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Directional Drilling - Advanced Trajectory Modelling

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Summary

Drilling operations are a significant cost in the process of recovering hydrocarbons. The operations are advanced and associated with large HSE and financial risks. The main objectives in a successful drilling operation are to construct safe and economically efficient wells, but the success also depends on hitting the target. As the drilling operation has very high standards of execution, a good drilling operation depends on a good well plan.

The planning phase is a large and complex process as it engineers all aspects of a drilling operation. This is key to create safe and economically efficient wells. Well trajectory planning is a mixture of many parameters but in the end it comes down to identifying the most optimum well path. That means they should be based on exact mathematical calculation models, to precisely calculate well bore trajectories. The industry uses a number of different planning tools that makes it possible to calculate and plan complex well path trajectories. Very few studies have addressed this topic in a systematic manner.

In this thesis, a large study has been made on the background of well planning and the well planning software's used in the industry today. The industry leader within well planning software is Halliburton Landmark's Compass. Compass has been used as a base study in this thesis. Work presented, has looked at three essential parts of the well planning software.

1. The Software Model
2. The Calculation Models
3. The Functions

The main objective of this thesis has been to identify the different calculation models used in these programs and to program suitable functions similar to those found in existing planning softwares, in an attempt to create a new and more user friendly well planning software. Also, there is not much in the literature or information supporting what the different software models do to create well paths – so a better understanding of the engineering of 3D well paths has been developed.

A study was done to find/map different calculation methods that develop precise wellbore coordinates. A number of calculation models were found, but the bulk of these models is presented as models that are used to calculate already drilled wells. However, two new methods were identified. The method called "Exact departures, Constant Turn Rate Method" was found to give accurate results and is also the main calculation model found in the well planning softwares. This is the main calculation model used to support the functions presented in this thesis.

The major part of the work presented in this thesis relates to the construction of precise and user friendly functions, that allow calculation of exact well paths. Using Compass as an offset to calibrate the programmed models, a substantial study has been done to understand and identify assumptions and how the presented functions work in Compass. The result is accurate program functions. The results show exact and accurate calculations - identical to compass.

This thesis also presents the basics behind the operational phase, including surveying and anti-collision.

Some work is left for further investigation. In the process of constructing a new well planning tool, a software or platform has to be programed to implement the functions presented in this thesis. Some of the functions presented also have some limitations that have to be finalized. Furthermore, more functions have to be developed, and programing of a plotting tool is also left for further work.

Sammendrag

Boreoperasjoner er en betydelig kostnad i prosessen med å utvinne hydrokarboner. Operasjoner relatert til boring er ofte svært avansert og forbundet med stor HMS og finansiell risiko. Hovedmålene i en vellykket boreoperasjonen er å konstruere trygge og kosteffektive brønner, men suksessen avhenger også av å treffe målet. Ettersom boreoperasjonen har svært høye krav til utførelse, er en god boreoperasjon avhengig av en god plan.

Planleggingsfasen er en stor og kompleks prosess som tar hensyn til alle aspekter av en boreoperasjon. Dette er nøkkelen til å skape trygge og kosteffektive brønner. Brønnbane planlegging er en blanding av mange parametere, men til slutt kommer det ned til å identifisere den mest optimale brønnbanen. Det betyr at de skal baseres på eksakte matematiske beregningsmodeller, for å beregne brønnbanene. Industrien bruker en rekke forskjellige planleggingsverktøy som gjør det mulig å beregne og planlegge komplekse brønnbaner. Svært få studier har adressert dette emnet på en systematisk måte.

I denne avhandlingen, har en stor studie blitt gjort på bakgrunn av brønnplanlegging og brønnplanleggings programmer som brukes i industrien i dag. Industrilederen innen brønnplanleggings programmer, er Halliburton Landmarks, Compass. Compass har vært brukt som en base studie i denne avhandlingen. Arbeidet som presenteres, har sett på tre viktige deler av brønnplanleggings programvarer.

1. Programvaren
2. Kalkulasjonsmodellene
3. Funksjonene

Hovedmålet med denne avhandlingen har vært å identifisere de ulike beregningsmodeller som brukes i disse programmene og programmere egne funksjoner som ligner på de som finnes i eksisterende programvarer, i et forsøk på å lage et nytt og mer brukervennlig brønnplanleggings program. Det er finnes ikke mye informasjon i litteraturen som støtter hva de ulike programmene gjøre for å lage brønnbaner - så en bedre forståelse for hva disse programmene gjøre har blitt avdekket.

En studie ble utført for å finne / kartlegge ulike beregningsmetoder som gir presise koordinater av brønnbanen. En rekke beregningsmodeller ble funnet, men mesteparten av disse modellene presenteres som modeller som brukes til å beregne allerede borede brønner. F.eks. surveying. Imidlertid ble to nye metoder identifisert. Metoden som kalles "Exact Departures, Constant Turn Rate" ble funnet til å gi nøyaktige resultater, og er også den viktigste beregningsmodellen som blir brukt i brønnplanleggings programmer. Dette er den viktigste beregningsmodellen som brukes til å støtte funksjonene som presenteres i denne avhandlingen.

Hoveddelen av arbeidet som presenteres i denne avhandlingen er knyttet til programmering av presise og brukervennlige funksjoner, som tillater beregning av eksakte brønnbaner. Ved å bruke Compass som en offset modell for å kalibrere og sammenlikne de programmerte funksjonene, har en betydelig studie blitt gjort for å forstå og identifisere forutsetninger og hvordan de presenterte funksjonene fungerer i Compass. Resultatet er nøyaktige program funksjoner. Resultatene viser nøyaktige og presise beregninger - identisk med kompass.

Denne avhandlingen presenterer også de grunnleggende aspektene bak borefasen, inkludert oppmåling og anti-kollisjon.

Noe arbeid gjenstår for videre arbeid. I prosessen med å konstruere et nytt brønn planleggingsverktøy, trengs en programvare modell eller en plattform for å implementere de presenterte funksjonene i denne avhandlingen. Noen av funksjonene som presenteres har også noen begrensninger som må ferdigstilles. Videre, må flere funksjoner utvikles, og programmering av et plotte verktøy gjenstår som videre arbeid.

Acknowledgments

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Last I would like to thank my family for support and encouragement during these five years at NTNU.

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Nomenclature

Symbols

Δ	Difference/Change	
A	Azimuth	[deg]
α	Inclination	[deg]
B	Build Rate	[deg/30 m]
β	Azimuth	[deg]
CL	Curve Length	[m]
D	Dogleg Severity	[deg/30 m]
$\overline{D}$	Average Dogleg Severity	[deg/30 m]
E	Positional Coordinate East	[m]
e	Error Radii	[m]
F	Curvature Factor	
G	Gravitational Force	[mG]
g	Gravitational Acceleration	[m/s^2]
H	Horizontal	
γ	Toolface Angel	[deg]
I	Inclination	[deg]
j	Positional vector	
M	Magnetic Force	[nT]
N	Positional Coordinate North	[m]
L	Length	[m]
ϕ	Dogleg Angel	[deg]
ω	Horizontal Inclination	[deg]
r	Radius	[m]
R	Radius	
T	Turn Rate	[deg/30 m]
$\bar{T}$	Average Turn Rate	[deg]
θ	Alignment	
Θ	Horizontal Scanning Angel	[deg]
t	Tangent Vector	
SF	Separation Factor	
S	Separation Distance	[m]
u	Tangent vector	
V	Positional Coordinate Vertical	[m]
x	Positional Coordinate East/West	
y	Positional CoordinateNorth/South	
z	True Vertical Depth	

Subscripts

1	Starting Point/Initial Value
2	Final Point/Value
h	Horizontal Plane
p	Point Reference well
m	Point offset well
o	Offset Well
r	Reference Well
v	Vertical Plane
x	Direction in Space
y	Direction in Space
z	Direction in Space

Abbreviations

3D	Three Dimensional
DLS	Dogleg Severity
HSE	Health Security and Environment
LWD	Logging While Drilling
MD	Measured Depth
MWD	Measurement While Drilling
TFO	Toolface Orientation
TVD	True Vertical Depth
WOB	Weight on Bit

1 Introduction

The process of making a well for hydrocarbon recovery contains many different aspects and phases. A large part of this process is the drilling operation. The total drilling process can be divided in two phases.

1. Well planning phase
2. The execution/surveying phase

An investigation of the literature about directional wells, shows that there is a strong focus on surveying. However, for the background of constructing well paths there is limited literature available. Both phases have in common that they create an exact mathematically representation of the well path from start to target. While the planning phase is a simulation of real life as it engineers all aspects, that often, starts with construction of a well. The execution/surveying phase is to calculate the drilled well path based on survey measurements. The importance of calculating exact and correct well paths is a key aspect. A poor and incomplete well plan can have a catastrophic outcome. During a drilling operation, much of the success depends on a good plan. The main goal of this thesis is to map the process of construction of well paths during planning.

A lot of engineering is done in the planning phase and this is essential to drilling safe and cost efficient wells. Safety is an important issue in the industry, and planning is important to avoid well collisions, drill string failure and avoid unnecessary exposure to unstable formations. By planning safe wells, the down time will be reduced and good planning has the potential of saving money by increasing the chances of hitting the target optimally. The drilling technologies available today make it possible to drill long and high deviated wells with multiple bends. As the drilling operations get more complex, good well planning tools are essential to reduce the risk of failures.

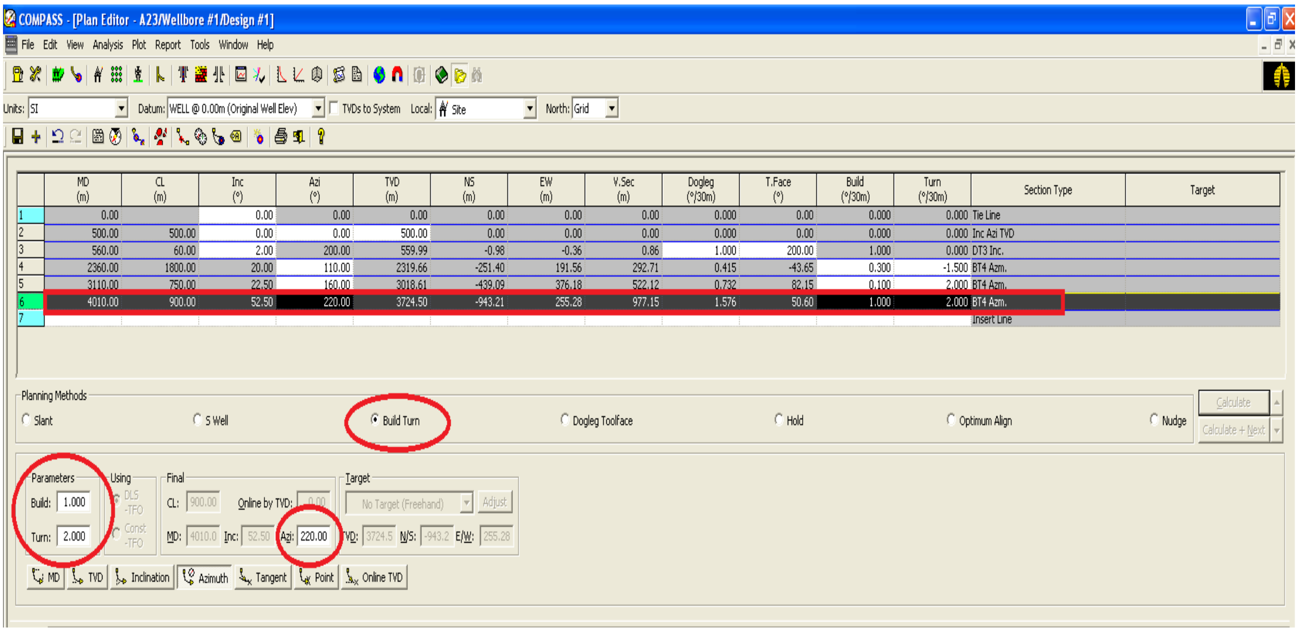
There are a lot of well planning tools available on the market. After studying these, the planning tools can be broken down in to three categories.

1. Software model- The full software package (including 2 & 3 below)

2. Calculation model/method - Calculates exact position between 2 points in space.

3. Function models - Allows the user to apply “2: calculation models” and produce a planned well path to the desired location by different input data.

The leading planning tool in the industry today, is Halliburton Landmark’s Compass. This is a large and powerful planning tool that provides multiple functions. Limited public information exists on how these functions are built and what calculation models are used in Compass. In an effort to contribute/make a new and more user friendly planning tool, calculation models and functions have been looked at, programed and compared with Compass in this thesis.



Units: SI
Datum: WELL @ 0.00m (Original Well Elev)
☐ TVDs to System
Local: Site
North: Grid

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	V.Sec (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type	Target
1	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	Tie Line	
2	500.00	500.00	0.00	0.00	500.00	0.00	0.00	0.00	0.000	0.00	0.000	0.000	Inc Azi TVD	
3	560.00	60.00	2.00	200.00	559.99	-0.98	-0.36	0.86	1.000	200.00	1.000	0.000	DT3 Inc.	
4	2360.00	1800.00	20.00	110.00	2319.66	-251.40	191.56	292.71	0.415	-43.65	0.300	-1.500	BT4 Azm.	
5	3110.00	750.00	22.50	160.00	3018.61	-439.09	376.18	522.12	0.732	82.15	0.100	2.000	BT4 Azm.	
6	4010.00	900.00	52.50	220.00	3724.50	-943.21	255.28	977.15	1.576	50.60	1.000	2.000	BT4 Azm.	
7													Insert Line	

Planning Methods
○ Slant ○ S Well ● Build Turn ○ Dogleg Toolface ○ Hold ○ Optimum Align ○ Nudge

Parameters
Build: 1.000
Turn: 2.000

Using
● DLS -TFO
○ Const -TFO

Final
CL: 900.00
Online by TVD: 0.00
MD: 4010.0
Inc: 52.50
Azi: 220.00

Target
No Target (Freehand)
Adjust
TVD: 3724.5
N/S: -943.2
E/W: 255.28

Figure 1-1: Compass software model, applying function models.

Figure 1-1shows a picture of the software model Compass. This figure illustrates the different function models offered in Compass. The highlighted row and circles represent the planed well section from applying a build&turn function with a set of input parameters.

This thesis is written on the background of creating a new and more user friendly planning program with main focus on well trajectory planning/modeling. The task related to uncover the techniques and calculations used as well as creating new planning tool is as follows:

- Look at where industry is today
- Investigate and discuss international standards for constructing a 3D well path and find calculation models used in the industry
- Establish a model for constructing 3D well paths based on calculation methods
- Discuss key elements in surveying during directional drilling

2 Well Planning

2.1 Requirements to Trajectory Planning Models

A well is constructed in several intervals as predetermined casing points are set to support formation pressure and increase wellbore stability. The different intervals often vary significantly in planning complexity. Figure 2-1 shows a typical well and the different casing points. The red lines illustrate offset or already drilled wells. To describe what type of requirements and typical aspects each section haves, a small explanation based on figure 2-1 is given below.

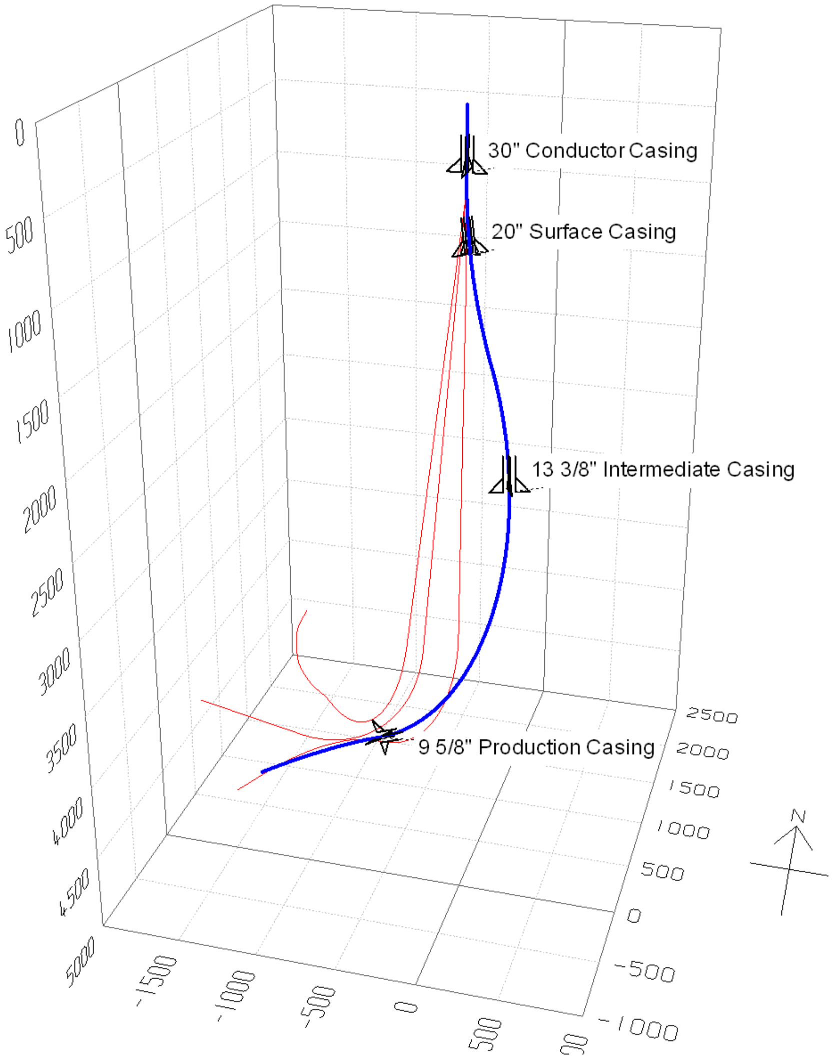


Figure 2-1: Typical well. Casing Points and Anti-collision (Compass)

30” Conductor section

This section is drilled vertical, as the formation is not stable enough for building or turning and since there often are a lot of already drilled wells. This makes anti-collision important as multiple wells often are drilled from the same rig position. This can be seen in figure 2-1 as all the offset wells have the same origin. As a result, surveying is important to make this section vertical and preventing any well collision. Depth control is also very important as shallow gas can give severe problems. (M. Grinrod, 1988) The typical calculations for this section are simple since the well path has no build or turn, and a simple tangent function is sufficient for this section.

20” Surface Casing

This section allows more maneuverability of the well path trajectory, but dogleg severity is kept low. The formations can still be a little bit unstable and the large diameter of the drill string and resulting casing prevents higher build and turns. Anti-collision is still an important factor, but wells often tend to separate during this stage. Even though the build and turns of this section is kept low, it is important to use accurate calculation methods. The most accurate calculation methods are always used as soon as the well path begins to build or turn in the planning phase. If more accurate methods than those used in the 30 “ section are not applied, the well path will go off plan quickly. Typical functions required in this section are build and turn curves, where a typical landing azimuth or inclination is important for next section.

13 3/8 “ Intermediate Casing

As hole diameter and BHA becomes smaller, there is lees constraint from the formation and it will be easier to maneuver the BHA. This allows for higher dogleg severity and more bends in the well path. However, inclination and other parameters have to be monitored to avoid hole collapse. As the well path becomes more curved and the target gets closer, it is even more important to use accurate calculation models, so that calculated well bore positions and other parameters are determined correctly. Anti-collision is always important and as target gets closer the possibility of encountering offset wells will get larger. The proximity of target also puts more requirements on functions to enable user to determine more endpoint parameters such as final position and inclination or azimuth.

9 5/8 Production Casing

This section is often landed directly above the target or reservoir. The actual position of the well bore is now very important to determine to prevent drilling in to the reservoir with the wrong type of mud potently damaging the production zone. This requires accurate calculation models to be used in both phases. Anti-collision will again be very important as multiple wells might already have been drilled into the same target. High values of dogleg severity are also allowed as drilling equipment is small and permits higher bending forces. This is crucial so that target can be reached. Functions that enable many/all endpoint parameters is needed to describe what drilling parameters are required to hit the target.

To sum up:

- The different well sections will have different well paths starting from vertical in the top to tight curve and bends in the end
- Anti-collision is always an important factor, but depending on the field and number of wells this will often be most important in the top and finishing sections
- Allowed dogleg severity will increase as formation gets stronger and hole diameter and BHA gets smaller.
- Accurate calculation models are important throughout the well in the planning phase. The need for accuracy will increase the deeper the well gets when drilling and running surveys. Accurate calculations of the drilled well path will prevent large divergence from the well plan.
- The closer you get to the target, the need for functions that offer the user to decide more end point parameters will increase.

2.2 Some basics of constructing a well path

All well paths comprise of sections that are from one fixed point to another. The well path starts from the well-head and are planned segment for segment down to the target. This way, it is easy to keep track of the well path. Any position along a well path will have a north, east and true vertical depth (TVD) coordinate. This translates to a 3D dimensional coordinate system, where any part of the well can be expressed by a position of x, y and z. For simplicity, the well-head is located at 0 degrees north, 0 degrees east and 0 m vertical depth. Each move made will cause a change in north, east, and true vertical depth. By closely and accurately planning the well path, a detailed plan of the well is formed.

Targets are often given with such coordinates by the subsurface team, and the drilling engineers plan the well from the well head to reach this target.

Segments in a 3D well path can be planned as:

- A tangent
- A 3D curvature
- 2D curvature.

To give an easy example of the directions a well path can take, consider this:

Look down a well with the top of your head facing north. If you tilt your head up you will look north. If you turn your head to the right, east, or left to the west. If you tilt your head towards your chest you will be looking south.

2.2.1 Inclination

As the well departs from vertical, the well will become “deviated”. This forms the inclination(I) of the well. The inclination is measured from zero degrees vertical and upwards to 90 degrees. Figure 2-2 (vertical 2D figure) shows how the well can/will deviate from the vertical axis creating what is called a deviated well.

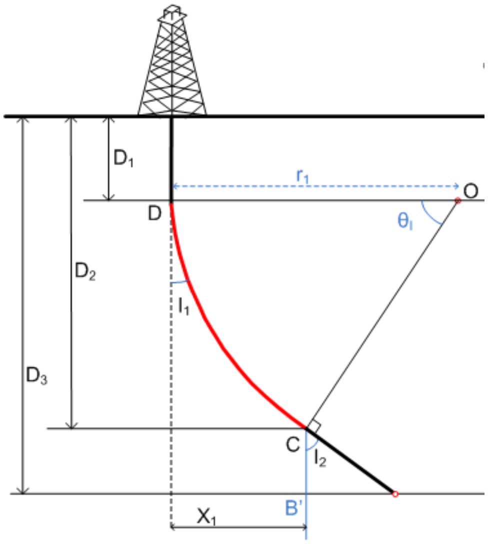


Figure 2-2: Inclination from vertical axis

The amount of change or the degree of how fast the well “builds” from vertical is given by the build rate. Build rate is given in degrees/30m or 100 ft. This means that if a section has a build rate of 3 deg/30 m the inclination of the well path well would increase with 3 degrees for every 30 m of drilled length or measured depth (MD). The total change in inclination of a section represented as ϕ in Figure 2-2 is called the dogleg of the section. It is simply given by equation 2.1

$$\phi = I_2 - I_1 \tag{2.1}$$

The inclination change will follow a circular arc with radius r, which is illustrated in Figure 2-2. The relationship between the radius and the build rate can be found by referring to circle with radius r, and curve arch, and described as:

$$r = \frac{180 * 30}{\pi * B} \tag{2.2}$$

The curve length can then be described by:

$$CL = \frac{r * \pi(I_2 - I_1)}{180} \tag{2.3}$$

2.2.2 Azimuth

The borehole can be represented by 360 degrees. Still looking down the well, it can go in any direction of this 360 degree circle where north is 0 or 360 degrees, directly east 90 degrees and so forth. This circle compass is now lying flat in the plane of north/south and east west. If the direction of the well path is to go towards the west the well would bend to the left when looking down, which would give a direction of 270 degrees counting from north.

This amount of direction change is called the azimuth (A), and is as described, the direction change in the horizontal plane. This is illustrated in Figure 2-3. Here it can be seen how the azimuth or well path is changing in the horizontal plane. The relationship between the radius and the turn rate can be expressed as in equation 2.2 and 2.3.

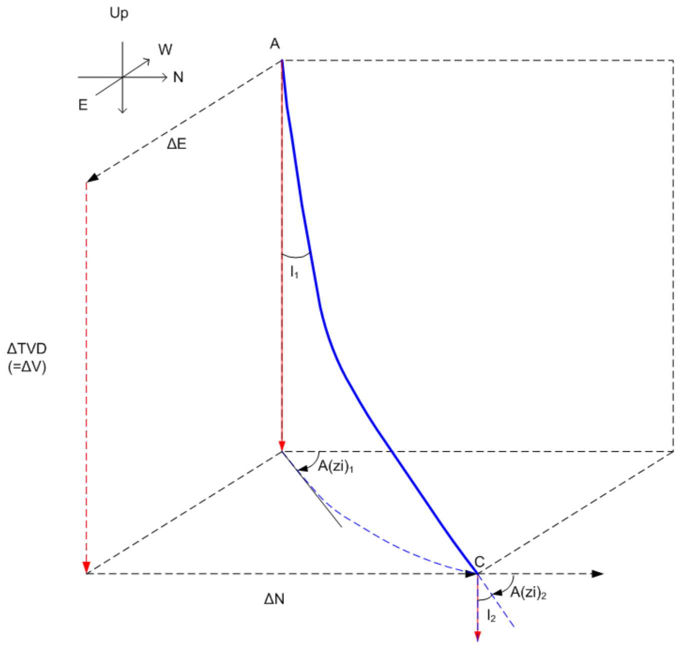


Figure 2-3: Inclination and Azimuth

How much the well path changes direction or turns in the horizontal plane is given by the turn rate. Build rate relates to inclination and turn rate to azimuth, which is similarly given by deg/30 m. The turn rate can also be negative resulting in moving along the circle in the opposite direction or counter clockwise. Positive turn rate gives east-ward turn and negative turn rate gives west ward turn, illustrated in figure 2-4. Her it can be seen that positive turn rate moves towards east (clock wise) and negative turn rate towards west (counter clockwise).

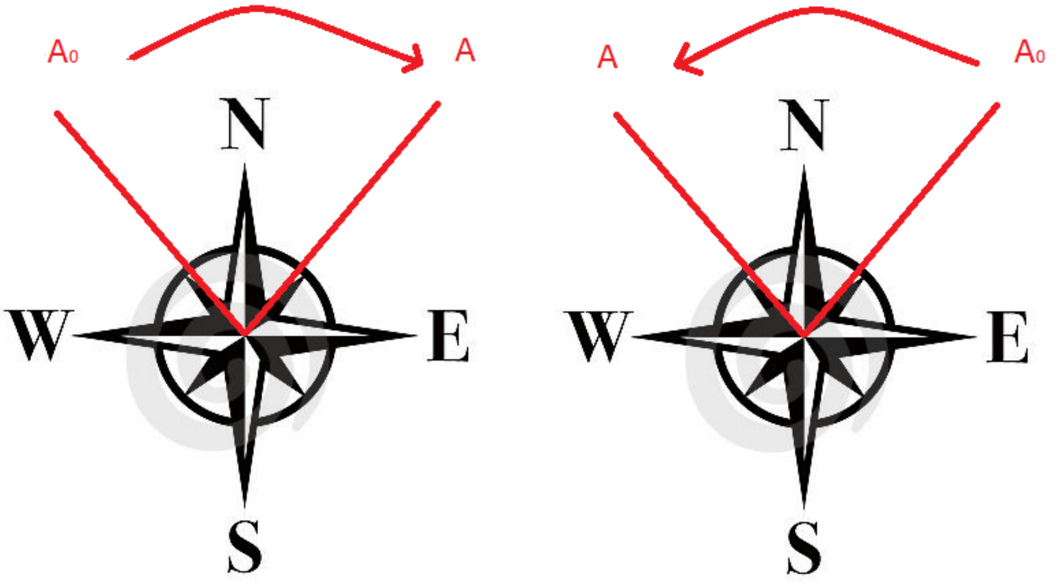


Figure 2-4: Positive and Neagtiv Turn Rates

Now included in the position of the well in the 3D space given by x, y and z coordinates, the well will have certain inclination (I) from vertical and is pointing or facing in a certain direction (A).

2.2.3 Dogleg Severity

Another important parameter that describes the well path and is the dogleg severity. Dogleg (ϕ) describes the overall angel change of the curve between two stations. The dogleg severity is directly connected to this and given by equation 2.4, given in deg/30 m.

$$D = \frac{\phi}{CL} * 30 \tag{2.4}$$

This is a very important parameter because it describes the curvature of the well path and is directly linked to the bending force of the pipe. As wells curve, there will be bending forces on the drill pipe that can cause a number of problems, such as drill pipe failure, stuck pipe problems under drilling and casing ware. Wellbore stability will also be affected when the wells curve. For this reason the dogleg severity will often act as a limitation to what kind of well path can be chosen. Drill pipes, casings, wellbore stability and safety factors related to stuck pipe often have a set value of tolerated dogleg severity. High build and turn rates will obviously lead to high dogleg severity, and this is why sharp turns and builds should be avoided.

G.J. Wilson (1968) presented an equation to calculate the dogleg severity in any point on the curved well path in terms of build and turn rates. The equation presented is given in equation 2.5. (G.J., 1968)

$$D = \sqrt{B^2 + T^2 * \sin^2(I)} \tag{2.5}$$

This equation was also derived and presented by Planeix and Fox (Michele Y. Planeix, 1979), for the Exact Departures Method.

Furthermore Lubinski developed an equation for calculating the dogleg severity between two survey stations. (Lubinski, 1987)

$$\bar{D} = \frac{2}{L_2 - L_1} * \sin^{-1} \sqrt{\sin^2\left(\frac{I_2 - I_1}{2}\right) + \sin^2\left(\frac{A_2 - A_1}{2}\right) * \sin(I_1)\sin(I_2)} \tag{2.6}$$

Gordon B. Guo et al made a comparison of dogleg severity calculations based on Lubinski, and the derived equations from different methods. The conclusion was that dogleg severity calculations resulting from different methods gave small differences, but that Lubinskis method was the most preferable method. (Gordon B. Guo, 1991)

3 Software model

The software model is a drilling software or a 3D well trajectory software used in both the planning and the surveying phase. There are a number of different software models that have been constructed, and the respective oil service companies often have their own software model. A widely used software model is Halliburton Landmark’s Compass. The software models often have a lot of programs linked to them where well planning is only a part of the entire software. This way it is possible to use information constructed in a geological program directly in the planning program.

The software model is a program that makes it possible to simulate a real life drilling operation. This is done is by reconstructing the drilling environment and execution, by using the other program as mentioned. In the software you can:

- Construct geological profiles, based on geological surveys, to best reconstruct the drilling environment.
- Chose a number of different tools and bottom hole assemblies
- Import all existing wells in field
- View field in 3D
- Decide coordinate datum, based on position of drilling operation

The software model puts everything together so that simulation is as close to real life as possible. Based on all these parameters, an informed decision can be made for a suitable trajectory of the well. Well trajectory paths are limited by a number of factors such as formation geology, adjacent wells, drill pipe stress (torque and drag) and casing wear.

The well planning part of the software model comprises various calculation methods to find exact and true coordinates for a well path. When constructing a well path, the functions in the software model allows the user to enter various input to get the desired well path (coordinates). E.g. using a desired turn rate to land at a specific azimuth. The different functions allow the user to construct a number of different well paths. As the well is planned in segments, which often have different limitations, the ability to construct different well types is important.

Planning wells in the software model enables the possibility to assess different options and use trial and error to find the best path. The planning process is about identifying the most optimum well trajectory considering safety and economical perspectives. The software model makes this possible.

The surveying part of the software is a bit simpler. This part manly takes in survey data and calculates the well path based on this. The software often has a number of different drilling measurement tools hardwired in. This way the survey information will be directly conceded to the tools that are used during surveying. The software is then able to provide correct anti-collision for the well. This will be discussed further in this thesis, see chapter 6.3.

Compass provides all the above features, and has strong computing capabilities. However, there are some uncertainties in how Compass processes some calculations. The manual supporting Compass is descriptive and shares a lot on how functions work, but Compass does not provide detailed mathematical descriptions and assumptions that are made when running calculations, as presented as point 2 in the introduction. This would help getting a better understanding of what the calculations actually do, and would offer a better way of running quality checks and being confident that calculations are what they really are presented to be. As this is a licensed software this is understandable, but it opens up the task of mapping these methods.

4 Calculation Methods/Models

Well planning makes an exact mathematical description of the well path in the three dimensional room, from start point to the target. The calculation models are the mathematical expression describing the well path. As mentioned earlier, the importance of describing the well path correctly is key to prevent problems under drilling which have the potential to of leading to large economic problems and potential undesired events.

There are several ways, or calculation models for making 3D well trajectories. The different calculation methods have their own way of describing the well path, and are often used in different stages of the drilling process. The well path will reassemble a curved line or circular arc. The goal is to a find a mathematical model to best represent the well path. The simplest models use straight lines, while the more complex models use the shape of a sphere and cylinder to describe the curve between the two points. If the well path is straight, as it would be in case of a tangent, even the easiest methods would give accurate results. However, when the path is curved, these easy approximations will not give accurate results, and the models used to describe the well path will get more complex.

A study of the literature identified the below methods, but there is limited documentation to where and when they are applied.

1. Tangential
2. Balanced Tangential
3. Minimum Curvature
4. Radius of Curvature
5. Constant Turn Rate
6. Constant Curvature

The different methods have different accuracy and advantages/disadvantages. It is important to understand these to handle situations as anti-collision and to hit the target. Calculation methods are used to make the well path, but they are also used during drilling by the directional driller when he wants to project from the physical location of the bit to some place deeper. This is often when the drilled path has deviated from the well plan, and applied to get back to the plan.

In the planning phase the most accurate results are needed. The plan represents how the well will be drilled, and directly influences the drilling operation. The planning phase uses simpler methods. The different calculation models, and which face they are used will be presented in the next subchapters.

4.1 Tangential method

The easiest model is called the tangential method. This method assumes that the well path is described by a straight line, using the inclination and azimuth of the lower survey station. Figure 4-1 shows how the assumed well path compared to the actual well path. This figure shows that this method gives large errors in wellbore position when the trajectory changes a lot between stations. The equations will not be given for this method, but is used as an example to show the errors of using this simplified method. Illustrated in figure 4-1, the calculated well path is represented in red and actual well path in grey. As you can see, the approximation is far from correct.

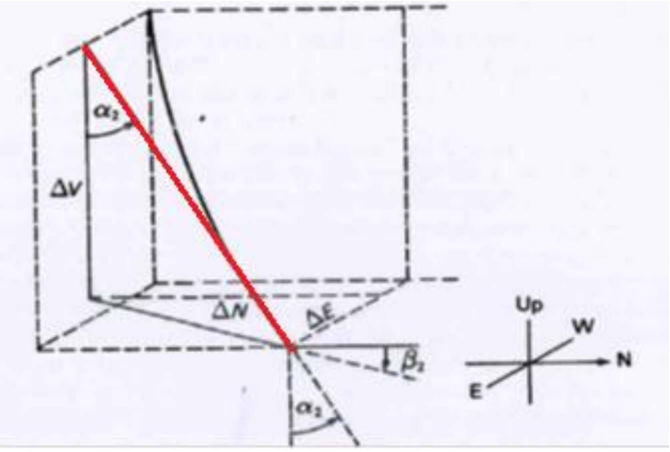


Figure 4-1: Tangential Method (Eck-Olsen, Fall 2013)

4.2 Balanced Tangential

The balanced tangential method is a more accurate method than the tangential method as it at least uses inclination and azimuth in both survey stations. The balanced tangential method assumes that the well path can be approximated by two straight lines as illustrated in Figure 4-2. Here you can see the actual well path as a circular arc and the approximated well path as two straight lines (in red). This method is clearly more accurate than the previous but clearly also gives errors when applied. The balanced tangential method is not often used, in either phase. This method is presented as further methods are based on this method, equations will not be given, but can be found in Appendix A.

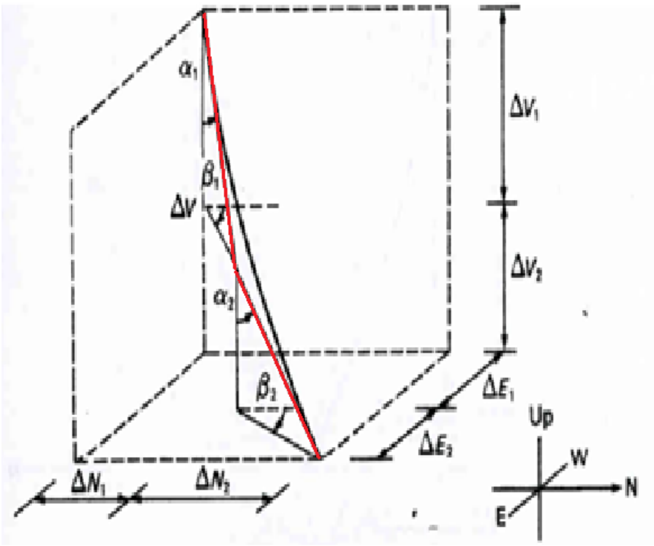


Figure 4-2: Balanced Tangential Method (Eck-Olsen, Fall 2013)

4.3 Minimum curvature

As the balanced tangential method gives errors in wellbore position, the minimum curvature method is an extension of this method. This method projects the well path as a circular arc between the two survey points, by applying a ratio factor. Figure 4-3, shows the projection. This ratio factor is based on the overall bending between the survey sections, defined as; dog leg angel ϕ. The minimum curvature method assumes that the circular arc is wrapped around a sphere with radius R.

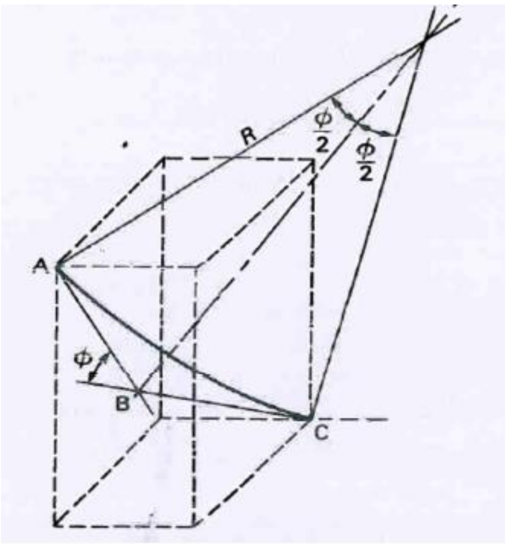


Figure 4-3: Minimum Curvature Method (Eck-Olsen, Fall 2013)

The derived equations for the north, east and vertical depth departure can be found in Appendix A while the final equations are presented below.

The dogleg angel can be described as follows:

$$\phi = \cos^{-1}[\cos\alpha 1 * \cos\alpha 2 + \sin\alpha 1 * \sin\alpha 2 * (\cos\beta 2 - \cos\beta 1\ )\ ] \tag{4.1}$$

The ratio factor can be described as follow:

$$F = \frac{2}{\phi}\left(\frac{180}{\phi}\right) * \tan\left(\frac{\phi}{2}\right) \tag{4.2}$$

With ratio factor calculated, the results of position $\Delta N, \Delta E\ and\ \Delta V$, can be calculated as follows:

$$\Delta N = F * \frac{L}{2}(\sin \alpha_1 \cos \beta_1 + \sin \alpha_2 * \cos \beta_2) \tag{4.3}$$

$$\Delta E = F * \frac{L}{2}(\sin \alpha_1 \sin \beta_1 + \sin \alpha_2 \sin \beta_2) \tag{4.4}$$

$$\Delta V = F * \frac{L}{2} * (\cos \alpha_1 + \cos \alpha_2) \tag{4.5}$$

The minimum curvature method is assumed to be quite accurate and is one of the most adopted for directional survey calculations. The calculations in this method are easily carried out and can be done on a handheld calculator. This is why this method is often used in the field (Eck-Olsen, Fall 2013) . The minimum curvature method is not accurate enough over long curvatures and not often used in planning stage as this require more accuracy. However, where the constant turn rate method, described in the next subchapter is not valid, minimum curvature is used in the programmed model supporting this thesis.

4.4 Radius of curvature

This method approximates the well path by assuming that the well path can be described as a circular arc in both the horizontal and vertical plane, with radius Rv and Rh. This is illustrated in figure 4-4. The circular arc is tangential to the inclination and azimuth in both stations and forms a circular arc between the two stations. The well path can be described as a circular arc in vertical plain which is wrapped around a right cylinder.

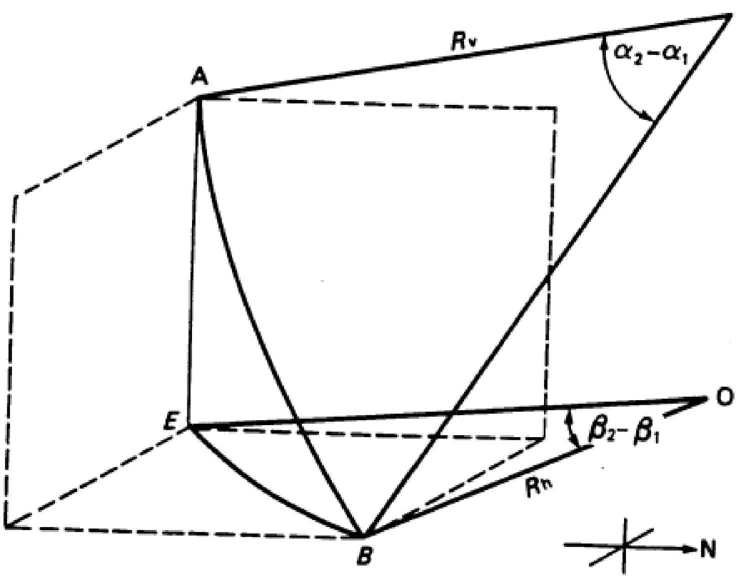


Figure 4-4: Radius of Curvature Method (Eck-Olsen, Fall 2013)

The radius in the vertical plane can be found from the relationship:

$$\frac{(\alpha_2-\alpha_1)}{360}=\frac{L}{2\pi R_v} \leftrightarrow R_v=\frac{L}{\alpha_2-\alpha_1} * \left(\frac{180}{\pi}\right) \tag{4.6}$$

Where α is the inclination and substrcipts represents survey station from top. The vertical increment can be described by :

$$\Delta V = R_v(\sin\alpha_2 - \sin\alpha_2) \tag{4.7}$$

By substituting Rv

$$\Delta V = \frac{L}{\alpha_2 - \alpha_1} * \left(\frac{180}{\pi}\right) * (\sin \alpha_2 - \sin \alpha_2) \tag{4.8}$$

The horizontal increment can be found from :

$$\Delta H = R_v(\cos \alpha_1 - \cos \alpha_2) \tag{4.9}$$

The radius in the horizonatal plane similiraly to that in the vertical plane, can be desrcibe as:

$$R_h = \frac{\Delta H}{360} \left(\frac{180}{\pi}\right) \tag{4.10}$$

The North increment can be found from:

$$\Delta N = R_h(\sin \beta_2 - \sin \beta_1) \tag{4.11}$$

Where β is the azimuth and subscripts respresent survey station from top. Substetuting in R_h and ΔH we get the North departure:

$$\Delta N = \frac{L}{\alpha_2 - \alpha_1} \left(\frac{180}{\pi}\right) \frac{(\cos \alpha_1 - \cos \alpha_2)(\sin \beta_2 \sin \beta_1)}{\beta_2 - \beta_1} \tag{4.12}$$

The same procedure can be made for the East departure.

$$\Delta \mathrm{E} = \frac{L}{\alpha_2 - \alpha_1} \left(\frac{180}{\pi}\right) \frac{(\cos \alpha_1 - \cos \alpha_2)(\cos \beta_1 - \cos \beta_2)}{\beta_2 - \beta_1} \tag{4.13}$$

This method produces good results when well path is more curved like during build and turn section. This method is a bit more complex but gives small errors. This method can be used in both the planing and operation phase. (Eck-Olsen, Fall 2013)

4.5 Exact Departures, Constant-Turn-Rate-Method

Planeix and Fox presented a new method of planning three dimensional direction wells. (Michele Y. Planeix, 1979). Their goal was to present a “better way” to calculate planned wells that give exact and relevant information of positional coordinates linked to the plan of the well. This means giving drillers relevant information about the sections being drilled such as build and turn rates, final inclinations and azimuths and exact kick off, and turn points. The method starts by defining a random point of a curved hole section.

A given point as a function of curve length can be expressed as:

$$\frac{dx}{dL} = \sin I(L) \cos A(L) \tag{4.14}$$

$$\frac{dy}{dL} = \sin I(L) \sin A(L) \tag{4.15}$$

$$\frac{dz}{dL} = \cos I(L) \tag{4.16}$$

Where I(L) and A(L) is the inclination and azimuth at point L. This was proven by J. E. Walstrom et al, in “Directional Survey Models”, and is illustrated in figure 4-5. (Walstrom J.E, 1969) In figure 4-5 it can be seen that different vectors are part of tangent to the curve given by:

$$u = \frac{dr}{dL} \tag{4.17}$$

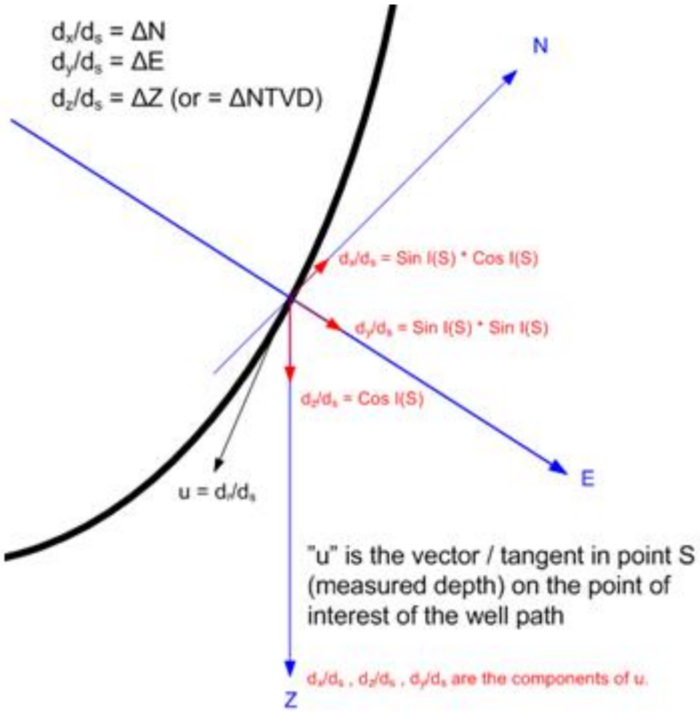


Figure 4-5: Point on Well Path, Tangent Vector.

As S is the curvilinear distance of the wellbore the build and turn rate can be expressed as:

$$B = \frac{dI}{dL} \tag{4.18}$$

$$T = \frac{dA}{dL} \tag{4.19}$$

Planeix and Fox assumed B and T to be constant over a certain build and turn segment, then by integrating equations 4.14 through 4.16 , find the formulas for exact departure. The results describing departure in north, east and true vertical depth are given below:

$$\Delta N = \frac{1}{T^2 - B^2}\,\{T[\sin(I)\sin(A) - \sin(I_0)\sin(A_0)] + B[\cos(I)\cos(A) - \cos(I_0)\cos(A_0)]\} \tag{4.20}$$

$$\Delta E = \frac{1}{T^2 - B^2}\,\{-T[\sin(I)\cos(A) - \sin(I_0) * \cos(A_0)] + B\,[\cos(I)\cos(A) - \cos(I_0)\cos(A_0)]\} \tag{4.21}$$

$$\Delta Z = \frac{1}{B}\,[\,\sin(I) - \sin(I_0)\,] \tag{4.22}$$

These formulas have also been derived by Gordon B. Guo et al, under the name“Constant-Turn-Rate-Method.” (Gordon B. Guo, 1991). This method gives good results and is the same method used in Compass. This method is sought to give exact results of the departure, and is a method that enable to plan wells with parameters that can be used directly in the field. As this model is one of the few methods discussed to some detail, it is the one chosen for most of the 3D functions in the programmed model supporting this thesis.

4.6 Constant curvature

Compared to mentioned methods that are based on geometrical concepts, this method is derived from drilling tendencies of the BHA. (Gordon B. Guo, 1991) The proposed method is based on, from field experience, that a given BHA with constant weight on bit has a tendency of drilling a curve with constant curvature. This assumption is strengthened from equation 4.23 which describes the relationship between tool face angel (γ), build rate (B) and hole curvature, known as dogleg severity (D)

$$D = \frac{B}{\cos(\gamma)} \tag{4.23}$$

Gordon B. Guo et al. presented the model as a better and more efficient way of representing the well path. They pointed out that constant curvature would make it possible to reduce toolface angel corrections and number of BHA changes, resulting in more cost efficient drilling. Another feature is the reduced dog leg severity. The paper shows how torque and drag numbers are lower when applying the constant curvature method. (Gordon B. Guo, 1991)

A small/summary of the mathematics behind the derivation of the constant curvature will be presented her, while a detailed derivation can be found in paper. (Gordon B. Guo, 1991).

Equations 4.24 through 4.26 show the departure of the coordinates as function of curve length, inclination and azimuth.

$$N = N_0 + \int_{L_0}^{L} \sin(I)\cos(A)\,dl \tag{4.24}$$

$$E = E_0 + \int_{L_0}^{L} \sin(I)\sin(A)\,dL \tag{4.25}$$

$$Z = Z_0 + \frac{1}{B}(\sin(I) - \sin(I_0)) \tag{4.26}$$

These are integrals_that have no close form solutions and have to be calculated numerically. The paper presents a method for solving this numerically, but this method was found to be time consuming and complex.

To avoid the numerical integrations the paper proposes two approximate alternatives, called “Picewise-Constant-Turn-Rate” and “Picewise-Radius of curvature”. Proved in the paper, “Pice-Wise-Constant Turn Rate” is the best approximation, creating the least difference in dog leg severity and lowest offset from target.

The simplified approximation sub-divides the whole planned section into a number of small segments, and uses the average turn rate $\bar{T}$in each segment given in equation 4.27. The departure in each direction is the calculated by substituting $\bar{T}$ with the turn rate T in the in “Exact departures Method” given by equations 4.20 through 4.22.

$$\bar{T} = \frac{1}{L_2 - L_1} \int_{L_1}^{L_2} T\, dl = \frac{\sqrt{D^2 - B^2}}{B(L_2 - L_1)} \ln \left[\frac{\tan \frac{I_2}{2}}{\tan \frac{I_1}{2}} \right] \tag{4.27}$$

Paper/Author claims that torque and drag was lower using this method.

5 Functions

In the software, the functions are the programed computing that utilize the calculation from the chosen models and give the well plan results. The functions use the mathematical expressions to calculate the departures. There are a lot of assumptions and pitfalls when programing the calculations. The functions are created to establish a user friendly environment that makes it possible to calculate and plan a well in segments as required. The functions work by determining input parameters such as end segment parameters. There are multiple different functions that calculate/construct the well path in different shapes. The well path to the target comprise of a number of segments. Each segment is often calculated using different function models. There is need for different functions, as each segment would have different constraints and/or goals. To cover the need of the user group, models with their unique functionality will be available in a professional software model.

The functions can be divided in different categories, dependent of their input parameter and the way it constructs the well segment:

- Build & Turn, 3D curve as function of TVD, Inclination, Azimuth or target
- Hold section, tangent (2 dimensional)
- Dogleg Toolface angel
- Curve to tangent
- Build &Turn, final inclination and azimuth

The functions take the desired input parameters and returns well path coordinates with desired final values. The different functions will be presented in the following subchapters. The program code for all functions is given in Appendix B.

5.1 Build and turn, 3D curves

These functions calculate the 3D well path between the start point and endpoint as a function of desired endpoint parameters. This can be the final inclination, azimuth, TVD or a given point or target. As the final values are the variables, the functions are based around these.

5.1.1 Build &Turn, Inclination

The model is a function of start point coordinates with its accompanying inclination and azimuth, build and turn rates, and final inclination. This model calculates the 3D well path to the desired inclination is met.

Step 1: Calculate the curve length (CL) of the curve contributing to inclination change in the vertical plane. Since the build rate and final inclination is given the curve length can be calculated combining equation 2.2 and 2.3, and are illustrated in figure 2-2, explaining the relationship between the constant radius of a circle arch and build rate. Equation 5.1 describes the curve length.

$$CL = (I_2 - I_1) * \frac{30}{B} \tag{5.1}$$

Step 2: Calculate the final azimuth in the end point of the segment. When the curve length and turn rate is known, the final azimuth can be found from looking at the same curve section as in step 1 only in the horizontal plane. Here the same circle arch can be found, and the final azimuth can be calculated by combining the same equations. The final azimuth can be describes as:

$$A_2 = A_1 - \frac{T}{30} * CL \tag{5.2}$$

Step 3: Convert build and turn rate to radians/m. As the turn and build rate is given in deg/30 m, these values are easily converted to radians per meter by dividing by 30m and converting degrees to radians.

Step 4: Input values for start and final inclination and azimuth together with respective build and turn rates in to equation 4.20 through 4.22 to calculate the departure in each direction respectfully.

Finally by adding the changes in North, East and TVD to the values for the start point, the new position with desired inclination have a complete set of coordinates.

The output from running this function is a step by step description of the well path, with segment length of typical 30 m. The values that will be presented are measured depth, curve length, inclination, azimuth, wellbore position in x,y,z, dogleg severity, and build and turn rates for each segment. By giving all these parameters values a driller will have a descriptive plan of how the well path should be drilled. A typical summary of the well plan is given in table 5.1. The 3D well path can be plotted, and is presented in figure 5-1. The well path starts with a vertical section, and then builds and turns to reach final inclination, presented by the red curve. This can be seen in both the table and figure 5-1, where the start point for this example is shown in the second column. In each plane you can see the shadow of the well path, which shows how the well path is projected in each plane.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	0	Tie Line
2	1000	1000	0	0	1000	0	0	0	0	0	0	Inc Azi MD
3	2500	1500	50	150	2316,73	-531,74	307	1	150	1	3	BT3 Inc.

Table 5.1: Summary of Well Plan, Build & Turn

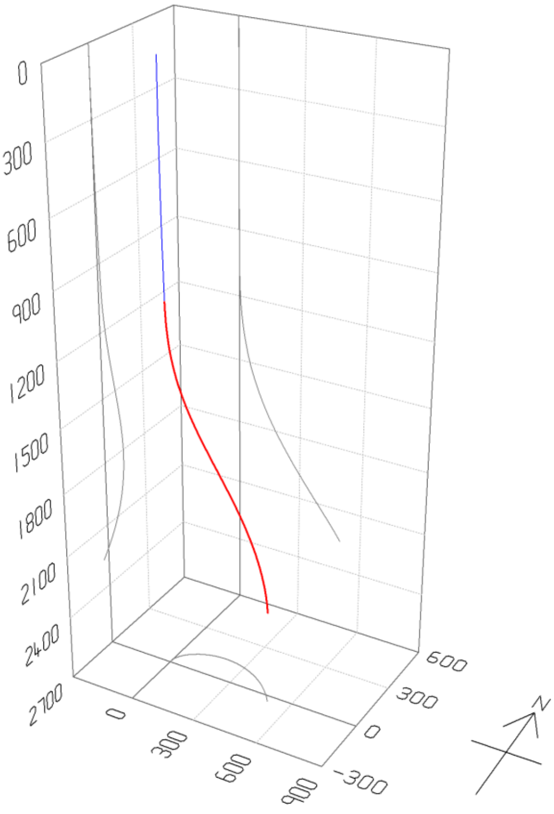


Figure 5-1: 3D Well Path, Build & Turn (Compass [1])

Azimuth has to stay within zero and 360 degrees. As the change in azimuth will be calculated with respect to the curve length required to reach desired inclination and the direction specified by the turn rate it could in theory cross north; 0 or 360 degrees. This can easily lead to trouble in a calculation. If turn rate is negative, turning west, and the north is crossed, the final azimuth can become negative or above 360 degrees if moving east. These two situations are illustrated in figure 2-4.

The function takes this in to account by checking if the change in azimuth (ΔA) leads to final azimuths above 360 or below 0 degrees, by using an “If-sentence”. If this happens, the module simply modifies the final inclination, by subtracting or adding 360 degrees depending on the turn rate. This is applied to all functions.

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[1] All well path trajectory plots have been plotted by using the plotting tool presented in Compass. The calculated values represented by the curves, have been calculated using the presented functions in this thesis, but a separate planning tool has not been programed, thus using the plotting tool in Compass.

By using “Exact departures” equations to calculate the departures, the build and turn rates also have to be checked. If B=T the departures will be divided by zero, which is a mathematical fault. The program checks for this and simply lets the user know if B and T are inputted with the same value, and notifies the user that build has been increased with 0.0001 to manage this problem. This is applied to all the functions that have build and turn as input values.

5.1.2 Build & Turn, Azimuth

This model, similarly to “Build and Turn, Inclination”, calculates the 3 dimensional curve between the start point and down to desired final azimuth. The model is function of the same input variables only substituting the final inclination with final azimuth.

The steps are the same only using the final azimuth to find the total curve length (CL), and accompanying final inclination. The output is the same as for the previous model.

In this model, angels when turning have to be addressed. Built in to this function, there is a failsafe. As presented earlier the turn rate can either be positive or negative, turning clockwise (east) and counterclockwise (west) respectively. As final azimuth is an input, there is a built-in control that checks whether or not the specified turn rate supplies the shortest route to the target. E.g. if initial inclination is 90 degrees and final inclination is input to be 340 degrees with positive turn rate, this will require a much longer curve or well segment; turn 250 degrees, than with a negative turn rate; turn 110 degrees. This might be because a large turn is necessary to avoid an obstacle or problematic formation. The model simply makes the user aware of the shorter route and asks if it should continue or not with this turn rate.

5.1.3 Build & Turn, True Vertical Depth

The same input values are used as in the previous functions, only switching the end point value to TVD. The values we are missing to calculate the curve and endpoint coordinates are final inclination and azimuth.

Step 1: Find final inclination. The change in TVD is known and expressed by build rate and inclination change, shown in equation 4.22. The final inclination can be found from rearranging this equation:

$$I_2 = (Z2 - Z1) * B + \sin I_1 \tag{5.3}$$

Step 2: Find curve length. This can be found using equation 5.1, as done in build turn inclination

Step 3: Find final azimuth.

Step 4: Convert build and turn rates from deg/30 m to rad/m.

Step 5: Insert input values and calculated values in to equation 4.20 through 4.22.

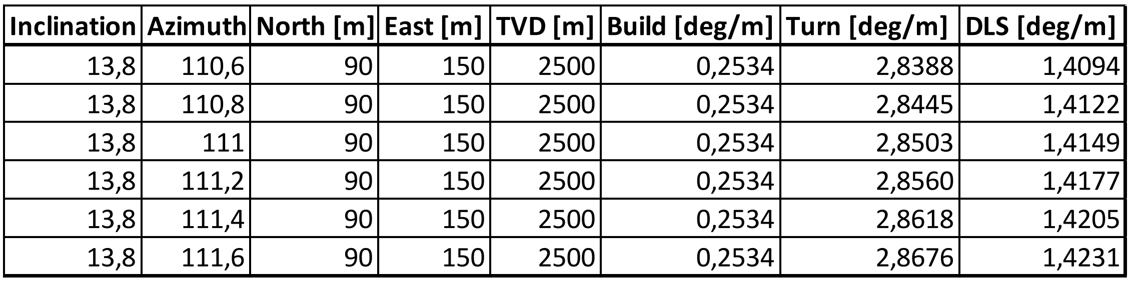
In this model you also have to take in to consideration the angels of azimuth. If you pass north (0 or 360 degrees) you will get negative or final azimuth values larger than 360 degrees.

5.1.4 Build & Turn, Point

This function has the same input values as the previous Build & Turn functions, but it is a function of a predetermined point or target, given by its position coordinates of north, east and true vertical depth (x,y,z).

The function goes through an iteration process trying to find proper final angles for inclination and azimuth to reach desired target or point, by using “Exact departures method” Eq. 4.20-4.22. The model finds the proper angles to reach the target within a set error.

The iteration process runs through every possible combination of final inclination and azimuth to find suitable build and turn rates to hit the target. As soon as the function finds a solution with in the given error, the values are stored in a table, which is the final output of this function. This table is given in table 5.2. Here, all the different solutions are presented.



Inclination	Azimuth	North [m]	East [m]	TVD [m]	Build [deg/m]	Turn [deg/m]	DLS [deg/m]
13,8	110,6	90	150	2500	0,2534	2,8388	1,4094
13,8	110,8	90	150	2500	0,2534	2,8445	1,4122
13,8	111	90	150	2500	0,2534	2,8503	1,4149
13,8	111,2	90	150	2500	0,2534	2,8560	1,4177
13,8	111,4	90	150	2500	0,2534	2,8618	1,4205
13,8	111,6	90	150	2500	0,2534	2,8676	1,4231

Table 5.2: Build & Turn, Target Calculations

The final table and plot will be similar to the previous functions.

5.2 Tangent

A tangent or a hold section, is a well path that does not change inclination or azimuth and is often referred to as a transport segment to reach a certain target or kick of point. As the inclination and azimuth do not change, the expression for describing this well path is simplified. By looking at equation 4.14 through 4.16 and integrating, it can be seen that the expression can be found easily:

$$dx = \int_{L_0}^{L} \sin I(L) * cosA(L)dL \tag{5.4}$$

Since both I(L) and A(L) are constant this yields:

$$\mathrm{dx} = \sin(I) * \cos(A) * (L - L_0) \tag{5.5}$$

Which reduces to:

$$dx = \Delta MD * \sin(I) * \cos(A) \tag{5.6}$$

This applies to each direction, giving the departure in east and true vertical depth as follows:

$$dy = \Delta MD * \sin(I) * \sin(A) \tag{5.7}$$

$$dz = \Delta MD * \cos(\mathrm{I}) \tag{5.8}$$

The same result can be found from simplifying the minimum curvature calculation model. This function is a function of start point, and MD of the target. When this function is run it asks to select what the tangent should be calculated from; TVD, MD or ΔMD (tangent length). After choosing method you are asked for the respective length.

The output is the same as for the build and turn model, but is presented in table 5.3. It can be seen that the tangent is put after the build and turn well path calculated in the previous models and illustrates a well plan with an extra well segment. The information about the tangent line is shown for segment 4. The well path is also plotted in figure 5-2. Here you can see tangent as an extra well segment on the build and turn curve, illustrated in red.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	0	Tie Line
2	1000	1000	5	2	998,73	43,58	1,52	0,15	2	0,15	0	Inc Azi MD
3	2350	1350	50	137	2165,65	63,45	505,51	1,708	54,17	1	3	BT3 Inc.
4	3283,43	933,43	50	137	2765,65	-459,5	993,17	0	0	0	0	Straight TVD

Table 5.3: Summary of Well Plan, Tangent

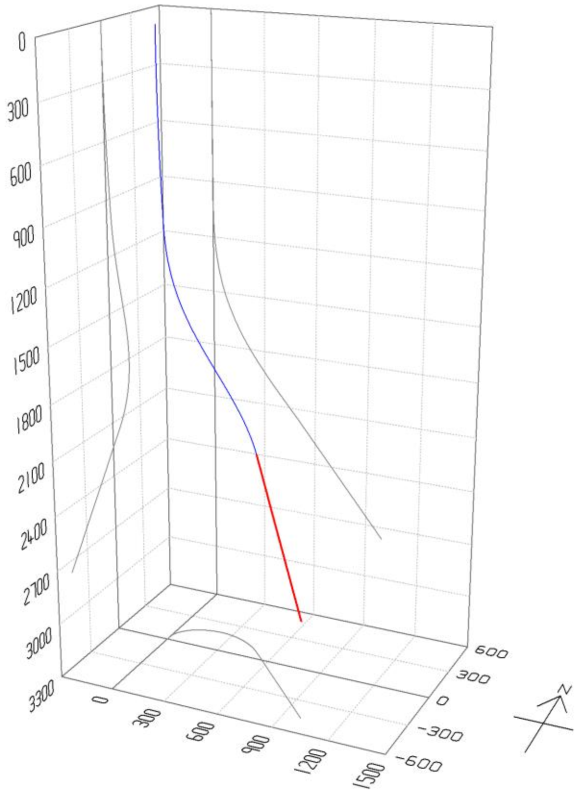


Figure 5-2: 3D Well Path, Tangent

From the projection of the well on to the different planes it can clearly be seen how the well path evens out into the tangent with constant inclination and azimuth.

5.3 Dogleg Toolface Angel

This function constructs a dogleg-curve defined by the toolface orientation. The dogleg-curve is assumed to be wrapped around a sphere. The input values of this function are; dogleg severity (D), tool face angel (γ) and the desired curve length (CL).

The tool face angel is measured from high side of the well at 0 degrees, and 180 degrees at low side. If the well bore has no inclination the tool face is measured from local north. Figure 5-3 illustrates the high side of the well and shows how the toolface angel will contribute to azimuth change.

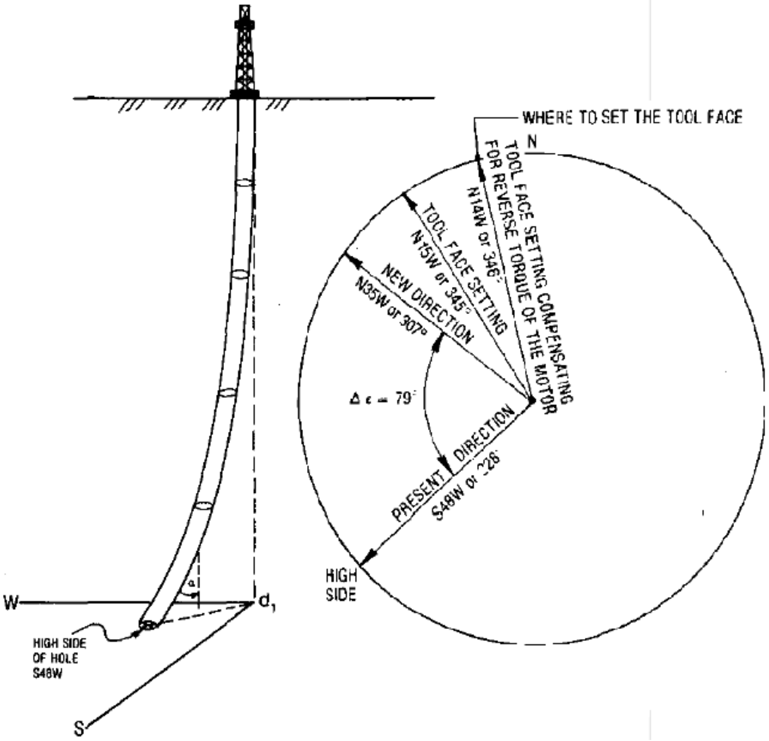


Figure 5-3: Dogleg Toolface, High Side of Well (Adam T, 1991)

Since this method is assumed to wrap around a sphere the minimum curvature has been used to calculate the departures. This is represented by equations 4.3 through 4.5. Since this method calculates a circular arc defined by the tool face angel and the radius from the dogleg, the following relationship between dogleg angel (ϕ) , curve length (CL) and dogleg severity can be expressed as: (Adam T, 1991)

$$D = \frac{\phi}{CL} \tag{5.9}$$

An input value important to this function is dogleg severity. This will indicate the total angel change over the section, and will dictate the degree of curvature allowed or tolerated in this curve. With input of DLS and toolface angel (γ) and the measured depth of the target the curve can be calculated and end point coordinates calculated.

From Applied Drilling Engineering (Adam T, 1986), formulas for changes in azimuth and inclination given by DL and TFO are presented. Derivation of these equations can be found in Appendix A.

$$dA = \arctan \frac{\tan(\phi) * \sin(\gamma)}{\sin(I_1) + \tan(\phi) * \cos(I_1) * \cos(\gamma)} \tag{5.10}$$

$$I_2 = \arccos(cos(I_1) * cos(\phi) - sin(I_1) * sin(\phi) * cos(\gamma)) \tag{5.11}$$

The output from running this function is summarized in the well plan described in table 5.4. Here, the dogleg toolface segment is added to the same build and turn curve from the previous functions, creating an extra well segment. The well path is plotted in figure 5-4.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	0	Tie Line
2	1000	1000	5	2	998,73	43,58	1,52	0,15	2	0,15	0	Inc Azi MD
3	2350	1350	50	137	2165,65	63,45	505,51	1,708	54,17	1	3	BT3 Inc.
4	3100	750	65,6	194,27	2588,84	-514,77	624,94	2	90	0,624	2,291	DT1 MD

Table 5.4: Summary of Well Path, Dogleg Toolface

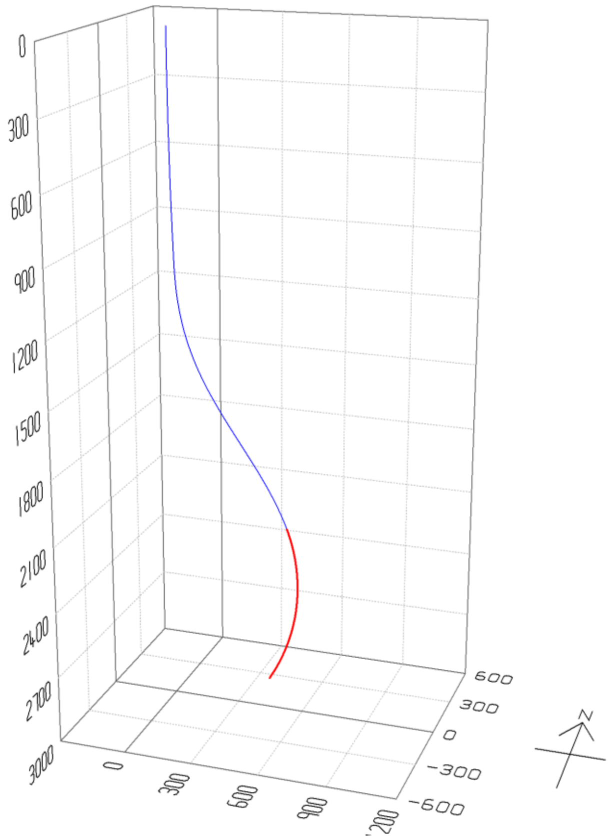


Figure 5-4: 3D Well Path, Dogleg toolface

5.4 Curve to Tangent to Target

This function constructs a well path with a build and turn curve, followed by a tangent to hit a desired target. The constraint of this method is that it must have sufficient build and turn rates to be able to point towards target within the given depth, between start point and set target.

Input values are similar to the build and turn models only that the final input parameter is a target to hit with a tangent. The way this model works is by constructing a build and turn curve with the given build and turn rates until either the azimuth of inclination is aligned with the target. After this, a second curve is added to align the remaining inclination or azimuth. This last curve will only use turn or build rate depending on which variable is reached first and will be a 2D curve in that sense.

The model uses iterations of the well path length to check if inclination or azimuth is in line with the target. The way it is done is to look at each separate plane for the two parameters.

There are several things that make this model complex. The first issue is to find when the azimuth or inclination is aligned with the target. The approach done to check this, is to run an iteration on the well path length (plan curve with lengths of 1m) and check if the well is aligned in the horizontal or vertical plane. This was done by comparing the azimuth angel with the angel formed between the tangent from that point and the target. This is illustrated in figure 5-5.

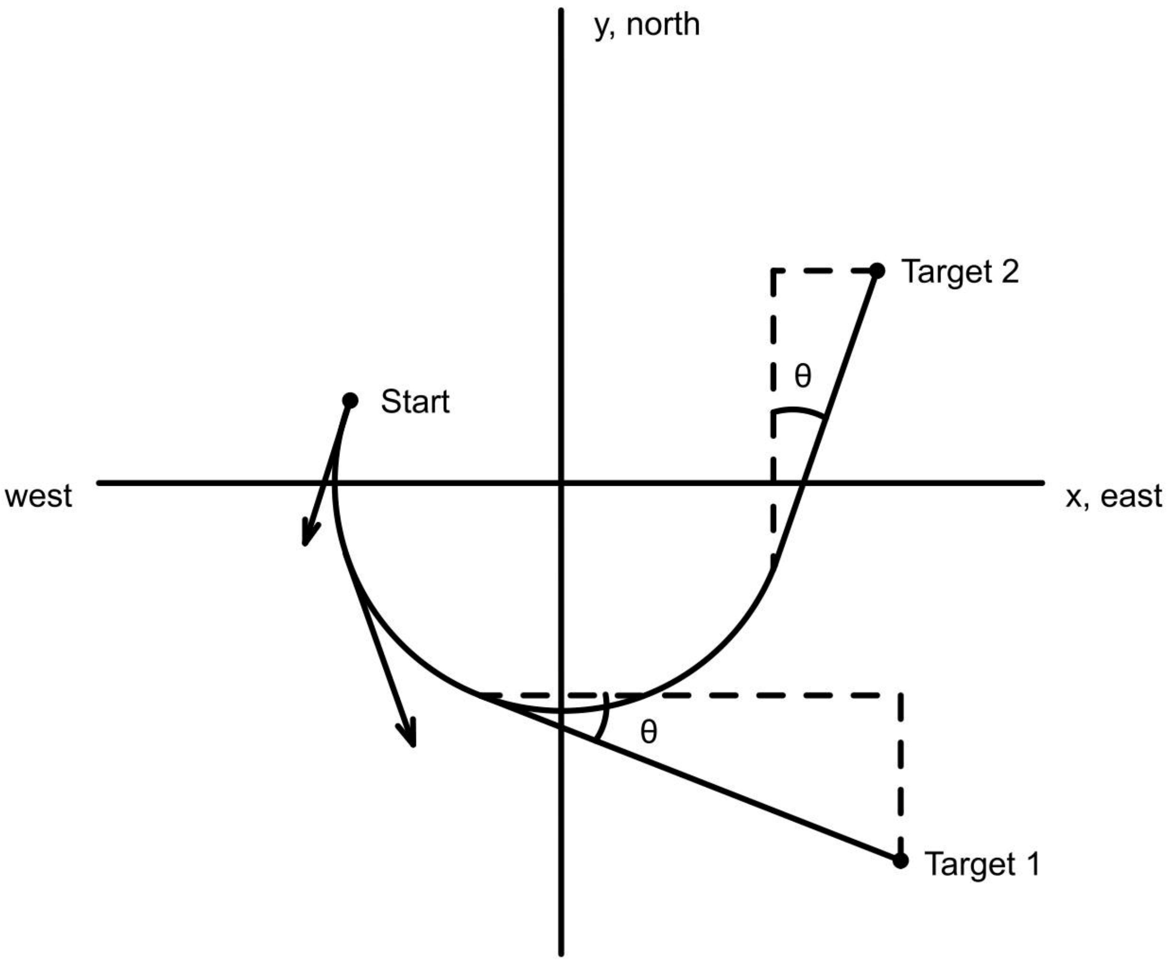


Figure 5-5: Shows Horizontal Plane With Varying Azimuth And Target Position.

Figure 5-5 shows how azimuth will be aligned with the target when the azimuth angel is equal to $\theta + 90.$ θ can be expressed by the distances between current wellbore position and the target, illustrated as dotted lines.

$$\theta = \tan^{1}\left(\frac{y}{x}\right) \tag{5.12}$$

This would only work when approaching the target in this direction. As can be seen from figure 5-5, when approaching target 2, the azimuth angel should be equal to $\theta.$ For this example θ can be expressed as:

$$\theta = \tan^{-1}\left(\frac{x}{y}\right) \tag{5.13}$$

Depending on the direction the well is approaching the target, the calculation to compare the azimuth to, changes. To solve this, the function first checks where the target is located compared to known current location. By considering that the start point is in 0,0,0 it can check where the target is located with respect to the current position. This is illustrated in figure 5-6, where target will be located in either of the zones. Each zone has its own verifying approach.

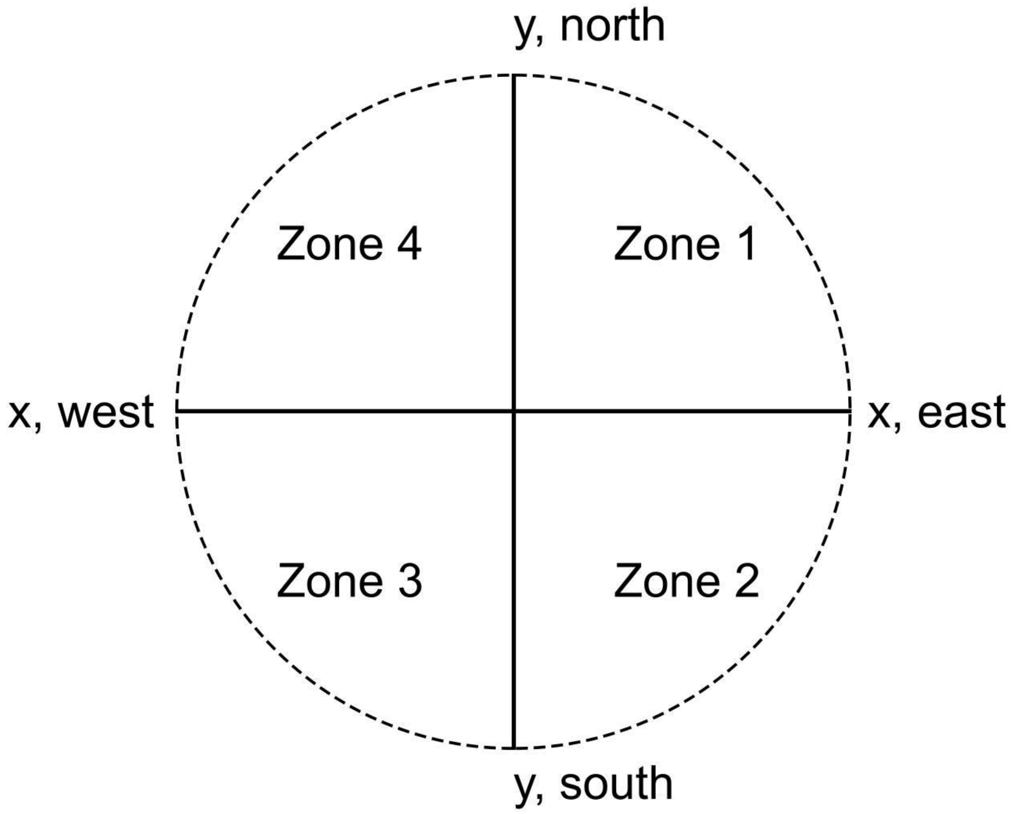


Figure 5-6: Zones in The Horizontal Plane, and Corresponding Angels to Each Zone

With this knowledge, it can be determined which approach is required to verify that the azimuth angel is aligned with the target. This can clearly be seen in the program code (Appendix B).

Calculating the inclination can be done by looking in the vertical plane, illustrated in figure 5-7. Here it can be seen how the inclination angel ϕ, forms an angel from the vertical axis down to the target.

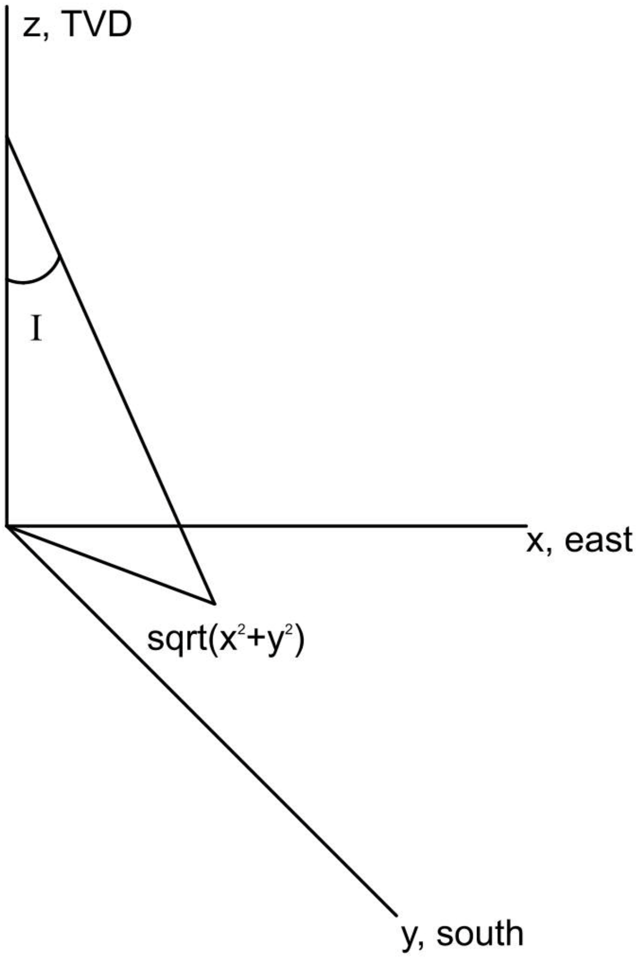


Figure 5-7: Scanning for Inclination Alignment

The inclination angel can be expressed by TVD (z) and the horizontal departure between the current position and the target, given in equation 5.14.

$$I = \tan^{1}\left(\frac{\sqrt{x^2 + y^2}}{z}\right) \tag{5.14}$$

The result from running this function is presented in table 5.5, and the plotted well path in figure 5-8. The start point can be seen in segment 2. Segment three uses the input build and turn rates until the azimuth for this case, is reached. The fourth segment shows a short build curve to reach the required inclination and the last segment is the tangent done to the target.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	Tie Line
2	1000,2	1000,2	2	200	1000	-16,4	-5,97	0,06	0,06	0	Inc Azi TVD
3	1617,29	617,09	16,4	140,35	1607,55	-106,84	22,79	0,84	0,7	-2,9	BT5 CH Tang
4	1650,16	32,87	17,17	140,35	1639,02	-114,15	28,85	0,7	0,7	0	(ditto)
5	2027,97	377,81	17,17	140,35	2000	-200	100	0	0	0	(ditto)

Table 5.5: Summary of Well Plan, Curve to Target

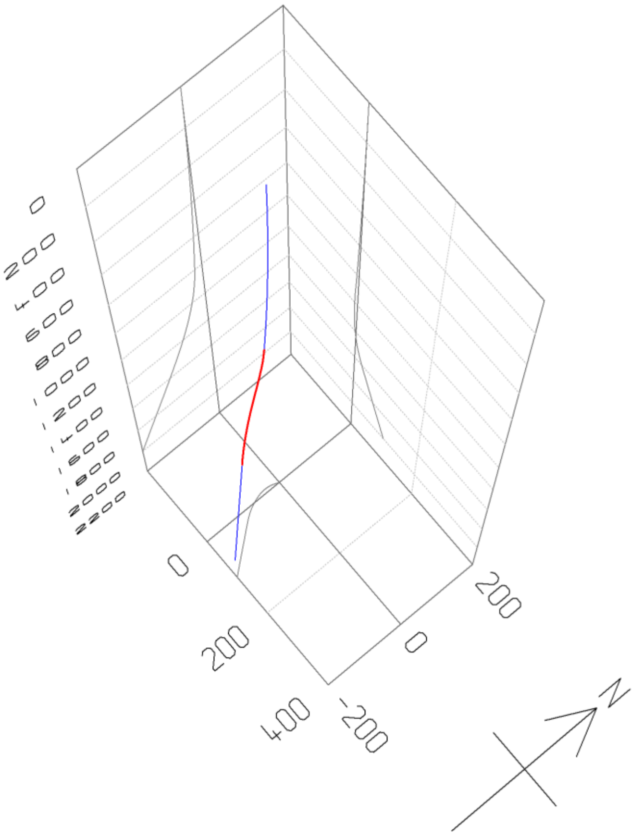


Figure 5-8: 3D Well Path, Curve to Tangent

From the shadow in the horizontal plane it can be seen how the well first curves, and then ends in a straight line, representing the tangent section to the target.

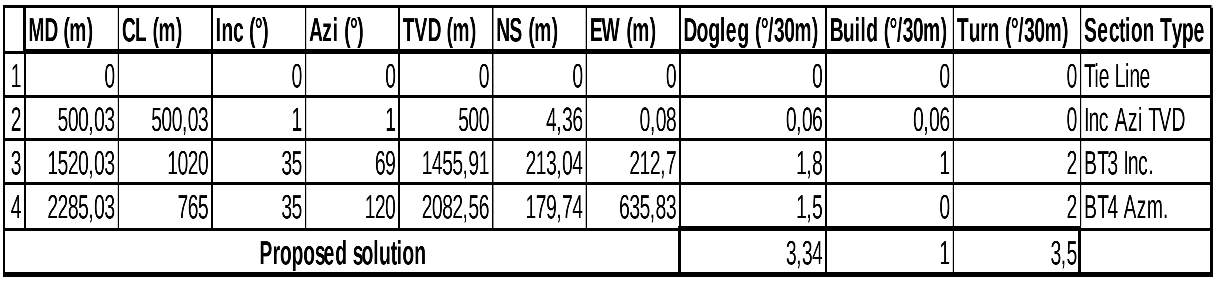
5.5 Build & Turn, Inclination and Azimuth

Unlike the previous Build & Turn functions, this function lets the user input both final inclination and azimuth, contrary to only one final parameter. The rest of the input values are still the same.

As it often is important to determine both final parameters this function designs a build and turn curve where this is achieved. The way this function works is that it checks which parameter will require the least curve length to reach input the parameter. It then constructs curve based on this length, and then stops turning or building until the last input parameter is reached. So the function will in principal be two curves.

The same goal can be achieved by lowering or raising either the build or turn curve, so that the curve length to reach both input values will be the same. The function takes this in-to consideration and gives, as output, the build and turn rates required to do so together with the dogleg severity this will cause. By doing this, the user will have a choice to reconstruct the well path segment, if dogleg severity is within the comfort zone.

However, if the well path is satisfying as is, the output will be a summary of the well path parameters and a plot of the well path, given and illustrated in table 5.6 and figure 4-9. In the table it can be seen how the function plans the well with two segments. The final inclination is reached first and then the second segment turns to meet the required final azimuth. The last row also proposes the alternative solution, and the dogleg severity it will give.



	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	Tie Line
2	500,03	500,03	1	1	500	4,36	0,08	0,06	0,06	0	Inc Azi TVD
3	1520,03	1020	35	69	1455,91	213,04	212,7	1,8	1	2	BT3 Inc.
4	2285,03	765	35	120	2082,56	179,74	635,83	1,5	0	2	BT4 Azm.
Proposed solution								3,34	1	3,5	

Table 5.6: Summary Well Plan, Build&Turn Inclination and Azimuth

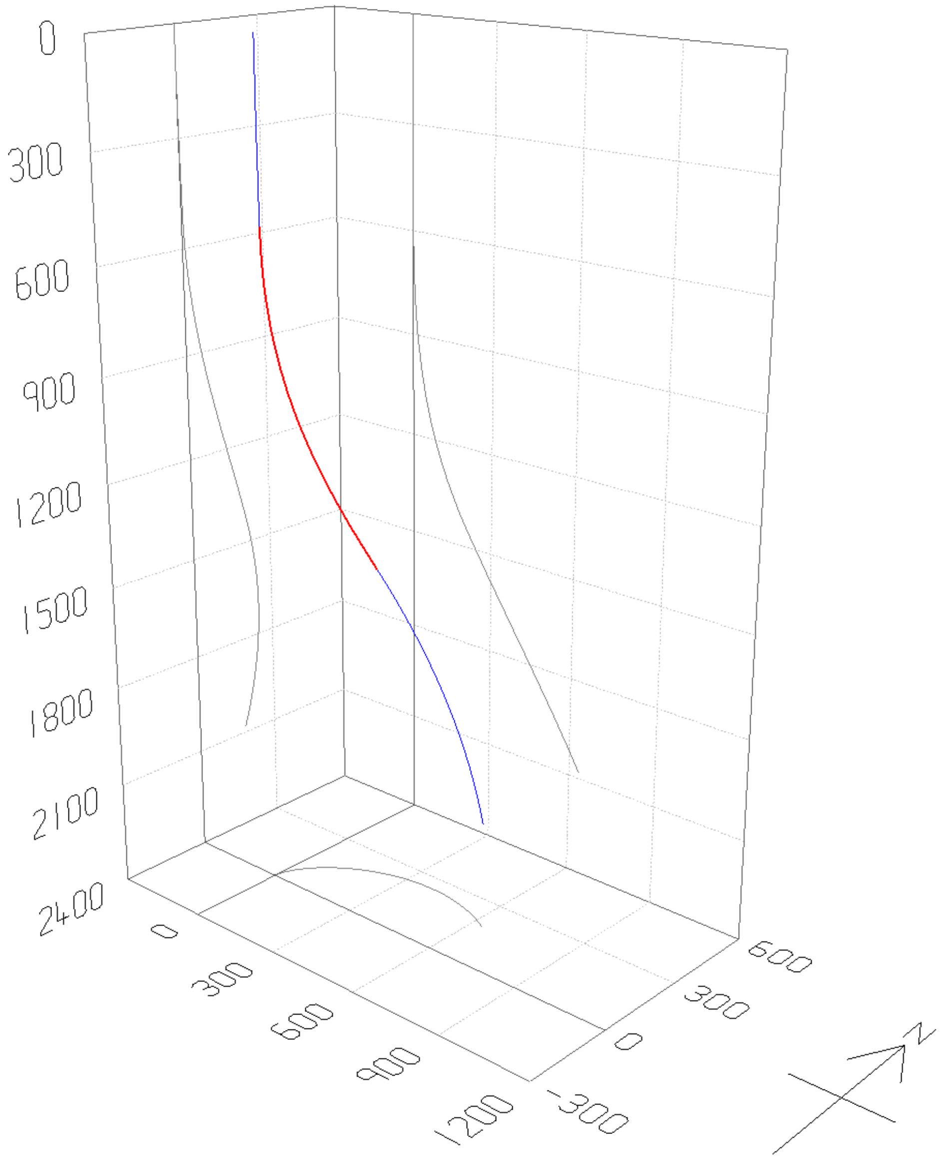


Figure 5-9: 3D Well Path, Buil&Turn Inclination and Azimuth

In this example, the inclination is reached first, and this can be seen, indicated by the shadow in the right plane. The inclination rises and then becomes constant, while in the horizontal plane the azimuth is turning the whole way.

5.6 Build turn to tangent with final position, inclination and azimuth.

Unlike all the other functions, this function takes in all final parameters. This is a function that makes more sense for a drilling engineer as final positional coordinates are just as important as inclination and azimuth, maybe even more so. This makes the models a lot more complex, and is more controlled by automated calculation. The input values of this function are the final position or target, together with inclination and azimuth and maximum DLS.

The goal of this function is to have a build &turn that results in a tangent to hit a predetermined target with given inclination and azimuth, unlike the other similar function that give random final inclination and azimuth. Based on the input variables, the model constructs a build and turn curve, until input inclination and azimuth is reached. It then creates a tangent based on these parameters, and the known vertical depth of the target.

As this function uses the dogleg severity as an input variable, the function has the ability to use a number of different build and turn rate relationships in the “buildandturn” section, as dogleg severity is a function of build and turn rate. The tangent is constructed from the end of the build & turn down to the target using the vertical depth between current position and the target. The function then checks if the target has the correct north/south and east/west coordinates.

If the function finds a solution with the given input parameters, the function returns a table with the summarized well plan together with the plotted well path. However, if the function does not find a possible solution, it displays that the function was not able to reach the target with the given input parameters. In addition to this, it calculates the closest possible solution, with a dogleg severity within 5 [deg/30m]. It then plots a figure that illustrates the closest solution with the input parameters, and the closest possible solution, together with a table showing the well plan summary this will incur. This is shown in figure 5-10, and table 5.7.

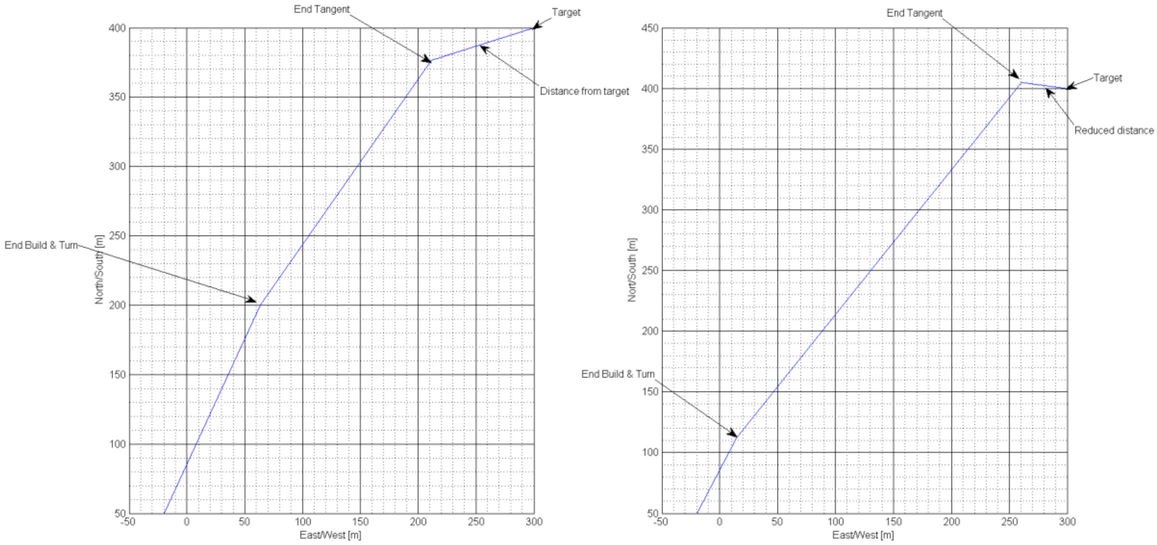


Figure 5-10: Picture 1: Best Solution With Input Parameters. Picture 2: Best Possible Solution

The first picture in figure 5-10 shows the best solution with the given input parameters and the second the best possible solution. The arrows indicate where the different well path sections end, and show the target and the distances from solution to target. The reason for this plot is to show the user what is wrong and how the curve with original parameters will look like. This way the user will have an illustrative description of why the input parameters do not work and by calculating the best possible solution, prevent the user from trying and failing with error bubbles until solution is calculated.

	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	Build (°/30m)	m	Error from Target()
1	0	0	0	0	0	0	0	0	0
2	15	15	800	50	-20	0	0	0	0
3	35	40	1500	400	300	4,83	3,51	4,83	39,97

Table 5.7: Summary of Well Plan, Build Turn Tangent, Final Parameters

5.7 Results, Plan a well

By applying the functions presented in the previous chapter it is possible to plan a complete well from start to target. To test out the programmed function to see if they give accurate results, a well was planned using the functions programmed and similarly constructing the same well in Compass.

The well was set to be drilled with kick off point at 350 m, and to reach a target with coordinates; 1300 m north, 700 m east and 4000 m TVD.

A well was constructed by using some of the different functions, this includes:

- Build Turn(Azimuth)
- Tangent
- Dogleg toolface
- Build Turn(Point)

The summary of the results are presented in table 5.8. The total well plan can be found in Appendix C.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	0	Tie Line
2	350,02	350,02	1	1	350	3,05	0,05	0	1	0,086	0	Inc Azi TVD
3	2585,02	2235	38,25	150	2418,29	-98,44	593,55	1	53,34	0,5	2	BT4 Azm.
4	2885,02	300	38,25	150	2653,89	-259,28	686,41	0	0	0	0	Straight MD
5	3685,02	800	45,43	110,95	3259,7	-581,47	1083,54	1	270	0,269	-1,464	DT1 MD
6	5189,47	1504,45	74,9	294,22	4000	-1300,01	700	3,66	79,5	0,588	3,655	BT6 Curve

Table 5.8: Summary of Well Plan, Planning a Well

From table 5.8 it can be seen that the first segment is a vertical section. Section two is a build turn curve, section three a tangent or hold, section four is a dogleg toolface curve, and last build turn curve using the point/target function.

The total well path is plotted in figure 5-11 and 5-12. To distinguish the different well segments figure 5-11 shows the different well segments as they are constructed towards the target. Figure 5-12 shows the well with a curtain profile, and presents the well path in from a different perspective.

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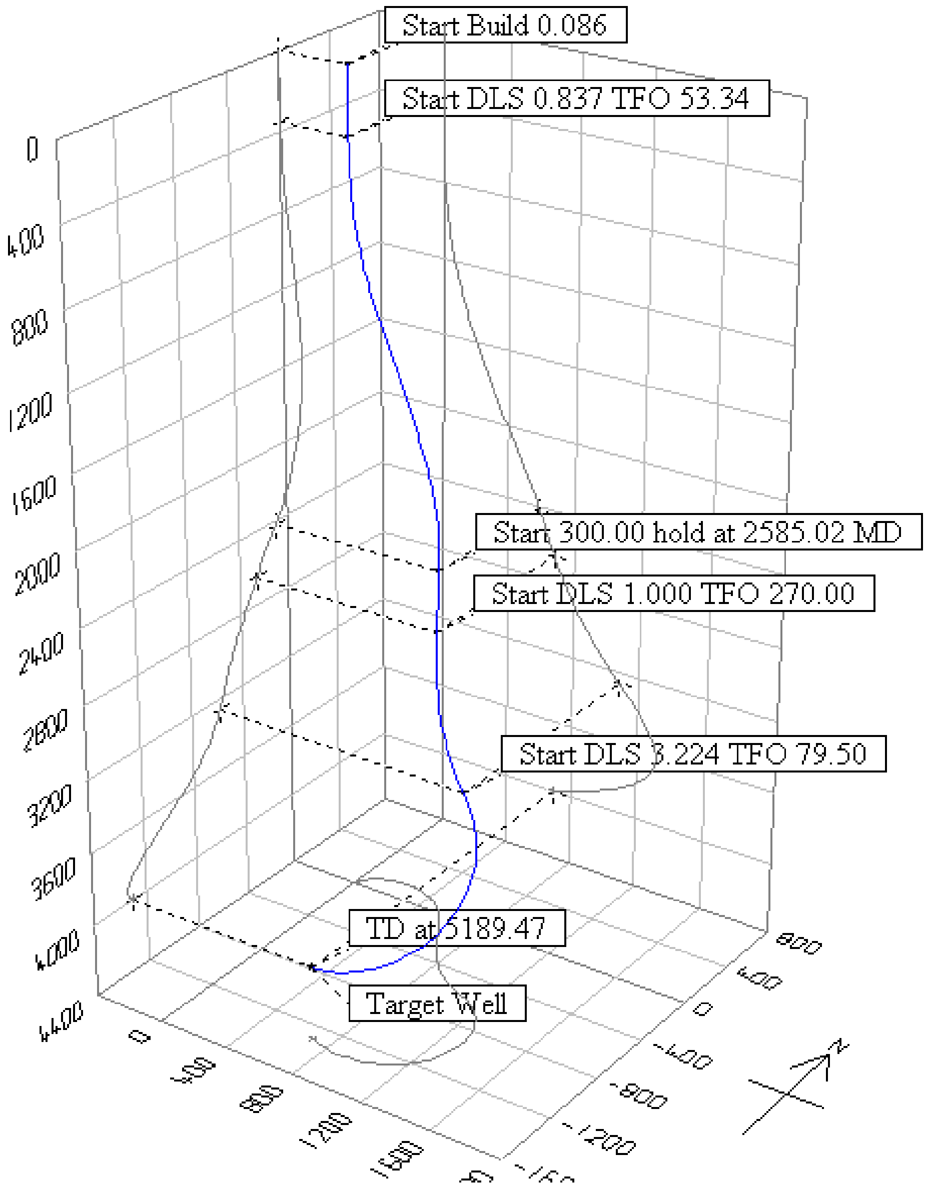


Figure 5-11: 3D Well Path, Planning a Well

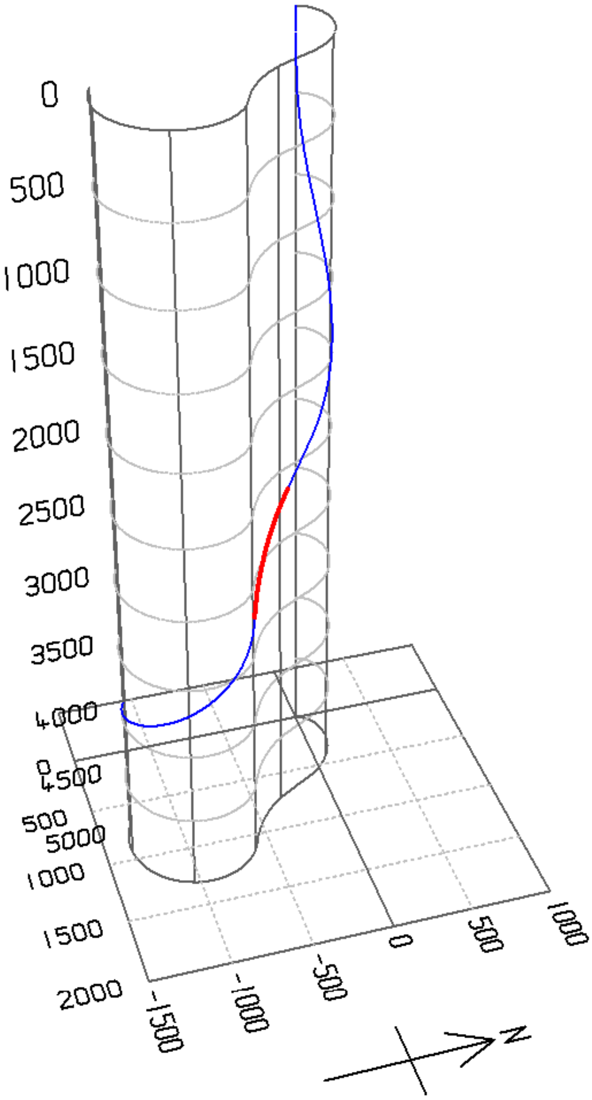


Figure 5-12: 3D Well Path, Planning a Well Curtain view.

To cross check the results from the functions the same well was constructed using Compass. The results are presented in table 5.9.

	MD (m)	CL (m)	Inc (°)	Azi (°)	TVD (m)	NS (m)	EW (m)	Dogleg (°/30m)	T.Face (°)	Build (°/30m)	Turn (°/30m)	Section Type
1	0		0	0	0	0	0	0	0	0	0	Tie Line
2	350,02	350,02	1	1	350	3,05	0,05	0	1	0,086	0	Inc Azi TVD
3	2585,02	2235	38,25	150	2418,29	-98,44	593,55	1	53,34	0,5	2	BT4 Azm.
4	2885,02	300	38,25	150	2653,89	-259,28	686,41	0	0	0	0	Straight MD
5	3685,02	800	45,43	110,95	3259,7	-581,47	1083,54	1	270	0,269	-1,464	DT1 MD
6	5189,47	1504,45	74,9	294,22	4000	-1300,01	700	3,66	79,5	0,588	3,655	BT6 Curve

Table 5.9: Summary of Well Plan, Planning a Well

By comparing the values in table 5.8 and 5.9 it can be seen that the calculated values are exactly the same. Each well segment consequently starts and ends with the same positional coordinates with corresponding inclinations and azimuths. The only parameter that does not give the same values is dogleg severity, presented in ninth column. This will be discussed in chapter 7.2.

6 Drilling Operation

6.1 Surveying and Measurement While Drilling

After complete engineering of a well, the planned trajectory is finalized and the drilling operation can start. As the well is drilled, the position of the trajectory is measured continuously. Measurements are taken while drilling (MWD).After the measured parameters are analyzed the information is used to calculate the well path position by using calculation models as presented in chapter 2.

MWD can give information about

- Directional data (Well Position)
- Formation characteristics (LWD)
- Drilling parameters (downhole WOB, torque;rpm)

As this thesis manly focuses on planning of directional drilling and surveying, only measurement techniques and error models will be discussed. Approximately 70 % of measured data relates to directional information. (TPG4215(1), Fall 2013)
For more information about tools and MWD measurement techniques, this can be found in Appendix D.

The sensors that are commonly used to measure the directional raw data use the magnetic and gravitational force of the earth to express the inclination and azimuth of well trajectory. The tool sensors are:

- Triaxial Accelerometers
- Triaxial magnetometers

The accelerometer uses the gravitational force of the earth to calculate the inclination of the wellbore. The magnetometers use the magnetic field of the earth to determine the azimuth of the well. A more extended description of the measurement tools can be found in Appendix D. A sketch of the two tools and the parameters they measure is given in figure 6-1.

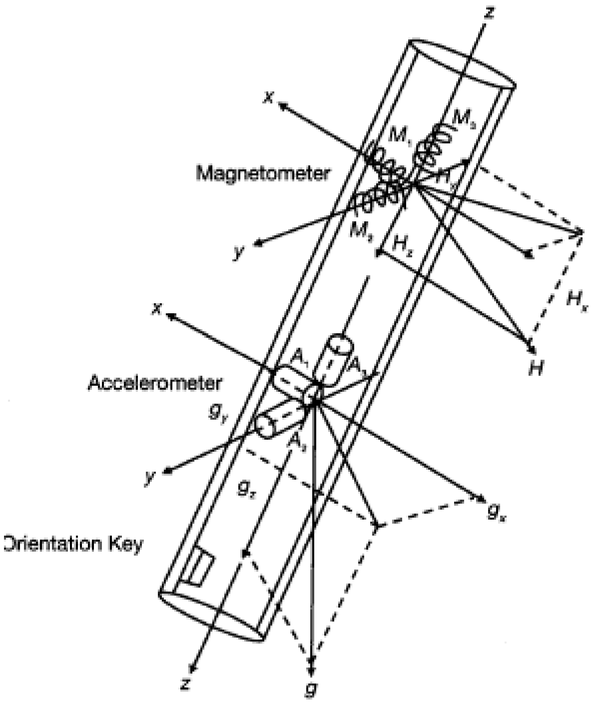


Figure 6-1: Magnetic Survey Tool (TPG4215(1), Fall 2013)

The information received from the accelerometers and the magnetometers are decoded in-to six parameters, three for each sensor. As illustrated in the figure 6-1, Gx, Gy and Gz for the accelerometer and Mx, My and Mz for the magnetometer, measured in mG and nT respectivly.

The inclination and azimuth can be derived from these parameters. As the values are measured in each direction the inclination can be found by geometry:

$$I = \operatorname{atan}\left(\frac{\sqrt{G_x^2 + G_y^2}}{G_z}\right) \tag{6.1}$$

The azimuth can be found by using values from both accelerometers and the magnetometers.

$$A = \operatorname{atan}\left(\frac{g * \left(G_x M_y - G_y M_x\right)}{M_z\left(G_x^2 + G_y^2\right) - G_z\left(G_x M_x + G_y M_y\right)}\right) \tag{6.2}$$

(TPG4215(1), Fall 2013)

To illustrate this process, a MWD survey for drilled section was required from Schlumberger. A short extract of the survey is presented in table 6.1, the entire survey run can be found in Appendix C. The survey consists of the measured values of the triaxial accelerometer and magnetometers for depth intervals of 25 ft. The table also shows the uncertainty reading of the azimuth.

Run #	MD	INC	AZ	Gx	Gy	Gz	Mx	My	Mz	QC	AZM_UNC
	Ft	DD.dd	DD.dd								
		64,05999	0,00001	mG	mG	mG	nT	nT	nT		deg
1	2500	64,06	109,45	437,64	623,49	-648,38	15896,97	42114,48	-22220,4	Good	0,98
1	2525	64,05	109,42	438,14	839,72	324,96	15928,96	36804,78	30281,86	Good	0,99
1	2550	67,25	109,43	387,19	857,7	-341,75	13305,77	48319,79	-3023,94	Good	0,99
1	2575	69,47	109,38	351,21	714,37	607,62	11546,32	25673,61	41575,76	Good	0,99
1	2600	72,04	109,6	308,75	-635,47	709,5	9370,99	-42584,8	24938,85	Good	1
1	2625	75,22	109,66	255,3	-387,77	886,79	6747,81	-32797	37448,52	Good	1
1	2650	77,43	109,37	217,83	72,16	-974,49	4988,35	18540,7	-46407,9	Good	0,99

Table 6.1: Short section of survey information from MWD run, Schlumberger.

By using the measured data from the survey run to calculate the inclination and azimuth of each segment length, it is possible to calculate the drilled well path trajectory using the calculation models presented in chapter 4. The desired calculation method used in survey calculations is as mentioned the minimum curvature method.

6.2 Error Modeling

The sensors and calculations behind the reported position of the well operate with some degree of error. This has to be taken into account when applying the measured and calculated position of the well path, such as in anti-collision calculations. The true position of the well has to be thought as the reported value plus the error of the measuring tools. To calculate and describe the error in the tool, an error ellipse is calculated by using a survey tool error model.

A survey tool error model describes how the positional uncertainties are calculated. (Co (Halliburton, 2011).There are a lot of different error models but the three most common models that are supported by Compass are:

- Cone of error
- Systematic error
- ISCWSA (The Industry Steering Committee for Wellbore Survey Accuracy)

Depending on the environment and the type of well, the most appropriate model for the task have to be chosen. The models require different type of parameters to calculate error margins. This information is usually provided by the survey contractor responsible for the tool. Details of the error model can also be found on the internet for many survey tools. Such websites are; Sperry-Sun, SDC and Anadrill.

The most commonly used error model to today is the ISCWSA error model. The two other models are outdated and have limitations when using magnetic surveying tools.

ISCWSA has built the survey error model based on a paper published by H.Williamson, titled: “Accuracy Prediction for Direction MWD.” (Williamson, 1999) This is an extension of the systematic error model. Using this model, solid state magnetic instruments are possible to use. The error model will not be described in detail in this thesis, but is mentioned as it is important for anti-collision calculations and positional uncertainty. Some parameters the error model takes into consideration are:

- Azimuth reading errors
- Depth error

- Inclination error

6.3 Anti-collision

Important in drilling is to avoid any accidents where human lives or the environment is exposed to danger. As there are uncertainties related to the position of the well being drilled, ref chapter 6.1, it is important to stay in a safe distance to other wells. Drilling into another well may result in an underground blowout. Therefore, it is important to take safety precautions to avoid the possibility of collision. In the following the well being planned will be referred to as the “reference well” and the already existing well as the “offset well”.

Anti-collision calculations are basically done to determine how close an offset well is to any point along the reference well. By checking this you will know how close an offset well is, so that you can continue to drill safely.

An offset well will be represented by a detailed plan or measured values describing the positional coordinates of a number of points along the well. When running anti-collision, the distance from the current position of the reference well to any offset well can be calculated.

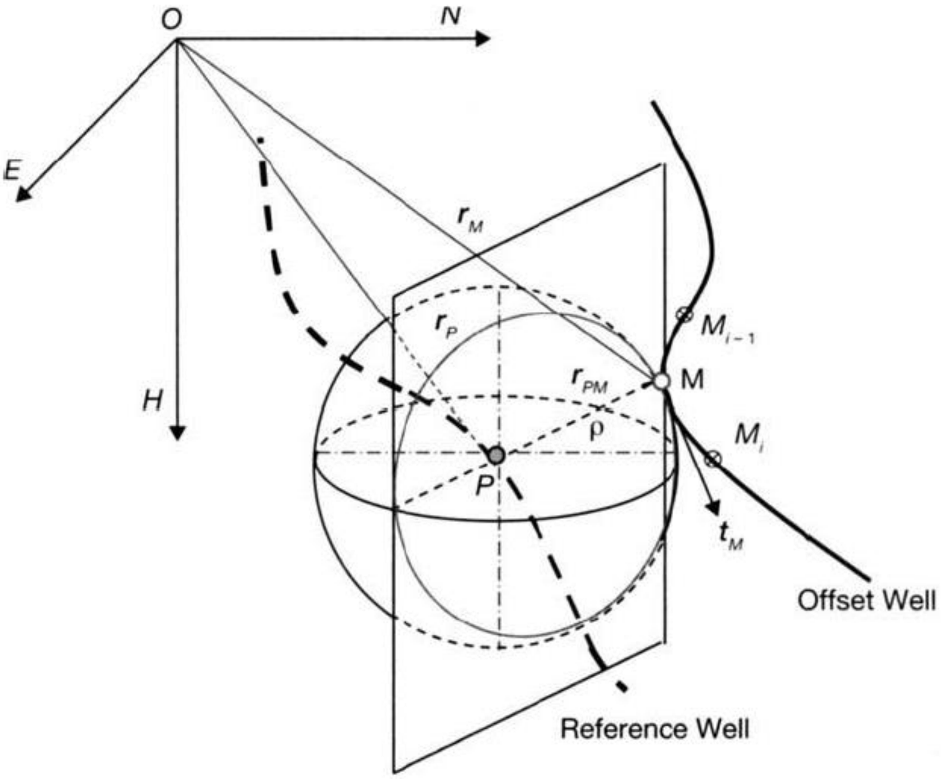


Figure 6-2: Anti-collision, Reference Well and Offset Well Source (TPG4215(2), Fall 2013)

Figure 6-2 shows the well paths of a reference well and an offset well, where P is a point on the reference well, with a positional vector j_p. The goal by running anti-collision is to determine at any point the closest distance to any neighboring well. Since the well paths can be considered to be continuous and smooth curves, there will always exist a spherical surface with center P, which can be drawn tangent to the trajectory of the offset well. (TPG4215(2), Fall 2013) This means that the radius of the sphere with center P, will be orthogonal to the unit tangent vector,t_m, of the closest point M..

By considering that the spherical surface touches the point M with positional vector j_m, the radius of the sphere can be described as:

$$r_s = |j_m - j_p| \tag{6.3}$$

The expression for the closes point, P, on the offset well can be described as:

$$\left(j_m - r_p\right) \times t_m = 0 \tag{6.4}$$

This can be written in scalar form as :

$$a(N_m - N_p) + b(E_m - E_p) + c(Z_m - Z_p) = 0 \tag{6.5}$$

Where

$a = \sin \alpha_m cos\beta_m$

$b = \sin \alpha_m \sin \beta_m$

$c = \cos \alpha_m$

(TPG4215(2), Fall 2013)

Considering point P with coordinates N_p, E_p, Z_p, the distance from any point P to any other point can be described by:

$$r = \sqrt{(N - N_p)^2 + (E - E_p)^2 + (Z - Z_p)^2} \tag{6.6}$$

By applying equation 6.6 the distance from point P to any other point from the offset well can be calculated. Figure 6-3 shows the point on the reference well denoted as, P, and five points of an offset well (A,B,C,D,E). From the figure it can be seen that the closest of these points is point C. However, the closest point to the reference point P, is actually point M, which is located in the section between point A and B.

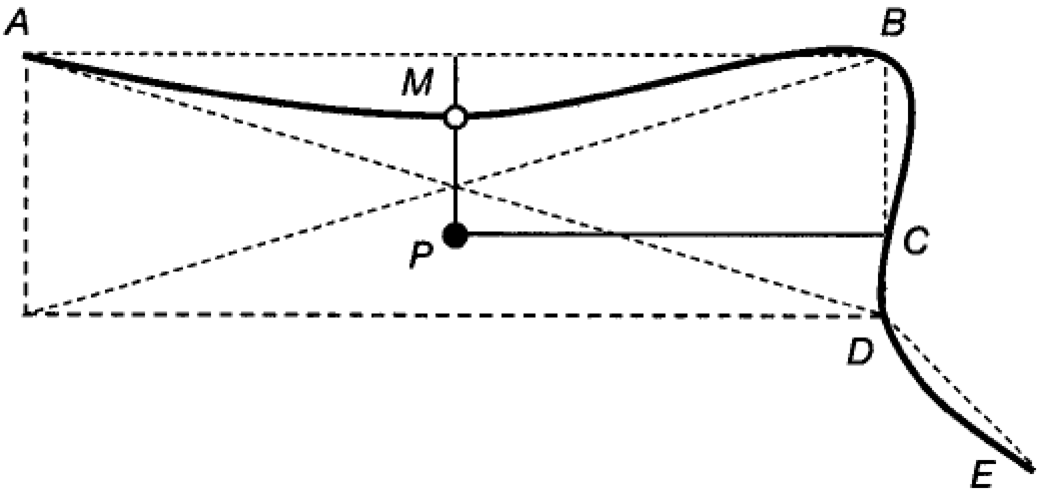


Figure 6-3: Anti-collision, Closest Point (TPG4215(2), Fall 2013)

This has to be checked and there are three ways of doing this.

1. Calculate the distance between, P and every calculated or measured point of the offset well, using equation 6.6. When the closest point is found, two sections on either side of this point have to be interpolated and each checked for a closer point.
2. Put in coordinates for two neighboring points from the offset well, sequentially, into equation 6.5. If $f(L_{i-1}) \times f(L) \leq 0$, then the closest point will be within this interval. Interpolate this section to find closest point.
3. For every section, between two calculated or measured points on the offset well, interpolate and find closest point. Comparing the closest point from each section, the lowest of these values will be the closest point. (TPG4215(2), Fall 2013)

Now the closest distance is located, but we do not know where this point is located as it can be at any point that is tangent to the sphere. To calculate the position of the closest point we have to apply two factors. (TPG4215(2), Fall 2013)

1. Horizontal scanning angel, Θ_h
2. Horizontal inclination, ω_h

The horizontal scanning angel is the angel between the horizontal projection of the scanning radius and the north direction. (ref) The horizontal scanning angel is given by (TPG4215(2), Fall 2013) :

$$\tan \Theta_h = \frac{E_M - E_p}{N_m - N_p} \tag{6.7}$$

The horizontal inclination angel is the angel between the scanning radius and the horizontal plane. The horizontal inclination is given by (TPG4215(2), Fall 2013):

$$\tan \omega_h = \frac{Z_m - H_p}{\sqrt{(N_m - N_P)^2 + (H_M - H_P)^2}} \tag{6.8}$$

As point P is moved along the reference well, each point will have a closest point on the offset well, with a calculated distance and direction relative to position of the reference well. This can be plotted and is illustrated in figure 6-4.

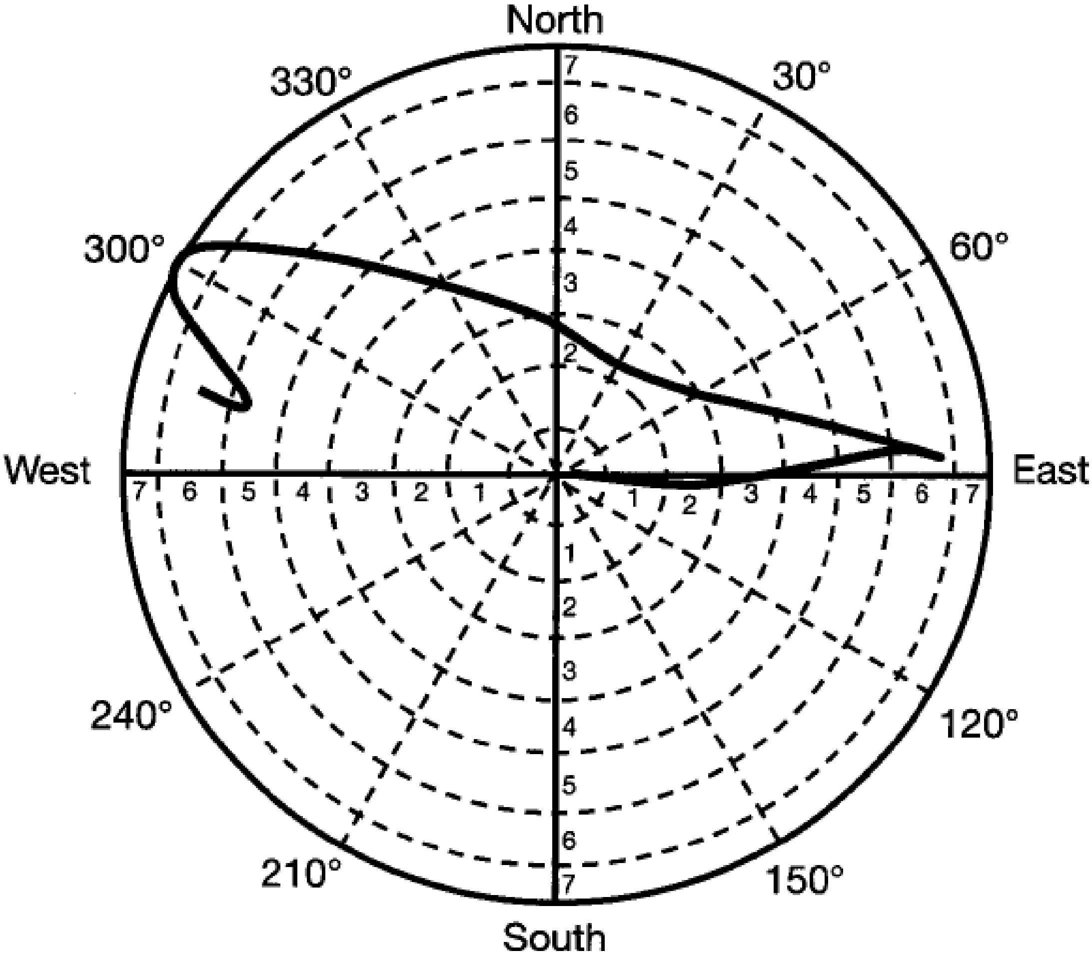


Figure 6-4: Shortest Distance Scanning Map (TPG4215(2), Fall 2013)

Figure 6-4 shows the closest distance to an offset well. The inner axis represent the separation and the outer circle indicates the direction to the closest point from the reference well.

The most common way of expressing the anti-collision is by separation factor. As mentioned in the previous chapter the measurement tools have errors related to them. The error ellipse that is created around the measured values isused in the calculation of separation factor as the position of the well bore is very important when it comes to anti-collision.

The separation factor is based on the minimum allowable separation between the two well paths and is given by the radii of the error ellipses as $e_r + e_0$

The separation factor can then be described as

$$SF = \frac{S}{e_r + e_0} \tag{6.9}$$

where S is the separation distance between the centers of each ellipse. This is illustrated in figure 6-5. By applying a separation factor it is possible to comprehend how close an offset well really is and makes it possible to set guidelines to what is acceptable etc. Some typical guidelines concerning the separation factor is given in table 6.2.

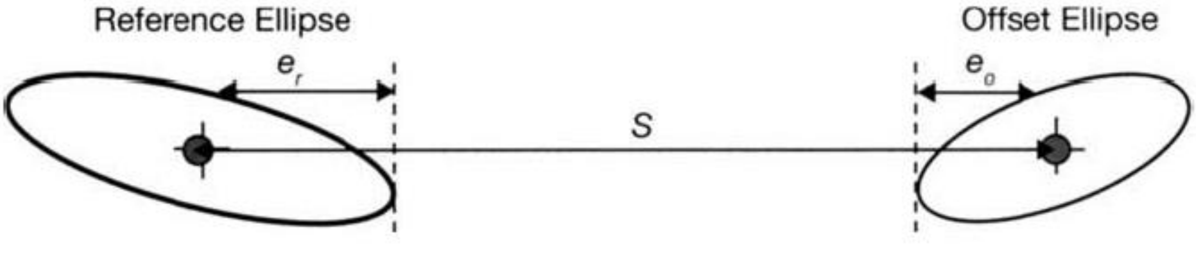
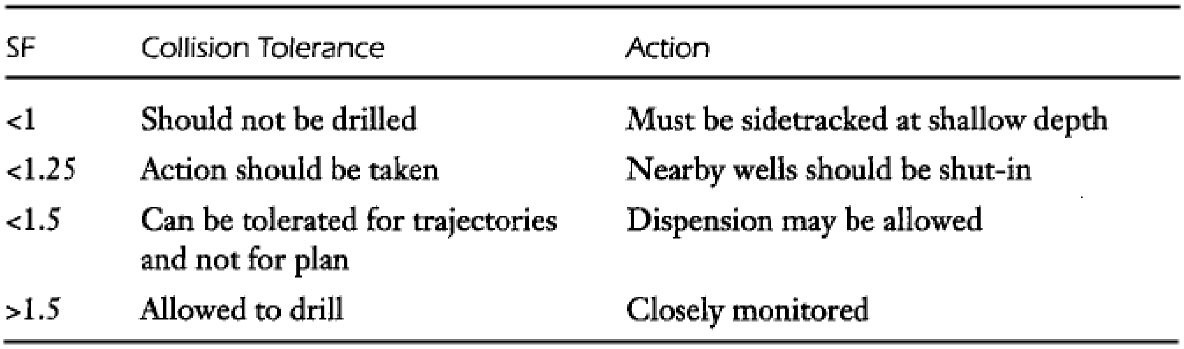


Figure 6-5: Separation Factor Anti-collision (TPG4215(2), Fall 2013)



SF	Collision Tolerance	Action
<1	Should not be drilled	Must be sidetracked at shallow depth
<1.25	Action should be taken	Nearby wells should be shut-in
<1.5	Can be tolerated for trajectories and not for plan	Dispension may be allowed
>1.5	Allowed to drill	Closely monitored

Table 6.2: Separation Factor Guidelines (TPG4215(2), Fall 2013)

Anti-collision is run in both the planning and execution phase. Figure 6-6 shows a flow diagram of the entire well operation from planning to execution. It also illustrates how anti-collision is run in both phases. (TPG4215(2), Fall 2013)

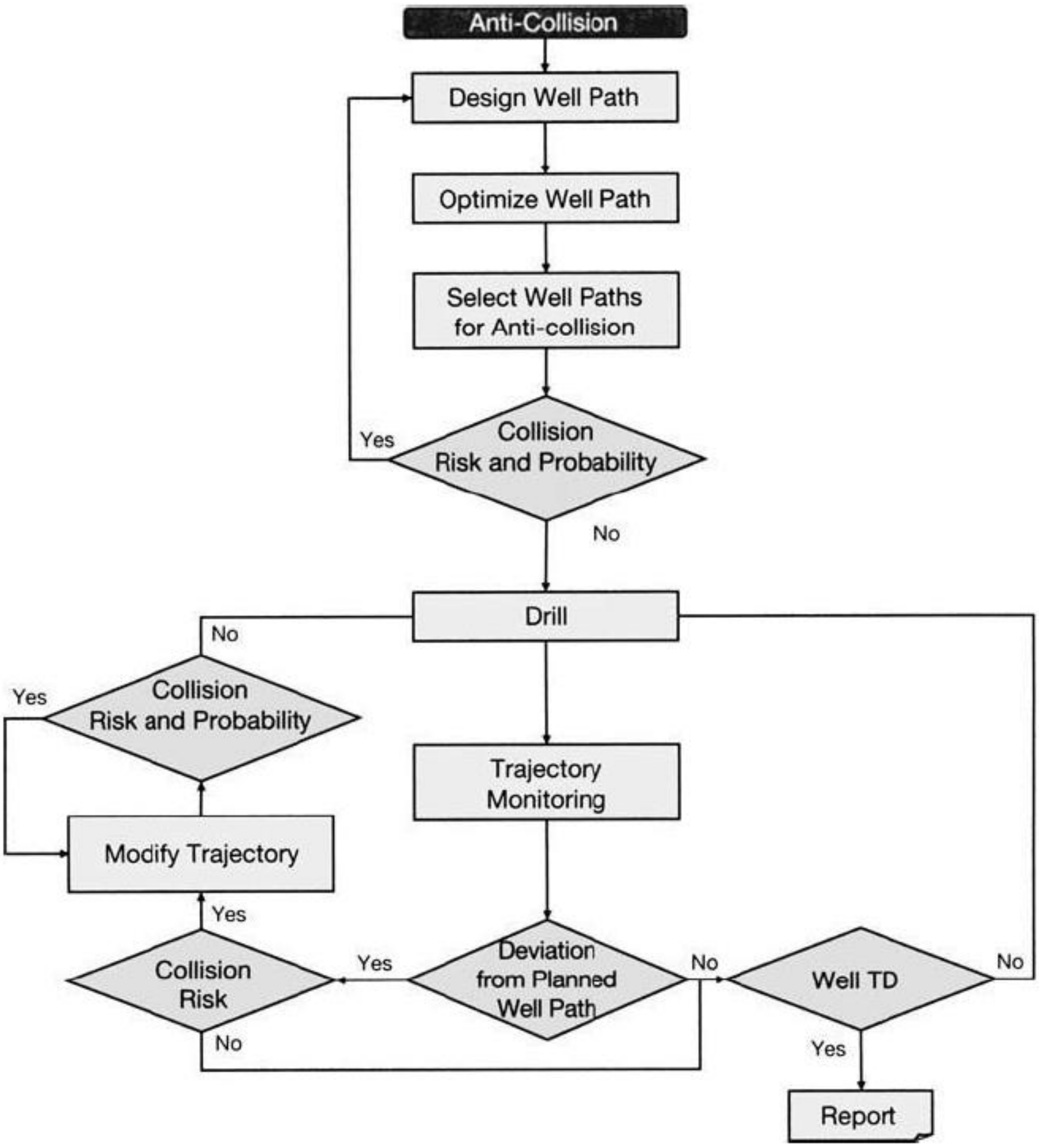


Figure 6-6: Flow Diagram Anti-collision for Planning and Execution Phase (TPG4215(2), Fall 2013)

7 Discussion

7.1 Software model

It is important for a software model to offer a user-friendly platform where a required well path can be accurately and safely constructed to reach the target and provide anti-collision. The software model should offer a variation of functions so that it is possible to construct any well path. A software model should also be able to provide some sort of plotting tool, so the user can visualize the calculated well paths.

The software used as offset in this thesis is Landmark's Compass. It is the industry leader within well trajectory planning. For this reason, it was decided to use Compass as the primary source to verify the calculation models and functions programmed in this thesis.

7.2 Calculation Models

Not many papers have been written on how to calculate exact positions of well paths. Several of the methods in the literature are incomplete in their description. The main bulk of papers and research done, focus on drilled well paths, i.e. surveying.

Based on the literature found, a study of calculation models was done to identify the most exact models. A trial and error process was conducted to check the accuracy of the models found in the literature. The results were finally compared to similar cases conducted in Compass.

The first two calculation methods presented in chapter 3, are very basic models that are not used in any aspects of the drilling phase today. They simply give too large errors and are not suitable for advanced well positioning. These functions have not been implemented in any of the functions.

The minimum curvature method is the main method that is used during drilling operations. It is well suited to calculate the drilled well path as this method is easy to use and give good acceptable results based on the survey data, as the well segment lengths are relative short. However, the minimum curvature method is not presumed to be accurate enough when it comes to the wellbore planning phase.

The main calculation model that has been used in this thesis is the “Constant Turn Rate Method” that was presented by Planeix and Fox. (Michele Y. Planeix, 1979), and later modified by Gordon B. Guo et al. (Gordon B. Guo, 1991). This method gives accurate results and show little error. During the trial and error process this method was programmed, and run for a number of different cases. The final results were compared to similar runs using Compass. The comparison showed consistent and in most cases identical results. Besides being an accurate model, the “Constant Turn Rate method” was found to be well suited for well planning. This model enables the use of actual drilling parameters making it a good model to use in functions. For this reason this model is the calculation model presented in the functions described in chapter 5.

The only function where this method has not been used is the dogleg toolface function. In this function the minimum curvature method has been used. The programed model for the dogleg toolface function gives the same results as the function in Compass.

It was found that the “Constant Turn Rate ” model does have some limitations. The ratio between the change in inclination and azimuth, have to correspond to the relationship between the build and turn rate. E.g. if $\Delta I = 30$ and $\Delta A = 60$, the turn rate has to be twice as large as the build rate. If this relationship is not the same the build and turn curve would reach the inclination first while final azimuth would not been reached. This problem is encountered when all four parameters are put directly into the model. This is not a problem in the first functions as either final inclination or azimuth is calculated/dependent on the length required to reach the input value. However, in the function where all final parameters are know it was found to give biased results if the ratio between build and turn rates did not match the changes in inclination or turn. It was therefore challenging to implement this calculation model in the last function. If the user input was set to be build and turn rates together with inclination and azimuth, an override would have to be done as soon as the ratio from the input values did not match. This is one of the reasons why dogleg severity was chosen to be one of the input values in the last function presented; “Build&Turn to tangent, with all final parameters”. This way the ratio would be locked by the inclination and azimuth change and the build and turn rates would follow this ratio.

The main method presented by Gordon B. Guo et al, (Gordon B. Guo, 1991), “Constant Curvature”, has not been implemented in any of the presented functions. The information and examples done in the paper was not complete and was considered to be inconclusive. The proposed method of solving the positional equations numerically was poor and did not offer any solution. The main improvements presented in this paper, was that the number of toolface corrections and BHA changes would be reduced, resulting in fewer number of trip-outs. In the drilling industry the use of 3DRSS steering systems allow the option to change steering parameters from surface while drilling. This will mitigate the problem where time consuming “trip-outs” and thus limit the benefits of improvements identified in this study.

As the Compass simulations gave identical results as the “Constant Turn Rate Method” identified, the “Constant Turn Rate Method” was chosen as the main calculation model supporting this thesis.

The reported dogleg severity calculated in the functions presented in this thesis differ from the values found in Compass. The method used to calculate the doglegs severity in the functions presented, is the method presented by G.J. Wilson (G.J., 1968) and given in equation 2.5. For simplicity this equation is repeated:

$$D = \sqrt{B^2 + T^2 * \sin(I)} \tag{7.1}$$

This method is used as it presented the best results under trials done in this thesis. Lubinskis method (Lubinski, 1987) which was preferred by Gordon B. Guo et al (Gordon B. Guo, 1991), was found to give some biased values to long segments intervals. Lubinskis method for this reason was found to give better results during an iterative planning of the well, as segments will be shorter. However, the calculated values do not correspond to the ones found by running Compass. It was not uncovered what method is used to calculate DLS in Compass. The method used in this thesis, was presented and tested by both Planeix and fox (Michele Y. Planeix, 1979) and Gordon B. Guo et al (Gordon B. Guo, 1991), and is considered to give more accurate results than Compass.

7.3 Functions

As the information related to well planning is limited, the construction of these models was not straight forward. The initial process was to identify what type of functions and applications that are needed to create well paths, and then comparing these to what functions are offered by Compass. By thinking of a typical well it is easy to imagine what type of functions are needed in each segment. It is important to be able to turn and build to avoid existing wells, maneuver away from unstable formations and land at certain azimuths and inclinations. Hold sections are also important so that long sections can be drilled optimally. Most importantly, it is imperative to have functions that provide exact and correct results, for safety and cost reasons.

The process started by looking at what sections are in a typical well. As discussed in chapter 1.2, a typical well will start vertically and then build and turn sections increase, as the depth increases. Functions that enable user to calculate curved well sections are important. In the first segments, functions that offer landing azimuth or inclination can be sufficient. As the target gets closer, the need to determine more final parameters becomes crucial. It is obvious that a number of different build and turn functions is required to plan a well. For this reason the main focus of the functions presented are different build and turn curves, based on different input parameters, as these are crucial and important functions. This will give the user the possibility to choose a number of different functions, to optimally plan a well.

By comparing these assumptions to what Compass offers, the presented functions were programed. This was a learning process where, as assumptions and functionality of the functions were uncovered, the more interesting and successful the functions became.

Programing these functions was a large part of the work done in this thesis. To develop a well-functioning script, a lot of parameters have to be evaluated and uncovered. Cases based on different well types have been programed to find the best possible solution, and iterations with steps up to 130 000 steps was necessary to find accurate solutions. Programing is a lot about finding creative solutions to solving problems.

Some examples of problems encountered is the turning angels which was presented under the build and turn functions as - azimuth cannot be below zero or over 360 degrees. This is somewhat intuitive but can quickly lead to inconclusive results.

Another problem is the turning angels in Build & Turn azimuth. The well path can go in both directions depending on the turn rate. More often than not, one of the directions will be the shortest. However, the shortest route will not always be possible to execute, due to formation obstacles etc., and the user may already be aware of this. To make sure that user is aware of this problem, the function determines the shortest route and notifies the user. The function then lets the user decide to continue with this route or not. This way the user will have an option to choose a more optimal route based on his knowledge of special conditions.

As the functions got more complex, it became clear how difficult it is to hit a predetermined target with user determined endpoint values. A large trial and error process was necessary to program the functions correctly. The solution used, was to plot the well path in the different planes so it became clear exactly why the well path did not hit the target, and automate the function to find possible solutions to prevent time consuming trial and error processes. This was very helpful and made everything easier to comprehend. For this reason a lot of the functions developed have such attributes that give alternative solutions, and illustrates what makes the well path miss the target, leading to no results. This was inspired by the limitations found in Compass, as this software does not offer any solution to the problems, and simply returns error warnings that input values will not reach the target. This required a lot of extra programing, as the functions have to be more automated. If the function does not find a solution, the function is programed using the findings obtained in this thesis to iterate until an acceptable solution is identified.

The two last models have such descriptive attributes. The Build & Turn inclination and azimuth, proposes an alternative solution and the build and turn to tangent with all final parameters, gives an illustrative description when the function does not have an exact solution. It also shows what the dogleg severity has to be in order to come close to a solution.

To verify that the presented functions are correct, the results were compared to similar cases run in Compass. All the results from the functions presented, were confirmed by the results from Compass. As this is the main programing tool used in the industry, this is a good indication that the presented functions are robust and give accurate results. This is shown in chapter 5.7.

7.3.1 Functionality

While the presented functions were proven to give accurate solutions, it also became clear that the functions have some limitations. The first six functions including the “dogleg toolface angel” function, do not enable the user to determine more than one end point parameter.

This is a disadvantage when planning wells. The final inclination, azimuth and final position are dependent on the input values for all these functions. The positional coordinates and the final parameters not determined as input, will be completely random. This means that a user has to try and fail numerous times, to get desirable final values. As an answer to this problem the two final functions where made.

The “Build and Turn, Final Inclination and Azimuth”, gives the user the possibility to determine both the final inclination and azimuth. The functions works according to Compass, if you design the two curves separately with build or turn equal to zero in the last section. To do this you still manually have to calculate the curve lengths so that the first curve will give either the desired inclination or azimuth. This function does this automatically. Another element that should be emphasized, is that the function also presents an alternative solution, by altering the input build or turn rate. This gives a solution, so that the curve will hit the target inclination and azimuth at same depth, resulting in only one curve. There are still limitations to this function as it does not let the user decide the final position of the well path, but it is a step in the right direction.

The last function was programed so that all final parameters can be determined by the user. When programing this model it was realized that it is very difficult to hit all parameters when user input is both build and turn rate. When build and turn rates are input values, the curved section will only have one possible curve. Just the smallest misalignment in the horizontal plane will construct the tangent passing the target. There is significant uncertainty in where the build & turn curve will end.

This is the reason this model takes in DLS. By using DLS as an input value, instead of build and turn rates, it was possible to calculate a large number different build and turn rate relationships, which results in higher possibility of reaching the target. To do this the function uses a “while loop” that runs calculations, with different build and turn rates while DLS is lower than the input value.

All the functions have been programed so that a user will have sufficient functions to plan and calculate any well path desired. After using and studying Compass, it became clear that more descriptive functions that help the user understand the calculations that are done and present alternative solutions, was something that was missing. To mitigate this limitation, all the functions developed here have been programed so that they present descriptive and alternative solutions, when the input variables do not offer a solution.

It is difficult to define an ideal function. Much is dependent on who the function is programed for. Due to user's varying background knowledge of well planning and the different aspects concerning angel changes and direction, it is difficult to program good functions. The first functions do not enable final parameters to be predetermined, but are very relevant to understand the concepts behind the process. Working with these problems gave a lot of learnings about how the well paths move in space and the principals behind azimuth change etc. These learnings were, were key in the process that enabled construction of functions with more complexity. These functions are maybe best suited in a learning phase, as their limitations prevent them to used in very complex wells. However, they will help to give understanding of the concepts to new users.

The more complex functions are more automated, to allow large iteration processes that run through a large number of calculations to find solutions. This takes some of the control away from the user, but is required to have any chance of hitting the target. Many different well path possibilities have to be run, to find a solution. This was concept I at first wanted to mitigate, as the it seemed as though the user lost control over how the well path would be constructed. But hitting the target is so difficult that a large volume of calculations have to tried, and this is simply to time consuming to be done manually.

7.3.2 Limitation and Proposed Solution to Curve to Tangent to Target

As discussed earlier this has model uses different calculations depending on the position of the target with respect to the start point. In some cases the turn required to hit the target will be so large that the azimuth will change zones as illustrated earlier in figure 7-1.

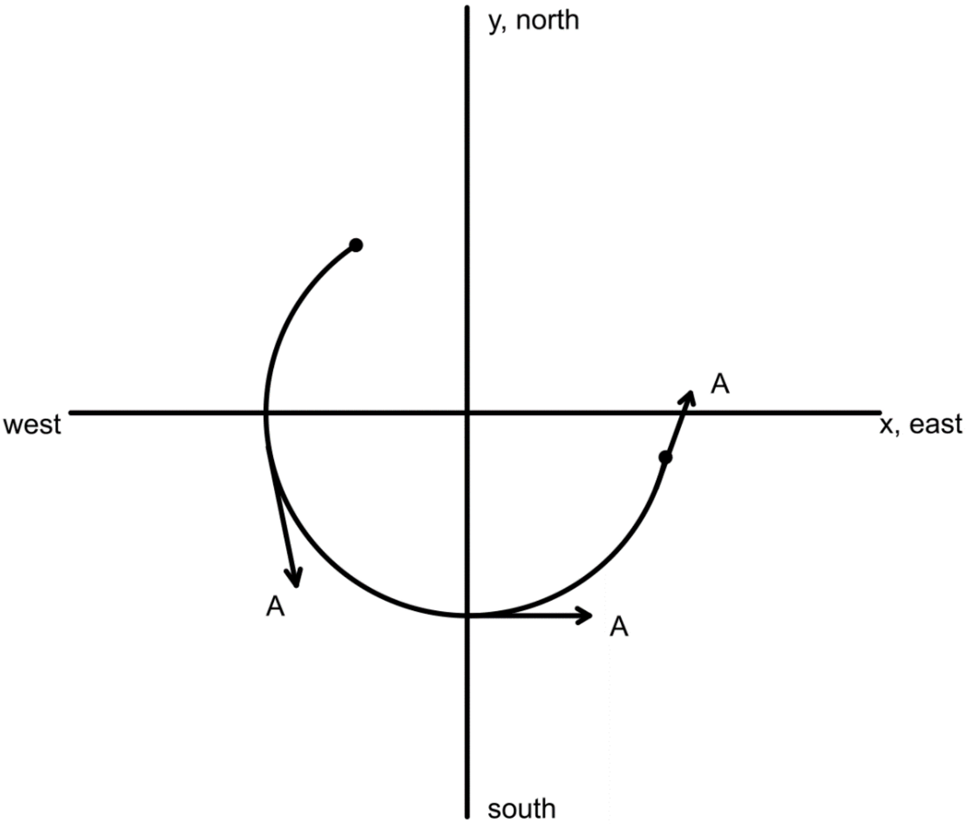


Figure 7-1: Large Turn Causes Zone Change

Figure 7-1shows how the well path will have to take a large turn in order to hit the target, and subsequently changing zones. The solution is to run a check and see if the azimuth has become larger or smaller than the upper and lower limit of that zone, referring to the angels each quadrant represent. If this happens, you can say that the zone changes by + - 1 zone, depending on the direction the well path has. In other words if it is turning east, positive T; + one zone, west with negative turn rate; -1 zone. Crossing north will give problems as the zone will become negative or get the value 5.

This can be handled by in the same process as checking zones for these specific cases:

- If zone is 1, Turn is negative and A2 is larger than upper limit
- If zone is 4, Turn is positive and A2 is lower than the lower limit

Unfortunately this was not implemented with success in to the function. In theory this should work but it was not completed. I think the problem is that if you constantly check the zones they will change constantly as the azimuth will go through one or several zones on its way to the target zone. This is listed under further work.

7.4 Industry leader Compass

Besides the manual supporting Compass, there is no clear information or studies done of which calculation models Compass uses and how the functions work. Compass is not clear on what it does to the input data to get the displayed results.

Compass offers a variety of different functions that let the user construct different type of well path trajectories, and offers a large variety of applications that makes it possible to construct geological formations etc. A question can be raised as to if it offers too much?

Compass is an excellent planning tool, but after studying and using Compass, it has become clear that it may have some flaws. Compass has so many alternatives that it is hard to get an overview of the software. Sometimes it is presented as a bit messy. Compass makes a lot of assumptions that is not documented in any of the manuals. It also seems to take shortcuts and is not consistent in using the methods it informs that it uses. When it comes to user friendliness, Compass also has room for improvement.

When input parameters are entered into the functions, Compass often presents undescriptive error warnings. These error warnings are more often than not undescriptive and ambiguous. Compass makes the process of using functions a trial and error, to select correct input values, instead of clearly stating what the problem is. This is one of the main focus areas of the functions presented in this thesis. An example of this is the turning angels. Compass simply does not let the user plan a well using the “longest route.” This is in my opinion very strange as this in some cases can be very crucial to avoid underground obstacles etc.

An unexpected observation was encountered when cross checking models with Compass. Compass clearly states that build and turn calculations are based on the cylinder model, which was found to be the “Constant Turn Rate Method”. However, when constructing a build and turn section from a vertical well with inclination and azimuth 0, Compass calculated the well using the minimum curvature method, thus giving different results from the presented function (Chpt. 5.1) which uses the “Constant Turn Rate Method”. This was found to be very confusing, as Compass is not consequent with the methods it uses. The user is given no notice that the curve uses another method, which is a serious omission. To show the difference by changing methods, the different methods were plotted in same diagram, only altering one case to initial inclination and azimuth to 1 degree. The difference in the result was significant. This is illustrated in figure 7-2.

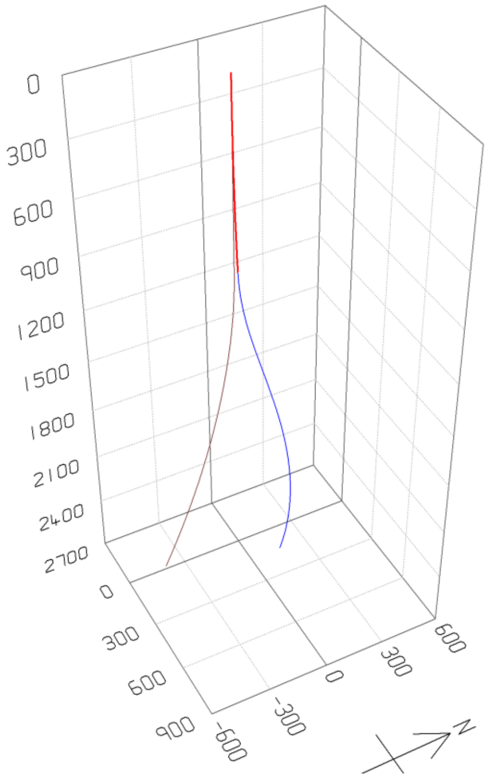


Figure 7-2: Anomaly in Compass

The blue line represents the well path calculated using constant turn rate, and the grey the minimum curvature. The change in method applied by Compass, is surprising, considering how big the difference between the two approaches will be.

In the build and turn to point function, anomalies were also encountered. When running the function for a case, no results were found for a given target. Compass, however, found a solution the function did not. The first assumption was that Compass again calculated the well trajectory with another method than presented in the manual. The same input values were tested with the minimum curvature method, and also these failed to give the same values as Compass. The method used by Compass is not clear. The function presented in this thesis failed to find a solution as the error was set to 0.5 meters. If error was set to a larger value the function would also have found the solution. Compass did not present any information that another method had been used, and presented the results spot on to the input values. This raises a concern that Compass switches to a more simplified method if the main method does not work, or that it gives a solution based on an error. If so, Compass should clearly let the user know that the proposed solution is not exact and notify the user of the error. The presented function is this thesis, lets the user set its own error level, so that the user will be aware of the uncertainty of the results.

Compass does not inform the user of these changes or factors, which leads to potential limitations in the use of the Compass software.

8 Conclusion

The basis for this thesis has been an attempt to construct a new and improved user-friendly well planning grogram. This study includes a review of available literature of well planning calculation models and the well planning program/software Compass, which is used frequently in the industry.

The literature study unveiled a large focus on surveying, and that information on well planning is limited. However, calculation models that present exact and correct well path position was found. These are the same calculation models that are used in the well planning softwares available in the market.

The work done in Compass shows that Compass have good functions and attributes, but also found some limitations when it comes to how the presented information works and what kind of assumptions are made for the calculations.

This thesis has tried to map a lot of these assumptions and anomalies that are found when using Compass, and tried to construct new and improved functions that are more accurate and more user-friendly.

A large number of functions have been programed and tested against Compass, giving excellent results and good functionality. Descriptive program code, and explanations to how the functions work have been presented. Some of the functions do have some limitations and is left to further work, with thoughts and proposed solutions.

It has become clear that the well planning software is very complex. To construct functions where all or many final parameters have to be reached require large iteration/iterative calculations.

When it comes to operational drilling phase the main calculation models have been addressed and methods behind surveying techniques have been presented. Anti-collision has been discussed and the calculation models identified. Implementing anti-collision calculations are left to further work.

9 Further work

In the process of constructing a comprehensive well planning software model there are still work outstanding such as:

- Functions with limitations need to be addressed
- Construct functions not covered under this thesis. This includes functions where all target parameters are input values, similar to optimum align found in Compass.
- Design and program a plotting tool that enables user to plot the calculated well path trajectories.
- Program software model that uses the presented and any further programed functions
- Implement anti-collision calculations

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Appendix A Derivations

A-1 Calculation Models

Derivations are taken from (Eck-Olsen, Fall 2013)

Tangential method:

From figure 3.2

$$\Delta V = L * \cos \alpha_2 \tag{A.1}$$

$$\Delta N = L * \sin \alpha_2 * \cos \beta_2 \tag{A.2}$$

$$\Delta E = L * \sin \alpha_2 * \sin \beta_2 \tag{A.3}$$

Balanced Tangential:

From figure 3.3

$$\Delta V = \frac{1}{2} L(\cos \alpha_1 + \cos \alpha_2) \tag{A.4}$$

$$\Delta N = \frac{1}{2} L \left(\sin \alpha_1 \cos \beta_1 + \sin \alpha_2 \cos \beta_2\right) \tag{A.5}$$

$$\Delta E = \frac{1}{2} L \left(\sin \alpha_1 \sin \beta_1 + \sin \alpha_2 \cos \beta_2\right) \tag{A.6}$$

Minimum Curvature:

From figure 3.4 it can be seen that F can be described as:

$$F = \frac{AB + BC}{arc\ AC} \tag{A.7}$$

And

$$AB = BC = R * \tan\left(\frac{\phi}{2}\right) \tag{A.8}$$

And

$$\frac{AC}{2 * \pi * R} = \frac{\phi}{360} \leftrightarrow AC = \frac{\pi R \phi}{180} \tag{A.9}$$

$$F = \frac{2}{\phi}\left(\frac{180}{\phi}\right) * \tan\left(\frac{\phi}{2}\right) \tag{A.10}$$

The ratio factor is then used in departure equations from the minimum curvature method, as presented.

A-2 Dogleg Toolface

Derivations are taken from (Adam T, 1991)

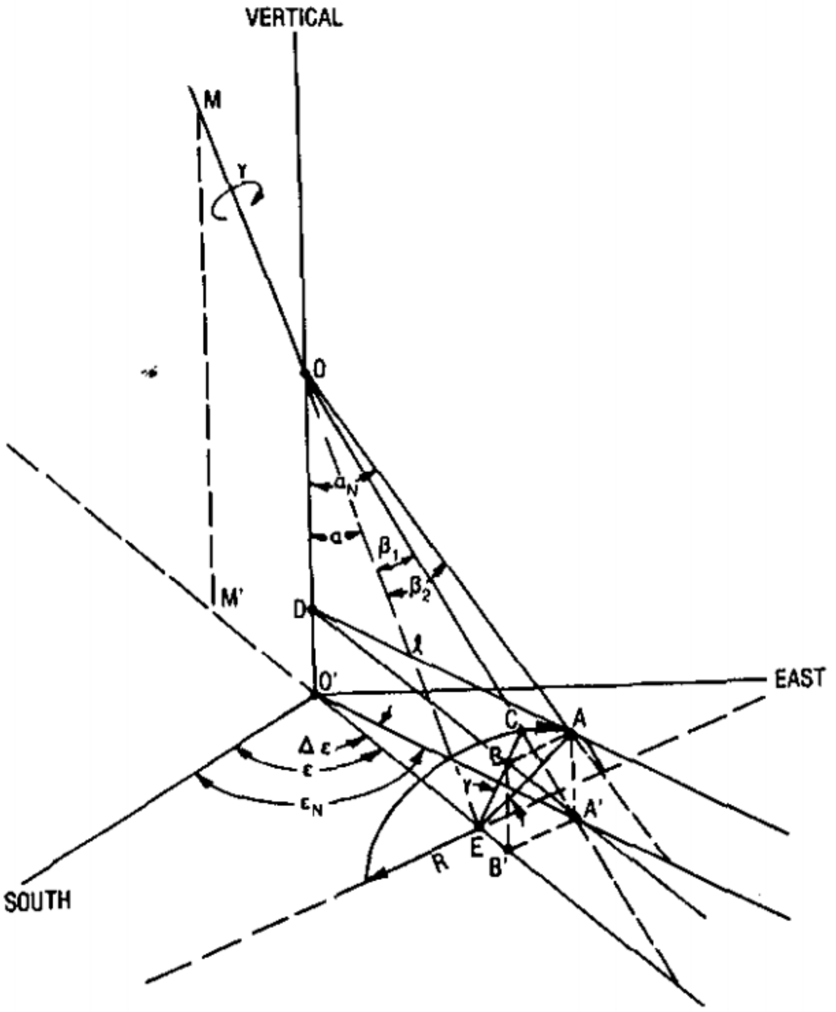

Figure A-1: Three Dimensional trajectory Change (Adam T, 1991)

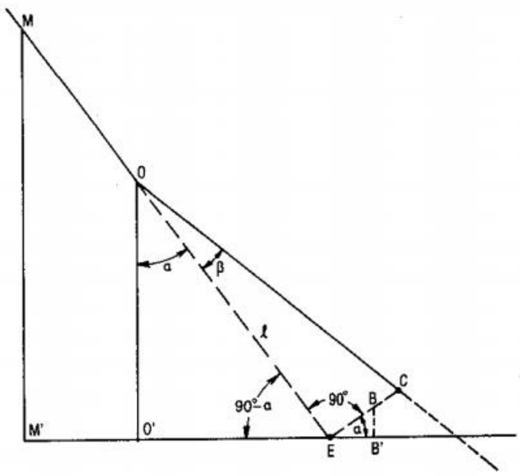

Figure A-2: Vertical Plane (Adam T, 1991)

Direction change:

From figure A-1 the change in direction, ΔA, is the angel formed by triangle A'O'B', where

$$\tan \Delta A = \frac{A'B'}{O'B'} = \frac{AB}{O'E + EB'} \tag{A.11}$$

Figure A-3 shows that line EA (radius r) from point A to point B and transcribes angel γ. It follows that

$$AB = r * \sin \gamma \tag{A.12}$$

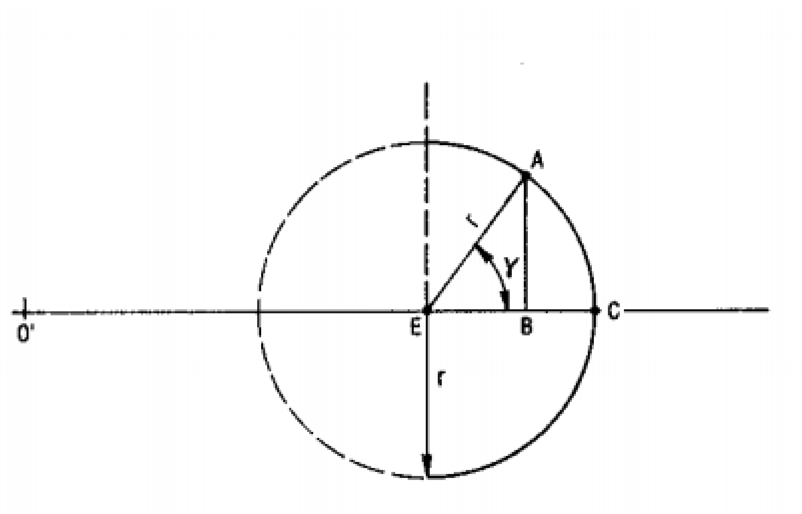

Figure A-3: Toolface Plane (Adam T, 1991)

Triangle EBB' (figure A-2) relates EB' to the angel α as

$$EB' = EB * \cos\alpha \tag{A.13}$$

From triangle EAB (figure A-3) EB is related to angle γ:

$$EB = r * \cos\gamma \tag{A.14}$$

Substituting EB in Eq.A-13 gives:

$$EB' = r * \cos\gamma * \cos\alpha \tag{A.15}$$

To determine O'E, consider triangles OEC and OO'E in figure A-2, where

$$r = l * \tan\beta \tag{A.16}$$

And

$$O'E = l \sin\alpha \tag{A.17}$$

Substituting these last two relationships for terms AB, O'E and EB' into Eq. A-11

$$\tan\Delta A = \frac{\tan\beta * \sin\gamma}{\sin\alpha + \tan\beta * \cos\alpha * \cos\gamma} \tag{A.18}$$

New Inclination

The new inclination angel, I2, can be derived by considering triangle AOD in plane OAA’O’ in figure A-1:

$$\cos I_2 = \frac{OD}{OA} = \frac{OO' - O'D}{OA} = \frac{OO' - AA'}{OA} = \frac{OO' - BB'}{OA} \tag{A.19}$$

Using triangles OO’E and EB’E (figure A-2), the inclination angel α, can be obtained from

$$OO' = l * \cos\alpha \tag{A.20}$$

And

$$BB' = EB * \sin\alpha \tag{A.21}$$

Substituting for EB (Eq. A-14) in the above equation yields

$$BB' = r_1 * \cos\gamma * \sin\alpha \tag{A.22}$$

Triangles AOE and COE are equal, and AO equals OC. From triangle AOE,

$$OA = OC = \frac{l}{\cos\beta} \tag{A.23}$$

Substituting for OA,OO’, and BB’ in Eq. A-19 yields

$$\cos\alpha_2 = \cos\alpha * \cos\beta - \sin\alpha * \sin\beta * \cos\gamma \tag{A.24}$$

Which gives

$$\alpha_2 = arc\cos(\cos\alpha * \cos\beta - \sin\alpha * \sin\beta * \cos\gamma) \tag{A.25}$$

Appendix B Program Code, Functions

B-1 Build&Turn, 3D Curves

Build&Turn, Inclination

```
function [ result ] = Build_Turn_inc( I1,A1,I2,T,B,NS1,EW1,Z1)
%Build&Turn Inclination. Build and Turn curve as function of
%final inclination. Units [deg],[deg/30m],[m]
%   This function uses Exaxt Departures method

 if B==T
   disp('Invalid B & T, can not be equal, B has changed') %Check if B=T
   B=B+0.0010;                                            % Alters B is so
end

result=zeros(2,6);

CL=(I2-I1)*30/B;  %Calcualte Cirvelength
A2temp=A1+T/30*CL; %Calcualte final Azimuth

if A2temp>360
    A2=A2temp-360;          %Checks that azimuth is within [0-360] deg
elseif A2temp<0
    A2=A2temp+360;
else A2=A2temp;
end

Brad=(B*pi/180)/30;         %Convert [deg/30m] to [rad/m]
Trad=(T*pi/180)/30;

%Calcualte final positional coordinates
NS2=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(A2)-cosd(I1)*cosd(A1)));

EW2=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(A2)-cosd(I1)*sind(A1)));

Z2=Z1+1/Brad*(sind(I2)-sind(I1));

D=sqrt(B^2+T^2*sind(I2)); %Dog leg Severity

result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;
result(1,4)=EW1;
result(1,5)=Z1;             %Makes table of results
result(1,6)=0;
result(2,1)=I2;
result(2,2)=A2;
result(2,3)=NS2;
result(2,4)=EW2;
result(2,5)=Z2;
result(2,6)=D;
end
```

Build&Turn,Azimuth

```
function [ result ] = Build_Turn_azi( I1,A1,A2,T,B,NS1,EW1,Z1)
%Build&Turn Azimuth. Build and Turn curve as function of
%final azimuth. Units [deg],[deg/30m],[m]
%   This function uses Exaxt Departures method

if B==T
   disp('Invalid B & T, can not be equal, B has changed') %Checks if B=T
   B=B+0.0001;                                           %Alters B if so
end

if T<0
    if A2>A1
        dA=360-A2+A1;                %Calcaltes the change in Azimuth,
    else dA=A1-A2;                   %for turning angels, so that user is
    end                              %aware of shorter route
else
    if A2<A1
        dA=360-A1+A2;
    else dA=A2-A1;
    end
end

if dA>180
    disp('Shorter to drill other direction');
    x=input('To continue anyway press 1, to quit and change T press 2');
    if x==2
        return              %Gives the user option to contiunue with big turn
    end
else disp('T-value is good')
end



CL=(dA)*30/abs(T);       %Calcualte curve lenght
I2=I1+B/30*CL;           %Calculate final incliantion

Brad=(B*pi/180)/30;              %Convert [deg/30m] to [rad/m]
Trad=(T*pi/180)/30;

%Calcualte final positional coordinates

NS2=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(A2)-cosd(I1)*cosd(A1)));

EW2=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(A2)-cosd(I1)*sind(A1)));

Z2=Z1+1/Brad*(sind(I2)-sind(I1));



D=sqrt(B^2+(T)^2*sind(I2));                 %Dog leg Severity
```

```
result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;
result(1,4)=EW1;
result(1,5)=Z1;
result(1,6)=0;%D2;           %Tabel of results
result(2,1)=I2;
result(2,2)=A2;
result(2,3)=NS2;
result(2,4)=EW2;
result(2,5)=Z2;
result(2,6)=D;

disp (dA)
end
```

Build&Turn, True vertical Depth

```
function [ result ] = Build_Turn_TVD( I1,A1,T,B,NS1,EW1,Z1,Z2)
%Build&Turn True Vertical Depth. Build and Turn curve as function of
%final true vertical depth. Units [deg],[deg/30m],[m]
%   This function uses Exaxt Departures method

if B==T
   disp('Invalid B & T, can not be equal, B has changed') %Check if B=T
   B=B+0.0010;                                            %Alters if so
end

Brad=(B*pi/180)/30;                       %Convert [deg/30m] to [rad/m]
Trad=(T*pi/180)/30;

I2=asind((Z2-Z1)*Brad+sind(I1));    %Calcualte final inclination
CL=(I2-I1)*30/B;                    %Calcualte curve lengt

A2temp=A1+T/30*CL;                   %Calcualte final Azimuth

if T<0
    if A2temp<0
        A2=A1+360+T/30*CL;  %Checks if Azimuth is below 0 and T is negative

    else A2temp>0
        A2=A2temp;
    end

else T>0                 %Checks if Azimuth is over 360 deg and T is positv
    if A2temp>360
        A2=A1-360+T/30*CL;
    else A2temp<360
        A2=Atemp;
    end
end

%Calcualte final positional coordinates
NS2=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(A2)-cosd(I1)*cosd(A1)));

EW2=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(A2)-cosd(I1)*sind(A1)));

Z2=Z1+1/Brad*(sind(I2)-sind(I1));

D=sqrt(B^2+T^2*sind(I2)); %Dogleg severity
```

```
result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;
result(1,4)=EW1;
result(1,5)=Z1;                %Table of results
result(1,6)=0;
result(2,1)=I2;
result(2,2)=A2;
result(2,3)=NS2;
result(2,4)=EW2;
result(2,5)=Z2;
result(2,6)=D;
end
```

B-2 Build&Turn, Point

```
function [ result ] = Point_Target( I1,A1,NS1,EW1,Z1,NS2,EW2,Z2)
%Build & Turn Point. This function constructs a build and turn curve to
%hit a predetermined target. It trys every possible of Build and Turn rate.
%This is a function of target coordiantes. Units [deg],[deg/30m],[m]
  %   This function uses Exaxt Departures method



count=0;  %Set found solutioins to zero
result=zeros(3,7);
error=5; %m               %Error use to check if final postion is correct

 for i=0:0.5:90               %Runs through every possible inclination
   for j=0:0.5:360           %Runs through every possible azimuth

       Brad=(sind(i)-sind(I1))/(Z2-Z1);%Calculate Build rate [rad/m]

       Bdeg=(Brad*180/pi)*30;         %Convert [rad/30m] to [deg/m]
       CL=(i-I1)*30/Bdeg;             %Calculate Curve leght
       Tdeg=(j-A1)/CL*30 ;            %Calculate Turn rate [deg/m]
       Trad=(Tdeg*pi)/(180*30);       %Convert [deg/30m] to [rad/m}

       %Calculate positional coordinates
       NS2t=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(i)*sind(j)-
       sind(I1)*sind(A1))+Brad*(cosd(i)*cosd(j)-cosd(I1)*cosd(A1)));

       EW2t=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(i)*cosd(j)-
       sind(I1)*cosd(A1))+Brad*(cosd(i)*sind(j)-cosd(I1)*sind(A1)));

       Z2t=Z1+1/Brad*(sind(i)-sind(I1));

       %Checks if target is reached

       if (abs(NS2-NS2t)<error && abs(EW2-EW2t)<error)
           count=count+1;       %Counts solutions found
           result(count,1)=i;
           result(count,2)=j;
           result(count,3)=NS2;
           result(count,4)=EW2;         %Tabel of results
           result(count,5)=Z2;
           result(count,6)=Bdeg;
           result(count,7)=Tdeg;
           result(count,8)=sqrt(Bdeg^2+Tdeg^2*sind(i));


       end
   end
end
disp(count)

if count==0
    disp('Try larger error');
end
```

B-3 Tangent

```
function [ result ] = Tangent( I1,A1,NS1,EW1,Z1,MD)
%Tangent. Constructs a tangetn from current.
% Function of final, True vertical depth(TVD), measured depth (MD)
% or tangent lenght(dMD). Lets you chose method.


x=input('Choose Method: 1=Z2,2=MD,3=dMD'); %User chose which method
y=input('Insert Value in [m]');
if x==1 %If method is TVD
    dZ=y-Z1;
    dMD=y/cosd(I1);  %Calcualtes the measured length of the tangent

    %Calcualte positional coordinates
    NS2=NS1+dMD*sind(I1)*cosd(A1);
    EW2=EW1+dMD*sind(I1)*sind(A1);
    Z2=y;

elseif x==2 %If method is MD
    dMD=y-MD; %Calcualtes the measured length of the tangent

    %Calcualte positional coordinates
    NS2=NS1+dMD*sind(I1)*cosd(A1);
    EW2=EW1+dMD*sind(I1)*sind(A1);
    Z2=Z1+cos(I1);

elseif x==3 %If method is dMD
    dMD=y;

    %Calcualte positional coordinates
    NS2=NS1+dMD*sind(I1)*cosd(A1);
    EW2=EW1+dMD*sind(I1)*sind(A1);
    Z2=Z1+dMD*cosd(I1);
end

result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;        %Table of results
result(1,4)=EW1;
result(1,5)=Z1;
result(2,1)=I1;
result(2,2)=A1;
result(2,3)=NS2;
result(2,4)=EW2;
result(2,5)=Z2;
```

B-4 Dogleg Toolface

```
function [ result ] = Dogleg_toolface( I1,A1,NS1,EW1,Z1,DLS,MD,TFO )
%Dogleg Tollface. Constructs a dogleged curve based on toolface orientation
%   Function of dogleg severity, measured depth and
%   toolface orientation. Units [deg],[deg/30m],[m].
%   This function uses Minimum curvature

result=zeros(2,6);
DL=DLS*MD/30; %Calculate Dogleg
                                        %Change in azimuth, direction
dA=atand((tand(DL)*sind(TFO))/(sind(I1)+tand(DL)*cosd(I1)*cosd(TFO)));

 if (A1+dA)>360
     A2=A1+dA-360;          %Check if azimuth is [0-360 deg]
    else A2=A1+dA;
 end

Tdeg=(dA/MD*30);            %Calcualte Turn rate
Trad=Tdeg*pi/180/30;        %Convert [deg/30m] to [rad/m]

I2=acosd(cosd(I1)*cosd(DL)-sind(I1)*sind(DL)*cosd(TFO));%Final inclination
Tdeg=(I2-I1)/MD*30;

F=2/DL*(180/pi)*tand(DL/2);       %Calcualte curve factor

%Calculate positinla coordinates
dNS=F*MD/2*(sind(I1)*cosd(A1)+sind(I2)*cosd(A2));
dEW=F*MD/2*(sind(I1)*sind(A1)+sind(I2)*sind(A2));
dZ=F*MD/2*(cosd(I1)+cosd(I2));

result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;
result(1,4)=EW1;            %Table of results
result(1,5)=Z1;
result(1,6)=0;
result(2,1)=I2;
result(2,2)=A2;
result(2,3)=NS1+dNS;
result(2,4)=EW1+dEW;
result(2,5)=Z1+dZ;
result(2,6)=DLS;
end
```

B-5 Curve to Tangent to Target

```
function [ result ] = Build_Turn_tangent( I1,A1,T,B,NS1,EW1,Z1,NS2,EW1,Z2)
% Build&Turn to Tangent. Build and Turn curve, resulting in
% a tangent to hit predetermined target.
% Build and turns to inclination or azimuth is alligned with target.
% Then constructs a tangent.
% Function of target positional coordinates.
% Units [deg],[deg/30m],[m]
% This function uses Exaxt Departures method


step=0.1;       %Step in iterativ operation(curve lenght)
error=0.01;     %Error to check allignment

Trad=(Tdeg*(pi/180))/30; %Convert build and turn rates to [rad/m]
Brad=(Bdeg*(pi/180))/30;


if NT>N1 && EWT>EW1
    zone=1;
    upperlim=90;
    lowlim=0;
elseif NT<N1 && EWT>EW1    %Finds position of target relativ to
    zone=2;                %initial position, by comparing coordiantes
    upperlim=180;
    lowlim=90;
elseif NT<N1 && EWT<EW1
    zone=3;
    upperlim=270;
    lowlim=180;
elseif NT>N1 && EWT<EW1
    zone=4;
    upperlim=360;
    lowlim=270;
end



for i =step:step:ZT-Z1     %Iterativ construction of build&turn to check
                           %if well bore is alligned with target.
                           %With steps of 0.1 [m].
    I2=I+Bdeg/30*i;        %Calcualting Inclination of curvelenght
    A2temp=A+Tdeg/30*i;     %Calcualting Azimuth of curvelenght

    if A2temp>360
        A2=A2temp-360;
    elseif A2temp<0         %Check that azimuth is with in [0-360 deg]
        A2=A2temp+360;
    else A2=A2temp;
    end

    %Positional coordiantes of wellbore

    N=N1+(1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
    sind(I)*sind(A))+Brad*(cosd(I2)*cosd(A2)-cosd(I)*cosd(A))));
```

```
EW=EW1+(1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I)*cosd(A))+Brad*(cosd(I2)*sind(A2)-cosd(I)*sind(A))));

Z=Z1+(1/Brad*(sind(I2)-sind(I)));

x=abs(EWT-EW);
y=abs(NT-N);        %Distance from curent position to target,
z=abs(ZT-Z);        % north, east and true vertical depth

%{
if zonetemp==1 && Tdeg<0 && A2>upperlim
    zone=4;
elseif zonetemp==4 && Tdeg>0 A2<lowlim   PROPOSED SOLUTION TO
    zone=1;                                     LIMITATION
elseif A2> upperlim
    zone=zonetemp+1
elseif A2<lowlim
    zone=zonetemp-1
 else zone=zonetemp;
end
%}
if zone==1
    h=atand(x/y);
    LS=0;
elseif zone==2            %Asigns verifying method of allignment
    h=atand(y/x);
    LS=(-90);
elseif zone==3
    h=atand(x/y);
    LS=(-180);
elseif zone==4
    h=atand(y/x);
    LS=(-270);
end


inc=atand(sqrt(x^2+y^2)/z); %Metod for inclination allignment




if h > (A2+LS)-error && h<(A2-90)+error %If azimuth is alligned
     disp('A2 reached')
     disp(A2);
     Trad=0.00000001;   %Turn is zero after this point
     Tdeg=0.000000001;
     Afinal=A2;         % Final azimuth reached
     I=I2;
     Nmidle=N;          %Positional coordinates of azimuth alligned
     EWmidle=EW;
     Zmidle=Z;
     dMD=i;
     count=1;   %Operator to determine which case happens
     break      %Auto expression to terminate "for loops"
end

if inc > I2-error && inc < I2+error %If inclination is alligned
     disp('I2 reached')
     disp(I2);
```

```
     Brad=0.00000000001;    %Build rate is zero after this point
     Bdeg=0.00000000001;
     Ifinal=I2;             %Final incliantion reached
     A=A2;
     Nmidle=N;
     EWmidle=EW;       %Positional coordinates of incliantion alligned
     Zmidle=Z;
     dMD=i;
     count=2;
     break
end
end



    for j= 1:step:ZT-Zmidle %Continue iterative process of
                            %curv lenghts, until next paramter is
                            %reached
         if count==2    %If inclination was reached first

        I2=Ifinal+Bdeg/30*j;
        A2temp=A+Tdeg/30*j;

         if A2temp>360
            A2=A2temp-360;
         elseif A2temp<0
            A2=A2temp+360;
         else A2=A2temp;
         end

%Positional coordiantes of curve lenghts
N3=Nmidle+(1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)
-sind(Ifinal)*sind(A))+Brad*(cosd(I2)*cosd(A2)-cosd(Ifinal)*cosd(A))));

EW3=EWmidle+(1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(Ifinal)*cosd(A))+Brad*(cosd(I2)*sind(A2)-cosd(Ifinal)*sind(A))));

Z3=Zmidle+cosd(Ifinal)*j;


        x=abs(EWT-EW3);     %Distance from curent position to target,
        y=abs(NT-N3);       % north, east and true vertical depth
        z=abs(ZT-Z3);

        if zone==1
            h=atand(x/y);
            LS=0;
        elseif zone==2
            h=atand(y/x);
            LS=(-90);
        elseif zone==3
            h=atand(x/y);
            LS=(-180);
        elseif zone==4
```

```
                h=atand(y/x);
                LS=(-270);
            end

                if h > (A2+LS)-error && h<(A2-90)+error %Check azi align
                    disp('A2 reached')
                    Afinal=A2;
                    disp(A2);
                    break
                end

            elseif count==1 %If azimuth is reached first


            I2=I+Bdeg/30*j;
            A2=Afinal;

    %Positional coordiantes of curve lenghts
    N3=Nmidle+(1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
    sind(I)*sind(Afinal))+Brad*(cosd(I2)*cosd(A2)-cosd(I)*cosd(Afinal))));

    EW3=EWmidle+(1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
    sind(I)*cosd(Afinal))+Brad*(cosd(I2)*sind(A2)-cosd(I)*sind(Afinal))));

    Z3=Zmidle+(1/Brad*(sind(I2)-sind(I)));

            x=abs(EWT-EW3);     %Distance from curent position to target,
            y=abs(NT-N3);       %north, east and true vertical depth
            z=abs(ZT-Z3);
            inc=atand(sqrt(x^2+y^2)/z);


           if inc > I2-error && inc < I2+error %Inclination alignment
                    disp('I2 reached')
                    Ifinal=I2;
                    disp(I2)
                    break

           end
           end
        end

        %Constructing the TANGENT

        dz=ZT-Z3;

        dMDTangent=dz/cosd(Ifinal);
        Nfinal=N3+dMDTangent*sind(Ifinal)*cosd(Afinal);
        EWfinal=EW3+dMDTangent*sind(Ifinal)*sind(Afinal);
        Zfinal=Z3+dMDTangent*cosd(Ifinal);

if count==2                   %Results depend on what case happens
    result(1,1)=Ifinal;
else result(1,1)=I;
end
if count==1
result(1,2)=Afinal;
else result(1,2)=A;               %Tabel of results
```

```
end
result(1,3)=Nmidle;
result(1,4)=EWmidle;
result(1,5)=Zmidle;
result(1,6)=0;
if count==2
result(2,1)=Ifinal;
else result(2,1)=I2;
end
if count==1
    result(2,2)=Afinal;
else result(2,2)=A2;
end
result(2,3)=N3;
result(2,4)=EW3;
result(2,5)=Z3;
result(2,6)=DLS;
result(3,1)=Ifinal;
result(3,2)=Afinal;
result(3,3)=Nfinal;
result(3,4)=EWfinal;
result(3,5)=Zfinal;
disp(result)
```

B-6 Build&Turn, Inclination and Azimuth

```
function [ result x,y,q ] = Build_Turn_inc_azi( I1,A1,I2,A2,T,B,NS1,EW1,Z1)
%   Calcualates build and turn curve, with final incliantion and azimuth.
%   The model builds and turns untill inclination or azimith is reached.
%   After this second curv with eiter build or turn.

if B==T
   disp('Invalid B & T, can not be equal'); %Checks if T=B.
   return
end

result=zeros(2,6);

if T<0
    if A2>A1                         %Calcualtes the change in Azimuth,
        dA=360-A2+A1;                %for turning angels, so user is aware
    else dA=A1-A2;                   %of shorter route
    end
else
    if A1>A2
        dA=360-A1+A2;
    else dA=A2-A1;
    end
end

if dA>180
    disp('Shorter to drill other direction');
    x=input('To continue anyway press 1, to quit and change T press 2');
    if x==2               %Gives the user option to contiunue with big turn
        return
    end
else disp('T-value is good')
end


Brad=(B*pi/180)/30;       %Convert build and turn rates to [rad/m]
Trad=(T*pi/180)/30;

CLinc=(I2-I1)*30/B;       %Calculates curve length for inc and azi
CLazi=(A2-A1)*30/T;

if CLinc<CLazi            %Determines if inclination has smaler curve length
    L1=CLinc;             %Curve lenght of first segment
    L2=CLazi-CLinc;       %Second cirve lenght
    Amid=A1+T/30*L1;      %Azimuth at this point
    c=0;                  %Operator to verify case

    %Positional coordiantes of first segment
    NSmid=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(Amid)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(Amid)-cosd(I1)*cosd(A1)));
    EWmid=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(Amid)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(Amid)-cosd(I1)*sind(A1)));
    Zmid=Z1+1/Brad*(sind(I2)-sind(I1));
    Dmid=sqrt(B^2+T^2*sind(I2)); %Dogleg severity of first segment
```

```
    %End point postitional coordiantes
    NS2=NSmid+1/(Trad^2)*(Trad*(sind(I2)*(sind(A2)-sind(Amid))));
    EW2=EWmid+1/(Trad^2)*(-Trad*(sind(I2)*(cosd(A2)-cosd(Amid))));
    Z2=Zmid+cosd(I2)*L2;
    D=sqrt(T^2*sind(I2))%Dogleg severity of second segment


else                % If inclianation curve length is not shortest
    L1=CLazi;           %Curve lenght of first segment
    Imid=I1+B/30*L1;    %Inclination at this point
    c=1;                %Operator to verify case

    %Positional coordiantes of first segment
    NSmid=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(Imid)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(Imid)*cosd(A2)-cosd(I1)*cosd(A1)));
    EWmid=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(Imid)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(Imid)*sind(A2)-cosd(I1)*sind(A1)));
    Zmid=Z1+1/Brad*(sind(Imid)-sind(I1));
    Dmid=sqrt(B^2+T^2*sind(Imid)); %Dogleg severity of first segment

    %From Imid to I2
    NS2=NSmid-1/(Brad^2)*(Brad*(cosd(A2)*(cosd(I2)-cosd(Imid))));
    EW2=EWmid-1/(Brad^2)*(Brad*(sind(A2)*(cosd(I2)-cosd(Imid))));
    Z2=Zmid+1/Brad*(sind(I2)-sind(I1));

    D=sqrt(B^2); %Dogleg severity of second segment


end

q=('To have one curve use this T or B, will give DLS');
if c==0
   x=(A2-A1)*30/L1;
   y=sqrt(B^2+x^2*sind(A2)); %Calcualtions to determine proposed solution

else
    x=(I2-I1)*30/L1;
    y=sqrt(x^2+T^2*sind(A2));
end
```

```
result(1,1)=I1;
result(1,2)=A1;
result(1,3)=NS1;
result(1,4)=EW1;
result(1,5)=Z1;
result(1,6)=0;
if c==0;                    %Tabel of result varies depending which case
    result(2,1)=I2;         %Tabel of results
    result(2,2)=Amid;
else
    result(2,1)=Imid;
    result(2,2)=A2;
end
result(2,3)=NSmid;
result(2,4)=EWmid;
result(2,5)=Zmid;
result(2,6)=Dmid;

result(3,1)=I2;
result(3,2)=A2;
result(3,3)=NS2;
result(3,4)=EW2;
result(3,5)=Z2;
result(3,6)=D;
result(4,1)=x;
result(4,2)=y;

end
```

B-7 Build&Turn, Target, final inclination and Azimuth

```
function result=NEW_buildturntangent(I1,A1,NS1,EW1,Z1,I2,A2,NS2,EW2,Z2,T,B)
%Build turn to tangent, with final position, inclination and azimuth.
%Function of Target and target parameters.
% Units [deg],[deg/30m],[m]
%   This function uses Exaxt Departures method
close all

error1=2;       %Error used to check solution with input parameters
error2=40;      %Base error used for best possible solution
c=0;            %Operator used to determine if input paramter give solution

f=(A2-A1)/(I2-I1); %Scale between change in azi and inc.
i=0;               %Start walue of turn/build rate

D=0;



while D<DLS        %Runs interativ computions on Build/turn rates,
                   %as long as dogleg severity is lower than Input
   i=i+0.01;       %Turn rate
   j=i/f;          %Build rate


Brad=(j*pi/180)/30; %Convert build and turn rates to [rad/m]
Trad=(i*pi/180)/30;

%Positional coordinates to reach input inc and azi
NSmid=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(A2)-cosd(I1)*cosd(A1)));
EWmid=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(A2)-cosd(I1)*sind(A1)));
Zmid=Z1+1/Brad*(sind(I2)-sind(I1));



%Constructs tangent from this postion, based on true vertical depth

dZ=Z2-Zmid;
dMD=dZ/cosd(I2);
NS2calc=NSmid+dMD*sind(I2)*cosd(A2);
EW2calc=EWmid+dMD*sind(I2)*sind(A2);

        result(1,1)=NS1;
        result(1,2)=EW1;
        result(1,3)=Z1;
        result(2,1)=NSmid;
        result(2,2)=EWmid;      %Tabel of results
        result(2,3)=Zmid;
        result(3,1)=NS2calc;
        result(3,2)=EW2calc;
        result(3,3)=Z2;
        result(4,1)=NS2;
        result(4,2)=EW2;
```

```
        result(4,3)=Z2;

    D=sqrt(j^2+i^2*sind(I2)); %Dogleg severity
    error3=sqrt((NS2calc-NS2)^2+(EW2calc-EW2)^2); %Error between curent
                                                  %postion and target

if error3<=error1       %Check if target is reached, within given error

       disp(result)
       plot(result(:,2),result(:,1)) %Plots well path in horizontal plane
       grid minor
       c=1;

       return %If Solution was found end function and return results
end
    end



    if c==0   %If target not reached
        subplot(1,2,1)
        plot(result(:,2),result(:,1)) %Plott the best result
        grid('minor')
        error3=0;

    disp('Can not reach target, with DLS')
    while D<5       %Starts new process of finding possibil solution

        i=i+0.01;   %Turn rate
        j=i/f;      %Build rate



Brad=(j*pi/180)/30;      %Convert build and turn rate to [rad/m]
Trad=(i*pi/180)/30;

%Positional coordinates to reach input inc and azi
NSmid=NS1+1/(Trad^2-Brad^2)*(Trad*(sind(I2)*sind(A2)-
sind(I1)*sind(A1))+Brad*(cosd(I2)*cosd(A2)-cosd(I1)*cosd(A1)));
EWmid=EW1+1/(Trad^2-Brad^2)*(-Trad*(sind(I2)*cosd(A2)-
sind(I1)*cosd(A1))+Brad*(cosd(I2)*sind(A2)-cosd(I1)*sind(A1)));
Zmid=Z1+1/Brad*(sind(I2)-sind(I1));




%Constructs tangent from this postion, based on true vertical depth
dZ=Z2-Zmid;
dMD=dZ/cosd(I2);
NS2calc=NSmid+dMD*sind(I2)*cosd(A2);
EW2calc=EWmid+dMD*sind(I2)*sind(A2);




D=sqrt(j^2+i^2*sind(I2)); %Dogleg severity
error3=sqrt((NS2calc-NS2)^2+(EW2calc-EW2)^2);%    %Error between curent
                                                  %postion and target
```

```
if(error3<=error2) %If solution is found within error, record results
        result(1,1)=NS1;
        result(1,2)=EW1;
        result(1,3)=Z1;
        result(2,1)=NSmid;
        result(2,2)=EWmid;
        result(2,3)=Zmid;
        result(3,1)=NS2calc;
        result(3,2)=EW2calc;
        result(3,3)=Z2;
        result(4,1)=NS2;
        result(4,2)=EW2;
        result(4,3)=Z2;

    error2=error3; %Error reduced, to find closer solution

       B=j; %Resulting build rate
       T=i; %Resulting Turn rate
       f=1; %Operater to determin that solution was found
       DLS=D;%Dogleg severity



end
    end

    end

if g==1 %If better solution was found
    disp('Use this B and T, error and DLS will be')
       disp(B);
       disp(T);
       disp(error2);
       disp(DLS);
       disp(result);
       subplot(1,2,2)               %Plot the better result
       plot(result(:,2),result(:,1))
       grid('minor')
else
    disp('Is not possible within error of, and DLS under 5')
end
```

Appendix C Results and Survey Run

C-1 Results, Detailed Well Plan

MD	Inc	Azi	TVD	North	East	DLS
0	0	0	0	0	0	0
30	0,09	1	30	0,02	0	0,086
60	0,17	1	60	0,09	0	0,086
90	0,26	1	90	0,2	0	0,086
120	0,34	1	120	0,36	0,01	0,086
150	0,43	1	150	0,56	0,01	0,086
180	0,51	1	180	0,81	0,01	0,086
210	0,6	1	210	1,1	0,02	0,086
240	0,69	1	239,99	1,44	0,03	0,086
270	0,77	1	269,99	1,82	0,03	0,086
300	0,86	1	299,99	2,24	0,04	0,086
330	0,94	1	329,99	2,71	0,05	0,086
350,02	1	1	350	3,05	0,05	0,086
360	1,17	1,67	359,98	3,24	0,06	0,501
390	1,67	3,67	389,97	3,98	0,09	0,502
420	2,17	5,67	419,95	4,98	0,18	0,504
450	2,67	7,67	449,93	6,24	0,32	0,507
480	3,17	9,67	479,89	7,75	0,55	0,51
510	3,67	11,67	509,84	9,5	0,89	0,514
540	4,17	13,67	539,77	11,5	1,34	0,518
570	4,67	15,67	569,68	13,74	1,92	0,523
600	5,17	17,67	599,57	16,2	2,66	0,528
630	5,67	19,67	629,43	18,88	3,57	0,534
660	6,17	21,67	659,27	21,78	4,66	0,541
690	6,67	23,67	689,08	24,87	5,95	0,548
720	7,17	25,67	718,87	28,15	7,46	0,555
750	7,67	27,67	748,61	31,61	9,2	0,563
780	8,17	29,67	778,33	35,24	11,18	0,571
810	8,67	31,67	808	39,01	13,42	0,579
840	9,17	33,67	837,64	42,93	15,93	0,588
870	9,67	35,67	867,24	46,96	18,72	0,597
900	10,17	37,67	896,79	51,11	21,81	0,607
930	10,67	39,67	926,3	55,34	25,2	0,617
960	11,17	41,67	955,75	59,65	28,9	0,627
990	11,67	43,67	985,16	64,02	32,92	0,638
1020	12,17	45,67	1014,51	68,42	37,28	0,648
1050	12,67	47,67	1043,81	72,85	41,97	0,659
1080	13,17	49,67	1073,05	77,27	47,01	0,671
1110	13,67	51,67	1102,23	81,69	52,39	0,682
1140	14,17	53,67	1131,35	86,06	58,13	0,694
1170	14,67	55,67	1160,41	90,38	64,22	0,706
1200	15,17	57,67	1189,4	94,62	70,67	0,718
1230	15,67	59,67	1218,32	98,77	77,48	0,73
1260	16,17	61,67	1247,17	102,8	84,66	0,742
1290	16,67	63,67	1275,94	106,69	92,19	0,755

1320	17,17	65,67	1304,64	110,42	100,08	0,767
1350	17,67	67,67	1333,27	113,98	108,32	0,78
1380	18,17	69,67	1361,81	117,34	116,92	0,793
1410	18,67	71,67	1390,28	120,47	125,86	0,806
1440	19,17	73,67	1418,66	123,37	135,14	0,819
1470	19,67	75,67	1446,95	126,01	144,76	0,832
1500	20,17	77,67	1475,16	128,36	154,71	0,845
1530	20,67	79,67	1503,27	130,42	164,97	0,858
1560	21,17	81,67	1531,3	132,16	175,53	0,872
1590	21,67	83,67	1559,22	133,55	186,4	0,885
1620	22,17	85,67	1587,06	134,59	197,55	0,898
1650	22,67	87,67	1614,79	135,26	208,97	0,912
1680	23,17	89,67	1642,42	135,53	220,64	0,925
1710	23,67	91,67	1669,95	135,39	232,57	0,939
1740	24,17	93,67	1697,37	134,82	244,71	0,953
1770	24,67	95,67	1724,69	133,82	257,07	0,966
1800	25,17	97,67	1751,9	132,35	269,63	0,98
1830	25,67	99,67	1778,99	130,41	282,35	0,993
1860	26,17	101,67	1805,98	127,98	295,24	1,007
1890	26,67	103,67	1832,85	125,05	308,26	1,021
1920	27,17	105,67	1859,6	121,61	321,4	1,034
1950	27,67	107,67	1886,23	117,65	334,63	1,048
1980	28,17	109,67	1912,73	113,16	347,93	1,061
2010	28,67	111,67	1939,12	108,12	361,29	1,075
2040	29,17	113,67	1965,38	102,53	374,68	1,089
2070	29,67	115,67	1991,51	96,38	388,07	1,102
2100	30,17	117,67	2017,51	89,66	401,44	1,116
2130	30,67	119,67	2043,39	82,38	414,76	1,129
2160	31,17	121,67	2069,12	74,52	428,02	1,143
2190	31,67	123,67	2094,72	66,08	441,18	1,156
2220	32,17	125,67	2120,19	57,06	454,23	1,17
2250	32,67	127,67	2145,51	47,45	467,12	1,183
2280	33,17	129,67	2170,7	37,27	479,85	1,196
2310	33,67	131,67	2195,74	26,5	492,38	1,21
2340	34,17	133,67	2220,63	15,16	504,69	1,223
2370	34,67	135,67	2245,38	3,24	516,75	1,236
2400	35,17	137,67	2269,98	-9,25	528,53	1,249
2430	35,67	139,67	2294,43	-22,31	540,01	1,262
2460	36,17	141,67	2318,73	-35,92	551,17	1,275
2490	36,67	143,67	2342,87	-50,08	561,97	1,288
2520	37,17	145,67	2366,85	-64,78	572,39	1,301
2550	37,67	147,67	2390,68	-80,01	582,4	1,314
2580	38,17	149,67	2414,35	-95,75	591,99	1,327
2585,02	38,25	150	2418,29	-98,44	593,55	1,334
2610	38,25	150	2437,91	-111,83	601,28	0
2640	38,25	150	2461,47	-127,91	610,57	0
2670	38,25	150	2485,03	-144	619,85	0
2700	38,25	150	2508,59	-160,08	629,14	0
2730	38,25	150	2532,15	-176,17	638,43	0
2760	38,25	150	2555,71	-192,25	647,71	0
2790	38,25	150	2579,27	-208,34	657	0
2820	38,25	150	2602,83	-224,42	666,29	0

2850	38,25	150	2626,39	-240,51	675,57	0
2880	38,25	150	2649,95	-256,59	684,86	0
2885,02	38,25	150	2653,89	-259,28	686,41	0
2910	38,26	148,66	2673,5	-272,58	694,3	1
2940	38,29	147,04	2697,06	-288,31	704,19	1
2970	38,34	145,43	2720,6	-303,78	714,53	1
3000	38,41	143,82	2744,12	-318,96	725,31	1
3030	38,51	142,22	2767,61	-333,87	736,53	1
3060	38,62	140,63	2791,07	-348,49	748,19	1
3090	38,76	139,05	2814,48	-362,82	760,29	1
3120	38,92	137,47	2837,85	-376,86	772,81	1
3150	39,1	135,91	2861,16	-390,6	785,77	1
3180	39,31	134,36	2884,41	-404,04	799,14	1
3210	39,53	132,82	2907,58	-417,17	812,94	1
3240	39,77	131,3	2930,68	-429,99	827,15	1
3270	40,03	129,8	2953,7	-442,5	841,77	1
3300	40,31	128,31	2976,62	-454,69	856,8	1
3330	40,61	126,84	2999,45	-466,56	872,23	1
3360	40,93	125,39	3022,17	-478,11	888,05	1
3390	41,26	123,96	3044,78	-489,33	904,27	1
3420	41,62	122,54	3067,27	-500,21	920,87	1
3450	41,99	121,15	3089,63	-510,76	937,86	1
3480	42,38	119,78	3111,86	-520,97	955,22	1
3510	42,78	118,42	3133,95	-530,84	972,96	1
3540	43,2	117,09	3155,9	-540,37	991,06	1
3570	43,63	115,78	3177,69	-549,55	1009,52	1
3600	44,08	114,49	3199,32	-558,37	1028,34	1
3630	44,54	113,22	3220,79	-566,85	1047,51	1
3660	45,02	111,98	3242,08	-574,97	1067,02	1
3685,02	45,43	110,95	3259,7	-581,47	1083,54	1
3690	45,53	111,56	3263,2	-582,75	1086,85	2,671
3720	46,11	115,21	3284,1	-591,29	1106,6	2,686
3750	46,7	118,87	3304,79	-601,17	1125,95	2,711
3780	47,29	122,52	3325,25	-612,37	1144,81	2,736
3810	47,88	126,18	3345,48	-624,86	1163,09	2,761
3840	48,47	129,83	3365,49	-638,63	1180,7	2,786
3870	49,05	133,48	3385,27	-653,62	1197,55	2,81
3900	49,64	137,14	3404,81	-669,8	1213,55	2,834
3930	50,23	140,79	3424,12	-687,11	1228,62	2,858
3960	50,82	144,45	3443,2	-705,51	1242,68	2,881
3990	51,4	148,1	3462,03	-724,93	1255,64	2,904
4020	51,99	151,76	3480,63	-745,3	1267,43	2,927
4050	52,58	155,41	3498,98	-766,55	1277,99	2,95
4080	53,17	159,07	3517,09	-788,6	1287,24	2,972
4110	53,75	162,72	3534,95	-811,38	1295,12	2,994
4140	54,34	166,38	3552,56	-834,78	1301,59	3,016
4170	54,93	170,03	3569,92	-858,72	1306,59	3,037
4200	55,52	173,69	3587,04	-883,11	1310,08	3,059
4230	56,1	177,34	3603,89	-907,85	1312,02	3,079
4260	56,69	180,99	3620,5	-932,83	1312,38	3,1
4290	57,28	184,65	3636,84	-957,95	1311,14	3,12
4320	57,87	188,3	3652,93	-983,1	1308,29	3,14

4350	58,45	191,96	3668,76	-1008,19	1303,8	3,16
4380	59,04	195,61	3684,32	-1033,09	1297,69	3,179
4410	59,63	199,27	3699,62	-1057,71	1289,96	3,198
4440	60,22	202,92	3714,66	-1081,92	1280,62	3,216
4470	60,8	206,58	3729,42	-1105,63	1269,69	3,235
4500	61,39	210,23	3743,92	-1128,73	1257,19	3,253
4530	61,98	213,89	3758,15	-1151,11	1243,18	3,27
4560	62,57	217,54	3772,11	-1172,67	1227,68	3,288
4590	63,15	221,19	3785,79	-1193,3	1210,75	3,305
4620	63,74	224,85	3799,2	-1212,92	1192,44	3,321
4650	64,33	228,5	3812,34	-1231,42	1172,82	3,338
4680	64,92	232,16	3825,19	-1248,72	1151,96	3,354
4710	65,51	235,81	3837,77	-1264,73	1129,93	3,369
4740	66,09	239,47	3850,07	-1279,37	1106,82	3,385
4770	66,68	243,12	3862,09	-1292,57	1082,72	3,4
4800	67,27	246,78	3873,82	-1304,26	1057,71	3,414
4830	67,86	250,43	3885,27	-1314,37	1031,89	3,429
4860	68,44	254,09	3896,44	-1322,85	1005,38	3,442
4890	69,03	257,74	3907,32	-1329,66	978,27	3,456
4920	69,62	261,4	3917,91	-1334,74	950,67	3,469
4950	70,21	265,05	3928,21	-1338,06	922,69	3,482
4980	70,79	268,7	3938,23	-1339,6	894,46	3,495
5010	71,38	272,36	3947,95	-1339,34	866,09	3,507
5040	71,97	276,01	3957,39	-1337,26	837,69	3,519
5070	72,56	279,67	3966,52	-1333,36	809,39	3,53
5100	73,14	283,32	3975,37	-1327,65	781,3	3,541
5130	73,73	286,98	3983,92	-1320,13	753,55	3,552
5160	74,32	290,63	3992,18	-1310,84	726,25	3,562
5189,46	74,9	294,22	4000	-1300	700	3,572

Table C-1: Detailed Well Plan

C-2 Schlumberger Survey Run

Run #	MD	INC	AZ	Gx	Gy	Gz	Bx	By	Bz	QC	AZM_UNC	dG	dB	dDip	dAz
	Ft	DD.dd	DD.dd												
		64,05999	0,00001	mG	mG	mG	nT	nT	nT		deg	mG	nT	deg	deg
1	2500	64,06	109,45	437,64	623,49	-648,38	15896,97	42114,48	-22220,4	Good	0,98	-0,8	22,27	0,12	0,34
1	2525	64,05	109,42	438,14	839,72	324,96	15928,96	36804,78	30281,86	Good	0,99	0,21	74,31	0,14	0,46
1	2550	67,25	109,43	387,19	857,7	-341,75	13305,77	48319,79	-3023,94	Good	0,99	0,05	31,26	-0,03	0,38
1	2575	69,47	109,38	351,21	714,37	607,62	11546,32	25673,61	41575,76	Good	0,99	0,31	31,31	0,03	0,5
1	2600	72,04	109,6	308,75	-635,47	709,5	9370,99	-42584,8	24938,85	Good	1	0,14	53,53	-0,05	0,56
1	2625	75,22	109,66	255,3	-387,77	886,79	6747,81	-32797	37448,52	Good	1	-0,16	56,95	-0,01	0,58
1	2650	77,43	109,37	217,83	72,16	-974,49	4988,35	18540,7	-46407,9	Good	0,99	0,01	44,61	0	0,39
1	2675	79,88	107,54	175,87	-967,55	187,62	3420,84	-49749,7	-5871,41	Good	1	0,01	33,42	-0,01	0,53
1	2700	81,65	105,04	145,4	279,91	950,2	2621,09	-1290,7	50150,16	Good	1,01	0,06	56,99	0,04	0,53
1	2725	79,19	104,55	187,86	-535,59	824,86	4796,41	-38874,4	31465,64	Good	1,01	0,14	64,32	0,01	0,57
1	2750	77,84	103,72	210,84	-796,77	-568,47	6108,01	-29502,5	-40169	Good	0,99	0,1	33,88	-0,05	0,45
1	2775	77,64	103,45	214,33	-205,49	956,2	6363,93	-25152,4	43015,49	Good	1,01	0,11	55,98	0	0,56
1	2800	77,37	103,43	218,83	539,58	814,37	6587,86	13167,03	48006,56	Good	1,01	-0,01	35,35	0,01	0,53
1	2825	76,11	104,23	240,32	-472,67	849,33	7419,6	-36475,4	33705,22	Good	1	0,13	36,84	0,01	0,57
1	2850	76,24	105,67	238,32	641,96	730,97	6939,75	19660,22	45702,99	Good	1	0,48	55,72	0	0,51
1	2875	76,22	106,47	238,32	549,58	-801,7	6747,81	39395,66	-30410,8	Good	0,99	-0,35	45	0,03	0,39
1	2900	76,29	105,36	237,32	413,74	880,29	6971,74	6162,07	49350,31	Good	1,01	0,08	41,61	-0,01	0,54
1	2925	74,37	104,23	269,79	344,33	900,77	8859,15	2323,73	49382,3	Good	1,01	0,24	46,26	0,04	0,55
1	2950	71,65	105,08	315,25	395,26	-864,12	10842,54	33382,27	-35881,8	Good	0,98	0,03	15,83	-0,01	0,39
1	2975	70,59	109,26	332,73	280,41	-901,58	10650,6	28264,49	-40105	Good	0,98	-0,04	28,67	-0,01	0,35
1	3000	71,01	109,53	325,74	-35,71	-946,03	10234,73	13294,98	-47335,7	Good	0,98	0,04	43,04	-0,03	0,37
1	3025	72,34	109,73	303,75	-188,51	-935,04	9115,07	5426,39	-49095,4	Good	0,99	-0,08	50,12	0,01	0,37
1	3050	70,59	108,16	332,73	-193,51	924,24	10970,5	-24352,7	42567,57	Good	1	0,05	75,2	0,09	0,58
1	3075	68,58	106,88	365,7	817,24	448,31	12889,9	33062,41	35528,88	Good	0,99	0,17	37,07	0,05	0,49
1	3100	66,63	106,15	397,17	386,78	833,84	14617,37	5266,46	47718,61	Good	1	0,19	6,15	0,04	0,56
1	3125	62,07	106,51	469,11	305,37	830,36	18136,28	948,33	46854,77	Good	1	0,27	73,1	0,06	0,57
1	3150	58,64	107,01	521,07	-813,75	262,03	20599,51	-45751,4	-1296,26	Good	0,98	0,05	13,56	0,01	0,47
1	3175	53,92	107,38	589,51	-674,92	-446,12	24022,45	-26143,9	-35497,9	Good	0,97	-0,1	28,2	0,06	0,32
1	3200	53,68	107,33	593	662,44	-460,11	24214,39	42594,27	-11054,4	Good	0,98	-0,04	49,38	0,04	0,32
1	3225	53,58	107,38	594,5	-770,3	236,06	24278,37	-43896,2	-2448,04	Good	0,98	0,13	44,41	0,05	0,45
1	3250	51,41	107,76	624,48	176,53	-762,24	25717,93	23914,37	-35881,8	Good	0,97	-0,06	29,5	0,01	0,25
1	3275	46,51	108,07	688,91	296,39	-662,86	29012,91	29384	-28555,2	Good	0,97	-0,21	27,04	0,01	0,22
1	3300	42,78	107,85	734,88	-611,5	-297,3	31476,14	-25792,1	-29387	Good	0,96	0,05	17,18	0,06	0,25
1	3325	39,86	108,16	768,35	634,47	-95,55	33267,59	36388,96	9837,67	Good	0,96	-0,11	97,73	0,06	0,3
1	3350	35,77	108,51	812,31	-296,38	-504,55	35442,91	-3177,88	-35273,9	Good	0,97	0	-72,82	-0,02	0,12
1	3375	35,13	108,01	818,8	-478,66	-320,77	35954,76	-17795,5	-30154,9	Good	0,96	0,09	8,88	0,04	0,16

Table C-2: Detailed Well Plan (Schlumberger)

Appendix D Signal Techniques and Measurement Sensors

D-1 Signal Techniques

Information is found in: (TPG4215(1), Fall 2013).

The need for live data from drilling process while drilling is something that the industry has wanted and tried to get for some time. The most direct approach would be to have electric conductors hardwire build in or welded in to drill pipe. But practically that is not easy. This would mean that each drill pipe would have to be made with a conductor inside. This is not only costly since all existing drill pipes are not equipped with such conductors, also the possibility of bad connections between pipe may result in bad stable signals.

Electromagnetic methods

Several companies have tested sending electromagnetic signal through the earth's crust. This can be done by mounting a transmitter to the BHA which sends signals in the form of a binary code, and is received by an antenna at the surface. There are several benefits by applying this method, such as ; no disruption to drilling process, transmitting signal while tripping and simpler rig up at surface.

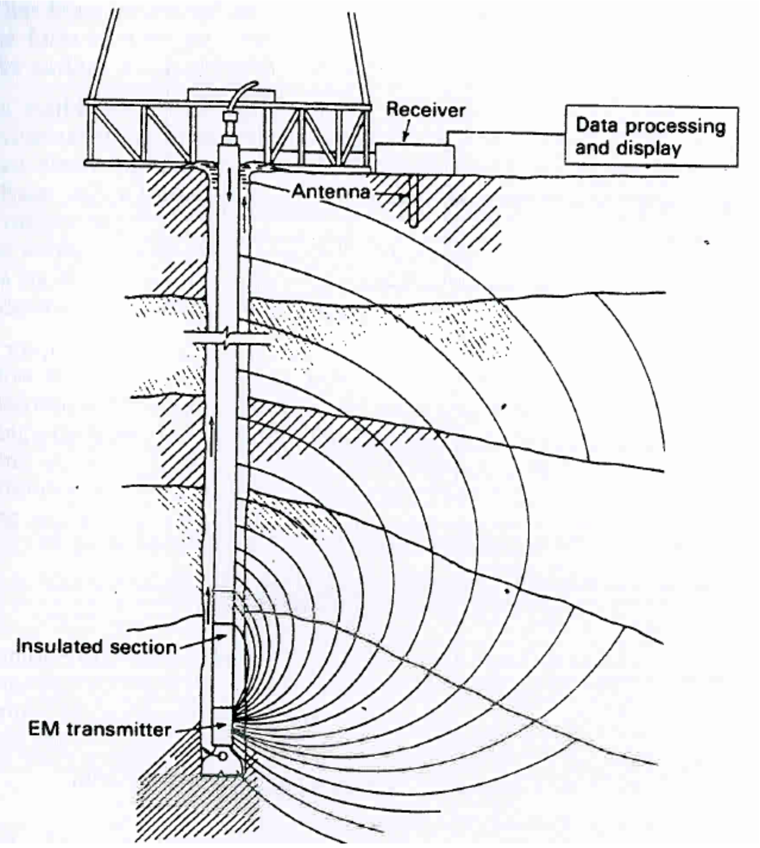

Figure D-1: Electro Magnetic Signal Technique (TPG4215(1), Fall 2013)

The downside from this approach is that only low frequency signals can be transmitted effectively. There is a strong possibility for attenuation of signals from electrical equipment on the rig and the transmitted signals. This method is therefore not commonly used.

Mud pulse telemetry

Although several companies are conducting research on the mentioned methods, the industry standard and the method used by most commercial tools is based on some sort of mud pulse telemetry.

Mud pulse telemetry is based on sending sound waves through the mud which are later picked up and interpreted on the surface. From the figure D-2 you can see the major components of a mud telemetry system.

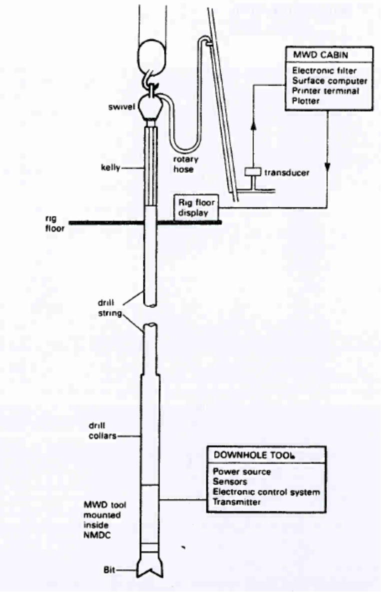

Figure D-2: Typical BHA Setup (TPG4215(1), Fall 2013)

To conduct measurements in this way would need a downhole power source to power the sensors and the transmitting device. This power source can be batteries or in most cases is made by a motor that uses the flow of mud to make electricity. The tool takes measurements when wanted and is activated by some physical change. This can be when drill string motion stops or when mud pumps are shut down. The tool then powers up the sensor which store the measurements and then activate the transmitter so that the information can be sent to the surface. The data is transmitted in the form of a coded message, binary code.

The signals are made by pressure variations in the mud. There are three different methods used in inducing these pressure differences. The first one is positive pulse system.

The positive mud pulse system uses a restrictor valve inside the drill pipe. When operated this valve acts as a temporary constriction of the mud flow which then creates a higher stand pipe pressure. This valve is controlled by a hydraulic actuator which is operated many times to make varying pressure signals in the mud that is picked up at the surface by a pressure transducer and decoded by a computer. Figure D-3 shows how a positive mud pulse system works.

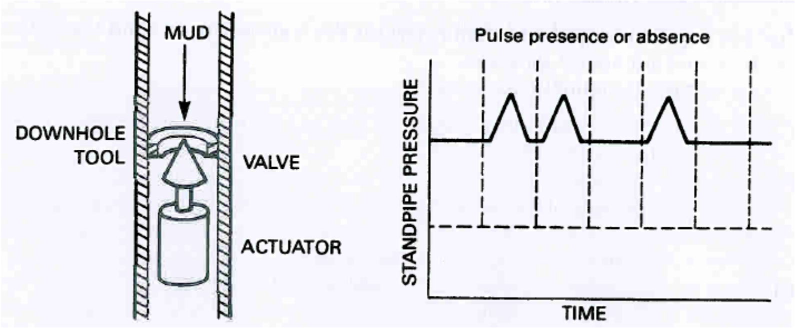

Figure D-3: Positive Mud Pulse System (TPG4215(1), Fall 2013)

Negative pressure works in a similar way. Rather than increasing standpipe pressure by using a restrictor valve, this method uses a valve that lets a small volume of mud to escape in to the annulus. When this valve is operated several times there will be a decrease in standpipe pressure and the pressure differences will be detected by the surface transducer. This is illustrated in figure D-4.

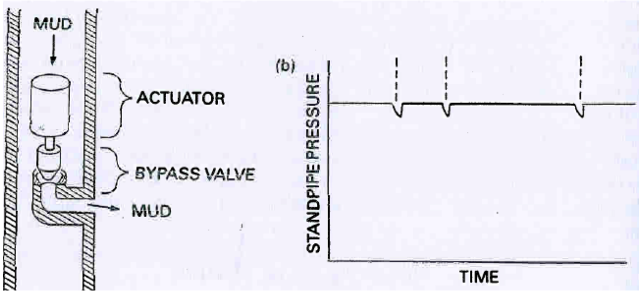

Figure D-4: Negative Mud Pulse System

Continuous wave system

This system does not use pressure pulses to transmit information. This method uses two slotted disks which are mounted in right angel to the mud flow. One of the slotted disks is stationary while the other is rotated by a motor. This creates a standing wave which acts as a carrier to transmit information. When information is sent, the speed of the rotating disk is slowed down, altering the phase of the carrier wave. This is detected on the surface and interpreted. This method allows more information to be sent, and is the most advanced method used. The downside of this method is that the complexity of the down hole equipment and surface components have limited this method. This is illustrated in figure D-5.

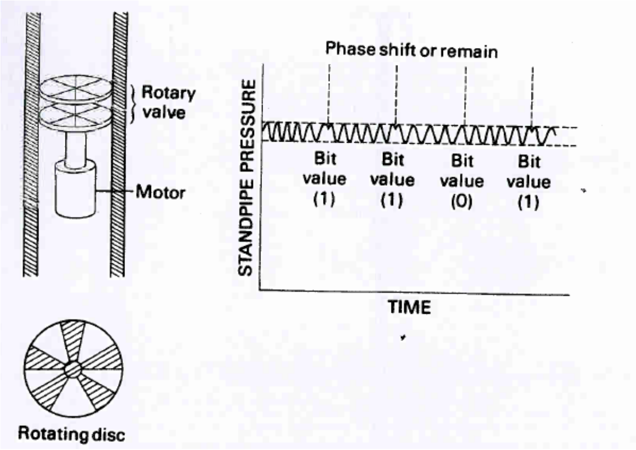

Figure D-5: Continuous Mud Pulse System (TPG4215(1), Fall 2013)

There are obvious upsides by using mud telemetry to transmit information to the surface. The method is fairly simple and normal equipment such as standard drill pipes can be used. The mud pulses travel at around 4000-5000 ft/s (TPG4215(1), Fall 2013) in the mud, but the amount of information that can be sent is a limiting factor. As tools get more sophisticated more information and higher transfer rates are need. This is why companies are researching the possibility of improving the data rates.

D-2 Measurement Sensors

Information is found in: (TPG4215(1), Fall 2013)

Survey tools can be categorized in to two groups:

- Magnetic survey instruments
- Gyroscopic survey instruments

The magnetic survey tools use the earth's magnetic field to determine the hole path direction. An important thing to know is that the earth's magnetic field varies based on where in the world the field is located. The magnetic field for drilling location must be determined before drilling starts such as: Magnetic north, vertical and horizontal components, local magnetic field., total field strength, the declination from true and magnetic north and dip angel of local magnetic field.

The magnetic survey tools use magnetometers and accelerometers to measure the earth's magnetic and gravitational force. By measuring the direction of the fields with respect to the orientation of the tool, you can find the inclination and azimuth.

Accelerometers

The accelerometers work by measuring the gravitational force of the earth. The accelerometers measure the gravitational force in a certain direction by measuring the electric current necessary to keep a proof mas in a constant position will tilted. When drill string gets tilted the mass will slide to the lower side due to the gravitational force. An electrical current is set up to oppose this force and the amount of current will determine the amount of gravitational force. This is done for three axes in a triaxial accelerometer. The vector sum of the three components should sum up to g (Graviational acceleration).This way you can measure the inclination dependent on how much the gravitational force is pulling in each direction. Figure D-6 shows an example of an accelerometer.

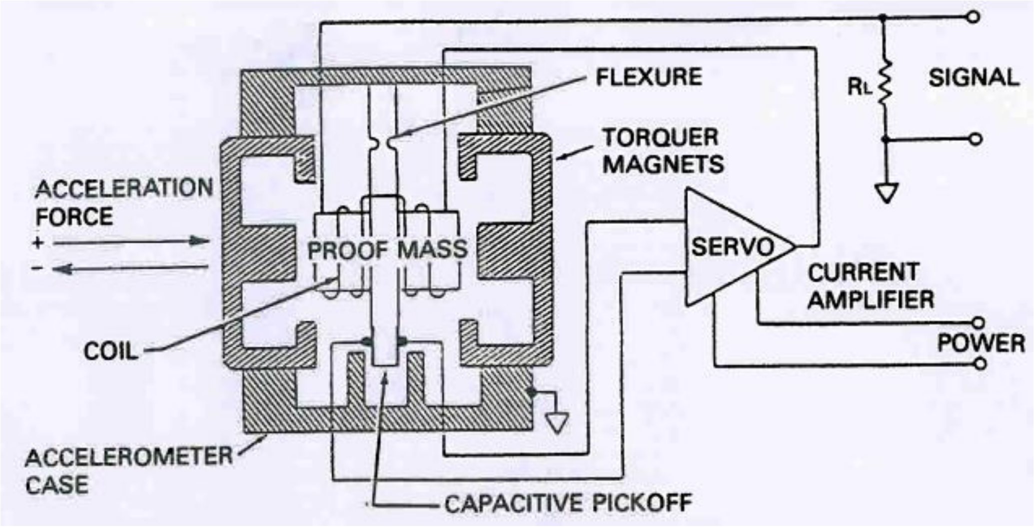

Figure D-6: Magnetometer (TPG4215(1), Fall 2013)

Magnetometers

A magnetometer measures the strength of the earth’s magnetic field along a fixed axis. The same principal of measuring the forces in three directions as the accelerometer applies to this tool. The magnetic field along the axis is calculated by measuring the generated current in a coil wrapped around an iron core. As the coil is positioned within a magnetic field, a current will be generated in the coil wire. Figure D-7 shows the coil positioned to the field lines of the magnetic field of the earth. The figure shows how by limiting the surface in contact with the filed lines, the current will decrease and thereby will indicate the inclination in one direction.

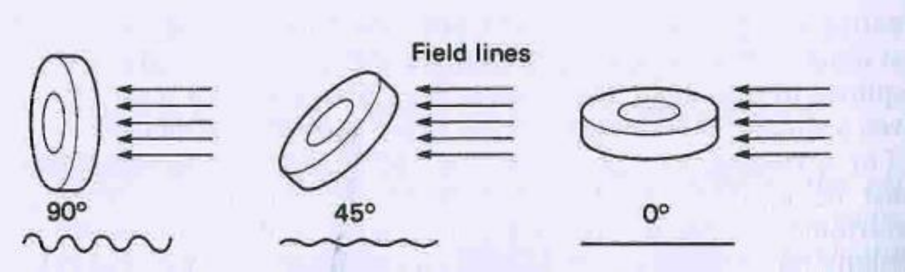

Figure D-7: Magnetometer, Magnetic Field Lines (TPG4215(1), Fall 2013)

A magnetometer will be used to measure the magnet field in each direction, which can be used to calculate the azimuth direction of the wellbore.