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Writer: **Moses Olaijuwon Ajetunmobi**	Moses Ajetunmobi ………………………………………… (Writer's signature)

Faculty supervisor: Mesfin A. Belayneh, Institute of Petroleum Technology, University of Stavanger

External supervisor(s): Mike Herbert, Sr. Drilling Engineer, Integrated Operation Advisor, ConocoPhillips

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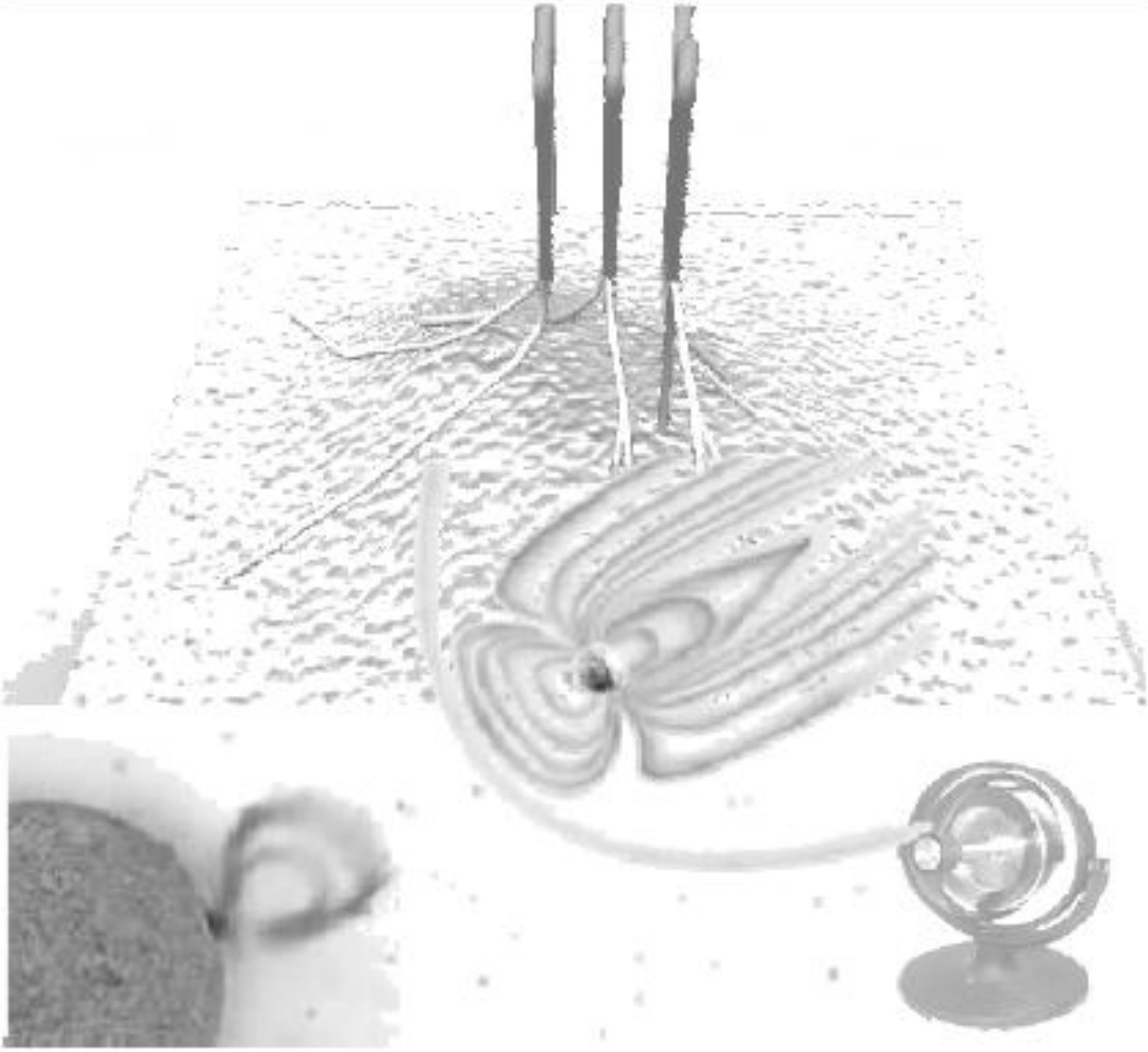
Stavanger, June 15, 2012

ConocoPhillips



Preface

This thesis is written and submitted by the author in partial fulfillment of the requirements for a Master Degree in Petroleum Engineering at the University of Stavanger (UiS), Stavanger, Norway. The thesis consists of cumulative work done from January 2012 to June 2012. The Master thesis has been supervised by Mike Herbert, ConocoPhillips Norway, Senior Drilling Engineer, Integrated Operation Advisor and Associate Professor Mesfin Belayneh, University of Stavanger (UiS). The thesis has been solely written by the author. However the content has been shaped by SPE papers and the references that is provided and inputs from my supervisors.

In summer of 2011, as I was finishing my summer internship with ConocoPhillips Norway, I contacted Mr. Herbert for possible master thesis. He didn't hesitate and he introduced me to Bernie MacDonald and Even Tveit, ADT Engineers Halliburton, before I know it, I got my hands and head full of different topics to work on after the brainstorming meeting. But particularly wellbore position uncertainty (depth measurements uncertainty) was in focus.

The process of completing this Master Thesis had been a hard one, however I've learnt a lot. I've obtained and deepened my knowledge and understanding in wellbore surveying, directional survey tools and wellbore positioning uncertainty. My ability to work independently and my analytical skills have been strengthened.

Acknowledgments

I would like thank Bernie MacDonald and Even Tveit for their contribution in the initial stage of my master thesis. I would also like to thank Leda Bott, Sr. Well Planner, Halliburton and Gail L. Thompson, Well Planner, Halliburton for showing me how to use COMPASS (well planning software) and for providing and explaining the resurvey data used in the position uncertainty analysis part of my master thesis.

I would like to extend my special gratitude to Professor Mesfin A. Belayneh and Mr. Mike Herbert for their great inspirations, ideas, comments, advices, articles and data for analysis. I'm very thankful for their willingness to share their experiences, knowledge and valuable time with me to make this thesis a success. Thank You All!

Moses Olaijuwon Ajetunmobi

Stavanger, June 2012

Abstract

The understanding of the subsurface geometrical position of the wellbore is crucial. The wellbore positioning data is relied upon by different disciplines or functional groups throughout the life of any given field. For example the geological and reservoir models rely heavily on subsurface geometrical position data. The drilling discipline depends on this data for planning of future injector or producing wells where the main objectives are to navigate through existing wells thus avoiding collision and hitting the target. Therefore the choice of survey tools and the work practices employed in gathering this data are essential.

This thesis provides a general overview of directional drilling & applications, survey calculations methods, survey tools and survey errors. The results of position uncertainty analysis performed on two resurveyed wells from the Ekofisk field on the Norwegian Continental Shelf are presented in this thesis. The analysis shows that the use of gyroscopic tools has a lower error rate compared to magnetic tools. Potential improvements in terms of technologies and work practices for planning and drilling of future wells have been suggested.

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List of Abbreviation

ROP = Rate of Penetration

NPT = Non-Productive Time

MWD = Measurement While Drilling

LWD = Logging While Drilling

ISCWSA= Industry Steering Committee on Wellbore Surveying Accuracy

MAP = “Most Accurate Position”

EOU = Ellipse of Uncertainty

WDP = Wired Drill Pipe

BHL = Bottomhole Location

PUA = Position Uncertainty Analysis

BHA = Bottomhole Assembly

RSS = Rotary Steerable System

1 Introduction

1.1 Background for the thesis

Due to the worldwide increase in drilling activities, the Oil companies or the operators are now facing increasing complex and crowded drilling operations especially in developed fields where there is high density of drilled wells. It is now a common practice for major operators to reenter and sidetrack from existing wellbore, thus navigating safely in the subsurface among the existing wells becomes a difficult challenge.

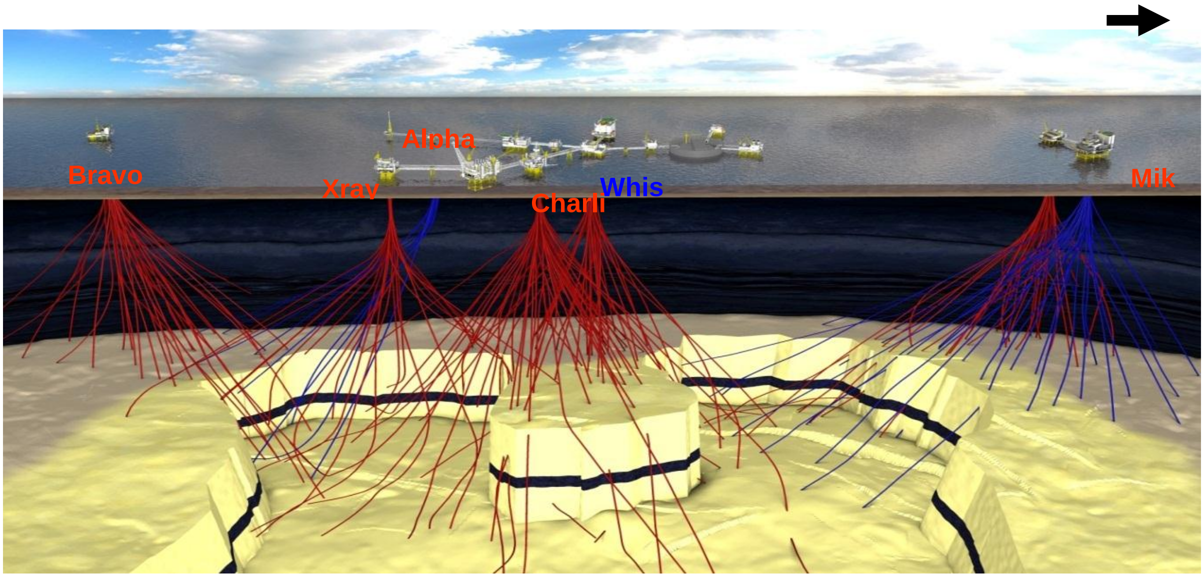


Figure 1.1: Ekofisk field Plattforms and wells .[7]

The Ekofisk field is one of the world's largest offshore fields and is over forty years old, with another forty years of expected continued production. As the reservoir is being depleted some of the old wells become uneconomical to remain in production, as such they are plugged and abandoned.

For the next forty years, ConocoPhillips the operator of the Ekofisk field has planned to drill more wells in order to effectively exploit the remaining reserves in the field. The major challenges for ConocoPhillips are hitting the target and navigating amongst existing wells. The first challenge can be solved by the help of a good reservoir simulation where the new distribution of hydrocarbon in place is shown. The latter needs good navigating technology in order to avoid interference or collision with adjacent wells.

The consequences of poor wellbore position (depth control) can be large. The effect on the Ellipse of Uncertainty can be significant which increases the possibility of collisions with nearby wells resulting in a potentially catastrophic well control issue. Poor depth control influences the accurate planning of injection and production wells. For example casing setting depth would be less accurate which can create hole instability or pressure issues resulting from poor shoe location. Modeling packages are also affected. The uncertainty associate with the obtained directional survey influences the geological and reservoir models employed in well positioning.

1.2 Scope and Objective of the thesis

Like many other oil companies, ConocoPhillips Norway is also faced with the "dual challenges of small geological targets and severe well congestion" which has led to increased importance of quantifying wellbore positional errors. For the last forty years in the Ekofisk field, over 700 well tracks have been drilled using different technologies and measurements to determine wellbore geometric position. There are uncertainty connected with these measurements resulting in not reaching or missing the desired targets.

Particular the resultant depth measurement uncertainty has had large consequences in not only during drilling and logging of these wells, but in the development of the field. Over the year the industry has been tolerant of poor quality control of this key data. The aim of this thesis is to:

- Review Directional drilling, applications, survey calculations, survey tools and survey errors.
- Examine the consequences of poor depth measurement uncertainty on the Ekofisk field through analysis and visualization.
- Suggest potential improvement in terms of technologies and work processes for the future wells.

2 Literature Review on Wellbore Position Uncertainties

For the last four decades or so, the analysis of wellbore position accuracies has been developed in order to ensure safe and economical drilling operations. The major developments in this field are given below:

- In 1971 the pioneering work of Harvey et al. [25] on analysis of directional-survey calculations was summed up. The pioneering work concluded that wellbore position uncertainties were dominated by random errors and effects.

- In 1981 Wolff and de Wardt [12] showed that the most significant contributors to wellbore position uncertainty are systematic errors. This model was thus recognized as the directional surveying standard for the industry at that time.

- In 1990 Thorogood [21] emphasized on the applications of error models. The importance of ensuring that the actual survey quality is validated in accordance with the applied error model was also addressed.

- In 1996 and 1997 significant contributions have been made to the development of new methods and applications by many companies and persons. The the necessity of describing the wellbore position accuracies and statistical characteristics in a proper way was also elevated. (Brooks and Wilson[22] 1996; Ekseth et al. 1997 [23]; Torkildsen et al. 1997)

- In 1998, Ekseth's PhD thesis [4] became the basis for subsequent developments of error models and estimation techniques.

- In 2000 a group of industry experts whom are members of the SPE Wellbore Positioning Technical Section (SPE WPTS) formerly known as the Industry Steering Committee on Wellbore Surveying Accuracy (ISCWSA) contributed in the publication of an error model for magnetic measurement while drilling (MWD) survey tools. This has now become the oil industry standard for magnetic survey tools error model. (Williamson 2000[13]).

- In 2004 Torkildsen et al. [24] presented a new method for wellbore position uncertainties estimation for gyroscopic survey tools.

- In 2008, Torkildsen et al. [14]presented a revised version of Torkildsen et al. 2004 with some identified limitations of the standardized magnetic MWD error model by Williamson (2000).

3 Directional Drilling and Survey Calculation

In this Chapter background of Directional Drilling Survey Calculations will be discussed. Directional Drilling applications and Well Planning will be reviewed.

3.1 Directional Drilling

Initially all oil wells were assumed to be vertical or that the bottom of the borehole was directly under the drilling rig. Today we know that it's not true. Directional Drilling in the oil industry dates back to the late nineteenth century when Rotary drilling techniques where being introduced. There was little or no attention paid to stabilizing of the drill string in order to control the well path at that time. Surveys taken at some later time showed that the assumed ''vertical wells'' where far from being vertical. The perception at the time before directional drilling was that a non-vertical well is a disadvantage. [1,2]

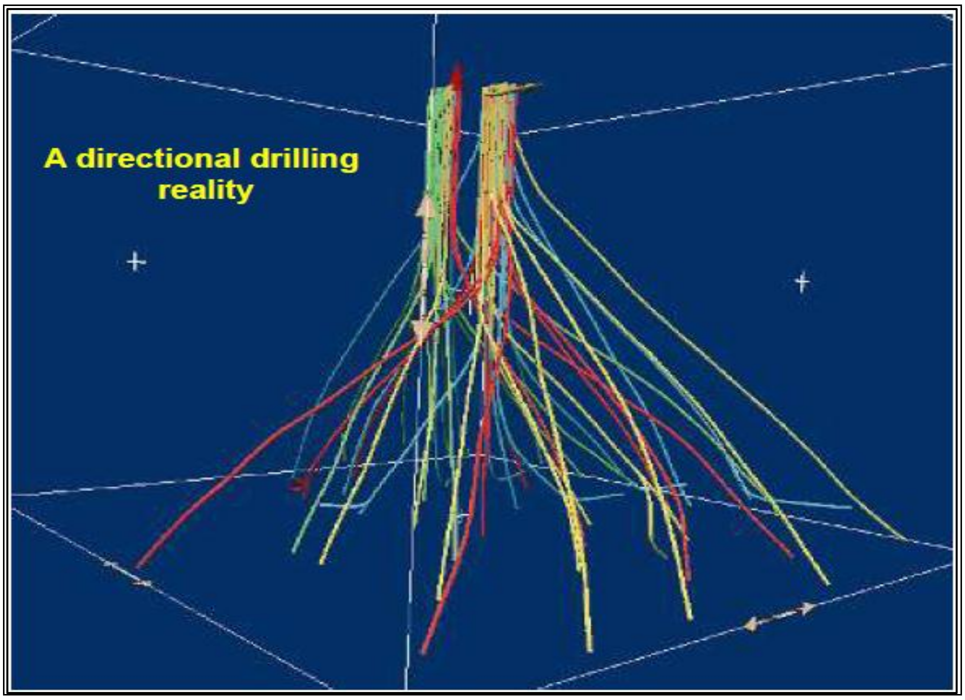


Figure 3.1: Directional Drilling. [7]

Survey instruments were developed in the late 1920's in order to measure inclination and azimuth of deviated wells. Deviation as high as 46°were measured at the time and an average deviation from the vertical was 13° [2]. In 1930 the first controlled directional well was drilled in California to reach the oil reserves offshore. The employment of directional drilling makes inaccessible oil reserves accessible [1]. According to T.A Inglis, Directional Drilling can be defined as ʺ the art and science involved in the deflection of a wellbore in specific direction in order to reach a pre-determined objective below the surface of the Earth.ʺ

3.2 Directional Drilling Applications

Generally, the applications of Directional Drilling can be grouped in thefollowing categories below [1,2,3]:

- Sidetracking;
- Multiple wells from offshore structures;
- Fault Drilling;
- Salt Dome Drilling;
- Controlling vertical holes;
- Drilling beneath inaccessible locations;
- Drilling Relief Wells;
- Shoreline Drilling
- Horizontal Drilling
- Drilling of Multilateral wells

3.2.1 Sidetracking

One of the primary applications of directional drilling is sidetracking from an existing wellbore. This operation is performed by simply deflecting the borehole by starting a new hole at any point above the bottom of the existing hole. Sidetracking is an operation that includes bypassing an obstruction or a fish which has been lost in the borehole, intersecting a producing formation at a favorable position, sidetracking away from a depleted part of the reservoir to a productive part, sidetracking an exploration well for better geological understanding and drilling a horizontal section from existing well bore. [1,2,3]

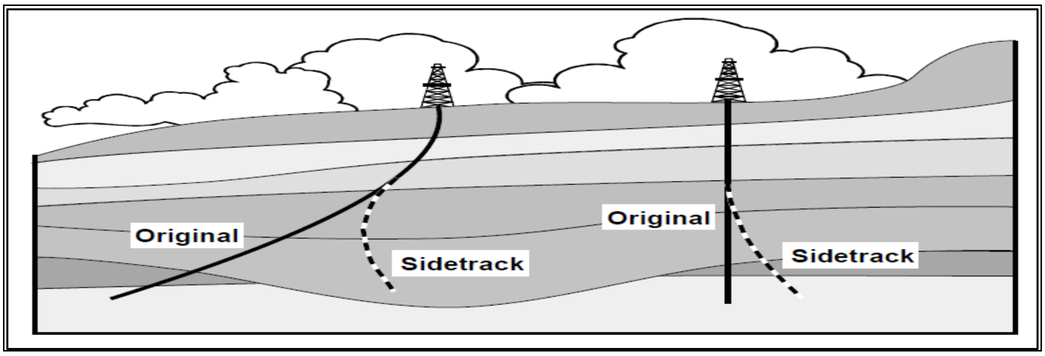


Figure 3.2: Sidetracking [3]

3.2.2 Multiple wells from offshore structures

Offshore Drilling is one of the most common applications of controlled directional drilling. From an installed fixed platform, multiple directional wells can be drilled. From a single directional well several inclined reservoirs can be intersected, targets may be entered at specific angles to ensure maximum penetration of the reservoir. [1,2,3]

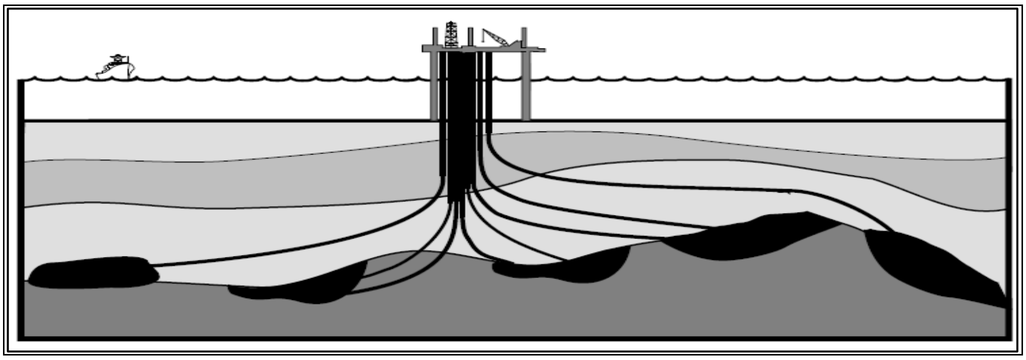


Figure 3.3: Multiple wells from offshore structures. [3]

3.2.3 Fault Drilling

Directional drilling is employed when the intension is to avoid drilling a vertical well through a steeply inclined fault plane. If vertical wells are drilled through the fault casing shearing problem may be encountered. [1,2,3]

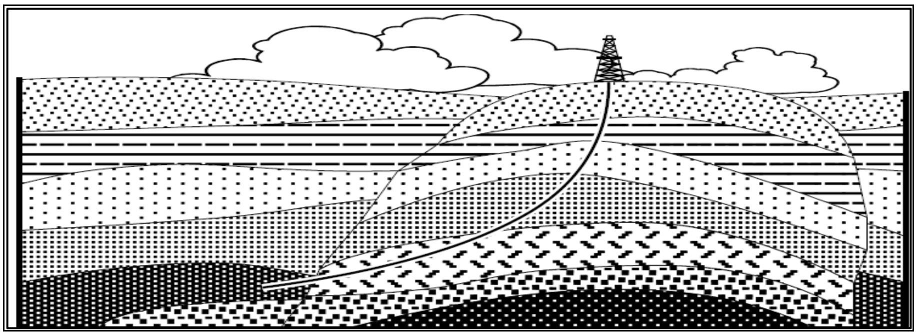


Figure 3.4: Fault Drilling. [3]

3.2.4 Salt Dome Drilling

Sometimes directional drilling programs are used to resolve the problems of drilling nearby subsurface geological obstruction such as salt dome. In this case, the well is drilled at one side of the salt dome and then deviated around and underneath the hanging cap thus avoiding drilling through the salt. The advantages of this are that one avoids the issue of stuck pipe, well collapse, fluid loss to the formation, etc. The Non Productive Time (NPT) is reduced dramatically. Figure 3.5 below illustrates the application of directional drilling in salt dome drilling. [1,2,3]

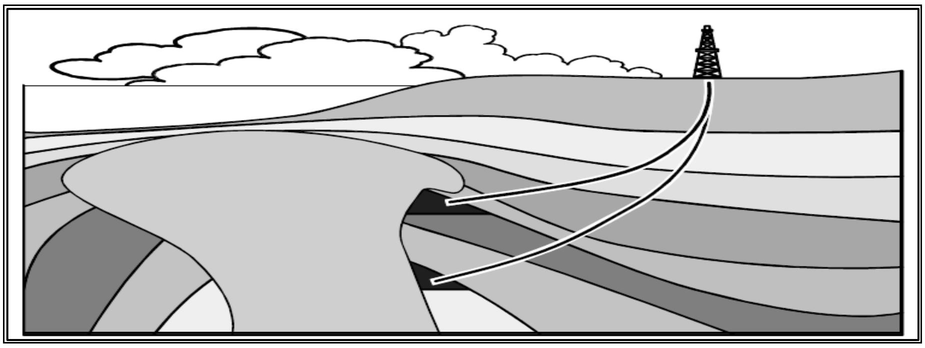


Figure 3.5: Salt Dome Drilling. [3,]

3.2.5 Controlling Vertical Wells

Directional techniques are used when the intension is to keep vertical wells on target i.e. to "straighten crooked holes" in order to avoid straying across lease boundaries. To achieve this, the deviation from the planned trajectory can be corrected for by changing the bottom hole assembly (BHA) or alter some certain drilling parameters. For serious deviations downhole motor or bent sub are used for the correction. [1,2,3]

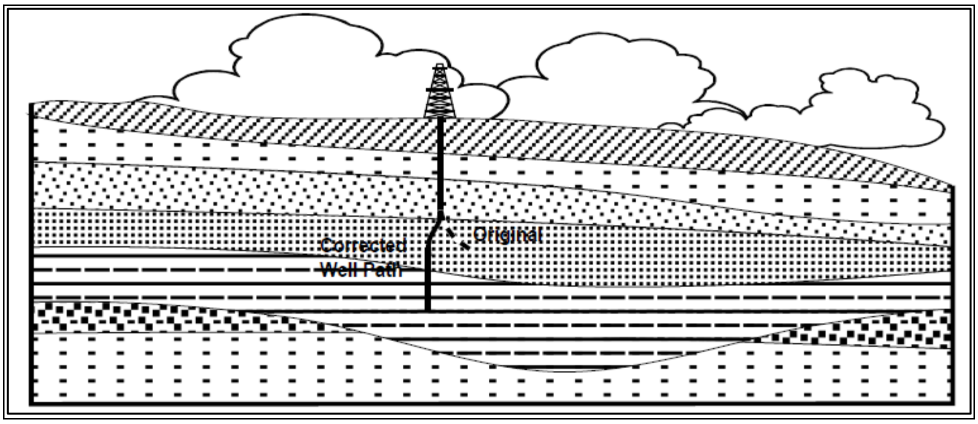


Figure 3.6: Controlling Vertical Wells. [3]

3.2.6 Drilling Beneath Inaccessible Locations

Directional drilling technique is employ to drill and exploit reservoirs where the surface location directly above the reservoir is inaccessible due to man-made obstructions or natural obstacles. [1,2,3]

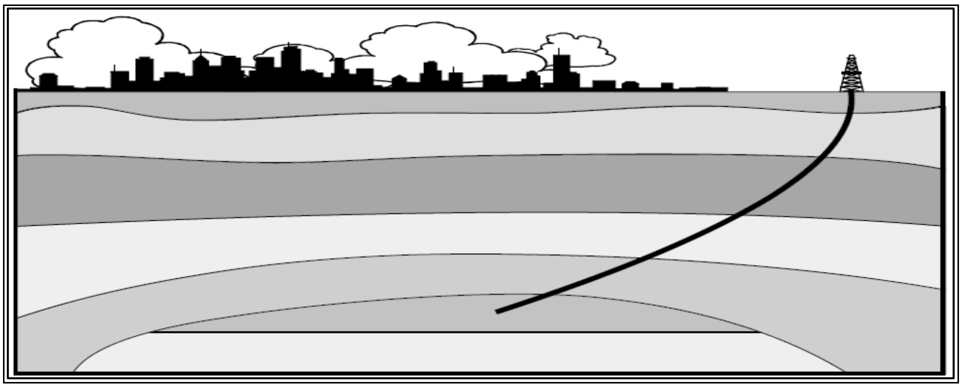


Figure 3.7: Drilling Beneath Inaccessible Locations. [3]

3.2.7 Drilling Relief Wells

In order to kill blowouts, directional techniques are used. One deviate relief wells to pass as close as possible to the uncontrolled well. To overcome the pressure and bring the blowout under control, heavy mud is pumped into the reservoir. [1,2,3]

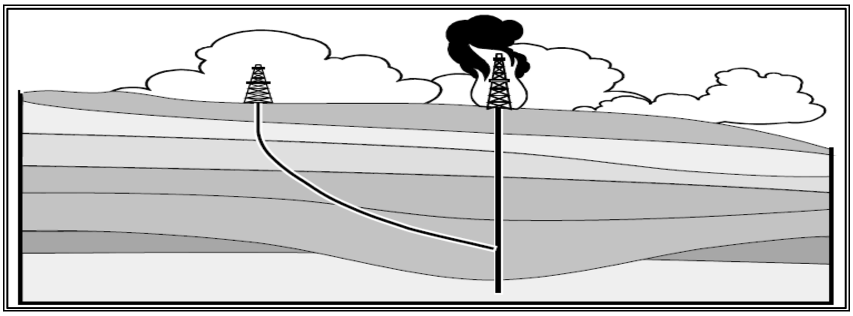


Figure 3.8: Drilling Relief Wells. [3]

3.2.8 Shoreline Drilling

This is a directional drilling application where the reservoir lying offshore but close to land is exploits by drilling a directional well from a land rig. This proves to be the most economically way of exploiting the producing formation. [1,2,3]

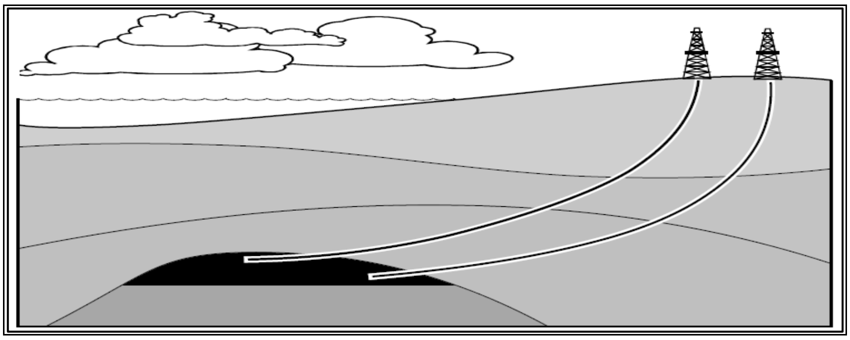


Figure 3.9: Shoreline Drilling. [3]

3.2.9 Horizontal Drilling

Another special application of directional drilling is horizontal drilling where the objective is to increase the productivity of different formations. This is a common practice in fracture reservoirs and thin layered formations. A horizontal drilling technique has the following advantages: fractured reservoirs productivity improvement, increasing drainage area, increased penetration of producing formation, increasing the efficiency of enhanced oil recovery (EOR) and gas or water coning problems prevention. [1,2,3]

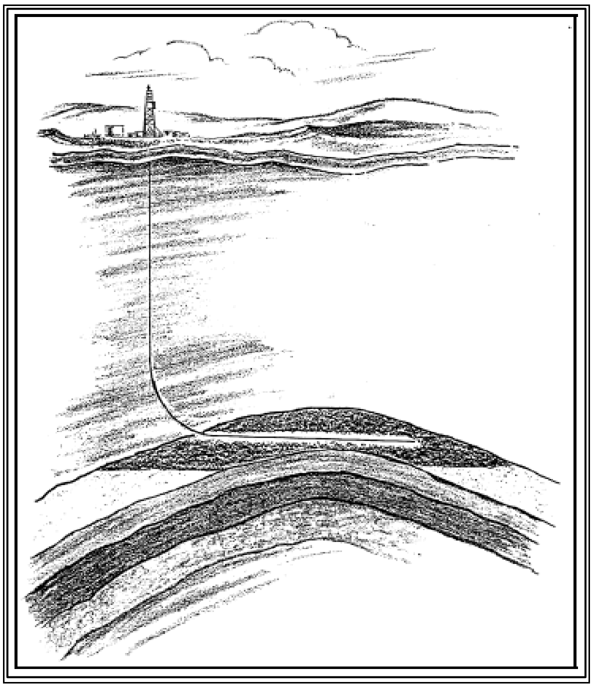


Figure 3.10: Horizontal Drilling[2]

3.2.10 Drilling of Multilateral Wells

The first multilateral wells were drilled in 1953 in Russia. Directional drilling techniques are used in drilling of multilateral wells. A multilateral well is a well in which there is more than one horizontal or directional branch drill from a single main bore (or mother bore) and connected back to the same main bore.

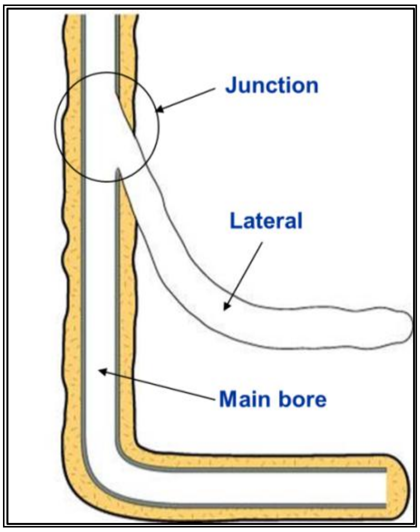


Figure 3.11: Multilateral Well [6]

3.3 Directional Well Planning

Well planning is an essential part of drilling directional wells. When done properly, it can reduce the overall cost of drilling directional wells. This vital process involves many individual from different companies and disciplines designing various programs for the well; mud program, casing program, drill string design, bit program, etc. In this section reference systems and coordinates will be discussed. [1,2,3]

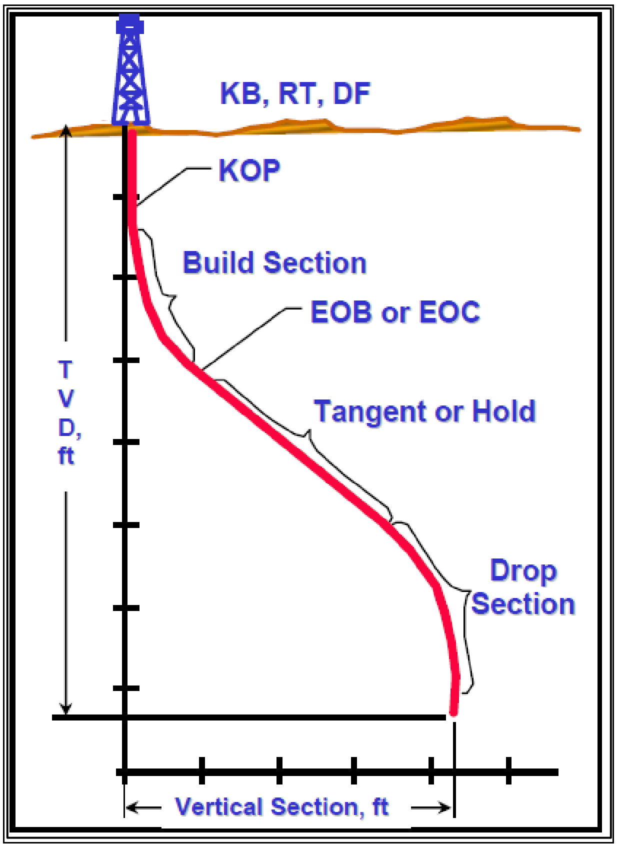


Figure 3.12: Important Parts of Directional Well. [2]

The Figure 3.12 above shows the important part of a directional well. Drilling depth measurement starts from KB (Kelly Bushing), RT (Rotary Table), DF (Drilling Floor). KOP (Kick Off Point) indicate where the directional well begins if the well is drilled vertical. The Build Section is the part of the wellbore where the inclination is increased. EOB or EOC (End of Build/Curve) indicates end of the build section. The Tangent or Hold Section is where the inclination is held constant. Not all directional wells has a Drop Section, this is where the inclination is reduced.

3.3.1 Reference Systems and Coordinates

All survey systems measure inclination and azimuth at a particular measured depth (MD) except for the Inertial Navigation Systems. For the course of the wellbore to be calculated, the measurements obtained are tied to fixed reference systems: depth references; inclination references; azimuth references. [1,2,3]

Depth References

There are two kinds of depths to be considered during the course of a directional well. These are Measured Depth (MD) and True Vertical Depth (TVD).

Measured Depth (MD): measured distance along the actual path of the borehole from the surface reference point to the survey point. MD is measured for example using pipe tally, wireline depth counter or mud loggers' depth counter.

True Vertical Depth (TVD): This is the vertical distance from the depth reference level to a point on the borehole course and can be calculated from the deviation survey data.

The rotary table elevation is used as the working depth reference in most drilling operations. Below Rotary Table (BRT) and Rotary Kelly Bushing (RKB) are used to indicate depths measured from the rotary table. A mean rotary table elevation is used in floating rigs since the rotary table elevation is not fixed. It is important to have a common depth reference in order to compare wells within the same field. In offshore drilling, Mean Sea Level (MSL) is sometimes used. [1,2,3]

Inclination References

The angle between the vertical and the wellbore axis at a particular point is the inclination of the wellbore. The direction of the local gravity vector gives the vertical reference which can be indicated by a plumb bob.

Azimuth Reference Systems

There are three azimuth reference systems for directional surveying: Magnetic North; True (Geographic) North; Grid North. [1,2,3]

Magnetic North: In all magnetic type surveying tools, the hole direction i.e. the azimuth referenced to Magnetic North. The final calculated coordinates are however referenced to True North or Grid North.

True (Geographic) North: is the direction of the geographic North Pole which lies on the Earth's axis of rotation. Meridians of longitude are used to show the direction on the maps.

Grid North: Though drilling operations occur in curved surface (Earth's surface), but a flat surface is assumed when calculating horizontal plane coordinates. Representing the surface of a sphere exactly on a flat well plan is not possible. Different projection systems are employed to apply necessary corrections to obtained measurements.

Example of Grid System: UTM System

The Universal Transverse Mercator (UTM) System is an example of a grid system. In UTM projection the chosen spheroid surface to represent the Earth is wrapped in a cylinder which touches the spheroid along a circle running around the Earth passing through both the North and South geographic poles. This circle is called the meridian. The relationship between True North and Grid North is shown by the convergence angle "a" in Figure 3.13 below. [3]

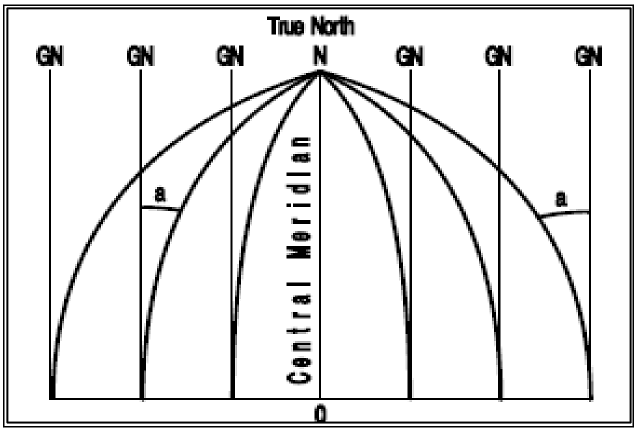


Figure 3.13: Relationship between True North and Grid North. [3]

Figure 3.14 below shows the UTM coordinates in Northings and Eastings. These are always positive numbers.

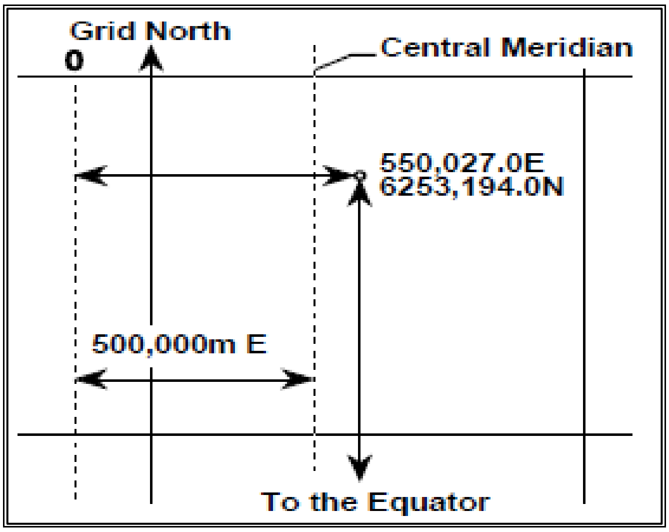


Figure 3.14: UTM in Northings and Eastings. [3]

Direction Measurements

The direction of the wellbore is measured on horizontal plane with respect to North reference (True or Grid North) using survey instruments. There are two systems: azimuth system and quadrant bearings system. [3]

Azimuth System: Directions are expressed as a clockwise angle from 0 ° to 359.99 ° , with North being 0 ° in azimuth system. Figure 3.15 below shows an azimuth system.

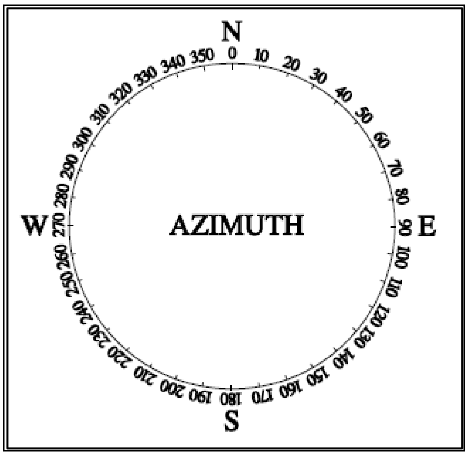


Figure 3.15: Azimuth System. [3]

Quadrant Bearing System: as illustrated in Figure 3.16 below, the directions are expressed as angles from 0°to 90°measured from North in the two Northern quadrants and from South in the two Southern quadrants.

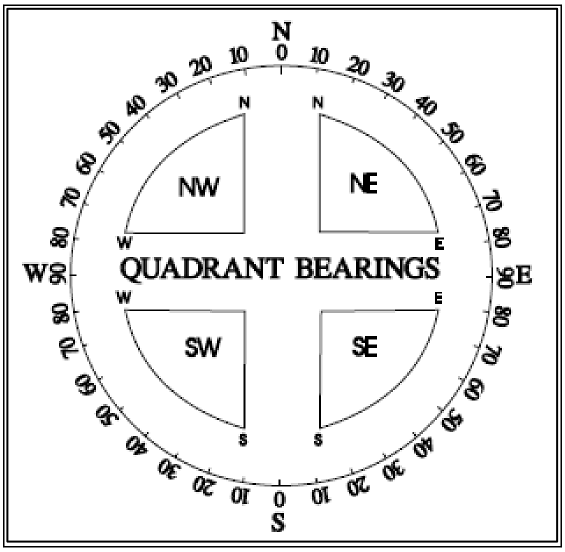


Figure 3.16: Quadrant System. [3]

How to convert from the quadrant system to azimuth and vice versa is illustrated in Figure 2.15 below. [3]

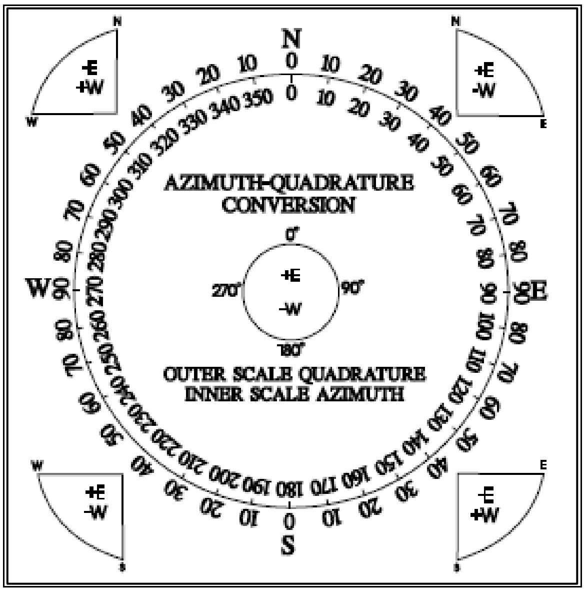


Figure 3.17: Converting from Quadrant to Azimuth Systems. [3]

3.4 Directional Survey Calculation Methods

In order to determine the bottomhole position relative to the surface location, directional surveys are taken at specified intervals. By using one of many survey calculation methods, the obtained surveys are converted to North-South (N-S), East-West (E-W) and True Vertical Depth (TVD). These are then plotted in both the horizontal and vertical planes. The plotted survey data aid in monitoring and adjustment to drilling operation.

Several methods can be used to calculate survey data, but in this chapter the following survey calculation methods that have been used in the Oil and Gas Industry shall be discussed: Tangential, Balanced Tangential, Average Angle, Radius of Curvature and Minimum Curvature method. [1,2,3]

Tangential Method (TM)

The Tangential survey calculation method was at one point in time the most widely used due to its easiness. Its equations are relatively simple which makes calculations easy to perform at the well site. However this is the least accurate method with its wellbore position errors greater than all the other survey calculation methods. Because of the severe nature of the large wellbore position error, this is not a recommended method to calculate directional surveys. [1,2,3]

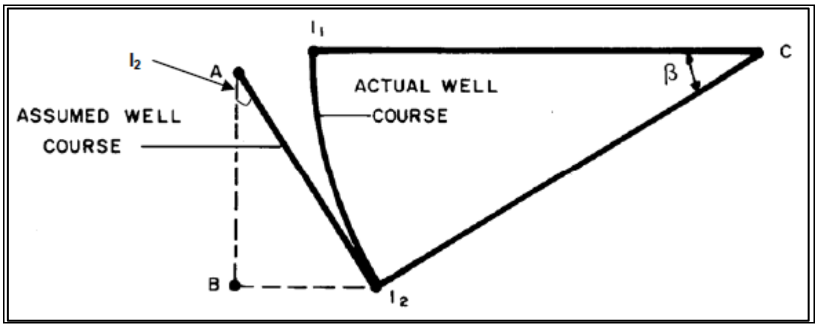


Figure 3.18: Tangential Calculation Method. [2]

Given two survey points, the tangential method assumes the course of the wellbore is a straight line and tangential to the lower survey station as illustrated in Figure 3.18 above.

Balanced Tangential Method (BTM)

The Balanced Tangential Method assumes that the actual wellpath can be determined by two straight line segments of the same length. This is a more accurate method than the Tangential Method as it considers both sets of survey data from the two assumed straight lines. The Balanced Tangential Method (BTM) can further be improved by applying a ratio (Minimum Curvature Method). Figure 3.19 below illustrates the principle behind the Balanced Tangential Method). [1,2,3]

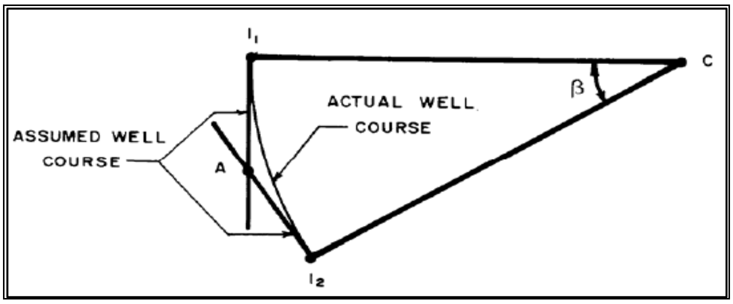


Figure 3.19: Balanced Tangential Method. [2]

Averaged Angle Method (AAM)

In the Averaged Angle Method, a straight line is assumed to intersect both the upper and lower survey stations. This straight line is defined by mathematically averaging the azimuth and inclination at both survey stations. This method is as accurate as the BTM (above), but its calculations are similar to that of Tangential Method. The Averaged Angle Method is a fairly accurate survey method that can be used in the field where a programmable calculator or computer is not available. Figure 3.20 below illustrates this method. [1,2,3]

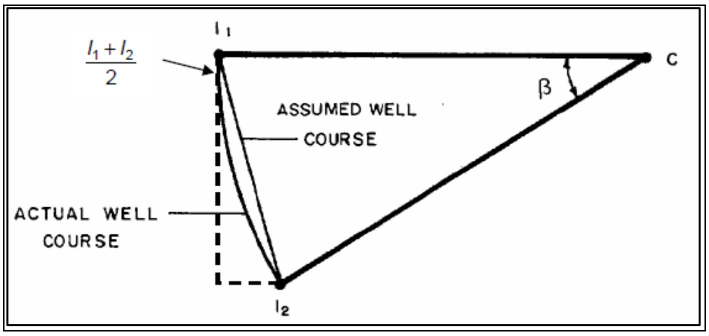


Figure 3.20: Averaged Tangential Method. [2]

Radius of Curvature Method (RCM)

This survey calculation method is considered to be one of the most accurate methods for calculating directional survey data. In Radius of Curvature Method (RCM), the wellpath is assumed to be a smooth curve between the upper and lower survey stations. The survey inclinations and azimuths at the upper and lower survey stations are used to determine the curvature of the arc.. Figure 3.21 below illustrates the Radius of Curvature Method.

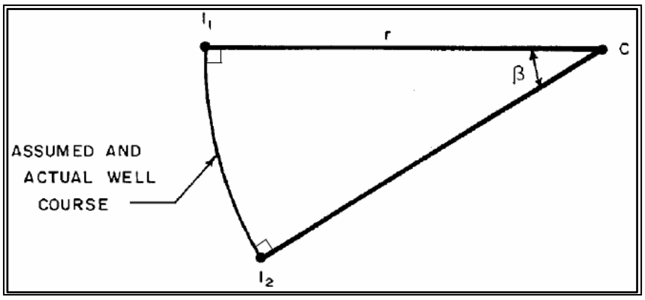


Figure 3.21: Radius of Curvature. [2]

Minimum Curvature Method (MCM)

Similar to the RCM, the Minimum Curvature Method (MCM) also assumes that the course of the wellbore is a curved path between the upper and lower survey stations. This method uses the same equations as the BTM multiplied by a ratio factor which is defined by the curvature of the wellbore. The result of this is a more accurate method of determining the wellbore position. The MCM is the one and most often adopted method for directional surveying calculations. The method is generally used in well planning today. Figure 3.22 illustrate the Minimum Curvature Method.

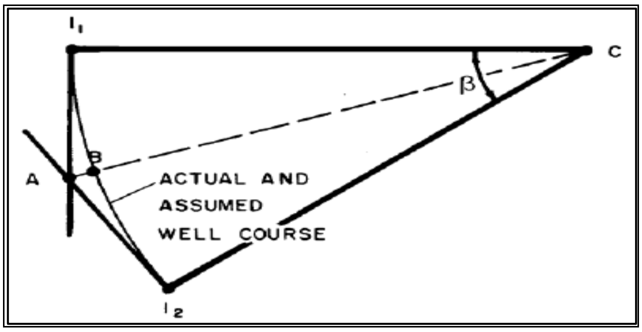
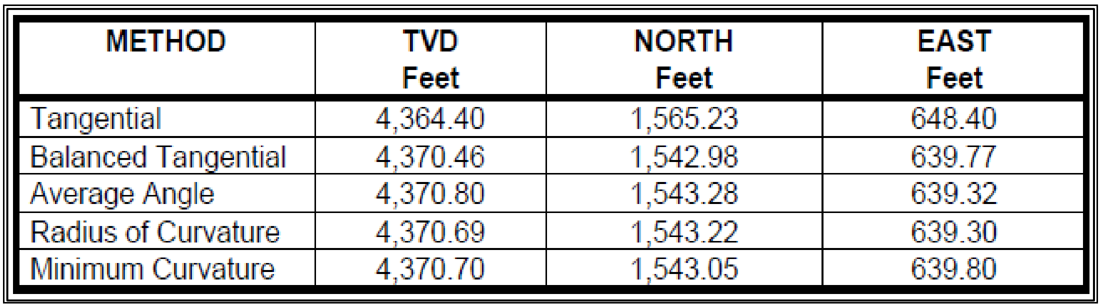


Figure 3.22: Minimum Curvature Method. [2]

Comparison of the Survey Calculation Methods

The Table 3.1 below is the results from an example where the following are calculated: TVD (ft.), North (ft.) and East (ft.) using each of the survey calculation methods discussed above.

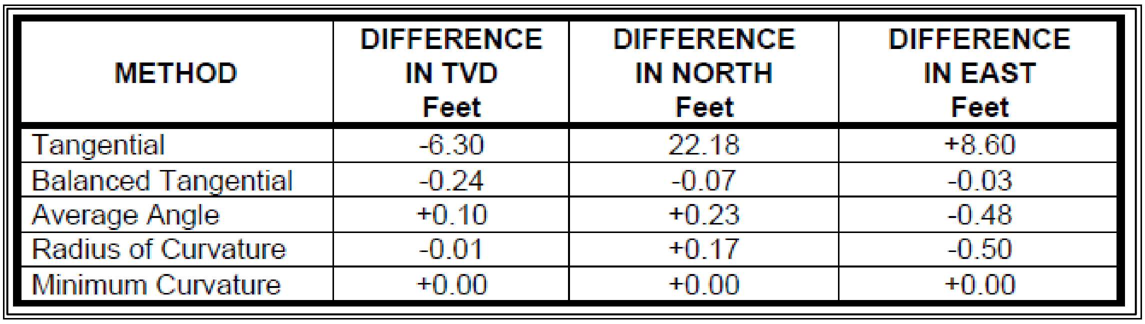
Table 3.1: Survey Calculation Methods Comparison. [2]



METHOD	TVD Feet	NORTH Feet	EAST Feet
Tangential	4,364.40	1,565.23	648.40
Balanced Tangential	4,370.46	1,542.98	639.77
Average Angle	4,370.80	1,543.28	639.32
Radius of Curvature	4,370.69	1,543.22	639.30
Minimum Curvature	4,370.70	1,543.05	639.80

Table 3.2 illustrates the relative difference between the Survey Calculation Methods from the example. As shown in the table below, the Tangential Method is the least accurate method as the TVD is under estimated and the horizontal coordinates i.e. North and East are over estimated. The Balanced tangential Method, however under estimated the TVD and the horizontal coordinates. Average Angle Method slightly over estimate the TVD where the North coordinate is over estimated and the East coordinate under estimated. The TVD estimated using the Radius of Curvature is relatively close to the Minimum Curvature method, but the North coordinate is slightly over estimated and the East coordinate is slightly under estimated.

Table 3.2: Relative Difference between the Survey Calculation Methods.[2]



METHOD	DIFFERENCE IN TVD Feet	DIFFERENCE IN NORTH Feet	DIFFERENCE IN EAST Feet
Tangential	-6.30	22.18	+8.60
Balanced Tangential	-0.24	-0.07	-0.03
Average Angle	+0.10	+0.23	-0.48
Radius of Curvature	-0.01	+0.17	-0.50
Minimum Curvature	+0.00	+0.00	+0.00

4 Directional Survey and Survey Instruments

Chapter 4 will give a background of Directional Survey, Survey Corrections and overview of Directional Survey Instruments available.

4.1 Directional Surveying

Directional survey (magnetic and gyro) or wellbore positioning technique as it is otherwise known is a necessary and essential part of the modern day directional drilling. This plays a more and more important role today as major oil companies or the operators are now faced with problems of hitting the target as planned and avoiding collision with adjacent wells. As the well is being drilled, the position of the wellbore underneath the surface must be determined thus there is a need for survey tools capable of measuring the inclination and azimuth of the borehole. From the cumulative survey results, the position of the wellbore relative to the surface can be calculated. [1,2]

According to T.A Inglis [1,], the aims in directional surveying are as follows:

- To monitor the actual wellpath as drilling continues to ensure that the target will be reached;
- To orient deflection tools in the required direction when making corrections to the well path;
- To ensure that the well being drilled is in no danger of intersecting an existing well nearby;
- To determine the true vertical depths of the various formations that are encountered to allow accurate geological mapping;
- To determine the exact bottom hole location of the well for the purposes of monitoring reservoir performance, and also for relief well drilling;
- To evaluate the dog-leg severity along the course of the wellbore.

4.2 Survey Corrections

Survey corrections may include the following: drill string magnetization, sag correction, grid correction and magnetic declination. Interpolation In-Field Reference modeling is (IIFR) is strongly encouraged in areas of magnetic convergence, anomalous magnetic field, steep magnetic variation and areas where they are large amount of magnetic structures. [20]

4.2.1 Magnetic Corrections

Magnetic instruments operate on the principle similar to the earth's magnetic field. The reading obtained from the instrument can be affected by factors that influence the magnetic field. In order to eliminate these factors, the reading should be corrected. [2] The current practice today is to employ the Interpolation In-Field Referencing (IIFR) with real-time survey data management.

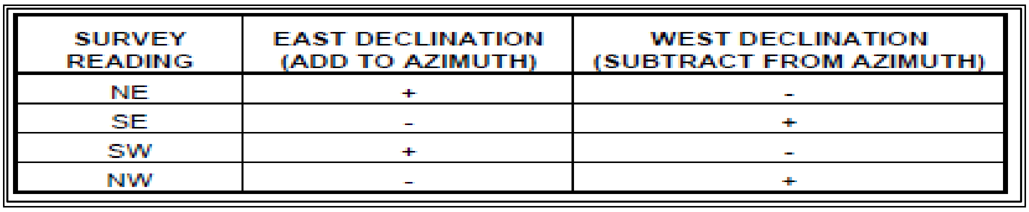
4.2.1.1 Magnetic Declination Correction

In magnetic survey instruments a magnetic compass is used pointing to the magnetic north. It is often the case that the magnetic north is not the same as the true geographical north i.e. the North Pole. It is therefore necessary to account for the difference between the magnetic north and the geographical north of the magnetic surveys. There is an angle formed between the direction of the true geographic north and magnetic north and this is called magnetic declination. [2]

With respect to the geographical north, the magnetic north can either be east or west or in the same direction at a given location on the earth. The azimuth read from the magnetic instrument must be corrected for using proper magnetic declination since the magnetic tool reads magnetic north. The line of 0° declination is known as the agonic line and there is no need to correct for geographical location that lies on this line. For a given location west of the agonic line, the magnetic needle will point to the east, for example 5°. The declination for the location is 5°. One measures the east declination clockwise from the true geographical north. A simple rule of thumb is that the declination is added to the instrument reading for a location west of the agonic line and for a location east of the agonic line the declination is subtracted.

The Table 4.1 below illustrates whether the correction is added or subtracted from the instrument reading depending on the quadrant applicable to the direction of the well. [2]

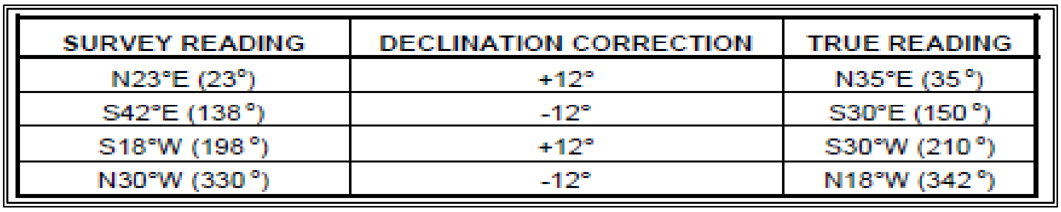
Table 4.1: Addition or Subtraction of magnetic Declination. [2]



SURVEY READING	EAST DECLINATION (ADD TO AZIMUTH)	WEST DECLINATION (SUBTRACT FROM AZIMUTH)
NE	+	-
SE	-	+
SW	+	-
NW	-	+

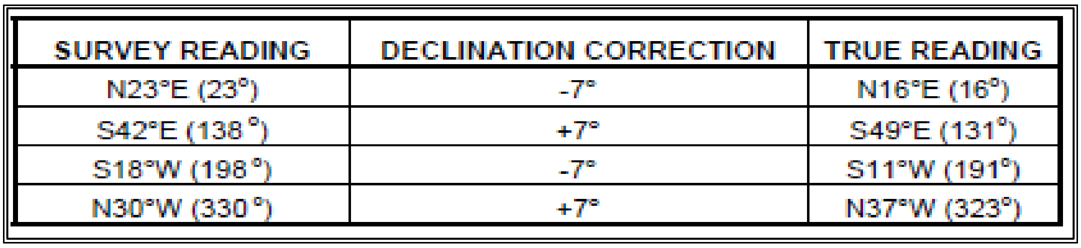
As examples to illustrate the use of Table 4.1 above, consider the magnetic declination at a well location to be 12° east and 7° west at another well location. The results are show in the tables below.

Table 4.2: Example magnetic declination at a well location of 12° east. [2]



SURVEY READING	DECLINATION CORRECTION	TRUE READING
N23°E (23°)	+12°	N35°E (35°)
S42°E (138°)	-12°	S30°E (150°)
S18°W (198°)	+12°	S30°W (210°)
N30°W (330°)	-12°	N18°W (342°)

Table 4.3: Example magnetic declination at a well location of 7° west. [2]



SURVEY READING	DECLINATION CORRECTION	TRUE READING
N23°E (23°)	-7°	N16°E (16°)
S42°E (138°)	+7°	S49°E (131°)
S18°W (198°)	-7°	S11°W (191°)
N30°W (330°)	+7°	N37°W (323°)

Figure 4.2 below is an isogonic chart showing the declination around the world in the year 2010. In figure 4.3 the annual change in declination is shown.

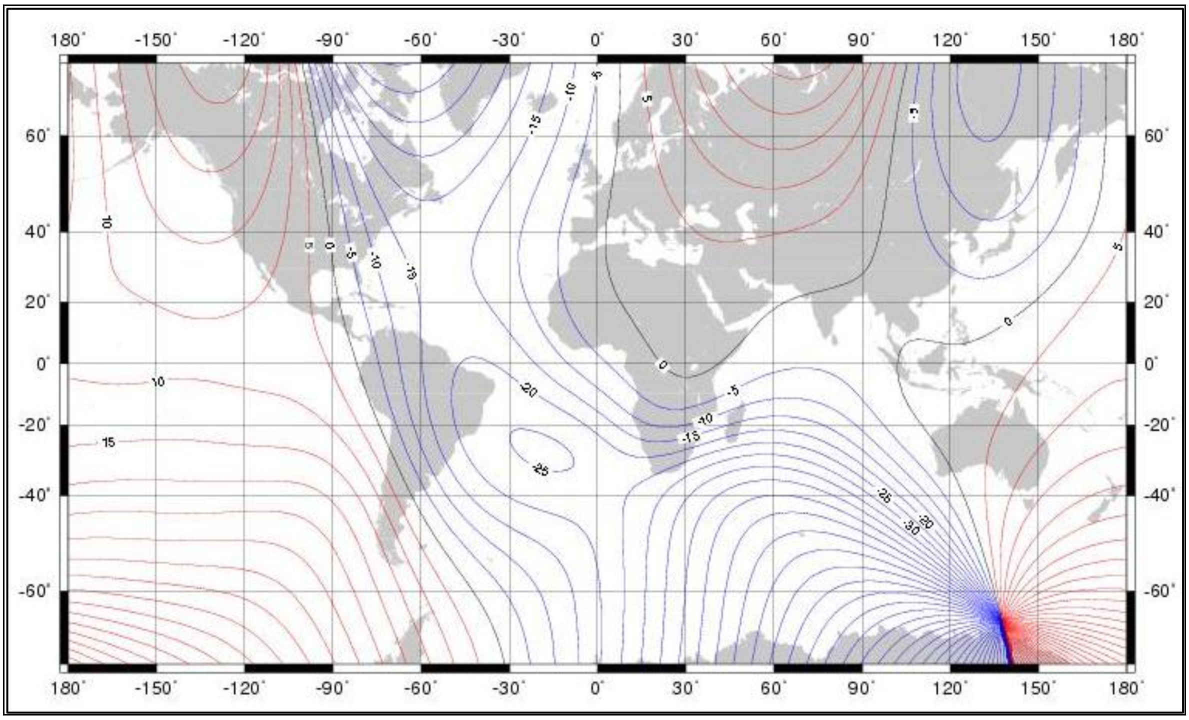


Figure 4.1: Declination (Magnetic Variation) at 2010 from World Magnetic Model 2010. [20]

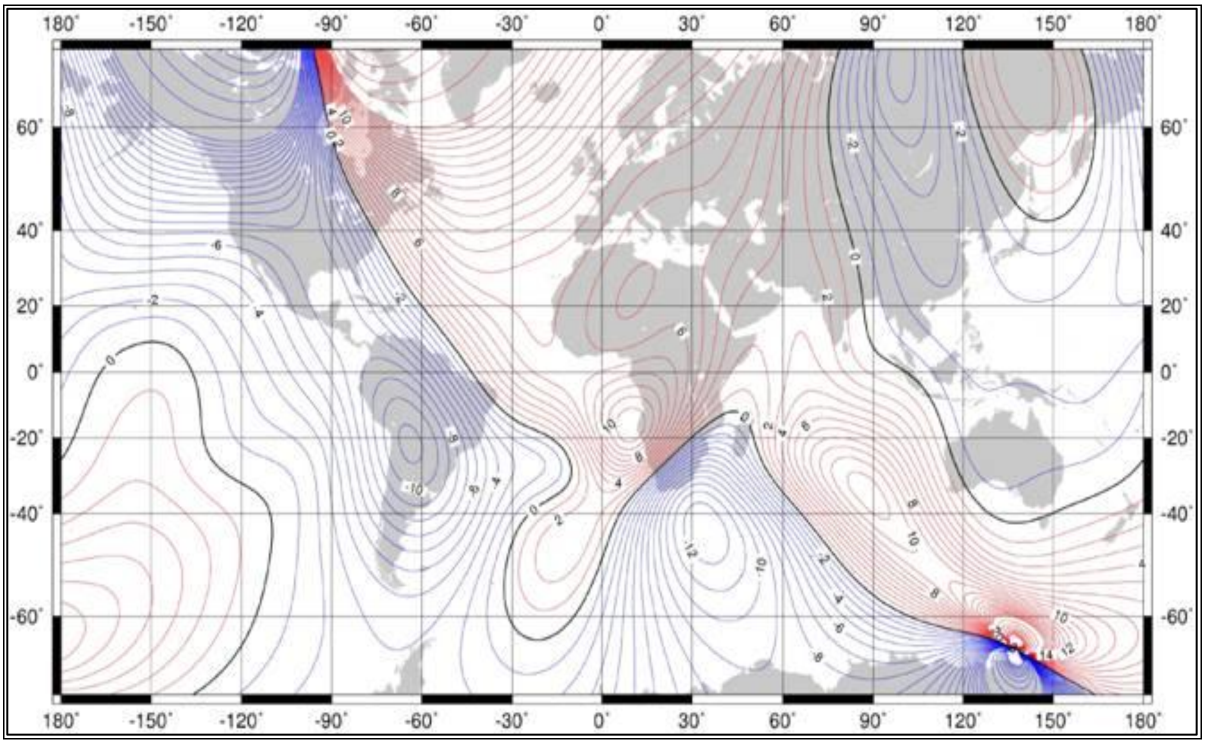


Figure 4.2: Annual Change in Declination- US/UK World Magnetic Chart, year 2010. [20]

4.2.1.2 Interpolation In-Field Referencing (IIFR)

This is the oil industry current practice of correcting directional well surveys obtained from magnetic survey tools such as MWD survey instruments. The survey tools measure the wellbore direction relative to the local geomagnetic field direction. According to the British Geological Survey (BGS), the Interpolation In-Field Referencing (IIFR= $B_{earth} + B_{crustal} + B_{external}$) is a referencing model that takes into account: the Earth's Magnetic Field (B_{earth}), Crustal Field Anomalies ($B_{crustal}$) and the External Field ($B_{external}$). [20]

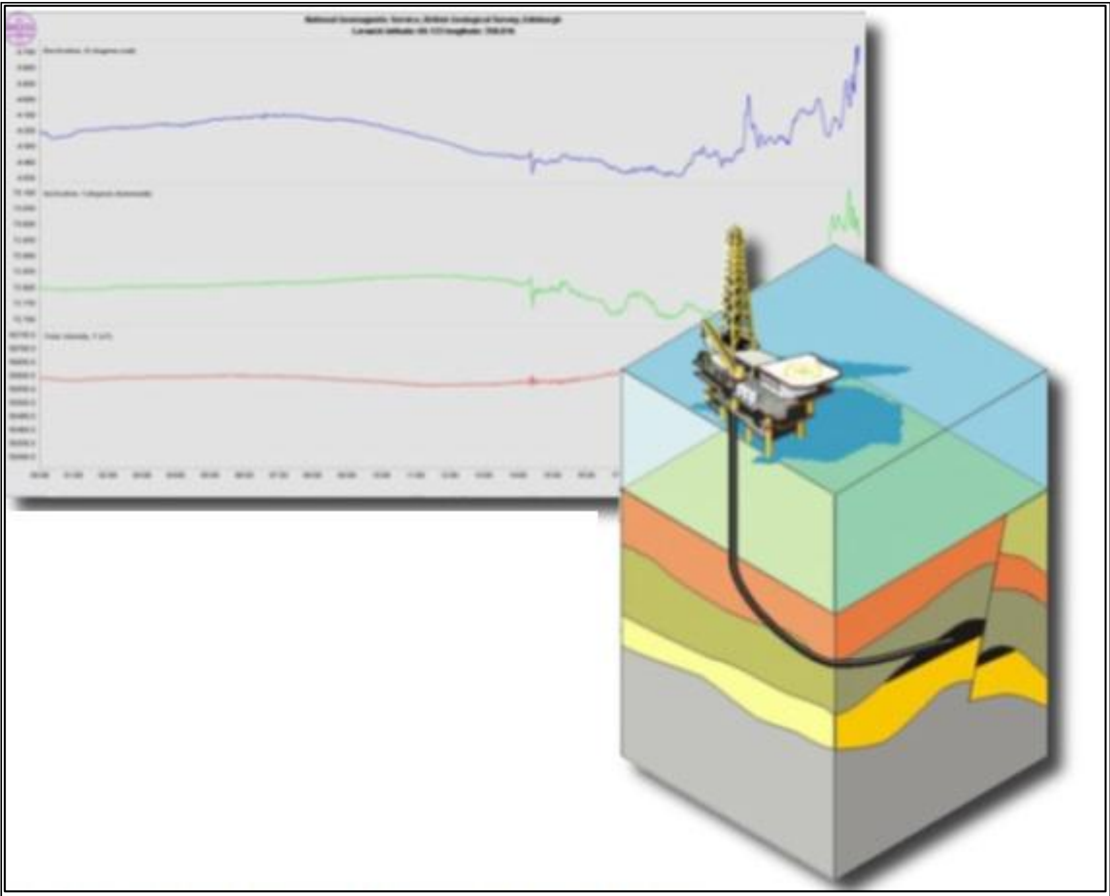


Figure 4.3: IIFR used for Directional Magnetic Survey Correction [20]

4.2.1.3 Non-Magnetic Drill Collar Selection

The presence of magnetic field around the tool influences the magnetic survey instrument. To minimize the effects of magnetic interference, the survey instrument is placed in a non-magnetic drill collar and thus the earth’s magnetic field can be measured using the survey instrument. More than one non-magnetic drill collar can be used. The selection of the non-magnetic collar is based on the following factors: inclination, azimuth, bottomhole assemblies and geographical location (by using zonal charts). [2] Non-magnetic drill collar spacing could be very poor and thus contributing largely to the uncertainty related to the survey tool. This magnetic correction was used before, but is not in used anymore.

4.2.2 Gyro Corrections

The conventional gyroscopic tools have to be corrected for drift and cross-borehole projection (inter-gimbal correction). Some corrections are also made to modern gyroscopic survey tools.

4.3 Survey Instruments

In directional surveying, the azimuth and inclination of a wellbore are determined by using directional survey instruments. These surveying instruments can be divided into two types: magnetic and gyroscopic. The magnetic survey tools use the Earth's magnetic field to find the direction of the wellbore i.e. the azimuth, while a gyroscope (gyro) is employed to determine the azimuth in gyroscopic tools. Both the magnetic and gyroscopic tools can further be divided into sub-categories. The figure below shows the different categories of survey tools. [2]

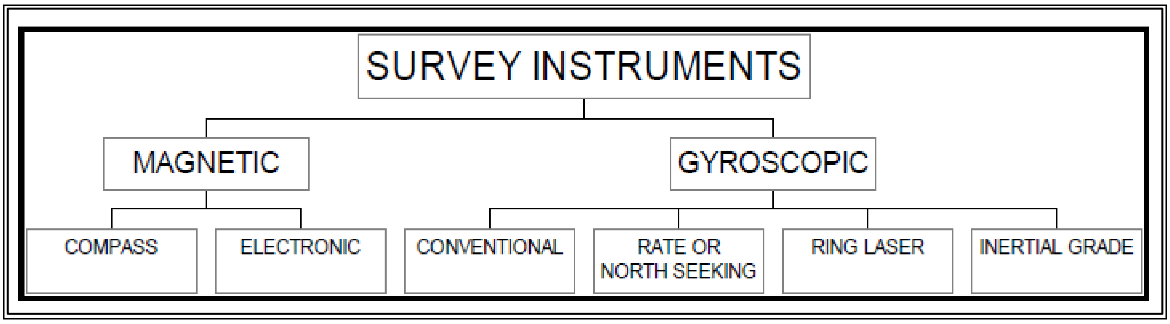


Figure 4.4: Survey Tools Categories. [2]

4.3.1 Magnetic Survey Tool

The magnetic survey tool can be divided into two categories: compass-based and electronic-based.

4.3.1.1 Compass Magnetic

A compass-based tool contains a camera and a compass. To determine the direction of the wellbore, different types of compasses are used.

4.3.1.1.1 Single Shot tools

The use of the ''single shot" tool dates back to 1930's when the accuracy of the survey tool ("acid bottle") used at that time is questionable. The single-shot survey tool uses a so called plumb bob to measure the inclination and a compass to measure the azimuth. A single shot tool takes one photograph of the angle-measuring device at a stationary survey point and records it on the film. At the surface the photographic film is retrieved and developed then the survey results can be directly read from the picture. A single-shot instrument is usually set in a non-magnetic drill collar and run on a slick line. It is also possible to drop or "go-devil" with a single shot tool. [1,2] Figure 4.2 below shows the main components of a single-shot surveying tool and the diagrammatic view of the single-shot instrument.

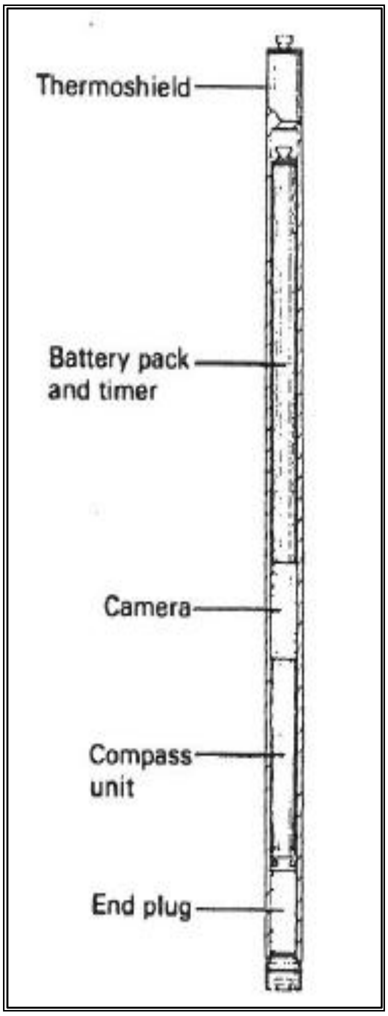


Figure 4.2: Major components of single shot instrument. [1]

4.3.1.1.2 Multi Shot tools

The principle of the multi-shot tool is similar to that of the single-shot tool. A multi-shot instrument can be placed in a non-magnetic drill collar and run in a cased hole. The usual way of running a multi-shot tool is to "go devil" with the instrument i.e. dropping the tool in the hole before tripping out. This makes it possible to survey the entire well as one pull out of the hole. The difference between a single-shot and a multi-shot instrument is that a multi-shot instrument is able to take series of pictures at pre-set interval. [1,2]

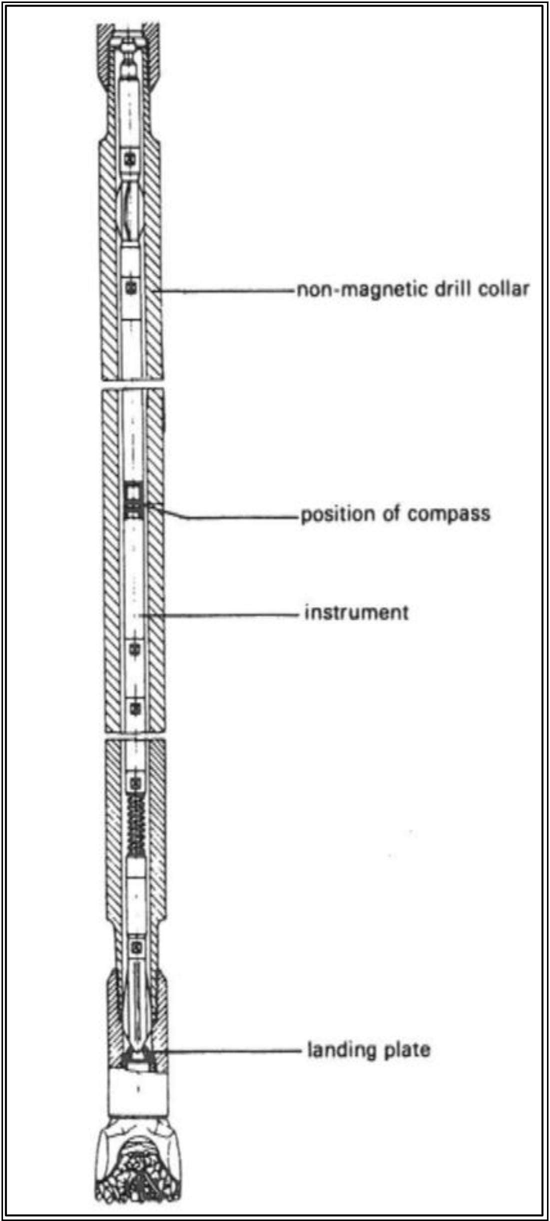


Figure 4.5: Position of multi-shot tool in a BHA before tripping. [1]

4.3.1.2 Electronic Survey Tools

In an electronic-based tool, the inclination is measured using accelerometers and the azimuth is measured using magnetometers. To determine the inclination a tri-axial accelerometer is employed to measure the earth's gravity components. The magnetometers on the other hand measure the earth's magnetic field in x, y and z direction in order to determine the direction of the wellbore. The vector sum of these components constitutes the azimuth of the wellbore. Surveys taken using electronic-based magnetic instruments are sent to the surface by wireline using electromagnetic waves or mud pulse telemetry. Survey data can also be recorded and stored in a computer chip downhole. The electronic-based survey instrument can be divided into three groups: steering tool (Old technology and not in use anymore), Measurement While Drilling (MWD) and electronic multi-shot (EMS). The division is based on the method used to transmit the data from downhole to the surface.

4.3.1.2.1 Steering Tool (Old technology)

The first electronic instrument to be developed is the steering tool. To measure the inclination and direction of the wellbore, the steering tool is equipped with two sets of built-in sensors. One set of the sensors consists of accelerometers which detect the earth's gravitation pull to determine the inclination of wellbore. The other set consists of magnetometers which detect the earth's magnetic field to determine the azimuth of the wellbore.

4.3.1.2.2 MWD Tool (Current technology)

Similar to the electronic multi-shot and the steering tool, the Measurement While Drilling (MWD) survey tool uses the same accelerometers to determine the inclination and the magnetometers to determine the direction of the wellbore. The difference between these three electronic survey instruments is that surveys data are sent to the surface on mud pulses through the drill string when using MWD tool. The schematic of MWD Transmission System is shown in Figure 4.6 below.

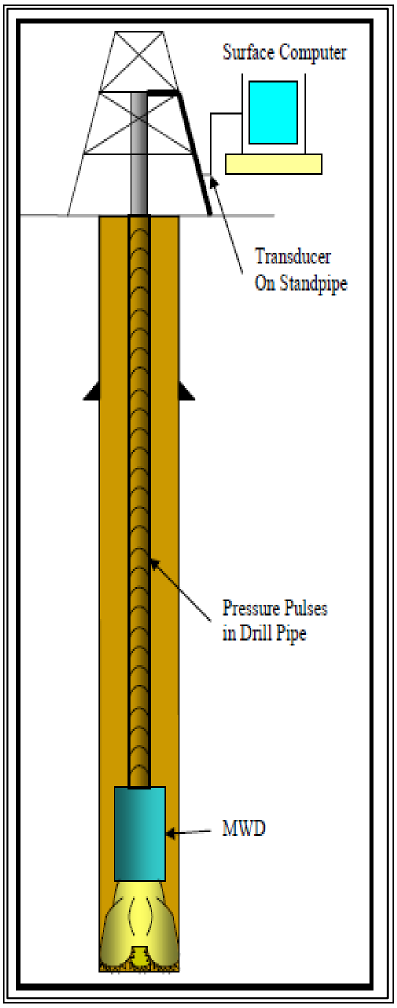


Figure 4.6: MWD Transmission system Schematic. [2]

In a MWD tool the electronic sensors record the raw directional data. In some MWD tools, survey data are calculated and converted to a binary code or a microprocessor is used to convert the data to a binary code. The Figure 4.7 below shows a typical positive pulse MWD. The survey data from downhole is displayed at the surface computer following the described steps below. [2]:

- A signal is sent to the pulser by the microprocessor
- The pulser position determines if the tool is sending a one or zero
- The pressure pulses travel up the drill string and a transducer mounted on the standpipe is used to change the mechanical pressure to an electronic signal
- The binary code is interpreted by the computer at the surface and survey data are displayed.

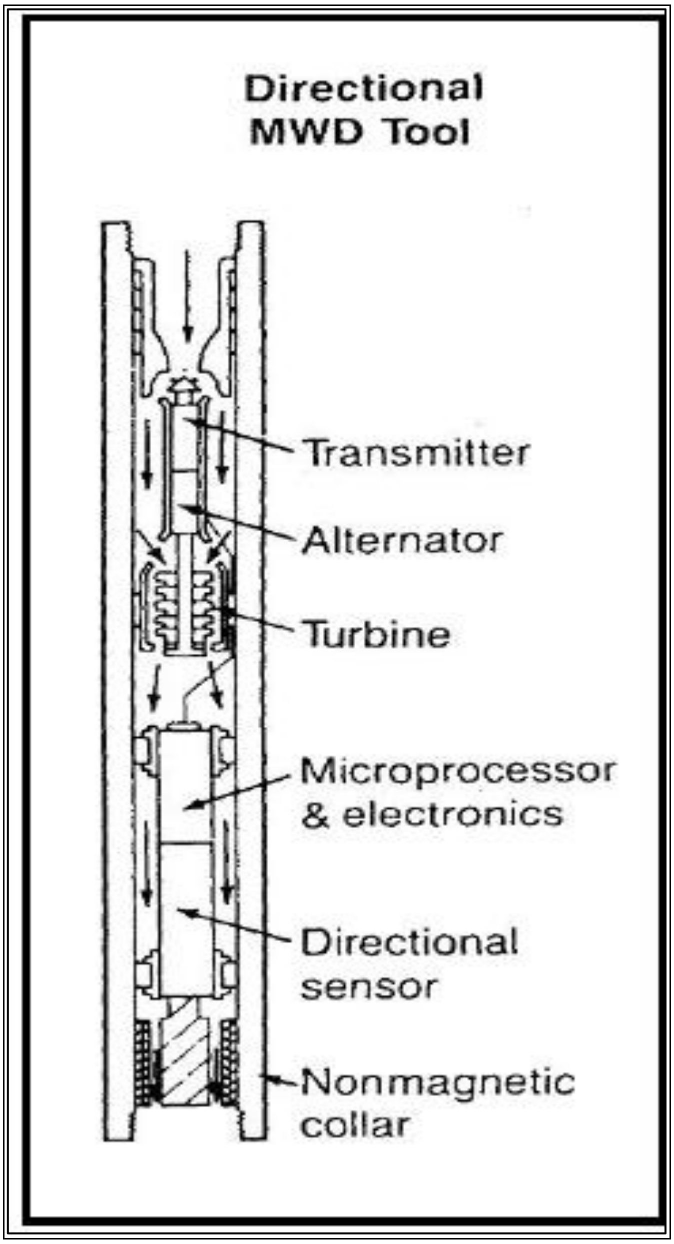


Figure 4.7: MWD Tool Simplified Diagram. [2]

4.3.1.2.3 Electronic Multi-Shot

The survey data taking using an electronic multi-shot tool is not transmitted to the surface but stored downhole in a computer chip. The wellbore survey is taking by simply dropping the tool in the hole. The result of the survey is obtained by retrieving the dropped tool using wireline or the drill string, connecting the retrieved tool to a dedicated computer which downloads the survey data from the chip. With the EMS tool, the survey data are read more accurately compared to the film-based multi-shot tool. [1,2]

4.3.2 Gyroscopic Survey Tool

In gyroscopic survey instruments, a spinning gyro is used to determine the direction of the wellbore. Gyroscopic tools can be divided into four types: conventional or free gyro, rate or north seeking gyro, ring laser gyro and inertial grade gyro. Gyros are used in areas where magnetic survey tools cannot be used for example in places where interference is expected and in cased hole. Gyroscopic instruments are often run as multi-shots on electric wireline. Gyros are also available as an integral part of MWD tools. [1,2,14]

4.3.2.1 Conventional or Free Gyro

A conventional or free gyro is the oldest of the four types of gyroscopic survey instruments. Though it's almost never used anymore, but it has been around since 1930's. The azimuth or direction of the wellbore is determined from a spinning gyro and the inclination is obtained by using accelerometers.

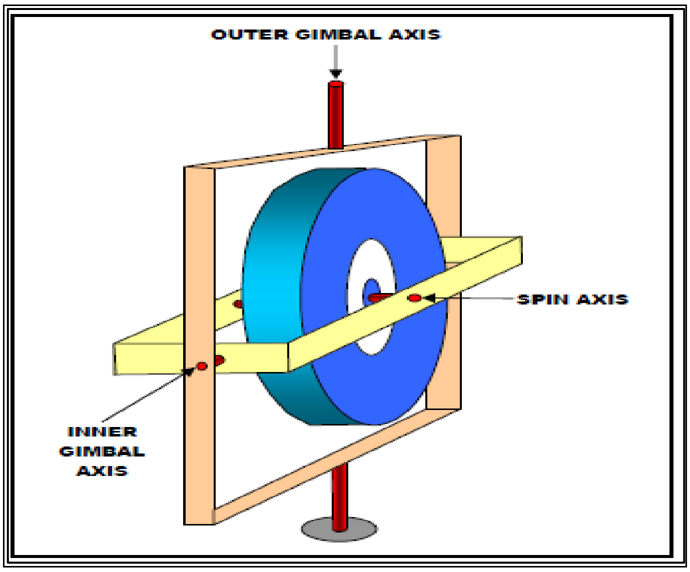


Figure 4.8: A Conventional or Free Gyro with Two Degrees of Freedom. [2]

4.3.2.2 Rate (Continuous) or North Seeking Gyros

Rate gyro and north seeking gyro are essentially the same. This type of gyro is developed to solve the problems related to conventional gyro. A north seeking gyro has only one degree of freedom and the rate integrating gyro is used to determine the true north. In a rate gyro, the earth's spin vector is resolved into vertical and horizontal components where the horizontal component is always pointing to true north. The figure below shows a rate gyro with one degree of freedom.

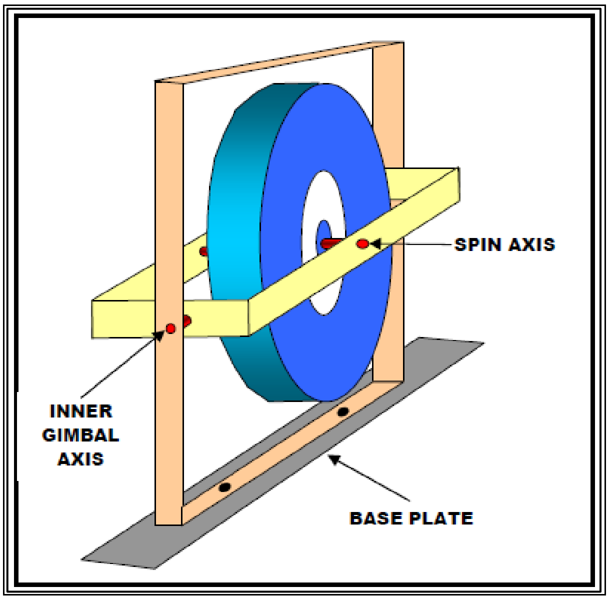


Figure 4.9: A Rate Gyro or North Seeking Gyro with One Degree of Freedom. [2]

A rate gyro compared to conventional gyro can have the following advantages [2]:

- The need to reference the gyro before in-run is eliminated thus increasing the accuracy of the gyro.
- The drift associated with the earth's spin is eliminated, due to the automatic compensation as the rate gyro measures the earth's spin during setup. Thus making the rate gyro less subjected to error.
- No need to sight in with a reference point when using a rate gyro thus eliminating another possible source of error.
- The forces acting on the gyro is measured using the rate gyro and the accelerometers are used to measure the gravity force. Both of the readings give calculation of the inclination and the azimuth.

- A rate gyro provides the opportunity to survey while moving therefore reducing the surveying time and making the survey instrument a more cost effective tool.

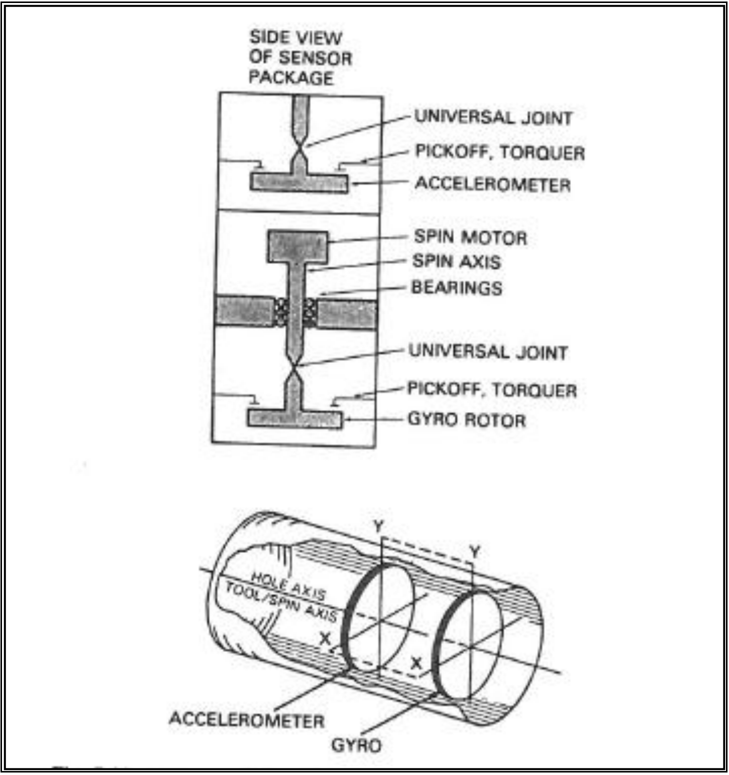


Figure 4.10: Rate Gyro. [1]

4.3.2.3 Ring Laser Gyro (RLG)

A different type of gyro is used to determine the direction of the wellbore in a ring laser gyro (RLG). The sensor in a RLG is made up of three ring laser gyros and three inertial grade accelerometers which are mounted to measure the X, Y and Z axis. A ring laser gyro is more accurate and quicker (no stoppage of the survey tool) than a rate or north seeking gyro. But due to the ring outside diameter of 5 ¼ in, the RLG is limited to be run only in 7 in or larger casing. Unlike a rate gyro, a RLG can't be run through a drill string. [1,2]

This survey instrument is not currently used in the oil industry. But it's used by other industry such as the mining industry.

4.3.2.4 Inertial Grade Gyro

The inertial grade gyro which is often called the Farraniti tool is the most accurate survey tool. The full navigation system of this gyro is borrowed from the aerospace technology and the survey obtained using this instrument is reliable due to its accuracy. Sometimes to determine the accuracies of some survey tools they are compared to the inertial grade gyro. The inertial grade gyro is equipped with three rate gyros and three accelerometers mounted on a stabilized platform. [1,2] Due to its large size of this survey tool, it is no longer used in the oil industry.

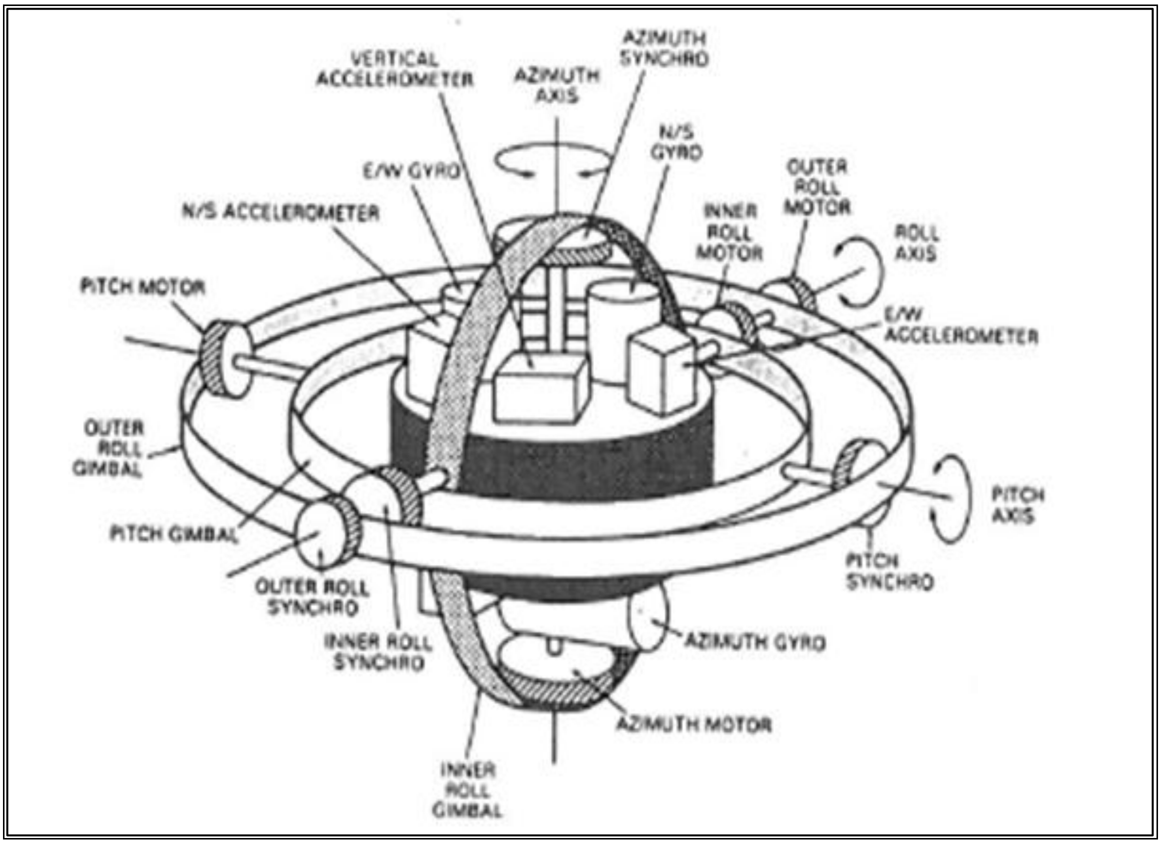


Figure 4.11: Inertial Navigation Tool. [1]

4.4 Survey Instruments Accuracy

There are many variables influencing the accuracy of survey tools. In magnetic surveys the following problems can be encountered: magnetic interference, hot spot in non-magnetic collars, declination correction errors, higher latitudes problems, and magnetic storms (sun spot activity). For film based surveys the readings are not accurate. The problems faced in a conventional gyro are: surface referencing, drift and tool misalignment. For other gyros quality control is the biggest problem where the tools must be properly calibrated and then checked again at the end of the survey. [2]

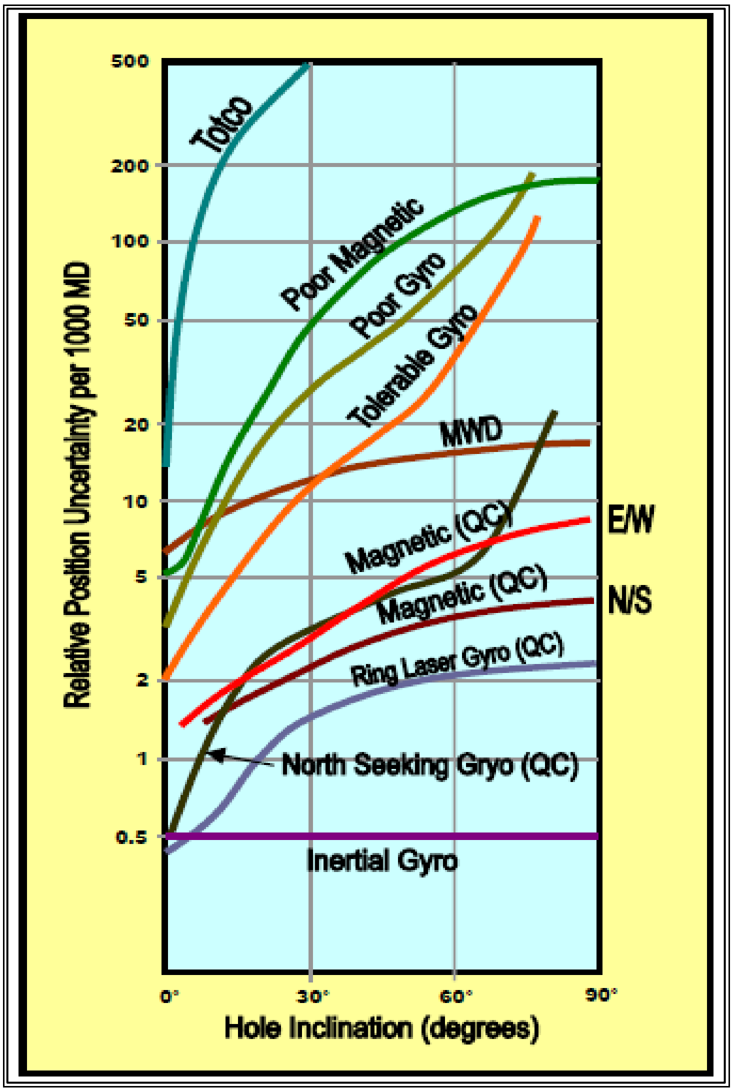
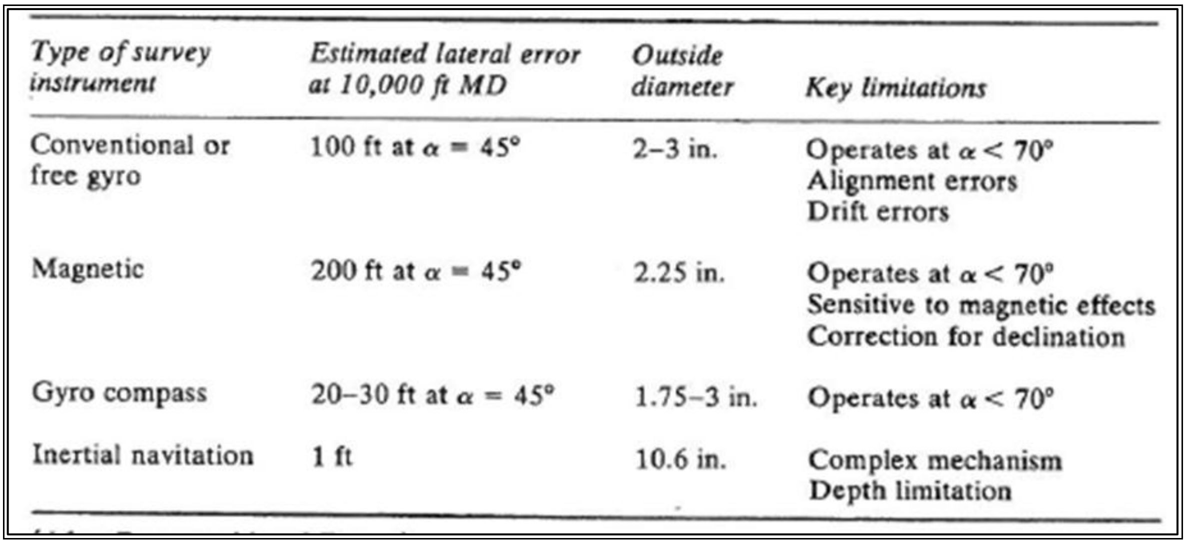


Figure 4.12: Survey Accuracy Data. [2]

The Survey Accuracy figure above illustrates that the most accurate survey instrument is inertial grade gyro followed by the ring laser gyro with good quality control. The rate or north seeking gyro accuracy is similar to that of the magnetic electronic tools with good quality control. The magnetic tools are more accurate if the wellbore is north/south rather than east/west. A MWD survey tool without substantial quality control is more accurate than a conventional gyro at an inclination above 30°. [2]

The table below shows the accuracy figures for the more commonly used surveying tools.

Table 4.4: Survey Instruments Comparison. [1]



Type of survey instrument	*Estimated lateral error at 10,000 ft MD*	*Outside diameter*	*Key limitations*
Conventional or free gyro	100 ft at $\alpha = 45^\circ$	2–3 in.	Operates at $\alpha < 70^\circ$ Alignment errors Drift errors
Magnetic	200 ft at $\alpha = 45^\circ$	2.25 in.	Operates at $\alpha < 70^\circ$ Sensitive to magnetic effects Correction for declination
Gyro compass	20–30 ft at $\alpha = 45^\circ$	1.75–3 in.	Operates at $\alpha < 70^\circ$
Inertial navitation	1 ft	10.6 in.	Complex mechanism Depth limitation

5 Directional Surveying Errors

In Chapter 5 the following will be discussed: Error in Surveying, Error Classification, Error Propagation Models and Sources of Error.

5.1 Error in Surveying

Experiments and measurements taking give the knowledge of the physical world. Understanding how to express, analyze and draw meaningful conclusions from measurement and experimental data is very important.

In dealing with measurement data, it is crucial to understand that all measurements of physical quantities are subjected to uncertainties. Measuring anything exactly is almost impossible. The aim in any measurement is to make the error as small as possible but it is always there. In order to draw reasonable and valid conclusions the error must be indicated and handled properly. [5]

Directional Surveying is like any measurement where there are errors or uncertainties in the survey data thus resulting in inaccuracy in determining the position of the wellbore. Even though there are possibilities of using sophisticated survey tools today, the wellbore coordinates can and are never determined exactly. To handle the directional survey data properly and draw valid conclusion, the error associated to the survey are quantified in a way to specify the wellbore position within a tolerance limits. The knowledge of the accuracy to which the depth, inclination and azimuth at the survey station can be measured which enables one to define an area of uncertainty around the survey station. The form of this area in three dimensions is an ellipsoid. The wellbore position lies within this ellipsoid. [1,4]

The level of tolerated uncertainty is an application dependent. In a conventional directional well, a lateral error of 10ft per 1000ft drilled might be permissible, while in order to avoid collision with adjacent wells, when kicking off from a multiwall platform, the maximum allowable error is limited to 2ft per 1000ft drilled. For the case of a relief well the tolerable error for bottom hole location must be within 50ft or less of the target. [1]

5.2 Errors Classification

There is no directional survey that is free from error. The errors found in directional surveys can generally be classified into three: random errors, systematic errors and gross errors. In order for one to understand both the individual and combined effects of the above mentioned errors, it is of great importance to have a good knowledge of the nature and behavior of each of them. [4]

5.2.1 Random Errors

Random errors are defined as errors that can be averaged out through a large number of repeated measurements. They are errors that are always present in any measurement. [4,5]

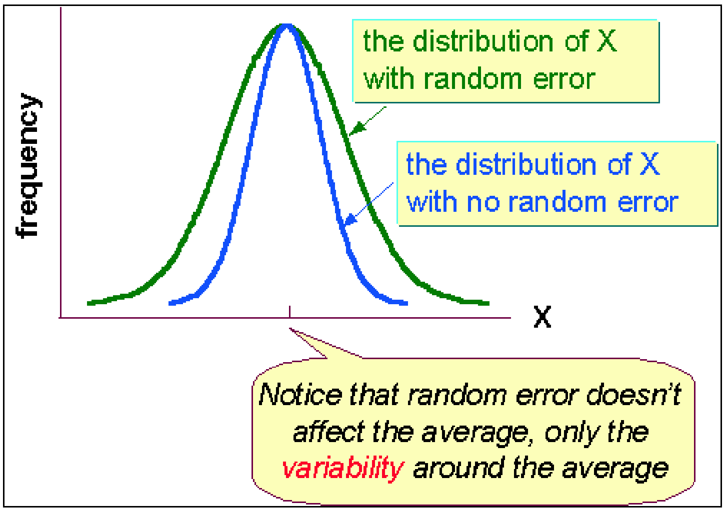


Figure 5.1: Random Errors[5]

The following are examples of random errors in directional surveys [4]:

- Unpredictable environmental variations
- Round off errors
- Orthogonality errors when sensors is rotating
- Mud pump induced fluctuation in mud pressure

5.2.2 Systematic Errors

Systematic errors are errors that are typically present. They have their sources from instrument, physical and human limitations. Systematic errors can also be defined as all the remaining errors when random and gross errors are removed. For a given number of measurements, a systematic error has the same size, sign or geometric dependent nature. [4]

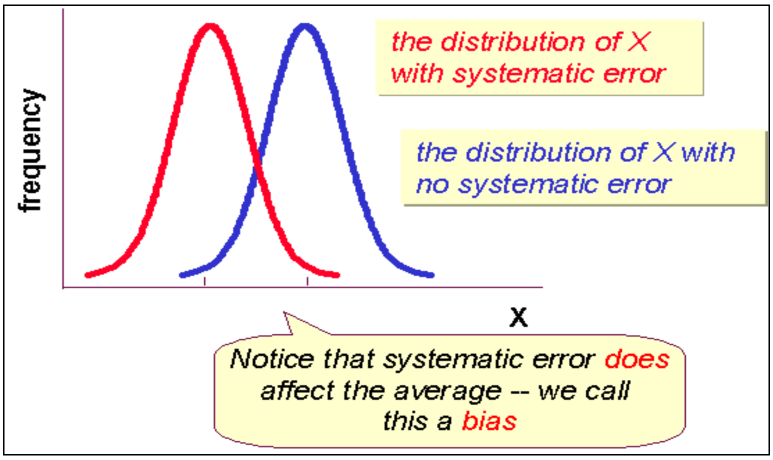


Figure 5.2: Systematic Errors. [5]

It is important to know that in directional drilling some errors are systematic at one level and random at another. A typical example is errors that are systematic in one survey and random between two surveys.

Here are some examples of errors that are systematic in one survey and random between different surveys [4]:

- Reference errors in connection with free gyro surveys
- Residual errors in magnetic declination corrections
- Drill collar sag for MWD instruments

Below are two examples of errors that are systematic for all survey in a given region:

- Magnetic measurements without magnetic declination corrections
- Errors in the geodetic reference network

5.2.3 Gross Errors

Gross errors are also known as “blunders”. These errors are usually caused by human faults or failures of instruments in use. These types of errors are significant and important to address in the oil industry. In directional surveys the following examples of gross errors can be encountered [4]:

- Use of wrong initialization parameters
- Use of wrong calibration constants
- Instrument used beyond operational specifications
- Single channel failure in multi-channel equipment
- Memory of processor error in the computer

5.3 Error Propagation Models

5.3.1 Walstrom Model

The Walstrom Error Model was first introduced in 1969 by Walstrom et al. [12] This is a random error propagation model for directional surveying. The validity of the model was soon questioned due to the inaccurate prediction of the uncertainties associated to directional surveys at that time. [4]

In Walstrom error model, the sources of directional survey error are treated as random error from one station to another which gives them the tendency to compensate each other. Many publications have proved that the Walstrom error model is invalid as it does not account for major directional drilling errors such as magnetic declination, drill pipe stretch, etc. which have significant systematic components. Due to the statistical error model used, the ellipse of uncertainty (EOC) calculated using the Walstrom error model is extremely small. The assumed randomness in the measuring errors thus cause under estimated value for the real positional uncertainty. It is strongly recommended that the Walstrom error model should not be used. [4, 12]

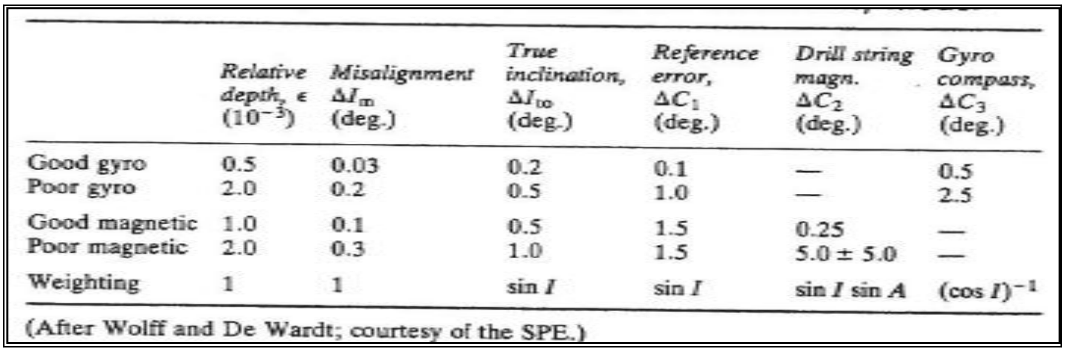
5.3.2 Wolff de Wardt Error Model

The Wolff de Wardt error model was developed by Shell KSEPL. Unlike the Walstrom error model, this error model is a systematic error propagation model for handling directional surveys. The Wolf de Wardt model was first introduced in 1981 based on the technology and instrument present at that time. For some time the Wolff de Wardt model was considered and accepted as the industry’s standard error model. The following errors are identified by the Wolff de Wardt error model [4, 12]:

- Error related to magnetic compass which encompasses effects such as instrument error, magnetic declination value and drill string magnetization.
- Error related to gyroscopic compass which includes gyro drift and initial orientation error.
- True inclination error or misalignment including the effects of bending and poor centralization.
- Errors related to depth measurement including drill pipe measurement measurements and wireline inaccuracies.

The table below shows the upper (poor magnetic andpoor gyro tools) and lower (good magnetic and good gyro tools) limits for each of the error sources.

Table 5.1: Input of Error Tolerances for Uncertainty Model by Wolff and de Wardt. [1]



	Relative depth, ϵ (10^{-3})	Misalignment ΔI_m (deg.)	True inclination, ΔI_{to} (deg.)	Reference error, ΔC_1 (deg.)	Drill string magn. ΔC_2 (deg.)	Gyro compass, ΔC_3 (deg.)
Good gyro	0.5	0.03	0.2	0.1	—	0.5
Poor gyro	2.0	0.2	0.5	1.0	—	2.5
Good magnetic	1.0	0.1	0.5	1.5	0.25	—
Poor magnetic	2.0	0.3	1.0	1.5	5.0 ± 5.0	—
Weighting	1	1	$\sin I$	$\sin I$	$\sin I \sin A$	$(\cos I)^{-1}$

(After Wolff and De Wardt; courtesy of the SPE.)

Wolff de Wardt model shows that by applying the error ranges in Table 5.1 for an inclined well the result can be shown in figure below. Figure 5.3 below illustrates that the lateral uncertainty for all types of survey instrument increases as the inclination increases.

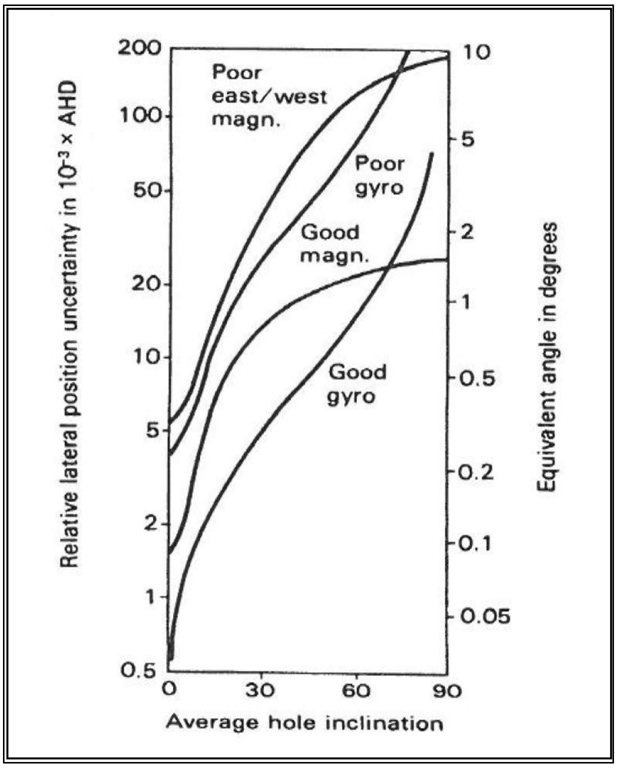


Figure 5.3: Survey Uncertainty Using Wolff de Wardt Error Model. [1,12]

The example below shows the essential differences between the Walstrom and the Wolff de Wardt error propagation model. [12]

Example: Assume the straight and inclined part of a well has the following directional characteristics:

- Measured depth or total depth along hole (AHD or DAH) = 2500m
- Number of Survey stations = 100 at 25m intervals
- Inclination (I ± ΔI) = 30° ± 0.5°
- Azimuth (A ± ΔA) = 90° ± 1.0°

The position of the bottomhole of the well in North, East and Vertical can be given using the following equations:

$$N = D_{AH} * \sin I * \cos A \qquad \text{Eq. (1)}$$

$$E = D_{AH} * \sin I * \sin A \qquad \text{Eq. (2)}$$

$$V = D_{AH} * \cos I \qquad \text{Eq. (3)}$$

Thus we have:

$$N = D_{AH} * sin\ I * \cos A = 0$$

$$E = D_{AH} * \sin I * \sin A = 1250$$

$$V = D_{AH} * \cos I = 2165$$

Assuming that the measuring errors at all 100 stations have the same magnitude, the position uncertainty according to Wolff de Wardt can be calculated by using the equations below:

$$\boldsymbol{\Delta N = D_{AH} * \sin I * \Delta A} \qquad \text{Eq. (4)}$$

$$\boldsymbol{\Delta E = D_{AH} * \cos I * \Delta I} \qquad \text{Eq. (5)}$$

$$.\boldsymbol{\Delta V = D_{AH} * \sin I * \Delta I} \qquad \text{Eq. (6)}$$

Therefore we have:

$$\Delta N = D_{AH} * \sin I * \Delta A = 2500 * 0.5 * \frac{\pi}{180}(1.0) = 22\ m,$$

$$\Delta E = D_{AH} * \cos I * \Delta I = 2500 * 0.87 * \frac{\pi}{180}(0.5) = 19\ m,$$

$$\Delta V = D_{AH} * \sin I * \Delta I = 2500 * 0.5 * \frac{\pi}{180}(0.5) = 11\ m,$$

The Figure 5.4 below shows basic relationship between the systematic error model and the positional uncertainty.

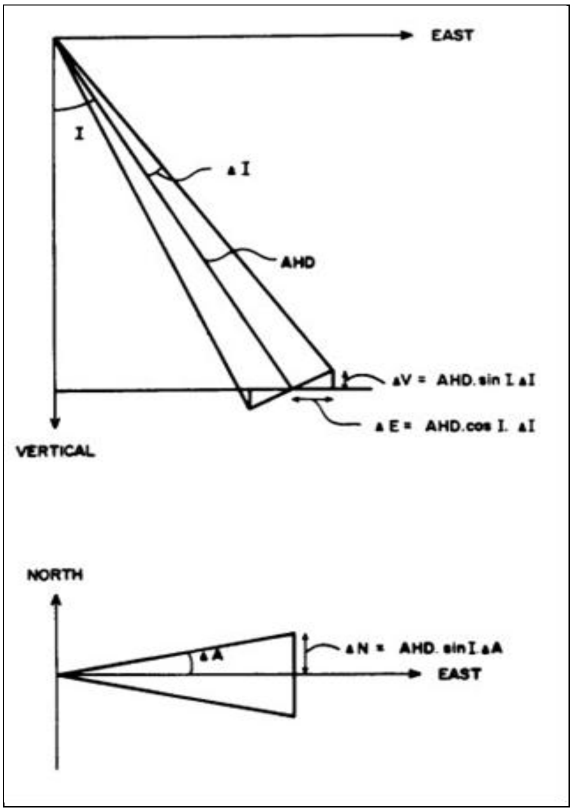


Figure 5.4: Relationship between systematic survey errors and position uncertainties. [12]

In the random error model by Walstrom, it is assumed that the measuring errors vary randomly from station to station. The measuring error randomness thus results in smaller value of the position uncertainty as compared to the Wolff de Wardt error model. In example given above the position uncertainty in the Walstrom error model will be ten times smaller than the Wolff de Wardt error model. This is found by taking the square root of the number of the survey stations (√100 = 10). [12]

The position uncertainty for Walstrom error model:

$$\Delta N\ (random) = \pm 2.2$$

$$\Delta E\ (random) = \pm 1.9$$

$$\Delta V\ (random) = \pm 1.1$$

5.3.3 Instrument Performance Model

The Instrument Performance Model known as IPM was developed by BP and presented as an alternative to the Wolff de Wardt model in 1988. It is the most comprehensive of the previously published error models at that time. The error model combines random-, systematic- and bias error propagation theory. In this model, systematic errors are divided into two: random between surveys and systematic between surveys. This is also called bias error. [4]

5.3.4 ISCWSA MWD & Gyro Error Model (Industry Standards)

5.3.4.1 ISCWSA MWD Error Model

This model is the industry standard error model for MWD surveys. It is a product of the work of two collaborative groups SPE WPTS (formerly ISCWSA) and Four Company Working Group consisting of Baker Hughes INTEQ, BP Exploration, Statoil and Sysdrill Ltd. [13]

5.3.4.2 ISCWSA Gyro Error Model

In regions where the accuracy of magnetic tools is questionable, gyroscopic surveying tools are used to complete and control the wellbore. The ISCWSA Gyro Error Model is the oil industry's standard method for estimation of wellbore position accuracies for gyroscopic tools. This error model consists of new set of error terms and a mathematical description of how the different error sources add to uncertainties in position depending on sensor configurations and operational modes. And its error propagation mechanisms chosen are similar to those in the ISCWSA's MWD error model. [14, 24]

Description:

In stationary and continuous operating modes, measurement of azimuth is different for each of the mode. The stationary mode is compatible with the overall format of the ISCWSA MWD model where a full and representative set of gyro error sources is included in the mode, whereas for the continuous mode a very simplified model is proposed, which provides a fairly representation of the error propagation with time. This model however represents a deviation from the ISCWSA model and existing well planning and survey management.

5.4 Sources of Error

5.4.1 Errors Related to Survey Calculation Method Used

The different survey calculation methods used in directional survey are discussed in detail in Chapter 3 above. At various stages in the wellpath for a given directional well, the inclination and azimuth will change. It is obvious that the tangential method is the least accurate and not suitable method to use as the error associated to this method is non-tolerable. For most operators today, the accurate and adopted survey calculation method is the minimum curvature method. [1,4]

5.4.2 Errors Related to Survey Instruments

Overview over the survey instruments are given in Chapter 4 above. As stated earlier, the survey tools can be divided into magnetic and gyroscopic tools. The common trait for magnetic and gyroscopic tool is that the operating mechanism that measures the required angles has inherent inaccuracies. For the magnetic compass, any magnetic field present will influence it. Due to the steel drill string an error of 10 degree in the compass reading can be caused by the magnetic field in some cases. The accuracy of the conventional gyroscope depends on accurate alignment on surface with the direction of the reference point. Failure in aligning the spin axis correctly will have an impact on the survey data generated by the instrument. [1,4,12]

Magnetic-Azimuth Error Sources:

In magnetic surveys the principal sources of azimuth uncertainty are: sensor error, misalignment of instrument, declination uncertainty and drill string magnetization.

5.4.3 Errors Related to the Borehole Environment

Survey tools may not be able to provide reliable results if their specified downhole temperature and pressure are exceeded. Limits on inclination may also be imposed by the specifications. For example in wells with inclinations above 70 degree, gyroscopic tools are normally not used. Also the reliability of magnetic compass is questionable at high angles of latitude due to the reduced horizontal component of the Earth’s magnetic field. Magnetic compass reliability is also reduced when drilling in an east-west direction. Another cause of error related to the borehole environment is survey tool misalignment with the axis of the borehole. The cause of this could be bending of the drill collars within the borehole or poor centralization of the tool within the drill collar. [1,4]

5.4.4 Errors in Reading or Reporting Survey Results

It can be difficult to read single-shot and multi-shot pictures. At low inclination it is easy to make reading error. Sometimes magnetic declination correction are totally omitted or applied incorrectly. [1]

Though this is not a problem today since the film based tools are not in use anymore, but the consequences this error source are large. This might had been one of the major contributors to the survey uncertainty acquired in the early stage of wellbore survey performed on the wells on the Ekofisk field.

5.4.5 Errors Related to Survey Depth

The measurement of the wellbore depth is influenced by major sources of error. Accurate measurement of the survey depth is very important as inclination and azimuth measurements are. Errors related to depth can arise from inaccurate wireline measurements or incorrect tally of drill pipe length, measuring tape, telescopic and suspension effects, drill string stretch, drill string temperature expansion, mud pressure effects, suspension effects, wireline stretch and measuring wheel effects. [1,4,12]

6 Position Uncertainty Analysis & Visualization

In this Chapter, Position Uncertainty Analysis will be performed on two resurveyed wells from the Greater Ekofisk field operated by ConocoPhillips Norway. Some figures, tables and column charts have been provided to aid in visualizing the analysis. For confidential issue the wells have been given generic names. Here in known as Well A and B.

The uncertainties to be analyzed are based on inherited errors from the past. These could be reading errors, calculating errors, poor quality of data, tool inaccuracy or/and limitation and poor work practices (poor record keeping and documentation) etc. It is the consequences of poor position uncertainty management in the past that the operator is dealing with today.

6.1 Analysis of Well A

Well A is a producing well, and the drilling of this well started in 1978 and was completed in 1981. The challenge faced by ConocoPhillips concerning this well is that the well possesses two well paths. The two directional surveys run in the well show that there are two different well paths with big ellipses of uncertainty. According to the survey reports and internal reports examined, the Wellbore Position 1 has an ellipse of uncertainty of 750 ft. in radius at target depth while the Wellbore Position 2 has an ellipse of uncertainty of 1400 ft. in radius at target depth. Combination of the uncertainties gives a radius of about 3200 ft. with some overlapping. Figure 6.1 illustrates the described scenario above. [8,9]

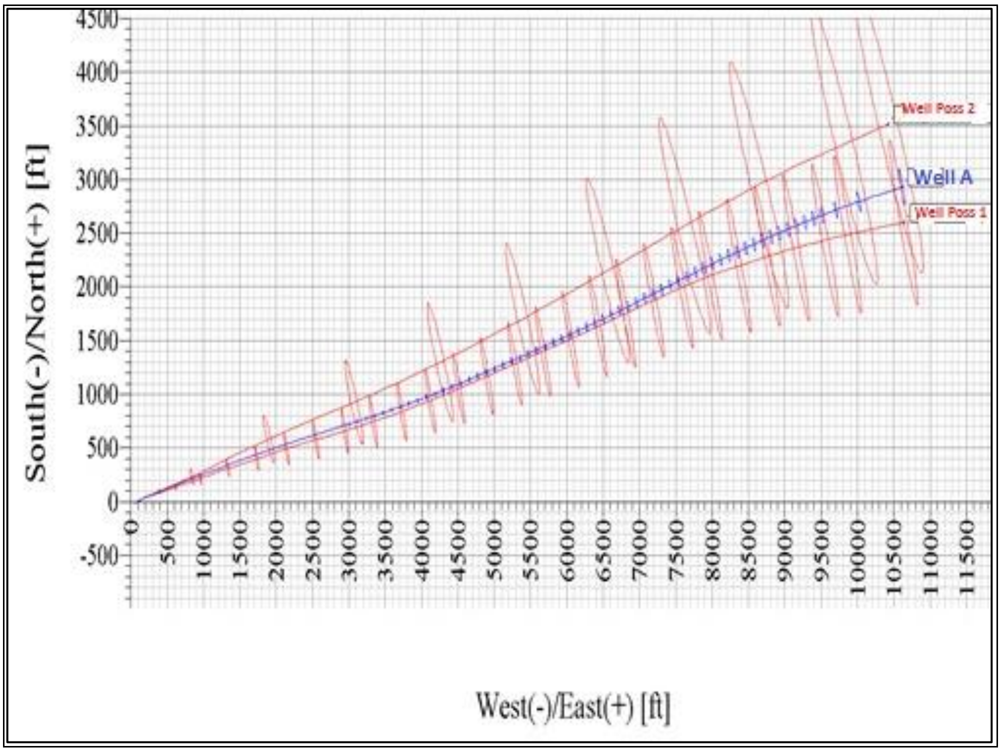


Figure 6.1: Plan or horizontal view of Wellbore position 1, 2 and the definitive wellbore position. [8]

First the well possessing two well paths is a big problem for the operator. Secondly the large ellipses of uncertainties at target depth are unacceptable. With two wellbore positions and large ellipses of uncertainties, it is almost impossible to plan and drill new wells around Well A.

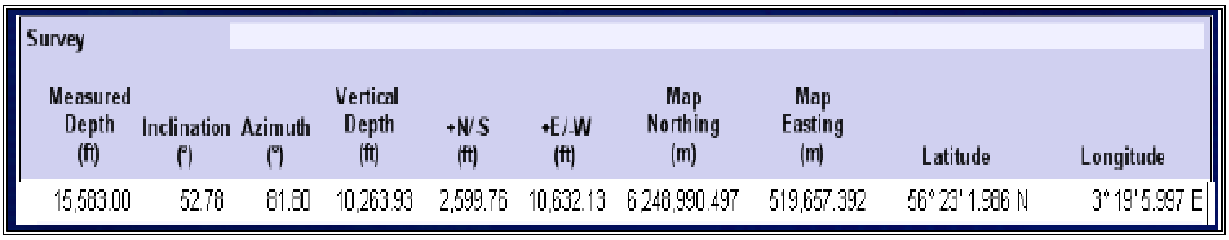
ConocoPhillips approach to the problem is to resurvey the well with the aim of obtaining just one well path with ellipse of uncertainty radius reduced to 200 ft or less (see Figure 6.1 above). This will enable the company to be sure of the location of Well A and provide an opportunity to drill and position new wells more accurately.

6.1.1 Wellbore Position 1

The survey program of the first survey i.e. Wellbore position 1 ran in this well is in five stages. The first stage is from 300 ft. to 1100 ft. using Tol Gyro/ Good Incl. surveying tool. The second stage is from 1200 ft. to 5800 ft., the third stage from 5900 ft to 14700 ft. and the fourth stage from 14770 ft. to 15142 ft. For stage 2, 3 and 4 the Poor Gyro / Good Inc.

Tool was used. The last stage which is stage five runs from 15577 ft. to target depth (TD) employing Poor Magnetic surveying tool. The tables below show the bottomhole location (BHL) and position uncertainty of Wellbore Position 1 before resurveying was performed.

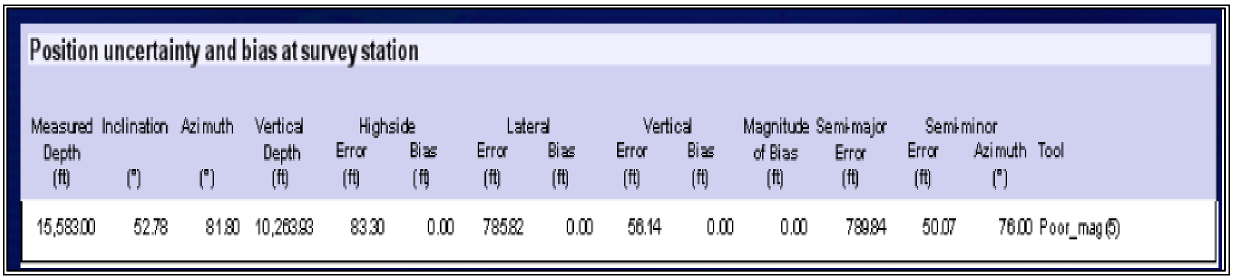
Table 6.1: BHL of Wellbore Position 1. [8]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
15,583.00	52.78	81.80	10,263.93	2,599.76	10,632.13	6,248,990.497	519,657.392	56° 23' 1.986 N	3° 19' 5.997 E

Table 6.2: Position uncertainty before resurvey for Wellbore Position 1. [8]



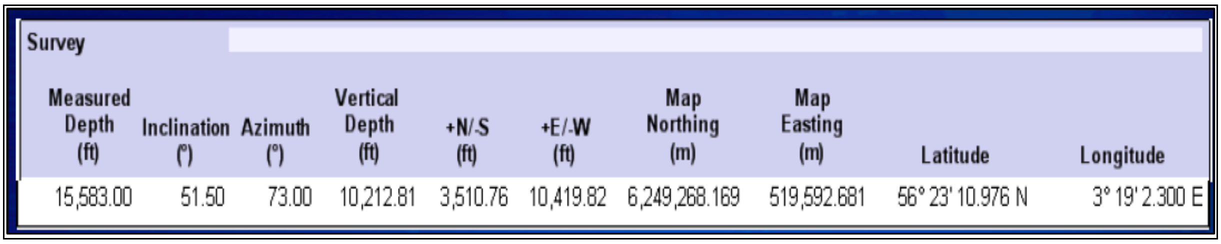
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
15,583.00	52.78	81.80	10,263.93	83.30	0.00	785.82	0.00	56.14	0.00	0.00	789.84	50.07	76.00	Poor_mag (5)

6.1.2 Wellbore Position 2

For the Wellbore Position 2, the survey program is in two stages. Stage 1 is run from 200 ft. to 1100 ft. (Measured Depth-RKB) using Tolerable Gyro with Good Incl. tool. Stage 2 is run from 1100 ft. to 15577 ft. using Poor Magnetic surveying tool. Table 6.3 below shows the bottomhole location before the resurvey of the well. Table 6.4 shows the position uncertainty of Wellbore Position 2 before the resurvey of the well.

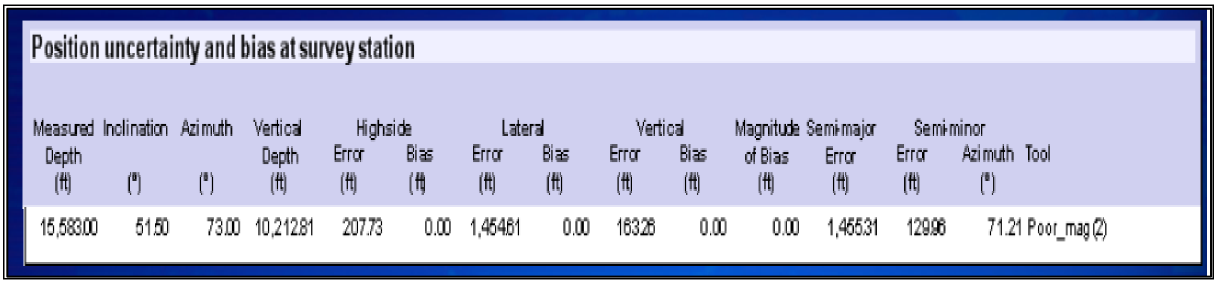
Table 6.3: BHL of Wellbore Position 2 before the resurvey. [8]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
15,583.00	51.50	73.00	10,212.81	3,510.76	10,419.82	6,249,268.169	519,592.681	56° 23' 10.976 N	3° 19' 2.300 E

Table 6.4: Position uncertainty Wellbore Position 2. [8]



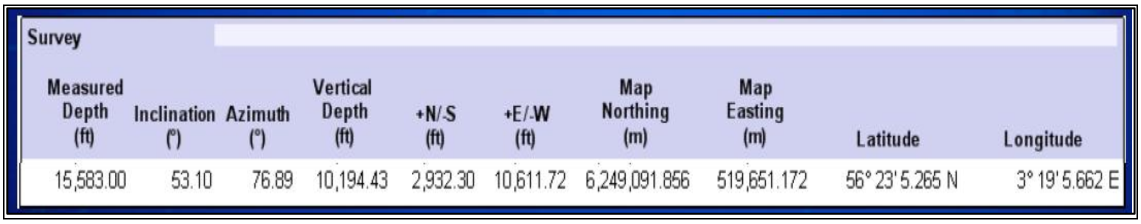
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
15,583.00	51.50	73.00	10,212.81	207.73	0.00	1,454.61	0.00	163.26	0.00	0.00	1,455.31	129.96	71.21	Poor_mag(2)

6.1.3 Wellbore Position of Well A After Resurvey

The resurvey of Well A was done in two stages. The first stage was from 367 ft. to 14220 ft. The second stage (tie-on) is from 14306 ft. to 15583 ft. For the first stage a surveying data called Gyrodata Continuous was used. While for the second stage data from old survey (Poor magnetic) after some necessary adjustment was tied on the resurveyed data. Table 6.5 and 6.6 below show the bottomhole location and the position uncertainty after resurveying.

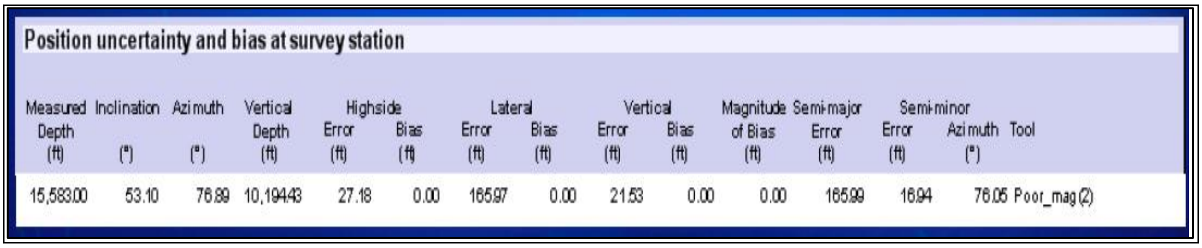
Table 6.5: Bottomhole Location (BHL) Well A after resurvey. [8]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
15,583.00	53.10	76.89	10,194.43	2,932.30	10,611.72	6,249,091.856	519,651.172	56° 23' 5.265 N	3° 19' 5.662 E

Table 6.6: Position Uncertainty after resurvey-Well A. [8]



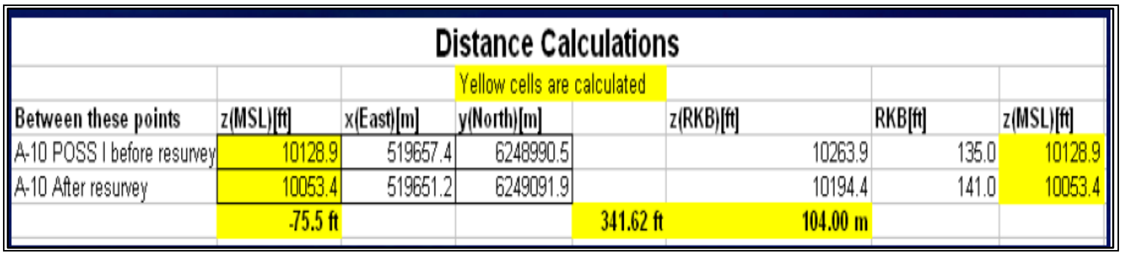
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
15,583.00	53.10	76.89	10,194.43	27.18	0.00	165.97	0.00	21.53	0.00	0.00	165.99	16.94	76.05	Poor_mag(2)

6.1.4 Distance Calculation After Resurvey

The difference (distances) between the Wellbore Position 1 (before resurvey) and the actual wellpath (after resurvey) are calculated and shown in Table 6.7 below.

Table 6.7: Distance calculations between Wellbore Position 1 and the actual wellbore after resurvey. [8]

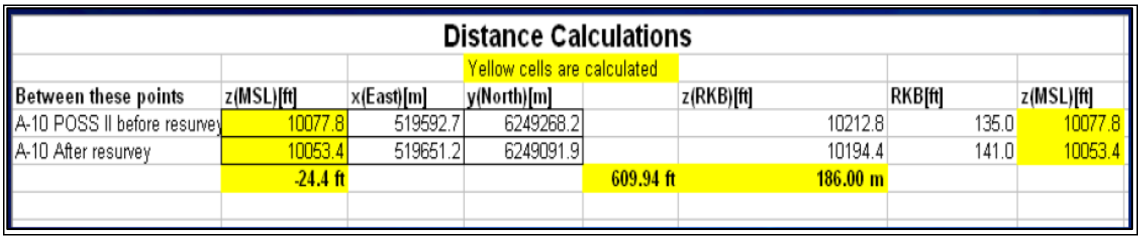


Distance Calculations

			Yellow cells are calculated				
Between these points	z(MSL)[ft]	x(East)[m]	y(North)[m]		z(RKB)[ft]	RKB[ft]	z(MSL)[ft]
A-10 POSS I before resurvey	10128.9	519657.4	6248990.5		10263.9	135.0	10128.9
A-10 After resurvey	10053.4	519651.2	6249091.9		10194.4	141.0	10053.4
	-75.5 ft			341.62 ft	104.00 m		

The distances (vertical and lateral) between the Wellbore Position 2 (before resurvey) and the actual Well A (after resurvey) are calculated and shown below.

Table 6.8: Distance calculations between Wellbore Position 2 and the actual wellbore after resurvey. [8]



Distance Calculations

			Yellow cells are calculated				
Between these points	z(MSL)[ft]	x(East)[m]	y(North)[m]		z(RKB)[ft]	RKB[ft]	z(MSL)[ft]
A-10 POSS II before resurvey	10077.8	519592.7	6249268.2		10212.8	135.0	10077.8
A-10 After resurvey	10053.4	519651.2	6249091.9		10194.4	141.0	10053.4
	-24.4 ft			609.94 ft	186.00 m		

6.1.5 Comparison, Discussion and Consequences

From Table 6.1, 6.3 and 6.5 above, one can see that at the same Measured Depth (MD) of 15583 ft., the inclination (I), azimuth (A), True Vertical Depth (TVD) and the horizontal coordinates (+N/-S & +E/-W) are different for before and after resurvey. Before resurvey, Wellbore Position 1 (I= 52.78, A=81.80 and TVD= 10263.93) has higher inclination, azimuth and true vertical depth than that of Wellbore Position 2 (I= 51.50, A=73.0 and TVD= 10212.81). The horizontal coordinates of Wellbore Position 1 are given as: +N/-S = 2599.76 ft. and +E/-W = 10632.13 ft and for Wellbore Position 2 : +N/-S = 3510.76 ft. and +E/-W = 10419.82 ft. After resurvey the measured inclination (I=53.10) is slightly larger than that of Wellbore Position 1 and 2. The measured azimuth after resurvey (A= 76.89) is in between the azimuth values for Wellbore Position 1 and 2. The TVD after resurvey is smaller than the TVD of Wellbore Position 1 & 2, while the horizontal coordinates of the well after resurvey is located between the horizontal coordinates of Wellbore Position 1 & 2.

As shown in Table 6.2, 6.4 and 6.6, the position uncertainty of Wellbore Position 2 (Highside error = 207.73 ft., Lateral error=1454.61 ft., Vertical error= 163.26 ft.) is very large compared to Wellbore Position 1 (Highside error = 83.30 ft., Lateral error= 785.82 ft., Vertical error= 56.14 ft.). After resurvey the position uncertainty (Highside error = 27.18 ft., Lateral error=165.97 ft., Vertical error= 21.53 ft.) is far much lesser.

From the survey results above, it is evident that the choice of directional surveying tools is important. According to the survey programs examined, the surveying of Wellbore Position 1 and 2 was conducted using a survey instrument called Tolerable Gyro /Good Inclination (Gyro Multi Shot). This type of gyro falls under the free gyro or conventional gyro. The error associated to conventional gyro are large and might have reason for the wellpath discrepancy and the large ellipses of uncertainty as shown in table 6.2 and 6.4 above. For the resurveying of the well, a Gyrodata Continuous tool was used (Gyro Multi Shot). This is a rate or north seeking gyro with lesser error.

The result of the resurvey gives the Well A one wellpath and shows that the wellbore (Well A) is located between Wellbore Position 1 and 2 with smaller ellipses of uncertainty as shown in Figure 6.1 and 6.3 (blue ellipses) This new result from the resurvey will aid in anti-collision analysis. Now the proximity factor is larger, with smaller ellipses around the wellbore and thus enhances better planning and drilling of new wells. Smaller TVD is calculated from the resurvey, meaning that the well is actually shallower than Wellbore Position 1 and 2 (Figure 6.2 below illustrates that).With much smaller vertical error (see Table 6.6 above), adjustment can be made to logs, geological and reservoir models.

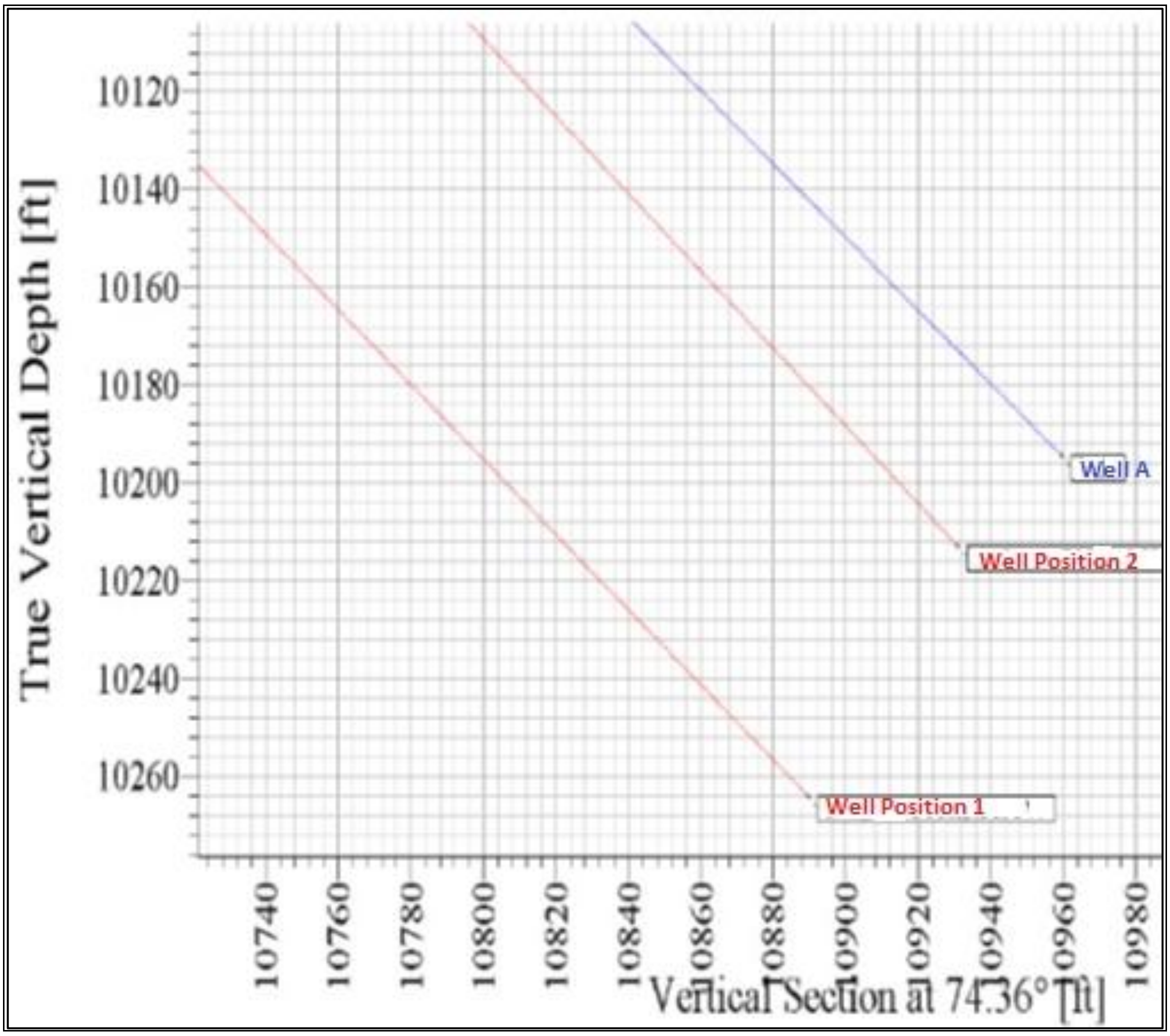


Figure 6.2: Vertical View of Wellbore position 1&2 and the actual wellpath (blue). [8]

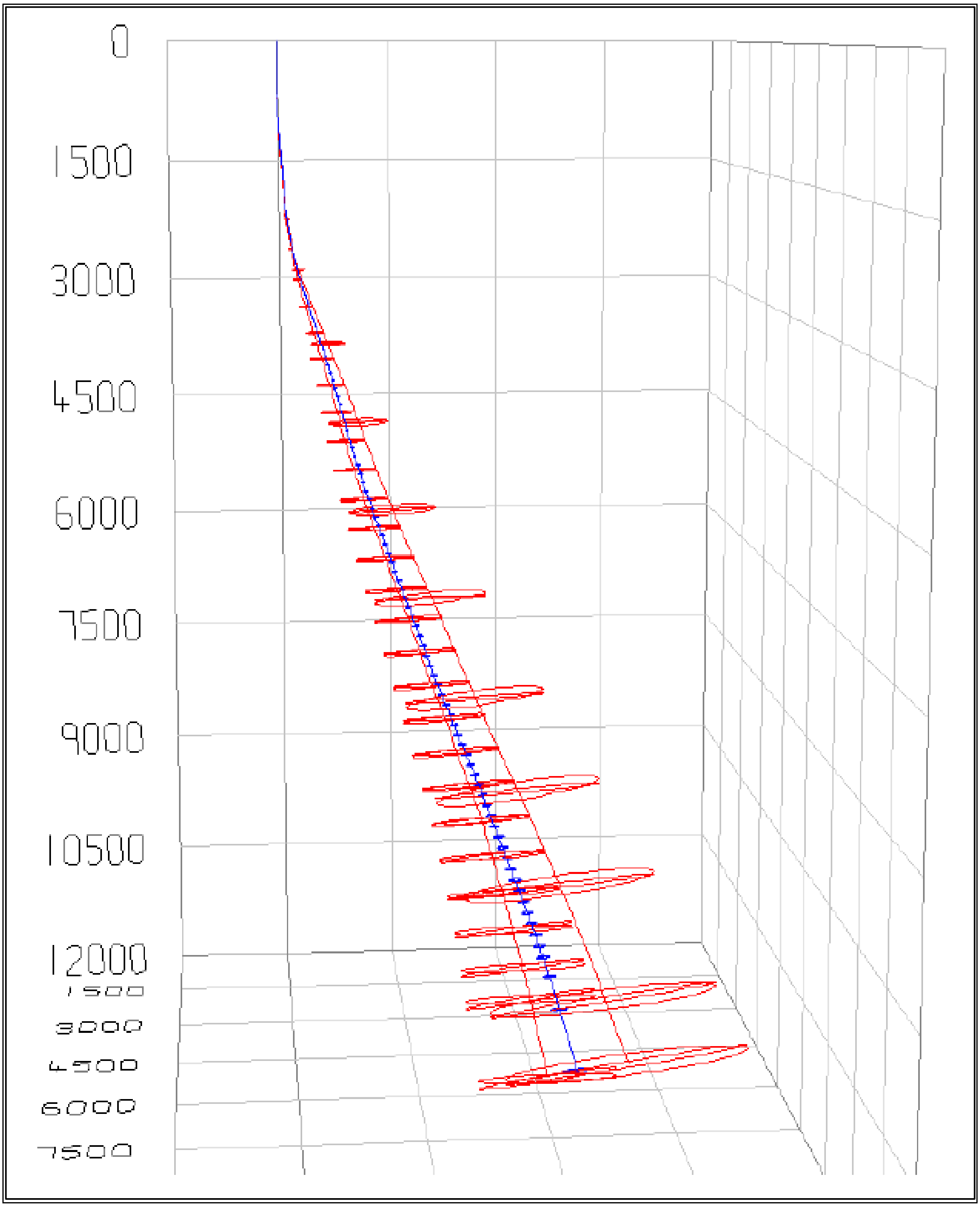
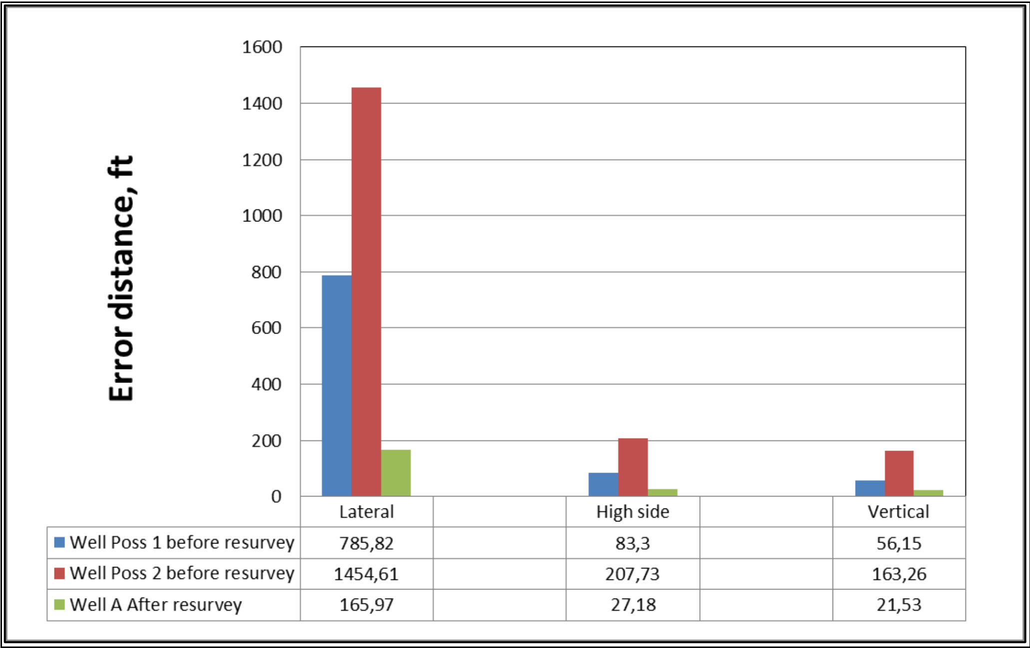


Figure 6.3: 3D view of Wellbore Position 1 & 2 and the actual wellpath. [8]

6.1.6 Position Uncertainty

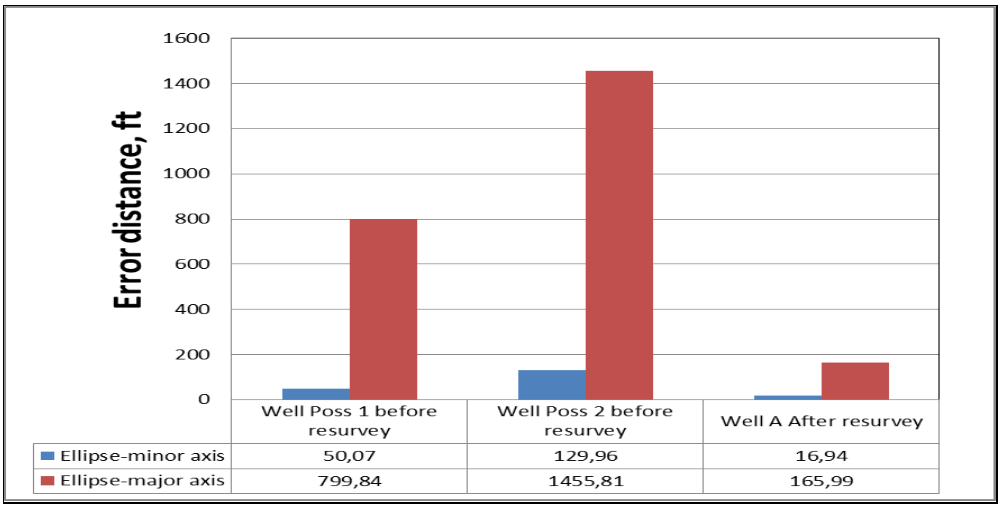
Figure 6.4 below illustrates the position uncertainty in lateral, high side and vertical. The visualization of the position uncertainty is a more convincing way of understanding the error in the analyzed well. It also helps to see the effect of the resurvey result.



	Lateral	High side	Vertical
🟦 Well Poss 1 before resurvey	785,82	83,3	56,15
🟥 Well Poss 2 before resurvey	1454,61	207,73	163,26
🟩 Well A After resurvey	165,97	27,18	21,53

Figure 6.4: Lateral, High side and Vertical Error Visualization (Excel Analysis).

Figure 6.5 below shows the error associated to the minor and major axis of the ellipses of uncertainty for Well Poss and Poss 2 before resurvey and Well A after resurvey.

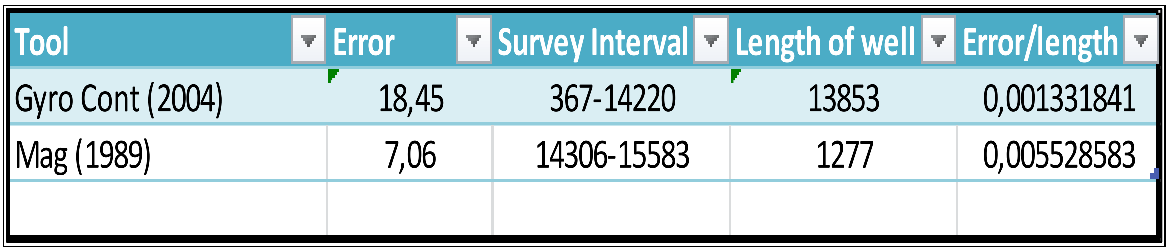


	Well Poss 1 before resurvey	Well Poss 2 before resurvey	Well A After resurvey
🟦 Ellipse-minor axis	50,07	129,96	16,94
🟥 Ellipse-major axis	799,84	1455,81	165,99

Figure 6.5: Ellipse-Minor & Ellipse Major Axis Error Visualization (Excel Analysis).

Table 6.9 below shows the comparison between Gyro Continuous (2004) survey instrument and Magnetic (1989) survey instrument. These are the two survey tools used in the survey program for Well A. The gyroscopic tool was ran from survey interval of 367-14220 ft. (length ran= 13853 ft.).The cumulative error for the tool is 18.45 ft. By dividing the cumulative error by length gives Error/Length of 0.00133. The magnetic tool was ran from 14306-15583 ft. (length= 1277 ft.), with 7.06 ft. as cumulative error, thus the Error/Length equals 0.005528. From this analysis "Error /Length", it can be concluded that the Gyro Continuous which was ran in 2004 is more accurate than the Magnetic in 1989. Figure 6.6 illustrates the result of the relative Error/Length analysis.

Table 6.9: Magnetic vs. Gyro continuous Error/Length Analysis (Excel Analysis)



Tool	Error	Survey Interval	Length of well	Error/length
Gyro Cont (2004)	18,45	367-14220	13853	0,001331841
Mag (1989)	7,06	14306-15583	1277	0,005528583

Figure 6.6 below visualizes the relative error/length with respect to the survey tool used.

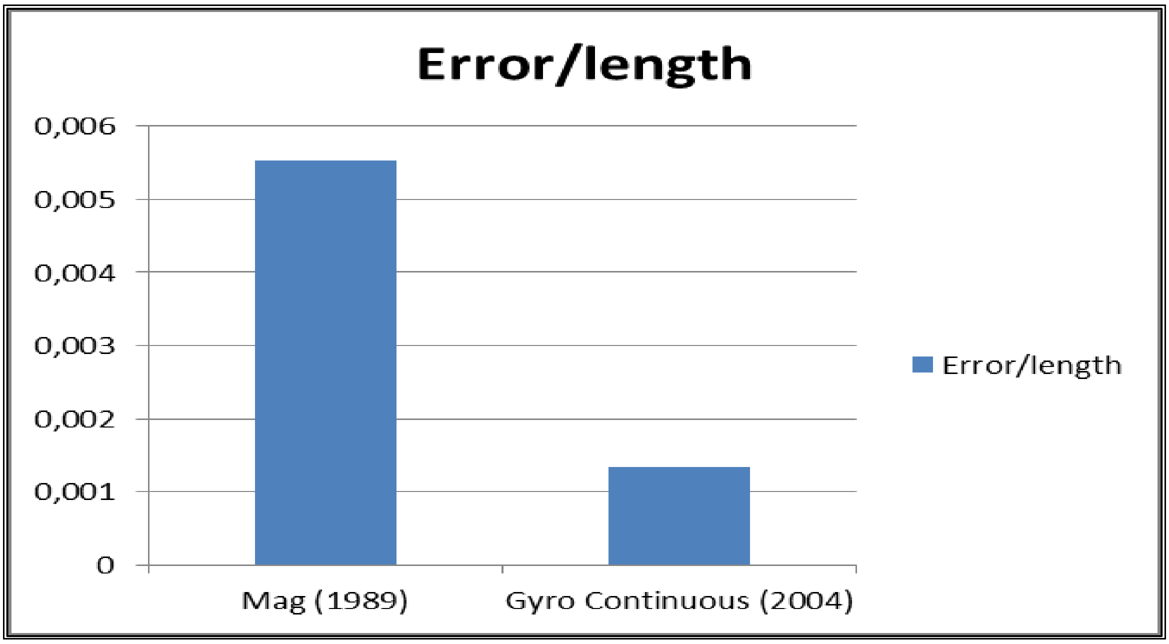


Figure 6.6: Magnetic vs. Gyro Cont. Error/Length Visualization (Excel Analysis).

6.2 Analysis of Well B & BT2

Well B is a producing well drilled in June 1997 and completed in October 1997. The well has a main bore identified by Well B, and a sidetrack identified by BT2. The operator of the field ConocoPhillips plan to drill eight more wells from the Victor Bravo templates and Well B tends to be an obstacle as the separation factor (1.5 or greater) required by the company’s anti-collision criteria is not met. The well was thus classified as a resurvey candidate and was resurveyed in April 2012. The aim for the resurveying of the well is to reduce the ellipse of uncertainty in order to safely navigate around the well.

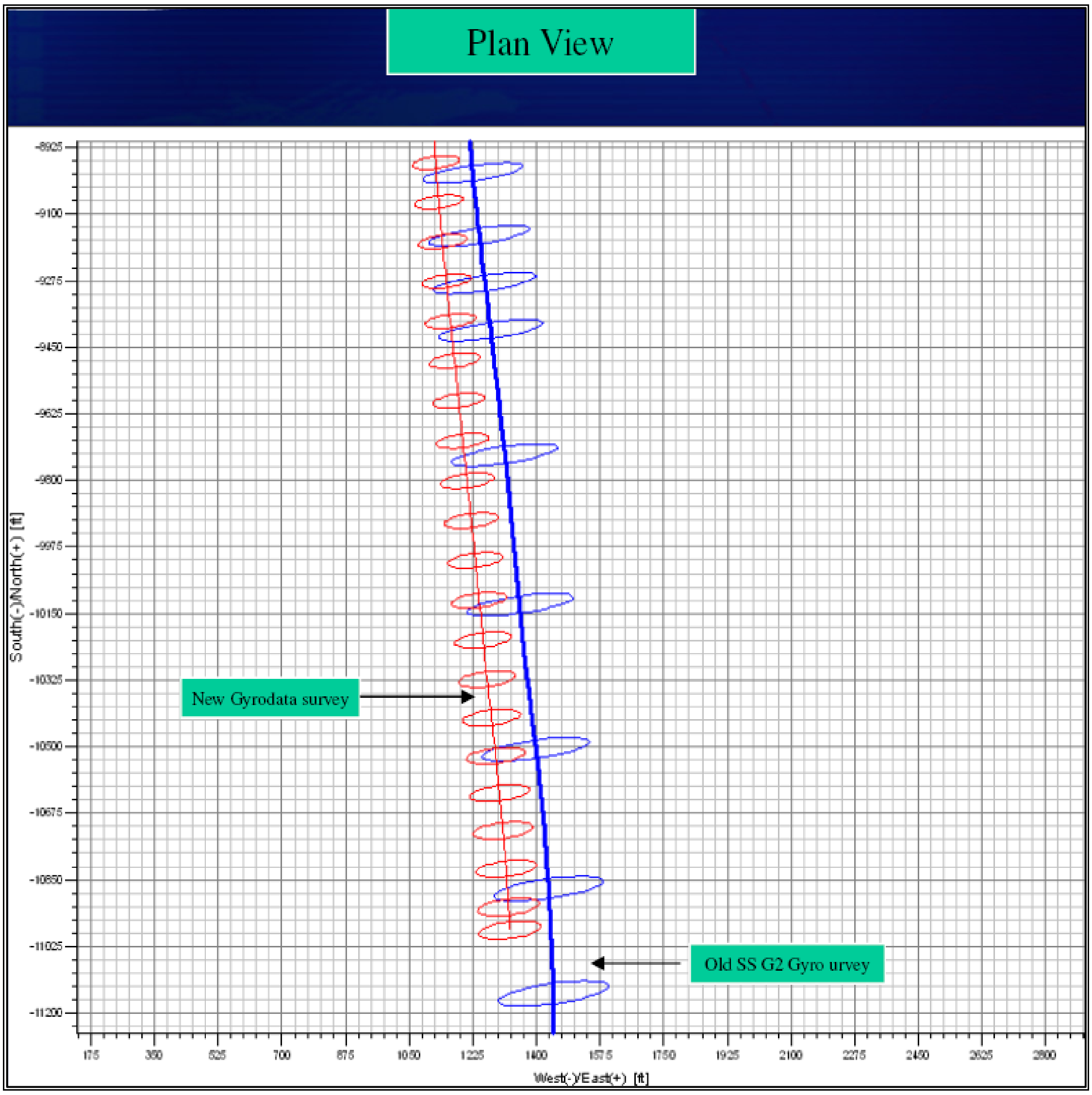
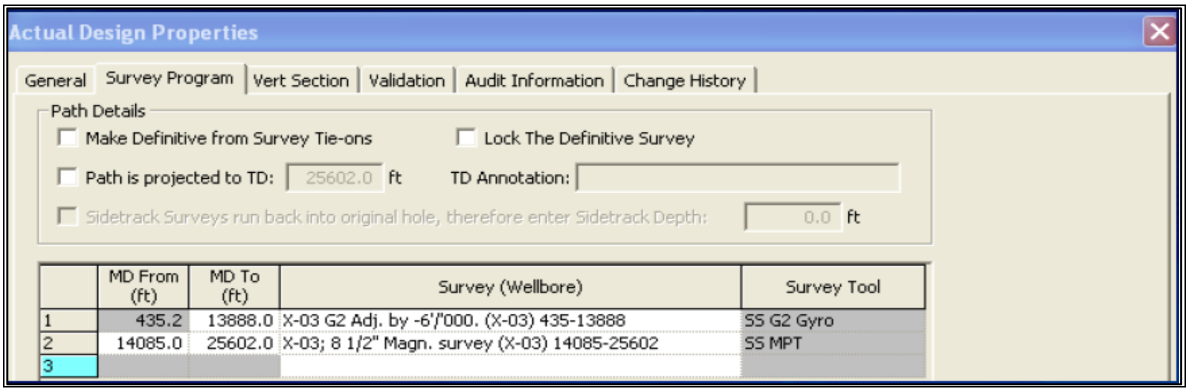


Figure 6.7: Plan View of Well B before and after resurvey. [9]

6.2.1 Survey Program, BHL & Position Uncertainty Old Well B

The old survey program of this well is in two stages. The first stage is run from 435.2 ft to 13888 ft using a Sperry Sun Gyro (SS G2 Gyro). The second stage is from 14085 ft to 25602 ft. A Sperry Sun Magnetic tool (SS MPT) was used in this stage. Table 6.10 below shows the described survey program above. Table 6.11 shows the bottomhole location (BHL) before resurvey and Table 6.12 illustrate the associated position uncertainty.

Table 6.10: Survey Program for Well B before resurvey. [9]



Path Details

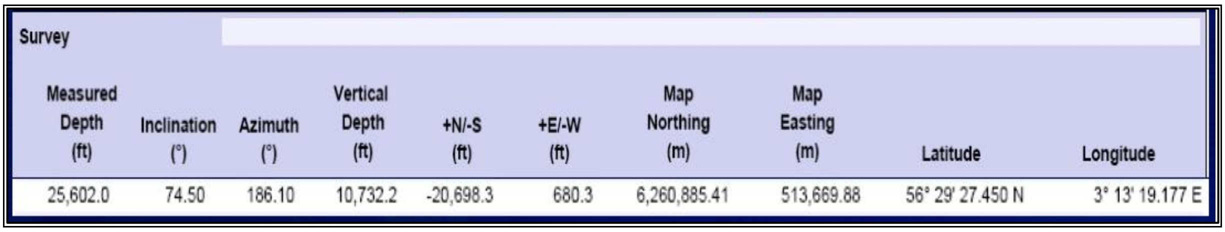
☐ Make Definitive from Survey Tie-ons ☐ Lock The Definitive Survey

☐ Path is projected to TD: 25602.0 ft TD Annotation:

☐ Sidetrack Surveys run back into original hole, therefore enter Sidetrack Depth: 0.0 ft

	MD From (ft)	MD To (ft)	Survey (Wellbore)	Survey Tool
1	435.2	13888.0	X-03 G2 Adj. by -6'/'000. (X-03) 435-13888	SS G2 Gyro
2	14085.0	25602.0	X-03; 8 1/2" Magn. survey (X-03) 14085-25602	SS MPT
3				

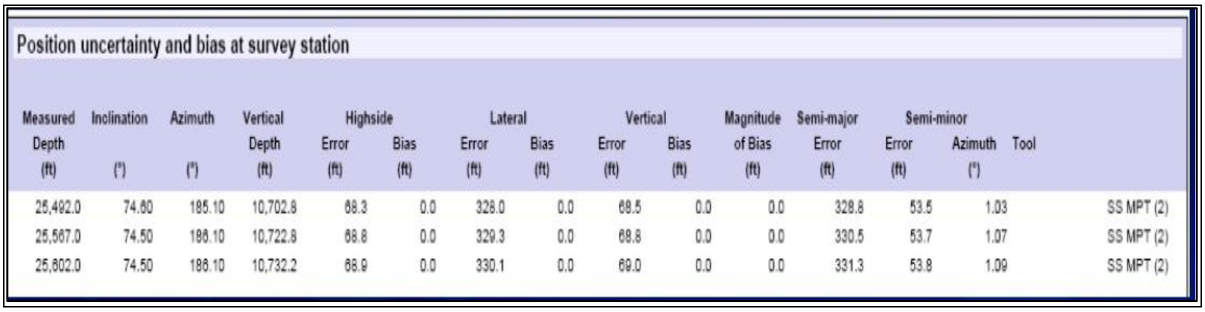
Table 6.11: Bottomhole Location for Well B before resurvey. [9]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
25,602.0	74.50	186.10	10,732.2	-20,698.3	680.3	6,260,885.41	513,669.88	56° 29' 27.450 N	3° 13' 19.177 E

Table 6.12: Position Uncertainty for Well B before resurvey. [9]



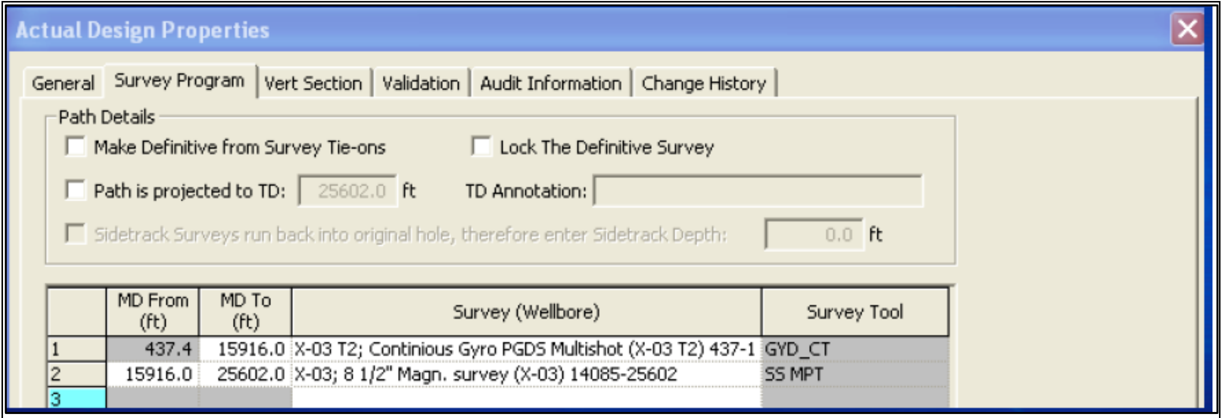
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
25,492.0	74.60	185.10	10,702.8	68.3	0.0	328.0	0.0	68.5	0.0	0.0	328.8	53.5	1.03	SS MPT (2)
25,567.0	74.50	186.10	10,722.8	68.8	0.0	329.3	0.0	68.8	0.0	0.0	330.5	53.7	1.07	SS MPT (2)
25,602.0	74.50	186.10	10,732.2	68.9	0.0	330.1	0.0	69.0	0.0	0.0	331.3	53.8	1.09	SS MPT (2)

6.2.2 Survey Program, BHL & Position Uncertainty New Well B

The new resurvey data is also in two stages. A continuous multi-shot gyroscopic tool called Continuous Gyro PGDS Multishot is used to survey the first stage from 437.4 ft to 15916.0 ft. For the second stage, survey data from Sperry Sun Magnetic tool (SS MPT) was used (tied-on) from 15916.0 to 25602.0 ft. The three tables below illustrate the new survey program, BHL and the position uncertainty consecutively.

Table 6.13: New survey program for Well B. [9]



Path Details

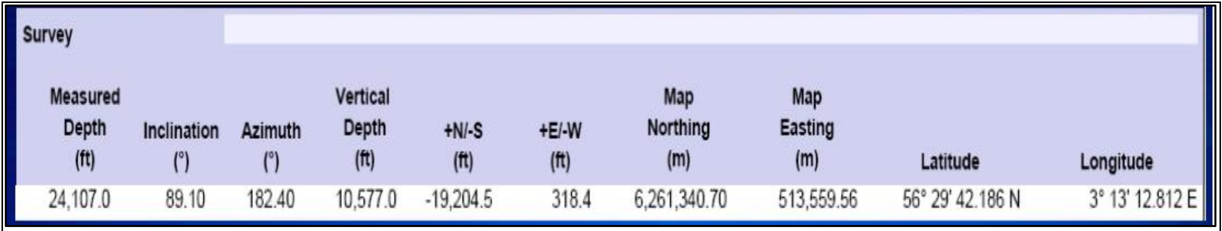
☐ Make Definitive from Survey Tie-ons ☐ Lock The Definitive Survey

☐ Path is projected to TD: 25602.0 ft TD Annotation:

☐ Sidetrack Surveys run back into original hole, therefore enter Sidetrack Depth: 0.0 ft

	MD From (ft)	MD To (ft)	Survey (Wellbore)	Survey Tool
1	437.4	15916.0	X-03 T2; Continious Gyro PGDS Multishot (X-03 T2) 437-1	GYD_CT
2	15916.0	25602.0	X-03; 8 1/2" Magn. survey (X-03) 14085-25602	SS MPT
3				

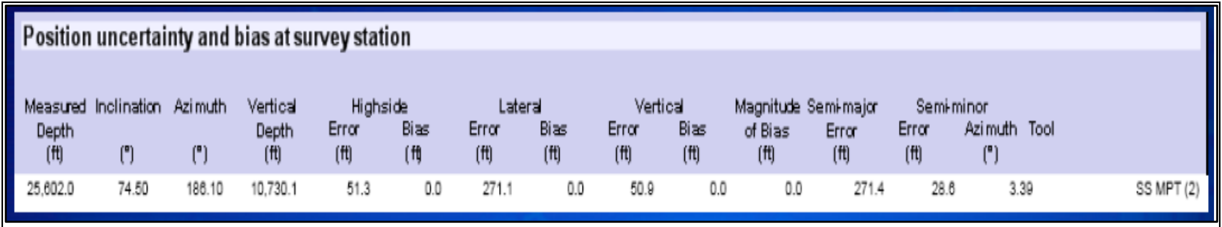
Table 6.14: New BHL after resurvey for Well B. [9]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
24,107.0	89.10	182.40	10,577.0	-19,204.5	318.4	6,261,340.70	513,559.56	56° 29' 42.186 N	3° 13' 12.812 E

Table 6.15: New Position uncertainty for Well B. [9]



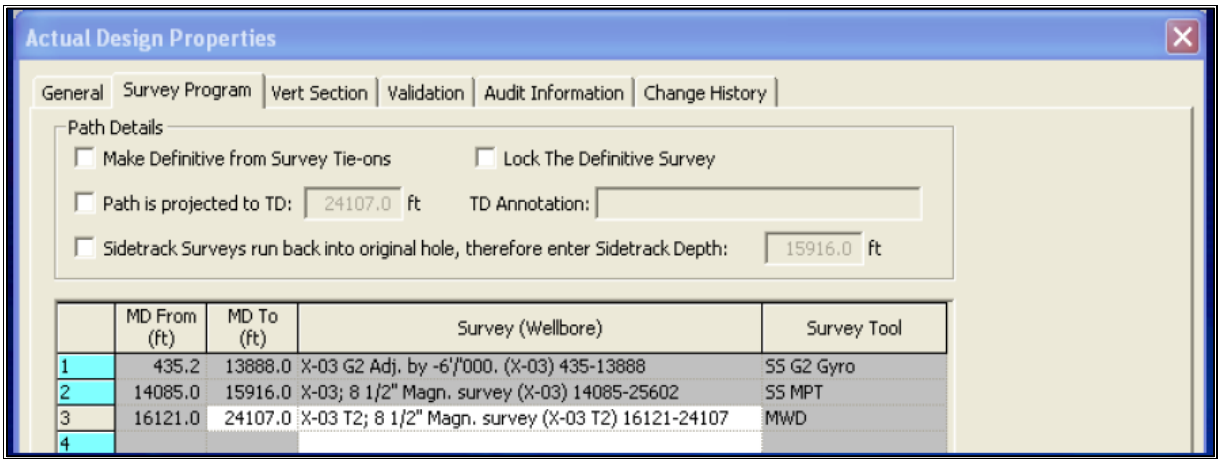
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
25,602.0	74.50	186.10	10,730.1	51.3	0.0	271.1	0.0	50.9	0.0	0.0	271.4	28.6	3.39	SS MPT (2)

6.2.3 Survey Program,BHL & Position Uncertainty Old Well BT2

The sidetrack Well BT2 old survey program is in three stages. The first and second stage is the same as for the main bore Well B (Table 6.10 above). The side tracking started after the 9 5/8 inch casing and the well was surveyed from 16121.0 to 24107.0 ft. using a magnetic survey tool MWD.

Table 6.16: Old Survey Program for Well B T2. [9]



Path Details

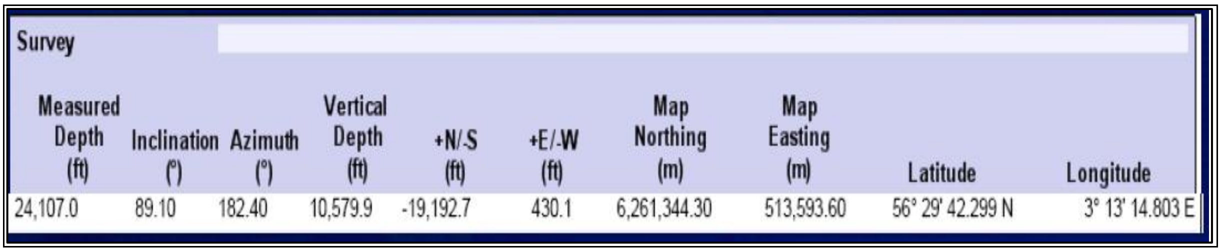
☐ Make Definitive from Survey Tie-ons ☐ Lock The Definitive Survey

☐ Path is projected to TD: 24107.0 ft TD Annotation:

☐ Sidetrack Surveys run back into original hole, therefore enter Sidetrack Depth: 15916.0 ft

	MD From (ft)	MD To (ft)	Survey (Wellbore)	Survey Tool
1	435.2	13888.0	X-03 G2 Adj. by -6'/'000. (X-03) 435-13888	SS G2 Gyro
2	14085.0	15916.0	X-03; 8 1/2" Magn. survey (X-03) 14085-25602	SS MPT
3	16121.0	24107.0	X-03 T2; 8 1/2" Magn. survey (X-03 T2) 16121-24107	MWD
4				

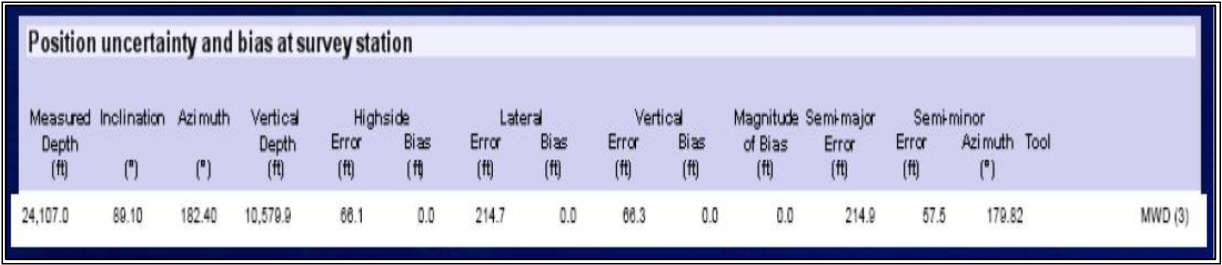
Table 6.17: BHL before resurvey for Well B T2. [9]



Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
24,107.0	89.10	182.40	10,579.9	-19,192.7	430.1	6,261,344.30	513,593.60	56° 29' 42.299 N	3° 13' 14.803 E

Table 6.18: Position uncertainty before resurvey for Well B T2. [9]



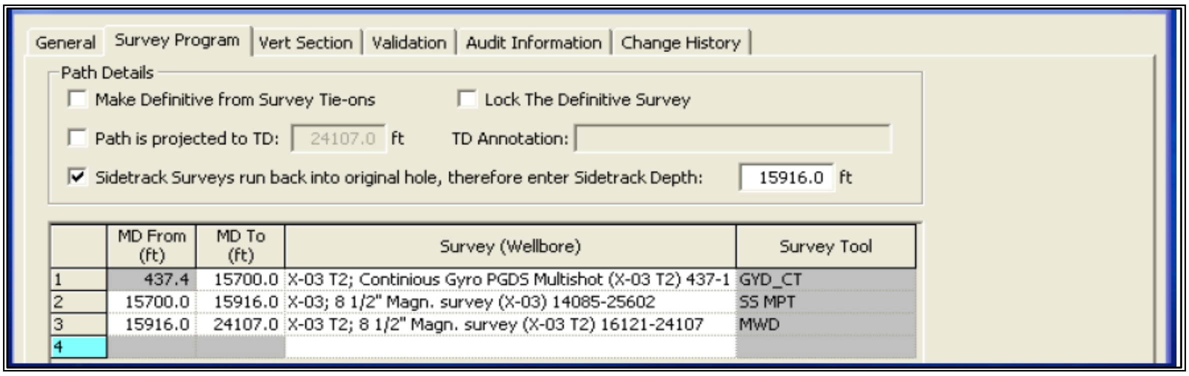
Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
24,107.0	89.10	182.40	10,579.9	66.1	0.0	214.7	0.0	66.3	0.0	0.0	214.9	57.5	179.82	MWD (3)

6.2.4 Survey Program,BHL & Position Uncertainty New Well BT2

The new survey program for sidetrack X-03 T2 is divided into three stages. A continuous multi-shot gyro was used for the first stage running from 437.4 ft to 15700.0 ft. For the second stage, from 15700.0 ft to 15916.0, tie-on from SS MPT magnetic tool was used .The third stage runs from 15916 ft to 24107.0 ft and a MWD survey tool was used.

Table 6.19: New survey program for Well B T2. [9]



☐ Make Definitive from Survey Tie-ons

☐ Lock The Definitive Survey

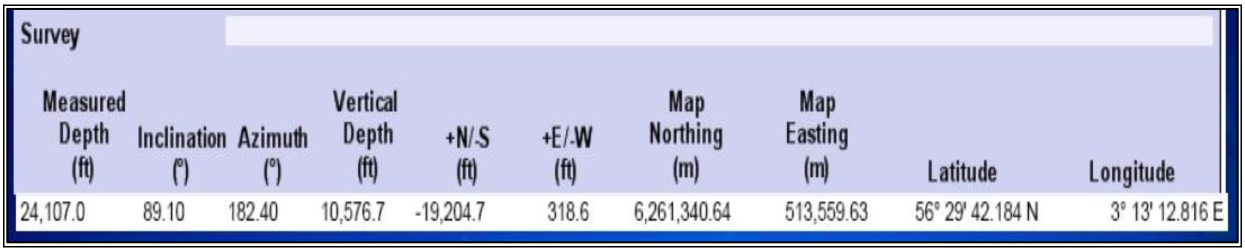
☐ Path is projected to TD: 24107.0 ft

TD Annotation:

☑ Sidetrack Surveys run back into original hole, therefore enter Sidetrack Depth: 15916.0 ft

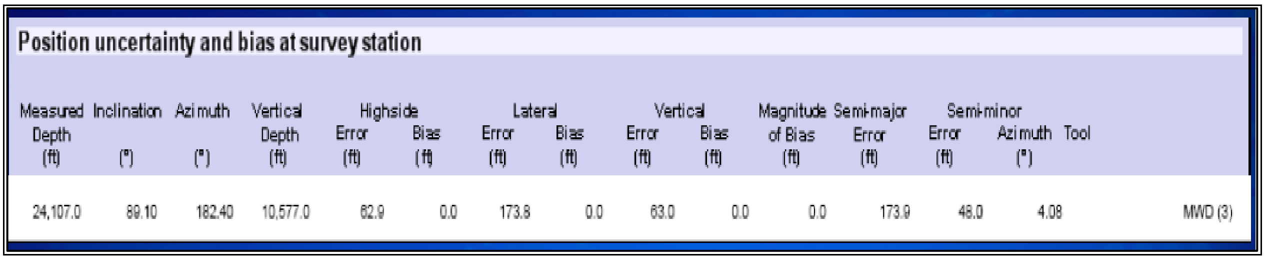
	MD From (ft)	MD To (ft)	Survey (Wellbore)	Survey Tool
1	437.4	15700.0	X-03 T2; Continious Gyro PGDS Multishot (X-03 T2) 437-1	GYD_CT
2	15700.0	15916.0	X-03; 8 1/2" Magn. survey (X-03) 14085-25602	SS MPT
3	15916.0	24107.0	X-03 T2; 8 1/2" Magn. survey (X-03 T2) 16121-24107	MWD
4				

Table 6.20: New BHL after resurvey for Well B T2. [9]


Survey

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	+N/-S (ft)	+E/-W (ft)	Map Northing (m)	Map Easting (m)	Latitude	Longitude
24,107.0	89.10	182.40	10,576.7	-19,204.7	318.6	6,261,340.64	513,559.63	56° 29' 42.184 N	3° 13' 12.816 E

Table 6.21: New Position uncertainty for Well B T2. [9]


Position uncertainty and bias at survey station

Measured Depth (ft)	Inclination (°)	Azimuth (°)	Vertical Depth (ft)	Highside Error (ft)	Highside Bias (ft)	Lateral Error (ft)	Lateral Bias (ft)	Vertical Error (ft)	Vertical Bias (ft)	Magnitude of Bias (ft)	Semi-major Error (ft)	Semi-minor Error (ft)	Semi-minor Azimuth (°)	Tool
24,107.0	89.10	182.40	10,577.0	62.9	0.0	173.8	0.0	63.0	0.0	0.0	173.9	48.0	4.08	MWD (3)

6.2.5 Comparison, Discussion and Consequences

There are clear differences in the position uncertainty of Well B for before and after resurvey (Figure 6.8). As shown in Table 6.12 and 6.15 above, at the same measured depth (MD) of 25602 ft. ,Well B shows the following errors before resurvey: Highside error = 68.9 ft. , Lateral error = 330.1 ft., Vertical error = 69 ft., Semi-major error = 331.3 ft. and Semi-minor error = 53.8 ft. After resurvey of Well B, the following reduced positional errors are obtained at the same measured depth (MD = 25602 ft.): Highside error = 51.3 ft., Lateral error = 271.1 ft., Vertical error = 50.9 ft., Semi-major error = 271.4 ft. and Semi-minor error = 28.6 ft.

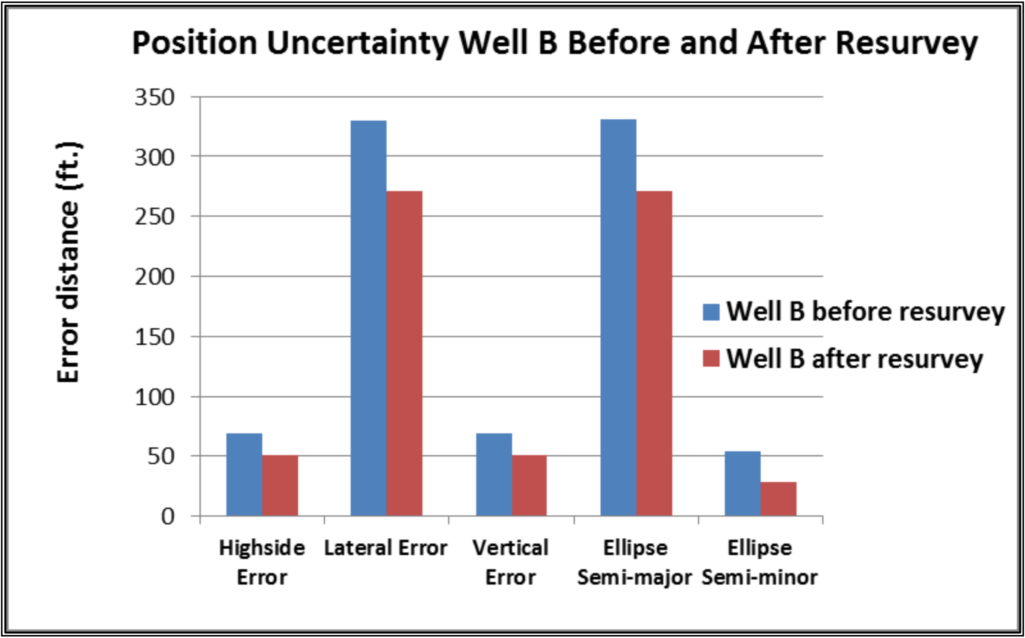


Figure 6.8: Comparison Position Uncertainty for Well B (Excel Analysis).

Figure 6.9 below illustrates the comparison of position uncertainty of Well B T2 before and after resurvey. As shown in Table 6.18 above, at MD of 24107 ft. the position uncertainty of Well B T2 is given as follows: Highside = 66.1 ft., Lateral error = 214.7 ft., Vertical error = 66.3 ft., Ellipse Semi-major error = 214.9 ft. and Ellipse Semi-minor error = 179.82 ft. The position uncertainty of Well B T2 after resurvey is illustrated in Table 6.21 at the same measured depth of 24107 ft. This is given as follows: Highside = 62.9 ft., Lateral error = 173.8 ft., Vertical error = 63.0 ft., Ellipse Semi-major error = 173.9 ft. and Ellipse Semi-minor error = 48.0 ft.

Figure 6.9 below illustrates the comparison between the position uncertainty of Well B T2 before and after resurvey.

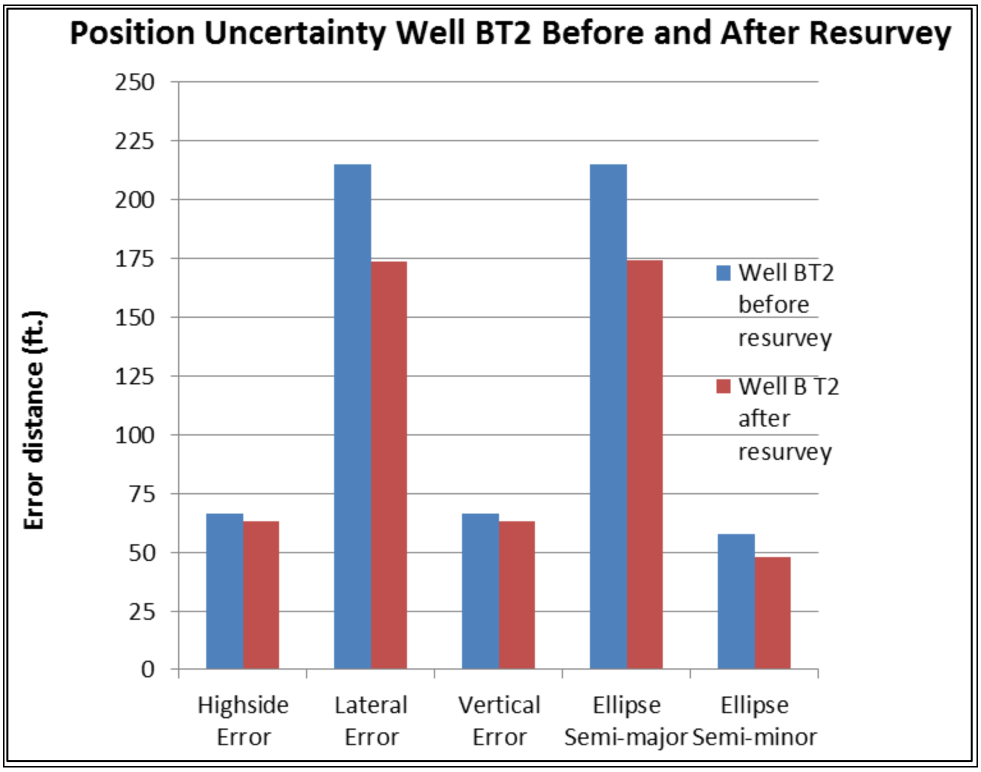


Figure 6.9: Comparison Position Uncertainty for X-03 T2 (Excel Analysis).

7 Suggested New Technologies and Work Practices

In Chapter 7, some New Technologies and Work Practices will be suggested for planning and drilling of future wells. The following shall be discussed : MAP-Method, Multi-Disciplinary Approach, Gyro-MWD Technology and Wired Drillpipe (WDP)Technology.

7.1 MAP- A New Wellbore Position Calculation Method

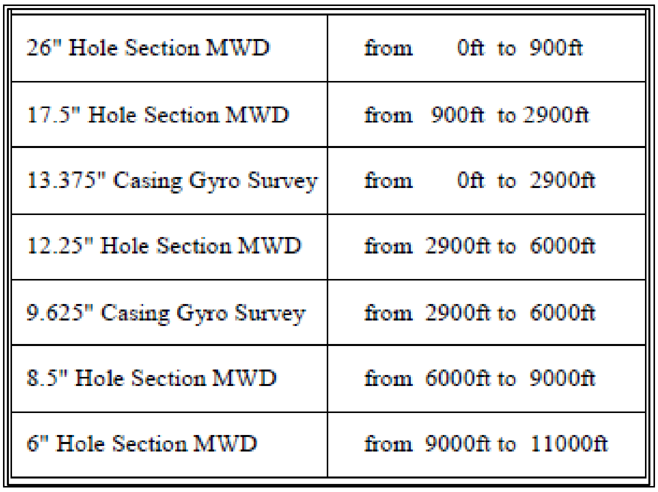
Today, the accepted practice for defining the wellbore position and its associated uncertainty, involves acceptance of the position obtained from the most accurate survey tool employed in each section of the well. It is becoming a common practice to survey each section of a modern wellbore many times for position by using one or more survey instruments; magnetic, gyroscopic or inertial survey instruments.

C.R. Chia et al. [15] presented a new wellbore position calculation method called the “Most Accurate Method” (MAP). The “Most Accurate Position” is a new wellbore position calculation method that statistically combines multiple wellbore surveys from survey instruments run in a given section into a single composite and more accurate well position.[15]

In this section, a practical example of the application of the “Most Accurate Position” will be given. This will be illustrated with figures and some explanations will be provided.

The Table 7.1 below shows a typical survey program for a planned direction well.

Table 7.1: Example survey Program. [15]



26" Hole Section MWD	from 0ft to 900ft
17.5" Hole Section MWD	from 900ft to 2900ft
13.375" Casing Gyro Survey	from 0ft to 2900ft
12.25" Hole Section MWD	from 2900ft to 6000ft
9.625" Casing Gyro Survey	from 2900ft to 6000ft
8.5" Hole Section MWD	from 6000ft to 9000ft
6" Hole Section MWD	from 9000ft to 11000ft

Figure 7.1 below illustrates a schematic plan view of the well position and the ellipse of uncertainty (EOU) for each part of the survey program. This further shows the scale of the EOU at the different Measurement While Drilling (MWD) survey and casing survey stages.

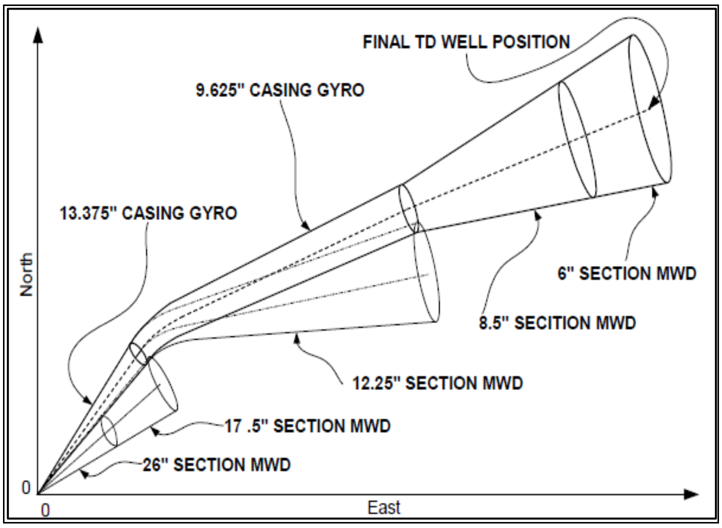


Figure 7.1: Schematic plan view of an example survey program for planned directional well. [15]

The example survey program in Table 7.1 above shows that the 26'' hole section and 17.5'' hole section are drilled before the 13.375''casing gyro was performed in the surface casing string. The resultant gyro survey usually exhibits significant shift in well position from the drilling surveys. But as long as the ellipse of uncertainty touches this can be statistically accepted. The 13.375''casing gyro survey is then used to update the current well position before the drilling of the next hole section commences. The drilling surveys of the 12.25`` hole section is tied on the 13.375''casing gyro until the section is drilled and the new casing gyro (9.625'') is carried out to validate and update the position of the well. The same steps are carried out to drill to target depth. [15]

According to C.R. Chia et al. [15] the method employed in Figure 7.1 is a less technically robust alternative compared to the MAP technique because only the single most accurate survey is used to update the position of the well despite several sections of the well have been surveyed more than once.

Figure 7.2 below illustrates a schematic plan view for the same planned directional well for the first series of drilling surveys and the first casing gyro survey. As shown in Figure 7.2, MAP technique is employed, where each of the overlapping surveyed datasets are combined to provide the most statistically correct position of the well and a reduced position uncertainty at current stage of drilling the well. In this case, the drilling survey of the next section is not tied on the 13.375 casing gyro, instead the MAP position (MAP Part 1) in the figure is used as the most accurate position and for the update of the wellpath. One can also see that the EOU of MAP Part 1 is smaller than the gyro survey alone.

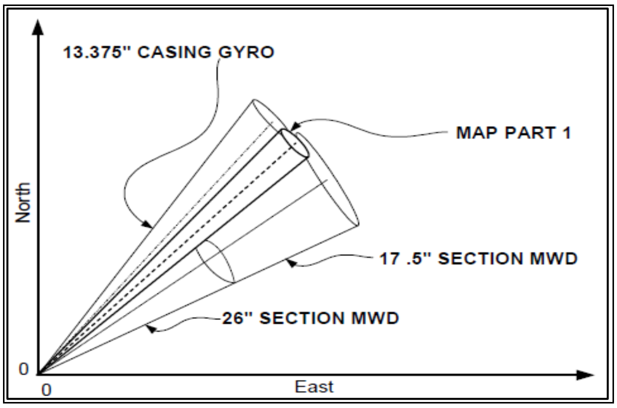


Figure 7.2: MWD (26'' and 17.5'' hole section) survey and Casing Gyro (13.375'') survey with tie-on point MAP Part 1. [15]

The Most Accurate Position and a reduced EOU is again obtained from the combination of the intermediate casing gyro survey and the MWD surveys as drilling progress continues. Both the intermediate casing gyro and the drilling surveys had been tied onto and continued from the position of the MAP Part 1 to provide a new tie-on point called MAP Part 2. The described scenario can be shown in Figure 7.3 below.

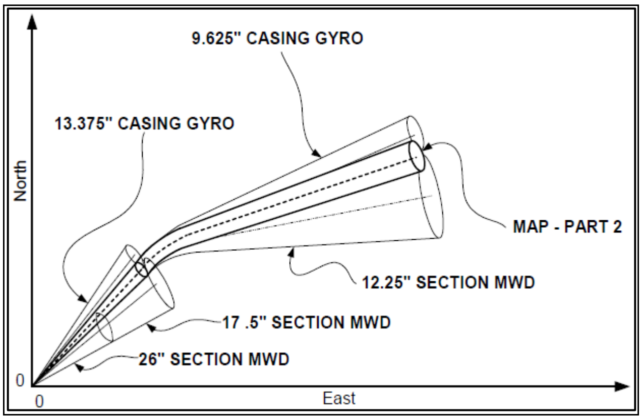


Figure 7.3 : 12.25'' hole section MWD survey and Intermediate Casing Gyro (9.625'') survey with tie-on point MAP Part 2. [15]

Figure 7.4 below shows that the 8.5’’ hole section and 6’’ hole section are drilled and surveyed with MWD surveys. The completion of these two sections indicates the end of the survey program and the final wellbore position is obtained. The figure also shows the contrast between the traditional approach (in Figure 7.1) and the new wellbore position calculation method i.e. MAP method. It can be clearly seen that the MAP method is a more suitable approach to wellbore positioning problem, where all available survey data from the survey program had been used.

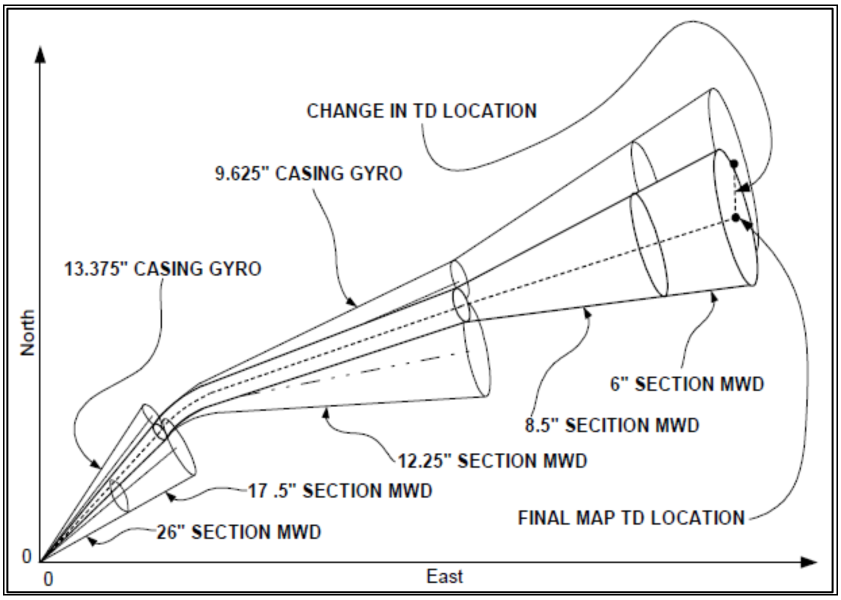


Figure 7.4: MAP technique vs. Traditional Approach. [15]

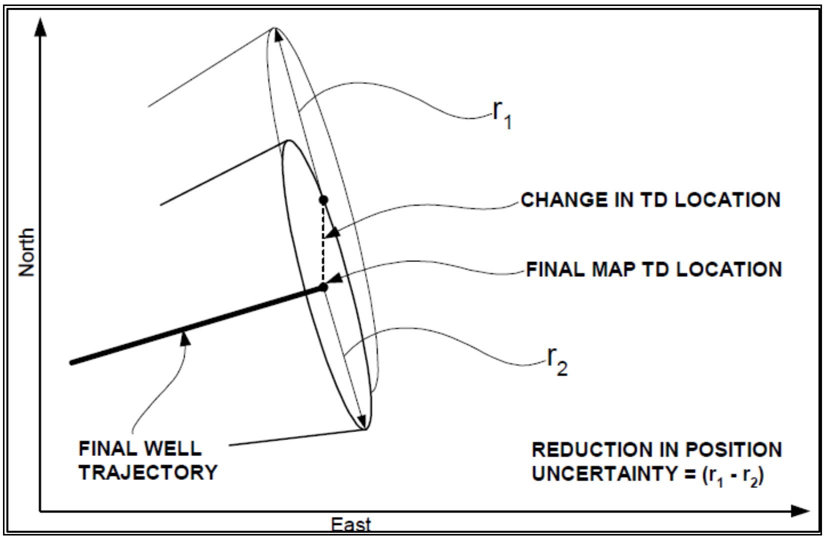


Figure 7.5: The Final MAP in Expanded View. [15]

Figure 7.5 above shows the final section and the end of the well in an expanded view. An overall change in the well position is shown with a significant reduced position uncertainty as a result of application of the Most Accurate Position (MAP) technique.

Advantages and Benefits of MAP

MAP’s main advantage is that the uncertainty is much smaller than any of the constituent surveys. MAP has major benefits of being able to drill smaller targets at larger distances, drilling of new wellbores in closer proximity to existing wellbores while maintaining accepted safety clearance rules, and improved reservoir delineation. [15]

7.2 Cooperation between Drilling and Geosciences for Well Planning Quality Improvement.

There have never been stronger emphases placed on improvement of the quality of well planning and reduction in risks associated to drilling complex wells than today. This course has led the Exploration and Production companies on a quest for an efficient, cost effective and multi-disciplinary, technology and work flow. This section of Chapter 7 will present a new software package developed by Roxar. The software package is a result of a collaborative work between Roxar and TotalFinaElf (TFE) with the aim of improving the quality of well planning focusing solely on multi-disciplinary (drilling, reservoir, geology and geophysics) work flow with the aid of three dimensional visualization tools. The functionality of this software will be discussed in the sub-sections below.

7.2.1 Multi-disciplinary Well Design

According to Eric Cayeux et.al [17] , the members of a multi-disciplinary team in well planning are expected to devote most of their time in evaluating different conceptual solutions rather than focusing on irrelevant details. To help in doing so, the steps of the well design has to be streamlined as much as possible in order to increase the process efficiency. Furthermore, interactive graphics can be used to enhance communication between members of the multi-disciplinary team due to limited or no knowledge of the concepts used in their individual discipline. Eric Cayeux et. al stated that "… each discipline might have its own requirements on the geometry of the path, drilling is, in the last resource the most constraining one, both in terms of geometric outlook and feasibility evaluation."

The following requirements are set for a system used to assist multidisciplinary asset teamwork [17]:

- The user shall have access to a whole range of graphical functions for both representing the data and positioning the geometric elements of the design using intuitive interactions
- In order to avoid interaction with numerical inputs, generation of target and well tracks shall be completely automatic.

- Availability of quick and precise evaluation functions to validate the feasibility of the design.

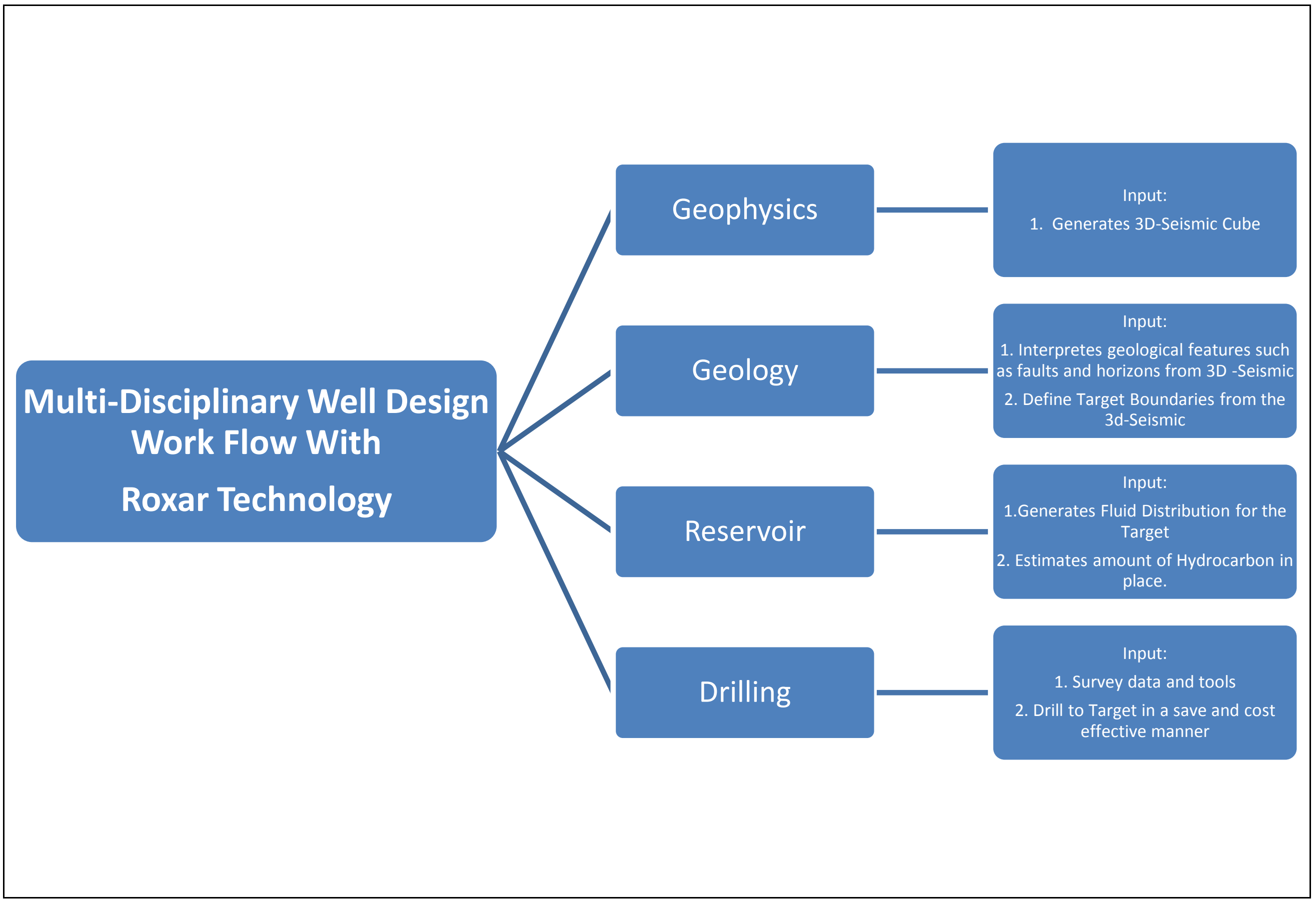


Figure 7.6: Multi-Disciplinary Well Design Discipline Inputs

Figure 7.6 above shows the various input from each discipline of a Multi-Disciplinary asset team and Figure 7.7 below illustrates the Multi-Disciplinary Work Flow employed in the Roxar Technology.

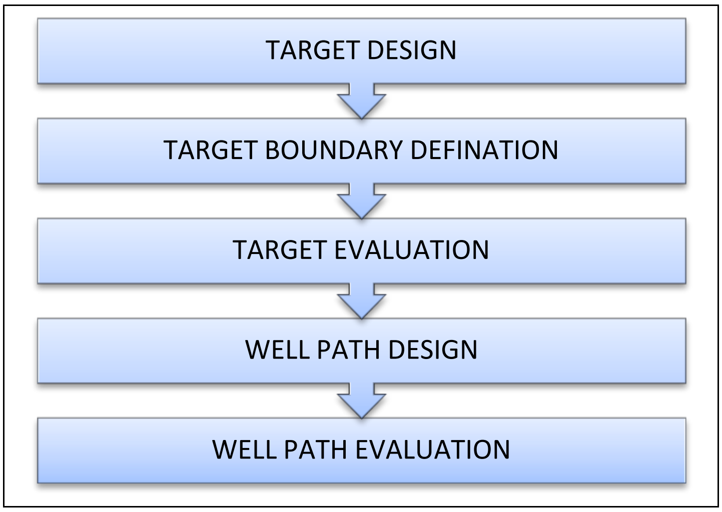


Figure 7.7: Multi-Disciplinary Well Design Work Flow Stages with Roxar Technology

7.2.1.1 Target Design

In a multi-disciplinary well design work flow, the stage that requires the most input from all the disciplines is the target design. A target axis shall respects constraints classified in three categories as follows: the direction of the target, curvature limits and vertical distance to formation tops or fluid contacts.

The Figure 7.6 below illustrates how target control points are used to define a target axis. It can be seen that both the position and the tangent at the control points affects the shape of the curve.

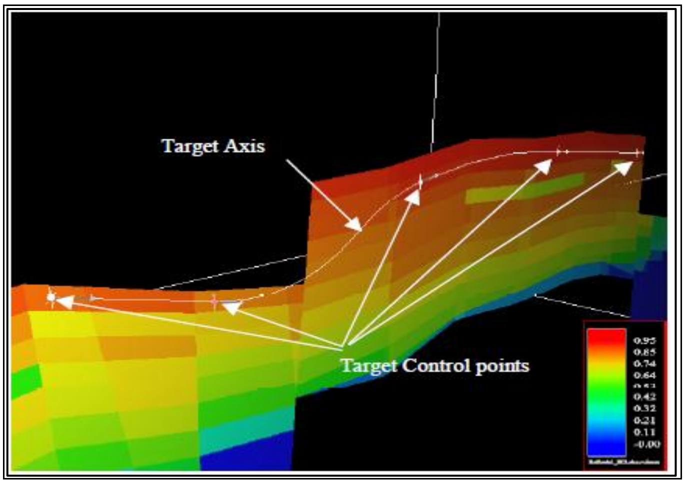


Figure 7.8: Building of Target Axis Using Target Control Points in Roxar Technology. [17]

7.2.1.2 Target Boundary Definition

In the reservoir, the target axis represents the optimum placement of the well. It is important to capture the acceptable limits for the final well position, since it is uncertain that the final well track will be precisely on top of the ideal curve. The boundary can either have an elliptical or rectangular shape. With available information from seismic data, structural model, volumetric petrophysical properties or reservoir, the limits of the boundary can be adjusted graphically.

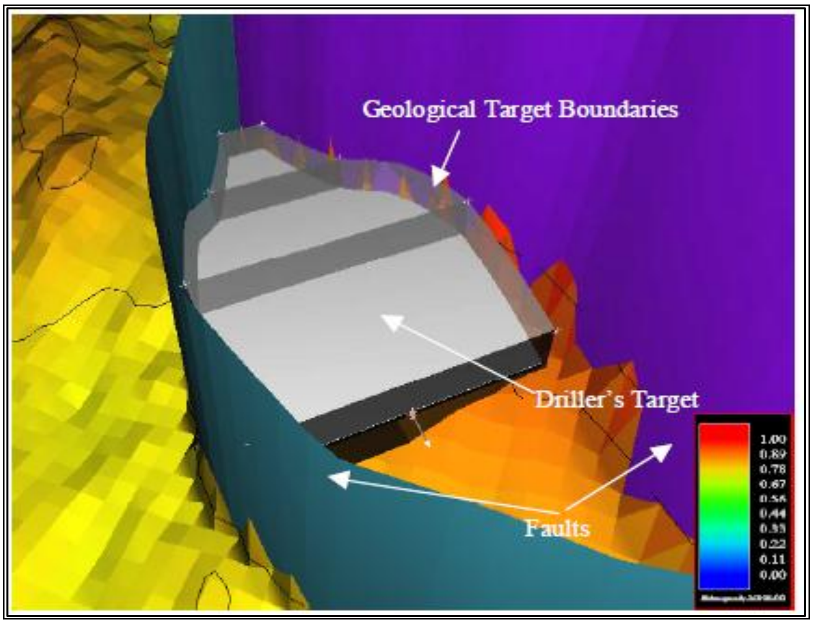


Figure 7.9: Defined Target and Target Geological Boundaries. [17]

7.2.1.3 Target Evaluation

Target Evaluation is the third stage of the Multi-Disciplinary work flow. This stage involves calculation of the hydrocarbon volume associated with the target axis. To estimate the bulk and fluid volumes, geometric filters and cell connectivity are used. In case of a time dependent evaluation, a streamline simulator, a near wellbore simulator or full field simulation can be used.

7.2.1.4 Well Path Design

Planned trajectories have been traditionally generated by using two types of approaches: "section-based" and "the spreadsheet methods". These two methods require a lot of input and vast knowledge of drilling practices and both are time consuming. In the Multi-Disciplinary work flow, the well path is generated by using an "iterative procedure". This procedure includes a new constraint at each step and the drilling program is readjusted according to the intersection with tops of formation. Figure 7.10 below shows the generated well path where using drilling program containing set constraints relative to formation tops. [17]

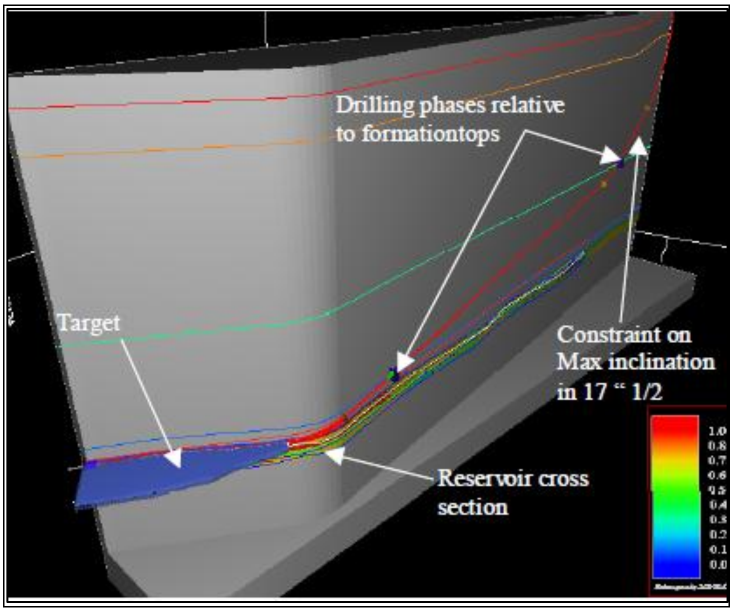


Figure 7.10: Generated Well Path Using a Drilling Program.[17]

7.2.1.5 Well Path Evaluation

In this stage by using a surveying program, the uncertainty on the wellbore position can be evaluated. The obtained uncertainty can thus be used to evaluate the proximity to geological features, generating a driller's target from the geological target. The uncertainty can also be used for anti-collision analysis: comparison to other wells or geological features such as faults, salt domes etc. It is also possible to run drill-string mechanical evaluations. Figure 7.11 and 7.12 below show anti-collision analysis and mechanical evaluation.

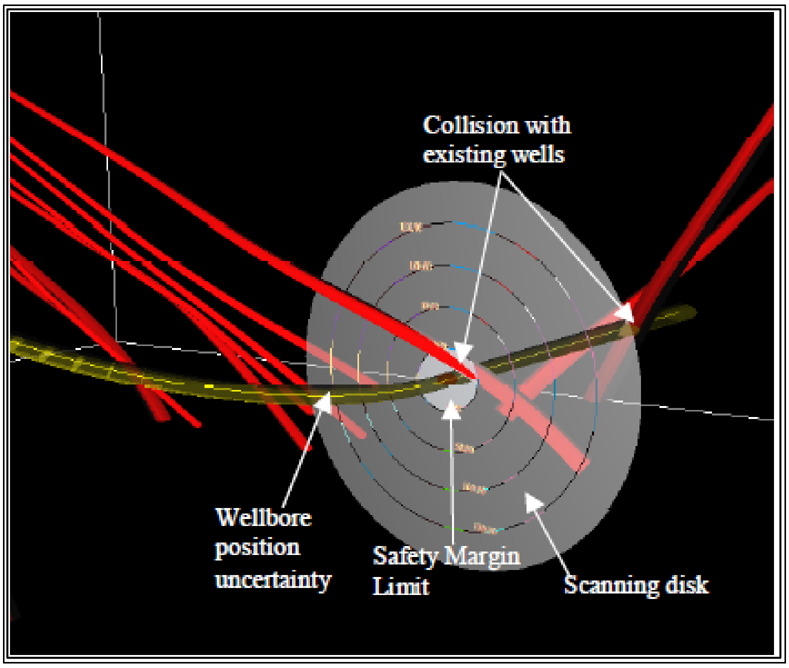


Figure 7.11: Collision Scanning[17]

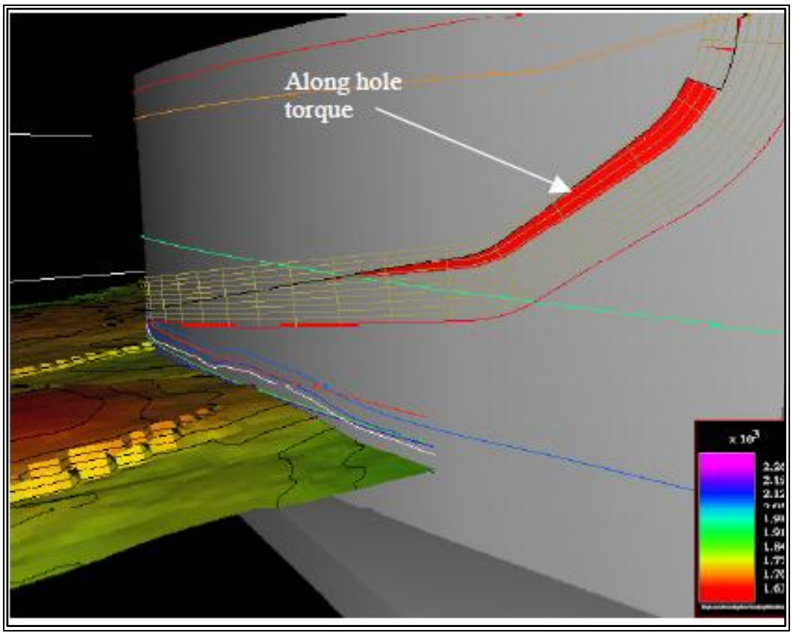


Figure 7.12: Along hole torque excess in top hole section for 8 1/2 " drilling string in drilling with rotation. [17]

7.3 Gyro Technology

In early 2001 Gyro Measurement While Drilling (MWD) Technology was first introduced and utilized. The idea was to replace the old, less accurate Gyro Single-Shot survey system for some certain applications, but due to high running cost of Gyro MWD at that time, Gyro Single-Shot maintained its domination of the market. The recent increase in oil prices, drilling activities and limited supply of rigs worldwide has caused the rig rates to increase dramatically. This has thus resulted in operating companies to look for ways to improve operation time and reduce nonproductive time (NPT) in order to optimize operations.[18]

7.3.1 Gyro Single-Shot Survey

Gyro Single-Shot orientation tools are normally run into the well using wireline. The tool is located above the motor or a standard MWD. Gyro Single-Shot tool is typically run every 50 ft to 100 ft. This will continue until the wellbore is cleared of magnetic interference, which can take up to 10 runs or more during a difficult kick off. The average run time depends on depth, for each run it can take 30-60 minutes. Figure 7.13 shows a typical Gyro Single-Shot Survey Tool. [18]

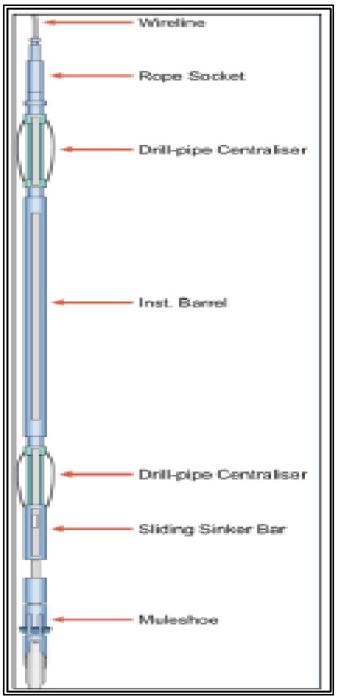


Figure 7.13: Gyro Single-Shot Survey Tool [18]

7.3.2 Gyro-MWD Technology

The main reasons for the development of Gyro-MWD are: to aid the directional driller by having the gyro sensors as close as possible to the bit, have the ability to obtain quick gyro orientation survey data in real-time, improve the quality and accuracy of survey data, save rig time and reduce NPT .

The Gyro-MWD tool face is real-time that enables survey data to be transfer to the surface in 3 minutes. In Gyro-MWD, magnetic MWD and gyro readings are obtained, which indicate clearance from magnetic interference present in the wellbore. [18]

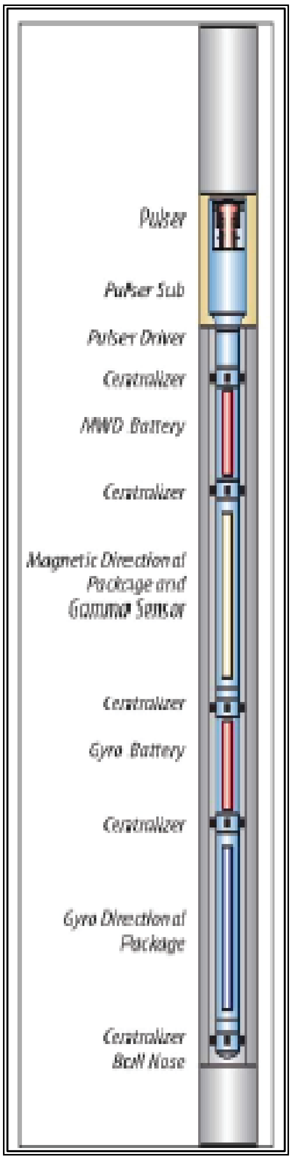


Figure 7.14: Gyro-MWD Survey Tool [18]

Advantages of Gyro-MWD

The advantages of Gyro-MWD Technology can be divided into five categories: safety, wellbore geometry, rate of penetration (ROP), time saving and others. [18]

Safety:

- Facilitate a more safer operation compare to Gyro Single-Shot
- No need for wireline unit and additional personnel to operate it.
- Reduced chances of collision with existing wells and
- Enables accurate wellbore survey.

Wellbore Geometry:

- Provides a better wellbore geometer avoiding the directional driller drilling 50 ft. to 100 ft. “blind”.
- Smoother wellbore profile is drilled with no unexpected left/right turns or doglegs due to the real-time inclination and azimuth readings (Figure 7.15).
- Reduced problems in running casing due to smoother well profile compared to wells drilled with conventional Gyro Single-Shot system (Figure 7.16)

Rate of Penetration (ROP)

- No need to stop and circulate before running the gyro
- No need to control the weight on bit (WOB). Optimum ROP is maintained.

Time Saving:

- Increase in rig time savings: high ROP, less time spent in obtaining surveys, no standby time between connections, reduced hole cleaning and circulating time, lesser time in running casing and tripping in/out of hole.

Other Applications:

- For orienting and setting whipstocks for sidetracking wells where regular MWD tools are affected by magnetic interference.

Figure 7.15 illustrates a wellbore geometry spider plot of a surface section planned versus the actual drilled using Gyro-MWD technology survey tool. Figure 7.16 shows a spider plot of a surface section planned versus the actual drilled using Wireline Gyro-Single-Shot survey instrument.

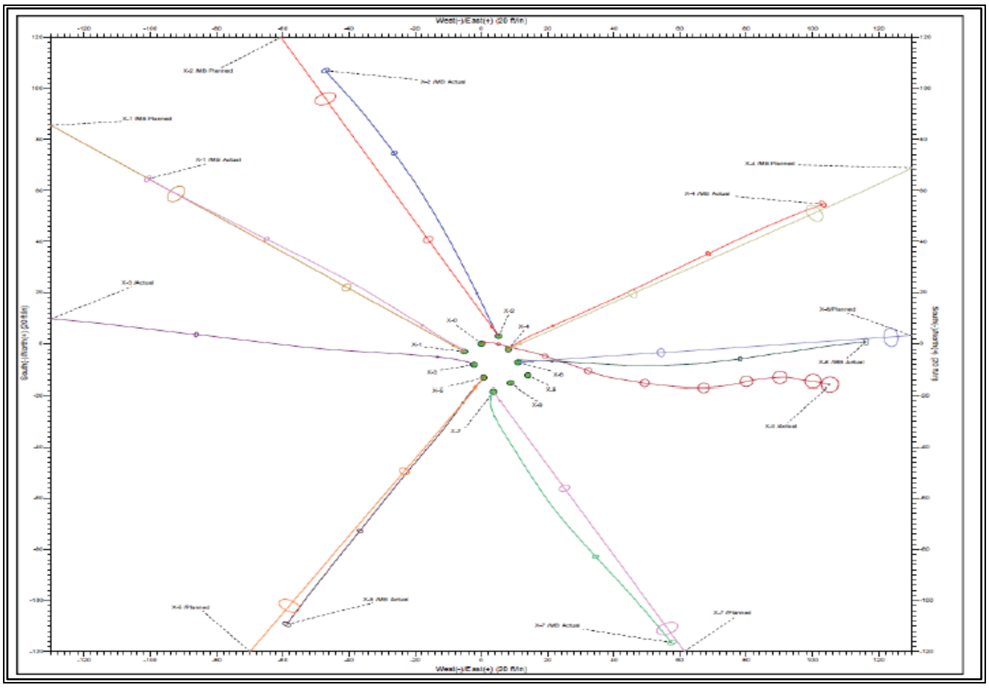


Figure 7.15: Wellbore Geometry- Planned vs. Actual Drilled using Gyro-MWD system [18]

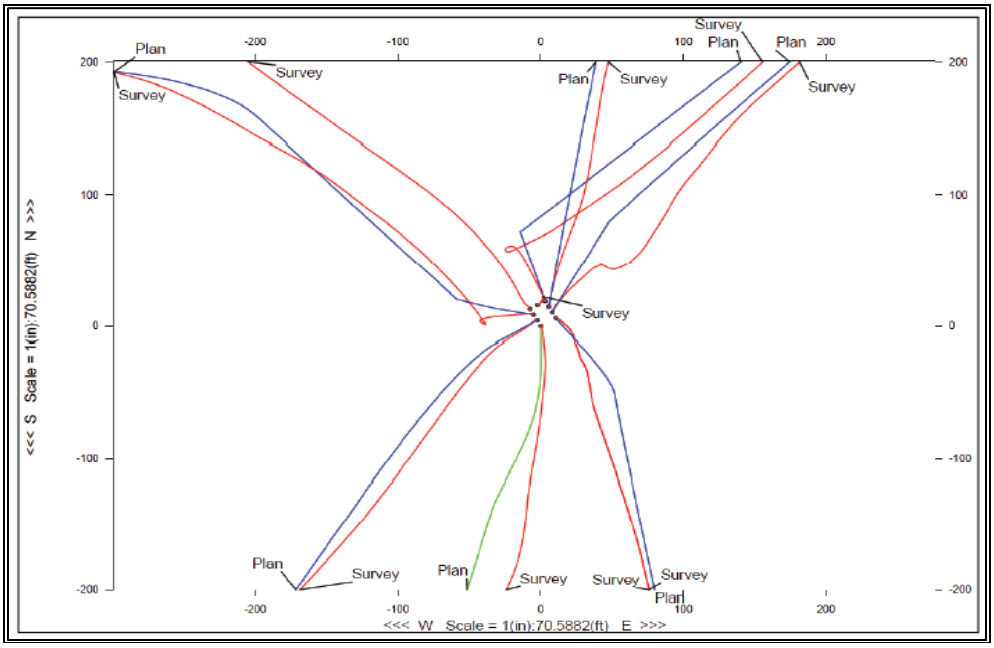


Figure 7.16: Wellbore Geometry- Planned vs. Actual Drilled using Gyro Single-Shot [18]

7.4 Wired Drill Pipe (WDP) Telemetry

One of the new emerging and promising technology for real-time data transmission is the Wired Drill Pipe Technology. The development of this technology came as a result of collaborative work between Statoil (formerly StatoilHydro), Schlumberger, GrantPrideco and IntelliServe in 2005/2006. The reasons for introducing this technology are listed below [19]:

- Improved HSE during drilling operations due to better well control;
- Improved well placement and interpretation of geology in real-time using new tools and technologies to reduce reservoir uncertainties, especially in ERD wells;
- Reduced non-productive time (NPT) in the drilling process with better utilization of time and depth based data;
- Greatly improved ability to transmit high frequency data from downhole to surface to make better and faster decisions.

According to T.S. Olberg et al. (2008) the WDP technology was successfully tested on the Visund Field (operated by Statoil) in the Norwegian North Sea .The test carried out was in two fold. The first part is the hardware and process operation of the wired drill pipe with a full range of MWD and LWD tools (see Figure 7.17 below). The second part of the test focus on the use of the acquired data in real-time by a multi-disciplinary team who turn data into valuable information to enhance decision making during drilling operations.

In the pilot test of the technology, WDP telemetry allows for several orders of magnitude increase in data transmission rates. Data were transmitted 10 000 times the fast mud telemetry and there is prospect of increasing the transmission rate to 1 megabit per second.

7.4.1 Wired Drill Pipe BHA, Data Flow and Processing

Figure 7.17 below shows the Bottomhole Assembly (BHA) used in the Wired Drill Pipe pilot test. As shown in the figure, the BHA is divided into two sections: the upper BHA and the Lower BHA section. The upper BHA consists of the heavy weight drill pipes (HWDP), jars, stabilizers, under reamer and the wired drill pipe (WDP) interface. The lower BHA section consists of stabilizer, LWD sub (sonic, nuclear and resistivity), MWD (directional measurement), rotary steerable system (RSS) and the bit. [19]

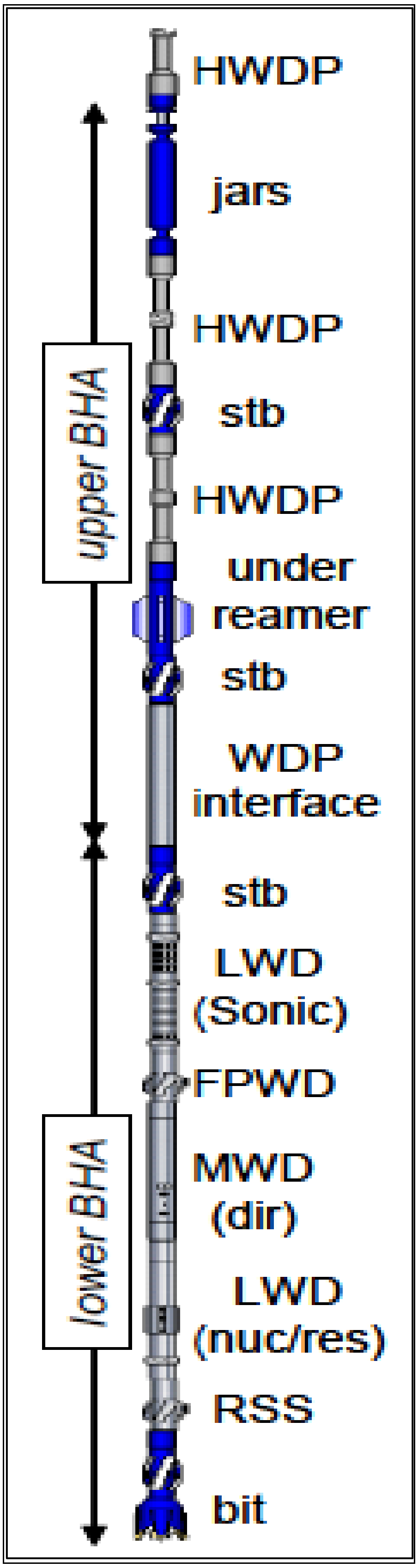


Figure 7.17: The WDP test BHA [19]

Figure 7.18 below illustrates the data flow from the downhole tools through the Wired Drill Pipe interface and to the surface hardware and software applicable for processing.

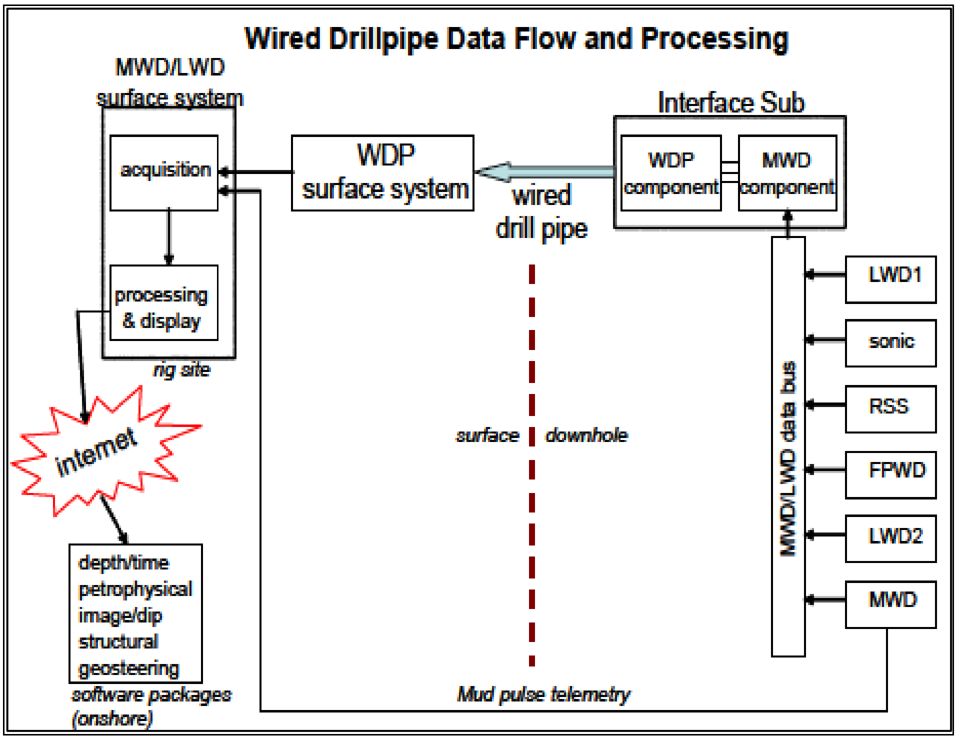


Figure 7.18: WDP Data flow and Processing[19]

7.4.2 Opportunities for Enhanced Decision

The opportunities according to T.S. Olberg et al. (2008) for enhanced decision making when using WDP technology are as follow: evaluating directional response, two way communication, real-time data visualization, evaluating hole opener performance in real-time, vibrations monitoring, annular pressure monitoring, formation pressure sampling with WDP, Petrophysical data depth and breadth and image data analysis. Evaluating directional response is the is discussed below.

Evaluating Directional Response:

One of the several opportunities for enhanced decision making when using WDP technology is that one can evaluate directional response. Figure 7.19 shows a scenario where the WDP technology aid in hitting the target. The downhole directional data transferred in real-time is used to evaluate the directional response and thus could correct the direction of the wellpath to hit the planned target.

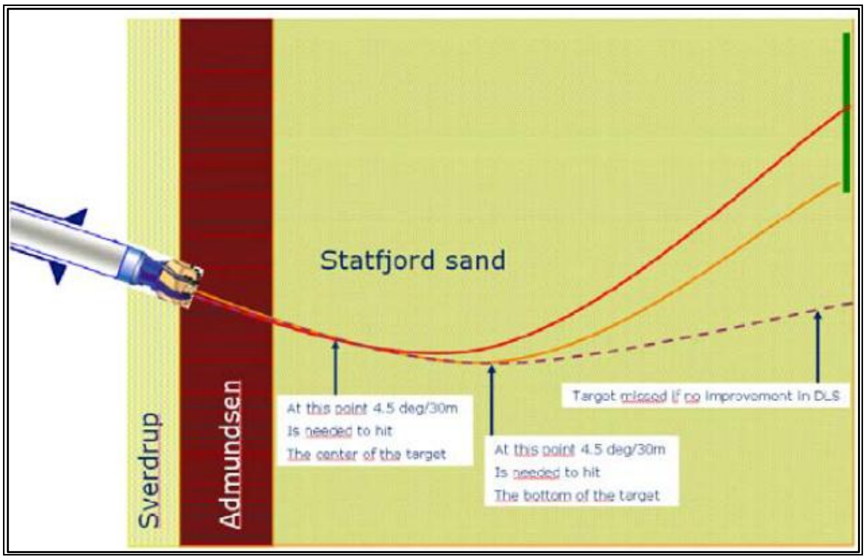


Figure 7.19 : Possible results on directional performance issues when landing the well[19]

Figure 7.20 shows directional performance at well landing with RSS down link commands. The plot is a real-time data. WDP data help the directional driller to make better decision.

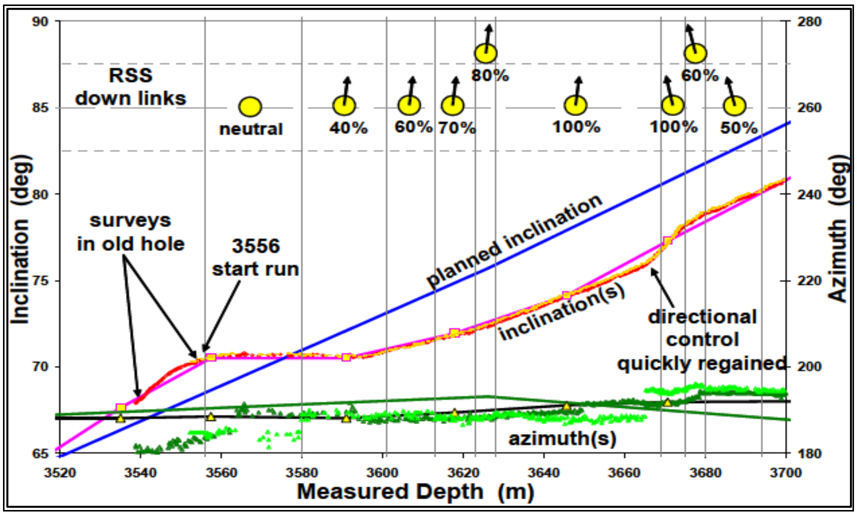


Figure 7.20: Directional performance at well landing with RSS down link commands. [19]

Comment

The WDP technology is a possible candidate for the oil industry standard way of acquiring directional survey data. The gathered data will be more accurate and reliable. The ellipse of uncertainty for any given wellpath will be smaller. Thus navigating amongst existing wells and positioning of new wells are easier and cost efficient.

8 Conclusion

A review of directional drilling, applications, survey calculations methods, survey tools and survey errors have been presented. It is evident that directional drilling can be employed in any type of drilling activity. The oil industry has used many different survey calculations methods but the most accurate and applied of the five methods presented in this thesis is the minimum curvature (Industry standard). Magnetic and gyroscopic survey tools are used to measure inclination and azimuth.

Accurate prediction of wellbore position is essential and depends on the choice of tool used to survey the well. Though the magnetic survey tool is still important for the oil industry, the gyroscopic survey tools are more accurate and widely used to complete surveys and used to control drilling activities in high magnetic interference areas where one cannot rely on magnetic tools. Based on the performed uncertainty analysis for old and resurvey wells, it is observed that gyroscopic survey instruments are more accurate than magnetic survey instruments.

Different aspects (error classification, published error propagation models and error sources) of directional surveying errors have been discussed. The oil industry has adopted two error models. The first model is the ISCWSA MWD for magnetic tools and the second is the ISCWSA Gyro for gyroscopic tools.

To examine the consequences of poor depth measurement uncertainty, Position Uncertainty Analysis (PUA) has been performed for two resurveyed wells from the Great Ekofisk field operated by ConocoPhillips. Some potential improvements in terms of technology and workflow have been suggested for planning and drilling of future wells.

As stated previously, the poor wellbore position uncertainty management or practices had led to various challenges faced today. In order to avoid these challenges in the future, the operator should invest in good work practices and reliable technologies. The proposed technologies and work flow i.e. “Most Accurate Position” method, Multi-Disciplinary software package by Roxar, Gyro.MWD technology and Wired Drillpipe (WDP) Technology will reduced the challenges in the future.

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