



University of  
Stavanger

Faculty of Science and Technology

## MASTER'S THESIS

Study program/ Specialization:  
Petroleum Technology-  
Drilling Technology

Spring semester, 2012

Open / ~~Restricted access~~

Writer: Ibrahim Hassan

.....  
(Writer's signature)

Faculty supervisor: Dr. Eirik Kårstad

External supervisor(s):

Title of thesis: Survey Interpolation: Software for calculating correct well path between survey stations

Credits (ECTS):30

Key Words:

Survey Interpolation  
Minimum Curvature Method  
Near Bit Inclination  
MWD

Pages: .....45.....

+ enclosure: ...16.....

Stavanger,15/06/2012  
Date/year

## **ACKNOWLEDGMENTS**

I would like to thank my supervisor Dr. Eirik Kårstad for his guidance and patience throughout the process of writing this Master's thesis. I would also like to express my gratitude to Dr. Mesfin Belayneh for his knowledge and assistance. In addition, I would like thank Robin Andrews for his help on Microsoft excel.

## **ABSTRACT**

In this Master's thesis a Microsoft Excel Visual Basic for Applications (VBA) scheme is developed to automatically interpolate and calculate between survey stations. Interpolation techniques of the assumed mathematical model of the Minimum Curvature Method (MCM) are used to determine borehole position by employing measured depth (MD), Inclination and Azimuth as input parameters. Output parameters are Dogleg Severity (DLS) and the 3D coordinates; True Vertical Depth (TVD), Northing (E) and Easting (E). The aim is to compare survey data from continuous near bit inclination (NBI) measured by the Baker Hughes's AutoTrak tool and survey data from OnTrak tool (MWD). The AutoTrak NBI tool measures inclination continuously while rotating and the OnTrak MWD tool measures directional coordinates usually at 10 – 30 m intervals. By using the measured NBI from the AutoTrak instead of using an interpolated inclination to calculate 3D coordinates between survey stations, especially the TVD, the aim is to compare end survey station interpolations of the MWD survey with the end results obtained utilizing the NBI for calculations. Comparison of the results showed that there is not much difference in calculated end results between NBI and MWD surveys.

# Table of contents

<b>ACKNOWLEDGMENTS.....</b>	<b>ii</b>
<b>ABSTRACT.....</b>	<b>iii</b>
<b>1 INTRODUCTION .....</b>	<b>1</b>
1.1 Background.....	1
1.2 Objective.....	1
1.3 Scope and Limitations .....	2
<b>2 LITERATURE REVIEW .....</b>	<b>3</b>
2.1 Papers relating to surveying methods.....	3
2.2 Directional drilling.....	3
2.2.1 Application of directional drilling .....	3
2.2.2 Types of directional wells.....	3
2.3 Well Surveying .....	5
2.3.1 Surveying Calculation Methods .....	6
2.3.2 Survey tools.....	7
2.3.3 Source of survey errors .....	9
2.3.4 Application of well surveying.....	9
<b>3 THEORY RELATED TO THIS THESIS .....</b>	<b>11</b>
3.1 Minimum curvature Method.....	11
3.2 Dogleg .....	12
<b>4 SURVEY INTERPOLATION CALCULATION .....</b>	<b>14</b>
4.1 Input Parameters for calculations.....	14
4.2 Minimum curvature method interpolation equations .....	15
4.3 Vertical section .....	16
4.4 Survey data .....	17
4.5 Spread Sheet .....	19
4.5.1 Structure.....	19
4.5.2 Process of calculations.....	22
<b>5 RESULTS .....</b>	<b>25</b>

5.1 Well 1 ..... 25

5.2 Well 2 ..... 30

5.3 Well 3 ..... 34

**6 DISCUSSION ..... 38**

6.1 Well 1 ..... 38

6.2 Well 2 ..... 39

6.3 Well 3 ..... 40

**7 CONCLUSION AND RECOMMENDATIONS FOR FUTURE  
WORK ..... 42**

7.1 Conclusion ..... 42

7.2 Recommendations for future work..... 42

**8 REFERENCES ..... 44**

**9 APPENDIX..... 46**

9.1 Source code: Interpolation of MWD data ..... 46

9.2 Source code: Interpolation of NBI data ..... 51

9.3 Source code: Average Inclination calculation from NBI data ..... 57

9.4 Source Code: Find NBI MD that closest the MWD survey station depth ..... 59

9.5 Source code: input window Frm\_Entry ..... 60

## LIST OF FIGURES

Figure 1. Most Common types of wellbore profile <sup>15</sup> .....	4
Figure 2. Typical relationships between True North, Grid North and Magnetic North. <sup>2</sup> .....	5
Figure 3. Baker Hughes Autotrak G3 Rotary steerable system. <sup>22</sup> .....	8
Figure 4. Steerable motor vs. AutoTrak rotary closes loop system. <sup>21</sup> .....	10
Figure 5. Minimum curvature method well path. <sup>2</sup> .....	12
Figure 6. Dogleg angle between two survey stations. <sup>14</sup> .....	13
Figure 7. Point Interpolation part input parameters sheet and structure .....	19
Figure 8. Picture showing Point Interpolation sheet calculated parameters and the formulas used when input values are entered.....	20
Figure 9. Format of raw MWD survey copied and pasted in imported survey sheet .....	20
Figure 10. Format of raw NBI data copied and pasted in Continuous measurement sheet.....	21
Figure 11. Facsimile of input window after the interpolate button in calculation sheet is pushed.....	21
Figure 12. MWD Measured depth vs. Inclination for well 1. ....	26
Figure 13. NBI Measured depth vs. Inclination (from 866.17m MD) of unfiltered data for well 1.....	27
Figure 14. Measured depth vs. Inclination after the data had been processed and interpolation calculations are performed.....	28
Figure 15. Measured depth vs. Inclination after interpolation had been done. ....	28
Figure 16. Vertical Section view after interpolation calculation. ....	28
Figure 17. Vertical plane Section view after interpolation calculation. ....	29
Figure 18. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used. ....	29
Figure 19. MD vs. MWD inclination for well 2.....	30
Figure 20. Inclination vs. NBI of unfiltered data for well 2.....	31
Figure 21. Measured depth vs. Inclination after the data had been processed and interpolation had been done. ....	31
Figure 22. Measured depth vs. Inclination after interpolation had been done. ....	32
Figure 23. Vertical plane view after interpolation calculation. ....	32
Figure 24. Vertical plane view after interpolation calculations.....	33
Figure 25. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used. ....	33
Figure 26. MD vs. MWD inclination for well 3.....	34
Figure 27. Inclination vs. NBI of raw well 3 NBI data. ....	35
Figure 28. Measured depth vs. Inclination after the data had been processed and interpolation have been done. ....	35
Figure 29. Measured depth vs. Inclination after interpolation have been done. ....	36
Figure 30. Vertical Section view after interpolation calculation .....	36
Figure 31. Vertical Section view after interpolation calculations. ....	37
Figure 32. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used. ....	37

## LIST OF TABLES

Table 1.A segment of raw NBI data .....	17
Table 2. A segment of Sag corrected raw MWD survey.....	18
Table 3.Final MWD survey with DLS and 3D coordinates calculated .....	18
Table 4.Raw NBI data for Well 1.....	23
Table 5.End survey stations for interpolated MWD and NBI and DualInc survey.....	39
Table 6.End survey stations for interpolated MWD and NBI and DualInc survey.....	40
Table 7.End survey stations for interpolated MWD and NBI and DualInc survey.....	41

# 1 INTRODUCTION

## 1.1 Background

The need to steer a well trajectory in the right direction and hit geologic location many kilometers downhole has forced the petroleum industry to really focus on tools and methods to identify wellbore location and path during drilling. In the early days of the petroleum exploration it was common to set the drilling rig right above the target downhole and drill. But it soon became necessary to drill wells to reach targets that are deviated from the reference location at surface. The earliest well known to be deliberately deviated was drilled in Huntington Beach, California in the early 1930s. The technique at the time was to set the drilling rig on the beach and drill a slanted hole to seabed.<sup>1</sup>

Throughout the years many tools and methods have been developed. Currently there are wide varieties of companies offering tools to deflect and steer wellbores in the right direction and measure wellbore inclination and Azimuth. The results of a directional survey are given in terms of inclination, azimuth and 3D coordinates TVD, northing and easting at the depth of the survey station. For many applications the accurate position and direction of the borehole should be determined at depths which may not coincide with the depth of survey stations. A tool for interpolating between survey stations is then required.

## 1.2 Objective

By using surveys from three wells in the North Sea this thesis work

- Focuses on interpolating between survey stations using both Near bit inclination(NBI) and the MWD survey measurements provided by Baker Hughes.
- Uses the NBI measurements to calculate directional coordinates and compare the result with the MWD survey interpolated between stations usually taken in 10-30 m intervals.
- The intent is to create an excel sheet that automatically interpolates between survey stations when a survey in an especial format is imported. This spreadsheet will be created employing modifications done on formulas used in excel sheet created by Morten Gjertsen and Inge Edvardsen in Baker Hughes's surveying group.
- Microsoft Visual Basic for applications (VBA) will be used to design the Microsoft(MS) Excel spreadsheet interpolator. No other software will be used.



### 1.3 Scope and Limitations

There have been comparisons of the different survey methods to determine which method gives the most accurate wellbore position and minimizes the effect of survey errors. Today, the MCM is viewed as the accepted standard for the calculations of 3D well surveying. But does the well path in between survey stations really follow a minimum curvature well trajectory. Assuming the well path is described by the minimum curvature means we might ignore true trajectory of the well. We can use the continuous NBI measurements from the AutoTrak to interpolate wellbore trajectory between survey stations and compare this with the well path interpolated using MWD survey measurements. The scope of this thesis work is based on:

- Literature review on directional drilling and survey calculation methods.
- Modification on the survey interpolation calculator made by Morten Gjertsen and Inge Edvardsen in Baker Hughes survey group and create an excel spread which, based on imported surveys, interpolates between survey stations using MCM.
- Comparison of interpolated survey of MWD survey data with the interpolated survey of NBI.

## 2 LITERATURE REVIEW

### 2.1 Papers relating to surveying methods

- 1957: J.E. Edison presents the average angle method
- 1968: G.J. Wilson presents radius of curvature method
- 1971: J.E. Walstrom presents the Balanced tangential method
- 1973: W.A. Zaremba presents the minimum curvature method
- 1991: Xiushan Liu presents the constant curvature method
- 2004: S.J. Sawaryn and J.L. Thorogood present their SPE paper named “a compendium of directional calculations using the minimum curvature method”

### 2.2 Directional drilling

#### 2.2.1 Application of directional drilling

Directional drilling is described as:

“The art of science involved in the deflection of a wellbore in order to reach a pre-determined objective below the surface of the earth”.<sup>1</sup>

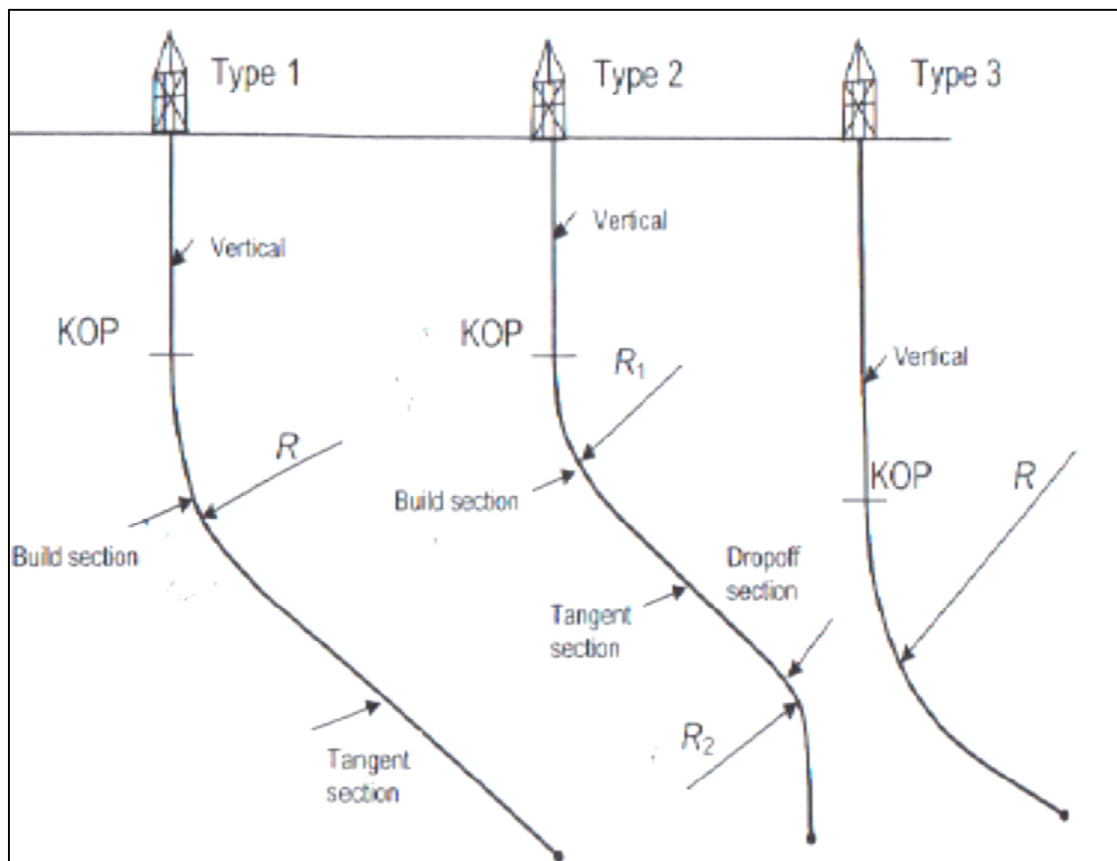
The Wellbore is planned along a predetermined trajectory to hit a subsurface target. The target may be geometric or may be adjusted real time based on Logging while drilling (LWD) measurements. There are many uses for directional drilling. Below is a short list of the main purposes:<sup>1</sup>

- Sidetracking a well: the well might need to be sidetracked due to a hindrance downhole. This hindrance might for instance be fish left in the hole. The previous wellbore is then plugged back with cement plug and a sidetrack is drilled.
- Avoid geologic problem: geological problem such as salt dome or a fault might be in the way before reaching target.
- Drilling completely vertical well: To drill an entirely vertical wellbore and keeping it vertical directional drilling can be used.
- Drilling relief wells to control blowouts when all the other methods fail.

#### 2.2.2 Types of directional wells

There are many types of wellbores. Below there is a description and an illustration of the most common types wellbore profiles.

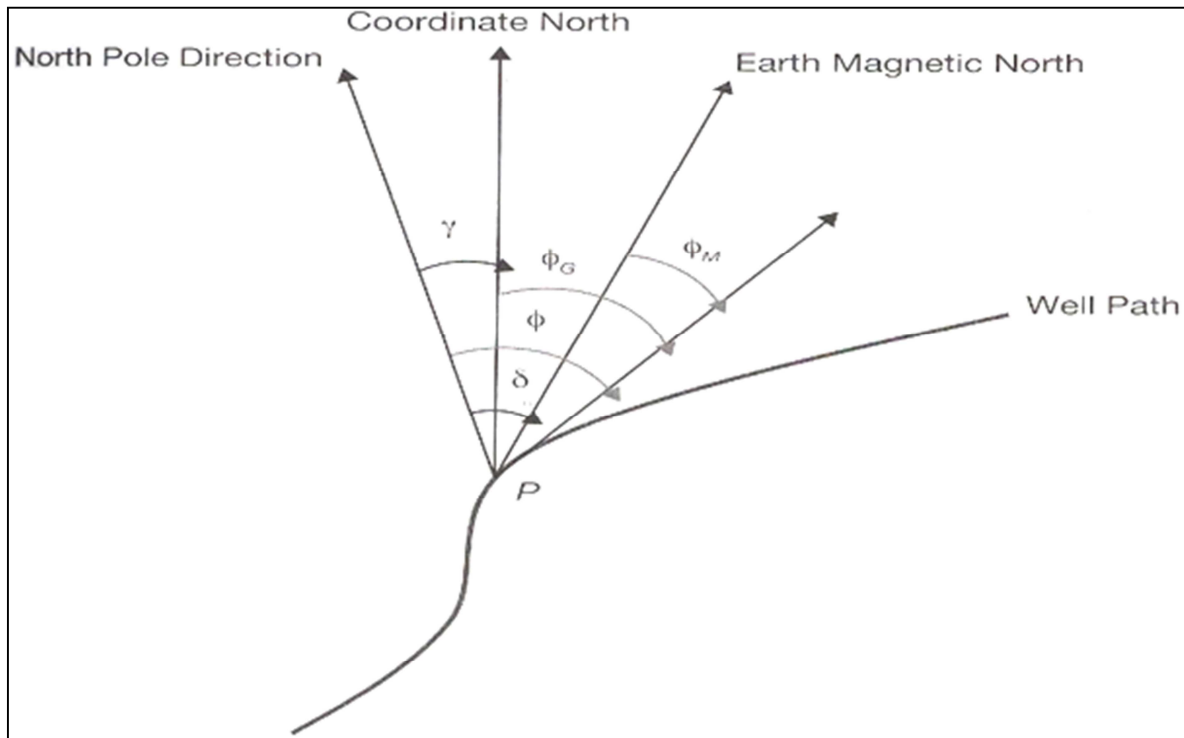
*Build and hold well profile (Type 1)* is the most common and simplest profile. The well is vertical until the KOP where it is kicked off and angle is built. When the desired inclination is reached, the well path is kept tangent or straight line until target is reached. *Build, Hold and Drop well profile (type 2)*, also called S-shaped wells, is the same in the upper section as the build and hold well profile. The well is kept vertical until KOP and inclination is built and the tangent section is drilled. After the tangent section, a drop-off section is drilled where inclination is reduced and the well path is almost vertical as it hits the target. *Deep build/kick-off (Type 3)* is a type of wellbore drilled when there is a hindrance such as salt dome or when well has to be sidetracked. The well drilled vertically to a deep KOP and then inclination is built quickly to target. *Horizontal well profile* and *Horizontal Drain hole well profile* are other types of wellbore trajectories. Theoretically, there are more than ten types of wellbore profiles. Three of the most common type of well trajectories are shown in **Figure 1** below. <sup>1, 2, 15</sup>



**Figure 1.** Most Common types of wellbore profile<sup>15</sup>

### 2.3 Well Surveying

During drilling it is close to impossible to make the actual trajectory precisely match the designed well path. For that reason, it is important to monitor the well trajectory and take corrective actions as well is being drilled. To achieve this goal there must be reliable survey measurement tools and techniques that determine inclination, azimuth and perhaps the tool face orientation at different points along the well path. Survey tools only provide an incremental departure from a known starting point. The known point is referred to as the tie-on, or tie line. The first survey station is recorded deeper than the tie-on. The tools measure MD, inclination and azimuth. The points of measurements are called survey stations. The measured parameters are then used to calculate the wellbore position in terms of the 3D coordinates N, E and TVD. Inclination angle is measured with respect to the vertical while azimuth is measured with respect to either magnetic or true north. But azimuth is typically reported in reference to true or grid north. As a result, azimuth needs to be corrected before being reported or used in calculations. True north is absolute north reference. Magnetic Declination is angle from true north to magnetic north, and Grid Convergence is angle from true north to grid north. **Figure 2** below shows relationship between True north, Magnetic north and Grid north (Coordinate North).<sup>2,5</sup>



**Figure 2. Typical relationships between True North, Grid North and Magnetic North.**<sup>2</sup>

### 2.3.1 Surveying Calculation Methods

All though the wellbore location is determined by measurements of inclination and azimuth at different survey stations, the real shape of the wellbore between stations are not known. Hence, it is industry practices to make assumptions utilizing several calculation methods. Following are the most popular survey calculation methods used for calculating well trajectory: <sup>1, 2, 4, 9, 12, and 13</sup>

#### 2.3.1.1 Average Angle Method

The average angle method utilizes the average of inclination and azimuth of two consecutive survey stations and assumes the wellbore to be tangent to the average angle.

#### 2.2.1.2 Balanced tangential method

This method divides the length between two survey stations into two halves. It assumes the first half of the length as tangent to the wellbore at the first survey station, and the rest of the length to as being tangent to the wellbore at the bottom survey station.

#### 2.3.1.3 Tangential method

This method is the predecessor to the balanced tangential method and utilizes the assumption that the wellbore is straight line defined by the inclination and azimuth of the lowest survey station. Using the tangential method is defect way of calculating wellbore position because it assumes all changes in direction occurs at survey stations, whereas changes occur over the course of a segment. Also, pipe failure may occur because it neglects any curvature in the wellbore.

#### 2.3.1.4 Radius of curvature method

The radius of curvature method assumes that the wellbore has the shape of a smooth arc when viewed in both the horizontal and vertical planes. The arc is tangent to the inclination and azimuth at each survey station. The well trajectory can therefore be described as an arc in the vertical plane which is wrapped around a right vertical cylinder. Although this method has shown improvement over the Tangential and Balanced tangential methods, it assumes, as the other two that changes in the wellbore correspond with depth of survey stations.

#### 2.3.1.5 Constant curvature method

This method, which was proposed by Gu et al. (1992), assumes the wellbore follows a constant curvature. It assumes the path can be drilled with constant tool face, and that curvature (DL) and build rates are constant with measured Depth.

### *2.3.1.6 Minimum curvature method*

This method uses the assumption that two successive survey stations lie on a smooth circular arc by using the angles measured. The arc is smoothed out by timing a ratio factor(RF). This method is basically the Balanced Tangential method timed with the dogleg ratio factor. It should be noted that this method is most widely used method in the industry today.

## **2.3.2 Survey tools**

### *2.3.2.1 Measurement While Drilling (MWD) Tools*

The inputs for the above mentioned methods are MD, inclination and azimuth. MWD tools are a reliable and fast way to measure these parameters and steer a well in the desired direction while keeping track of wellbore trajectory. MWD tools use accelerometers which measure local acceleration and magnetometers that measure strength of earth's magnetic field. When drilling with OnTrak MWD system, surveys are taken after every stand (approx. every 10-30m). The pumps are shut down and when a new connection is made up and pumps are turned back on, the tool's directional sensors measures Inclination and Azimuth.

The OnTrak needs to be stationary and non-rotating to take an accurate survey. The AutoTrak, which has a directional sensor that measures inclination continuously, is capable of accurately measuring inclination while being rotated. This makes it an ideal tool to use when for instance Geosteering. The NBI measured can then be compared to OnTrak inclination measurements to get a more accurate wellbore position.

Many companies such as Baker Hughes offer different types of MWD tools. One of the most used MWD tools is the Baker Hughes AutoTrak G3 rotary steerable system which consists of AutoTrak steering unit with an OnTrak system for real-time MWD/LWD measurements. **Figure 3** below shows Baker Hughes's AutoTrak G3 rotary steerable system.<sup>2, 19</sup>

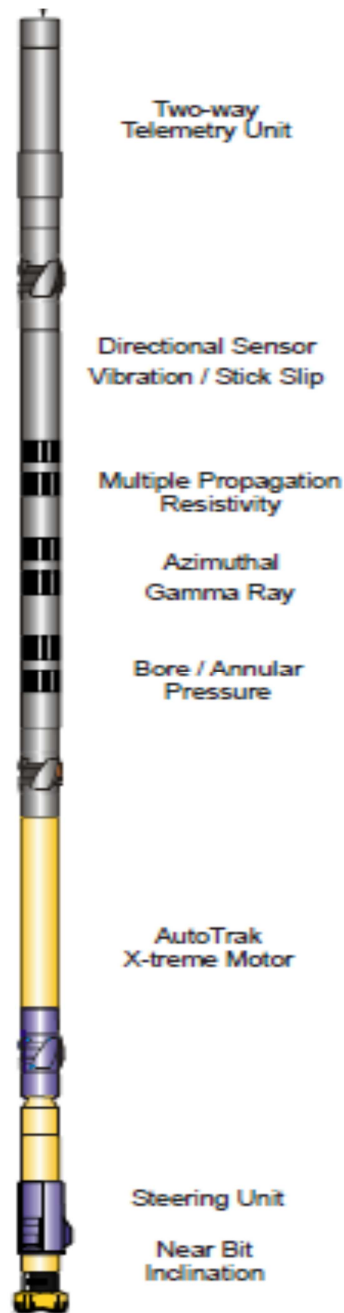


Figure 3. Baker Hughes Autotrak G3 Rotary steerable system. <sup>22</sup>

### 2.3.2.2 Gyro Measurement while drilling

Gyro measurement while drilling was introduced as an alternative to Gyro single shot tool for some applications. While the Gyro single shot is run on wireline, the Gyro MWD is real-time tool run alone or with regular MWD tool on drill pipe. Gyro MWD is commonly used in the top sections to get a more accurate magnetic interference measurement. This will in turn reduce the risk of colliding with an existing

wellbore when drilling from a platform. The Gyro-MWD technology is also used for orienting and setting whipstock for sidetracking wells where regular MWD tools are affected due to magnetic interference.<sup>20</sup>

### 2.3.3 Source of survey errors

Despite the top modern and sophisticated survey tools that are used today, there is uncertainty associated with surveys and measured values can never be precisely. As a result, models have been developed to quantify the error related to each survey tool. There are usually two types of survey errors. The first one is human error and the second one is the uncertainty error which is the expected inaccuracy of a survey. To reduce surveying errors tools must be checked and calibrated before running in hole.

There are many sources of survey errors. Below is a list of the main survey errors.<sup>1, 6, 10, 19, 21</sup>

- *Survey tool error*: This is the error that comes from the measuring devices in the survey tool. Such device can be the magnetic compass. It might measure magnetic field that is not the earth's. This magnetic field might for example be magnetic field from the drill string or from steel in a nearby well. The magnetic declination which is the correction from magnetic north to true north might also be uncertain. Any error in the magnetic declination will greatly affect the measured azimuth. Another survey tool error might be directional sensor error. The largest contributor to this might be calibration errors.
- *Borehole environment error*: Tool misalignment is one of the borehole environment errors. It is caused by the axis along the hole not being parallel with the centerline of the borehole. The cause of tool misalignment might be bottom hole assembly (BHA) SAG (distortion of the tool under gravity). Another borehole environment error occurs when downhole parameters such as pressure and temperature surpasses the specifications of the survey tools.
- *Hole Depth errors*: This is errors related to the survey measured depth. It is one of the key inputs when calculating 3D coordinates TVD, Northing and E. This error arises from incorrect drill pipe lengths, inaccurate wireline measurements and etc.

### 2.3.4 Application of well surveying

#### 2.3.4.1 Torque and drag design

When planning a 3D well trajectory, one of the most important considerations is Torque and drag. If the Torque and drag are not carefully considered, the drill string might fail. The torque and model used makes special assumptions that simplify the analysis and is used to model real drill strings. The most important factor influencing the torque and drag forces is the hole curvature. The well path should be redesigned with smaller curvature if the drill string seems to fail when simulating these forces during the design stage.



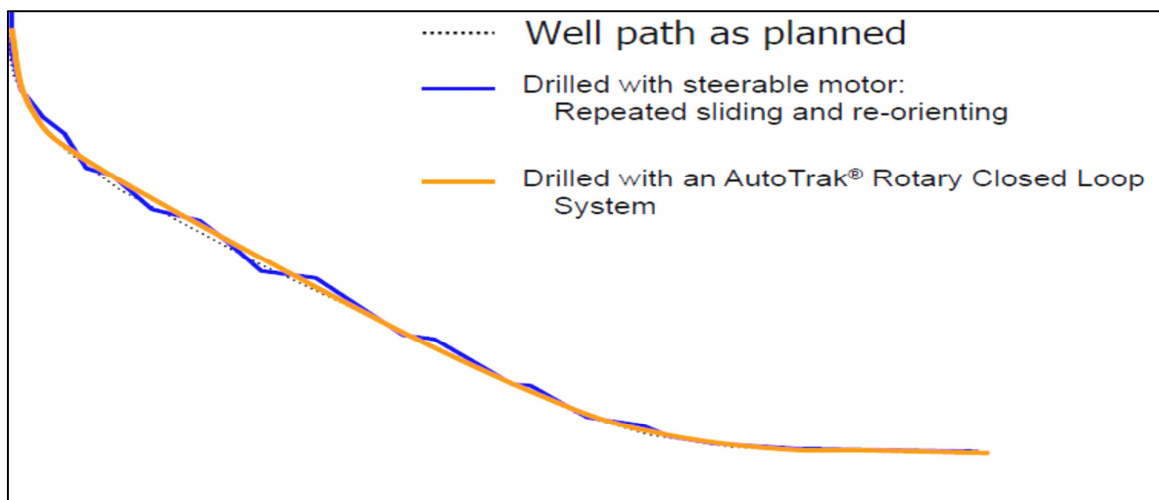
There are many causes for excessive torque and drag such as: sliding friction, tight hole, collapsing or swelling clay/shale, keyseats, differential sticking and cuttings buildup.<sup>1,12</sup>

The minimum curvature method assumes the bending part in the equilibrium equation used to calculate torque and drag is discontinuous at survey stations. Some authors mean this is one of the main weaknesses of using the minimum curvature method. Due to the missing bending stresses the method might not represent the real drill string configuration.<sup>15,16,17</sup>

#### 2.3.4.2 Well path geometry

Drilling with Positive displacement motor (PDM) may create a hole that does not follow the ideal well path of the minimum curvature assumption due to alteration of the tool face orientation which creates tortuous well path. Different directional drillers have different habits. This means a well drilled with motor where the tool face orientation is altered many times during a section, there will be up and down changes of inclination between survey stations. This will contribute to high instantaneous dogleg. when drilling with Rotary steerable system the tool adjusts steering parameters automatically. Thus, creating a smother hole curvature. The tool can steer while rotating and is programmed beforehand with target parameters and will in theory adjust inclination and azimuth to reach target. This will also reduce drill string and casing wear significantly.<sup>21</sup>

**Figure 4** illustrates well path drilled with steerable motor vs. one drilled with baker Hughes's AutoTrak rotary closed loop system.



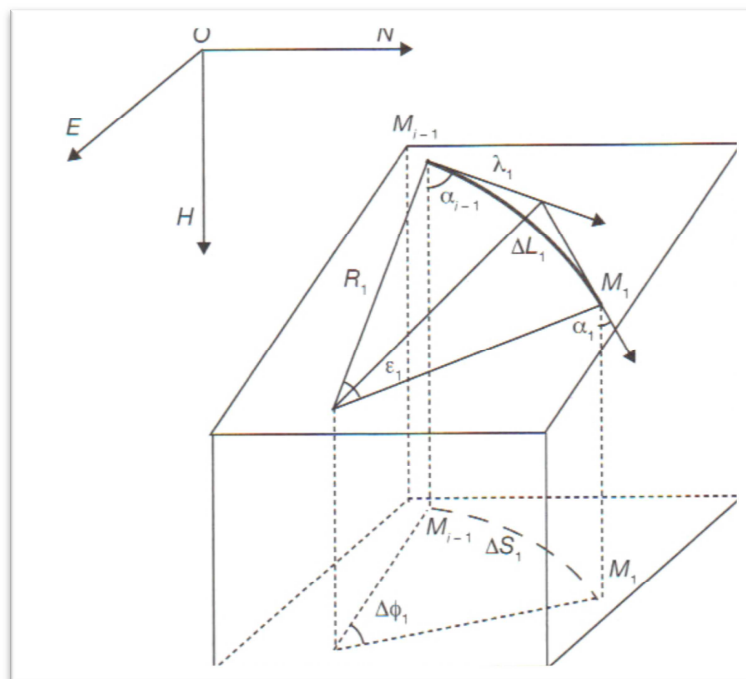
**Figure 4.**Steerable motor vs. AutoTrak rotary closes loop system.<sup>21</sup>

### 3 THEORY RELATED TO THIS THESIS

While the well is being drilled and after it has reached a planned target point, it is important to measure and calculate its actual path. Actual path never coincides with planned trajectory. As a result, one of the main goals of well surveying is to see how far we are off the designed well trajectory. Normally, a MWD or gyro tool is used to measure inclination and azimuth at different survey station. The wellbore trajectory between survey stations is not known. Hence, we have to make assumptions. One of those assumptions is that the wellbore follows a minimum curvature between survey stations. By using the Minimum curvature method we can calculate well coordinates in terms of Easting, Northing and True vertical depth. <sup>4,13</sup>

#### 3.1 Minimum curvature Method

As previously mentioned, in the minimum curvature method the well path between two survey stations lie on a circular arc and the segment between the two stations have a minimum curvature. This is the method most widely used in the industry today. It was developed to calculate well's positions from directional surveys. **Figure 5** below illustrates well path following minimum curvature method. Given the MD, inclination and azimuth angles of the upper and lower survey station, the dogleg angle in the Minimum curvature method can be calculated using following equation: <sup>1, 12,13</sup>



**Figure 5. Minimum curvature method well path.<sup>2</sup>**

$$DL = \cos^{-1}(\cos \alpha_{i-1} \cos \alpha_i + \sin \alpha_{i-1} \sin \alpha_i \cos(\phi_i - \phi_{i-1})) \quad (1)$$

Where

DL= dogleg angle

Using this Dogleg angle the ratio factor can be calculated as:

$$RF = \frac{\Delta L_i}{DL} \tan \frac{DL}{2} \quad (2)$$

By using these two above values the wellbore position can be calculated in terms of Eating(E), Northing(N) and True vertical depth (TVD):

$$\Delta N = RF(\sin \theta_1 \cos \phi_1 + \sin \theta_2 \cos \phi_2) \quad (3)$$

$$\Delta E = RF(\sin \theta_i \sin \phi_1 + \sin \theta_2 \sin \phi_2) \quad (4)$$

$$\Delta TVD = RF(\cos \theta_1 - \cos \theta_2) \quad (5)$$

### 3.2 Dogleg

Dogleg is a term that refers to the amount of curvature in the well path. Usually it calculated between two survey stations and quantified as degrees per unit of distance called Dogleg Severity (DLS). Dogleg achieved depends on formation parameters such as dip angle, strike, hole inclination, gauge of hole, bit type and length, weight on bit and bottom hole assembly. The DLS is import to monitor because it influences the forces applied to the drill string. One needs to know Dogleg severity in order to calculate pipe curvature and thus, calculating the bending stress in the pipe for a given tensile load. Also, DLS is used to evaluate quality of well trajectory design.

**Figure 6** below shows dogleg between two survey stations.<sup>2,13,14</sup>

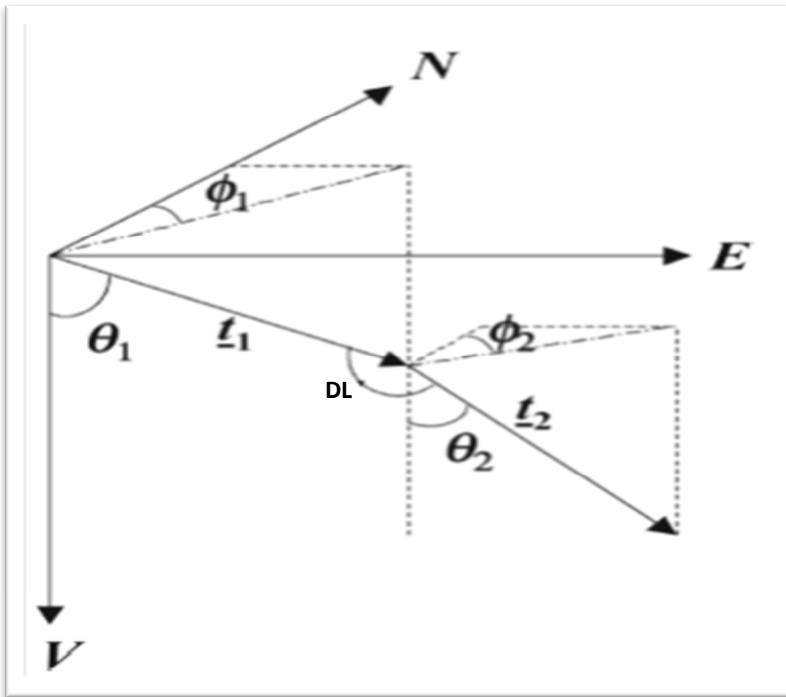


Figure 6. Dogleg angle between two survey stations.<sup>14</sup>

## 4 SURVEY INTERPOLATION CALCULATION

In this section, the calculations done using the minimum curvature interpolation technique will be outlined. Also, assumption and background calculations in the excel spreadsheet will be described.

### 4.1 Input Parameters for calculations

The survey data received are for three wells named Well 1 and Well 2 and Well 3. For each well, I received

- MWD survey data that contained MD, inclination and azimuth.
- Continuous NBI measurements that contained MD and inclination measurements.
- Dual Inc(average inclination of NBI and MWD) surveys.

The following are the only tools used in this thesis

- Survey data for the three wells mentioned above
- Excel spread sheet to automatically interpolate between survey stations and calculate 3D coordinates E, N and TVD.

#### *Wellbore Position Data*

Dogleg severity (DLS), TVD, N and E are acquired by calculations utilizing the measured data the assumed mathematical model the minimum curvature method. Positive northing represents a distance north of the coordinate origin point (0.0N, 0.0E); negative northing represents a distance south. Positive Easting represents a distance east of the coordinate origin point (0.0N, 0.0E) and negative easting represents a distance west.

#### *Dogleg severity*

DLS is well curvature between two survey stations in degrees per unit of distance (°/30m) and is a calculated parameter using the dog leg angle calculated utilizing inclination and azimuth

$$DLS = 30 \frac{DL}{L_2 - L_1} \quad (6)$$

## 4.2 Minimum curvature method interpolation equations

When we want to find inclination and azimuth at a certain point between two survey stations we need to use interpolations techniques. Such calculations are important for correct casing design, prediction of torque and drag and to calculate hole cleaning parameters. Many of the values in the calculation are measured values that are obtained from survey tools such as MWD or Gyro as previously described. The measured values at survey stations are: MD, inclination and azimuth. All the other values are calculated using formulas earlier mentioned together with the interpolation formulas below.

When interpolating between survey stations and calculating wellbore coordinates, the first thing one need to do is to calculate the dogleg angle between the survey stations. Instead of using the dogleg from Equation 1, the dogleg angle proposed by Sawaryn et al. (2004) is used for calculations in this thesis. The unique thing about this equation is that it is of a general nature and do not assume any shape of the wellbore between two survey stations. Here are the formulas used in the excel spreadsheet for interpolating between two survey stations by using the minimum curvature method:<sup>13</sup>

$$DL = 2 \sin^{-1} \left\{ \left( \sin^2 \left( \frac{\theta_2 - \theta_1}{2} \right) + \sin \theta_1 \sin \theta_2 \sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right) \right)^{\frac{1}{2}} \right\} \quad (7)$$

Where

$\theta_2$ = inclination for the lower survey station

$\theta_1$ = Inclination for the upper survey station

$\phi_i$ = azimuth for the lower survey station

$\phi_{i-1}$ = azimuth for the upper survey station

Consequently, the interpolated DL angle at the point of interest is calculated by use of following equation.

$$\alpha^* = \frac{S^* \alpha_{12}}{L_2 - L_1} \quad (8)$$

Where

$\alpha^*$ = subtended angle at the point of interest

$S^*$ =section length between the upper/lower survey station and point of interest

$L_1$ =The depth of the upper survey station

$L_2$ =The depth of the lower survey station

Next, the interpolated azimuth is calculated as following:

$$\Phi^* = \tan^{-1} \left( \frac{\sin \theta_1 \sin \Phi_1 \sin(\alpha_{12} - \alpha^*) + \sin \theta_1 \sin \Phi_2 \sin \alpha^*}{\sin \theta_1 \cos \Phi_1 \sin(\alpha_{12} - \alpha^*) + \sin \theta_2 \cos \Phi_2 \sin \alpha^*} \right) \quad (9)$$

Where

$\Phi^*$ =interpolated azimuth at desired point

The interpolated inclination angle can then be calculated using following equation:<sup>15</sup>

$$\theta^* = \cos^{-1} \left[ \cos \theta_2 \cos(DLS(L_2 - L_2)) + \left( \frac{\cos \theta_1 - \cos \theta_1 \cos \alpha_{12}}{\sin \alpha_{12}} \right) \sin(DLS(L_2 - L_1)) \right] \quad (10)$$

The RF or the dogleg ratio factor as it is sometimes referred to, is used to smooth the wellbore section so that it is represented by a smooth circular arc.

The ration factor is given as:

$$RF = 2 \frac{\tan\left(\frac{DL}{2}\right)}{DL} \quad (11)$$

Finally, wellbore positional data in terms of E, N and TVD is calculated according to equation 3 to 5.<sup>2</sup>

### 4.3 Vertical section

Vertical projection shows the well path when viewed from the side. It is plotted against the TVD and used for determining if the wellbore is above or below the proposed plan and the length of the horizontal section. It also shows the location of kick-off point, build and drop section. The vertical section will be calculated and plotted for all three wells. To calculate the vertical section one needs:

- Target Bearing:
- Vertical section origin: a north east coordinate point to start with

Following are the equations used to calculate the vertical section.<sup>1</sup>

First one needs to calculate the closure distance (CD) which is the shortest distance between the reference surface location and the horizontal projection of the last survey point.

$$CD = \sqrt{((\text{Northing})^2 + (\text{Easting})^2)} \quad (12)$$

Closure angle (CA) can then be calculated from following equation:

$$CA = \tan^{-1} \left( \frac{\text{Easting}}{\text{Northing}} \right) \quad (13)$$

The directional difference (DD) which is the angle difference between CD and Target bearing is:

$$DD = \text{Target bearing} - CA \quad (14)$$

Finally, the vertical section(VS) is calculated from following equation:

$$VS = CD \times \cos DD \quad (15)$$

#### 4.4 Survey data

Because the Dual Inc. survey DLS, RF and 3D coordinates N, E and TVD calculations were done using average inclination of NBI and MWD, I had to recalculate these coordinates using the last measurement point before the first pure MWD measurement in the final Dual link survey data as Tie-in point for each well using minimum curvature method. **Table 1** below illustrates a segment of raw NBI data and **Table 2** shows segment of the MWD survey listing for Well 1 as received. **Table 3** shows a segment of final MWD survey where 3D coordinates are calculated for Well 1.

Table 1.A segment of raw NBI data.

Measured depth(m)	NBI(degrees)
1117,27	5,032
1117,71	4,878
1118,19	4,988
1118,87	4,988
1119,22	5,076
1119,53	5,076
1120,4	4,988



**Table 2. A segment of Sag corrected raw MWD survey.**

<b>MD</b>	<b>Inclination</b>	<b>Azimuth</b>
[m]	[°]	[°]
886,70	1,91	248,22
913,10	2,09	250,74
942,70	2,67	247,94
970,80	3,13	246,44
999,60	3,79	246,18
1028,90	4,30	246,64
1057,30	4,82	248,42
1086,30	5,03	246,94
1115,20	5,01	244,91
1144,20	5,05	246,87
1173,40	5,12	246,26

**Table 3. Final MWD survey with DLS and 3D coordinates calculated**

<b>MD</b>	<b>Inclination</b>	<b>Azimuth</b>	<b>TVD</b>	<b>North</b>	<b>East</b>	<b>DLS</b>
[m]	[°]	[°]	[m]	[m]	[m]	[°/30m]
999,6	3,79	246,18	999,44	-6,19	-2,36	0,69
1028,9	4,3	246,64	1028,66	-7,02	-4,25	0,52
1057,3	4,82	248,42	1056,97	-7,88	-6,34	0,57
1086,3	5,03	246,94	1085,87	-8,82	-8,64	0,25
1115,2	5,01	244,91	1114,65	-9,86	-10,95	0,19
1144,2	5,05	246,87	1143,54	-10,89	-13,27	0,18

The course length between two survey stations in the regular MWD survey can vary depending on several factors.

- Different drillers have different habits. For a new connection, one driller will stop drilling at where the block is just few centimeters above the floor, while another will stop further up which will result in segments of various lengths
- Check surveys are sometimes taken even before we have Kelly down to check if the well is on the correct path. This is for instance done if the Directional Driller is unsure about the course the well is heading.

## 4.5 Spread Sheet

### 4.5.1 Structure

The spread sheet consists five sheets. The first sheet, named Point Interpolation is where one can interpolate between two known survey points using minimum curvature. This sheet is a slightly modified version of the “Minimum Curvature Interpolation” excel spreadsheet created by Morten Gjertsen and Inge Edvardsen in Baker Hughes survey group. Besides minor changes, the main difference between this new one and the original sheet is I changed the initial interpolated inclination formula to Equation 10.

The first survey station, named Station above comparison depth, is where one enters MD, Inclination, Azimuth and three dimensional coordinates (TVD, N and E) of the survey station above the point of interest. The second station, named Station below comparison, is where one enters MD, inclination and azimuth of the survey point below point of interest. Here one does not need to enter three dimensional coordinates TVD, North and East. These will automatically be calculated based on the information entered in the station above comparison point using the minimum curvature method. The next to do is to enter the MD of the point of interest under MD in interpolation station. When this is done, interpolation calculation will be performed between survey stations using interpolation equations outlined above. The point interpolation sheet is independent of the other sheets.

**Figure 7** below shows picture of how the input parameters are entered and the structure of the Point Interpolation sheet. The calculated parameters and the formulas used are illustrated by **Figure 8**.

MINIMUM CURVATURE INTERPOLATION						
	MD	INC	AZI	TVD	NORTH	EAST
STATION ABOVE COMPARISON DEPTH	730,00	0,18	20,43	729,99	-3,51	4,19
STATION BELOW COMPARISON DEPTH	740,00	0,10	50,00	739,99	-3,49	4,20
INTERPOLATION STATION	735,00	0,14	30,90	734,99	-3,50	4,20

**Figure 7.** Point Interpolation part input parameters sheet and structure

24	DLS	0,0105304	[*/m]	Dogleg Severity per meter			
26	$\alpha_{12}$	0,00184	[Rad]	0,1053037	[Deg]	Dogleg between survey station	$\alpha_{12} = 2 \sin^{-1} \left\{ \left[ \sin^2 \left( \frac{\theta_2 - \theta_1}{2} \right) + \sin \theta_1 \sin \theta_2 \sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right) \right]^{\frac{1}{2}} \right\}$
28	$\alpha^*$	0,00092	[Rad]	0,0526518	[Deg]	Interpolated Dogleg	
30	$\alpha$	0,00092	[Rad]	0,0526518	[Deg]	Dogleg interpolation (P*-P <sub>2</sub> )	$\frac{\sin \phi^*}{\cos \phi^*} = \frac{\sin \theta_1 \sin \phi_1 \sin(\alpha - \alpha^*) + \sin \theta_2 \sin \phi_2 \sin \alpha^*}{\sin \theta_1 \cos \phi_1 \sin(\alpha - \alpha^*) + \sin \theta_2 \cos \phi_2 \sin \alpha^*}$
32	$\phi^*$	0,53935	[Rad]	30,902555	[Deg]	Interpolated Azimuth	
34	$\theta^*$	0,002369		0,135749	[Deg]	Interpolated Inclination	$\theta^* = \cos^{-1} \left[ \cos \alpha_1 \cos(DLS(L_2 - L_1)) + \left( \frac{\cos \alpha_{i-1} - \cos \alpha_{i-1} \cos \alpha_{12}}{\sin \alpha_{12}} \right) \sin(DLS(L_2 - L_1)) \right]$
36	RF	1				Ratio Factor	
38	$\Delta$ TVD	4,999981				Vertical depth	$\Delta$ TVD = $\frac{1}{2} \Delta$ MD ( cos I <sub>1</sub> + cos I <sub>2</sub> ) RF
40	$\Delta$ N/S	0,012442				North/South	$\Delta$ N = $\frac{1}{2} \Delta$ MD ( sin I <sub>1</sub> cos A <sub>1</sub> + sin I <sub>2</sub> cos A <sub>2</sub> ) RF
42	$\Delta$ EW	0,005784				East/West	$\Delta$ E = $\frac{1}{2} \Delta$ MD ( sin I <sub>1</sub> sin A <sub>1</sub> + sin I <sub>2</sub> sin A <sub>2</sub> ) RF

Figure 8. Picture showing Point Interpolation sheet calculated parameters and the formulas used when input values are entered.

The second part of the spreadsheet, which comprises of five interconnected sheets, is where one can import survey data. There are two types of survey data that must be imported. The sheet named Imported survey is used to insert the raw MWD survey. The sheet next to it, named Continuous measurement is where one inserts NBI data comprising of MD and inclination. Copy the raw survey data and paste. It is a requirement that the imported data to always be the same format. In other words, the 1st survey point on row 3 for the MWD survey and row 2 for NBI data, and the order of the columns matching the template as shown in Figure 9 and Figure 10 below.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	MD	Inclination	Azimuth	TVD	North	East	DLS														
2	[m]	[°]	[°]	[m]	[m]	[m]	[*/30m]														
3	0	0	48.26	0	-5.42	2.23	0														
4	312.1	0	48.26	312.1	-5.42	2.23	0														
5	320	0.19	48.26	320	-5.41	2.24	0.72														
6	330	0.43	48.26	330	-5.38	2.28	0.72														
7	340	0.62	49.82	340	-5.32	2.35	0.57														
8	350	0.63	54.07	350	-5.25	2.44	0.14														
9	360	0.57	52.77	360	-5.19	2.52	0.18														
10	370	0.62	54.23	370	-5.12	2.6	0.16														

Figure 9. Format of raw MWD survey copied and pasted in imported survey sheet

	A	B
1	Measured Depth(MD)	Inclination
2	866,17	1,208
3	867,13	1,121
4	867,13	1,208
5	867,32	1,23
6	867,67	1,165
7	867,85	1,143
8	868,11	1,274
9	868,54	1,099
10	868,6	1,121
11	868,77	1,096

Figure 10. Format of raw NBI data copied and pasted in Continuous measurement sheet

The next task after these sheets are filled is to go to “Calculation” sheet. To begin the calculations the “Interpolate” button is pushed. A new window will then appear where one can input several parameters. Facsimile of the Calculation window together with the input window is shown in **Figure 11** below. The interpolated survey data will appear in Interpolation-Survey and Interpolation-Continuous sheets after the input parameters are inserted. Also, in the two latter sheets, the vertical section calculations will be done. The bearing angle used here is the closure angle of last survey station. The calculation tab in the Calculation sheet contains all of the formulas that are used in the interpolation. The formulas can also be manually changed in this sheet.

The input parameters needed in the input window are:

- Number of interpolation points
- Boundary Averaging NBI

The boundary averaging NBI and background calculations are explained below.

	A	B	C	D	E	F	G	H	I	J
1		MD	INC	AZI	TVD	NORTH	EAST	DLS	DL	
2	Survey #1	4535,40	59,91	271,32	3739,55	-566,86	-1587,63	0,0500		
3	Survey #2	4563,00	60,04	271,32	3753,3615	-566,3048	-1611,5202	0,0400	0,1215	
4					$\Delta$ TVD	$\Delta$ N/S	$\Delta$ E/W	DLS		
5					11,59	0,46	-20,04	0,0044		
6										
7										
8		MD	INC	AZI	TVD	NORTH	EAST	DLS	DL	
9	Interpolated	4558,56	60,02	271,32	3751,1433	-566,3934	-1607,6751	0,1321	0,1020	
10										
11										
12		$\alpha_{12}$	$\alpha^*$	$\theta^*$	$\theta^*$				RF	
13	Radians	0,0021	0,0018	-1,5478	1,0475				1,0000	
14	Degrees	0,12	0,10	-88,68	60,02					
15										

Figure 11. Facsimile of input window after the interpolate button in calculation sheet is pushed.

## 4.5.2 Process of calculations

### 4.5.2.1 Finding centerline depth in NBI survey

Because the MDs in the continuous measured data (NBI) may not coincide with the depths of survey stations in the MWD survey in all the wells, a reasonable way of setting the two depths equal had to be created. This is important for the reason that the desire is to compare inclinations, azimuth and three dimensional coordinates (TVD, N and E) at the same survey depth stations between the two data. Following is procedure to equate depth in the NBI survey to depth in the MWD survey stations.

- Find continuous MD that is closest to the MWD depth target value in NBI survey. Starts with first MD greater than the target value and calculate the difference between this and the target value.
- Compare this to the difference between the MWD survey station depth and the last NBI MD before the current depth.
- The NBI MD with the smaller difference is chosen as Centerline depth and set equal to the MWD depth.

### 4.5.2.2 NBI averaging

To find the average inclination at the centerline depth, I first tried to look at the centerline depth in the NBI measurement and calculate the average of the measured inclination of four data(2 above and two below) around the centerline point plus centerline inclination . But it soon became obvious that in some sections of the raw NBI data there are or might be consecutive faulty measured inclination values. So another way of solving the problem was needed. Here is the procedure to find the average inclination in the raw NBI survey data

- Take the smallest between a chosen degree and chosen percent cutoffs of the last inclination value.
- Compare each inclination 15 steps above and 15 steps below to the last inclination value in the previous survey station. If within the range calculated in the step above then it is considered a "good" measurement
- Average all the "good" points from step above
- Compares the 5 points around the central point (2 forward + 2 back + centerline) to the average of all good points. If within 2 degrees it is used in the inclination average calculation. If there are no points within 2 degrees then the average in step 3 is used. If there were no "good" points in step 2 then the last inclination angle from previous depth is used

Here is an example to explain the procedure:

**Table 4.Raw NBI data for Well 1**

<b>point#</b>	<b>Measured depth(m)</b>	<b>NBI(degrees)</b>
1	1117,27	5,032
2	1117,71	4,878
3	1118,19	4,988
4	1118,87	4,988
5	1119,22	5,076
6	1119,53	5,076
7	1120,4	4,988
8	1120,55	5,098
9	1121,13	4,922
10	1121,73	4,966
11	1122,37	5,01
12	1122,77	4,988
13	1123,76	4,9
14	1124,24	5,032
15	1124,87	5,01
16	1125,35	5,01
17	1125,94	5,076
18	1126,05	4,878
19	1126,65	4,966
20	1126,94	4,9
21	1127,43	7,163
22	1128,1	4,944
23	1128,61	5,098
24	1128,92	4,988
25	1129,77	5,01
26	1130,35	5,032
27	1131,52	5,054
28	1131,93	5,054
29	1133,31	4,922
30	1133,82	5,164
31	1134,26	4,922

Let us say the last survey NBI measured was inclination was 5.032 degrees. First, I begin by looking at point #16 in **Table 4** which is chosen to be a centerline point. Looking 15 steps below and 15 steps above this point and using for instance +/- 5 degrees and +/-30% as my filtrations boundary conditions, I choose

the smallest between the two boundary conditions from last inclination. In this case +/-30% is the smaller (+/- 1.5096 degrees of last inclination) and is therefore used as boundary condition. The program takes all points that satisfy the condition and include in the average calculation and compares this average to 5 points around the central point (2 below + 2 above + centerline). If within +/-2 degrees these are used to calculate inclination average. If there are no points within +/-2 degrees then the value calculated in the first average is used. If there were no "good" points in the table to calculate the first average, then the last inclination angle is used.

#### 4.5.2.3 Other Parameters

The continuous measured data NBI only includes MD and inclination. For the purpose of interpolation, we need to know measured azimuth at survey station in order to interpolate. The azimuth measured at survey stations with the MWD survey tool is used in the NBI inclination interpolation data at all survey station depths. For instance, for an arbitrary MD 60m meters MD, for the NBI interpolation calculation, the azimuth measured at 60m MD from the MWD survey tool is used in the centerline point. Then, the TVD, N and E are calculated using formulas provided earlier. This is done throughout the interpolation calculations. The Azimuth for the interpolated points in the NBI interpolation is calculated and is not from the MWD survey tool.

As mentioned, the NBI survey received only includes MD and inclination. For that reason, the first survey data used in the NBI interpolation is also pulled directly from the survey data at the same depth in the MWD survey.

The script utilized to create the scheme in Microsoft Visual basic for Applications (VBA) is attached in the appendix.

## 5 RESULTS

In this chapter, the results of the calculations done on the survey data for all three wells using minimum curvature method interpolation techniques are presented.

The raw MWD data received is SAG corrected. Assumptions made of the received data is that it is already quality checked (QC) and assumed to be satisfactory readings. Because this thesis focuses on creating an Excel spreadsheet that automatically interpolates between survey stations and compares well paths, no corrections or QC are done in the received survey data. Any errors in the raw data other than the faulty reading in NBI data are disregarded.

After many trial-and-error reiterations, the cut-off boundary averaging NBI values chosen were  $\pm 3.5$  degrees and  $\pm 30\%$ . Also, inputs of 5 interpolations points are used.

The results are presented in various plots. The first plots are illustrations of the raw data, whereas the last plots show the data after filtrations and interpolation calculations has been done. Furthermore, for each well there is a plot showing horizontal plane view after interpolation calculations.

To give an illustration how the data would look like if different boundary averaging NBI filtrations values were used, there is one MD vs. inclination plot for each well that shows when boundary averaging of  $\pm 2$  degrees and  $\pm 10\%$  are used.

### 5.1 Well 1

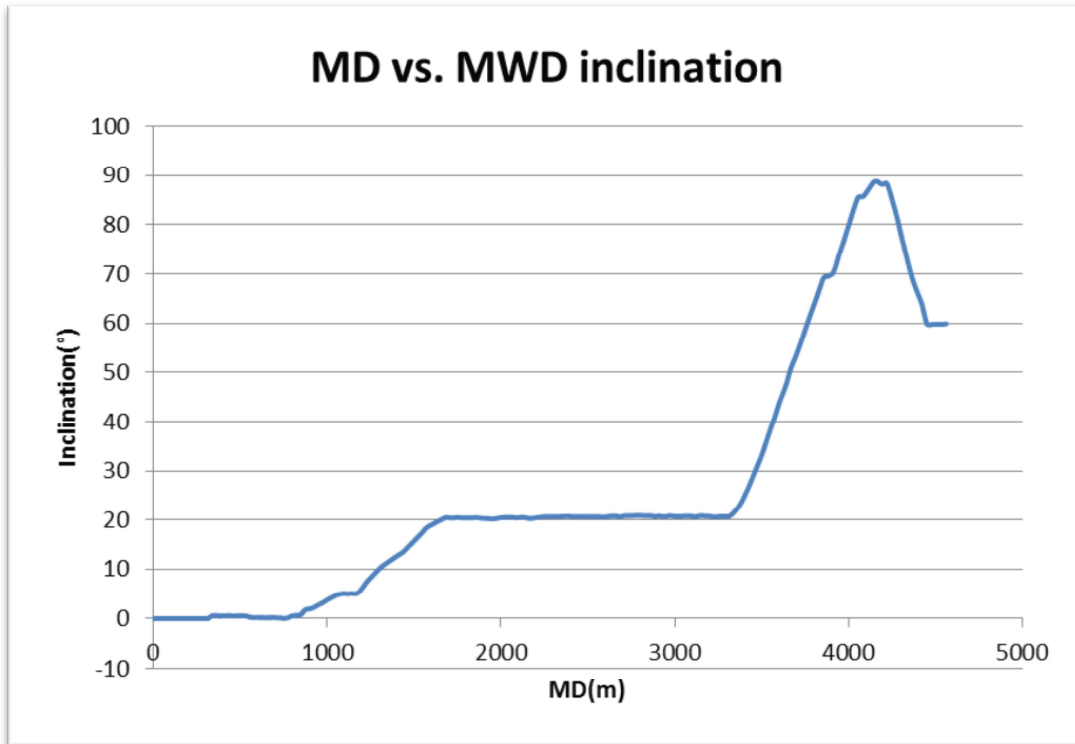
The survey for this well is from the North Sea. The depth from rig floor to seabed is 312.10 m MD.

The well is almost vertical down to 886m with a small variation in inclination and there is not much departure to north or east. The Kick off point (KOP) is at approximately 880 m where there is an increase (build) in inclination down to 1677m MD. This is followed by a tangent section down to 3344 m MD where the inclination is kept around 20 degrees. After the tangent section another build section is drilled where the inclination is increased quickly to 88.8 degrees down to 4163.5 m MD. From this point a drop section is drilled where the inclination is reduced to 59.9 degrees at total depth (TD) 4563m MD.

From 312.1 m MD to 880 m MD this well was surveyed with a Generic gyro – continuous tool that measured inclination and azimuth every 10 meters. The MWD survey measurement begins at 886.5 m MD. The AutoTrak NBI measurements begin at 886, 17 m. Because we do not have NBI measurements above this depth, comparison with the MWD data will be from this depth.



**Figure 12** below illustrates how inclination changes with MD for the entire well using MWD inclinations before interpolation calculations. **Figure 13** how inclination changes with MD before interpolation calculations using raw NBI measurements.



**Figure 12.**MWD MD vs. Inclination for well 1.

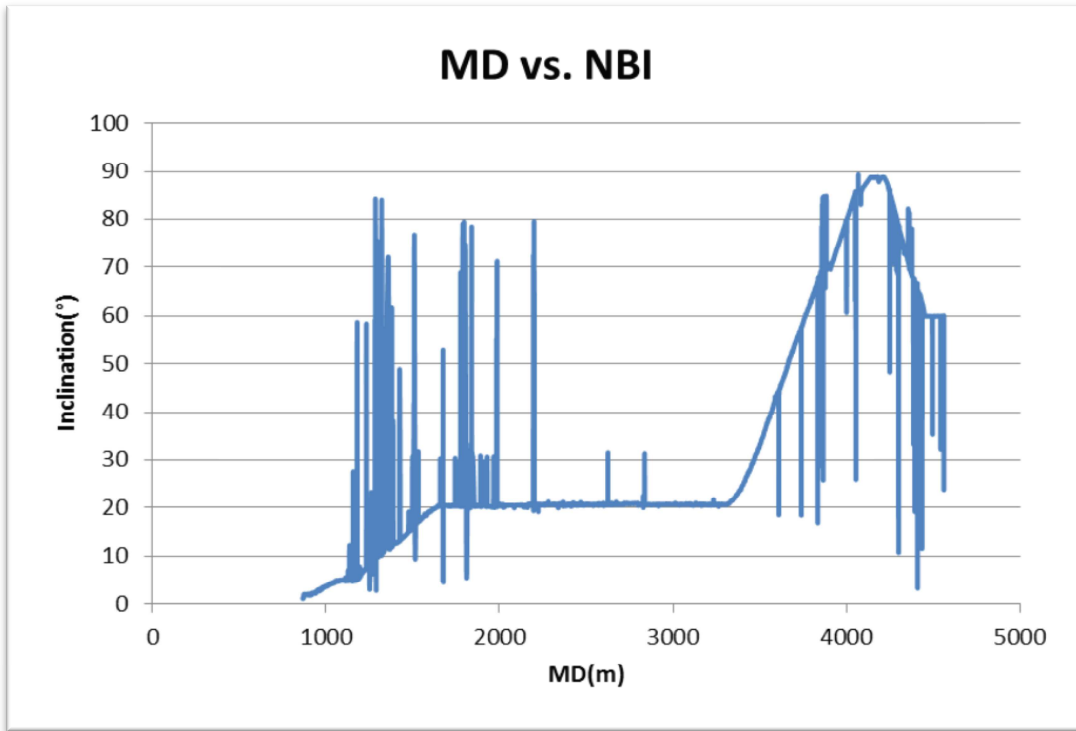


Figure 13. NBI MD vs. Inclination (from 866.17m MD) of unfiltered data for well 1.

The results after interpolation calculation are shown in the following figures for NBI data and MWD data.

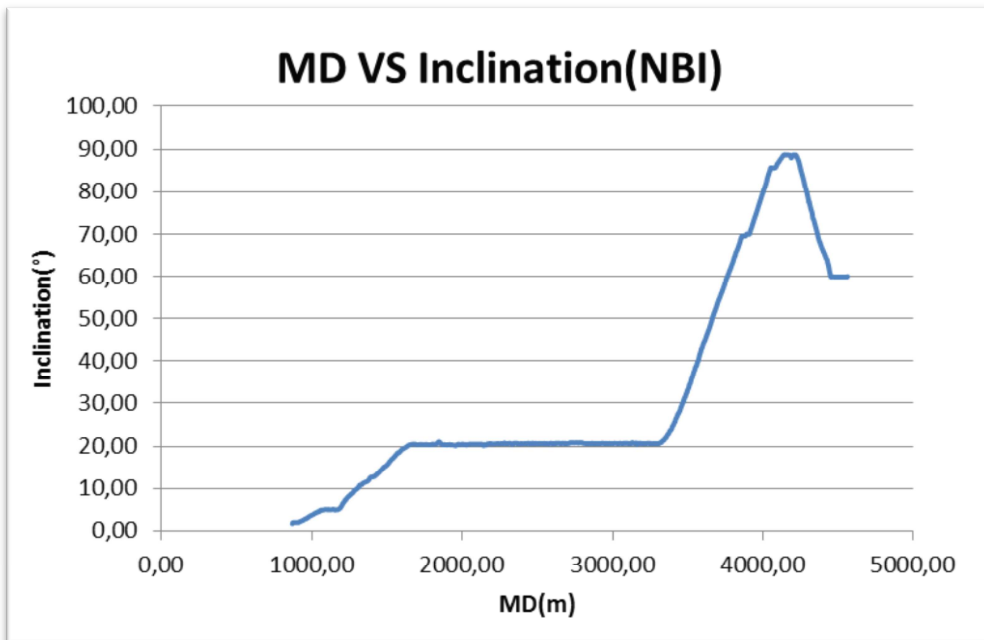


Figure 14.MD vs. Inclination after the data had been processed and interpolation calculations are performed.

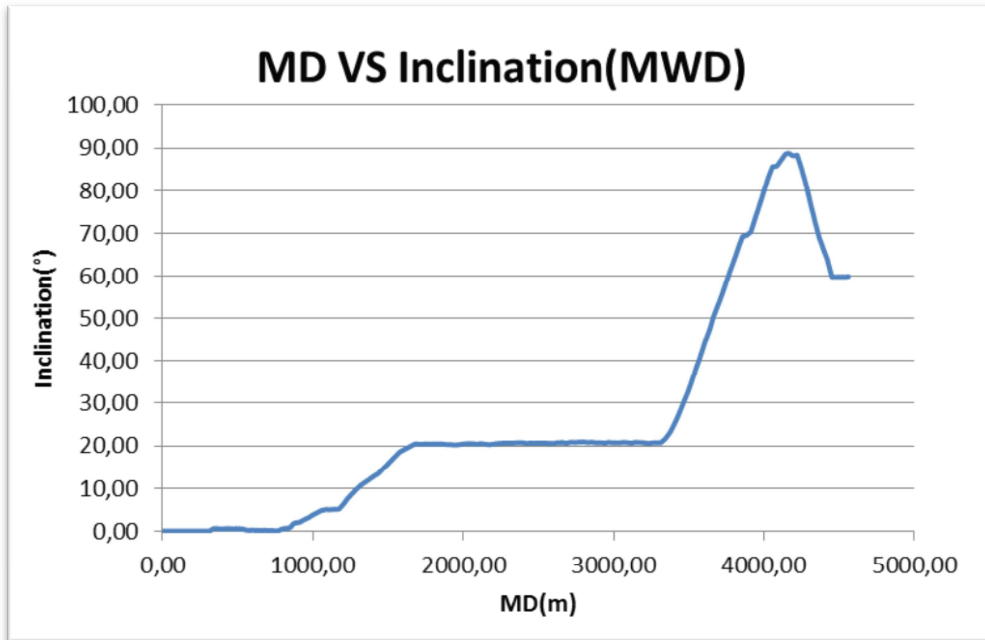


Figure 15.MD vs. Inclination after interpolation had been done.

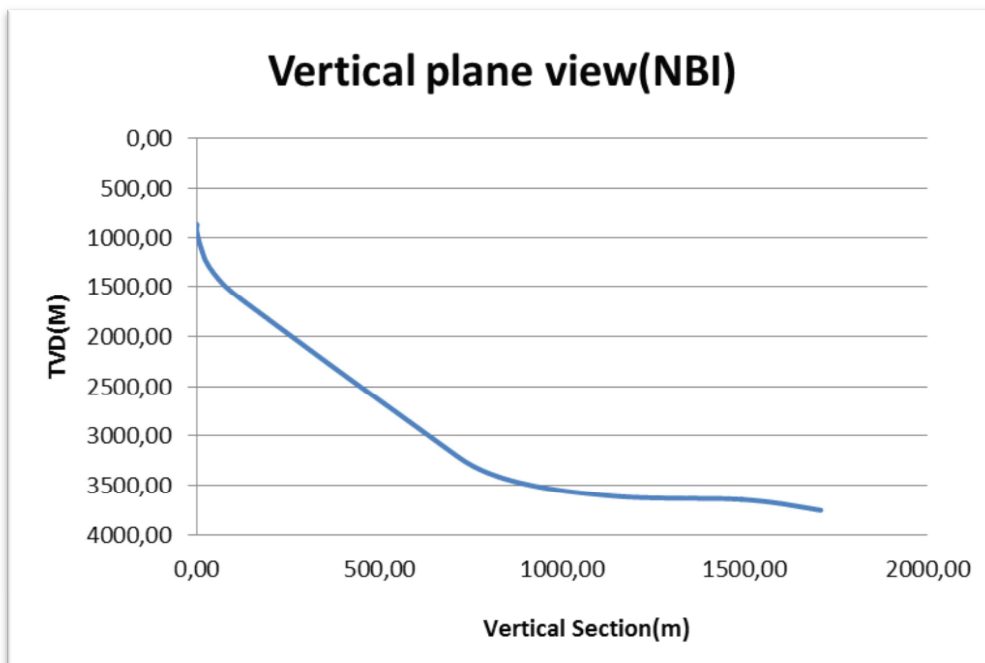


Figure 16.Vertical Section view after interpolation calculation.

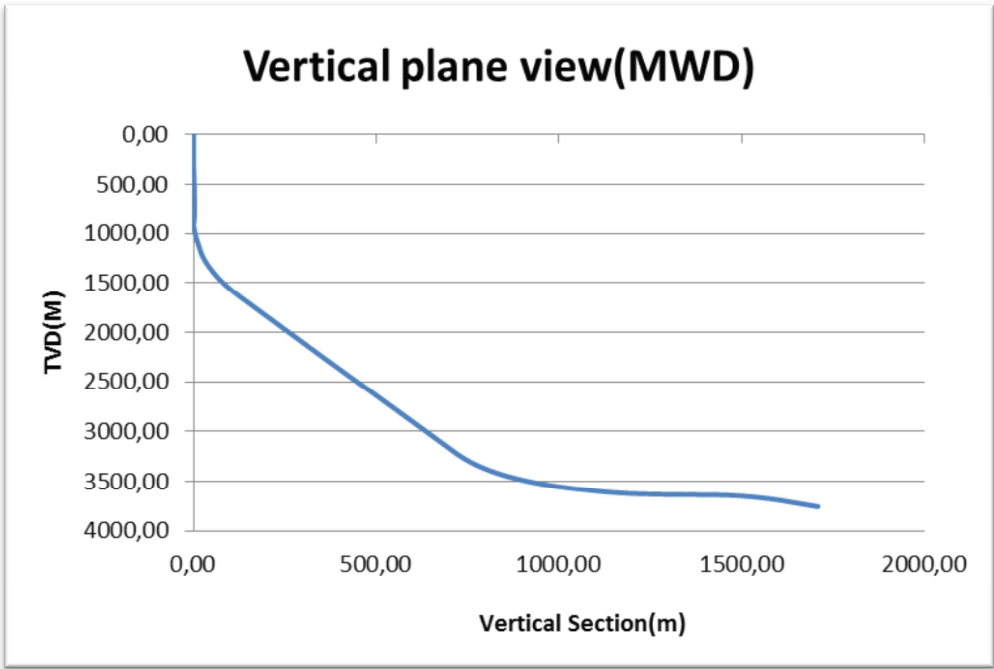


Figure 17. Vertical plane Section view after interpolation calculation.

Figure 18 shows MD vs. inclination when boundary averaging of +/-2 degrees and +/-10% is used

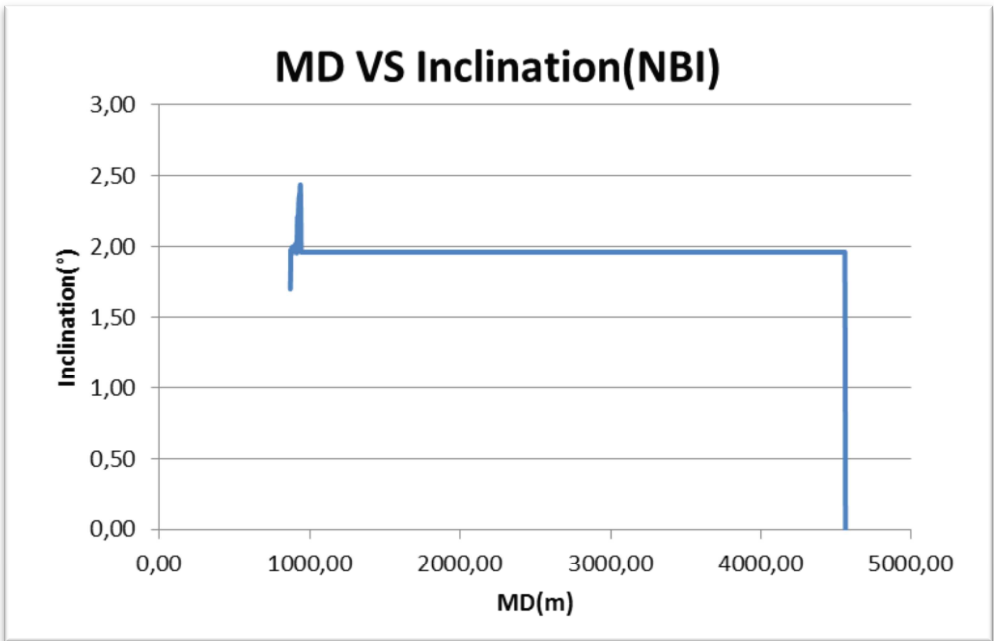


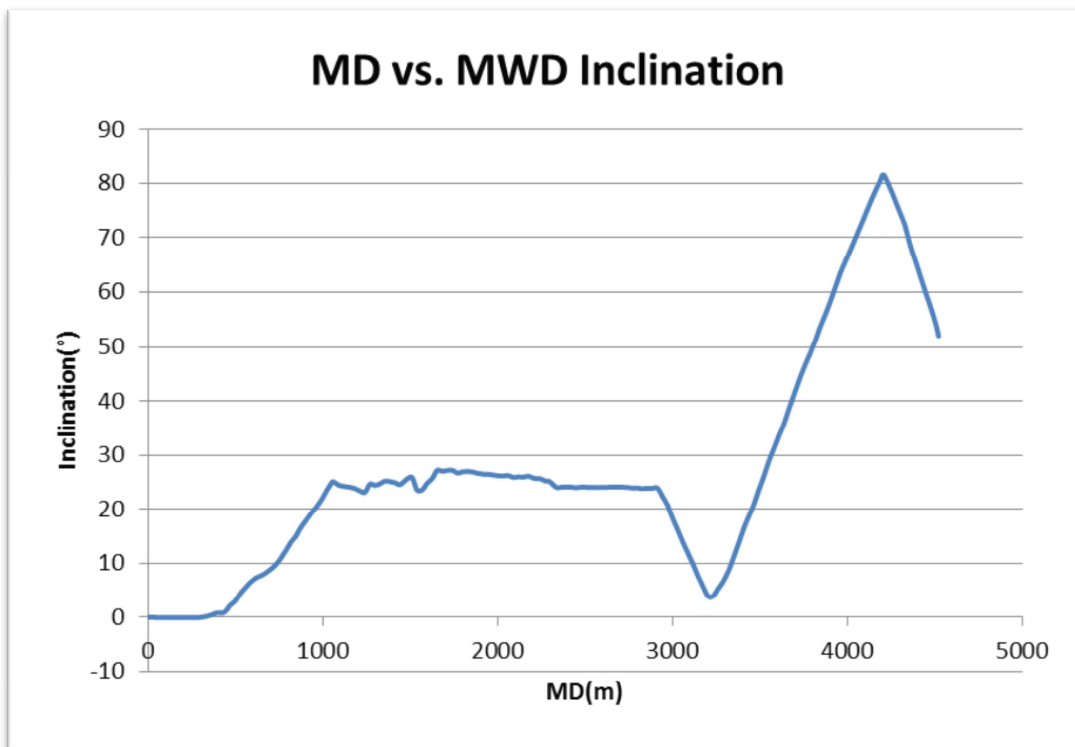
Figure 18. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used.

## 5.2 Well 2

The survey data for this well is also from the North Sea. The depth from rig floor to seabed is 291.8 m MD. From 291.8 m MD to 395.2 m MD there is no MWD survey. The MWD survey measurement begins at 395.2 m MD. The Inclination increases to 24-25 degrees from 395.2 m MD to 1047m MD. The well is then drilled with almost constant inclination from this point and down to 2912, 5m MD where the inclination is dropped. This drop section is drilled down to 3202, 8m where, again, the inclination is increased rapidly up to 81.54 degrees. This section is then followed by another drop section down to target at 4521.1m MD.

The NBI measurement begins at 2263.9 m MD. Therefore, comparison with the MWD survey starts at this point. There are no Azimuth measurements included in the raw data.

The Plots in **Figure 19** and **Figure 20** show MD vs. inclination of raw data.



**Figure 19.** MD vs. MWD inclination for well 2.

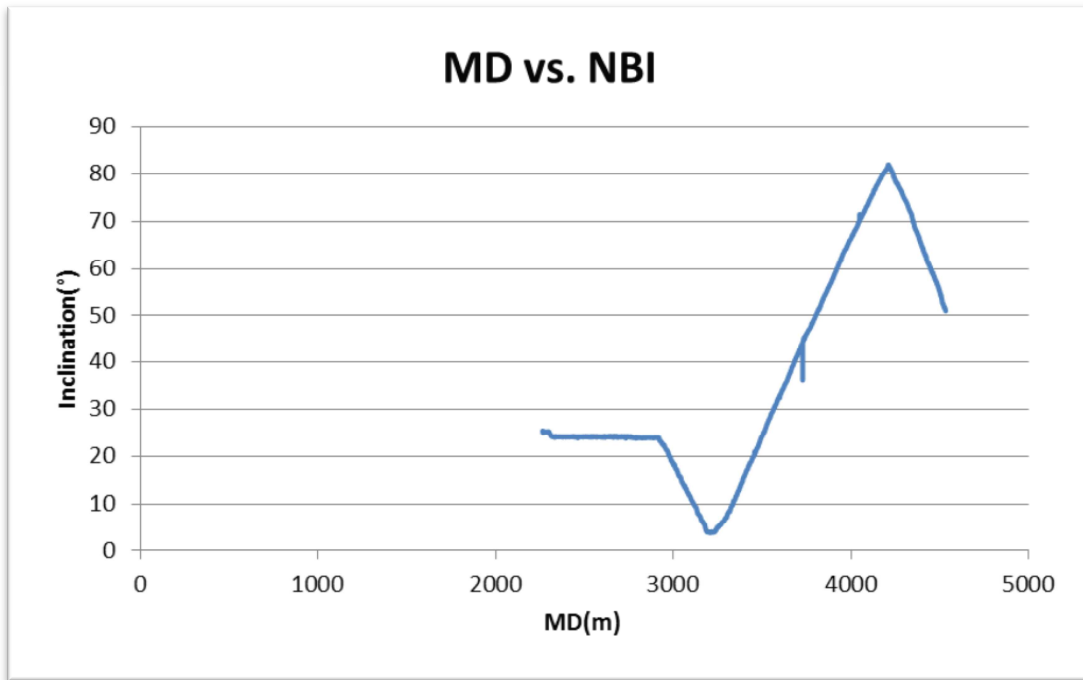


Figure 20. Inclination vs. NBI of unfiltered data for well 2

The data after interpolation calculation are plotted in the following figures.

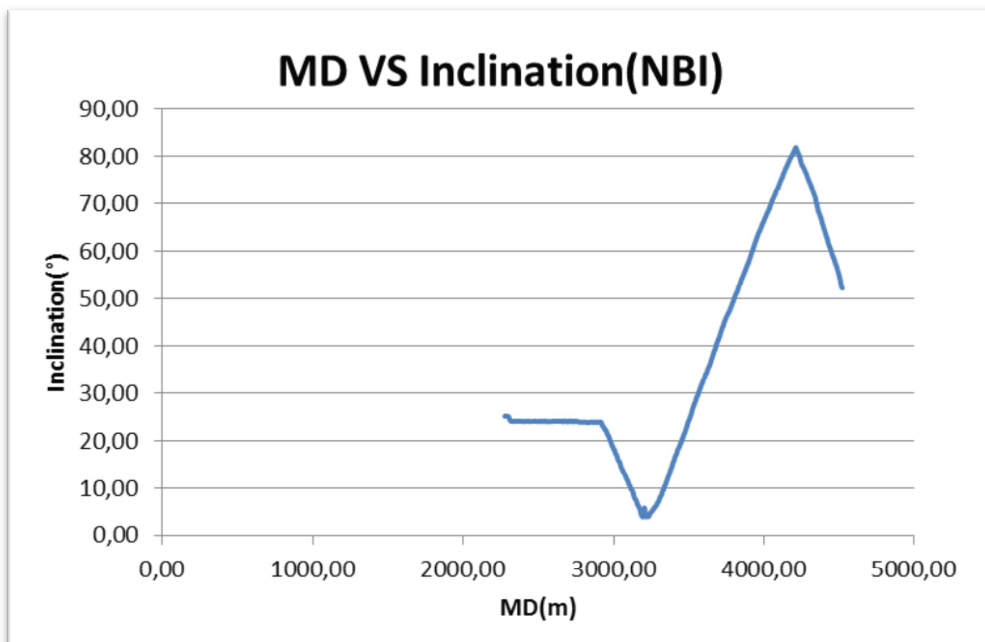


Figure 21. MD vs. Inclination after the data had been processed and interpolation had been done.

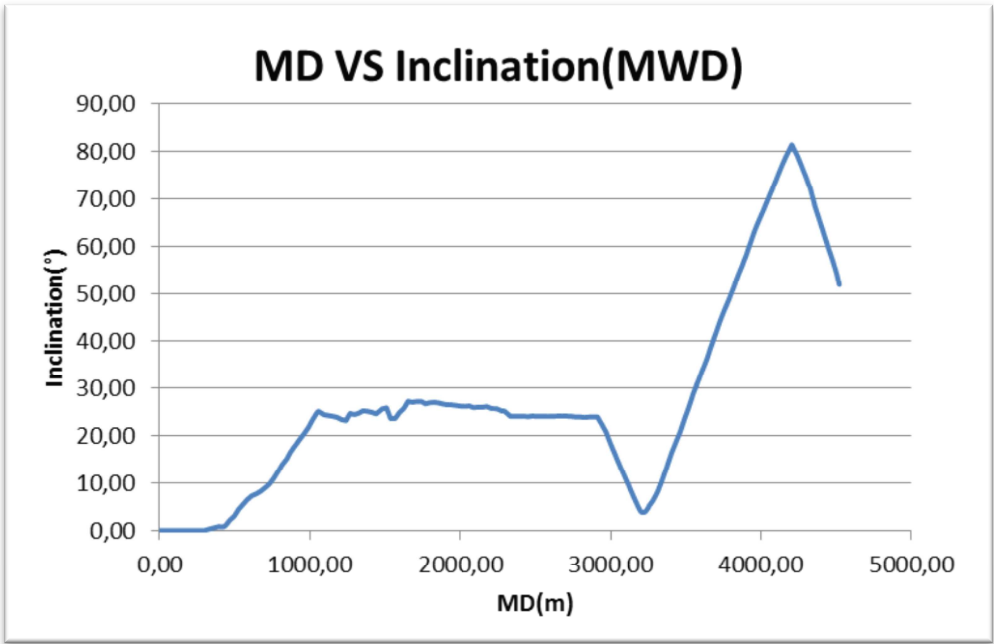


Figure 22.MD vs. Inclination after interpolation had been done.

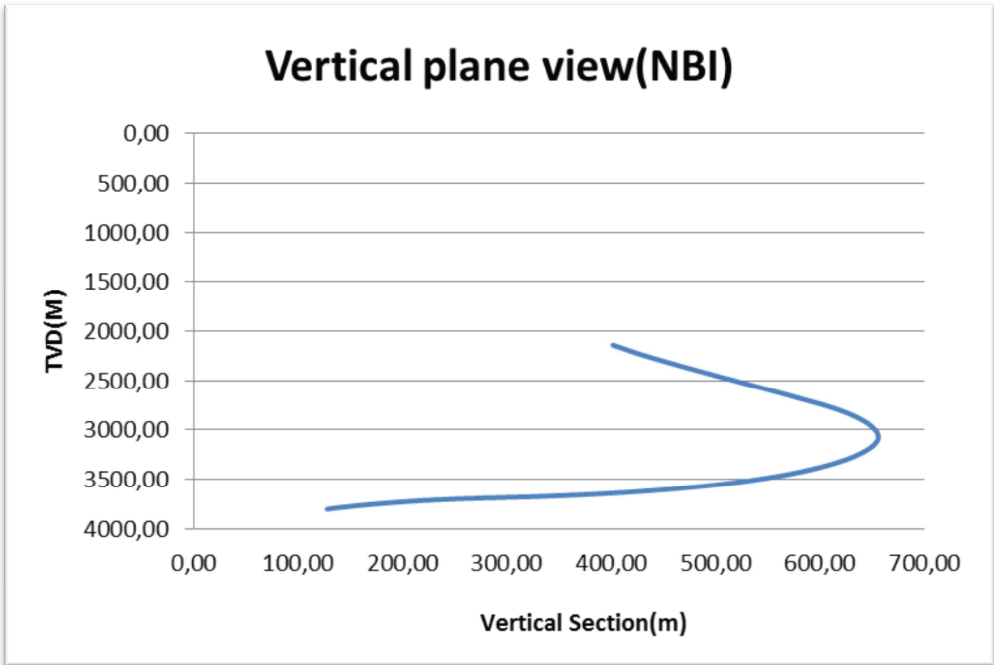


Figure 23.Vertical plane view after interpolation calculation.

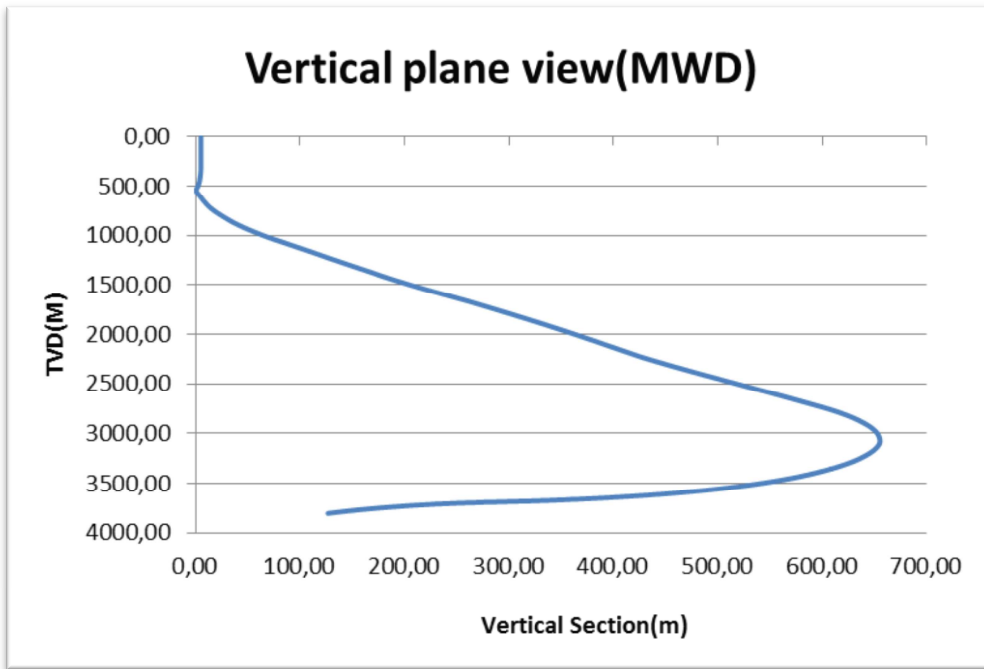


Figure 24. Vertical plane view after interpolation calculations.

Figure 25 illustrates how inclination would change when interpolated and plotted against MD if the conservative boundary averaging of +/-2 degrees and +/-10% is used.

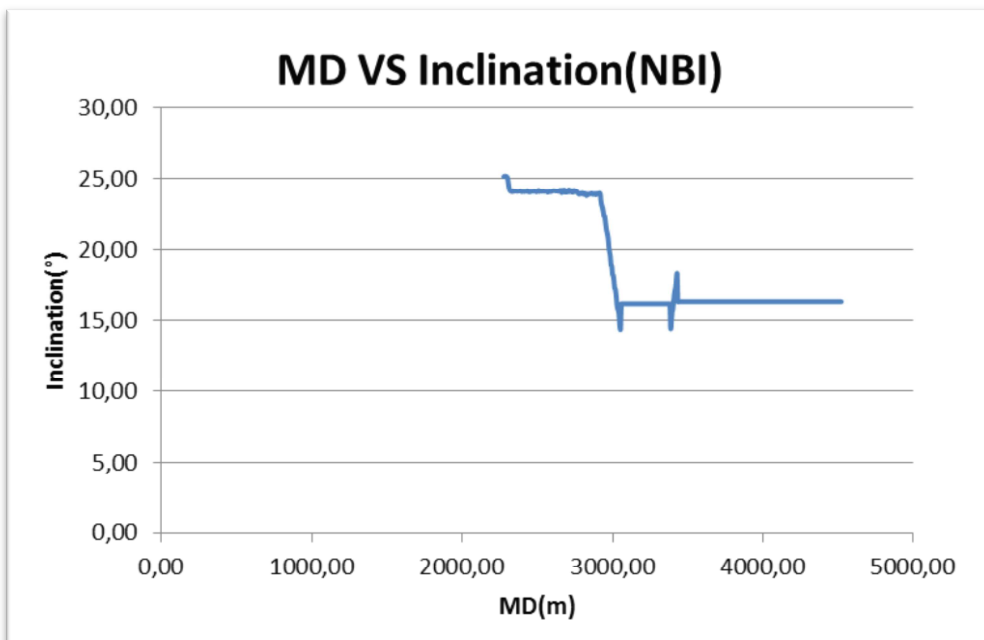


Figure 25. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used.

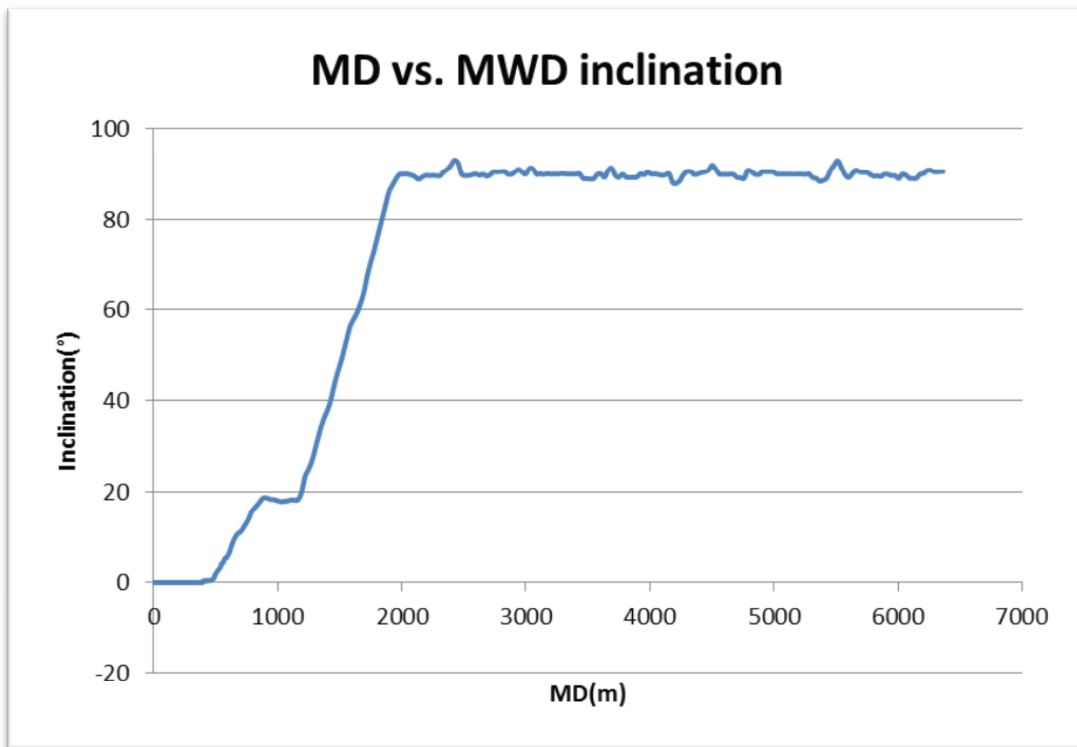


### 5.3 Well 3

The survey received for this well is also from the North Sea. The depth from rig floor to seabed is 363.30 m MD. From 393.20 m to 608 m a Gyro is used to measure inclination and azimuth. After this there is a section where only OnTrak is used to measure inclination and azimuth. But the MWD survey received only contained pure MWD OnTrak measurement from 1086.3m MD. As a result, the survey measurements from the DualInc are used at depths above this point. The pure NBI survey received began at 1100.94 m MD and there are no Azimuth measurements included in this data.

This well is drilled with high inclination. The inclination is rapidly increased right from the beginning until it reaches around 90 degrees at approximately 1950 m MD. After this the well is kept almost horizontal with small variations in the inclination down to TD at 6363 m MD.

**Figure 26** below illustrates how inclination changes with MD for the entire well using MWD inclinations before interpolation calculations. **Figure 27** how inclination changes with MD before interpolation calculations using raw NBI measurements.



**Figure 26.** MD vs. MWD inclination for well 3.

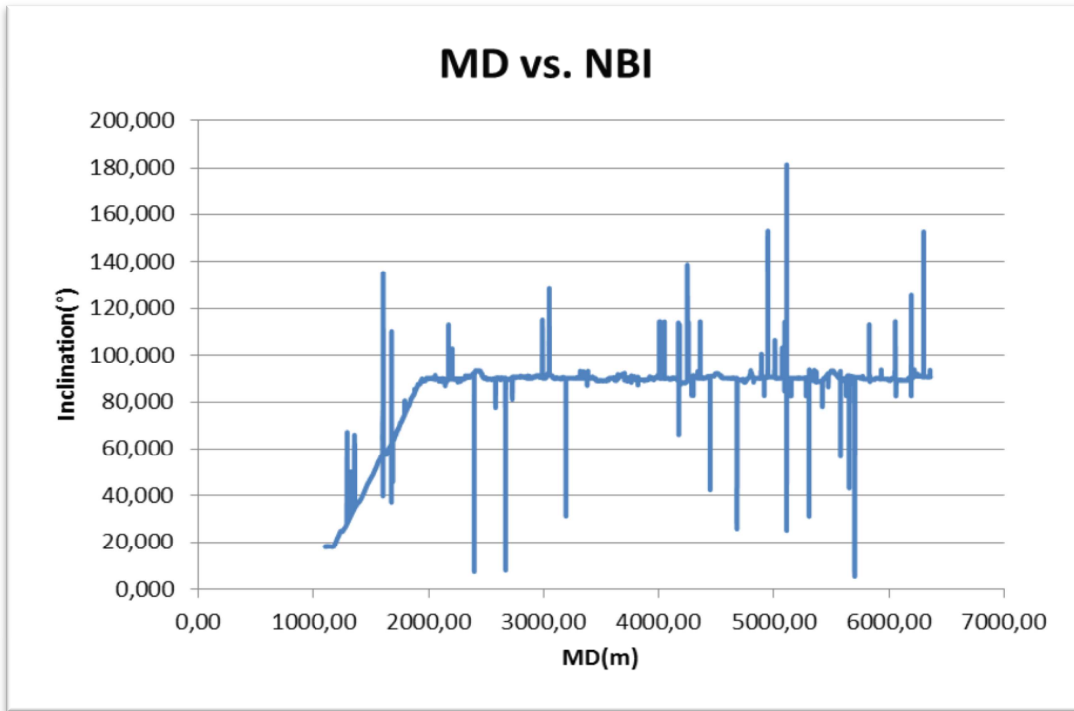


Figure 27. Inclination vs. NBI of raw well 3 NBI data.

The data after interpolation calculation are plotted in Figure 28 to Figure 31 for NBI data and MWD data.

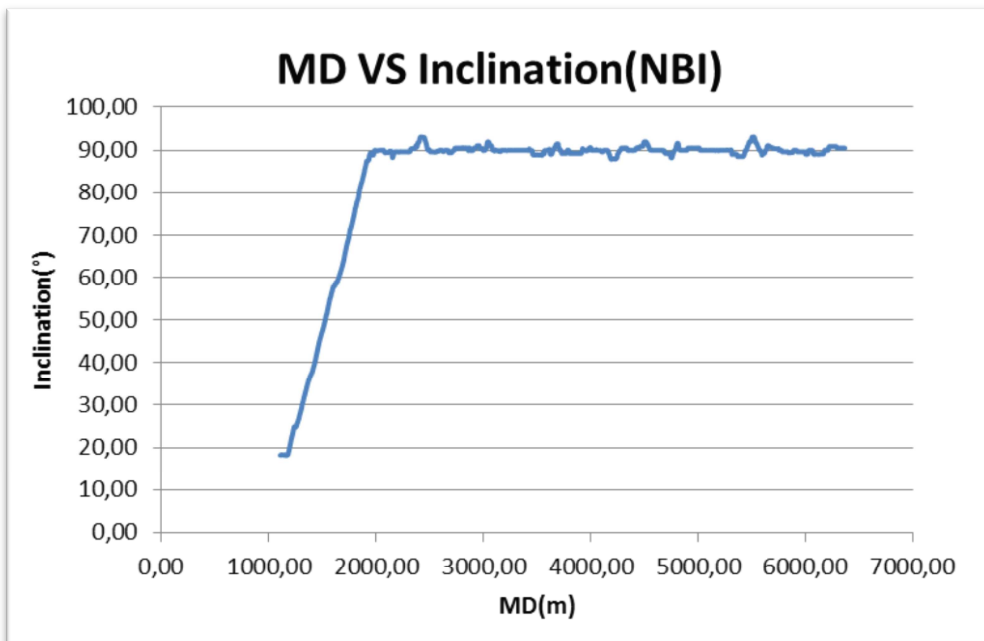


Figure 28. MD vs. Inclination after the data had been processed and interpolation have been done.

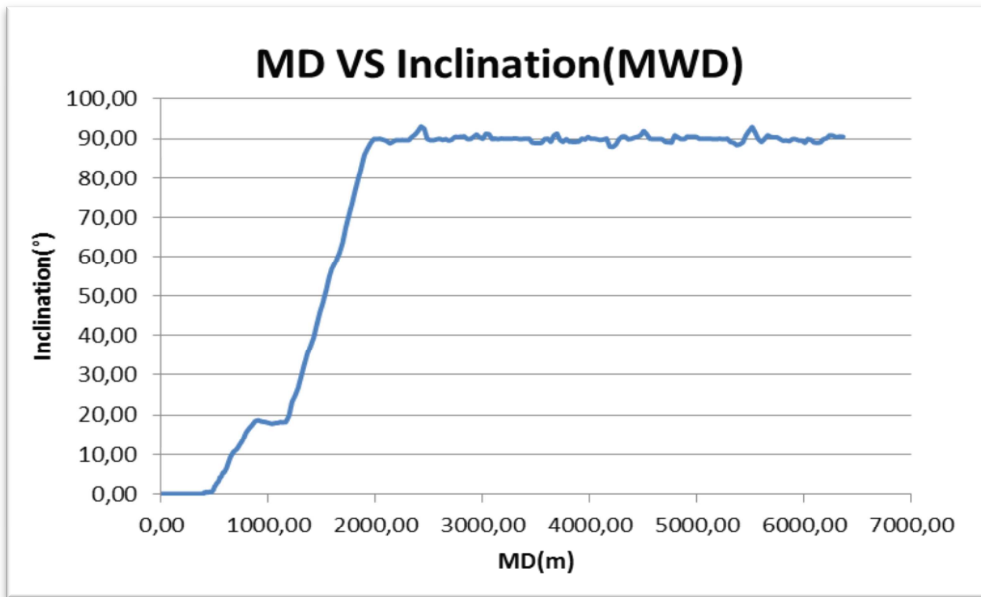


Figure 29. MD vs. Inclination after interpolation have been done.

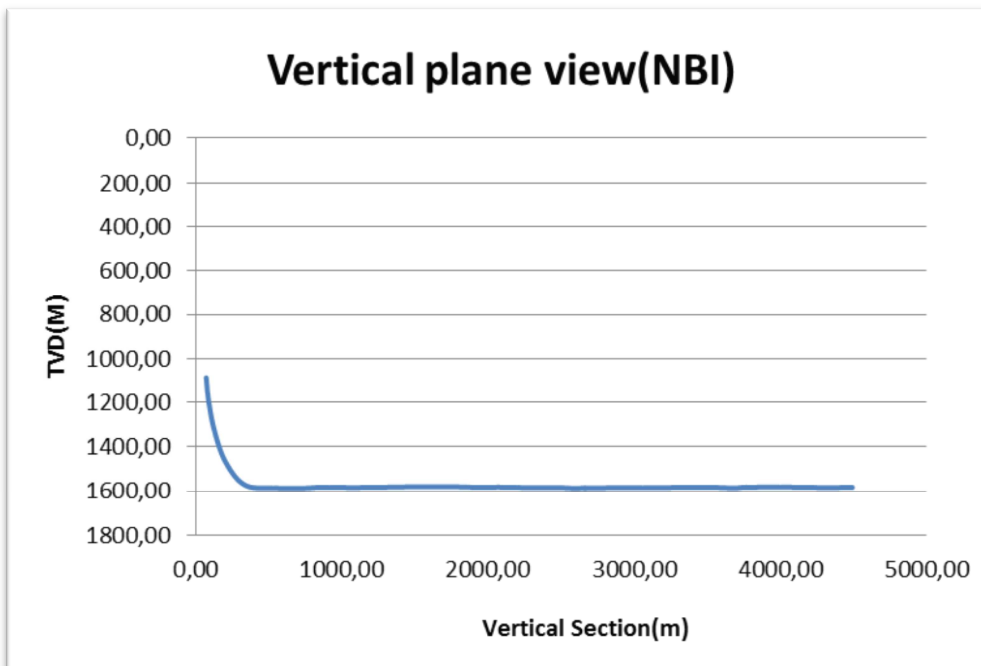


Figure 30. Vertical Section view after interpolation calculation

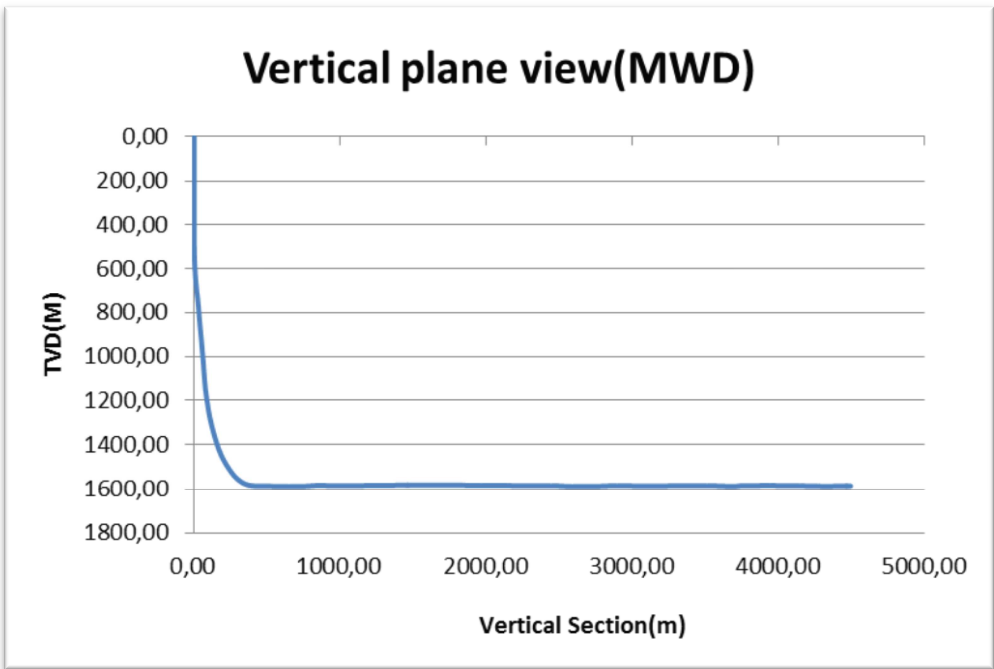


Figure 31. Vertical Section view after interpolation calculations.

Figure 32 illustrates how Figure 27 will look like if the conservative boundary averaging of +/-2 degrees and +/-10% is used.

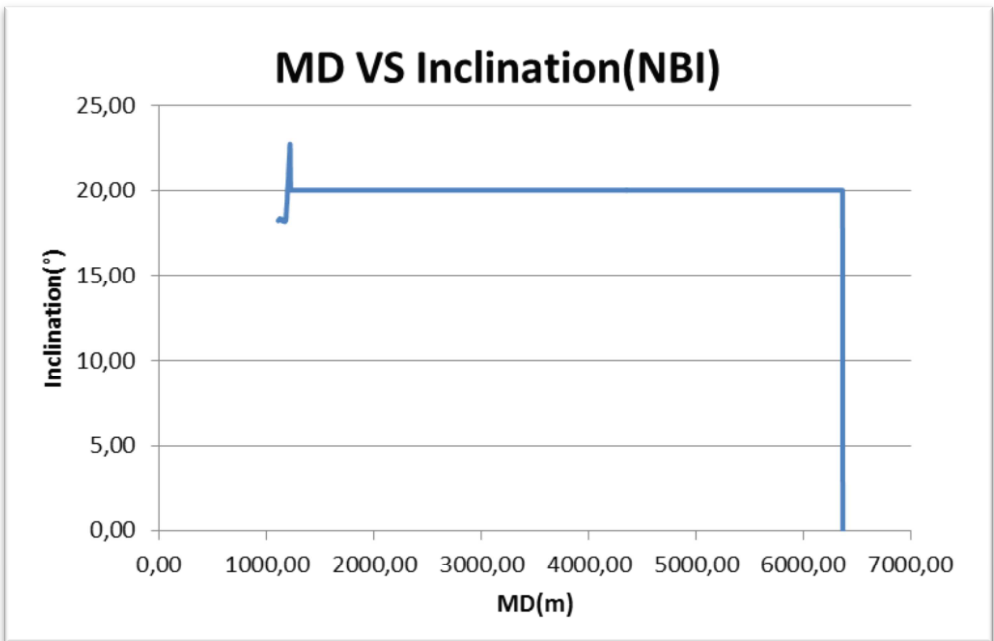


Figure 32. MD vs. Inclination when boundary averaging of +/-2 degrees and +/-10% is used.

## 6 DISCUSSION

In this chapter a discussion and explanation of the result above will be presented.

The result of interpolation calculation using the excel spreadsheet will be compared for MWD interpolated, NBI interpolated and the final well report by Baker Hughes the DualInc survey.

Baker Hughes posts the average inclination of the MWD and NBI in the DualInc final survey and uses this to calculate DLS and 3D coordinates TVD, Northing and Easting.

The filtration condition used by Baker Hughes to decide whether to include NBI in the average calculation is +/-0.35 degrees of the MWD inclination. If this criterion is not met, Baker Hughes posts pure MWD SAG corrected inclination in the final DualInc. survey. Thorough

### 6.1 Well 1

The raw NBI data received for this well contained many faulty measurements. In some sections there were consecutive erroneous measurements which lead to messy graph when MD vs. Inclination curve was plotted as seen in. After trying different NBI boundary averaging condition, +/-3.5 degrees and +/-30% was found to be most suitable. The result of using this filtration conditions are shown in **Figure 14**. **Figure 18** illustrates how the NBI data would have looked like if +/-2 degrees and +/-10% is used as boundary conditions. Due to low filtration values, the graph displays a constant inclination before it drops to zero at TD. This is caused by the conditions in the VBA macro code that sets inclination equal to previous inclination if there are no good values to calculate average inclination.

The result of the interpolation is shown in **Figure 14** to **Figure 17** . Comparisons of the data in these graphs show that there is not much difference in interpolated values between the MWD interpolated data and NBI interpolated data. There is small difference between NBI/MWD and DualINC. survey in DLS (0.07). Because the same Azimuth values were used in the survey stations in the two survey data, not much difference in the DLS, Northing and Easting were expected. For that reason, a comparison of TVD is more appropriate.

At TD, the difference in TVD between the MWD and NBI data was 0.91 m. This end TVD after interpolation calculations is also in correspondence with the TVD in the DualInc survey data. The difference between end DualInc TVD (3753.91 m) and the end MWD calculated TVD (3754.26 m) was

0.33 m. The difference between end NBI data calculated TVD (3753.36 m) and DualInc end TVD was 0.55 m.

Furthermore, comparison of the data reveals that there is not much difference in inclination at the end between DualInc survey, MWD interpolated and NBI interpolated survey. The results of the interpolations computations at the last survey station and end survey station for DualInc are summarized in **Table 5**.

**Table 5. End survey stations for interpolated MWD and NBI and DualInc survey.**

	MD	Inclination	Azimuth	TVD	North	East	DLS
	[m]	[°]	[°]	[m]	[m]	[m]	[°30m]
Interpolated MWD	4563,00	59,93	271,32	3754,27	-566,48	-1611,52	0,11
Interpolated NBI	4563,00	60,04	271,32	3753,36	-566,30	-1611,52	0,11
DualInc received by Baker Hughes	4563	59,925	271,32	3753,91	-566,37	-1611,41	0,04

For the comparison of well paths in a vertical plane view, the trajectories in **Figure 16** and **Figure 17** that there is not much difference among the trajectories projected on such a vertical plane view.

## 6.2 Well 2

For this well there are not much faulty NBI data. Therefore, the NBI readings as seen in **Figure 20** shows similar trend as the regular MWD survey inclination measurements. The only point that shows faulty reading is at 3728.19 m MD. When using +/-2 degrees and +/-10% as Boundary averaging NBI input parameter, the graph displayed in **Figure 25** states that there are not much changes in Inclination. These illustrations do not coincide with real well path shown in the figures above it. Again, this is because there are no good values to calculate average inclination and previous inclination is used in the centerline depth. When +/-3.5 degrees and +/-30% was used, **Figure 21** shows that the graph became smoother and followed the real well path.

Comparison of the interpolated data showed no great difference in end TVD between NBI interpolated and MWD interpolated and the DualInc survey received by Baker Hughes. The values of the different parameters at the end survey stations for all three survey data are presented in **Table 6** below.

**Table 6. End survey stations for interpolated MWD and NBI and DualInc survey.**

	MD	Inclination	Azimuth	TVD	North	East	DLS
	[m]	[°]	[°]	[m]	[m]	[m]	[°/30m]
Interpolated MWD	4521,1	52,02	197,18	3802,46	96,81	-81,76	4,48
Interpolated NBI	4521,1	52,27	197,18	3801,71	97,64	-82,61	4,48
DualInc received by Baker Hughes	4521,1	52,02	197,18	3802,46	96,81	-81,76	4,48

The difference in the Northing and Easting is minimal, but as earlier stated the same azimuths are used at all survey stations. Thus, not much difference is expected in the Northing and Easting between the different survey data.

The difference in inclination is also minimal between MWD interpolated and NBI interpolated at end survey stations. This small difference combined with the use of the same Azimuths at all survey stations contributes to small or no difference in end DLS.

Additionally, there is a relatively good match in TVD. The difference in end TVD is only 0.75 m. this small value is not believed to greatly influence the optimal well placement, especially Because the final TVD reported in the final DualInc survey is calculated using the average inclination of NBI and MWD data.

Vertical section

The vertical plane view showed by **Figure 23** and **Figure 24** show no discrepancies between NBI survey and the MWD survey. Also, there are relatively no differences between end vertical section calculated and end vertical section value in the received DualInc survey

### 6.3 Well 3

The raw NBI data received for this well also contained many faulty measurements. As shown by **Figure 27** there was many points with erroneous measurements which lead to chaotic graph. For this well, the overall filtration boundary averaging NBI was also +/-3.5 degrees and +/-30%. The result of using this filtration conditions are shown in **Figure 29**. **Figure 32** illustrates how the NBI data would have looked like if +/-2 degrees and +/-10% are used as boundary conditions. It shows similar trend as the plot for

Well 1 when the same boundary conditions were used. The inclination is constant before it drops to zero at TD. This is caused by the same condition in the VBA macro code as earlier mentioned.

This well is long and most of well is drilled with high inclination around 90 degrees. **Table 7** below shows the end station parameters for all three survey data.

**Table 7. End survey stations for interpolated MWD and NBI and DualInc survey.**

	MD	Inclination	Azimuth	TVD	North	East	DLS
	[m]	[°]	[°]	[m]	[m]	[m]	[°/30m]
Interpolated MWD	6363	90,52	151,62	1584,16	-3421,99	2911,62	0
Interpolated NBI	6363	90,53	151,62	1581,74	-3421,99	2911,62	0
DualInc received by Baker Hughes	6363	90,52	151,62	1582,73	-3422	2911,61	0

The difference in end TVD between Interpolated NBI survey and MWD survey was greater for this well than the results of previous two wells. The TVD difference at end survey station was 2.42 m which can be argued to be due to the length of the well and that the well is horizontal for the most part of the wellbore.

There are no considerable differences in inclination between these two surveys, and **Figure 28** and **Figure 29** show this observation in the MD vs. inclination curve.



## **7 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK**

### **7.1 Conclusion**

In this thesis a Microsoft Excel spreadsheet VBA scheme was developed to interpolate between survey stations by importing NBI survey and MWD survey data in certain format. The Minimum curvature interpolation procedures are used to interpolate between survey stations.

Because the raw NBI data received contained numerous faulty measurements a method of averaging NBI around a centerline point was developed. This is important because the objective is to compare the results of interpolations at the same depth between the NBI and MWD surveys. This way of averaging NBI around a depth point uses two filtrations criteria which reduces the risk of faulty measurements to be included in the average inclinations. Because Baker Hughes uses average inclination of MWD and NBI survey in the DualInc. surveys, this way of averaging will contribute to getting more accurate average inclination values.

Because there are no continuous azimuths included in the NBI data, the same azimuth is used in both survey data at survey stations. Therefore, no great emphasis was put on comparing the results of the DLS, northing, and easting due to these parameter's dependence on azimuth. Comparison of the end survey station TVD and inclination for both survey data showed minimal difference in Well 1 and Well 2. The difference in inclination between the survey data in Well 3 was also negligible. But comparison of the end TVD between the interpolated survey data in Well 3 revealed larger differences. Because the calculated end TVD is a cumulative, the larger difference in TVD for Well 3 might be due to the extended wellbore compared to the other two wells.

Additionally, comparisons of the interpolated survey results to the final Dual Inc. survey, also received by Baker Hughes, revealed minimal difference. Because the DualInc. survey is final well survey, the results indicate that the code developed works excellent and the filtration method of NBI is a good way to get a much cleaner average inclination. The results also indicate the assumption made that the well path follows the assumed mathematical model of MCM is reasonable.

### **7.2 Recommendations for future work**

This code developed in this thesis uses MCM interpolation technique to interpolate between survey stations. An attempt was made to extend the code to handle a script using Constant curvature method

(CCM). But due lack of time it was deemed impossible for the short time given to finish this thesis. Thus, for future work, the spreadsheet may perhaps be developed to use CCM interpolation techniques.

The wells where the received surveys are from are all drilled with Baker Hughes's AutoTrak G3. As earlier mentioned and illustrated in **Figure 4** wells drilled with this tool creates a smoother hole than well drilled with PDM. Therefore, another recommendation is to test this spreadsheet with wells drilled with PDMs.

As mentioned, the same azimuth is used at survey stations in the MWD and NBI centerline points because there were no azimuths measurements included in the NBI data. This makes it difficult to compare DLS, N and E between the two survey data due this parameter's dependence on azimuth. Therefore, another survey data which has its own azimuth should be compared with MWD interpolated survey data.

Finally, it is possible to make the spread sheet more user-friendly by for instance making it possible to import several surveys at the same time.

## 8 REFERENCES

- 1 Inglis, T.A., "Directional Drilling", Graham & Trotman, 1987.
- 2 G.Robello Samuel and Xiushan Liu, "Advanced Drilling Engineering-Principles and design", Gulf Publishing Company, 2007.
- 3 Walstrom, J.E., Harvey, R.P., Eddy, H.D., "A comparison of various directional survey models and an approach to model error analysis", SPE 3379, August 1972.
- 4 Zaremba, W. A., "Directional Survey By The Circular Arc Method", SPE Journal, February 1973.
- 5 Howard, L. T., Mason, C.M., "A Systematic Approach to Well Surveying Calculations", SPE 3362, December 1972.
- 6 Tugwell, A.G., "Aspects of Effective Well Management", Aberdeen Drilling Management Ltd., 2008
- 7 Torkildsen, T., Bang, J., "Directional Surveying: Rotating and Sliding Operations Give Different Wellbore Position Accuracy" SPE Annual Technical Conference and Exhibition, 1-4 October 2000, Dallas, Texas.
- 8 Ekseth, R., Torkildsen, T., Brooks, A., Weston, J., Nyrnes, E., Wilson, H., Kovalenko, K., "High-Integrity Wellbore Surveying", SPE Drilling & Completion, December 2010.
- 9 Wilson, G.J., "An improved Method for Computing Directional Surveys", Journal of Petroleum Technology, August 1968.
- 10 Williamson, H.S., "Accuracy Prediction for Directional Measurement While Drilling" SPE Drilling & Completion, December 2000.
- 11 Xiushan L., Rushan, L., Sun, M., "New Techniques Improve Well Planning and Survey Calculation for Rotary-Steerable Drilling", IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, 13-15 September 2004, Kuala Lumpur, Malaysia.
- 12 Guo, B., Miska, S., Lee, R.L., "Constant Curvature Method for Planning a 3-D Directional Well", SPE Rocky Mountain Regional Meeting, 18-21 May 1992, Casper, Wyoming.
- 13 Sawaryn, S.J., Thorogood, J.L., "A Compendium of Directional Calculations Based on the Minimum Curvature Method", SPE Drilling & Completion, March 2005.
- 14 Sawaryn, S.J., Tulceanu, M.A., "A Compendium of Directional Calculations Based on the Minimum Curvature Method--Part 2", SPE Annual Technical Conference and Exhibition, 11-14 November 2007, Anaheim, California, U.S.A.
- 15 Robert. F. M., Stefan Z.M., "Fundamentals of Drilling Engineering" Society of Petroleum Engineers, 2011.
- 16 Aadnoy, B.S, Cooper, I., Miska, S.Z., Mitchell, R.F., Payne, M.L., "Advanced Drilling and Well Technology", Society of Petroleum Engineers, 2009.

- 17 R.F Mitchell: How good is the torque and drag model? SPE 105068
- 18 Aadnøy, B.S., Andersen, K.: "Friction Analysis for Long-Reach Wells, SPE/IADC 39391,
- 19 P.E. BERGER, R. SELE , "Improving Wellbore Position Accuracy of Horizontal Wells by Using A Continuous Inclination Measurement From a Near Bit Inclination MWD Sensor" , SPE International Conference on Horizontal Well Technology, 1-4 November 1998, Calgary, Alberta, Canada
- 20 "Use of Gyro\_MWD Technology Offshore\_ A Step Change in Drilling Performance in Saudi Aramco", Abu Dhabi International Petroleum Exhibition and Conference, 1-4 November 2010, Abu Dhabi, UAE
- 21 R. Mathur "Automated Drilling Systems" Baker Hughes, 2010
- 22 Hahne, U., Risdal, G., Ruzska, J., Wahlen, L.S., " Integrated BHA Concept of the Latest Generation Rotary Closed-Loop System for Hole Sizes from 5 7/8" to 18 1/4", IADC/SPE Drilling Conference, 2-4 March 2004, Dallas, Texas, U.S.A.

## 9 APPENDIX

### 9.1 Source code: Interpolation of MWD data

**Sub Interpolate()**

.....

**'Interpolates Azimuth, TVD, Northing, Easting between two survey points**

**'using the values measured at each point**

.....

**Dim tempInclFormula, tempAZFormula, tempRFFFormula As String**

**Dim SurveyCount, IntCount, ColCount, RowCount, IntPntCount As Long**

**Dim MD1, MD2, INCL1, INCL2, AZ1, AZ2, IntIncr As Double**

**Dim SurveySheet, IntSheet, CalcSheet As String**

**SurveyCount = 3 'First row of imported survey**

**IntCount = 3 'First row of resulting interpolation**

**SurveySheet = "Imported Survey" 'sheet containing the imported survey**

**IntSheet = "Interpolation - Survey" 'sheet containing the resulting interpolation**

**CalcSheet = "Calculation" 'sheet containing formulas for calculations**

**tempInclFormula = Sheets(CalcSheet).Cells(9, 3).Formula 'Save formula to restore after script is executed**

**tempAZFormula = Sheets(CalcSheet).Cells(9, 4).Formula**

**tempRFFFormula = Sheets(CalcSheet).Range("H13").Formula**

**Sheets(IntSheet).Select 'clear contents of interpolation sheet**

**Range("A3:L3").Select**

**Range(Selection, Selection.End(xlDown)).Select**

**Selection.Font.Bold = False**

**Selection.ClearContents**

## On Error GoTo ErrorHandler

Application.ScreenUpdating = False

Sheets(IntSheet).Range("H" & IntCount) = 0 'Writes alpha12 to DL column

Sheets(IntSheet).Range("H" & IntCount).Font.Bold = True

Sheets(CalcSheet).Unprotect

While (IsNumeric(Sheets(SurveySheet).Range("A" & SurveyCount + 1)) And  
Sheets(SurveySheet).Range("A" & SurveyCount + 1) <> "")

'Loops until the last imported survey point

MD1 = Sheets(SurveySheet).Range("A" & SurveyCount) 'Depth

MD2 = Sheets(SurveySheet).Range("A" & SurveyCount + 1)

INCL1 = Sheets(SurveySheet).Range("B" & SurveyCount) 'Inclination

INCL2 = Sheets(SurveySheet).Range("B" & SurveyCount + 1)

AZ1 = Sheets(SurveySheet).Range("C" & SurveyCount) 'Azimuth

AZ2 = Sheets(SurveySheet).Range("C" & SurveyCount + 1)

If MD2 < MD1 Then

MsgBox ("There is an error in the imported Survey Data. The measured depth in Row " &  
SurveyCount + 1 & " on sheet " & SurveySheet & " is less than the previous survey point.")

StopProgram = True

GoTo ErrorHandler

End If

For ColCount = 1 To 7

Sheets(IntSheet).Cells(IntCount, ColCount) = Sheets(SurveySheet).Cells(SurveyCount,  
ColCount) 'Values at first survey point

Sheets(IntSheet).Cells(IntCount, ColCount).Font.Bold = True

Sheets(CalcSheet).Cells(2, ColCount + 1) = Sheets(SurveySheet).Cells(SurveyCount,  
ColCount)

Sheets(CalcSheet).Cells(3, ColCount + 1) = Sheets(SurveySheet).Cells(SurveyCount + 1, ColCount) 'values at next survey point

Next ColCount

Sheets(IntSheet).Range("H" & IntCount + NumIntPnts + 1) = Sheets(CalcSheet).Range("I3")

'Writes alpha12 to DL column

Sheets(IntSheet).Range("H" & IntCount + NumIntPnts + 1).Font.Bold = True

IntPntCount = 0

IntIncr = (MD2 - MD1) / (NumIntPnts + 1) 'calculates interpolation increment to achieve desired number of interpolation points

Do Until IntPntCount = NumIntPnts

'Loops until desired number of interpolation points has been reached

IntCount = IntCount + 1

Sheets(CalcSheet).Cells(9, 2) = Sheets(IntSheet).Range("A" & IntCount - 1) + IntIncr

'enters depth value at interpolation point to calculation sheet

If INCL1 = INCL2 Then

'If the inclination angle is the same at each survey point then use the value from the 1st for interpolation

tempInclFormula = Sheets(CalcSheet).Cells(9, 3).Formula

Sheets(CalcSheet).Cells(9, 3) = INCL1

End If

If AZ1 = AZ2 Then

'If the azimuth is the same at each survey point then use the value from the 1st for interpolation

tempAZFormula = Sheets(CalcSheet).Cells(9, 4).Formula

Sheets(CalcSheet).Cells(9, 4) = AZ1

End If

If Sheets(CalcSheet).Cells(13, 3) = 0 Then

'If the DL is zero then use a ratio factor of 1

tempRFFFormula = Sheets(CalcSheet).Range("H13").Formula

Sheets(CalcSheet).Range("H13") = 1

End If

For ColCount = 1 To 8 'writes calculated values to interpolation sheet

Sheets(IntSheet).Cells(IntCount, ColCount) = Sheets(CalcSheet).Cells(9, ColCount + 1)

Next ColCount

'reinstate formulas

Sheets(CalcSheet).Cells(9, 3).Formula = tempInclFormula

Sheets(CalcSheet).Cells(9, 4).Formula = tempAZFormula

Sheets(CalcSheet).Range("H13").Formula = tempRFFFormula

IntPntCount = IntPntCount + 1

Loop

IntCount = IntCount + 1

SurveyCount = SurveyCount + 1

Wend

For ColCount = 1 To 7 'write the last survey point to the interpolation sheet

Sheets(IntSheet).Cells(IntCount, ColCount) = Sheets(SurveySheet).Cells(SurveyCount, ColCount)

Sheets(IntSheet).Cells(IntCount, ColCount).Font.Bold = True

Next ColCount

RowCount = 3

While Sheets(IntSheet).Range("A" & RowCount) <> ""

'Loops through each row and enters formulas to calculate Closure distance/Angle, Directional Difference and Vertical Section

Sheets(IntSheet).Range("I" & RowCount).Formula = "=SQRT((E" & RowCount & ""^2)+(F" & RowCount & ""^2))" ' Calculate Closure Distance

Sheets(IntSheet).Range("J" & RowCount).Formula = "=DEGREES(ATAN(F" & RowCount & "/E" & RowCount & "))" ' Calculate Closure angle

Sheets(IntSheet).Range("K" & RowCount).Formula = "=\$Q\$1-J" & RowCount & "" 'Calculate Directional difference

Sheets(IntSheet).Range("L" & RowCount).Formula = "=abs(I" & RowCount & ""\*(COS(RADIANS(K" & RowCount & ""))))" ' Calculate Vertical Section

RowCount = RowCount + 1



**Wend**

**If BearingAngle = -9999 Then**

**'if the user did not enter a bearing angle then use the Closure Angle calculated from the last Survey Point. This input is turned off. Can turn it on under Frm\_Entry**

**Sheets(IntSheet).Range("Q1").Value = Sheets(IntSheet).Range("J" & RowCount - 1)**

**Else**

**Sheets(IntSheet).Range("Q1").Value = BearingAngle**

**End If**

**ErrorHandling:**

**'reinstate formulas**

**Sheets(CalcSheet).Cells(9, 3).Formula = tempInclFormula**

**Sheets(CalcSheet).Cells(9, 4).Formula = tempAZFormula**

**Sheets(CalcSheet).Range("H13").Formula = tempRFFFormula**

**'Formatting**

**Sheets(CalcSheet).Protect**

**Sheets(IntSheet).Select**

**Range("A3:L3").Select**

**Range(Selection, Selection.End(xlDown)).Select**

**With Selection**

**.NumberFormat = "0.00"**

**.HorizontalAlignment = xlCenter**

**End With**

**Range("Q1").Select**

**With Selection**

**.NumberFormat = "0.00"**

**.HorizontalAlignment = xlCenter**

**End With**

**Range("A1").Select**

**Application.ScreenUpdating = True**

**End Sub**

## 9.2 Source code: Interpolation of NBI data

```
Sub Interpolate_Continuous()
```

```
.....
```

```
'Interpolates Azimuth, TVD, Northing, Easting between two survey points
```

```
'using inclination and depth from NBI survey
```

```
.....
```

```
Dim tempInclFormula, tempAZFormula, tempRFFFormula As String
```

```
Dim SurveyCount, IntCount, RowCount, ColCount, IntPntCount, PastSurvey, NextSurvey As  
Long
```

```
Dim ContCount As Long
```

```
Dim NextCont As Long
```

```
Dim MD1, MD2, INCL1, INCL2, AZ1, AZ2, IntIncr, AvgIncl As Double
```

```
Dim SurveySheet, IntSheet, CalcSheet, ContSheet As String
```

```
SurveySheet = "Imported Survey" 'Sheet containing the imported survey
```

```
IntSheet = "Interpolation - Continuous" 'sheet containing the resulting interpolation
```

```
CalcSheet = "Calculation" 'Sheet containing the formulas for calculations
```

```
ContSheet = "Continuous Measurement" 'Sheet containing the imported the NBI data
```

```
SurveyCount = 3 'First row of imported survey
```

```
IntCount = 3 'First row of resulting interpolation
```

```
ContCount = 3 'First row of NBI data
```

```
PastSurvey = IntCount
```

```
NextSurvey = IntCount + NumIntPnts + 1
```

```
tempInclFormula = Sheets(CalcSheet).Cells(9, 3).Formula 'Save formula to restore after script  
is executed
```

```
tempAZFormula = Sheets(CalcSheet).Cells(9, 4).Formula
```

```
tempRFFFormula = Sheets(CalcSheet).Range("H13").Formula
```

```
Sheets(IntSheet).Select 'Clear contents of interpolation sheet
Range("A3:L3").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Font.Bold = False
Selection.ClearContents
```

**On Error GoTo ErrorHandler**

```
Sheets(IntSheet).Range("H" & IntCount) = 0 'Writes alpha12 to DL column
Sheets(IntSheet).Range("H" & IntCount).Font.Bold = True
```

```
While (Sheets(ContSheet).Range("A" & ContCount) > Sheets(SurveySheet).Range("A" &
SurveyCount)) And (IsNumeric(Sheets(SurveySheet).Range("A" & SurveyCount + 1)) And
Sheets(SurveySheet).Range("A" & SurveyCount + 1) <> "")
```

'loops until the first point of survey data is greater than the first imported continuous data

```
SurveyCount = SurveyCount + 1
```

Wend

```
Do Until Sheets(ContSheet).Range("A" & ContCount) > Sheets(SurveySheet).Range("A" &
SurveyCount)
```

'Move ContCount until value is one more than survey point

```
ContCount = ContCount + 1
```

Loop

```
Application.ScreenUpdating = False
```

```
Sheets(CalcSheet).Unprotect
```

```
For ColCount = 1 To 7
```

```
Sheets(IntSheet).Cells(PastSurvey, ColCount) = Sheets(SurveySheet).Cells(SurveyCount,
ColCount) ' Enter 1st Survey Point onto Interpolation sheet
```

```
Sheets(IntSheet).Cells(PastSurvey, ColCount).Font.Bold = True
```

```
Next ColCount
```

While (IsNumeric(Sheets(SurveySheet).Range("A" & SurveyCount + 1)) And  
Sheets(SurveySheet).Range("A" & SurveyCount + 1) <> "")

**'Loops until the last imported survey point**

For ColCount = 1 To 7

Sheets(IntSheet).Cells(NextSurvey, ColCount) = Sheets(SurveySheet).Cells(SurveyCount +  
1, ColCount) **'Enter next Survey Point onto Interpolation sheet**

Sheets(IntSheet).Cells(NextSurvey, ColCount).Font.Bold = True

Next ColCount

MD1 = Sheets(IntSheet).Range("A" & PastSurvey) 'Depth

MD2 = Sheets(IntSheet).Range("A" & NextSurvey)

AZ1 = Sheets(IntSheet).Range("C" & PastSurvey) 'Azimuth

AZ2 = Sheets(IntSheet).Range("C" & NextSurvey)

NextCont = FindContPnt(ContSheet, ContCount, Sheets(IntSheet).Cells(NextSurvey, 1))

**'Finds the NBI point that is closest to the next survey point**

If NextCont = -999 Then GoTo ErrorHandling **'Checks for error code. If there is no more  
NBI data, clean up and exit sub**

AvgIncl = GetAverage(ContSheet, NextCont, Sheets(IntSheet).Cells(PastSurvey, 2))

**'Calculates the average inclination from the 5 measured values closest to the next survey point**

For ColCount = 1 To 7

**'writes data to the calculation sheet all equal to survey points except**

**'inclination which uses the average values calculated above**

Sheets(CalcSheet).Cells(2, ColCount + 1) = Sheets(IntSheet).Cells(PastSurvey, ColCount)

Sheets(CalcSheet).Cells(3, ColCount + 1) = Sheets(IntSheet).Cells(NextSurvey, ColCount)

Next ColCount

Sheets(IntSheet).Range("B" & NextSurvey) = AvgIncl **'Assigns avg inclination to survey  
point**

**For ColCount = 1 To 3**

**'Enters depth, inclination and azimuth to calculation fields to calculate new TVD, North and East with average inclination**

**Sheets(CalcSheet).Cells(9, ColCount + 1) = Sheets(IntSheet).Cells(NextSurvey, ColCount)**

**Next ColCount**

**For ColCount = 2 To 6**

**'writes new TVD, Northing and Easting to interpolation Sheet**

**Sheets(IntSheet).Cells(NextSurvey, ColCount) = Sheets(CalcSheet).Cells(9, ColCount + 1)**

**Next ColCount**

**For ColCount = 1 To 7**

**'writes new TVD, Northing and Easting to 2nd Point on Calculation Sheet**

**Sheets(CalcSheet).Cells(3, ColCount + 1) = Sheets(IntSheet).Cells(NextSurvey, ColCount)**

**Next ColCount**

**Sheets(IntSheet).Cells(NextSurvey, 8) = Sheets(CalcSheet).Cells(9, 9) 'Writes alpha12 to DL column**

**Sheets(IntSheet).Cells(NextSurvey, 8).Font.Bold = True**

**'restores Inclination, Azimuth formulas that were written over above**

**Sheets(CalcSheet).Cells(9, 3).Formula = tempInclFormula**

**Sheets(CalcSheet).Cells(9, 4).Formula = tempAZFormula**

**IntPntCount = 0**

**IntIncr = (MD2 - MD1) / (NumIntPnts + 1) 'calculates interpolation increment to achieve desired number of interpolation points**

**Do Until IntPntCount = NumIntPnts**

**'Loops until desired number of interpolation points has been reached**

**IntCount = IntCount + 1**

**ContCount = FindContPnt(ContSheet, ContCount, MD1 + (IntPntCount + 1) \* IntIncr)**

**'Finds the continuous data point that is closest to the desired interpolation point**

**If ContCount = -999 Then GoTo ErrorHandler**

**AvgIncl = GetAverage(ContSheet, ContCount, Sheets(IntSheet).Range("B" & IntCount - 1))** 'Calculates the average inclination from the 5 measured values closest to this measured point  
**Sheets(CalcSheet).Cells(9, 3) = AvgIncl** 'write calculated inclination to the calculations sheet

**Sheets(CalcSheet).Cells(9, 2) = Sheets(ContSheet).Range("A" & ContCount)** 'Enters depth from continuous measurement on calculation sheet

**If AZ1 = AZ2 Then**

'If the azimuth is the same at each survey point then use the value from the 1st for interpolation

**Sheets(CalcSheet).Cells(9, 4) = AZ1**

**End If**

**If Sheets(CalcSheet).Cells(13, 3) = 0 Then**

'If the DL is zero then use a ratio factor of 1

**Sheets(CalcSheet).Range("H13") = 1**

**End If**

**For ColCount = 1 To 8** 'writes calculated values to interpolation sheet

**Sheets(IntSheet).Cells(IntCount, ColCount) = Sheets(CalcSheet).Cells(9, ColCount + 1)**

**Next ColCount**

'reinstate formulas

**Sheets(CalcSheet).Cells(9, 4).Formula = tempAZFormula**

**Sheets(CalcSheet).Range("H13").Formula = tempRFFFormula**

**IntPntCount = IntPntCount + 1**

**Loop**

**IntCount = IntCount + 1**

**PastSurvey = NextSurvey**

**NextSurvey = IntCount + NumIntPnts + 1**

**SurveyCount = SurveyCount + 1**

**Wend**

RowCount = 3

While Sheets(IntSheet).Range("A" & RowCount) <> ""

**'Loops through each row and enters formulas to calculate Closure distance/Angle, Directional Difference and Vertical Section**

Sheets(IntSheet).Range("I" & RowCount).Formula = "=SQRT((E" & RowCount & "^2)+(F" & RowCount & "^2))" **' Calculate Closure Distance**

Sheets(IntSheet).Range("J" & RowCount).Formula = "=DEGREES(ATAN(F" & RowCount & "/E" & RowCount & "))" **' Calculate Closure angle**

Sheets(IntSheet).Range("K" & RowCount).Formula = "=\$Q\$1-J" & RowCount & "" **'Calculate Directional difference**

Sheets(IntSheet).Range("L" & RowCount).Formula = "=abs(I" & RowCount & "\*(COS(RADIANS(K" & RowCount & "))))" **' Calculate Vertical Section**

RowCount = RowCount + 1

Wend

If BearingAngle = -9999 Then

**'if the user did not enter a bearing angle then use the Closure Angle calculated from the last Survey Point. Is turned off, so closure angle from last survey point will be used as Bearing.**

Sheets(IntSheet).Range("Q1").Value = Sheets(IntSheet).Range("J" & RowCount - 1)

Else

Sheets(IntSheet).Range("Q1").Value = BearingAngle

End If

**ErrorHandling:**

Sheets(CalcSheet).Cells(9, 3).Formula = tempInclFormula **'Reinstate inclination formula**

**'Formatting**

Sheets(CalcSheet).Protect

Sheets(IntSheet).Select

Range("A3:L3").Select

Range(Selection, Selection.End(xlDown)).Select

With Selection

.NumberFormat = "0.00"

.HorizontalAlignment = xlCenter

End With

```

Range("Q1").Select
With Selection
    .NumberFormat = "0.00"
    .HorizontalAlignment = xlCenter
End With
Range("A1").Select
Application.ScreenUpdating = True

```

```
'reinststate formulas
```

```

Sheets(CalcSheet).Cells(9, 3).Formula = tempInclFormula
Sheets(CalcSheet).Cells(9, 4).Formula = tempAZFormula
Sheets(CalcSheet).Range("H13").Formula = tempRFFFormula

```

```
If Err.Number <> 0 Then MsgBox ("An error was encountered: " & Err.Description)
```

```
End Sub
```

### 9.3 Source code: Average Inclination calculation from NBI data

```

Function GetAverage(ContinSheet As String, Continuous As Long, LastIncl As Double) As
Double
.....
.....

Dim nDex, Count As Integer
Dim Total As Double
Dim CurrentIncl As Double
Dim PastIncl As Double
Dim TrimmedMean As Double
Dim MyRange As Range
Dim StepValue As Double
Dim StepQty As Integer
Dim RangeString As String
Dim MinInclRange As Double

```



```

StepQty = 15 'Number of points forward and back to look at
TrimmedMean = 0
If StepQty > Continuous Then
    StepQty = Continuous - 2 'Safety check to make sure there is no negative in the range below
End If
PastIncl = LastIncl
RangeString = ""
MinInclRange = Application.WorksheetFunction.Min(NBIAngle, NBIPercent / 100 * LastIncl)
For nDex = -StepQty To StepQty
    .....

    'Builds a string representing a range of "good" cells where the inclination value
    'is within MinInclRange from the LastIncl (previous inclination)
    .....

    If Abs(Worksheets(ContinSheet).Range("B" & Continuous - nDex) - LastIncl) <
MinInclRange Then
        RangeString = RangeString & "B" & Continuous - nDex & ","
    End If
Next nDex

If RangeString <> "" Then
    RangeString = Left(RangeString, Len(RangeString) - 1) 'Removes last comma from string
    Set MyRange = Worksheets(ContinSheet).Range(RangeString) 'Sets string as Range
    TrimmedMean = Application.WorksheetFunction.TrimMean(MyRange, 0) 'Calculates the
average over the range. Can exclude extremes if one changes the TrimMean %
End If

Total = 0
Count = 0
For nDex = -2 To 2
    CurrentIncl = Sheets(ContinSheet).Range("B" & Continuous + nDex)
    If IsNumeric(CurrentIncl) Then
        If Abs(CurrentIncl - TrimmedMean) < 2 Then
            Count = Count + 1
            Total = Total + CurrentIncl
        End If
    End If
Next nDex

```

```

    End If
  End If
Next nDex

```

```

If Count = 0 And TrimmedMean <> 0 Then

```

```

  GetAverage = TrimmedMean 'Because none of the nearby values are okay use the trimmed
  mean

```

```

ElseIf Count = 0 Then

```

```

  GetAverage = LastIncl 'If trimmedmean is zero use the Last Inclination point

```

```

Else

```

```

  GetAverage = Total / Count

```

```

End If

```

```

End Function

```

#### 9.4 Source Code: Find NBI MD that closest the MWD survey station depth

```

Function FindContPnt(ContinSheet As String, StartCont As Long, TargetVal As Double)

```

```

.....

```

```

'Finds NBI survey measured depth that is closest to the target value.

```

```

'Starts with 1st measured depth greater than the target value and calculates the difference

```

```

'between this and the target value. It then compares this to the difference between the

```

```

'target value and the last continues measured depth before the current depth.

```

```

'The continuous measured depth with the smaller difference is chosen

```

```

.....

```

```

  Dim Counter As Long

```

```

  Counter = StartCont

```

```

  Do Until (Sheets(ContinSheet).Range("A" & Counter) > TargetVal) Or
  Sheets(ContinSheet).Range("A" & Counter) = "" Or Not
  (IsNumeric(Sheets(ContinSheet).Range("A" & Counter)))

```

```

  'Loop until the value from the continuous sheet is greater than the target value or there is
  no more NBI

```

```

  Counter = Counter + 1

```

```

Loop
If Sheets(ContinSheet).Range("A" & Counter) = "" Or Not
(IsNumeric(Sheets(ContinSheet).Range("A" & Counter))) Then
    FindContPnt = -999 'Send error code to the calling subroutine
End If
If Abs(Sheets(ContinSheet).Range("A" & Counter) - TargetVal) <
Abs(Sheets(ContinSheet).Range("A" & Counter - 1) - TargetVal) Then
    FindContPnt = Counter
Else
    FindContPnt = Counter - 1
End If
End Function

```

## 9.5 Source code: input window Frm\_Entry

```

Private Sub Btn_OK_Click()
If Not (IsNumeric(CMB_IntPnt.Value) Or IsNumeric(Txt_Angle.Value) Or
IsNumeric(Txt_Percent.Value)) Then
    'error checking for code entered in the userform
    MsgBox ("There is an issue with one of the values you have entered.")
    Exit Sub
ElseIf IsNumeric(Txt_Bearing.Value) Or Txt_Bearing.Value = "" Then
    'Assigns entered values to global variables
    NumIntPnts = CInt(CMB_IntPnt.Value)
    NBIAngle = CDBl(Txt_Angle.Value)
    NBIPercent = CDBl(Txt_Percent.Value)
    If Txt_Bearing.Value = "" Then
        BearingAngle = -9999 'Send msg that bearing angle was left blank
    Else
        BearingAngle = CDBl(Txt_Bearing.Value)
    End If
Else
    MsgBox ("There is an issue with one of the values you have entered.")
    Exit Sub

```

```
End If
Unload Me
End Sub
```

```
Private Sub Txt_Angle_KeyPress(ByVal KeyAscii As MSForms.ReturnInteger)
'Restricts the allowable keypresses to numbers and decimal
If KeyAscii = Asc(Application.International(xlDecimalSeparator)) Then
If InStr(Txt_Angle.Value, Application.International(xlDecimalSeparator)) <> 0 Then
'If there is already one decimal separator in the number than ignore the keypress
KeyAscii = 0
End If
ElseIf KeyAscii < Asc(0) Or KeyAscii > Asc(9) Then
KeyAscii = 0
End If
End Sub
```

```
Private Sub Txt_Percent_KeyPress(ByVal KeyAscii As MSForms.ReturnInteger)
'Restricts the allowable keypresses to numbers and decimal
If KeyAscii = Asc(Application.International(xlDecimalSeparator)) Then
If InStr(Txt_Percent.Value, Application.International(xlDecimalSeparator)) <> 0 Then
'If there is already one decimal separator in the number than ignore the keypress
KeyAscii = 0
End If
ElseIf KeyAscii < Asc(0) Or KeyAscii > Asc(9) Then
KeyAscii = 0
End If
End Sub
```

```
Private Sub Txt_Bearing_KeyPress(ByVal KeyAscii As MSForms.ReturnInteger)
'Restricts the allowable keypresses to numbers and decimal
If KeyAscii = Asc(Application.International(xlDecimalSeparator)) Then
If InStr(Txt_Bearing.Value, Application.International(xlDecimalSeparator)) <> 0 Then
```

**'If there is already one decimal separator in the number than ignore the keypress**

**KeyAscii = 0**

**End If**

**ElseIf KeyAscii < Asc(0) Or KeyAscii > Asc(9) Then**

**KeyAscii = 0**

**End If**

**End Sub**

**Private Sub UserForm\_Initialize()**

**Dim Count As Integer**

**Txt\_Bearing.Value = ""**

**Txt\_Percent.Value = 30 'Default percent NBI**

**Txt\_Angle.Value = "3" & Application.International(xlDecimalSeparator) & "5" 'default angle  
NBI**

**For Count = 1 To 10 'Populates combobox with 1 to 10**

**CMB\_IntPnt.AddItem Count**

**Next Count**

**CMB\_IntPnt.ListIndex = 4 ' Number of interpolation points between measured values - Default  
to 5**

**End Sub**

**Private Sub UserForm\_QueryClose(Cancel As Integer, CloseMode As Integer)**

**If CloseMode = 0 Then StopProgram = True 'User has clicked "x"**

**End Sub**

**Private Sub UserForm\_RemoveControl(ByVal Control As MSForms.Control)**

**End Sub**

**Private Sub UserForm\_Zoom(Percent As Integer)**

**End Sub**