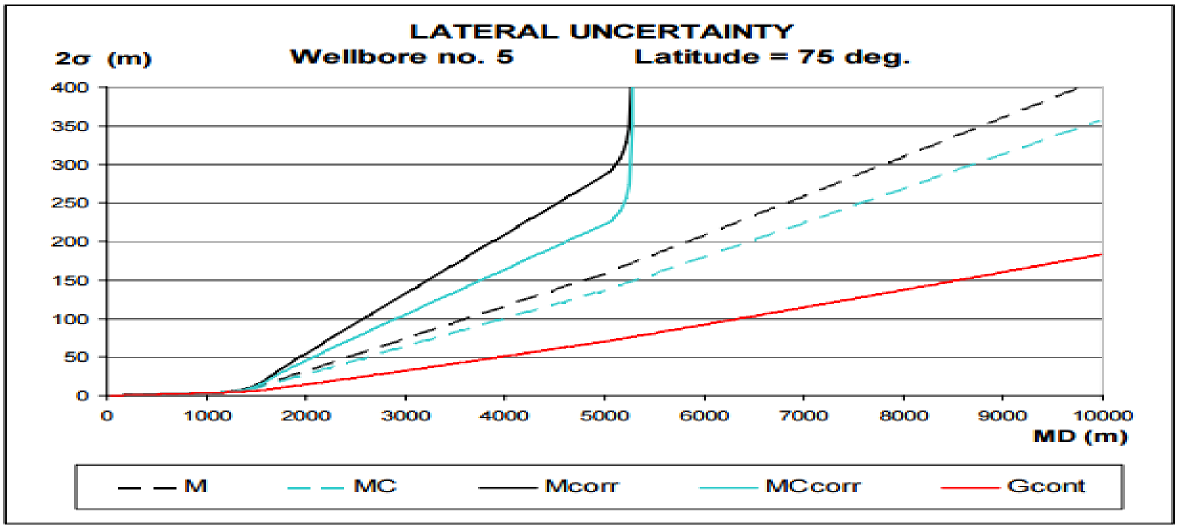


Figure 4.6: The different services and their associated deviation at 75° latitude [85]

In figure 4.6, the y- axis represents the standard deviation and the x-axis represents the measured depth. The MC method takes into account the main field and the crustal field, this method represents the program that have the same foundation as the IIFR program. The reason behind this representation is that: during the analysation of the results, the MC and the program similar to the IIFR showed similar results [85]. The results displayed on this graph are recorded for a deviated well with two kick off points. Beside from that, this graph highlights the enhanced deviations experienced while drilling at higher latitude degrees, which are clearly higher than for a 60° north well.

It is very important to remember that the IIFR program was not tested in this experiment. Only a program with the same foundation was put to test. However, due to the resemblance between the two techniques, this issue may also be related to and possible affect the accuracy of the IIFR program at higher latitudes. Therefore, this issue may be of concern and needs more investigation. For more information about the simulations and experiments, the following source [85] can be visited.

4.2.3 BGGM

The IIFR program estimates the magnetic field at the drilling site by taking into account the following three parameters: B_{external} , B_{magcrust} and $B_{\text{geomangetic field}}$ (equation 3.1). The $B_{\text{geomangetic field}}$ represents the core field, descending from the earth`s core. Estimations of this parameter is usually obtained by utilizing a global geomagnetic model. There are a numerous versions and types of such models available in the market. However, BGS uses their own geomagnetic model named BGGM, for estimating the core field to be used in the IIFR method.

The main issue related to the use of the BGGM for estimating the core field is that: other global geomagnetic models are available, which are more accurate and precise than the BGGM. By utilizing one of these models, more accurate estimations of the core field can be obtained. Which in turn, would enhance the survey results of the IIFR method. One example of a model, which is more accurate than the BGGM is the HDGM model.

One way of visualizing or assessing the capabilities of geomagnetic models is to review the graph named: global geomagnetic power spectrum. In this spectrum, the main field descending from the earth`s core is dominating at very long wavelengths. However, for wavelengths shorter than 2500 km or harmonic degrees ≥ 16, the magnetized crustal formations dominates the spectrum. One important factor related to this graph is that: global geomagnetic models are constructed with a specific number of harmonic degrees. Therefore, harmonic degrees higher than the programmes degrees represents the omission error for the specific model. The omission error corresponds to the area beneath the spectral curve in this graph. The spectrum of the main field is reasonably high, and relative low harmonic degrees are needed to cover the main field. However, the spectrum that belongs to the magnetized crustal rocks are fairly low and flat. In order to cover this region, the programmed needs to contain a large number of harmonic degrees to reduce the omission error. The global geomagnetic power spectrum for both the BGGM and HDGM model is presented in the figures below.

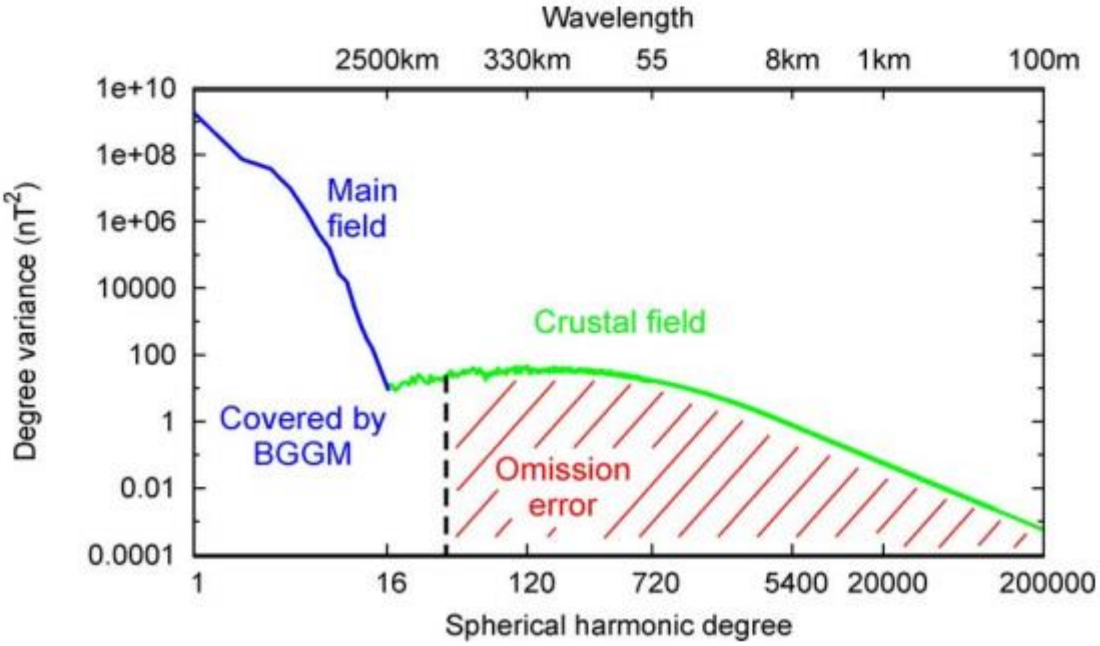


Figure 4.7: The global geomagnetic power spectrum for the BGGM model [86]

In figure 4.7, the curve is referred to as the spectral curve. This curve is highlighted with two different colours. The blue colour represents the wavelengths belonging to the main field, while the green indicates the wavelengths of the magnetized crustal rocks. The area between the harmonic degrees of the model and the remaining degrees is named the omission error, which is highlighted by the red marks. The remaining area under this curve is un-marked, and represents the wavelengths covered by the BGGM model. The lower x-axis represents the harmonic degrees, the upper x- axis represents the wavelengths. While the y- axis represents the degree variance parameter [86].

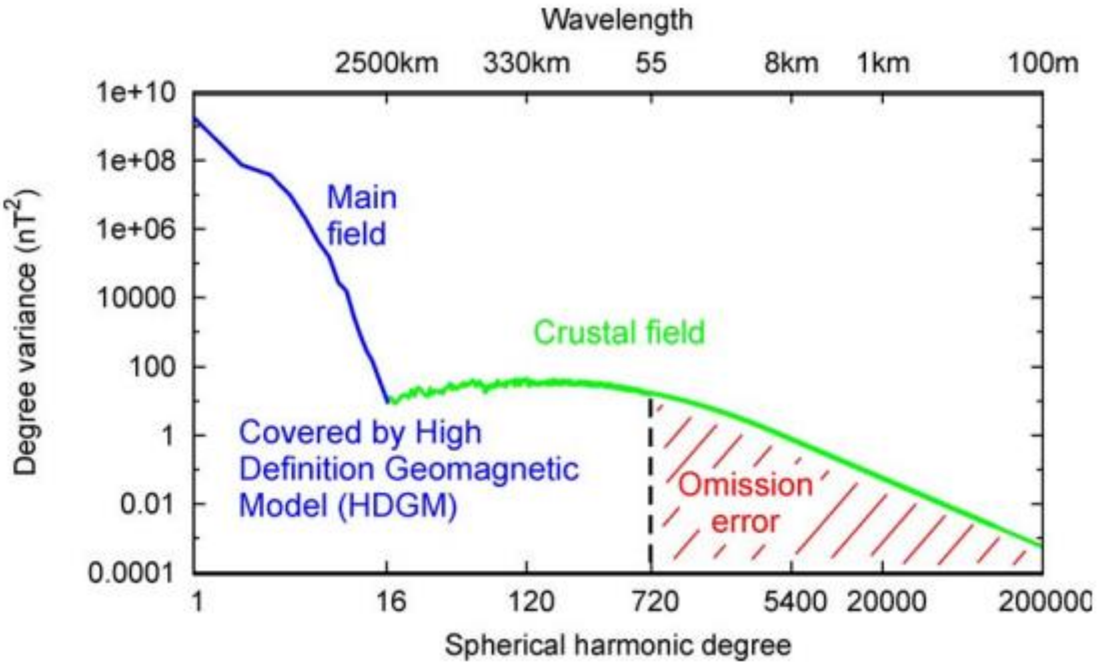


Figure 4.8: The global geomagnetic power spectrum for the HDGM model [86]

The figures 4.7 and 4.8, clearly indicates the difference in accuracy between these two global geomagnetic models. From figure 4.7, it can be observed that the BGGM is programmed with 16 harmonic degrees. Due to this fact, this model covers the longer wavelengths, while the smaller wavelengths belonging to the magnetized crustal formations are left unconsidered. This in turn results in large omission errors. Figure 4.8 displays that the HDGM model is programmed with 720 harmonic degrees, which gives this model the capabilities to account for smaller wavelengths descending from the magnetized crustal rocks and reduced omission errors. The high number of harmonic degrees gives the HDGM model a resolution of 28 km wavelengths, while the BGGM has a resolution of 400 km. The dissimilarities in the resolution yields 0,5° difference in declination between these two models [86].

Another important factor to highlight is the uncertainties related to the HDGM model compared to the error model of BGGM. The uncertainties associated with the HDGM model is much lower than for the BGGM model. This comparison is visualized in the table below:

Models	Total field	Dip	Declination (constant)	Declination
BGGM	130 nT	0,2°	0,36°	5000° nT
HDGM	107 nT	0,16°	0,30°	4118° nT

Table 4.3: The uncertainties associated with the BGGM and HDGM [86]

This section clearly indicates that a refinement of the BGGM model may be beneficial for the IIFR method. Boosting or redeveloping the BGGM model to match or improve its capabilities above other models can enhance the results derived from the IIFR method. By doing so, the $B_{\text{geomagnetic field}}$ can be estimated more accurately and it will enhance the predictions of the magnetic field at the drilling site.

4.2.4 Magnetized crustal rocks

The IIFR method does not contain any assumptions about the geophysical or geometrical characteristics of the various sources of the magnetized crustal formations, when determining the contributions from the B_{magcrust}. Assumptions related to the orientation, size, dimensions and direction of magnetization, which may be important for estimating accurate values of B_{magcrust} are not a part of this technique. Information and data of anomaly fields descending from local geological surveys and mapping, should be carefully assessed in order to determine the probability of the occurrence of shallow positioned magnetic elements, their size, shape and other magnetic characteristics. In some scenarios, while extrapolating and determining the magnetized crustal rock estimations derived from high altitudes to the sub-surface surroundings, the presence of shallow magnetic sources with differing dimensions and magnetic characteristics can results in considerable errors and inaccuracies.

Another difficulty that has been experienced with the use of the IIFR method, is related to accurate estimations of the magnetized crustal fields. Prediction of this parameter may be challenging especially as a function of the drilling depth, when the anomaly field sources are positioned near the observation points.

4.2.5 Errors and statistical viewpoint

Errors and inaccuracies may occur during the implementation process of the IIFR method. There are especially two types of errors, which are more likely to occur:

1. The first type of error is related to the correction process involving the anomaly fields. This error may occur when correcting procedures for the anomaly fields is being accomplished between drilling location and the local magnetic observatory.
2. The second error is associated with the algorithm utilized to predict the external variations measured at the local magnetic observatory, from the external variations measured at the monitoring station, which is positioned further away from the drilling site.

The error associated with the correction procedures of the anomaly fields, may propagate in the calculations and cause significant deviations if the distance of the local magnetic observatory is close to the drilling location. Particularly, if the geological setting is abundant with local spatial anomaly fields. However, in order to minimize this type of error in the IIFR program, it is very important to ensure that the distance between the local magnetic observatory and the drilling location is not to close to each other, this is particularly important in an offshore environment.

The magnitude and size of the second error is a function of these factors:

a) The geographical location in terms of latitude degrees of the local magnetic observatory and the distant monitoring facility.
b) The distance between the local magnetic observatory and the distant monitoring facility.
c) The quantity of magnetic observatories involved in the IIFR method.
d) The quality of the data, which is recorded by the sensors utilized in the distant magnetic facility and the local magnetic observatory.

To summarize this paragraph: if the drilling site is conducted at high latitudes, the magnitude of the errors are a function of the distance between the local magnetic observatory and the distant magnetic facility. However, if the drilling operations is planned at moderate latitudes, larger errors would be expected if the distance between the distant monitoring facility and the local magnetic observatory is far away from each other.

Another limitation related to the IIFR technique is associated with the current calculations for the wellbore position. These calculation shortfalls includes that: this method has a statistical viewpoint associated with the ellipses of uncertainty, and a curve is assumed between the survey points.

4.2.6 Limited area evaluation and geographical positions

The various assumption that are a part of the IIFR method, is contributing to limit the total area for which the information may be assessed and evaluated. This limitation is a hinder for analysing data, collected from larger areas by the various magnetic surveys conducted both at land and sea. One of the biggest benefits of analysing data from a wide and enlarged areas is that: A more holistic view can be achieved of the process and it can help to identify contexts.

The spatial proportion of magnetic field fluctuations can be very limited during irregular magnetic variations and storms. Alongside with this, the correlation of the magnetic disturbances observed at the drilling location and the distant monitoring facility is more or less much smaller in magnitude, compared at times with more stability in the geomagnetic field. Due to the fact that magnetic storms and fluctuations is often related with geographical positions, an investigation of the precision availability must be performed at the specific locations and sites.

In this segment, the various limitations and drawdowns of the IIFR technique was absorbed and highlighted. In order to improve the performance of this method, attention and resources must be allocated for further refinement of this industrial tool. These improvements will be very essential for the performance of the IIFR and bolster its viability in even more challenging magnetic environments. Especially, since the exploration and production industry is moving its business further northwards at higher latitudes. An improved IIFR, fully capable of delivering navigational guidance with high quality, will reaffirm the industrial importance and position of this tool.

4.3 Field case study

In this segment, an assessment will be performed of the practical capabilities of the IIFR method. The investigation will be carried out by analysing case studies, where the magnetic MWD survey instrument combined with the IIFR has been utilized. These field cases will also display the grade of success and industrial needs, which are fulfilled by the IIFR technique. The cases studies have been acquired from the integrated operation manager of one of the key operator organizations, operating on the Norwegian continental shelf. This organization is also a major key player worldwide and is an important contributor in the global market.

Major focus of this segment will be on survey measurements and calculations of the various geomagnetic parameters, used in directional drilling applications of these wells. The survey measurements obtained from the BGGM model and the IIFR technique will be highlighted and assessed, and thereby compared with geomagnetic values computed from the IGRF model. This comparison will be carried out to evaluate the practical capabilities, precision and reliability of the IIFR method with the free to use model named IGRF.

Any information in the operation sequence related to the performance capabilities of the magnetic MWD survey instrument and IIFR will also be highlighted and presented. This also includes any quality control measurements. By doing so, the limitations, advantages and reliability of the magnetic MWD survey tool and IIFR can be highlighted and compared with other survey methods.

Prior to elaboration and presentation of the field case study, it is necessary to underline some important information. The location of the different wells, drilling facilities, site or any sensitive information which could reveal the location of the well or involved organizations will be kept confidential, due to requests and policies of the operative company. The case study was requested from regions located as far north as possible. The main intention behind this request was first to map the practical capabilities of the magnetic MWD instrument and IIFR method in high latitude regions. By doing so, a holistic view can be formed of the performance capabilities of these two industrial tools, in harsh magnetic environments. This field case study is from wells that are located above 56 ° north, which is sufficient to cause large deviations in the survey measurements. Beside from that, the survey measurements with the magnetic survey methods have been taken both during stable conditions and during magnetic storms, or irregular fluctuations. The varying magnetic environment is helpful in the process to map the performance of the IIFR method and MWD instrument.

4.3.1 General information

The main objective of this drilling operations was to drill a horizontal producer well on the Norwegian continental shelf, which is going to intersect two oil bearing reservoirs. In other words, the well will be intersecting the first reservoir, while ending in the second. Alongside this main well, two technical sidetracks were also drilled. These two sidetracks were drilled with the help of the wellbore path of the main well. After using a considerable length of the main well, the direction of the sidetracks were changed by installing a whipstock in the main well. The wellbore configuration of this well can be related to the structure of a multilateral well, with many wells shooting out from one main foundation.

Different survey methods were utilized separately and in combination with each other. In order to enhance the survey measurements, several corrections were also included in the survey process. More detailed information on which survey method used in different well sections and correction methods will be given in the next segment.

4.3.2 Main well

Relevant information about the main well is stated in the table below. In this table, only the main runs required to finish the well is included. Runs required to for instance implement remedial actions for correcting minor drilling related problems or fishing operations are not included in this table. The various drilling parameters included in this table, describes the end configurations or settings of the well. Beside from that, type of survey tool and corrections applied are also stated. Table 4.4 is followed by two figures (figure 4.9 and 4.10). In figure 4.9, the orientation and direction of the well is depicted in a vertical section of the wellbore. This Figure also displays the pre-determined targets along the wellbore path and the casing setting depth. In figure 4.10, the same information is delivered as in figure 4.9, but in a bird-eye perspective.

Run number	*Hole size*	*MD (ft)*	**Geographical Azimuth**	**Inclination (drilling)**	**Survey method**	**Type of correction**	**Additional information**
1	26``	RKB – 1984	240, 31 °	5 °	Gyro	MS+ Gyro correction	Vertical from RKB to the kick-off point at 1200 ft. The 20`` casing was set at 1958 ft.
2	17,5`` * 20``	1984 – 3356	238,28 °	27,28 °	Magnetic MWD	MWD+IIFR+MS+SAG	17`` casing was installed at 3350 ft.
3	16``	3356 – 5063	254,50 °	23,31 °	Magnetic MWD	MWD+IIFR+MS+SAG	13,625 `` casing was installed at 5049 ft.
4	12,25`` * 13,5``	5063 – 11050	322,24 °	72 °	Magnetic MWD	MWD+IIFR+MS+SAG	10,75`` liner was installed at 11047 ft. The first reservoir is intersected.
5	9,5 ``	11050 – 15324	315,93 °	72 °	Gyro+ magnetic MWD	Gyro correction+ SAG+ RT	7,625`` casing was installed at 15284 ft. The second reservoir is penetrated.

Table 4.4: Relevant information about the main well

There are some important information and indications related to the utilization of the different survey methods and correction factors in table 4.4, which must be underlined and highlighted. To begin with, while drilling the vertical section only the gyroscopic instrument is installed and utilized in the BHA. After completing this well section, this tool is replaced with the magnetic MWD survey instrument in rest of the drilling operation and is used until the end. However, from run 2- 4 the MWD tool is combined with the IIFR correction method, even while intersecting the first reservoir zone. These operational changes indicate that the magnetic MWD survey instrument is not reliable without the IIFR method, and proves the capabilities of the IIFR correction technique. A conclusion that can be derived from this information is that the IIFR correction method delivers satisfactory or even excellent results and is a highly reliable instrument for quality control, which is sufficient to replace the gyroscopic instruments. This also proves the industry`s confidence in the IIFR method as a tool for navigation and well positioning, and its reputation in the upstream sector of the petroleum industry.

However, the IIFR method is replaced with the gyroscopic instrument when the last well section is being drilled, which is an important economical segment of the whole well. These operational changes may indicate two things. Firstly, the survey accuracy of the IIFR is largely lagging behind the gyroscopic tool. Alternatively, stable magnetic conditions may have eliminated the need for additional correction for the magnetic MWD survey instrument. It is clear that the gyroscopic instrument will be used as the primary survey method in the last section, and that the magnetic MWD tool is used as a secondary tool for quality control. It is well established that the IIFR method boosts the accuracy of the MWD tool, therefore it would be highly short- sighted to use the MWD tool alone as a quality control measure. Especially since the magnetic surveys from the MWD are significant distorted during magnetic storms. Therefore, the probabilities for stable magnetic conditions are high and due to this fact: the IIFR method is not included.

Another important observation from table 4.4 is that correction for SAG is used during the whole drilling operation. This is an indication of the considerable threat posed by the phenomenon termed sag on the survey accuracy, and the importance of reducing or eliminating sag.

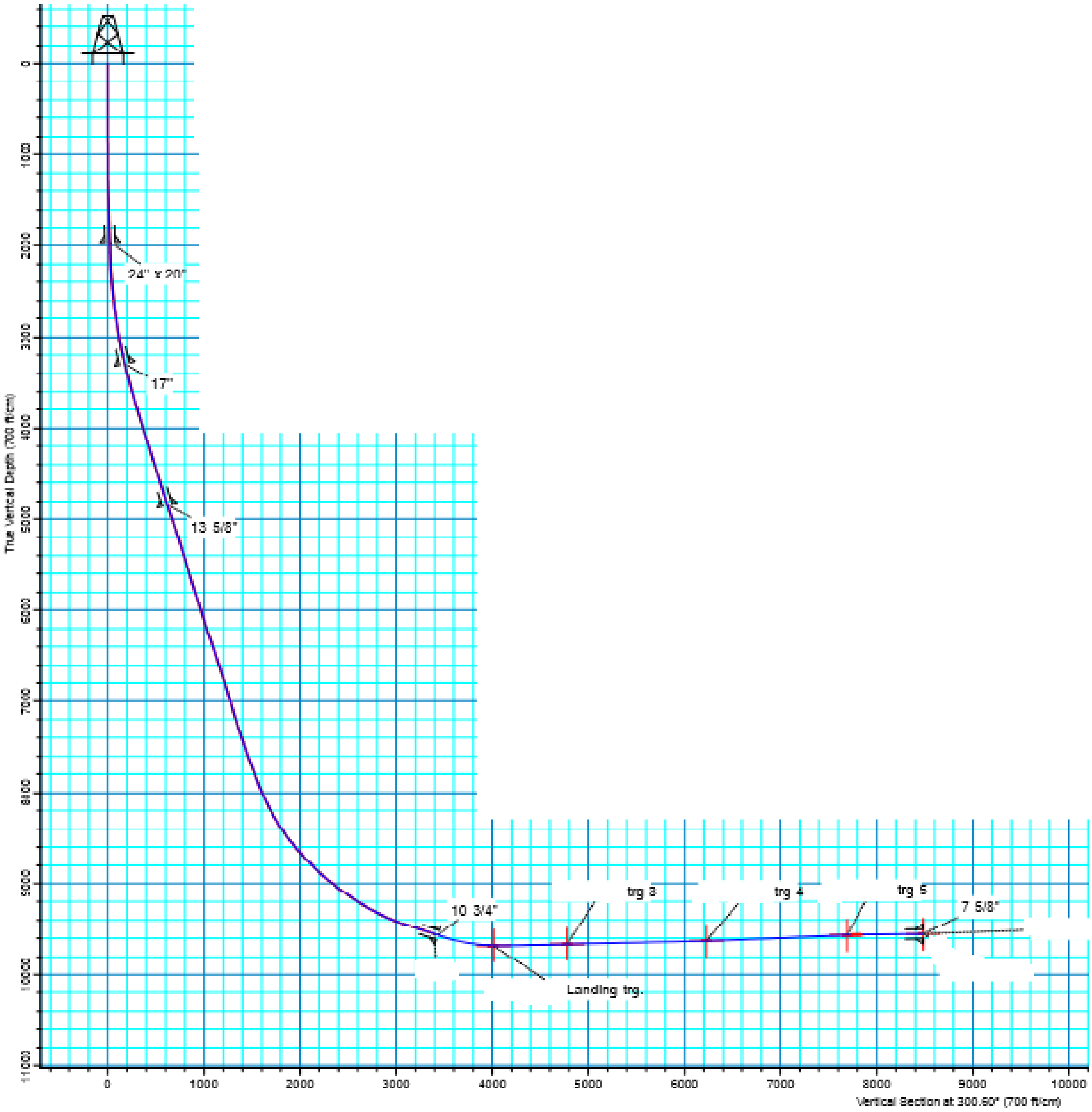


Figure 4.9: The vertical section of the main well

Figure 4.9, highlights the orientation and direction of the wellbore path. Alongside with this, information related to the casing setting depth and planned targets (indicated by the red crosses) are also included. The x-axis represents the horizontal distance, while the y-axis represents the vertical distance. The white spots on this figure represents sensitive information, which has been censored on the request.

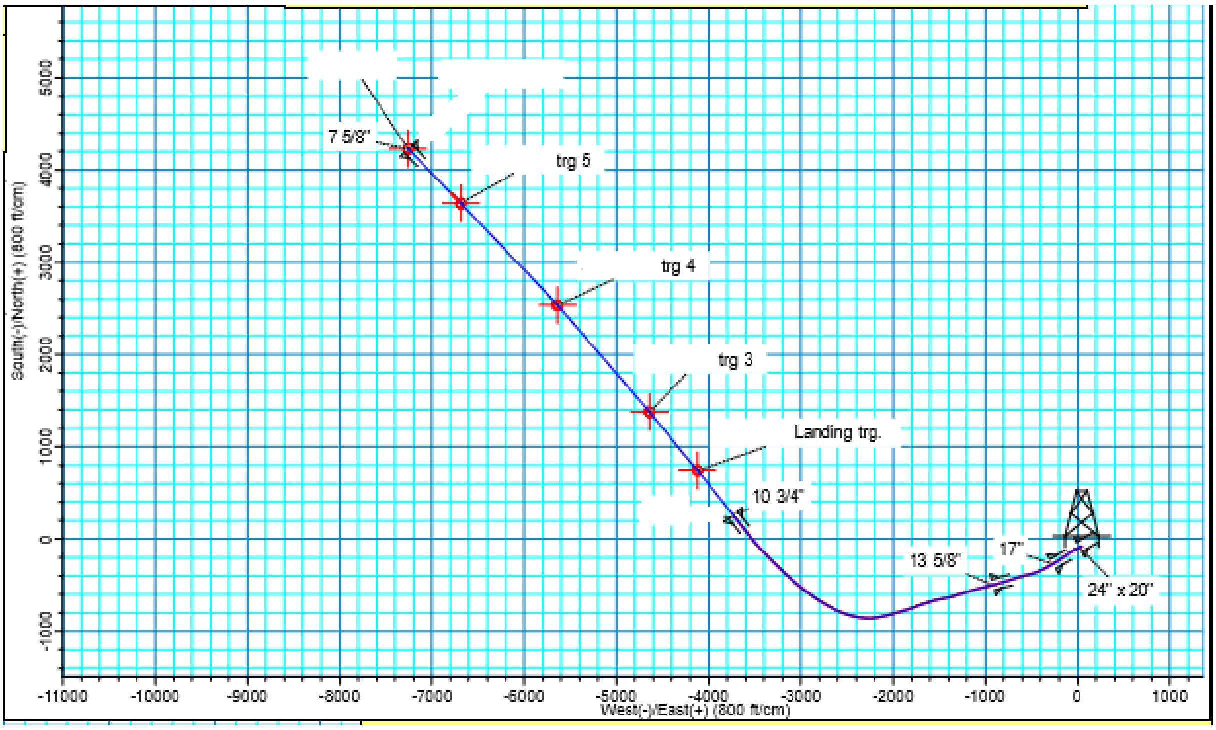


Figure 4.10: The orientation of the wellbore path in a bird- eye perspective

Figure 4.10, also contains information related to casing setting depth and planned target (red crosses). The x-axis represents the west and east directions, while the y-axis represents the north and south directions. The drilling facility is defined as the origin position of the graph.

Operational sequence

There is limited information about the performance of the various survey methods during drilling of the main well. The information gathered for each well segment is presented in the table below.

Run number	Survey instrument	Information
1	Gyro	Gyro surveys displayed that the well was close to vertical. Due to this fact, no corrections were applied.
2	MWD+ IIFR	Good magnetic MWD surveys obtained.
3	MWD+ IIFR	No remarks on the survey method. May indicate satisfactory result.
4	MWD+ IIFR	No remarks on the survey method. May indicate satisfactory result.
5	Gyro+ MWD	Quality test of both survey principles indicated good results and passed the requirement sheet.

Table 4.5: operational sequence of the main well

As mentioned, there is not much information to extract about the performance of each tool. However, the fact that the MWD tool without the IIFR passed the quality test in the 5th run strengthens the statement about stable magnetic conditions.

Survey calculations

The survey corrections and measurements for the IIFR method were not given for the main well. However, the IIFR technique calculates $B_{geomagnetic\ field}$ by using the BGGM model. This model was used in the drilling operation to calculate important geomagnetic parameters for the well. These values were then fed to the IIFR method to correct and monitor the field variations at the drilling site. Due to this reason, even without the absolute values from the IIFR method, the values derived from the BGGM can be interpreted to give a performance estimate of the IIFR.

The numbers computed by the BGGM model is compared with numbers obtained from the freely accessible IGRF model calculator (link is provided on page 83). In order to ensure that the confidentiality of the operator company is maintained, limited information can be revealed about the parameters fed to the IGRF calculator. However, the reference point in the calculator was set to mean sea level, and the coordinates of the well were fed in geodetic coordinates. The values of the different geomagnetic parameters obtained from the two model are listed in the table below.

Model	**Declination**	**Magnetic dip**	**Field strength**	**Well section**	**Model validity**
BGGM14	-0,07 °	70, 25 °	50 088 nT	Well slot	2014-2015
IGRF - 12	-0,036 °	70, 233 °	50 068 nT	Well slot	2015-2020

Table 4.6: Geomagnetic parameters derived from BGGM14 and IGRF – 12

From table 4.6, it can be observed that the difference between the values computed by the two models are very small. A negligible or minimal difference exists between the values, especially for the magnetic dip and field strength. A small deviation is observed in the declination parameter between the computed values of these two models. However, this difference is not of a large magnitude.

In contrast to the free- to –use IGRF model, annual license must be purchased to utilize the BGGM model. During the analysation of the various benefits and advantages of the IIFR method, it was observed that studies performed on the uncertainties involved in global magnetic models [77], concluded that the estimation of the geomagnetic field computed from the global models were accurate during the early stages of their release. However, the precision of these models deteriorate as a function of time. In order to preserve its accuracy, the BGGM model is updated annually. The IGRF model on the other hand, is updated every 5th year. Due to this fact, utilization of the IGRF model for well positioning may not be appropriate during the last stages of this model.

However, the measurements from the BGGM model was acquired in 2015, during the initial stages of the drilling operation. This implies that the accuracy of the IGRF model was at its highest. On the other hand, an expired version of the BGGM model was used in this drilling operation. This means that the accuracy of this version was degraded, compared to its newest edition. Due to this fact, the declination provided by the BGGM model for this well may contain errors larger than the IGRF predictions of the declination. To conclude this observation: expenses and resources related to the use of IIFR method can be reduced by putting an effort into the free- to- use IGRF model, and by utilizing estimations provided by this model in the IIFR method for well positioning. Nevertheless, in order to utilize the IGRF model for IIFR applications, frequent updates are necessary for boosting the reliability and accuracy of the IGRF model. By doing so, the IIFR method will be optimized from an economical viewpoint, which in turn will enhance the method`s competitive abilities in the market.

4.3.3 Sidetrack 1

Similar to the main well, the necessary information about this technical sidetrack is provided in the table below. Alongside this table, figures describing the orientation and direction of well is included as well.

Run number	***Hole size***	***MD (ft)***	***Azimuth***	***Inclination (Drilling)***	***Survey method***	***Type of correction***	***Additional information***
1	9,5``	10533 – 11062	314,47 °	73,03 °	Gyro+ magnetic MWD	MWD+IIFR+SAG	Tie- on with parent well at 10501,1 ft MD. 7,75`` liner was installed at 11059 ft.
2	6,5``*7``	11062 - 11971	320,94 °	89,14 °	Magnetic MWD	MWD+IIFR+MS+ SAG	

Table 4.7: Relevant information about the first sidetrack.

One pattern that is also repeated in the main well (table 4.4) and for this sidetrack (table 4.7) is the use of sag correction. This observation underlines the importance of sag mitigation for improved survey analysis and well positioning. Initially the sidetrack is being drilled with gyro and the magnetic MWD survey instrument, combined with the IIFR. However, the gyro is dropped in the last well run and the rest of the sidetrack is drilled with the MWD and IIFR. This change displays the industry`s confidence and reputation of the IIFR method. Which proves the well positioning capabilities of this tool.

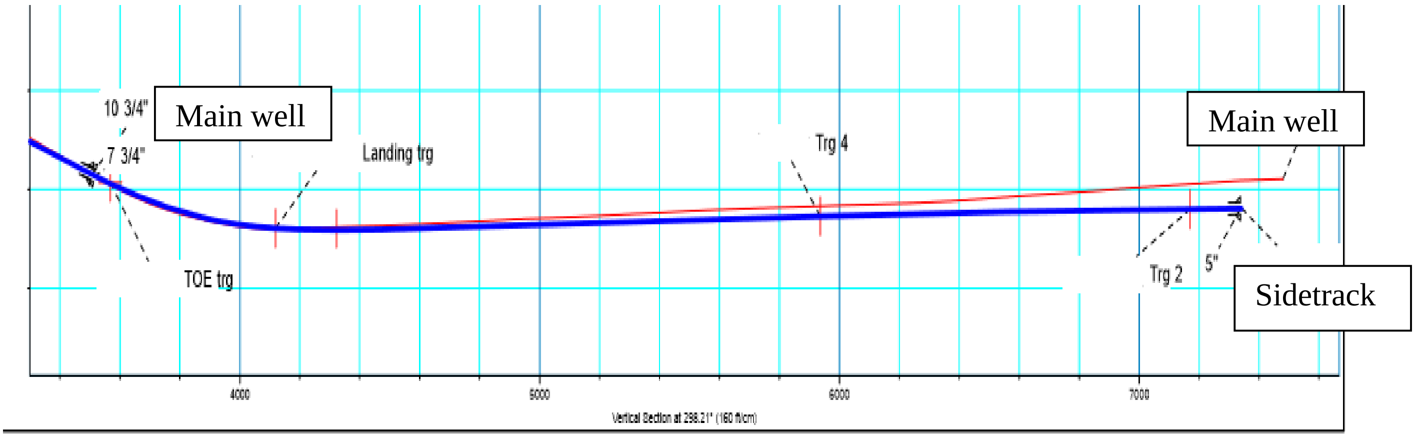


Figure 4.11: The vertical section of the first sidetrack

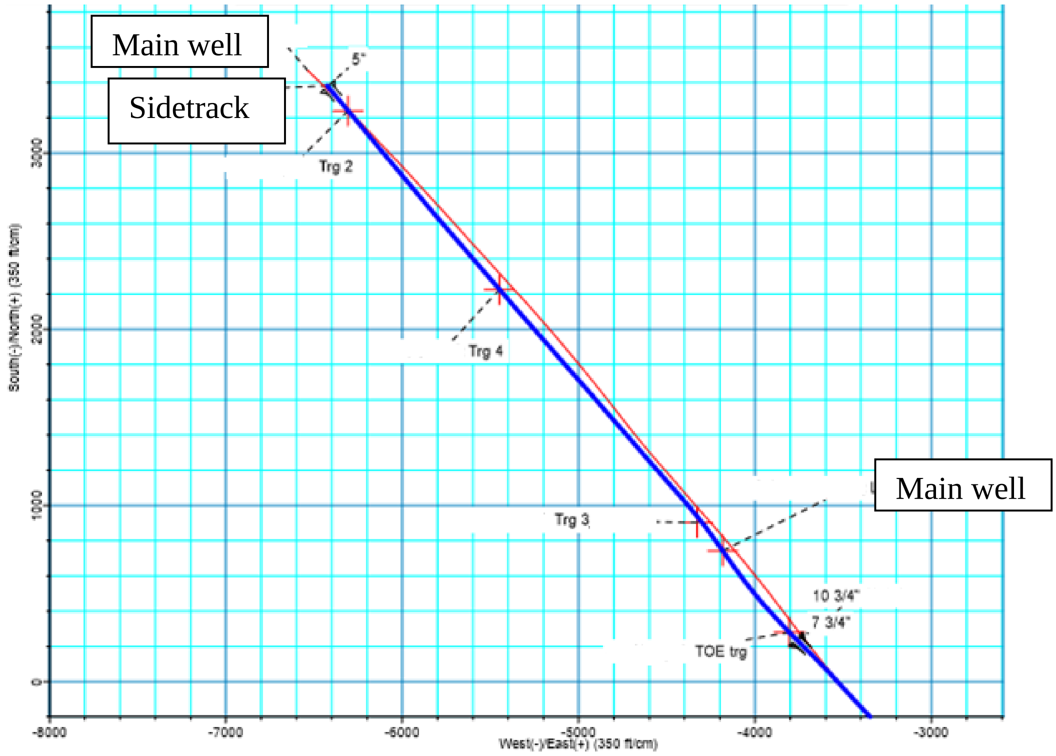


Figure 4.12: The orientation of the wellbore path in a bird- eye perspective.

Operational sequence

Before diverging the trajectory of the sidetrack from the main parent wellbore, a quality test of the survey methods was conducted. The result of the quality control is displayed in the table below.

Survey method	**MD (ft)**	**Azimuth**
Magnetic MWD+ IIFR	10373,6	315,65 °
Gyro 1	10373,6	316,37 °
Gyro 2	10373,6	316,71 °

Table 4.8: Operational sequence of the first sidetrack

The survey measurements derived from the quality control demonstrates good correlations between the different survey methods. These results clearly highlights the high accuracy performance of the IIFR method, which is on pair with the gyroscopic instruments. Beside from that, this test also concludes that the magnetic MWD survey instrument and IIFR can be run as the primary survey tools in drilling operations, without the need for assistance by gyroscopic instruments. This in turn leads to reduced costs and lowered technical risks.

While drilling this sidetrack, the IIFR method also proved its potential as a tool for improved decision- making. Measurements obtained from the magnetic surveys, showed that the azimuth of the sidetrack turned less away from the main well than what was initially planned. This incident occurred when the trajectory of the sidetrack was changed from the main parent wellbore with the help of a whipstock. The magnetic surveys also highlighted that the difference between the sidetrack trajectory and the casing sections of the main parent well, was much less than initially determined in the drilling program. In order to reduce the risk of collision with the adjacent well, the decision to steer the sidetrack away from the main well to achieve sufficient separation was taken. A satisfactory distance was achieved between these two wells, with the help of the magnetic MWD tool and IIFR.

Survey calculations

The survey measurements for the 9,5`` well section is displayed in the figure below. Important changes from the measurements of the main well is that: the latest edition of the BGGM model is used, and corrected values from the IIFR method are included. Geodetic coordinates and mean sea level was chosen as the reference point for the IGRF calculator. Beside from that, the calculations were performed in the middle of 2015.

Model/method	**Declination**	**Magnetic dip**	**Field strength**	**Well section**	**Model validity**
BBGM15	-0,12 °	70,23 °	50 049 nT	9,5``	2015- 2016
Magnetic MWD+ IIFR	-0,257 °	70,272 °	50 117,5 nT	9,5``	___
IGRF-12	-0,051 °	70,23 °	50 065 nT	9,5``	2015-2020

Table 4.9: Survey calculations of the first sidetrack

Apart from the magnetic dip, there are considerable deviations in the measurements obtained from the different models and methods. The estimation of the declination by the global geomagnetic models are inaccurate and suppressed, compared to the corrected estimations of the IIFR technique. These errors are present in both of the global geomagnetic models, even though the latest version of the BGGM model is used and during the initial release stages of the IGRF model. This observation highlights the limitations related to the use of global geomagnetic models alone for survey applications, which used to be a common practice among survey teams. In order to derive the most accurate geomagnetic descriptions of the wellbore, consideration and correction for $B_{geomagnetic\ field}$ in the survey data alone, cannot yield the most precise predictions of the geomagnetic parameters. In order to enhance the accuracy of the magnetic surveys, contributions from $B_{external}$ and $B_{magcrust}$ must be included in the surveys. The IIFR method incorporates $B_{magcrust}$, $B_{external}$ and $B_{geomagnetic\ field}$ in the estimations of the geomagnetic field, which in turn enhances the accuracy of the survey data. This observation underlines the precision and correction capabilities of the IIFR method, and limitations of the global geomagnetic models.

Another aspect that must the highlighted is the capabilities to achieve industrial targets and precision limits. Accurate and optimized well positioning requires high accuracy in the estimations of the geomagnetic parameters. The desired accuracies from the industry are as following: 0,1 ° in declination, 0,05 ° in magnetic dip and 50 nT in field strength. From table 4.9, the difference between the BGGM and IIFR estimations are as following: 0,137 ° in declination, 0,042 ° in magnetic dip and 68,5 nT. These differences indicates that the BGGM model only managed to predict the magnetic dip within the industrial limits, while failing to achieve the accuracies required by the industry in the remaining parameters. The difference between the IGRF and IIFR estimations were as following: 0,206 ° in declination, 0,042 ° in magnetic dip and 52,5 nT. Just as the BGGM mode, the IGRF model failed to meet the industrial requirements for declination and field strength. This observation clearly highlights the capabilities of the IIFR method to satisfy accuracy limits set by the industry, and precision shortages of the global geomagnetic models.

4.3.4 Sidetrack 2

The table below provides important information about the second sidetrack. this table is followed by two figures, which describes the trajectory of the borehole.

Run number	*Hole size*	*MD (ft)*	*Azimuth*	*Inclination (Drilling)*	*Survey method*	*Type of correction*	*Additional information*
1	9,5``	10130 – 11040	323,49 °	57,82 °	Gyro+ magnetic MWD	MWD+IIFR+SAG +gyro correction+RT	Tie- on with parent well at 10130 ft MD. 7,75`` liner was installed at 11037 ft.
2	6,5``*7``	11040-14800	308,97 °	89,79 °	Magnetic MWD	MWD+IIFR+MS+ SAG	5`` liner was installed at 14795 ft.

Table 4.10: Relevant information about the second sidetrack.

The survey method configurations and the type of corrections used for drilling this sidetrack is same as the first sidetrack.

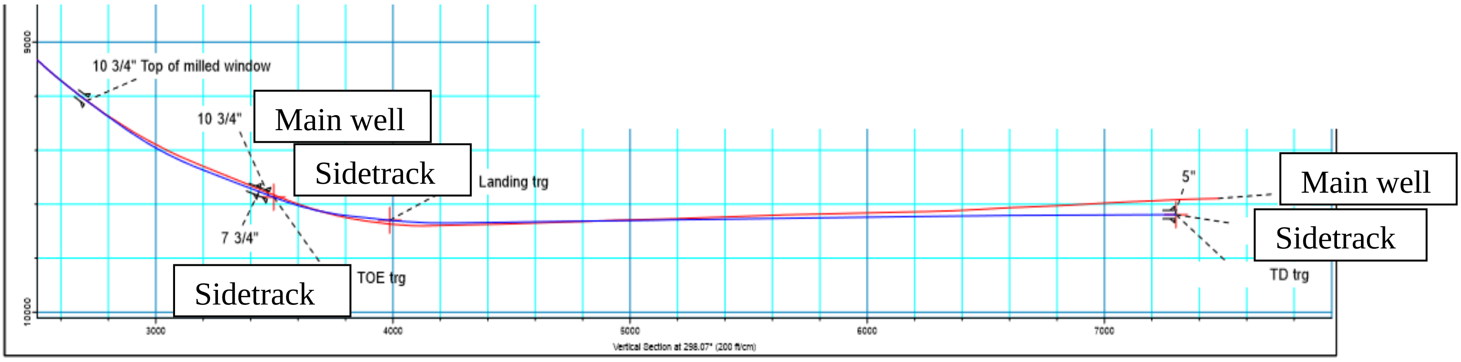


Figure 4.13: The vertical section of the second sidetrack

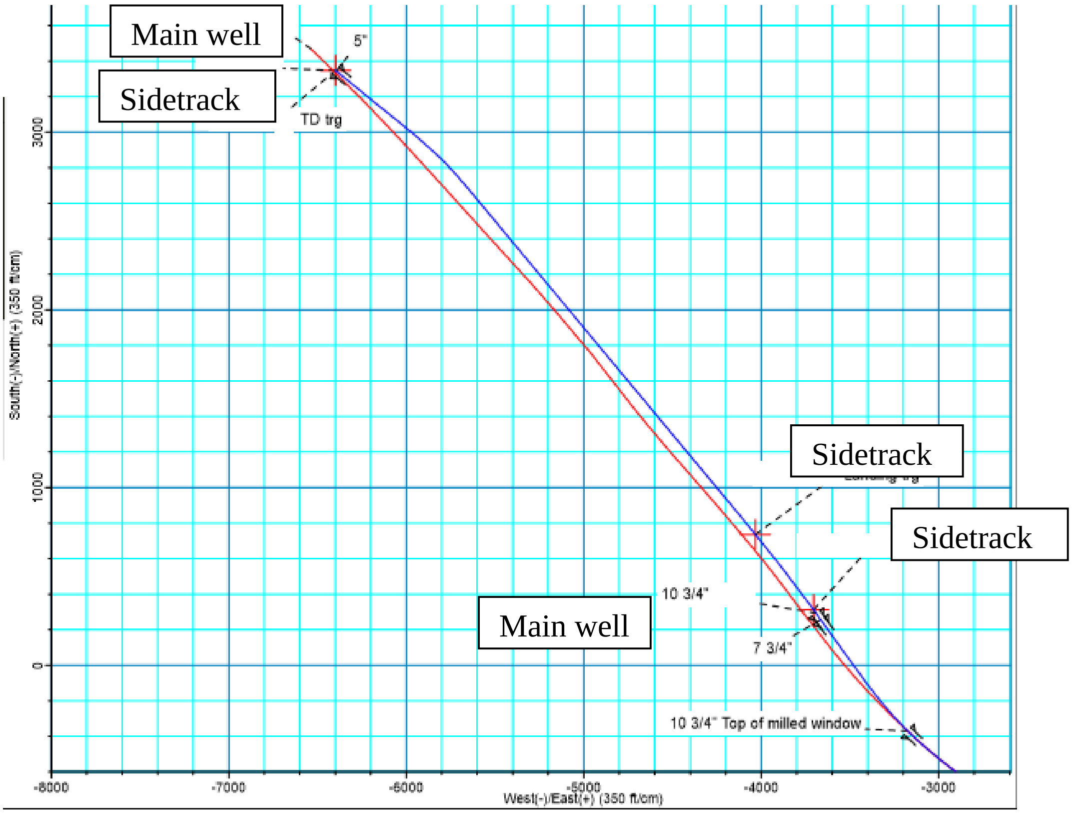


Figure 4.14: The orientation of the sidetrack path in a bird- eye perspective

Operational sequence

There was minimal information about the survey instruments in the operational sequence of this sidetrack. The limited data stated was related to comments on results of the quality test, which was passed by both of the survey instruments.

Survey calculations

The survey measurements in table 4.11 are taken for the 9,5`` well section of the second sidetrack. Same coordinate system and reference level is chosen for the IGRF calculator and model editions are the same as for the first sidetrack.

Model/method	**Declination**	**Magnetic dip**	**Field strength**	**Well section**	**Model validity**
BBGM15	-0,11 °	70,23 °	50 052 nT	9,5``	2015- 2016
Magnetic MWD+ IIFR	-0,256 °	70,277 °	50 121,7 nT	9,5``	___
IGRF-12	-0,058 °	70,23 °	50 065 nT	9,5``	2015-2020

Table 4.11: Survey calculations of the second sidetrack.

The numbers derived from the different geomagnetic tools highlights the accuracies and inaccuracies of the different approaches, especially in the declination and field strength of the geomagnetic field(table 4.11). Again, enhanced precision is obtained when all magnetic elements are taken into consideration. The IIFR method incorporates all magnetic sources to give refined estimations of the magnetic field at the drilling site. This in turn leads to optimized wellbore positioning and increased reputation of the IIFR tool in the market. Table 4.11 also displays the disadvantage of the global geomagnetic field models. These models are only configured to consider the $B_{geomagnetic\ field}$ parameter, while the remaining parameters are excluded from the estimation process. This leads to large-scale errors and inaccuracies, which are depicted by table 4.11.

Just as in the survey measurements for the first sidetrack, both global geomagnetic field model fails to meet the desired industrial accuracies in declination and field strength. These limitations makes the global geomagnetic field models less appropriate for well positioning applications. On the other hand, the IIFR technique manages to meet the industrial targets. Which in turn reaffirms its use in the industry as a tool for well placement and positioning.

Chapter five: Conclusion and future recommendation

5.1 Conclusion

In this master project, the capabilities and features of the IIFR technique to monitor and correct the geomagnetic field at the drilling site were assessed. The competency and efficiency of this industrial tool to optimize well positioning, and function as a catalyst to generate continuous flows of good decisions during directional drilling operations were evaluated. Alongside with this, the potential of the IIFR method to accentuate and complement the limitations of the MWD magnetometers were studied. Finally, an investigation of the potential limitations of this method were also included in this work. The analytical process included presentations of case studies, comparisons with other geomagnetic and gyroscopic instruments, literature investigations, meetings with subject matter experts and presentation of analysis/experiments. Through extensive amounts of investigations and evaluations, a verdict on the capabilities and capacities of the IIFR method were delivered.

The IIFR technique is capable to address and complement the shortages of the MWD magnetometers- it gives the operator company the ability to use all the magnetic data available in conjunction with the sensor data to improve the wellbore positional accuracy and confidence. This method enhances the industrial-reputation and accuracy of the magnetic MWD survey instrument, which in turn improves the capacity of this survey tool. Conclusions and observations from the case study, displays the industry`s high expectations and confidence in the IIFR method. The survey accuracies delivered by the IIFR method is on pair with the precision obtained by using the gyroscopic instruments. In the field case study, the magnetic MWD survey tools accompanied with the IIFR were the prioritized survey instrument over the gyroscopic tools, even while drilling important well sections. The IIFR technique satisfies industrial needs and requirements for accuracy, which in turn optimizes the well positioning operations. The competitive abilities of the magnetic MWD survey tool is boosted by the IIFR method as well, which enhances the desirability of this magnetic survey tool. Alongside with this, the IIFR method is also a sound tool for quality control of the survey measurements.

Fluctuations in the geomagnetic field are monitored and corrected by the IIFR method in real- time. The instant data delivery of the orientation and direction of the wellbore trajectory to the operative company, improves the quality of critical steering and navigation decisions. The delivery of real- time data makes the IIFR method a tool for improved decision- making. The estimations of the geomagnetic field at the drilling site provided by the IIFR method, incorporates contributions from all magnetic elements to provide accurate predictions of the geomagnetic field. This in turn enhances the error reduction potential of the IIFR technique. Global geomagnetic models provide estimations of the geomagnetic field at the drilling site by only taking into account the main field. Due to this fact, the estimations provided by these models contains large errors, which exceeds the industrial accuracy limits and targets. Due to this fact, utilization of global geomagnetic field models for survey applications contributes with increased errors in well positioning operations.

However, limitations and shortages were also recognized in the IIFR method during the investigations. The accuracy provided by the IIFR method is a function of the distance between the drilling site and the magnetic observatories. Analysis and experiments concluded that the improvement rates obtained from the IIFR technique decreased as the distance to the local magnetic observatory increased. This method is also prone to errors during the implementation process. These inaccuracies are related to the algorithm used for computing the contributions from the external disturbances, and corrections implemented for anomaly fields. There are also limited assumptions related to the size or physical properties of the magnetized crustal formations. Beside from that, assumptions of this method also contributes to limit the total area, from which information can be extracted and processed.

There are also some concerns related to the use of this survey tool. The use of global geomagnetic field for estimating the core field should be limited, or replaced by improved editions of free- to- use model, like the IGRF. Finally, the errors associated with this method should be examined further in extreme high latitude areas, during periods of abnormal external disturbances. There are also some concerns associated with the calculations of this method.

To summarize, the IIFR technique is an industrial acknowledged tool for improved well positioning and decision- making in directional drilling operations. The advantages and benefits are many, which enhances the viability of the magnetic MWD survey instrument. However, the technique is associated with some concerns and limitations. Allocation of resources is a must for implementation of measures to compensate or eliminate the identified shortages.

5.2 Suggestions for future analysis and research

The influence of drilling mud, by its components and external factors on the geomagnetic field have been studied in a number of analysis and experiments conducted by several intellectuals. However, these studies have been performed in static environments [1, 2]. Where the drilling fluid system have been stirred a number of times in order to ensure that the mud components are evenly distributed, after that the effect of various factors have been studied and analysed. Usually, survey measurements are taken at predetermined survey points or stations, under a static condition with no drillpipe rotation and circulation. However, drilling in difficult and challenging downhole environments, can enforce the survey team to take magnetometer measurements in a dynamic environment. Beside from that, the author of this thesis have pointed out that a considerable amount of time can be spared and drilling efficiency can be enhanced, if robust magnetometers are developed that maintains sufficient measurement quality during drilling and circulation. Different types of models are available to predict the influence of drilling fluid on the magnetometers in dynamic conditions. However, there is a scope for improvement in these models. Therefore, it is important to further investigate the influence of drilling fluid and its components on the geomagnetic field in a dynamic environment.

This study is recommended for future analysis and investigations in order to accurately map the effect of drilling fluid on the geomagnetic field in a dynamic environment, which in turn can enhance the understanding of the magnetic fields in dynamic conditions, well positioning and navigation phase and finally prove the capabilities of the magnetometers under challenging environments. Beside from that, the magnitude of electrical currents and influence of the electromagnetic induction process is unrevealed in static conditions. Due to this fact, a better understanding of these two factors will be achieved by conducting the recommended studies. This in turn will provide the petroleum industry with a holistic view of magnetism and its effect in a drilling environment.

5.2.1 Experimental setup and necessary equipment

The suggested study should be approached with a practical mind-set. In other words, carried out with the help of experiments. A possible layout of the laboratory setting is presented in figure 5.1; this illustration also includes various equipment and tools required to accomplish the various aims and objectives of this study.

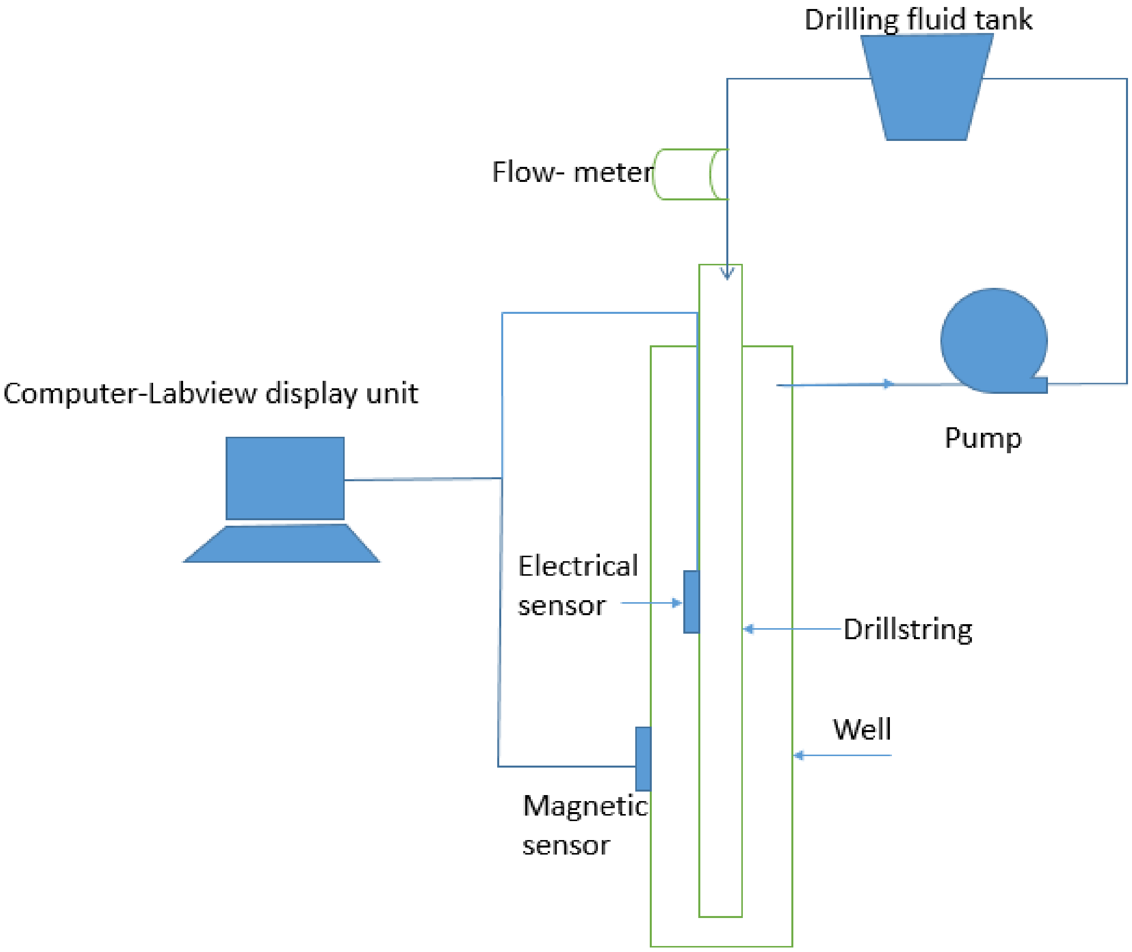


Figure 5.1: Experimental setup

A list of every individual equipment, alongside with an explanation of its purpose is presented below:

1. Flow- meter. This component is required to measure the flow velocity of the circulating fluid through the different components. By doing so, the dynamic environment can be varied, through different flow velocities and flow regimes.
2. The drilling fluid tank. The drilling fluid will be stored in this item. Fresh stirred mud will be stored here and circulated around in the environment. Finally, the drilling fluid will return to this point.
3. Pressure pump. This is one of the most crucial elements of this study. The whole dynamic environment will be provided by this component, with the help of pressure. However, it is important to select a pump with sufficient power that is capable to provide different flow velocities and flow regimes. The effect provided by the pump should be able to overwhelm the frictional losses.
4. Electrical sensors. This technological device is needed to measure the magnitude of the electromagnetic induction process and electrical currents presence in the system.
5. The magnetic sensors will be utilized to measure the magnetic fields created in the system, which in turn will reveal the level of distortion caused to the magnetometers.
6. A displaying unit is implemented in order to translate the recorded information by the sensors into a readable and assessable format.
7. A metallic rod will represent the drillstring. There are two main purposes behind the usage of this tool: First, this component is used to depict a drilling environment, Secondly, this conductive object will function as a propagation element for the induction process. An insulation object would not have allowed electrons to pass freely through the system, and thereby hindered the electromagnetic induction process and electrical currents.
8. The last element in the system is the well, which will be represented by a plastic tube. A tube is required to contain the flowing fluid.

5.2.2 Objectives

The goals and aims of this scientific research could be comprised of the following:

- Map the magnitude of the magnetic distortions caused to the magnetometers, by the drilling fluid in a dynamic environment.
- Assess and investigate the scope and size of the electromagnetic induction process and presence of electrical currents, in a drilling environment.
- Perform a literature study on magnetic fields in fluids, colloidal chemistry and the occurrence of electric fields in a drilling environment.
- To build appropriate experimental setup with proper magnetic isolation for research on magnetic fields and electrical currents.
- Investigate the colloidal relationship among and between particles with differing magnetic susceptibility, and their influence on the geomagnetic field.

- Compare oil based mud against water based mud. Prepare one simple mud of each type, which is suitable for drilling. After that, the base fluid should be stirred with one component at a time. Circulation and measurements should be completed for each component, to investigate the effect of each mud component. Finally, the whole mud system alongside with its elements should be circulated through the whole setup. By doing so, it will be easier to identify the main component that have the biggest influence on the geomagnetic field.
- Assess the effect of different flow regimes on the geomagnetic field.
- Study the relationship between different magnetic components, and their behaviour when exposed to an external magnetic field.
- Assess the propagation properties of oil based mud and water based mud for electrical currents and magnetic fields.
- Point out the effect and interaction of swarf and casing wear on the magnetic properties of muds, and its effect on the colloidal "harmony" existing within the mud system.
- Asses the performance of magnetic and electrical sensors. In other words, verify their capabilities and reliability for measurement of electric currents and magnetic fields.
- Assess and evaluate the performance/reliability of an industrial proven sensor with an external sensor: Compare these two sensors in terms of measurement and uncertainty.

5.2.3 Important factors

In order to enhance the credibility of the research, it is important to have some factors in mind, especially during the planning and execution phase of this study. First, this study is very prone to environmental noise. Magnetic sensors are known for their sensitivity, even magnetic interference in the size of nTs will be perceived by the sensors. Therefore, it is very important to ensure proper magnetic isolation of the surrounding environment. The lab-facility should be located at a remote area, without any nearby roads or parking slots. Any metallic object with magnetic properties should be removed from the laboratory, and the use of any metallic equipment in the laboratory setting should be limited or forbidden. If metallic elements have to be incorporated, for instance the steel rod, try to select a rod that is a non-permanent magnet or with non- magnetic characteristics. Another precaution that can be taken in order to limit environmental bias, is to combine the isolation process with an external magnetic sensor to measure the environmental bias. The recorded magnetic field from the external sensors is then subtracted from the measurements recorded by the internal sensors.

Secondly, the electrical sensors are going to be installed inside the plastic tube or the "well". By adopting this configurational setting, the wires will run from the metallic rod and out to the computer. Due to this, there is a risk of leakages to the laboratory environment. In order to limit the leakages, a bath tube should be placed under the "well". The bath will contain the mud spills and prevent it from being lost. Beside from that, any insulator material should not be in direct contact with the electrical sensors or any of its components. An insulator will hinder movement of free electrons and subdue the electromagnetic induction process. Due to this fact, avoid using rubber-sealing elements around the wires belonging to the sensors. The final factor to remember is to involve intellectuals with relevant expertise and experience from experimental studies.

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