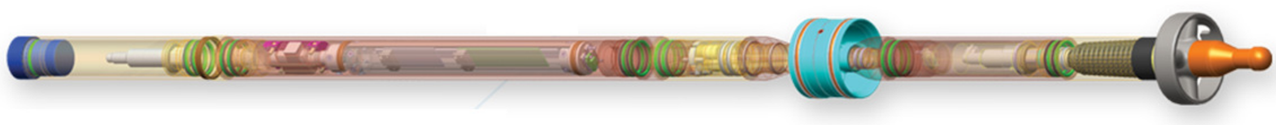

OPERATIONS MANUAL

CHAPTER 3 EM THEORY

REV A: 2013 July9

XFLD-0003

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1. BASIC CONCEPTS

1.1. BASIC ELECTRICITY

OHM'S LAW

Ohm's Law (Equation1) states that the voltage between the two points is proportional to the current flowing through the two points. In Figure 1 below, if a voltage (V) is applied across Resistance (R), a current of magnitude (I) will flow across these 2 points:

$$V = I * R$$

Where V= voltage (volts), I= current (Amps) and R= Resistance (Ohms)

Equation 1 Ohms Law

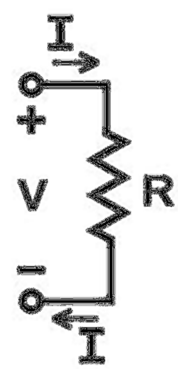


Figure 1: Electric Circuit

V (voltage) is also referred to as the potential difference between the two points. The Resistance (R) quantifies the opposition to the flow of the current ((I). For a given voltage or potential difference, if you increase the current, the resistance will decrease. An analogy for this in nature is a waterfall, where:

- The height of the waterfall represents the potential difference,
- The amount of the water moving represents the current, and
- The profile of the rock bed beneath the water fall which opposes the water from flowing across represents the resistance.

RESISTIVITY

The electrical resistance of a wire increases if the length of wire is longer, and decreases if the wire is thicker (cross sectional area is increased), depending ultimately on the properties that make up the wire. The resistance is expressed as:

$$R = \frac{\varrho * L}{A}$$

Where L =Length, A= Cross sectional area, ϱ *= Resistivity*

Equation 2: Resistivity

The Resistivity (ϱ) takes into consideration the material properties. It can be thought to be a value of resistance per unit length and used to calculate the resistance if the geometry is known. The resistivity varies according to temperature. The opposite of Resistivity is conductivity, which shows how easy it is for current to flow through. The Unit of Resistivity is Ohm.m (Ohm-meters).

POWER

The Power in an electric circuit is the product of the voltage (V) and the current (I). This represents the energy transferred across in a unit time. The unit of Power is Watts.

$$P = I * V$$

Where P = Power (Watts), I = current (Amps), V = voltage (Volts).

Equation 3: Power

1.2. ELECTROMAGNETIC WAVES

Electromagnetic (EM) waves are emitted by various energy sources around us. Some examples include: cell phones, radio, TV, air force communication. EM waves are also used in the oilfield by EM-MWDs to send information acquired while drilling to the surface.

Electrical fields are produced by charge distribution which exists between two points and cause current to flow which in turn produce magnetic fields. Magnetic fields are also produced by variation in the electrical fields and generally do not have a start or end point.

Typically, electric fields are generated by energy devices; in turn, these also generate a magnetic field. These two fields vary in time and oscillate to create an EM wave.

FREQUENCY

Frequency is an important aspect of EM wave theory. It is measured in Hertz as the number of oscillations per second. EM waves that travel through the formation with a lower frequency are able to travel further than those with higher frequencies; however EM Waves with higher frequency can carry more information at a given time. An EM-MWD has to send a lot of information to surface; as such, it is advisable to send the highest frequency that can be sent and received on surface.

In most cases, an EM-MWD tool is run with the highest frequency in shallow zones close to the surface. The frequency is decreased as drilling progresses and the tool gets deeper.

AMPLITUDE

The **amplitude,** or height of an EM wave, represents the strength or power of the EM Wave. This could either be the current or the voltage. EM waves with higher amplitude will travel further into the formation and have a higher probability of being detected on surface.

The amplitude of an EM wave in millivolts (viewed on surface via surface equipment) gives us an idea of the strength of the signal. The EM wave shown in Figure 2 below oscillates over a period of 1 second, the amplitude increases from 0 to 1mV, decreases to 0, decreases to -1mv and then increases to 0. This represents 1 cycle in 1 second, or a frequency of 1 Hz.

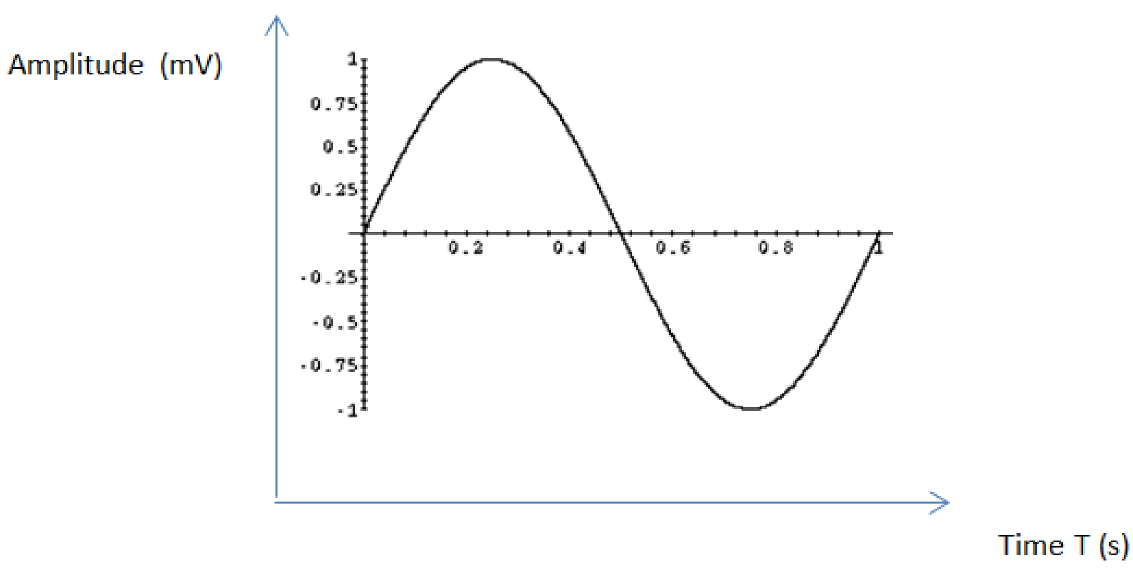


Figure 2: 1x EM Wave cycle with 1Hz Frequency

The EM Wave shown in the Figure 3 completes 1 x cycle in 2 seconds; hence the frequency is 1/2 or 0.5 Hz. In other words, this is half as fast as the Wave in Figure 2.

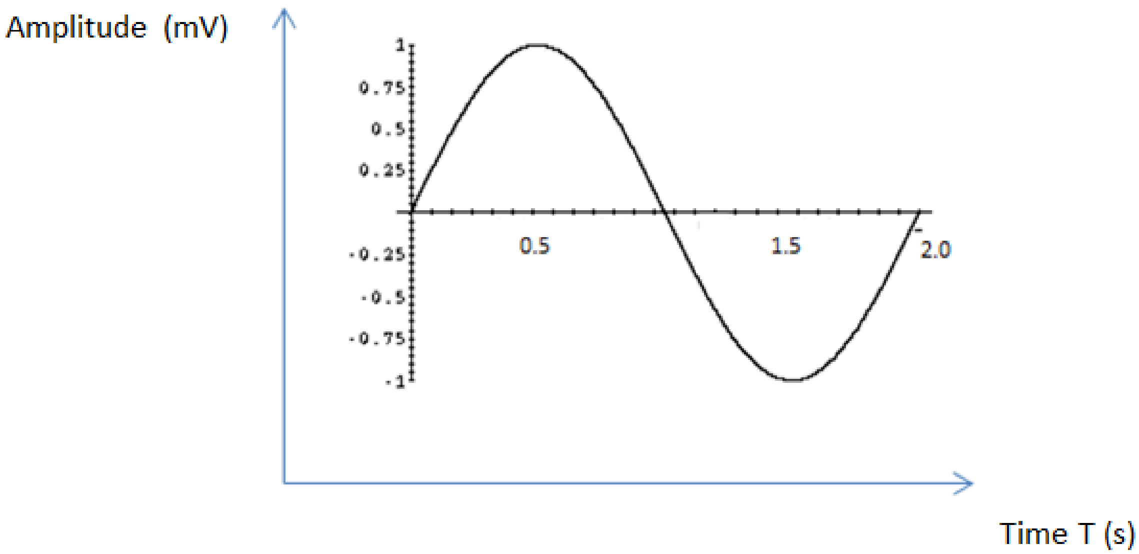


Figure 3: EM Wave cycle with 2Hz Frequency

PHASE SHIFT KEYING

In order to send information to the surface, the EM-MWD transmits EM wave signals using a technique known as Phase Shift Keying, or PSK. The information that the EM-MWD has to send up-hole is converted into binary 1’s and 0’s. This information is then encoded into symbols.

The EM wave has a 0 to 360° form as shown in Figure 4. The phase of the wave can be shifted by 90°, 180°, or 270°, depending on the symbol that needs to be transmitted.

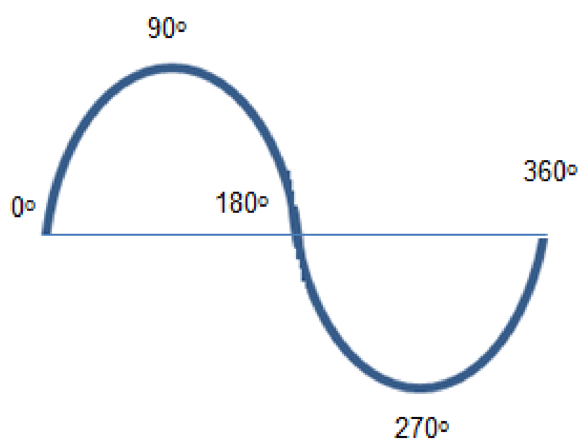


Figure 4: EM Wave 1 cycle 360°

BINARY PHASE SHIFT KEYING

The simplest form of phase shift keying is Binary Phase Shift Keying (BPSK). Here the tool uses a normal EM wave to send a 1 and an EM wave phase shifted by 180° to send a 0. Examples of how bits are transmitted using BPSK are illustrated in Figure 5.

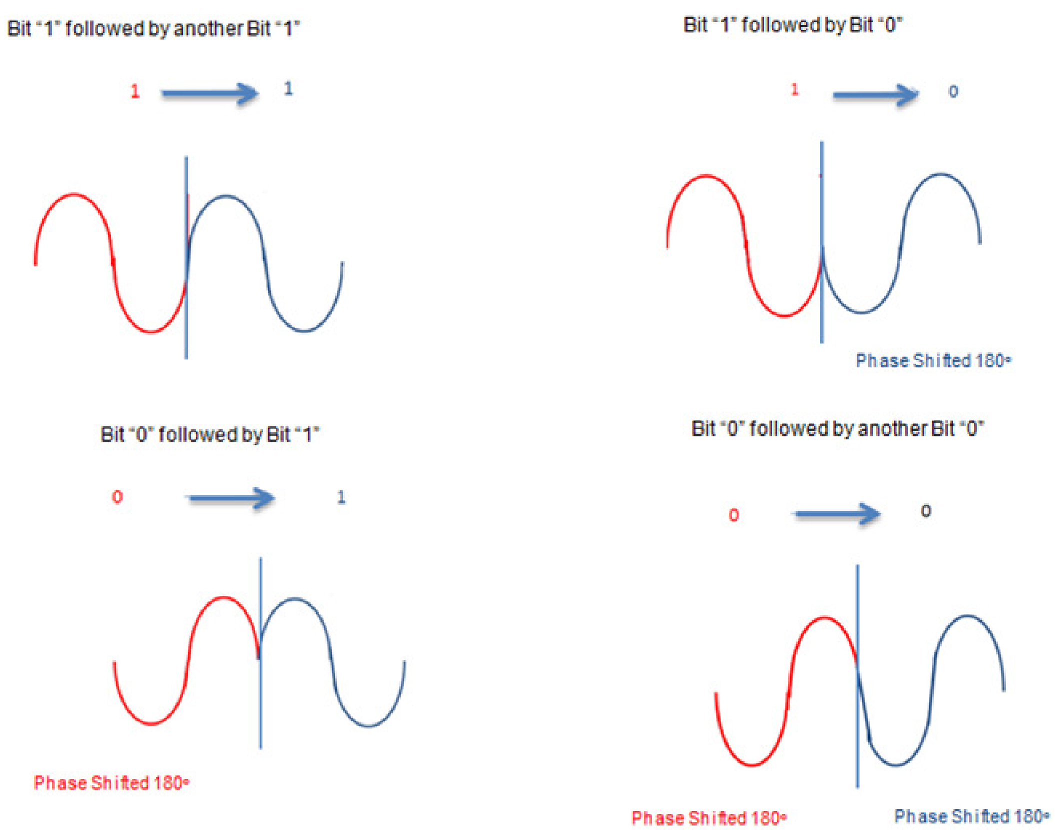


Figure 5: BPSK Transmission

BPSK is widely employed in the MWD industry to send information up-hole; however, this technique has data rate limitations. In order to send data at double the rate, the Quadrature Phase Shift Keying (QPSK) technique described below is utilized.

QUADRATURE PHASE SHIFT KEYING

With Quadrature Phase Shift Keying (QPSK), the EM-MWD can shift the phase of the wave by 0, 90˚, 180˚ & 270°. Each phase shift corresponds to a 2 bit symbol. This is different from BPSK described above, where a phase shift corresponds to a 1 bit symbol.

PHASE SHIFT (°)	SYMBOL
0	00
90	01
180	11
270	10

Table 1: Phase shifts and corresponding Symbols

Examples of how the different symbols in the EM wave are transmitted using QPSK are provided below in Figure 6. QPSK is typically able to provide data twice as fast as BPSK. Currently, QPSK transmission is available for 0.5, 1, 2, 4, 8, 10, 12 Hz.

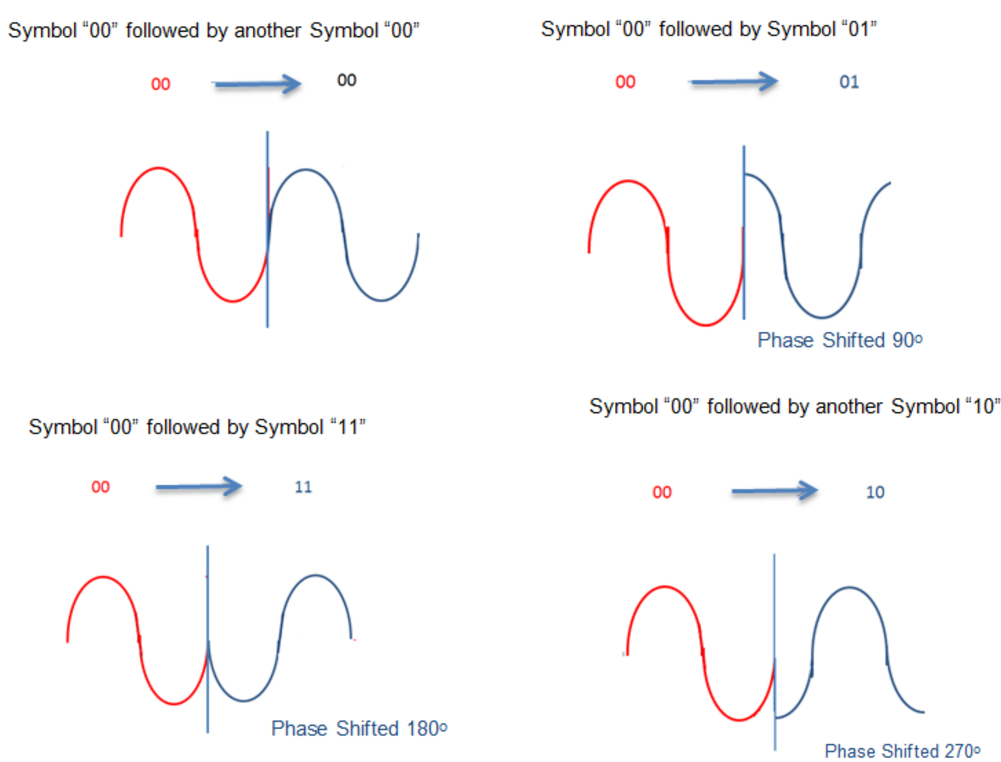


Figure 6: QPSK Phase Shift Schematic

2. XEM THEORY OF OPERATION

2.1. PRINCIPLE OF OPERATION

The XEM-MWD system sends down-hole information by injecting Electromagnetic (EM) signals into the earth's formations and receiving them on surface. The drill string is broken into two sections, separated electrically by an isolation gap. The isolation gap in the drill string is accomplished by the use of a Gap Sub. A voltage is applied between the two half's of the Gap sub allowing an electrical signal current with a low but non zero frequency to be transmitted from the upper half of the Gap Sub through the formation to the lower half of the Gap sub.

There is a tiny bit of current that will eventually find its way from the Upper Gap sub via the drill string all the way to the surface and return via the formation through the Drill bit to the Lower Gap Sub. A small voltage will develop as a result of this current flowing between the two references points on surface as illustrated in Figure 7. This voltage is proportional to the signal current generated down hole. The two reference points are usually the BOP (Blow Out Preventer) and an antenna driven into the ground at a considerable distance away from the BOP.

It is possible to detect a signal as small as 0.1mV provided the electrical noise from the rig and other sources is low. The signal needs to be higher than noise so that it is not masked by the noise and can be decoded. The received signal is fed to the surface receiver where it is amplified and decoded to provide the down-hole information.

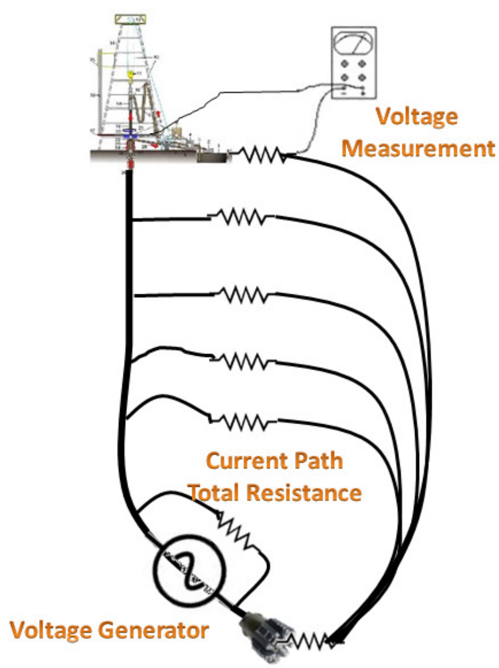


Figure 7: XEM Well Site Schematic

EM propagation in the region near the Gap sub is influenced by the current and voltage on the Gap Sub and as such the current signal is attenuated geometrically after leaving the Gap Sub.

When the EM current signals travel further away from the Gap sub, EM propagation is influenced by changes in the electric and magnetic fields which exist as a result of the injection. In this region also known as the Far field region the EM signal is attenuated exponentially.

EM propagation is described by Maxwell's Equations. Ignoring the geometric affect associated with the near region and assuming homogenous formation and a low transmission frequency Maxwell's equation can be modified to the "Far field Equation" below:

$$i = I * e^{-\left(kd\sqrt{f}\sqrt{1/R}\right)}$$

Where: i =*current returning to the gap sub*

f= frequency of the EM signal

d= Depth of the gap sub

R= Mean resistivity of the formation,

I= Injected current

K= Constant of proportionality

Equation 4: Far Field propagation Equation

Interpretation of this equation shows that the signal on surface will be smaller if the:

- Well gets deeper (distance between the Gap Sub and the receiver on surface is increased)
- Frequency of the EM signal is increased
- Formation mean Conductivity is increased (Resistivity is decreased)

The EM signal received on surface is affected by the following:

- Condition of the Gap Sub and the DPG probe
- Tool configuration
- Environmental effects
- Surface software and hardware configuration

Each of these is briefly described in the following sections.

2.2. GAP SUB AND DPG PROBE

GAP SUB

The Gap Sub as shown in Figure 8 has a lower and an upper half, isolated by the insulation in the center. The upper half also has a key sleeve for locking the XEM tool preventing it from moving and a Scribe mark to align the tool with the high side of the motor.

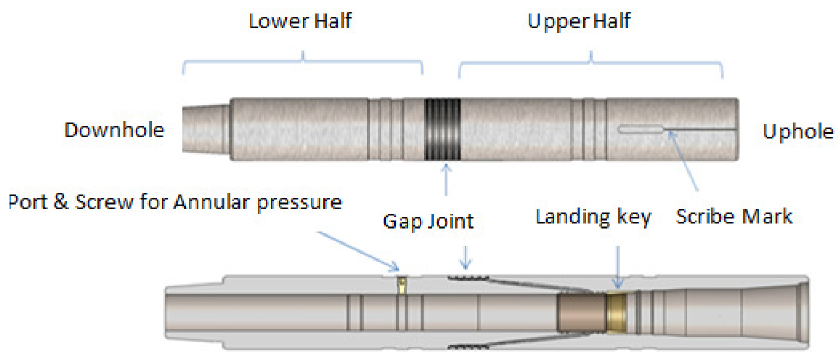


Figure 8: Gap Sub External and Internal View

The DPG (Dual Pressure Gauge probe) of the XEM tool has a Landing Spider, a Grounding Spider and an Insulation Gap between the two Spiders as shown in Figure 9.

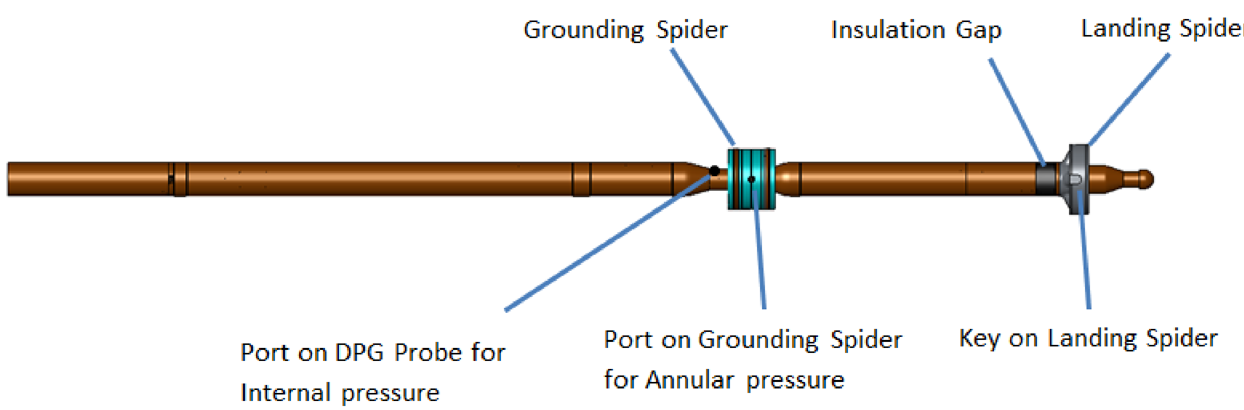


Figure 9: DPG Probe Components

The DPG probe is installed in the Gap Sub prior to drilling activity as illustrated in Figure 10. When the DPG probe is installed in the Gap sub, The Landing spider on the DPG probe has a key that locks into the key sleeve in the Upper Half of the Gap sub. This creates an Electrical connection between the

Landing spider and the Upper half of the Gap sub. A screw driven through a Port on the Lower Gap sub electrically connects the Grounding Spider on the DPG probe with the lower half of the Gap sub.

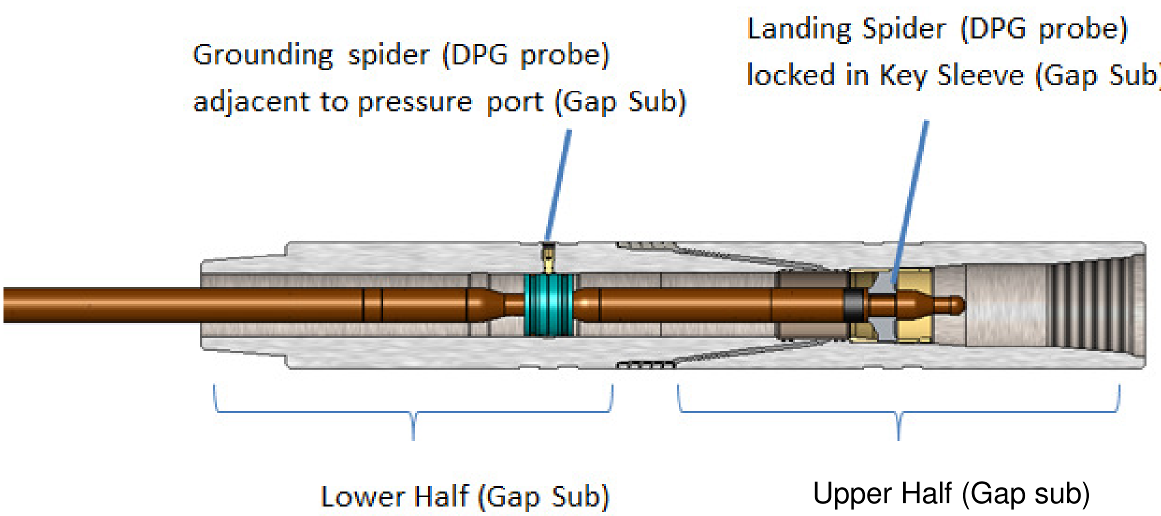


Figure 10: DPG Grounding Spider and Landing Spider Detail

The tool applies a voltage across the Insulation Gap in the DPG Probe. This creates a Potential difference between the Landing spider and the Grounding spider in the DPG probe. This also creates a Potential difference between the Upper and Lower Half of the Gap sub and causes the signal current to be injected.

When high signal current needs to be injected the voltage across the Gap is increased. With a high signal current it will be easier to detect the signal on surface but the tool batteries may deplete quickly shortening the duration of the run. When low signal current needs to be injected the voltage across the Gap is reduced, with a low signal current the batteries last longer but the signal may be too weak on surface to detect. In practice at the start of the run a low signal current is injected but is increased progressively as the tool goes deeper. This is achieved by downlinking or communicating to the tool from surface.

The insulation across the gap is important in both the Gap Sub and the DPG probe and needs to be checked prior to the job. At the end of each run when the tool is on surface the data needs to be dumped and provided to the command center. Based on this data the Command Center will be able to advise if the condition of Gap Sub and DPG probe is ok for the next run.

If the screw that connects the Grounding spider to the Gap sub is ported (has a channel in between) pressure from outside the Gap sub also known as Annular pressure can be routed and measured by the DPG probe. A separate port in the DPG probe allows the String pressure also known as internal pressure to be measured. If a Ported screw is run the condition of the Screw needs to be checked before the run. If the screw in the port is eroded the adjacent areas in the Gap sub will be washed away resulting in damage to the Sub. Alternatively a Non-ported screw can be run; in this condition annular pressure measurement cannot be provided.

2.3. TOOL CONFIGURATION (FREQUENCY, SCALE FACTOR, TARGET CURRENT)

When preparing the XEM for a job the FST loads the configuration files into the tool. Configuration files are defined for every area where XEM services are provided. If XEM Services are to be provided for the first time in a new area, the XEM signal is modeled as a function of Depth, Formation Resistivity and Frequency prior to the job. The Model helps the District Engineers to create tool configuration files that will be used for the job.

Up to 8 different configuration files can be loaded into the tool at one time. During the job the tool can be downlinked to change the tool configuration. Downlinking is communicating from the surface to the tool by turning the Pumps ON and OFF in a predefined sequence.

A typical configuration file has the following description:

09-19-12-DynX_XEM_IDLE_ATF_5-3 deg_Gamma_LITH_BPSK_4Hz-2c-1_1.V9Cfg

A description of each of the term and related theory is given below:

09-19-12: Date the configuration file was created

DynX_XEM: Indicates a DynamX probe is included; allows Shock and Vibration measurements to be provided.

IDLE: Indicates IDLE mode is enabled; the tool will look for user defined values of Inclination and temperature before turning ON.

ATF_5_3 deg Refers to Auto tool face Angle. When building at Inclination = 5°, the tool will switch from magnetic to gravity tool face. When Dropping Angle, at Inclination = 3°, the tool will switch back from gravity to magnetic tool face. These can be changed based on job requirements.

Gamma: A Gamma Ray probe is included in the XEM tool string.

LITH: Lithium Batteries are normally used to provide Power to the XEM tool; 1 x Lithium Battery Pack can provide up to 50 Amp Hour capacity.

Alkaline batteries are available for air drilling or harsh drilling conditions; these are more resistant to shock and vibration than Lithium batteries, but have a less capacity of 20Amp Hours.

2 or 3 battery packs can be included in the tool string to increase capacity. This makes the tool longer but can be run for longer duration and support higher target currents.

BPSK: BPSK is the telemetry in the tool. XEM can also be configured for QPSK. With QPSK the data can be transmitted twice as fast as BPSK.

4 Hz: 4 Hz is the **Frequency** of the EM signal. The XEM can transmit at a Frequency range from 0.5 – 12 Hz. Above 12 Hz, signal attenuation is significant and there may be problems detecting the signal on surface, below 4 Hz, data transmission is slow. At the start of the job the highest frequency that will allow the signal to be detected is chosen. This is reduced as the well gets deeper and the signal strength on surface decreases.If a tool is operating at a frequency f_o, the signal will appear across a range of frequencies. The Band width B for this range, the lowest frequency f_L and the highest f_H are illustrated in Figure 11.

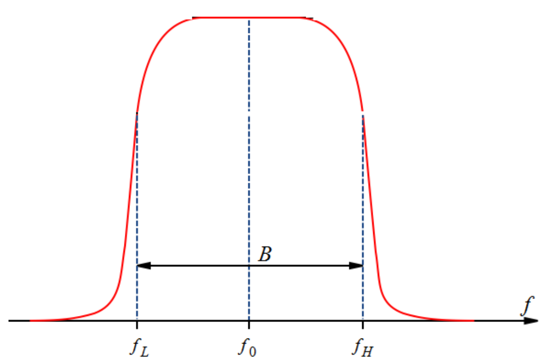


Figure 11 Frequency Band

The Band width depends on the symbol rate chosen to transmit the data

$$Frequency\ Band\ \ Width\ (B) = 1.25 *\ Symbol\ Rate$$

*Where the Symbol Rate = Bit Rate (for BPSK) & Symbol Rate = Bit Rate *2 (for QPSK)*

Equation 5: Frequency Band Width

The Highest and Lowest frequencies at the end of the range are a function of the Operating frequency and the Band width:

$$High\ Frequency(\ fh) = Operating\ Frequency(fo) + (\frac{Band\ Width\ (B)}{2})$$

$$Low\ Frequency(\ fL)\ = Operating\ \ Frequency\ (fo) - (\frac{Band\ Width(B)}{2})$$

Equation 6: High and Low frequencies

It is important to know the High and Low frequency values to adjust filter settings in order to remove noise. The Band width, High and Low frequencies are calculated for different data rates in Table 2.

2c: 2c refers to 2 sine waves for each bit. The XEM signal contains **Cyclic redundancy** for each bit of information sent up hole (i.e. the sine waves are repeated a number of times to produce each bit).The more the redundancy the greater the chance the signal will be decoded correctly however, greater redundancy slows data speed.

It is common to use a redundancy level of 2 at low frequencies. At 12 Hz and higher it is possible to use a higher redundancy level of 3. It is recommended to avoid using a redundancy of “1” to avoid decoding issues.

Table 2, shows the Bandwidth, Lower/ Upper Frequency limits associated with different Frequencies, Redundancies and data rate.

Operating Frequency Hz	Redundancy Cycles/Symbol	Symbol Rate* (Symbol/second)	Band Width Hz	Lower Band Limit Hz	Upper Band Limit Hz
0.5	1	0.5	0.625	0.1875	0.8125
1	1	1	1.25	0.375	1.625
1	2	0.5	0.625	0.6875	1.3125
2	1	2	2.5	0.75	3.25
2	2	1	1.25	1.375	2.625
2	4	0.5	0.625	1.6875	2.3125
4	1	4	5	1.5	6.5
4	2	2	2.5	2.75	5.25
4	4	1	1.25	3.375	4.625
6	2	3	3.75	4.125	7.875
8	1	8	10	3	13
8	2	4	5	5.5	10.5
8	4	2	2.5	6.75	9.25
8	8	1	1.25	7.375	8.625
10	1	10	12.5	3.75	16.25
10	2	5	6.25	6.875	13.125
10	5	2	2.5	8.75	11.25
10	10	1	1.25	9.375	10.625
12	1	12	15	4.5	19.5
12	2	6	7.5	8.25	15.75
12	3	4	5	9.5	14.5
12	4	3	3.75	10.125	13.875
12	6	2	2.5	10.75	13.25
12	12	1	1.25	11.375	12.625

** Bit rate = Symbol rate (BPSK) *Bit rate = Symbol rate * 2 (QPSK)*

Table 2 XEM Frequencies, Redundancy, Bandwidth, Upper & Lower Frequency Limits

-1 1 Amp is the intended **Target current** that will be injected in the formation. The intended value of the Target current is programmed into the EM-MWD prior to being run in the hole. The target current setting can be changed from 0.2 to 5 Amps. The tool will try to maintain this value of current flowing across the gap sub into the formation by adjusting the gap voltage.

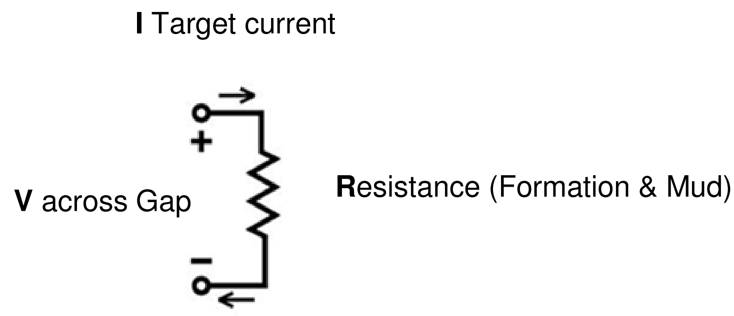


Figure 12: voltage across gap Sub

As a theoretical example:

- If the intended target current is 1 Amp or 1000mA
- The resistance seen in front of the gap sub is 4 Ω (This factor depends on the Formation Resistivity, Mud Resistivity and the contact point, where the string makes contact with the formation.)

From Ohm's law V= I x R

- The tool will adjust the Gap voltage to be 4V
- If the Alkaline batteries used can provide 14Volts, the tool will apply a Scale factor of 4V/14 V or 28 %

As another example

- If the Intended target current is 1 Amp or 1000mA
- The resistance seen in front of the gap sub is 25 Ω
- From 1 amp x 25 Ω = 25 Volt; the tool would need to provide 25 V
- If new batteries are used they will be able to provide a maximum of 14V.
- Due to the design, the tool can only provide a maximum Scale factor of 80%.

- In this case 80% of 14V = 11.2V is the maximum that can be applied across the Gap.
- The actual current (Measured Load) will be 11.2V/25 Ω = 0.448 A.

If the batteries are partially depleted and can only provide 10V , at 80 % scale factor the tool will only be able to provide 80% of 10 V = 8V. With this the actual current or **Measured Load** current would be 8V/ 25 Ω or 0.32 A. Measured Load current is not the same as the current pulled from the battery. (i.e. 1 amp Measured Load is not equal to 1 amp from battery).

The **Scale factor** is analogous to a throttle which delivers anywhere between 0 - 80 % of available engine power to move a vehicle. If the Formation Resistivity is high or if Air /Oil based mud is being used as the drilling fluid, a high scale factor of 80% may be used. This is because it is difficult to push current into the formation in these conditions. The maximum limit is currently set at 80% due to requirements to transfer the voltage from the battery to the Gap Sub.

If the Formation has low Resistivity and Water Based mud is used the Scale factor could be as low as 10%. The voltage across the Gap sub is maintained in order to achieve the intended target current. As discussed in Example-1, this voltage across the gap Sub will depend on:

I. Points where the string makes contact with the Formation
II. Formation Resistivity
III. Mud Resistivity

The target current is optimized to ensure that adequate signal is available on surface to ensure that there will be adequate battery life for the duration of the run. A low value is initially set for drilling close to the surface but increased progressively during the run when the signal level on surface becomes low.

_1 _1 indicates that this is the first configuration loaded in the tool

V9 This is the software Version in use. It is important to ensure that the configuration files in the tool have the same software version as the receiver used on surface to decode the information.

2.4. ENVIRONMENTAL FACTORS (FORMATION RESISTIVITY, DRILLING MUD, CASING)

The formation Resistivity and Mud Resistivity affect signal transmission from the tool to the surface and have to be considered to determine the suitability of EM-MWD for the job. If the signal is low on surface and there are issues decoding, the tool configuration may have to be changed by Downlinking to increase the Target current and reduce the frequency.

FORMATION RESISTIVITY

1. High formation Resistivity - In front of the Gap Sub

If the formation resistivity in front of the Gap Sub is too high it will block the EM signal current from being injected into the formation. The current will flow through the path of lesser resistance which could be the mud if conductive, instead of the formation. The EM signal on surface drops to low level in the high resistivity zone but rises back after drilling the zone.

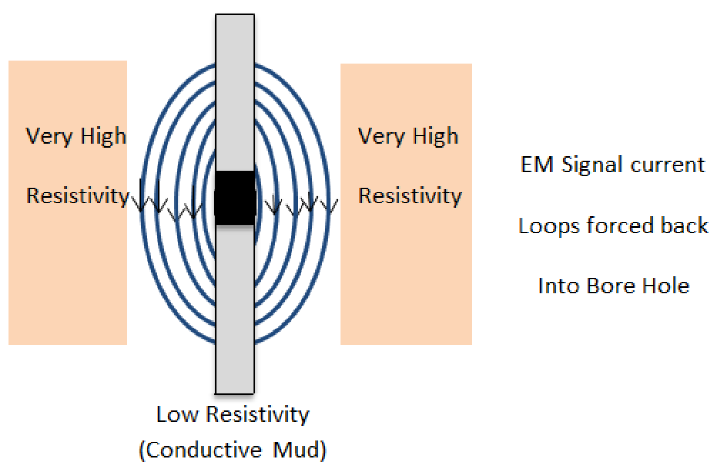


Figure 13: Formation Resistivity

2. Conductive Formation above the tool

Skin effect causes current to flow only at the surface instead of flowing uniformly in a conductor. The more conductive (Less Resistive) the conductor the more the skin effect. Skin affect in conductive formations will cause the EM signal current to travel near the wellbore instead of travelling deeper into the formation which will attenuate the signal. Skin effect increases with

- High Formation Conductivity (Low Resistivity)
- High Frequency; Higher the Frequency the more the skin effect

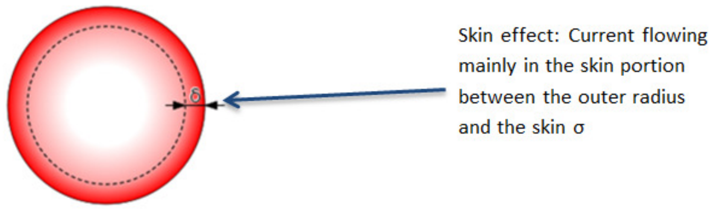


Figure 14 Skin effect

EM signal current experiencing skin effect will get attenuated and be small when reaching the surface. In conductive formations there are limitations as to how deep you can drill when using EM –MWD systems.

DRILLING MUD

1. With Dry Air or OBM

Drilling mud affects Current injection into the formation. Oil based Mud or Dry Air acts as an insulator and creates a high resistance across the Gap sub, making it difficult to push the current from the Gap sub into the formation. Current transfer relies on the drill string making contact with the formation. Even with significant effort (Scale factor as 80 %) only a fraction of the intended Target current is transferred from the Gap Sub, causing a very small current signal to reach the surface.

2. With Mist/ Foam or WBM

With air drilling it is recommended to carry out misting preferably at 10-15 gpm (at least at minimum of 5gpm) to improve the signal quality. The mist creates a channel for the signal into the formation in addition to reducing shock and vibration.

When using Mist, Foam or Water based Mud there is a low Resistance across the gap sub, making it easy to push the current from the Gap sub into the formation through the Mud channel. The Total value of the intended Target current can be transferred with very little effort (Scale factor can be as low as 10%).

If the Mud is very conductive (Low resistivity) a significant portion of the signal will return directly below the Gap Sub instead of going through the formation. It may not be possible to drill deep with High conductivity Mud.

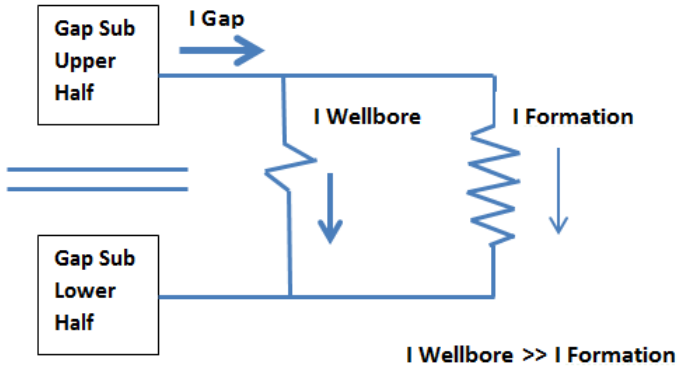


Figure 15 current Transfer Model in High Conductivity Mud

CASING

The XEM signal is attenuated much faster in casing than in Open formation (Casing is Conductive). If the Casing shoe set very deep (Long Casing) the attenuation will be significant and in certain cases it may not be possible to detect the signal. The signal strength improves after the Gap sub exits the Casing shoe.

HORIZONTAL WELLS

The amount of current signal that reaches the surface depends mainly on the Vertical Depth also known as TVD. The deeper the well (More TVD) the more the signal is attenuated before reaching the surface. In case of horizontal Wells where the TVD remains constant but the MD or Measured Depth changes considerably there will be a slight attenuation in the signal in the horizontal section. If the horizontal section is drilled in with Conductive mud and in a Conductive formation such as the case with water injection wells there could be more attenuation on the signal.

While drilling extended horizontal the Top Drive is operated at a higher current setting. This causes noise interference with the EM current signal and affects signal detection on the surface.

SHARP CONTRAST IN FORMATION RESISTIVITY

If there is a sharp Resistivity contrast in formations above the EM tool, the normal pattern of the EM current signals can be disrupted. If there are a number of contrasts this may affect the EM signal transmission to the point that adequate signal strength may not be received on surface.

2.5. SURFACE CONFIGURATION (ANTENNAS, SURFACE NOISE, SIGNAL DETECTION)

This section provides information on antenna configuration, Receiver settings and their effect on the signal quality. A summary is provided on sequence of steps that can be followed through to improve signal quality and maximize the possibility of decoding the signal.

ANTENNA CONFIGURATION

A reference antenna is installed on the BOP; another antenna (Antenna #2) is installed by driving a stake into the ground at a suitable position far away from the Well Head. The EM signal on surface is measured between the reference antenna and antenna # 2. If the signal is not strong enough, either the reference antenna or antenna # 2 can be moved to the Well Head of a nearby Well (Antenna # 3), as illustrated in Figure 16.

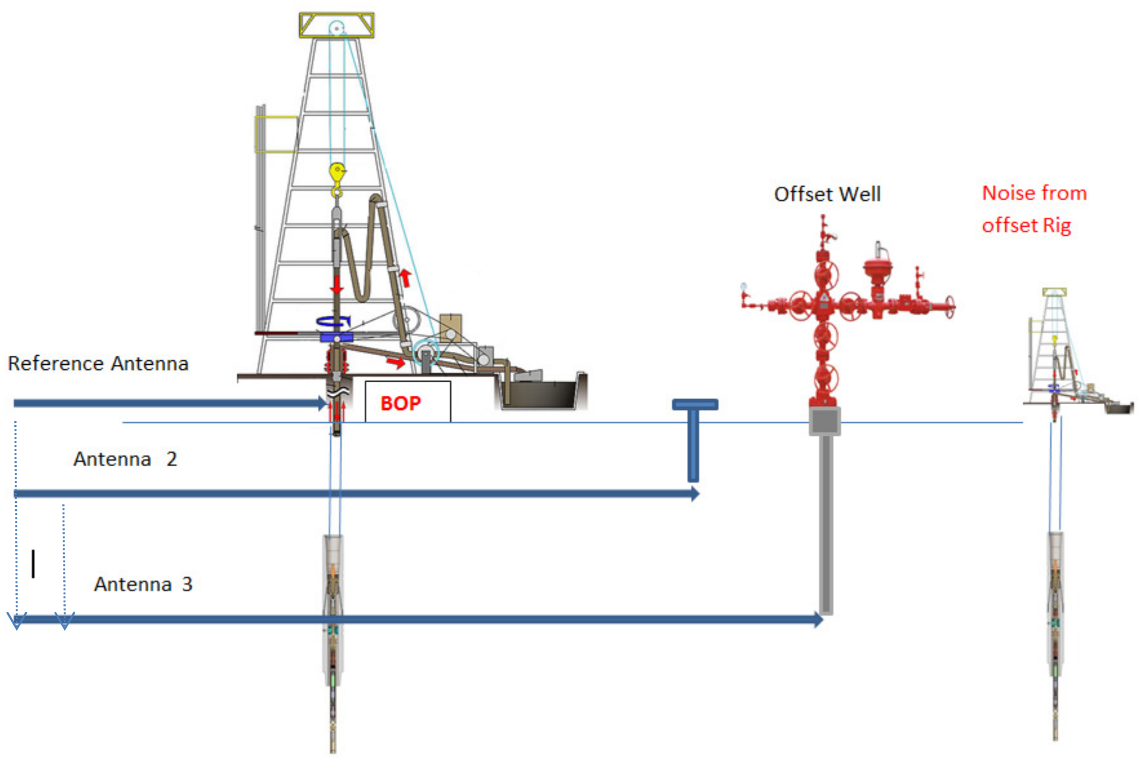


Figure 16: Well site antenna placement

Some useful rules on antenna placement are as follows:

- If a horizontal section is being drilled, Antenna # 2 needs to be placed in the direction of the well trajectory.

- The greater the distance between the Reference Antenna and antenna #2, the more the voltage drop. The signal strength increases by a factor of 2, if the distance between the stakes is increased by a factor of 10.

  If the signal strength is 1mV with a separation of 50m between the 2 antennas,
  The signal strength will be 2mV with a separation of 500m between the 2 antennas

The FST should have the antenna placed as far from the well as reasonably possible

- A suitable place for an antenna is a moist or wet place with fresh water near the rig. This increases the stake size and reduces the electrode's resistance with the ground thereby increasing the signal strength. If the water is salty, it may pick up sources of noise which could interfere with the signal.
- An EM-MWD operating on a nearby Rig with the same frequency can cause interference, and in this case, the frequency has to be modified by communicating (downlinking) to the EM-MWD from the surface. As an example If 2 tools in nearby wells are operating at 4Hz it may be required to change the frequency to 2 or 6 Hz on the one of the tools

SURFACE NOISE

During drilling operations, electrical noise on the surface from the top drive, engines, pumps, and other drilling equipment, affect the signal received on surface. A number of rigs have unstable power supplies, which vary or fluctuate when the drilling load is increased. It is common to see more noise during tough drilling conditions particularly when more torque is experienced while drilling. A spectrogram on the XEM receiver provides a history of the tool signal and noise.

The following can be seen in the spectrogram in Figure 17: Spectrogram- Good quality signal.

- A clean tool signal at 4 Hz with high amplitude and no visible noise sources.
- Stable signal voltage with a consistent amplitude at 10V indicating no electrical noise.
- Consistent bright red trace showing that the signal has been strong historically.

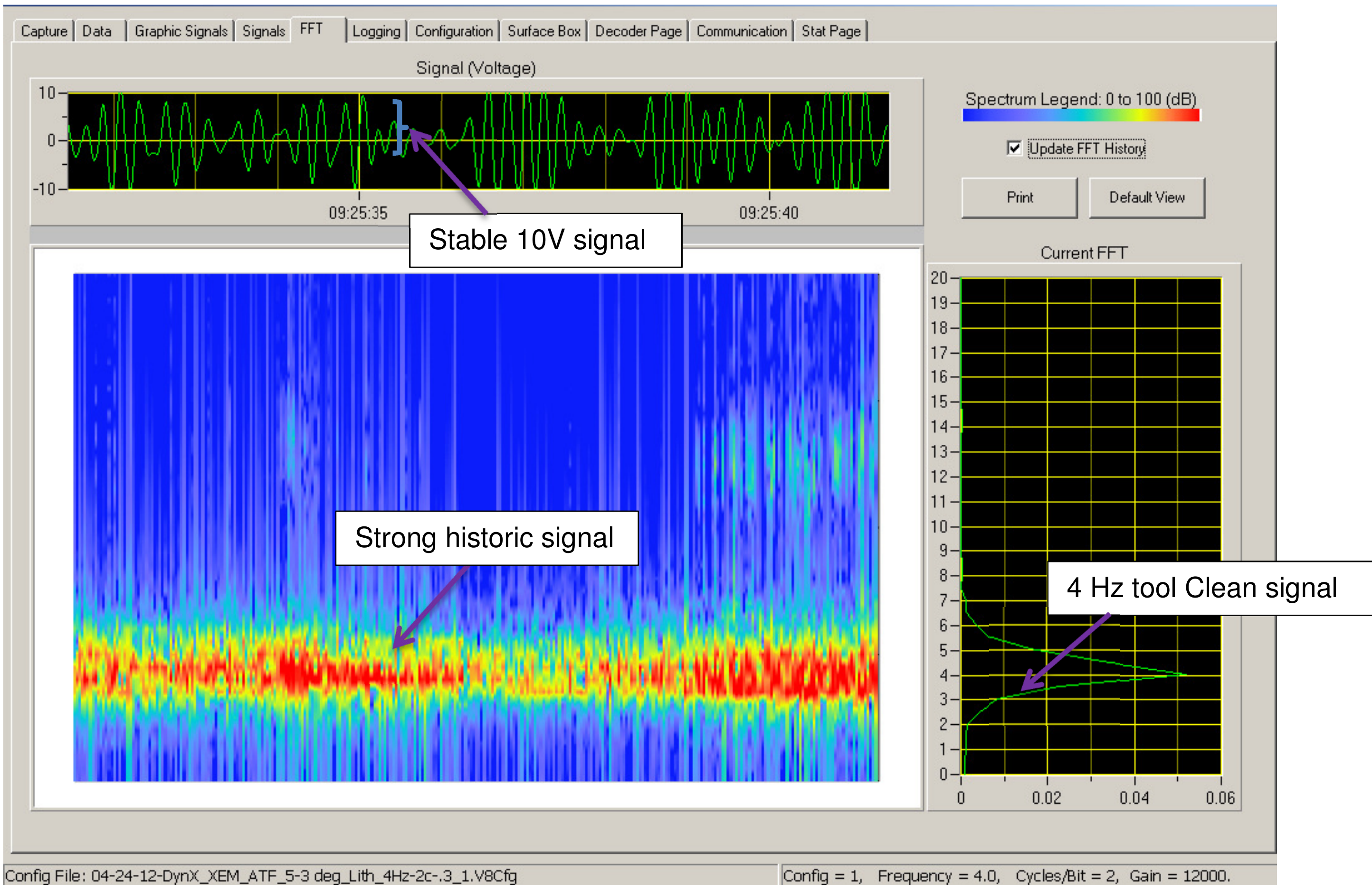


Figure 17 Spectrogram Good Quality signal

The following can be seen in Figure 18: Spectrogram - Signal with Noise:

- Fluctuating signal with the signal amplitude changing. This is normally seen when there is electrical noise on the power supply to the XEM Receiver probably due to the condition of the Rig drilling equipment including the Top Drive, Pumps and Engines.
- Noise at 1-2Hz frequency due to drilling equipment from the Top Drive. Noise Harmonics can also be at 10Hz and other frequencies. Under tough drilling conditions high torque & drag is experienced, there is usually more surface noise due to the high current required to operate the Rig equipment.
- The 4Hz signal trace history is not consistently strong showing blue patches and red patches. The amplitude of the signal is also low; there may have been problems decoding the signal. Recommendations on how to improve the signal quality are given at the end of the section.

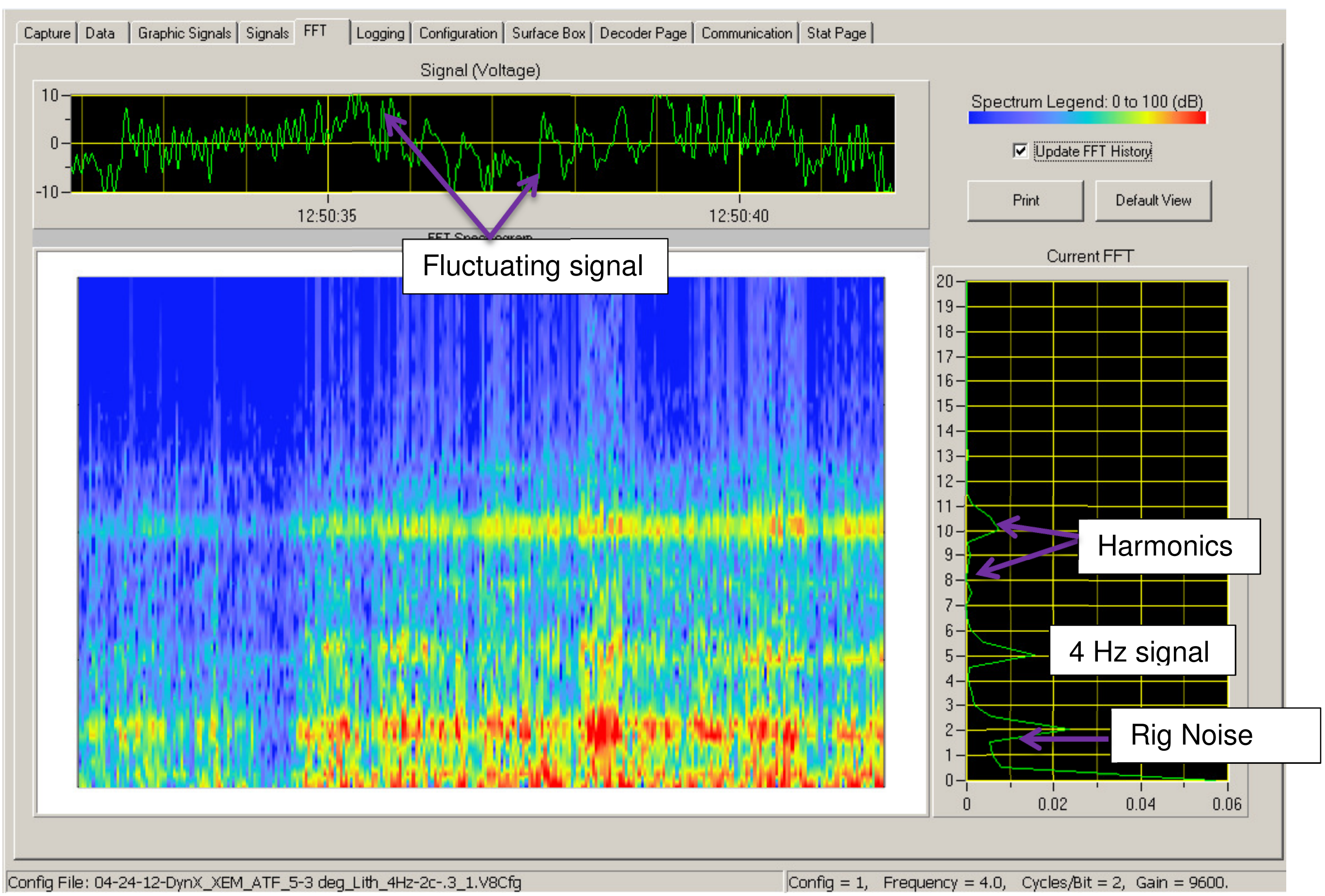


Figure 18 signal with Noise

Signal to Noise ratio (SNR)

The Signal to Noise Ratio (SNR) is a measure of signal strength versus noise level measured in Decibels (DB); this is a better indicator of signal quality as opposed to the signal strength as it provides an indication of the signal in contrast with the noise.

$$SNR = 20 * \ Log_{10}\left(\frac{(V1 - BN)}{BN}\right)$$

Where SNR= signal to Noise ratio (DB), V1= signal voltage (V), BN=Base Noise (V)

Equation 7 signal to Noise ratio

From experience when the SNR> 6 DB or higher there is a better chance of decoding the signal.

RECEIVER CONFIGURATION

Some parameters that can be adjusted in the receiver to improve the quality of the signal include:

Gain

The signal from the antenna fed into the receiver is small and needs to be amplified so that it can be decoded by the receiver. The total Gain is the product of the Gains of 4 separate amplifiers. The receiver software looks at the value of the signal and automatically adjusts the Gain so that the signal value is 3 Volts.

In Figure19 below, a total gain of 200 = (2 x 10 x 10 x 1) is applied. The Gain from each of the amplifiers can be seen in bracket 2x10x10x1.

The raw voltage signal = (3/200) or 0.015 Volts.

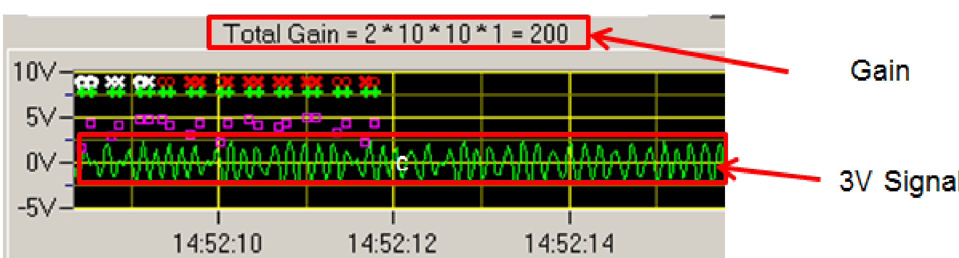


Figure 19 Filtered signal Trace and Gain Applied

The Gain is applied automatically by the receiver but can also be adjusted manually. The receiver can apply a maximum gain up to 296,000; however from practical experience when a Gain > 20,000 needs to be applied the signal quality is not good and there are issues decoding the signal.

Band Pass Filters

The XEM receiver has a band pass filter which allows signal frequencies within a defined range to pass through and rejects or attenuates frequencies outside that range. The FST needs to provide the lower limit f_L and an upper limit f_H. These limits have to be chosen with care to ensure the tool signal is not attenuated. These values are based are based on the Frequency, redundancy and telemetry provided in Table 2. The schematic below shows a Band pass filter where the frequencies outside the limits are attenuated by 3dB (a factor of 2).

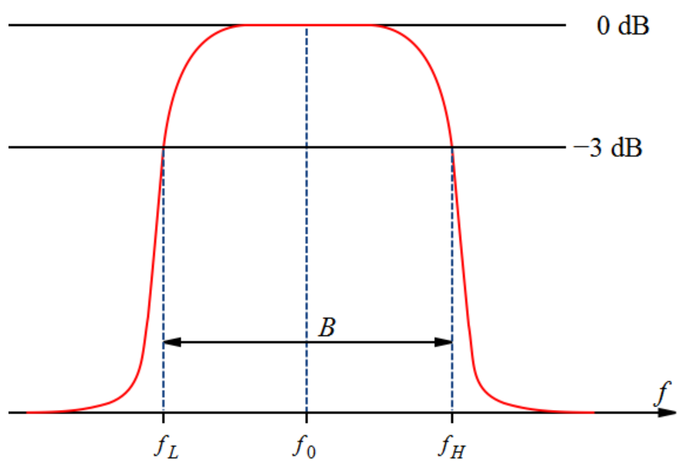


Figure 20 Band Pass Filter

Notch Filters

A “Notch” filter is a selective filter that can stop a specific frequency while allowing all other frequencies to pass through. If noise is seen at a particular frequency on the Spectrogram, the FST can input this value into the Receiver configuration as the Notch frequency. The XEM Receiver allows a single noise source to be removed thereby improving the SNR.

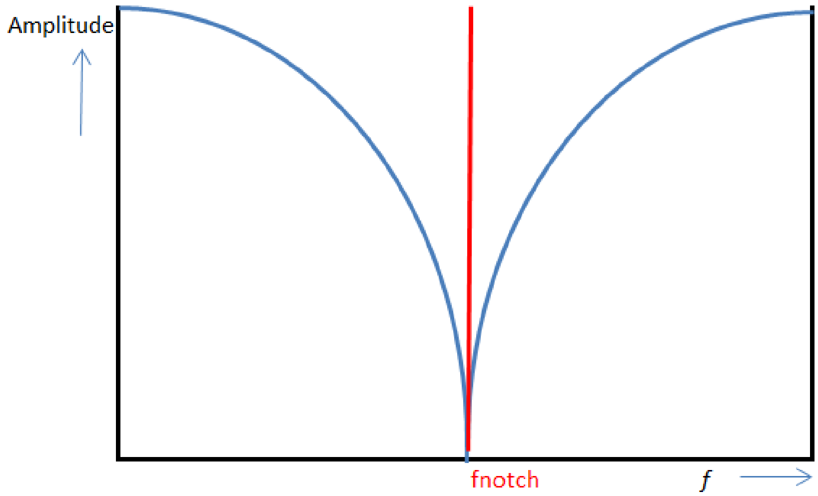


Figure 21 Spectrogram with tool operating at 4 Hz frequency

Long Header Correlation

The EM signal contains “Long Headers” at the start of a Transmission sequences such as a Survey; these allow the Receiver to be synchronized with the transmitted signal. Whenever the receiver sees a Long Header pattern it compares it with a known pattern and establishes the correlation on a scale of 0-100% as seen in Figure 22.

When the receiver has not been decoding it still keeps looking for a Header. Sometimes it may lock on to noise and try to decode it as data. To prevent this, a user defined “NOT DECODING” threshold can be entered. The default value for this is set at 70 %; this means the Long Header correlation has to be greater than 70% before the receiver synchronizes itself with the header and starts decoding data.

If the Pumps are switched off the XEM will stop sending tool face/ logging data and start sending Surveys. In this case the Receiver is already decoding but needs to re-synchronize itself with the Long header for the Survey. It is possible for the receiver to see a false header due to noise and think it is a header. In this case the Receiver will try to decode a Survey even when the tool is sending other data. A user defined “Decoding threshold” (default value set at 80%) allows the receiver to be extra sure that it is seeing a new header.

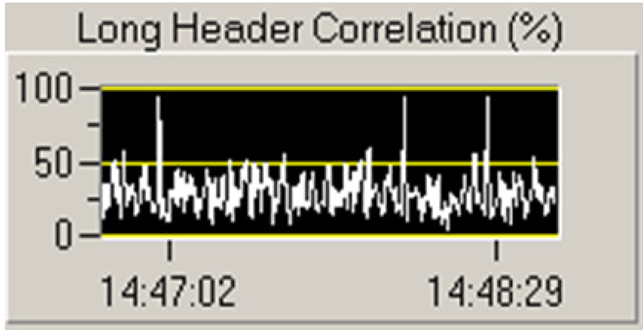


Figure 22 Long Header Correlation

HOW TO IMPROVE THE SIGNAL QUALITY ON SURFACE

If there are issues with signal detection on surface the following sequence of steps can be followed through:

1. Review the Automatic Gain calculated by the receiver. If the Gain computed by the receiver < 20,000 and the signal is weak the Gain should be increased.
2. Review the signal to Noise Ratio (If the SNR is < 6, identify sources of noise following the steps below).
3. Review the spectrogram on the XEM receiver and
   a. If the signal fluctuates: an isolation transformer (if available) can be included to isolate the XEM power from noise associated with the Rig power supply.
   b. If noise consistently appears at a single frequency in the tool signal bandwidth the noise can be supressed by applying a notch filter at that frequency.
   c. The Band Pass filter limits should be set to match the signal Bandwidth calculated for the frequency, data rate in table-2.
   d. Confirm that another EM-MWD is not operating at the same frequency on an adjacent Rig. If a tool nearby is operating at the same frequency, change the tool frequency by downlinking to the tool.
4. Check the antenna cables to ensure they are connected properly with the antenna stakes and not electrically connected with other cables. A signal strength generator can be used to isolate issues with the receiver and surface cables.
5. If Air drilling is in progress, confirm that the Rig is misting.
6. Increase the spacing between the 2 antenna as much as possible; Either the Reference antenna or the other antenna can be moved to a nearby Well Head.
7. After confirming with the command center and the Coordinators the tool can be downlinked to a configuration with Higher Target current setting and or Lower frequency.

2.6. MODELING OF EM SIGNAL

The EM-MWD signal is modeled for every new location and field prior to the job. The Operations Engineering team updates the model based on resistivity data for the area. The Schlumberger E-Pulse Model is currently used to predict the EM signal strength at various TVDs.

Inputs to the model include:

- Casing Shoe depth for the last Casing
- Formation Resistivity data
    - Data from offset wells in LAS format
    - The Resistivity data is averaged by the program. Averaging between 0 – 50Ohmm can be specified by the user.
- Mud Resistivity
    - The Mud Resistivity is obtained from Mud samples for water based mud using a mud Resistivity test box. For Oil based Mud a value of 100Ohmm is used.
- Antenna “Stake” distance
    - The distance between the reference Antenna and the 2nd Antenna
- Tool operating Frequency in Hz
- Collar Size (4 ¾”, 6.5 ”, 8”)
- Tool power settings
    - The XEM Output settings are provided in Amps. These are translated into Power (Watt) by the District Engineers.

The EM Model is run by the District Engineers prior to the job to see if it is suitable to run and the depth at which the EM Signal strength will be received on surface. The model currently does not account for:

- Other wells in the area
- The well profile: Only the TVD is taken into consideration.
- The Current signal variation in the tool due to environmental conditions.

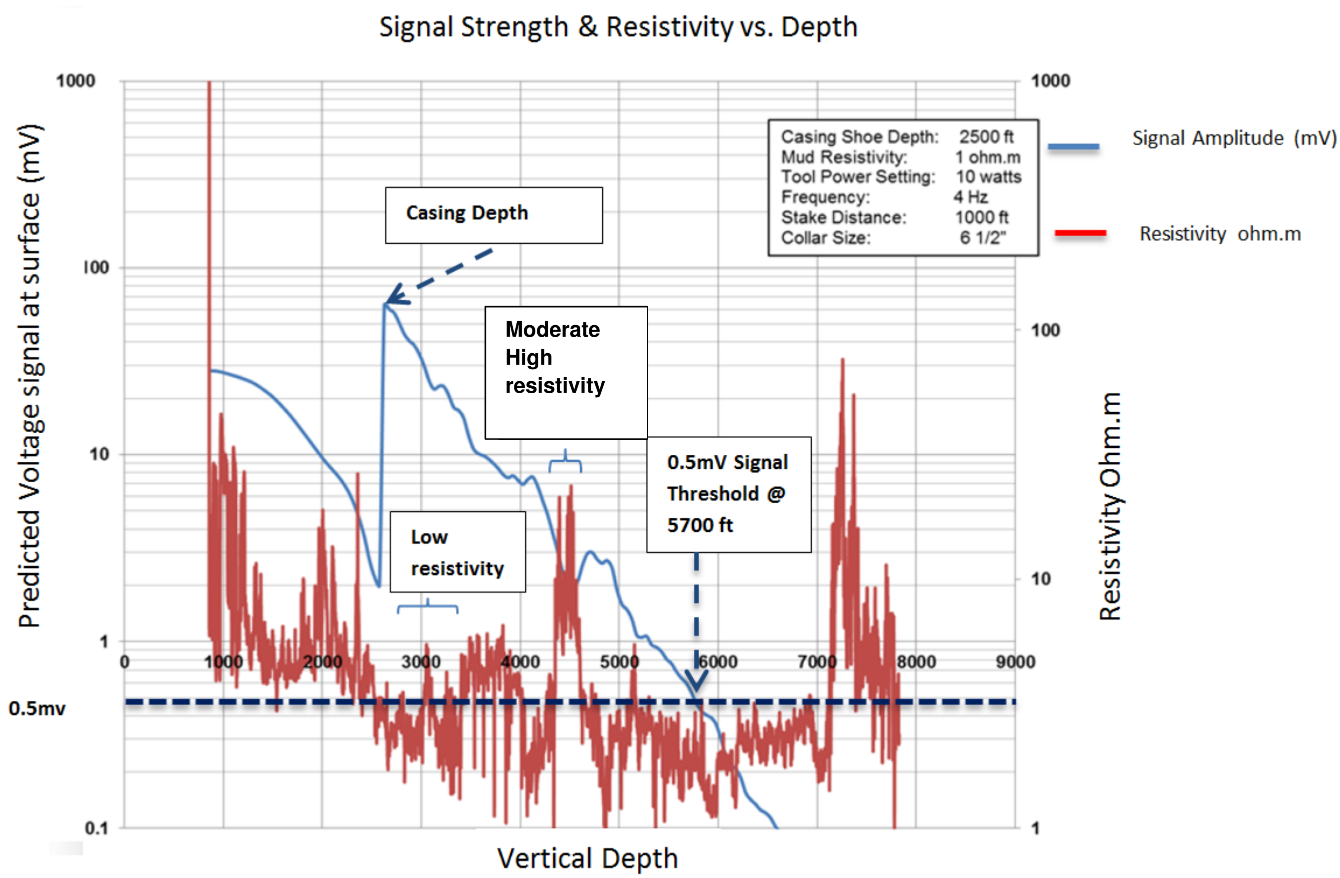


Figure 23 signal strength as function of Depth

Figure 23 shows the EM signal model based on resistivity data (in Red) and provides values of the signal strength (in Blue) received at surface for a 4 Hz EM signal in a well from surface to 9000ft.

The Signal is attenuated in the Casing

- The Outermost Casing Shoe is set at 2500ft. The tool signal is attenuated at a very steep rate from surface to the casing shoe. The signal improves immediately after the Casing Shoe (60mV after the shoe).

The Signal is attenuated in conductive formation

- In the zone from 2500 - 3300ft the formation Resistivity is 2-4Ohmm; the signal is attenuated at sharp rate. The rate of attenuation decreases when the formation Resistivity increases to 6-9 Ohmm in the interval from 3300ft to 4000ft.

In zones with High Resistivity it is difficult to push the Signal into the formation.

- At 4300-4500ft the Resistivity increases above 10Ohmm. The signal strength decreases to 2mV but increases to 3mV after this zone

The signal is gradually attenuated to 0.5mV at 5700ft after which it may be difficult to receive signal on surface with this tool configuration.

2.7. EM SIGNAL PROTOCOL

The data from the tool is transmitted in sequences. There are 3 type of sequences:

- *Survey* sequence- transmitted when the pump are switched off.

Data sequences transmitted when the pumps are on, there are two types of data sequences:

- *Tool Face Logging*- sent during Sliding drilling and include Tool faces, gamma ray, Annular Pressure, shocks.
- *Logging with Rotation* - sent when string rotation >5rpm. These messages do not include toolfaces, allowing other information including gamma ray to be transmitted at a faster rate. The tool needs to have a DynamX probe to sense String rotation.

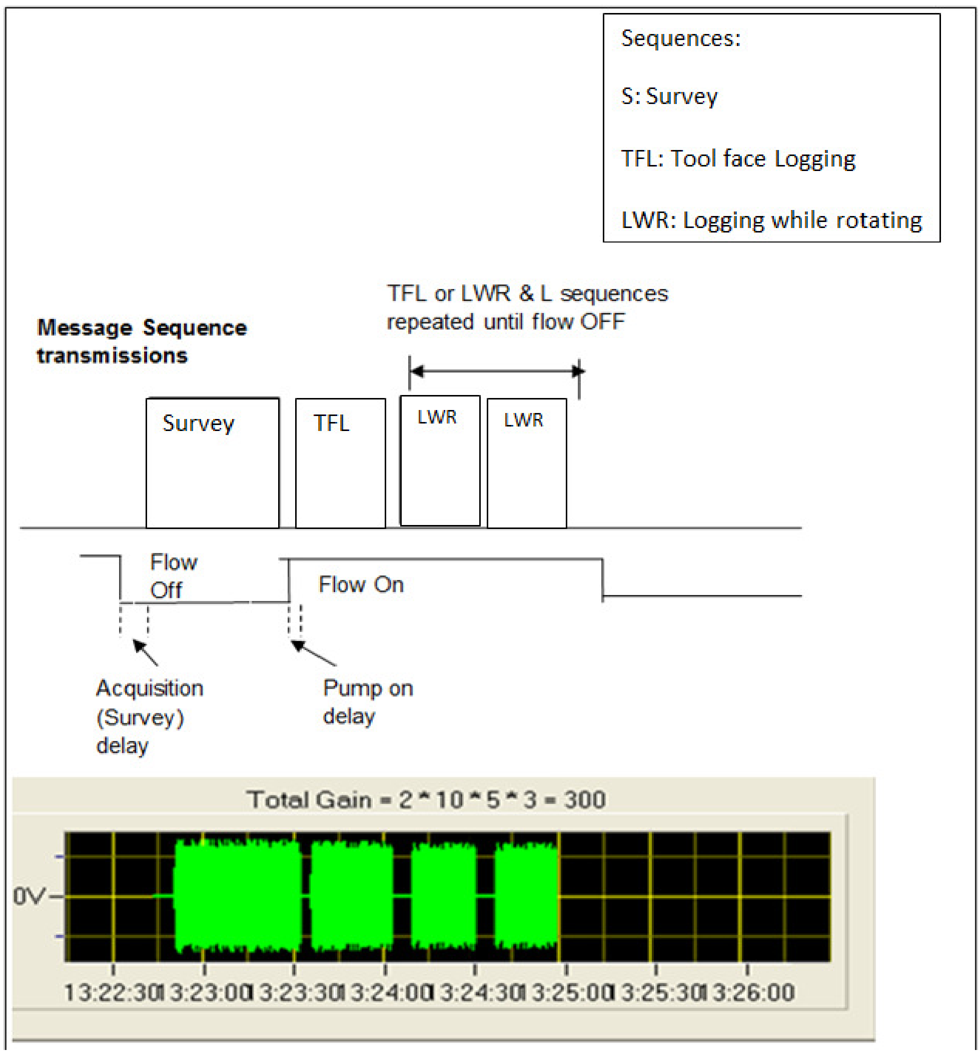


Figure 24 XEM Transmission

TRANSMISSION SEQUENCE

The tool transmission sequence is defined as part of the configuration file and programmed into the tool prior to the run. These contain a number of Message Sequences:

Each Message sequence including (Survey, tool face logging, logging with rotation) contains the following information:

- LH (Long Header): Allows the receiver to recognize that a message is being transmitted.
- ID (Identifier): Allows the receiver to recognize the specific Message that is being sent up hole.
- SynC Delay: This is a gap for synchronization.
- MH Messsage Header: This contains the Header for the Actual data.
- Msg Message Data: This contains the Signals that will be transmitted depends on the configuration programmed in the tool. A signal is the name of the data that the tool will send; for example, D&I Inclination, D&I Azimuth, Gamma, temperature, etc.
- Tx Time: This is the transmission time for the Message

MESSAGE SEQUENCES

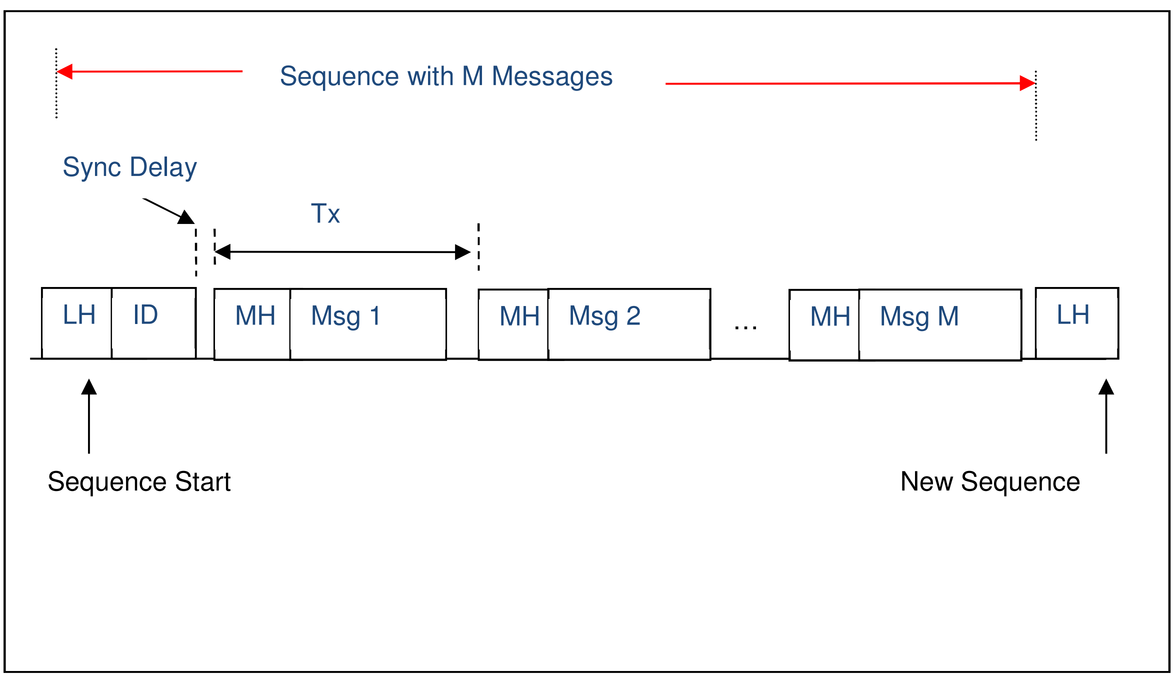


Figure 25 Message Sequence

Messages can get corrupted when they reach the surface. Additional numbers of bits are sent up hole for the receiver to correct the data. These are known as parity bits. There are three different combinations type of Parity Bits currently used (shown in the Table below).

PARITY TYPE	NO OF BITS	DESCRIPTION
No Parity	0	
Parity Bit (Even)	1	signal Data + Parity Bit = Even # of Ones
CRC 3	3	CRC algorithm

Table 3: Parity Bit checks

- No Parity: This means no additional bits are added to the data bits.
- Parity Bit (Even): These are used when the number of Bits in a signal value < 8 (Example Scale Current has 5 Bits).

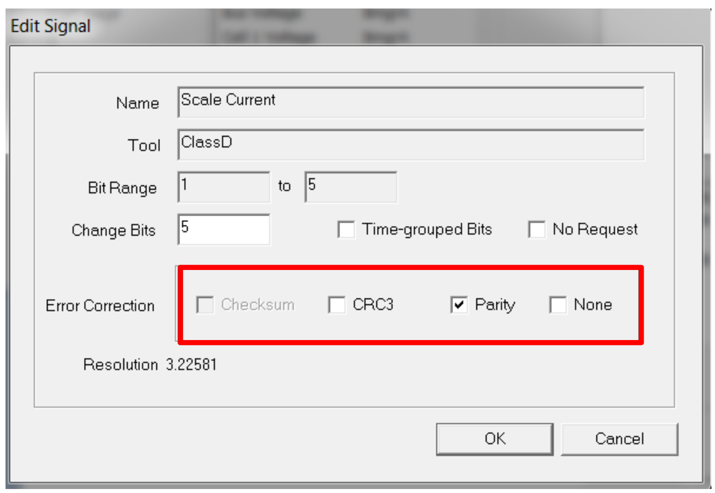


Figure 26 Parity Bit

A Parity bit is added so that the number of 1's is even. For Example if the *Scale current* (5 bits) is 00010 in binary, the value transmitted will be 000101, 1 is added as the parity bit to make the total number of "1"s =2 an even number.

CRC3: If the number of Bits in a signal value > 8 a 3bit CRC code is added to provide correction. They are chosen to accompany important data such as gamma ray on logging jobs. As an Example if the Measured Load current is 00000010101, a 3 bit CRC3 code eg 010 will be added: 00000010101010. The CRC3 code is determined by the receiver.

A signal + Parity Bits total must be less than 32 bits.

CONFIGURATION

The Configuration is accomplished by the Configuration editor" The Header has Advanced and User Configurable parameters

ADVANCED CONFIGURATION PARMETERS

The Advanced configuration contains the Long Header and Message ID. These are not modified by the Field User.

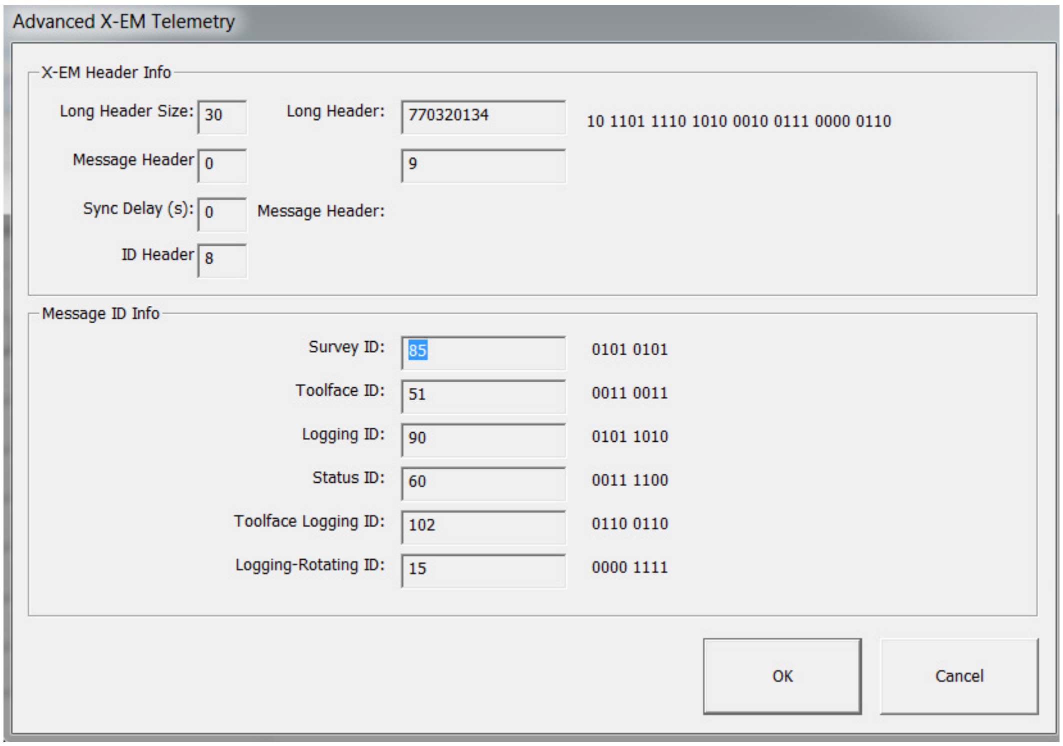


Figure 27 Advanced Configuration Parameters QPSK

Figure 27 shows an Example of the Long Header and the Message ID when sending a sequence of messages with QPSK Telemetry.

- The Long Header size is 30 Bits and bit configuration is 770320134
- The Message IDs are 8 bit words.
    - The Survey Frame ID is 85=0101 0101(In Binary).

USER CONFIGURABLE PARMETERS

The Data sequences can be modified by the user. An Example of the Survey Data sequence is shown in Figure 28. This Survey Data sequence consists of different type of Data Points which are transmitted during a Survey. One of the Data points is “Inclination”.Inclination has 12 bits, a 3 bit CRC correction code and a Resolution of 0.04396.

$$\textit{Resolution} = \frac{Maximum\ Value - Minimum\ Value}{(2^{No\ of\ Bits} - 1)}$$

Equation 8 Resolution

The Maximum Range is from 0 -180° with 12 bits; Resolution= $\frac{180-(0)}{2^{12}-1}$ = 0.043956.

The total Message transmission time is 51.33 seconds. This length must be >= (MH + Sync Delay + Message Data transmit time). The Number of Messages can be repeated in a Transmission sequence For the Example the number of Messages is 1. A space of 2 seconds is typically provided to see the transmission sequence in the presence of noise; this can be reduced to 0 if required.

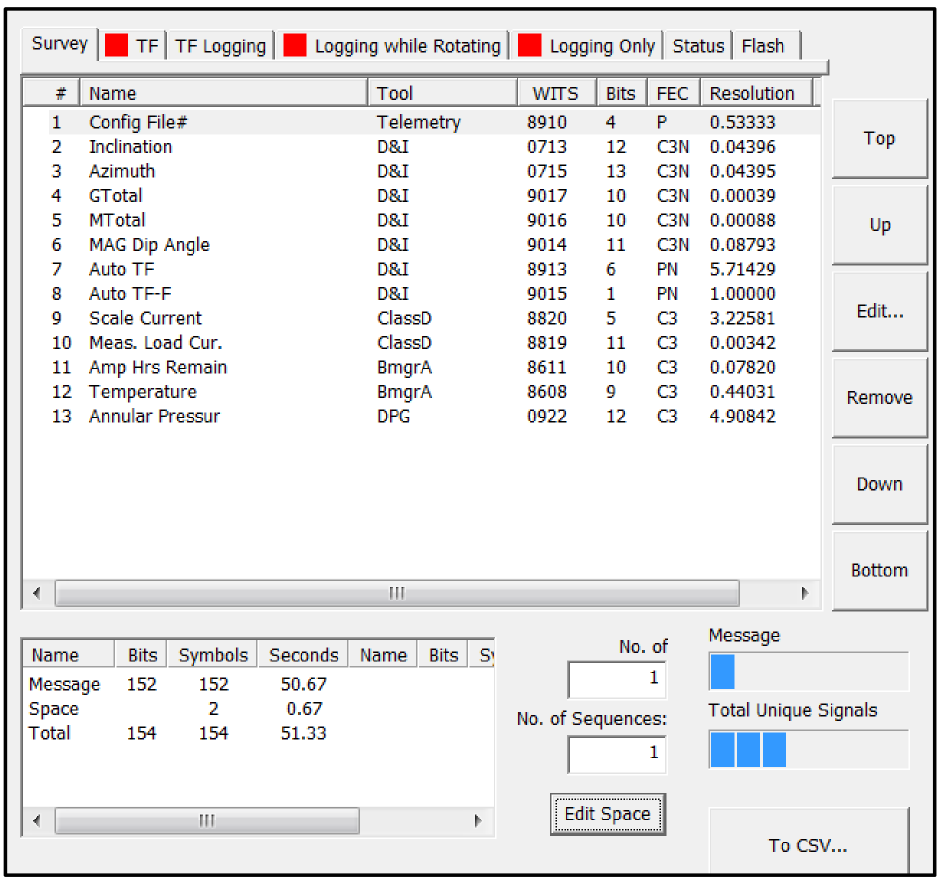


Figure 28 Survey Data

Further details on how to create Configuration files are given in the Operations chapter.

3. DIRECTION AND INCLINATION

3.1. THE EARTH'S GRAVITATIONAL FIELD

There exists a gravitational field around the earth; which pulls all objects towards the center of the earth. The force of gravitation is given by the formula:

$$F = \frac{G * m * M}{R^2}$$

Where m is mass of the object, M= mass of the earth, R is the distance between them & *G= gravitational constant*

Also $F = mg$ *Where* $g = \frac{G*M}{R^2}$ *is the acceleration due to the force of gravity.*

Equation 9: Earth's Gravitational force

The value of acceleration due to the force of gravity is 9.7 m/s^2. This is also commonly known in the industry as 1G.The gravitational force is not constant throughout the surface of the earth but varies slightly with:

1. Latitude: The value of the force of gravity is larger at the poles than at the equator. This is because the earth is not a perfect sphere and slightly flattened at the top.

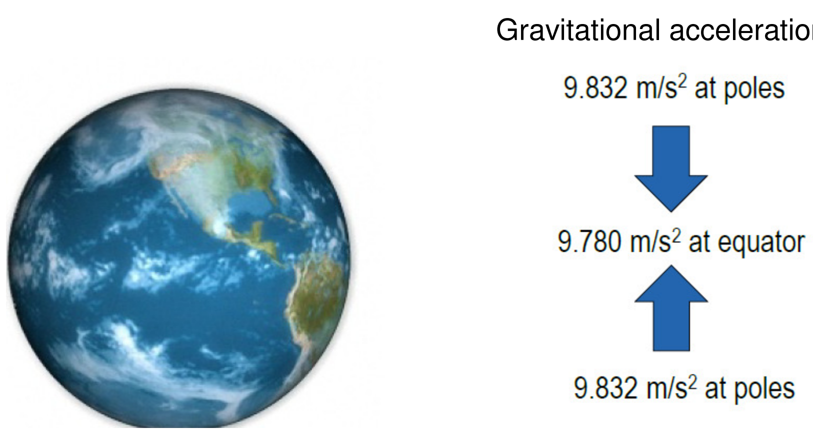


Figure 29 Latitude

2. Altitude: the force of gravity decreases as we go higher above the earth. This can be seen on the formulae for the earth's gravitational force when R is increased, F is reduced.

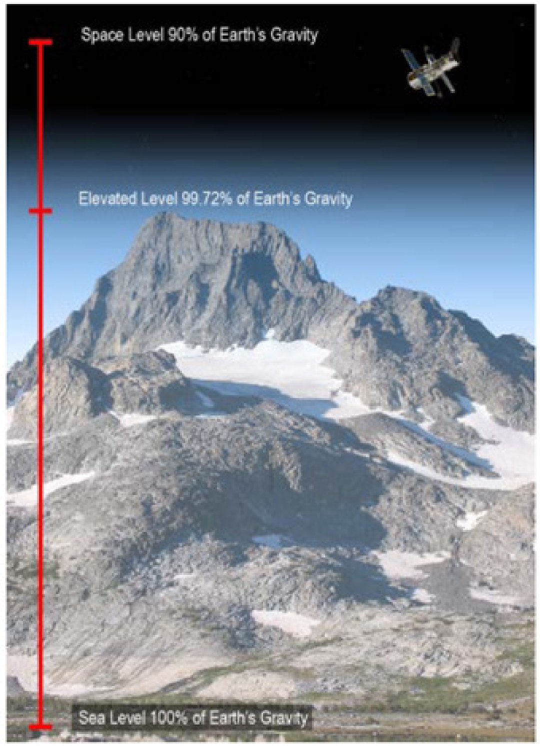


Figure 30 Gravity changing with altitude

3. Variations in the earth's crust due to the terrain and density of the material.

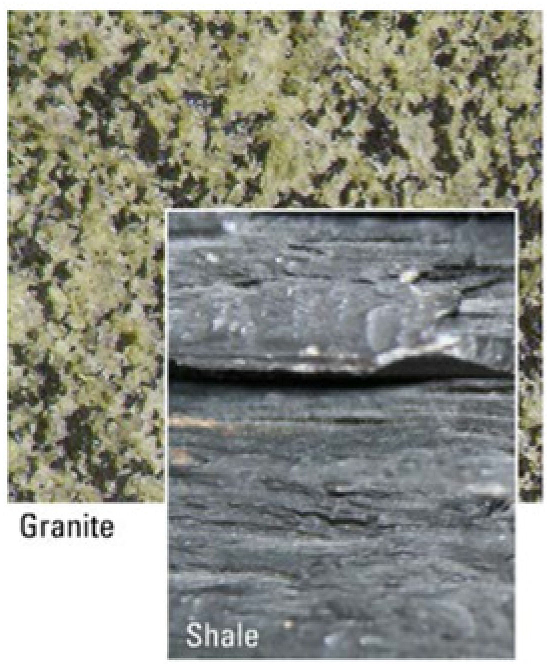


Figure 31 Material with different Density

3.2. XEM GRAVITY MEASUREMENTS

A basic accelerometer works like pendulum mass which attempts to hang in alignment with the gravity vector. If the accelerometer is tilted, force is applied to the pendulum to restore the pendulum to its original position. This force, if measured and calibrated, can be used to estimate the gravitational force seen by the accelerometer.

An accelerometer which hangs vertically will measure the total gravity vector. An accelerometer which is tilted with an angle α will see a force = Total gravity force * Cos α. When the tilt angle α is 90° or the accelerometer is horizontal the accelerometer will read 0.

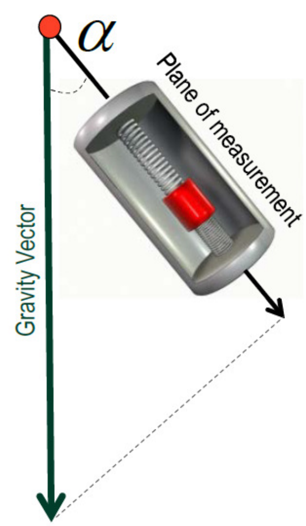


Figure 32 accelerometer Inclined with α

The XEM tool has 3 accelerometers arranged at 90° to one another and placed along the x, y and z axis Ax is parallel to the tool axis while Ay and Az are perpendicular to the tool axis, and to one another.

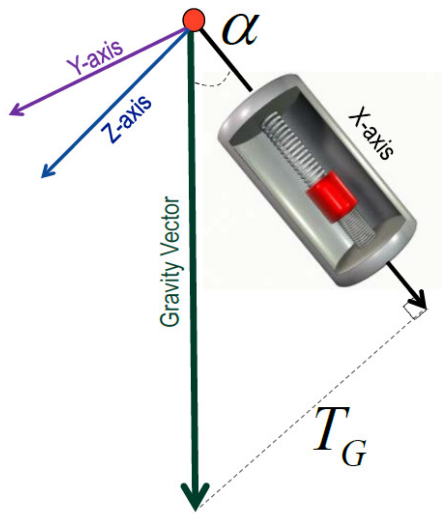


Figure 33 Tri-axial Accelerometers

When the tool is vertical, Ax measures the gravitational force, as it is in line with the gravity vector, while Ay and Az measure close to 0. When the tool is horizontal, Ax is close to 0, as it is perpendicular to the gravitational vector, whereas Ay or Az (depending on position) can measure the gravitational force or 0. When the tool is tilted (Not horizontal or vertical) each of the three accelerometers measures a portion of the total gravitational force.

TOTAL GRAVITATIONAL FORCE

The total gravity force is a vector measured from all 3 accelerometers:

$$Total\ Gravity\ force\ (\,G\ Total) = \sqrt{Ax^2 + Ay^2 + Az^2}$$

Equation 10: Total gravity force

The X, Y, Z accelerometer measurements also known as the raw measurements can be sent up hole during the Survey measurements. The calculated value of the G Total should be 1G with a tolerance of +/- 0.0025. This can be used to identify failed sensors & determine the equality of the MWD inclination measurement.

INCLINATION

Inclination is the angle between the gravity Vector (Vertical) and the tool axis. The Inclination is 0° when the well is vertical and 90° when the well is horizontal. The 3 accelerometers (Ax, Ay, Az) are utilized for the Inclination.

$$Inclination = Cos^{-1}\left(\frac{Ax}{GTotal}\right)$$

Equation 11: Inclination

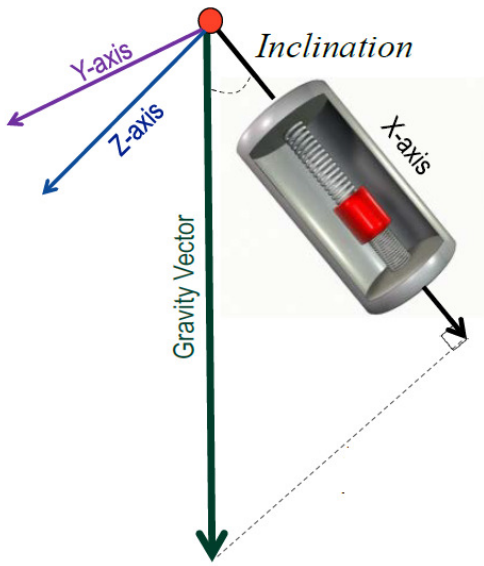


Figure 34: Inclination

ROLL TEST

As a quality check for the accelerometers sometimes a Roll test is taken. In a Roll test the tool is rotated about the tool axis in different quadrants, the value of Ax does not change; the values of Ay and Az keep changing however the resultant vector seen in the tool horizontal plane given by $\sqrt{(Ay^2 + Az^2)}$ remains constant.

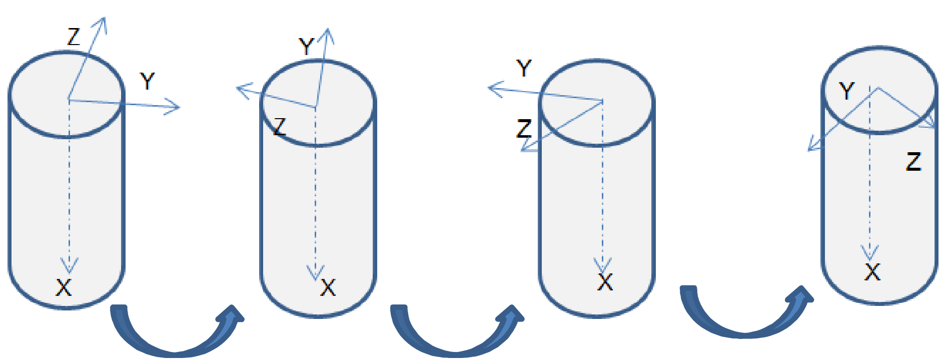


Figure 35 Roll Test measurements

GRAVITY TOOL FACE

When drilling with a motor when the Inclination of the well needs to be changed, string rotation is stopped and the well is steered in the desired direction in Sliding mode. In the sliding mode only the portion of the string below the motor is rotating while the entire string above the motor does not rotate. Gravity tool Face (GTF) is the Angle in which the Motor is steering with respect to the high side of the hole while drilling in sliding mode.

GTF is measured in the Perpendicular plane (Figure 36). The gravity tool face:

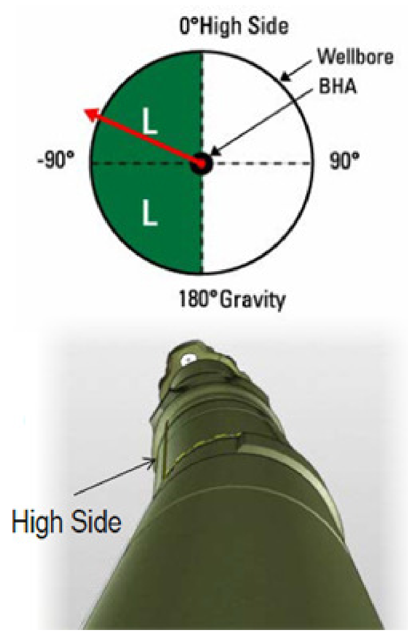


Figure 36 Gravity tool face

- Can be used for steering the hole UP, LEFT, DOWN and RIGHT. When the well needs to be steered
  - UP the GTF is kept at 0°
  - Down the GTF is kept at 180°
  - Left the GTF is kept at -90°
  - Right the GTF is kept at +90 °
- Is provided when the Inclination exceeds a value (typically 3° to 8°) such that the hole is not vertical and has a high side.

- Uses accelerometers Ay and Az
- Is measured from 0 to 180° and 0 to -180°
- Gravity tool faces can be sent as frequently as desired. Update depends on the tool configuration.

The gravity tool face can be calculated by the formula

$$GTF = Tan^{-1}\left(\frac{Ay}{Az}\right)$$

Equation 12: Gravity tool Face

3.3. THE EARTH'S MAGNETIC FIELD

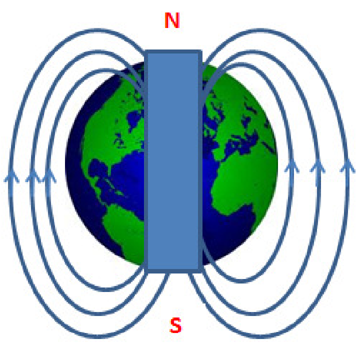
The earth functions as a magnet; magnetic field originates from the inner magnetic core creating flux lines leaving the South and coming back in the North. This allows a compass to point to the magnetic North providing a reference for navigation.

The earth's magnetic field is a vector with 3 components, the magnetic field strength, Declination and magnetic DIP Angle.

Magnetic Field strength: Represents the magnitude or Intensity of the magnetic field and is measured in Nano Tesla. The magnetic field strength is used as a quality check for MWD Survey.

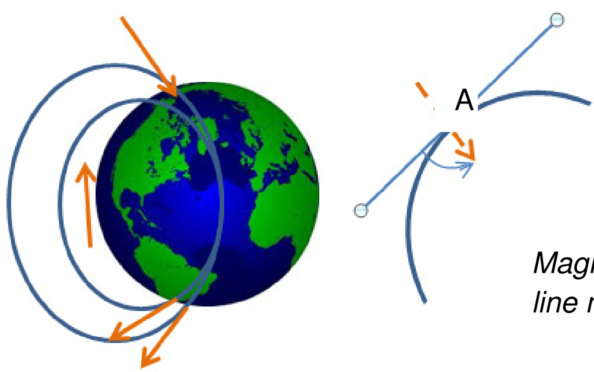
Declination: This is the Angle between the True North and the Magnetic North measured from the True North. The Well direction measured by the MWD is referenced to the Magnetic North. Declination is *added* to reference the Well direction to the True North. If the magnetic North is west of the True North Declination is Negative, if the magnetic North is east of the True North Declination is positive.

Dip Angle: This is the angle the magnetic field makes with the tangent to the earth's surface. It is 0° at the equator and 90° at the North Pole (-90° at the South Pole). The magnetic DIP Angle is used as a quality check for MWD Surveys.



The earth acts as a magnet. The magnetic Field creates Flux Lines from South to the North.

Declination at Point P. The magnetic North is west of the True North. Declination is Negative in the figure



Magnetic DIP at Point A: This is the Angle the Flux line makes with the tangent at the earth's surface.

Figure 37 Components of magnetic Field Vector

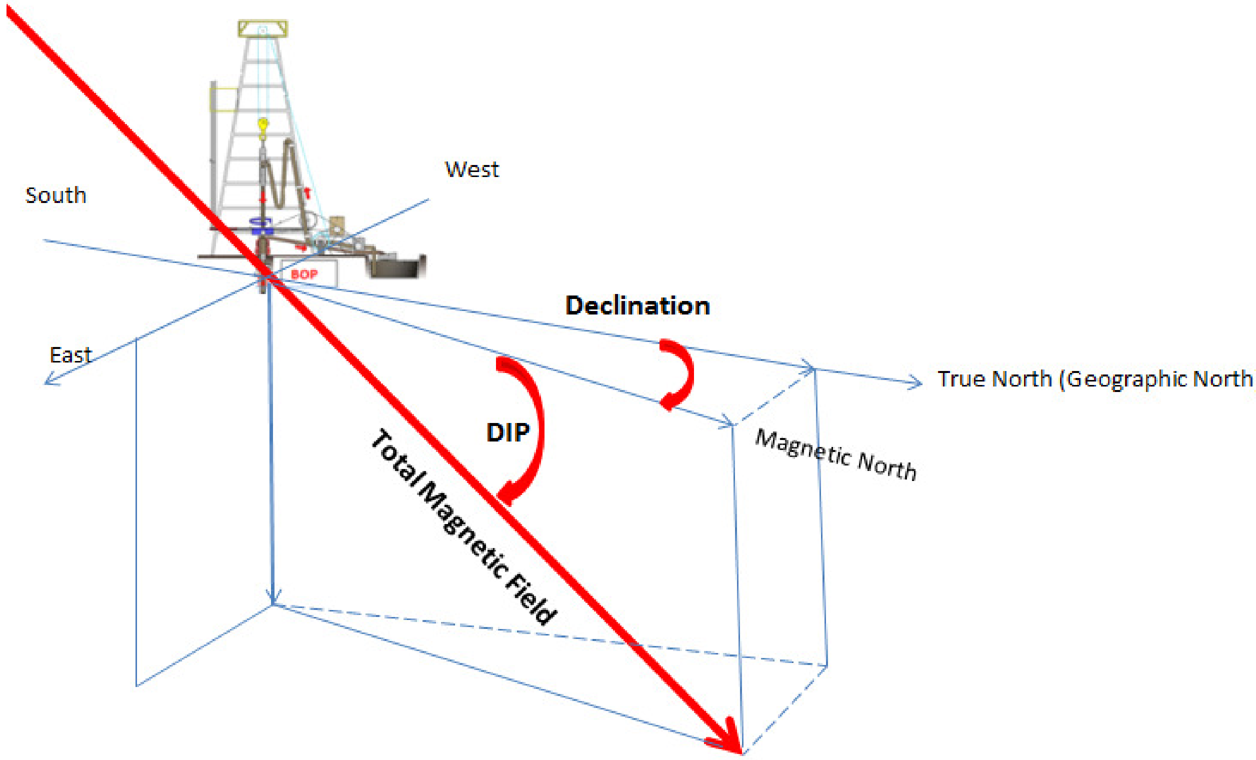


Figure 38 Declination, DIP and the Total magnetic field at a surface location

The Location of the magnetic North keeps changing with time. The location over a period of years is shown in Figure 39. This changes the value of the magnetic Field vector components including the Declination, DIP and the Magnetic field.

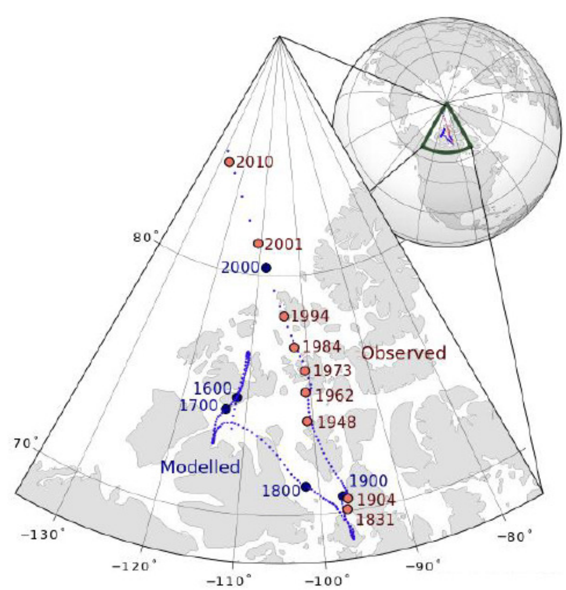


Figure 39 Changing Location of the magnetic North

Variations in the magnetic field occur on an hourly basis. Changes in the magnetic field intensity at a particular location in Colorado are given in Figure 40.

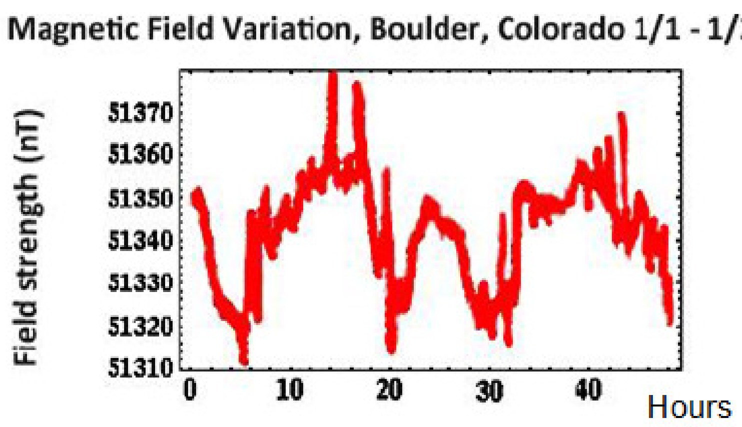


Figure 40 Changing magnetic Field strength

Observatories scattered across the globe monitor the intensity and change in the behaviour of the magnetic field. This data is used to generate Models which provide values of Declination, Field strength & DIP for any given location at a specific time. Commonly used models include:

BGGM (British Global Geomagnetic Model) This Model is updated every year and used globally throughout the drilling industry.

HDGM High Definition Geomagnetic Model uses new data processing methods taking into account local crustal magnetization and provides better accuracy as compared with the BGGM.

The NOAA National Oceanic and Atmospheric Administration maintain a calculator at the website http://www.ngdc.noaa.gov/geomag-web/ which is widely used in North America.

For high accuracy MWD work particularly at high latitudes a technique called *In Field referencing* is used to map local anomalies and used to correct one of the models in used.

The Operating Company decides which geomagnetic model or technique will be used for the job. It is important to follow the same model that is being used by the Operating Company so that the Well Azimuth is corrected accordingly. If the correct value for Declination is not used the well will be steered off the target.

3.4. XEM MAGNETIC MEASUREMENTS

MAGNETOMETERS

The directional/ DynamX probe has a 3 Axis flux Gate Magnetometers arranged at 90° s to one another. The magnetometer consists of two primary coils through which an alternating current is passed. There is a secondary coil surrounding the two primary coils. If there is no external magnetic field, then symmetrical voltage pulses are generated in the secondary coil each time the AC current changes direction.

However, if an external magnetic field exists (such as the earth's magnetic field) the voltage pulses are distorted in the secondary coil. The magnetometer tries to neutralize this distortion by applying a bucking current; the magnitude of this current is proportional to the magnetic field strength aligned with the axis of the magnetometer.

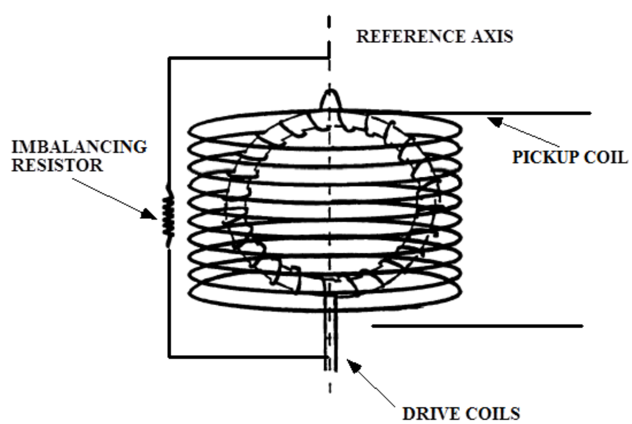


Figure 41 Magnetometer

The 3 x Magnetometers are placed at 90° to one another. Magnetometer Mx is placed along the tool axis, while My and Mz are perpendicular to the tool axis and to one another.

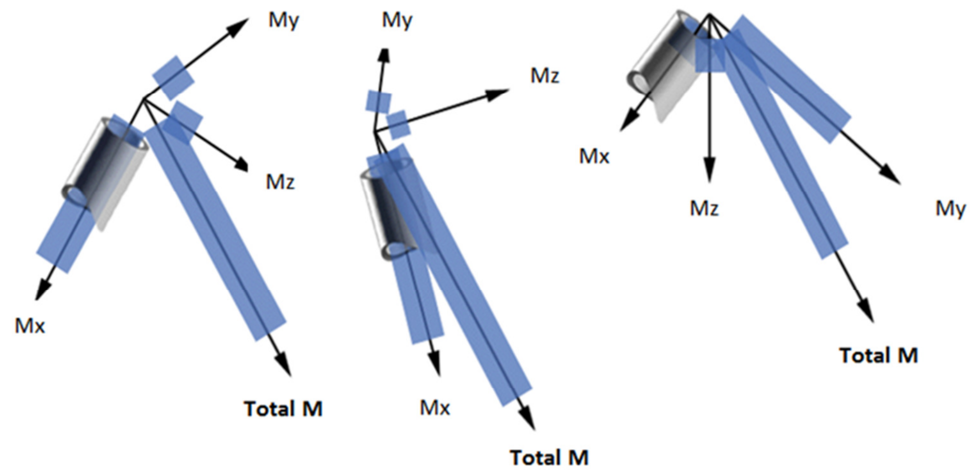


Figure 42 Magnetometers Mx, My and Mz

The Total magnetic Field is calculated by the 3 Magnetometers in the tool with the equation below:

$$Total\ Magnetic\ force\ (Total\ M) = \sqrt{Mx^2 + My^2 + Mz^2}$$

Equation 13: Total Magnetic field

The reference value can be used as a quality check when compared with the measured value. The difference between the reference and the measured value should not exceed ±300nT.

ROLL TEST

As a quality check for Magnetometers sometimes a Roll test is taken. In a Roll test the tool is rotated about the tool axis in different quadrants, the value of Mx does not change; the values of My and Mz keep changing however the resultant vector seen in the tool horizontal plane given by $\sqrt{(My^2 + Mz^2)}$ remains constant.

AZIMUTH

The EM-MWD measures the Azimuth of the wellbore by measuring the direction of the earth's magnetic field relative to the tool. Azimuth is the angle between north reference and a horizontal projection of the current survey position.

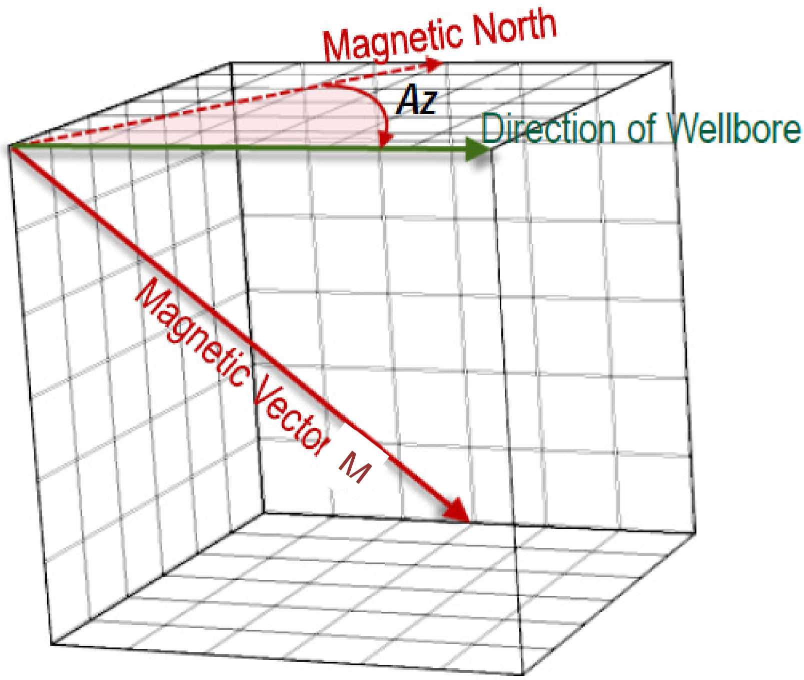


Figure 43: Azimuth

The Azimuth is calculated with the equation below, both accelerometers and Magnetometers are used for computing the Azimuth.

$$Azimuth = Tan^{-1}\left(\frac{(M_Z A_Y - M_Y A_Z) * \sqrt{G\ Total}}{M_X * (A_Y^2 + A_Z^2) - M_y A_Y A_X - M_X A_X A_Z}\right)$$

Equation 14 Azimuth Computation

MAGNETIC TOOL FACE (MTF)

The magnetic tool face refers to the Angle at which we are steering the well with respect to the Reference North. At low inclination (generally below 3.5°), the wellbore does not have a high side. Instead, the wellbore is referenced to the magnetic North. This can be magnetic, True or Grid depending on the correction applied.

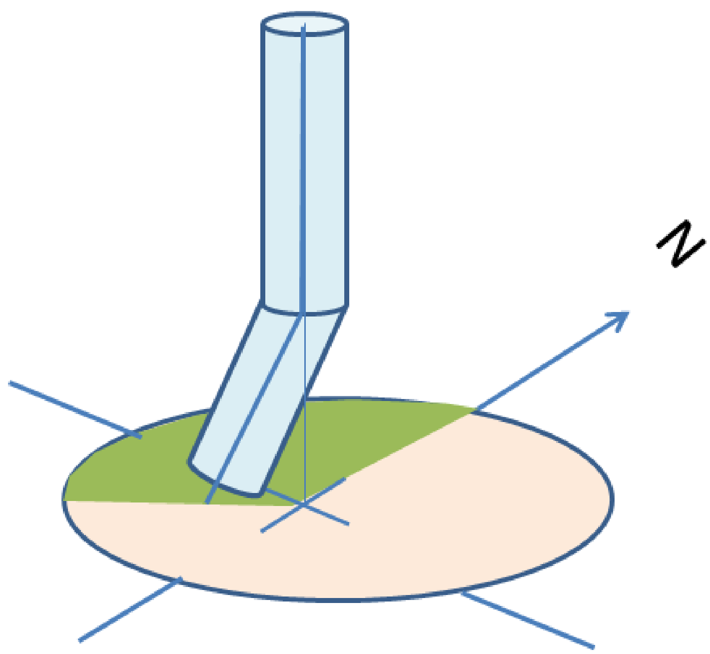


Figure 44 Magnetic tool face

The formula for the magnetic tool Face is given below:

$$Magnetic\ Tool\ Face = tan^{-1}\left(\frac{M_Y}{M_Z}\right)$$

Equation 15 Magnetic tool Face

The magnetic tool Face

- Is measured in the horizontal plane
- Can be used for steering the NORTH, SOUTH, EAST and WEST. In order to steer the well:
    - NORTH the MTF is kept at 0°
    - EAST the MTF is kept at 90°
    - Left the MTF is kept at -90°
    - Right the MTF is kept at 90°
- Is provided when the Inclination is below a value (typically 3°to 8°) such that the hole is Vertical.
- Uses Magnetometers My and Mz
- Is measured from 0 to 360°
- Magnetic tool faces can be sent as frequently as specified in the tool configuration.

DIP COMPUTATIONS

The XEM Dip Angle computation is performed using the 6 Axis. The computed Dip is checked against the reference value provided by the geomagnetic software. The values should be between +/- 0.45 °.

$$DIP = Sin^{-1}\left(\frac{(M_x G_x + M_y G_y + M_z G_z)}{\sqrt{Gx^2 + Gy^2 + Gz^2} * \sqrt{Mx^2 + My^2 + Mz^2}}\right)$$

Equation 16 Magnetic DIP

3.5. SURVEY ACCEPTANCE CRITERIA

Currently Tools are being calibrated to meet the Schlumberger Tolerance criteria for Surveys:

- Allowable Azimuthal Error due to Drill String Interference = +/- 0.5°
- Total gravity force calculated during Surveys = +/- 0.997.5 G to 1.002.5 G
- Total magnetic Field calculated during Surveys = +/- 300nT
- Total magnetic Dip = +/- 0.45°

Prior to the job the drill string magnetic interference has to be estimated. The amount of Azimuth error due to interference needs to be ≤ 0.5° otherwise steps have to be taken to modify the BHA to keep the Azimuth error below the value.

3.6. CONTINUOUS SURVEYS

Surveys are typically acquired at every connection: at intervals of 30 feet, or 90 feet. The surveys are used to calculate true vertical depth and vertical section. The accuracy of these calculations depends upon the distance between the survey points.

When the string is rotating, the Ax and Mx (sensors along the tool axis) provide good measurements, while measurements from the sensors perpendicular to the tool are affected by vibration.

The tool uses the Ax and Mx transmitted in real time and the other axis measurements from the last decoded survey to calculate a Survey. This way the Rig does not have to stop to take a survey. The continuous survey measurements can be sent up-hole in real time. With this information, it is easier for the Directional Driller to see the results of steering. It is possible to obtain these surveys every couple of feet of drilling.

Continuous surveys are not very accurate at low inclinations, and become more accurate after Inclination is > 30°. In addition, for continuous surveys to be reliable, it is important that actual surveys are accurate and taken frequently.

3.7. COORDINATE SYSTEMS, PROJECTIONS, MAPPING AND CORRECTIONS

Directional Wells are plotted on maps to ensure that they achieve the target and stay within assigned leases. In order for a point to be plotted, coordinates on a wall plot use NORTH, EAST and TVD. Axes are perpendicular to each other.

- The Axis origin is defined by a zero coordinate (This origin is defined by a zero coordinate).
- TVD axis is oriented vertically down.
- The North reference is defined and provided by the Oil Company.

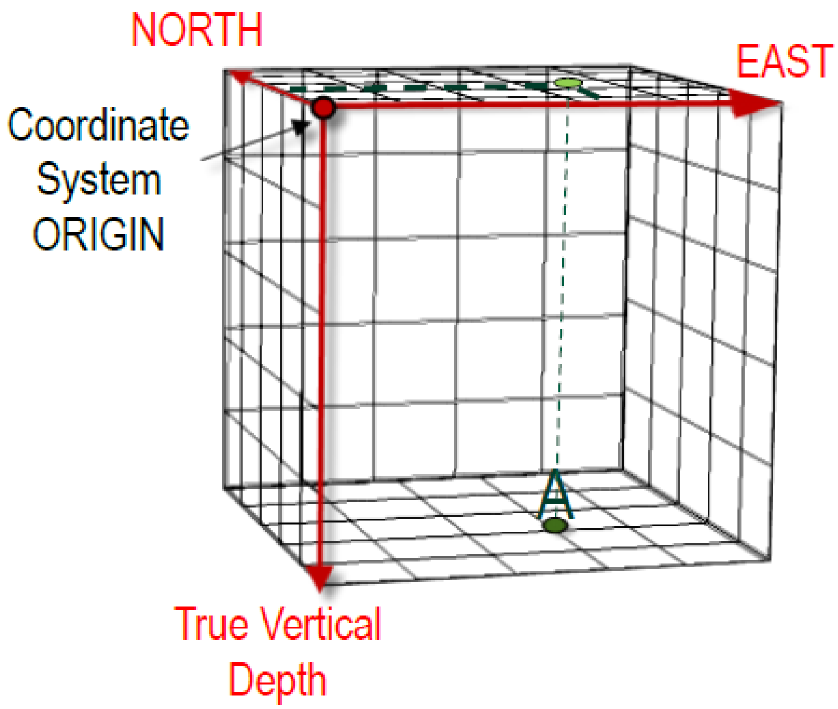


Figure 45 Coordinate system

We normally use North, East and TVD to work at the well site and are familiar with these dimensions as it is easy for us to visualize things in x, y & z. These types of dimensions are ok for plotting coordinates in small areas such as house plots. Oil companies however deal with large fields covering large area; the earth's surface is curved and irregular in places while paper is flat;

Large errors can be introduced while plotting the curved surfaces on flat paper. In order to minimize the error the steps listed below are followed through:

1. An elliptical model of the earth's surface is created to allow mathematical calculations.
2. The reference elevation for the well is determined (Usually above Mean sea Level). This is necessary to determine the vertical depth.
3. A "Geodetic datum" is used allowing the elliptical model to represent the actual surface of the earth.
4. The complex 3D ellipse model generated with the geodetic datum is projected in 2D on paper using a map projection.
5. A Projection system divides the concerned area into grids. Well coordinates are referenced to specific grids within the grid system. North/ South or East West coordinates are assigned from the origin.

6. A scale factor is given to convert the actual curved surface of the earth to straight distances on the Grid.
7. A convergence correction is applied to convert the Grid North reference to the True North.

When working within the projection we then have North, East, and Vertical Depth with a scale factor and grid convergence. More Explanation of these steps are provided below:

REFERENCE SURFACES

There are three ways in which the earth's surface can be represented

- *Terrain*: This is the actual surface of the earth we walk around and includes irregular surfaces such as mountain peaks valleys and Sea bed.
- *Geoid*: This is the surface approximated by the Mean Sea Level (MSL). The force of gravity is uniform throughout and points vertically down towards the earth as a plumb line.
- *Ellipsoid*: This is a mathematical model that approximates the Geoid by rotating an ellipse about a polar axis. The polar axis of the ellipsoid is shown as "b" in Figure 46. This allows mathematical Calculations as the Geoid and terrain are too complex. The Plum line "Vertical" used in the Geoid differs from the "Vertical" used for the Ellipsoid.

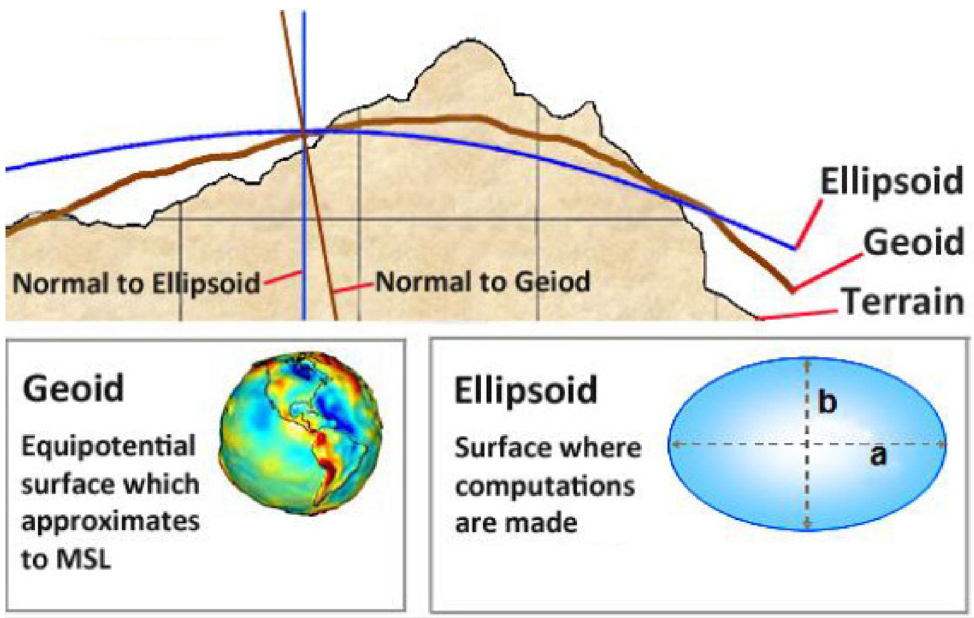


Figure 46 earth Surface represented by Ellipsoid, Geoid, and Terrain

ELEVATION AND HEIGHT

A reference elevation is established for the Drill floor from the Mean Sea Level. The Mean sea level changes with tides and varies at different times; Models such as the NAVD88 "North American Vertical Datum 1988" can provide a reference elevation for the Mean Sea Level. The GPS system can be used to provide the Height or reference of the ellipsoid from the reference Mean sea level. The correct reference elevation is required for Vertical Depth computations.

GEOGRAPHIC COORDINATES

Geographical coordinate system divides the earth into lines running from North to south called Meridian also known as longitudes and lines running from East to West called Parallels or latitudes. The reference Meridian runs through a point call Greenwich in England. Meridians run from 0° to 180° East of Greenwich and from 0° to 180° West of Greenwich. The Reference parallel is the Equator midway between the North and South Pole. Parallels run from the 0° (Equator) to the North Pole (90° North) and 0° Equator to the South Pole (90° South).

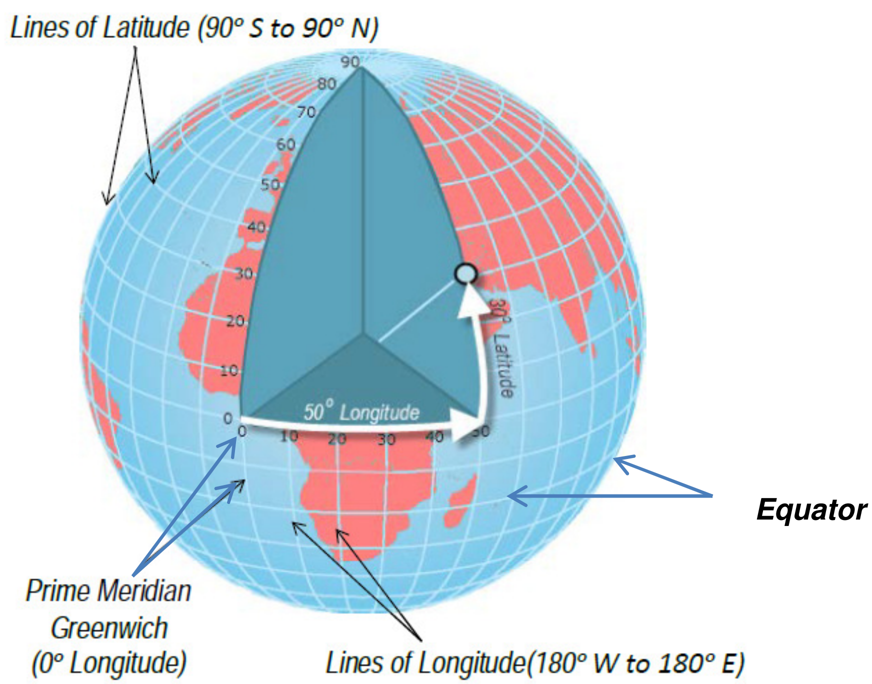


Figure 47 Latitude, Longitude Geographic coordinates

GEODETIC DATUM

A geodetic datum maps an ellipsoid to the earth's surface. There are two types of geodetic datum.

- *Local datum* created by observation of stars using specialized Survey Instrument. This type of geodetic datum can only be used regionally.
- *Global datum* created by observing the orbit of navigation satellites covers the entire surface of the earth. The WGS 84 is an example of a global datum used for the GPS system.

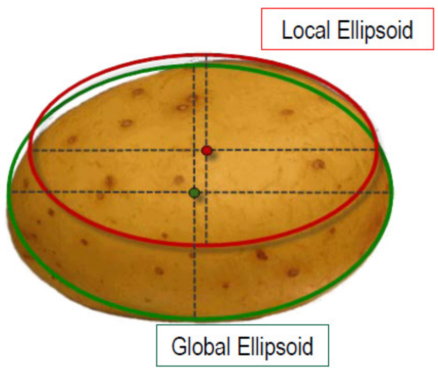


Figure 48 Local and Global Ellipsoid assigned to the earth's Surface

MAP PROJECTIONS

Map projections transform curved surface to flat plane. The 3D sphere is projected on to 2D paper. This is similar to an orange being open up and laid flat on a piece of paper. There are different ways to do this; common method uses projects the shadow of the Earth on a surface; this surface can be a cone, cylinder or flat paper as shown in Figure 49.

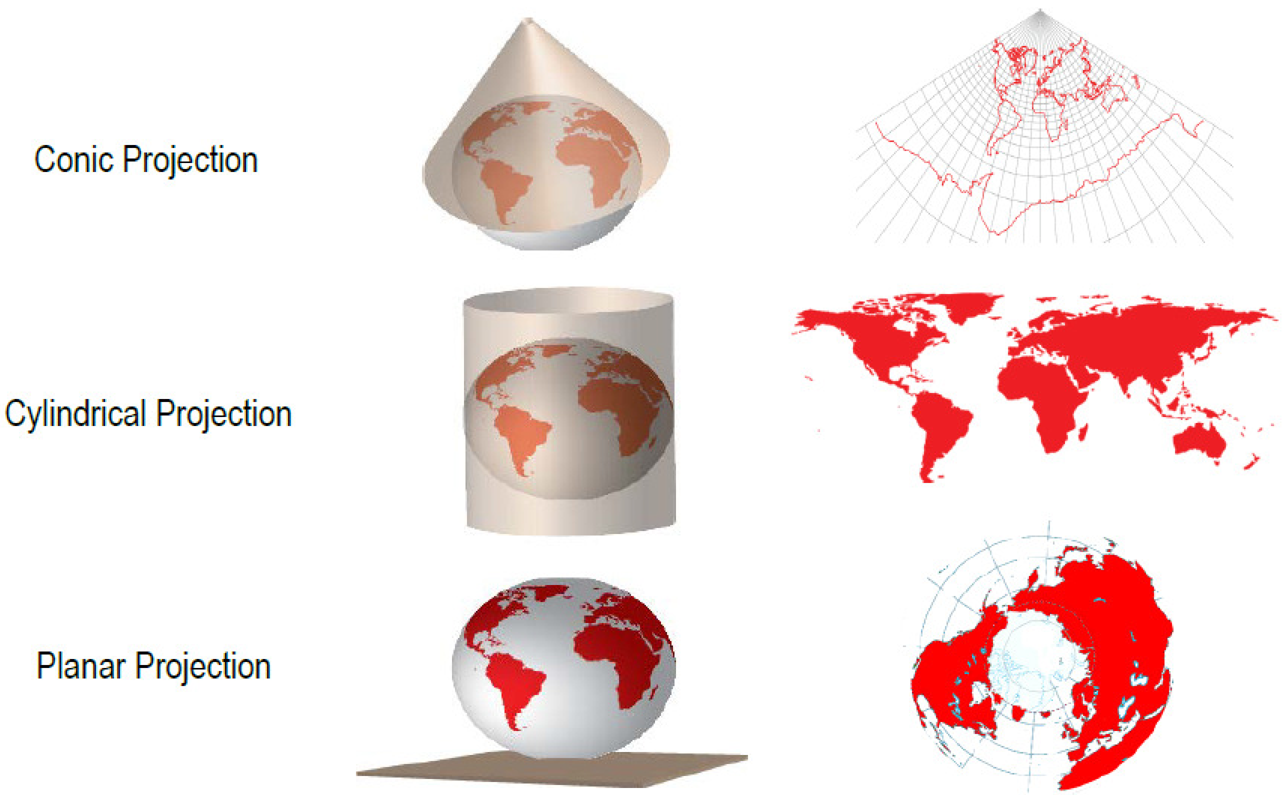


Figure 49 Cone, cylinder, planer projections

The two most common methods in the industry are the Universe Transverse Mercator system and the Lambert conformal projection.

Universe Transverse Mercator system projects the earth's surface on a cylinder and unwraps the cylinder into flat paper. The projection of the sphere is then divided into Longitudinal Zones.

1. A rectangular grid system is imposed on the projection with the Reference Latitude as the X axis and the Central meridian as the Y axis.

2. Northings are measured from the reference Latitude, Easting's are measured from the central meridian.
3. A scale factor is given to compensate for the distortion from plotting on a curved to flat surface.
4. A grid convergence is given for correcting the straight Grid North to curved Geographic North.

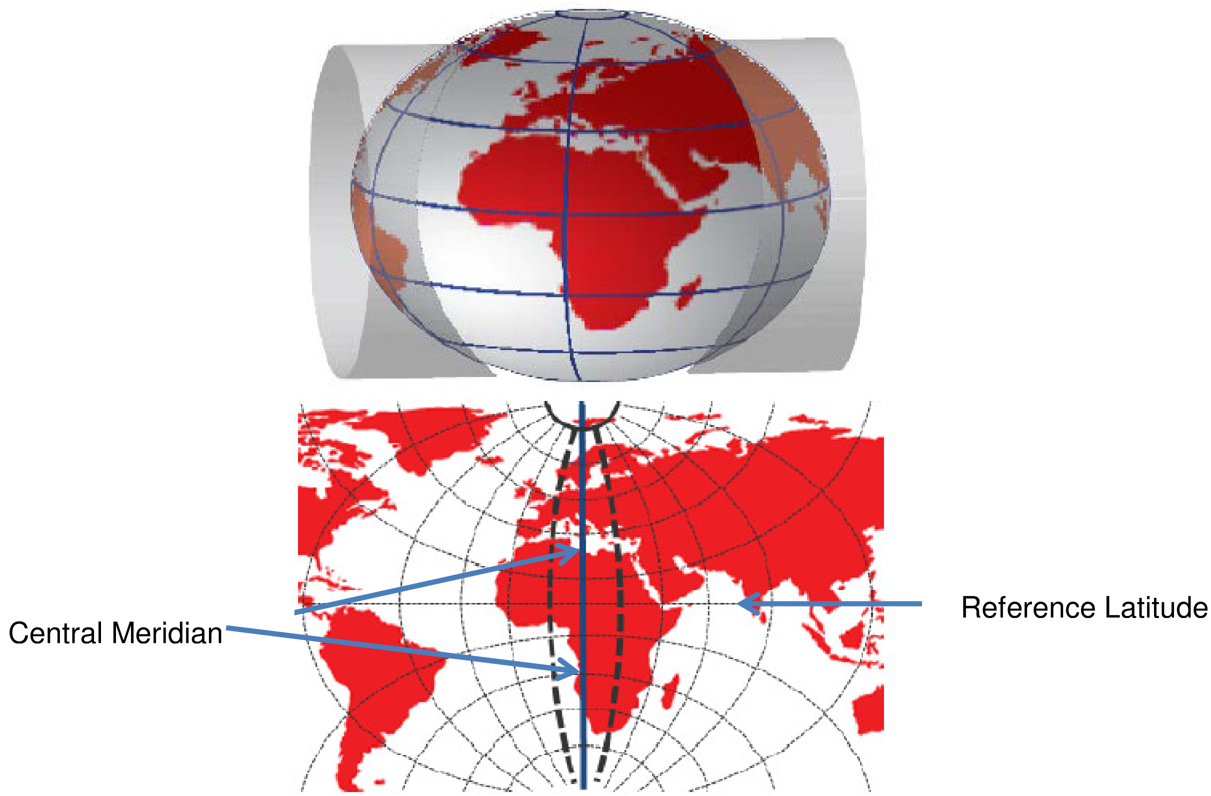


Figure 50 UTM System showing a grid projected from sphere onto paper

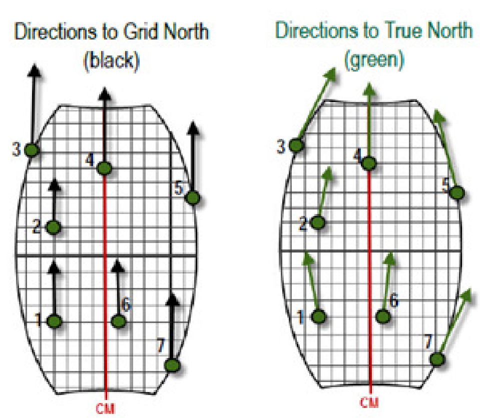


Figure 51 directions True North and grid North

An Example of data using the Transvers Mercator coordinate system is shown below:

Datum	*e.g. NAD83*
Projection Type	*e.g. Transverse Mercator*
Projection Name	*e.g. Mississippi State Plane Coordinate System*
Zone Name	*e.g. West*
Central Meridian	*e.g. 90°20' W*
Latitude of Origin	*e.g. 29°30' N*
Central Scale Factor	*e.g. 0.99975*
False Easting	*e.g. 2,296,583.333 (NB = 700,000 meters)*
False Northing	*e.g. 0*
Units	*e.g. US Survey feet*

Figure 52 Sample Data using TM projection

In the example given in Figure 52:

- NAD83 is the Geodetic datum
- The Mississippi state plane Transverse coordinate system projection is used
- Transverse Mercator system is divided into a number of longitudinal zones. West is the specific zone or grid used in this example
- 90° 20' W is the longitude of the central meridian for the West Grid or zone
- 29° 20' N is the latitude of the zone origin for the West zone
- 10,000ft measured on the surface will be 9997.5ft on paper
- A false Easting is given to avoid having a negative values

Lambert conformal projection: Lambert coordinates are derived from a conical, conformal projection of the earth's surface onto a flat plane. A conformal projection is one where the angles, and shape or form, of an area is not deformed. Lines of latitude (parallels) are unequally spaced arcs of concentric circles, more closely spaced near the center of the map. Instead of being tangent to the earth's surface, the Lambert cone is considered to penetrate the earth along one standard parallel and emerge along another, as shown in the Figure 53 Along the two standard lines of latitude (parallels) in a Lambert projection, the scale is exact. This means the scale is constant in the East-West direction.

Lines of longitude are equally spaced radii of the concentric circular arcs of lines of latitude, thereby cutting the lines of latitude at right angles. These meridians are represented by straight lines that meet at a common point outside the limits of the map. Along lines of longitude, the scale changes in the North-South direction. The pole in the same hemisphere as the standard parallels is a point. The other pole is at infinity.

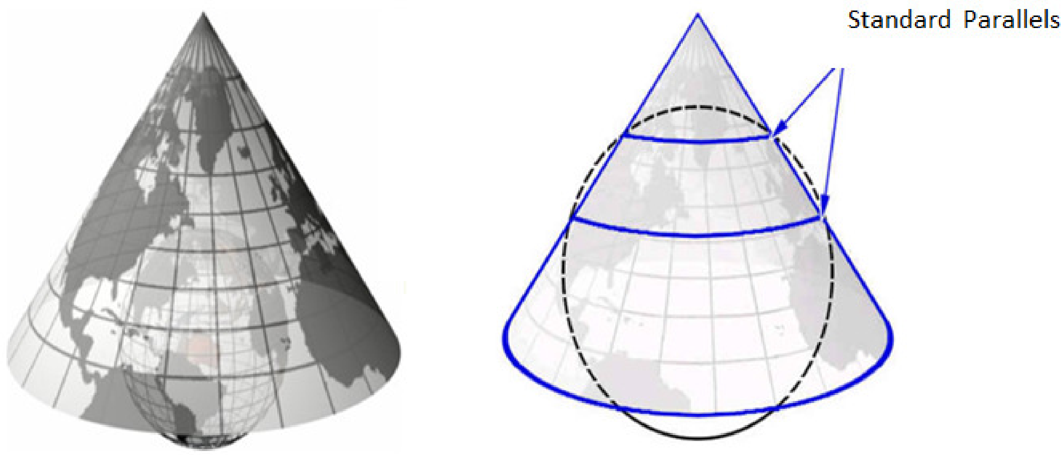


Figure 53 Lambert Conformal projection

A sample data with Lambert conformal projection is given below.

Datum	*e.g. NAD27*
Projection Type	*e.g. Lambert Conformal Conic*
Projection Name	*e.g. Texas State Plane Coordinate System*
Zone	*e.g. South Central*
Central Meridian	*e.g. 99°00' W*
Latitude of Origin	*e.g. 27 °50' N*
**North Standard Parallel*	*e.g. 30°17' N*
**South Standard Parallel*	*e.g. 28°23' N*
False Easting	*e.g. 2,000,000*
False Northing	*e.g. 0*
Units	*e.g. US Survey feet*

Figure 54 Sample Data with Lambert conformal projection

GRID CONVERGENCE

At any point on the surface of the earth we can point to the North Pole also known as the Geographic or True North. When using Mapping projections such as the Transverse Mercator map projections the earth's surface is divided into Grid systems. The North for these Grid systems is not always the same as the Geographic North.

In this example below the blue line represents the direction of the North (N) from point A. When using the Grid system which involves dividing the sphere into bands or "Grids" the direction of the Grid North "Na" is not the same as the True North.

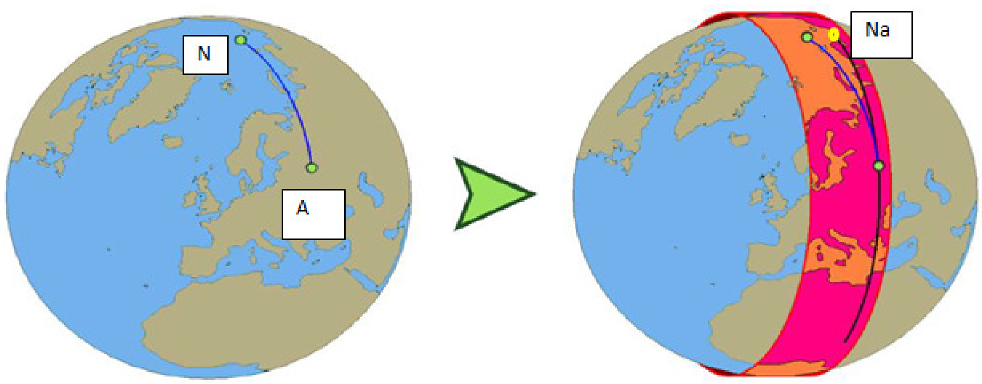


Figure 55 Geographic and Grid North

If the Grid or the Red cylinder wrapped cylinder on the earth in Figure 55 is unwrapped the two lines will appear as in Figure 56. There is an angle between the Grid North and True North. Because all True North lines converge to a single point, the angle from True to Grid North is referred to as the 'Convergence' Angle.

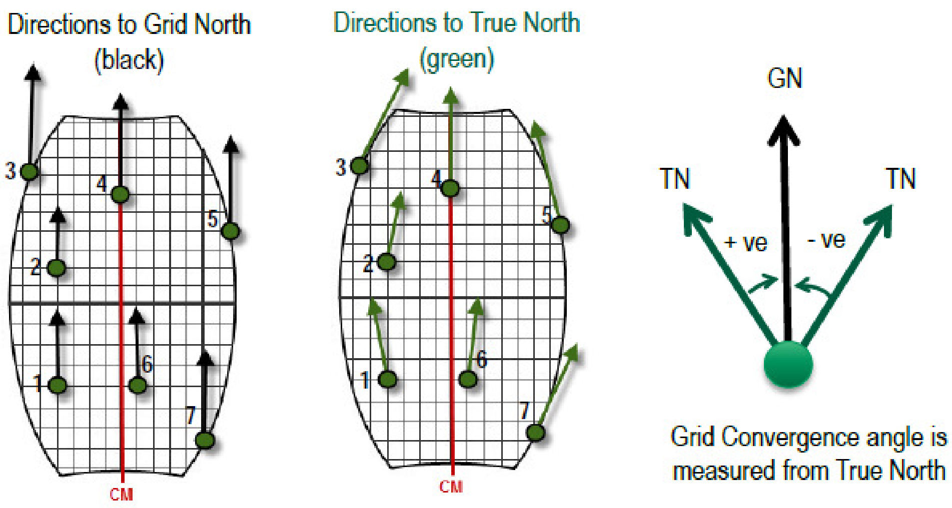


Figure 56 Grid Convergence

When converting the well reference from True North to Grid North the Grid Convergence has to be subtracted from the original Azimuth. It helps to draw an arrow diagram when visualizing the directions

DECLINATION CORRECTION, GRID CORRECTION, TOTAL CORRECTION

The Well Heading or Azimuth provided by the MWD tool is referenced to the magnetic North

If Azimuth is referenced to the magnetic North, Declination needs to be added to reference it to the True North (This correction is applied when the Client use the True North as the reference).

- If the magnetic North is on the right (East) of the True North, Declination is positive
- If the magnetic North is on the left (West) of the True North, Declination is negative

If Azimuth is referenced to True North, Grid convergence needs to be subtracted to reference it to Grid North (This correction is applied when the Client use the Grid North as the reference).

- If the Grid North is on the right (East) of the True North, Grid convergence is positive
- If the Grid North is on the left (West) of the True North, Grid convergence is negative

The Total correction needs to be applied in the XEM receiver software so that Well Azimuth can be corrected accordingly.

The total correction applied

= Declination if the Operator uses True North as the reference

= (Declination - Grid Convergence) if the Operator uses Grid North as the reference

Examples Correction from the Magnetic North reference to True north

1. In the Example below Figure 57

- The Well Heading is 88° referenced to the magnetic North
- Declination is - 8° (magnetic North is West of True North)
- The Well Heading then becomes 88° + (- 8°) = 80° referenced to the True North

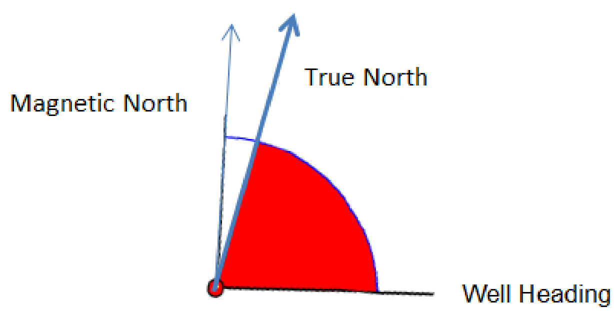


Figure 57 Declination Correction

2. In the Example below (Figure 58)

- The Well Heading is 60° referenced to magnetic North
- Declination is +15° (magnetic North is East of true North)
- The Well Heading then becomes 60°+15° = 75° referenced to the true North

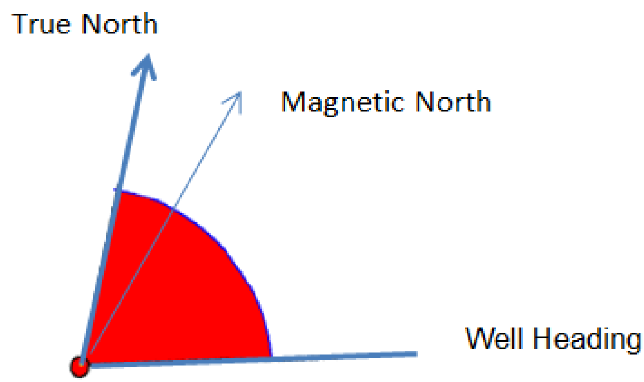


Figure 58 Declination Correction

Example Correcting from True North reference to Grid north

3. In the Example below in the Figure 59

- The Well Heading is 63° referenced to the True North
- Grid Convergence is + 3° (Grid North is East of true North)
- The Well Heading then becomes 60° – (3°) = 57° from the True North

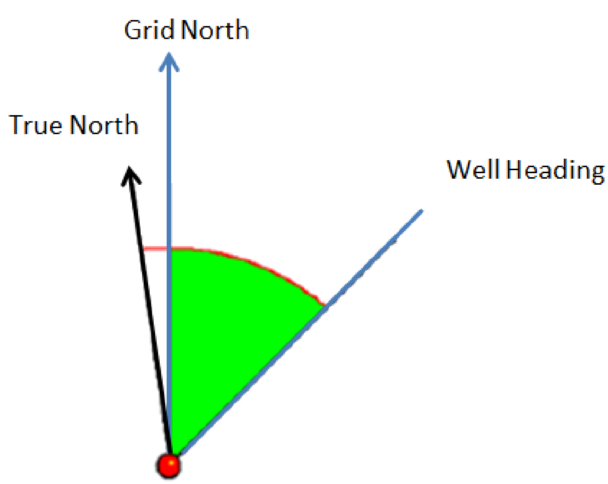


Figure 59 Grid Correction

4. In the Example below in the Figure 60

- The Well Heading is 312° referenced to the True North

- Grid Convergence is - 0.7° (Grid North is West of True North)
- The Well Heading then becomes 312.4° – (- 0.7°) =313.1° referenced to the Grid North

Figure 60 Grid correction

Example Correcting from magnetic North to True North and to Grid North

5. In the Example below in the Figure 61

- The Well Heading is 88° referenced to the magnetic North
- magnetic Declination is - 8°(Grid North is West of True North)
- Grid Convergence is - 2°(Grid North is West of True North)
- The Well Heading = 88°+(-8°) = 80° referenced to the True North

  = 80° - (-2°) = 82° referenced to the Grid North

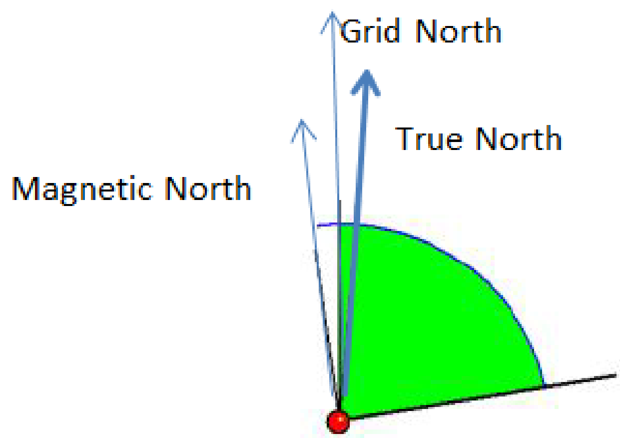


Figure 61 Total Correction

3.8. MAGNETIC INTERFERENCE

When using Magnetometers, magnetic interference can affect the Azimuth, magnetic tool Face and computed values for the Total magnetic Field and DIP. The two types of interference are:

External Interference: External objects such as casing, Nearby Wells, Fish left down hole due to stuck pipe, magnetic Formation including Pyrite & Hematite can cause interference on the MWD Surveys. In most cases, when the tool is approximately 30 feet away from the external source (Displacement), interference decreases and the Total magnetic Field, DIP seen on Surveys start to fall within the acceptance criteria. A Gyro which derives Azimuthal measurements from the earth’s rotation (instead of the magnetic field) should be used when there is external interference.

Drill string Interference: The Drill string (made from iron) becomes magnetized when rotating under the effect of the earth’s magnetic field. The Drill string components are like a chain of magnets. The direction of Interference is along the tool or X axis. The quantity of Drill string interference is constant for the same BHA.

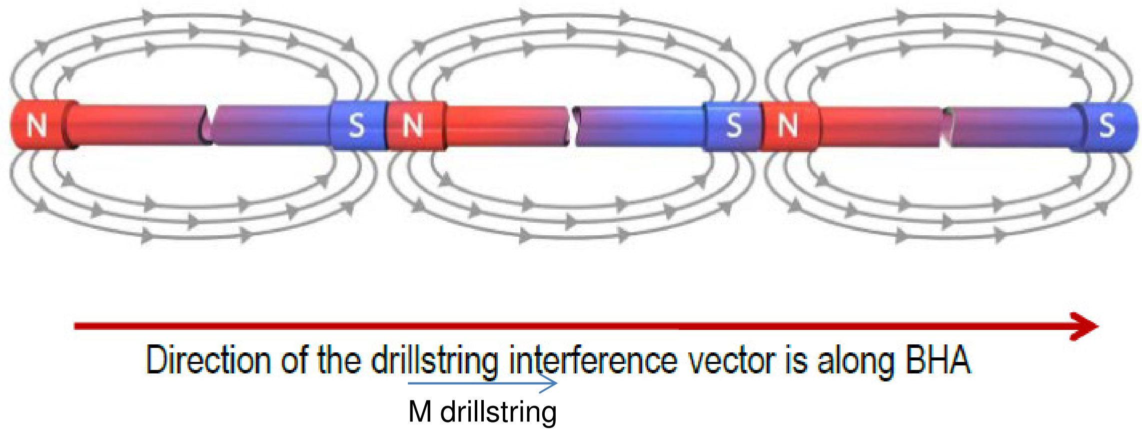


Figure 62 Drill string Interference

The Total magnetic Field Vector seen by the tool is a combination of the earth's magnetic field and the Drill string magnetic field.

$$\vec{M}_{Tool} = \vec{M}_{EARTH} + \vec{M}_{Drillstring}$$

Drills string interference affects X Axis Magnetometer measurements; Azimuth, magnetic Field strength and computed Dip.

Magnetic interference due to the Drill string can be reduced by isolating the XEM MWD tool with NMDC (Non Magnetic Drill collar) added above and below the tool.

When the tool is vertical the earth's magnetic field is projected on to the horizontal plane, the projection of the Drill string error on the horizontal plane is very small and The Total magnetic field seen by the tool is less affected by error; there is a small error in the Azimuth value.

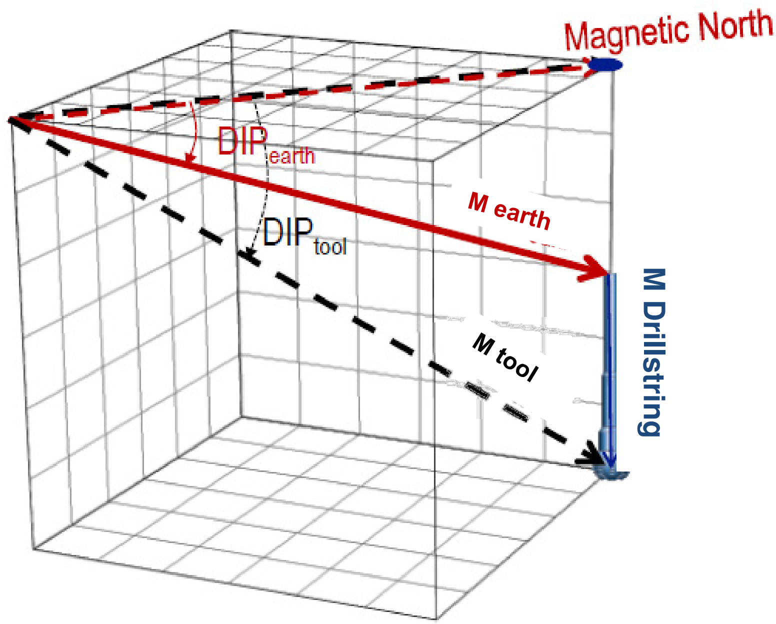


Figure 63 Drill string Interference on Vertical well

When the well has an inclination and is drilled towards the magnetic North/South, the projection of the drill string error on the horizontal plane increases. The Total magnetic field seen by the tool increases however it is in the same direction as the earth's magnetic field. (Figure 64)

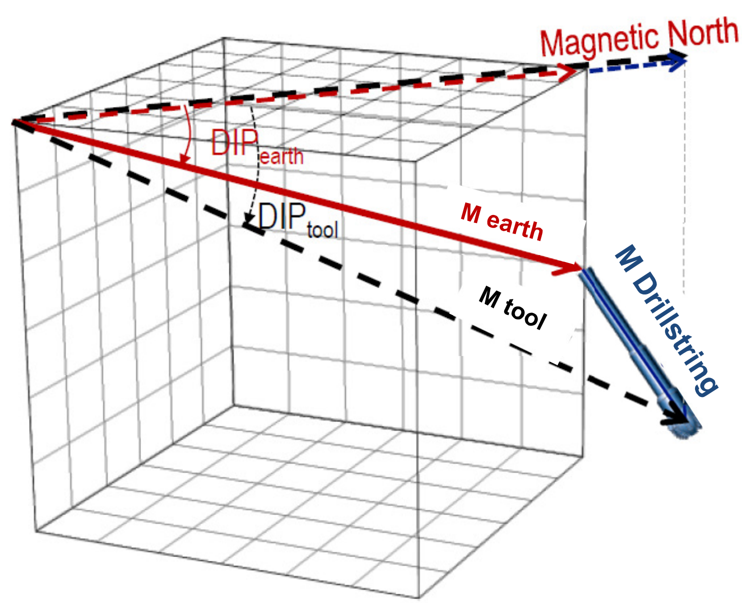


Figure 64 Drill String Interference on Deviated Well towards the magnetic North

When the Well is drilled in the East/ West direction there is a significant projection of the Error in the horizontal plane. This shifts the resultant Total magnetic field in the horizontal plane and the Azimuth value is affected significantly by the error. (Figure 65)

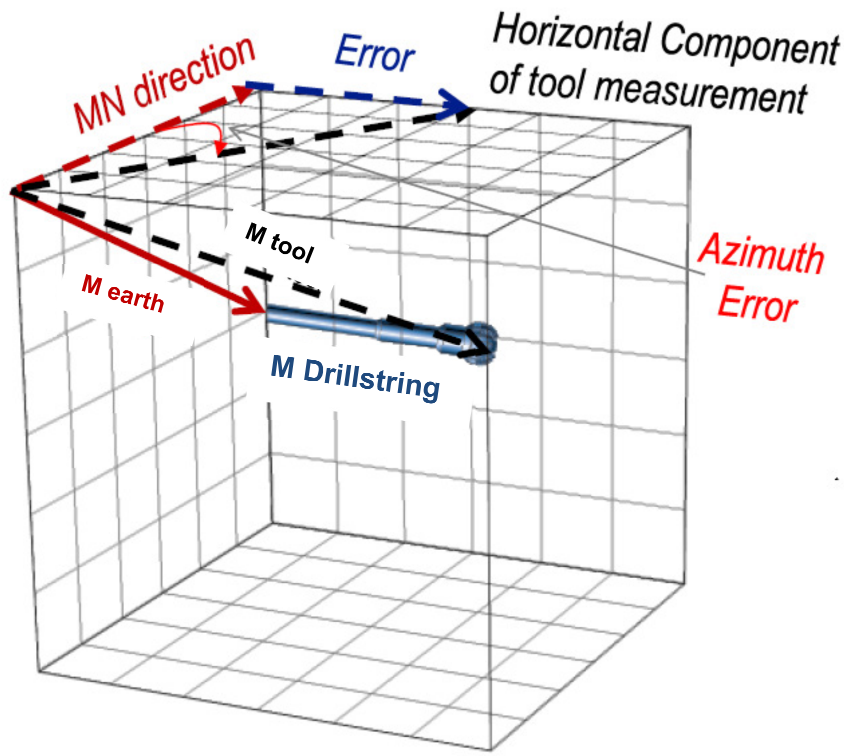
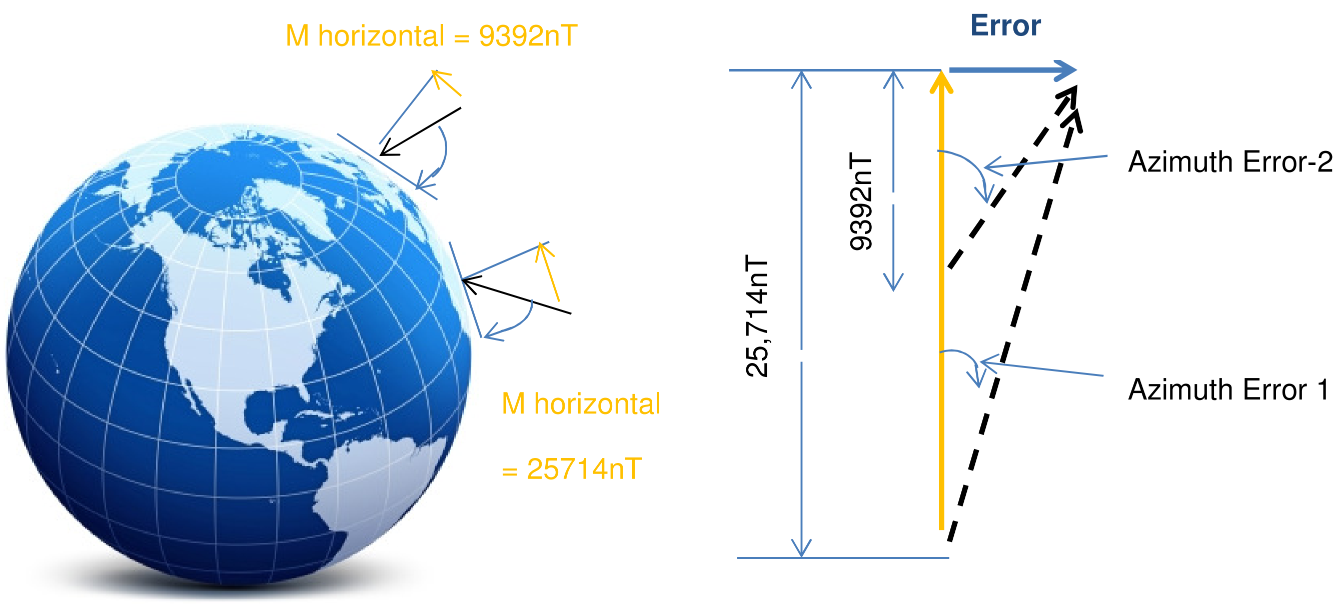


Figure 65 Drill String Interference Deviated Well towards the East/West

When drilling in places with high Latitudes the horizontal component of the earth's magnetic field is small (3992nT in Alaska), as opposed to (25,7114nT in the Gulf of Mexico). The Error is the same in both places. The effect of the error on the Azimuth is much more significant in Alaska. (Figure 66)



Azimuth Error 2 (Higher Latitude) > > Azimuth Error 1 (Low Latitude) with the same error

Figure 66 Azimuth Error at High Latitude

In Summary

Drill string Interference is constant for the same BHA

The Azimuthal Error is smaller when drilling

- At Low Inclination
- Close to the magnetic North

The Azimuth Error is greater when drilling

- At higher Inclination
- Drilling East /West
- At higher latitude

3.9. ESTIMATION OF DRILL STRING INTERFERENCE

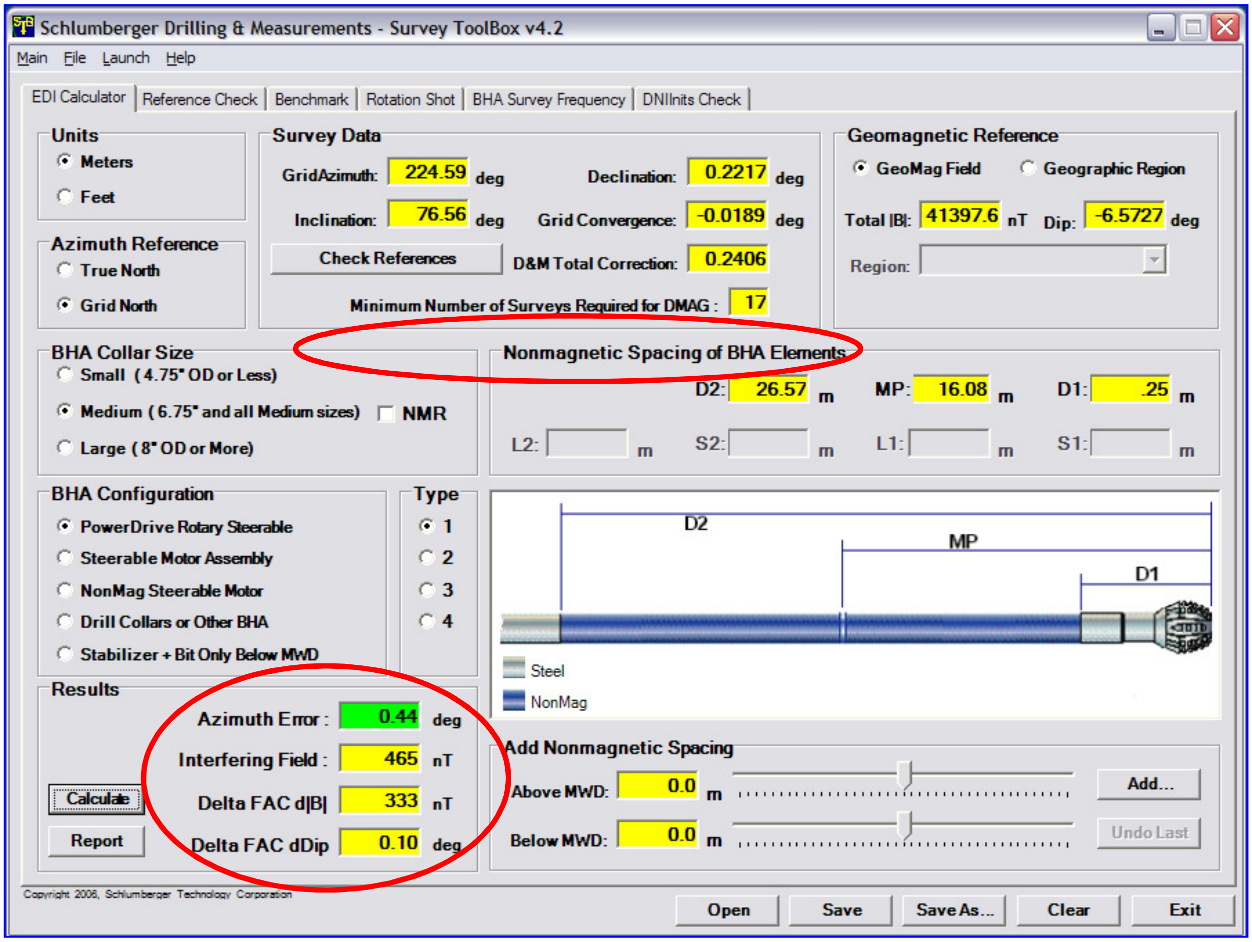


Figure 67 Survey tool Box user interface

The Schlumberger Survey tool Box program estimates the Drill String Interference during the job planning phase. If Azimuth error due to Drill sting interference > 0.5°, NMDC Non Mag collars can be added above or below the MWD to increase the spacing from magnetic materials. If it is not possible to add NMDC due to availability or drilling constraints an alternative is to use the *Schlumberger DMAG* software to correct Azimuth error. This should however be carried out as a last resort after discussions with the District Engineers.

The Estimation of Interference estimates axial interference based on:

- The Pole strength of the Magnetized components that make up the BHA and the non mag spacing from the magnetometers.
- Effect of orientation of the BHA relative to the earth's magnetic field.

Inputs Include:

- *Unit: feet or meters.*
- *Azimuth Reference: Azimuth referenced to True or Grid North.*
- *Survey Data:* This includes the Worst case for the planned trajectory in the well. Based on the well plan a table is created for planned Survey stations. The Absolute value of the product of Sin (inclination) & Sin (Azimuth) is calculated at each planned station. Worst case Inclination and Azimuth values are taken from the Survey with the highest product value. In Table below the Survey at 1000ft has the highest product value 0.66. Based on this Inclination = 50° and Azimuth = 120° should be used.

WORST CASE SENARIO

Depth	Inc	Azi	Sin(inc)	Sin (Azi)	ABS|Sin(inc)*Sin(azi)|
0.00	0.00	60.00	0.00	0.87	0.00
200.00	10.00	80.00	0.17	0.98	0.17
400.00	20.00	90.00	0.34	1.00	0.34
600.00	30.00	100.00	0.50	0.98	0.49
800.00	40.00	110.00	0.64	0.94	0.60
1000.00	50.00	120.00	0.77	0.87	0.66
1200.00	60.00	140.00	0.87	0.64	0.56
1400.00	70.00	140.00	0.94	0.64	0.60
1600.00	80.00	150.00	0.98	0.50	0.49
1800.00	90.00	160.00	1.00	0.34	0.34
2000.00	90.00	180.00	1.00	0.00	0.00

Table 4 Worst Case Surveys for Survey tool Box

- *The Declination, Grid convergence and Total correction* for the location are required.
- *Geomagnetic reference* includes either the Total magnetic Field strength & DIP or Geographic Region.
- *BHA type*: Includes the magnetic and NMDC components in the BHA. There are 4 types of BHA. A schematic of the BHA type 1 is illustrated in figure 67.
- *Non Mag Spacing of BHA elements*: Type 1 BHA requires the following
- *MP:* Survey Measurement Point offset from the Bit (Location of the Magnetometers).
- *D1:* Starting offset from bit for Nonmagnetic material below MWD.

- *D2*: Ending offset from bit for Nonmagnetic material above MWD.
- *BHA Configuration*: This includes the type of Drill string components; some have more metal and create more interference than others. The example in Figure 67 has a Powerdrive in the BHA.
- *BHA Collar Size:* The Includes the nominal OD of the BHA components. In this case BHA OD is 6.75".

The Results Include:

- Azimuth Error:This is the expected error in measured azimuth due to drill string interference. If the error > 0.5°s, more non-mag must be added to isolate the survey sensor in the BHA so that the error can be reduced to ≤ 0.5°.
- DELTA FAC d |Dip|: This is the expected error in magnetic DIP due to drill string interference. If this value is ≤ 0.45° the error is negligible and can be ignored. If the value is above 0.45° (e.g. 1.1deg) there is a very high chance the survey Dip values during the job will be in the range of +/-1.1deg of the Geomag calculated value during the job.

On the job if the difference between the computed DIP and the Geomag reference:

- Is > 0.45° but < the DELTA FAC d |Dip| criteria, the error is likely due to drill string interference provided there are no other issues (survey method, failed sensors, etc.).
- Is > than 0.45° & also > DELTA FAC d |Dip| (e.g 1.8°) the error could be due to (casing, fish, calibration, failed sensor etc.) instead of drill string interference.

DELTA FAC d |H|: This is the expected error in Total magnetic field value due to drill string interference. If this value < 300nT error is negligible and can be ignored. If the value > 300nT (e.g. 500nT) there is a very high chance the survey total magnetic field strength values will be in the range of +/-500nT of the Geomag calculated value during the actual job.

On the job, if the difference between the total magnetic field from the tool and the reference:

- Is > 300nT but < DELTA FAC d*/H/* criteria, the error is likely due to drill string interference. If there are no other issues (survey method, failed sensor etc.).
- Is > 0.45° & also > DELTA FAC */H/* (e.g1.8°) there is a high chance there are other reasons for the error (casing, fish, calibration, failed sensor etc.) the error could be due to (casing, fish, calibration, failed sensor etc.) instead of drill string interference.

When it is likely that the error is due to drill string Magnetism, the surveys can be corrected by the DMAG software. If there are no critical concerns with the well trajectory the Survey may be reported and corrected by DMAG latter.

When it is likely that the error is due to other sources, the Surveys cannot be corrected; the root cause of the error has to be investigated before drilling ahead (In cases of Deviated Wells).

MINIMUM NUMBER OF SURVEYS TO RUN DMAG: The DMAG software (explained latter) corrects Azimuth values for drill string interference. A number of Surveys are required to train the software. These surveys should have no other problem except drill string interference. That means if some surveys have casing, fish, nearby well interference, or driller moved the pipe, e.t.c they do not count. The number indicated here represents the minimum number of Surveys

This output provides the number of Surveys that are required to train the Survey tool Box .If the Survey tool Box output says 20 surveys are needed and only 12 surveys are available; the DMAG result will not be as accurate as can be. The solution is just to take the extra surveys randomly at any time or depth while drilling or at TD. These extra surveys can also be taken after slow pump rates, after pumping pills, when the Power Drive is about to be down linked, at TD, while circulating bottoms up. The depth for the extra surveys also does not matter.

Interfering field means the estimate of the magnitude of the magnetic field generated by the BHA that will interfere with the D&I package. This is a reference value.

Assumptions

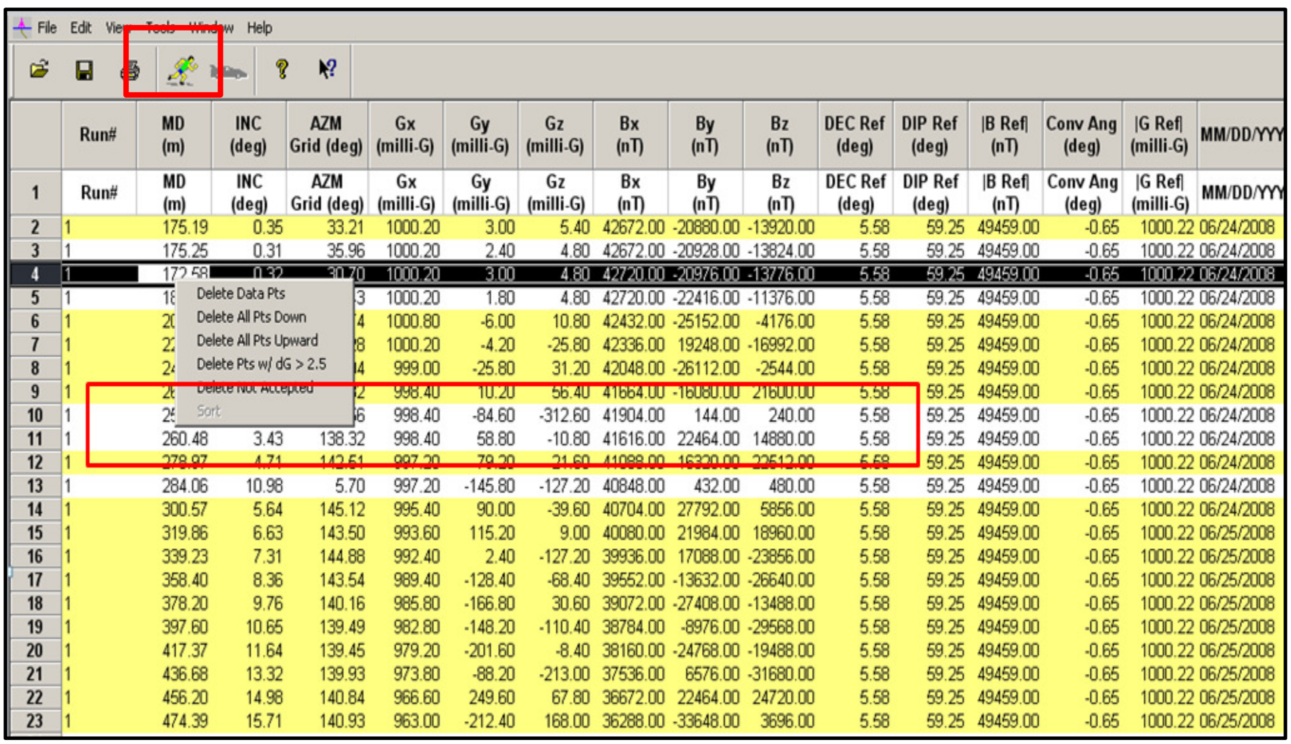
The Survey tool Box is not an absolute values but an estimate at best. The following are some assumptions:

- All steel components have the same material & all NMDC have the same material.
- It does not account for stabilizer size, so it assumes a steel stabilizer will have the same interference as a steel sub the same length.
- It calculates the same amount of interference from an 8 1/4” & 9 ¼” Motor.
- It does not account for differences in the ID of the components.

DRILLSTRING MAGNETIC CORRECTION

DMAG is a Schlumberger Multi-station program used to correct Drill string interference. This program trains itself with a number of input Surveys using raw accelerometers and magnetometers including Gx, Gy, Gz, MX, BY, BZ (DMAG uses the term B instead of M & G instead of A).

- Only Surveys affected by Drill string interference can be corrected.
- A minimum number of Surveys are required to train the software. Low Inclination Wells require few 6-10 good quality Surveys, High Inclination, East-West require 15-25 good quality Surveys.
  - Surveys affected by Pipe Movement, Incorrect Declination/ Grid convergence, tool failures, External Interference (Casing, Formation, Fish, Nearby wells) cannot be corrected.
  - The DMAG correction algorithm will have issues correcting Surveys that are both above 85° inclination and within 5° azimuth of either due east or due west. Expert guidance from a Survey Specialist must be obtained to validate the DMAG results in this case
  - DMAG magnetically characterizes the BHA. So if any component in the BHA is changed out, processing must be restarted using only surveys taken with that BHA.



	Run#	MD (m)	INC (deg)	AZM Grid (deg)	Gx (milli-G)	Gy (milli-G)	Gz (milli-G)	Bx (nT)	By (nT)	Bz (nT)	DEC Ref (deg)	DIP Ref (deg)	|B Ref| (nT)	Conv Ang (deg)	|G Ref| (milli-G)	MM/DD/YYY
1	Run#	MD (m)	INC (deg)	AZM Grid (deg)	Gx (milli-G)	Gy (milli-G)	Gz (milli-G)	Bx (nT)	By (nT)	Bz (nT)	DEC Ref (deg)	DIP Ref (deg)	|B Ref| (nT)	Conv Ang (deg)	|G Ref| (milli-G)	MM/DD/YYY
2	1	175.19	0.35	33.21	1000.20	3.00	5.40	42672.00	-20880.00	-13920.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
3	1	175.25	0.31	35.96	1000.20	2.40	4.80	42672.00	-20928.00	-13824.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
4	1	172.58	0.32	30.70	1000.20	3.00	4.80	42720.00	-20976.00	-13776.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
5	1	[illegible]	[illegible]	[illegible]	1000.20	1.80	4.80	42720.00	-22416.00	-11376.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
6	1	[illegible]	[illegible]	[illegible]	1000.80	-6.00	10.80	42432.00	-25152.00	-4176.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
7	1	[illegible]	[illegible]	[illegible]	1000.20	-4.20	-25.80	42336.00	19248.00	-16992.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
8	1	[illegible]	[illegible]	[illegible]	999.00	-25.80	31.20	42048.00	-26112.00	-2544.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
9	1	[illegible]	[illegible]	[illegible]	998.40	10.20	56.40	41664.00	-16080.00	21600.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
10	1	[illegible]	[illegible]	[illegible]	998.40	-84.60	-312.60	41904.00	144.00	240.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
11	1	260.48	3.43	138.32	998.40	58.80	-10.80	41616.00	22464.00	14880.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
12	1	278.97	4.71	142.51	997.20	79.20	21.60	41088.00	16320.00	22512.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
13	1	284.06	10.98	5.70	997.20	-145.80	-127.20	40848.00	432.00	480.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
14	1	300.57	5.64	145.12	995.40	90.00	-39.60	40704.00	27792.00	5856.00	5.58	59.25	49459.00	-0.65	1000.22	06/24/2008
15	1	319.86	6.63	143.50	993.60	115.20	9.00	40080.00	21984.00	18960.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
16	1	339.23	7.31	144.88	992.40	2.40	-127.20	39936.00	17088.00	-23856.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
17	1	358.40	8.36	143.54	989.40	-128.40	-68.40	39552.00	-13632.00	-26640.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
18	1	378.20	9.76	140.16	985.80	-166.80	30.60	39072.00	-27408.00	-13488.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
19	1	397.60	10.65	139.49	982.80	-148.20	-110.40	38784.00	-8976.00	-29568.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
20	1	417.37	11.64	139.45	979.20	-201.60	-8.40	38160.00	-24768.00	-19488.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
21	1	436.68	13.32	139.93	973.80	-88.20	-213.00	37536.00	6576.00	-31680.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
22	1	456.20	14.98	140.84	966.60	249.60	67.80	36672.00	22464.00	24720.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008
23	1	474.39	15.71	140.93	963.00	-212.40	168.00	36288.00	-33648.00	3696.00	5.58	59.25	49459.00	-0.65	1000.22	06/25/2008

Figure 68 INPUTS TO DMAG

Figure 68 shows a batch of Surveys that need to be corrected for Drill string interference. The information in the Survey batch includes:

- Depth, Inclination and Azimuth.
- Gx, Gy, Gz, Bx, By, Bz. Reference values (Declination, DIP, Field strength (B), Grid Convergence, gravity).

Figure 69 below shows the corrected results for the INCc, AZIc, Gxc, Gyc, Gzc, Bxc, Byc, and Bzc.

- A QC column labels the Surveys that have been corrected with reasonable confidence as good.

DMAG - [DMAG Corrected Static Surveys]

File Edit View Tools Window Help

	Run#	MD (m)	INCc (deg)	AZMc Grid (deg)	Gxc (milli-G)	Gyc (milli-G)	Gzc (milli-G)	Bxc (nT)	Byc (nT)	Bzc (nT)	QC	AZM_Unc (deg)	dG (milli-G)	dB (nT)	dDIP (deg)	dAZM (deg)
1	Run#	MD (m)	INCc (deg)	AZMc Grid (deg)	Gxc (milli-G)	Gyc (milli-G)	Gzc (milli-G)	Bxc (nT)	Byc (nT)	Bzc (nT)	QC	AZM_Unc (deg)	dG (milli-G)	dB (nT)	dDIP (deg)	dAZM (deg)
2	1	175.19	0.35	37.25	1000.09	2.60	5.60	42615.78	-20829.29	-1394[illegible].41	Good	9.64	-0.11	-18.87	-0.01	4.04
3	1	203.60	0.73	115.79	1000.69	-6.40	11.00	42375.91	-25098.65	-420[illegible].69	Good	4.80	0.55	-29.02	0.01	1.05
4	1	223.21	1.49	125.32	1000.09	-4.60	-25.60	42279.97	19273.98	-1701[illegible].74	Good	2.49	0.21	23.13	0.20	-0.96
5	1	242.25	2.34	127.20	998.89	-26.20	31.39	41992.14	-26058.06	-257[illegible].57	Good	1.75	-0.49	28.12	0.07	0.16
6	1	261.84	3.29	135.79	998.29	9.79	56.59	41608.36	-16032.25	2155[illegible].34	Good	1.40	-0.28	69.71	0.08	0.48
7	1	278.97	4.69	142.87	997.09	78.79	21.79	41032.69	16347.78	2247[illegible].84	Good	1.19	0.21	97.74	0.19	0.36
8	1	300.57	5.62	145.25	995.29	89.58	-39.39	40648.92	27812.71	582[illegible].87	Good	1.12	-0.13	137.36	0.21	0.13
9	1	319.86	6.61	143.76	993.49	114.78	9.20	40025.28	22008.29	1892[illegible].77	Good	1.07	-0.08	-18.30	-0.07	0.26
10	1	339.23	7.29	144.67	992.29	2.00	-126.98	39881.36	17115.31	-2387[illegible].02	Good	1.04	0.16	72.10	0.13	-0.21
11	1	358.40	8.38	143.26	989.29	-128.79	-68.19	39497.58	-13585.75	-26654.51	Good	1.02	-0.26	89.91	0.14	-0.28
12	1	378.20	9.79	139.99	985.69	-167.18	30.79	39017.86	-27353.26	-13509.64	Good	0.99	0.02	69.83	0.09	-0.17
13	1	397.60	10.66	139.24	982.69	-148.59	-110.18	38730.03	-8932.62	-29580.92	Good	0.98	-0.27	87.32	0.15	-0.25
14	1	417.37	11.67	139.25	979.09	-201.98	-8.20	38106.39	-24714.89	-19506.[illegible]9	Good	0.97	-0.48	-28.02	-0.02	-0.20
15	1	436.68	13.32	139.75	973.69	-88.59	-212.76	37482.75	6609.79	-31691.[illegible]8	Good	0.96	0.37	68.92	0.14	-0.18
16	1	456.20	14.96	141.06	966.49	249.17	67.98	36619.25	22488.00	24677.6[illegible]	Good	0.95	0.18	95.67	0.15	0.22

Figure 69 OUTPUTs from DMAG

4. DYNAMX

4.1. INTRODUCTION

Shock and Vibration causes:

- Damaged bits and drill string components.
- Drilling to slow down; some of the energy that will be used for drilling is lost due to shock and vibration thus decreasing the Rate of penetration.

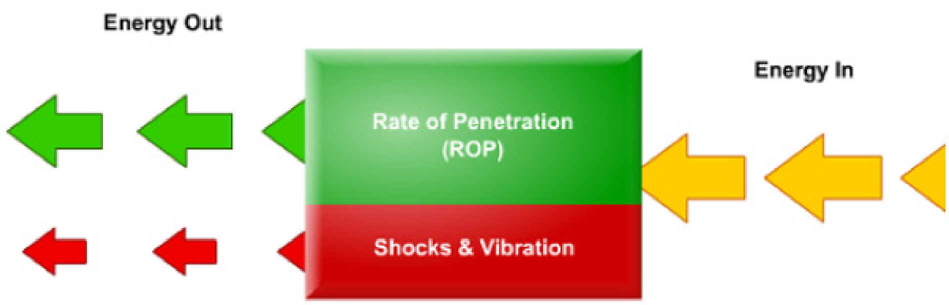


Figure 70 Reduced ROP due to S&V

- Fatigue in Drill string components when they are exposed to shock and vibration. This results in Twist offs, Washout in string components and Invaded tools.
- Over gauged hole; this may require more cement volume (after drilling) thus increasing the well cost.

The DynamX probe monitors shock and vibration and can be used to:

- Reduce Drilling risk due potential twist offs, washouts and invasion in drill string components.
- Reduce the overall cost of drilling.
- Optimize drilling performance by adjusting drilling parameters including Weight on Bit and RPM
- Data is provided in Real Time through WITS; Recorded Memory data is also available for post-run analysis and optimization of drilling parameters for subsequent runs.
- Provides a “traffic light system” for easy identification of risk levels at the drill floor.

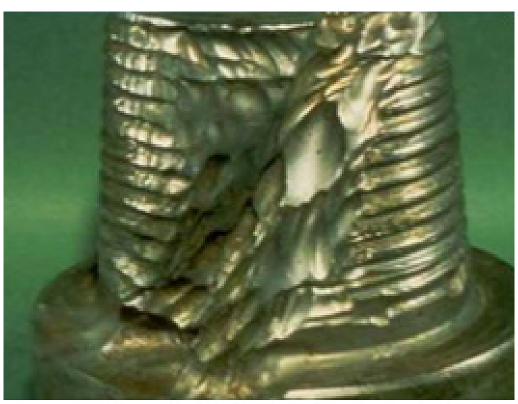
EXAMPLES OF SHOCK & VIBRATION

Failure due to fatigue from torsional shocks

Damaged Insert Bit due to axial shocks

Cracked Drill pipe due to axial shocks

Stabilizer Damage



Washout accelerated due to Shock & Vibrations

Figure 71 Examples of Shock & vibration

4.2. SHOCK & VIBRATION

SHOCK

Shock is an instantaneous violent shake experienced when the Drill String collides with formation during the process of drilling. The amplitude or energy is measured in "G".

- 1 G = force of gravity.

VIBRATION

Vibration is the dissipation of energy after acquiring the shock. The string tries to keep moving in alternately opposing directions till the energy absorbed is dissipated. Excessive Vibrations are seen during Air drilling conditions as there is no mud to absorb or dampen the shock energy.

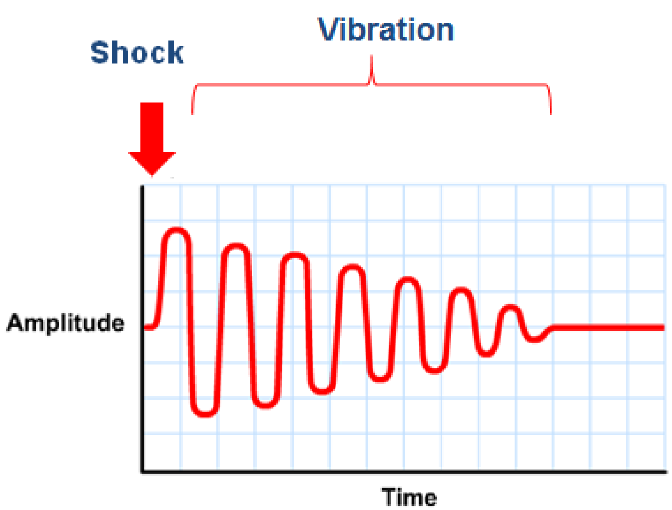


Figure 72 Shock & Vibration

XEM SHOCK AND VIBRATION MEASUREMENTS

The DynamX probe has 3 Axis accelerometers used for Lateral and Axial Shock measurements. Axial shock is associated with up and down motion of the BHA; Sometimes the string can be seen moving up and down on surface while drilling; this is referred to as bit bounce. Axial shocks are one of the main reasons for damaged bits.

Lateral shocks are associated with sideways motion and associated with poor BHA stabilization resulting in damages to drill string components.

Accelerometers register a shock count per second when the shock value exceeds a user defined threshold for Gs (default value is set at 50G); Shocks exceeding the absolute value of (+/-50G) will be registered as a shock count. As an example, in the Figure 73 an initial shock of 150G is experienced by the tool which eventually dampens out. During the process of dampening it causes other shocks to be registered. The shock threshold is 50G. A total of 12 shocks which have amplitude>Absolute (+/- 50G) are registered over a period of 1 second.

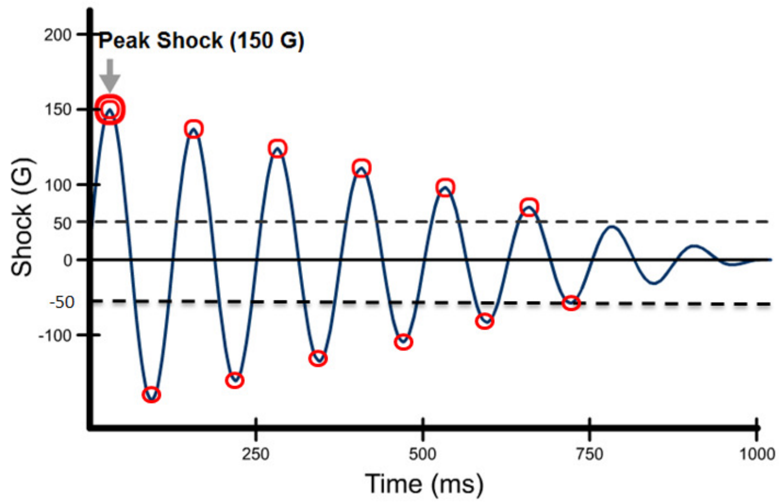


Figure 73 Peak Shock & additional shocks above (+/- 50G)

The Shock count value taken every second is averaged over a 30 seconds period. Based on the average value a shock Risk level is computed by the tool. Shock Risks can be defined for user defined values if the shock counts/per second exceed user defined thresholds. The default Shock-risk values are given in the Table below:

Shock Risk	Shock Risk Level	Shocks>50G's
0	None	cps≤ 2
1	Low	2≤ cps ≥30
2	Med	30≤ cps ≥100
3	High	cps ≥ 100

Table 5 Shock Risk Levels

- *Level-3* indicates "high" shock Risk level. Drilling parameters (RPM, Weight on Bit) need to be changed to avoid an imminent string failure. In some cases the string has to be lifted off bottom to change the parameters to dissipate the energy.

- *Level-2* indicates "medium" shock Risk level. Drilling parameters (RPM, Weight on Bit) need to be changed to avoid a likely shock failure.

- ***Level-1*** indicates a "low" shock Risk level or risk. Even with a low level the string accumulates cumulative fatigue which over a long period of time can cause failure.

The XEM is run in Air drilling Operations where it is common to see excessive shocks. It is recommended to carry out Misting to lubricate the hole at 10-15 gpm (if possible) to reduce shocks and vibration on the string. Misting also improves the quality of the EM signal.

4.3. RPM/STICK & SLIP MEASUREMENTS

STRING RPM (REVOLUTIONS PER MINUTE)

The XEM provides down-hole string revolution per minute measurements as seen by the DYNAMX probe. The DynamX probe has 2 x Magnetometers, MAG Y and MAG Z perpendicular to one another and to the tool axis. When the drill string rotates 1 revolution, the Magnetometers turn around and see variation in the earth's magnetic from minimum to maximum. The number of sinusoids are counted over a 20 seconds period and multiplied by 3 to provide the "Revolutions per minute" measurement.

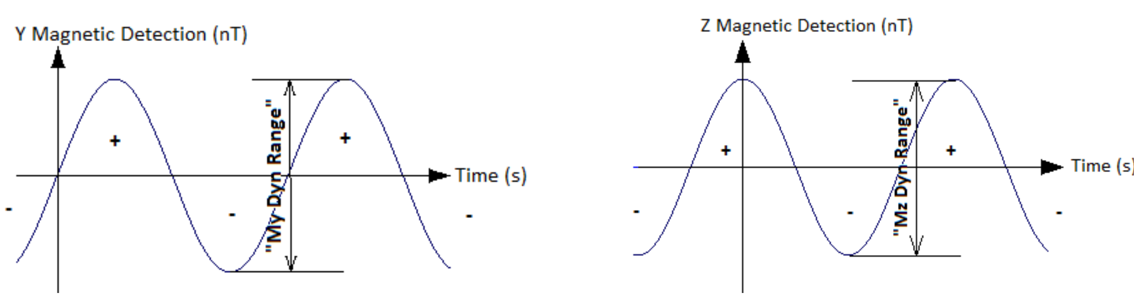


Figure 74 RPM Measurements from Magnetometers

INSTANTANEOUS STRING RPM (REVOLUTIONS PER MINUTE)

The string rotation RPM is measured over a 1 minute period. During the One minute period the value of the RPM can change considerably. As such is it is necessary to provide an instantaneous RPM which is updated every second.

The 2 Magnetometers in the DYNAMX module are offset at 90˚, plotting the responses from the values from the y and Z magnetometer over time results in a circle. The angle difference between the 2 points is dΘ in 1 second gives the Instantaneous RPM.

$$Instantaneous\ RPM = \frac{\mathrm{d}\Theta}{dt}, \text{ where } \Theta = \arctan(\frac{\mathrm{Mag\ Y\ response}}{Mag\ Xresponse})$$

Equation 17 Instantaneous RPM

To minimize noise Weighted averaging is taken from 4 points to compute the instantaneous RPM. Instantaneous RPM is used to calculate Stick Slip, Negative RPM, and Stall Threshold and provide a Rotation flag to the Tool.

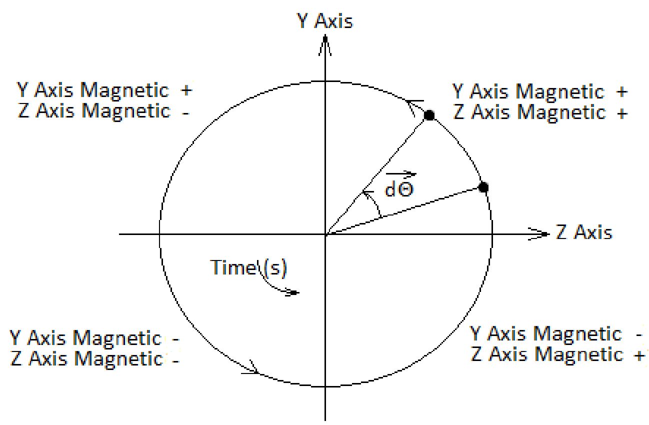


Figure 75 Instantaneous RPM

STICK SLIP MEASUREMENT

When rotating in the hole the string experiences friction causing the speed to slow down while turning, this causes energy to be trapped in the string while turning, when the trapped energy is suddenly released the string moves very fast. The fast and slow movement of the string is called Stick and Slip. This can also be seen as fluctuations in surface torque and surface rpm. Stick and Slip is expressed as a % between the maximum and minimum RPM. This amount of Stick and slip varies with the speed of rotation, configuration of the BHA and the lubricity of the Mud. Sometimes in extreme cases of stick and slip the string stops turning; there are periods of no rotation.

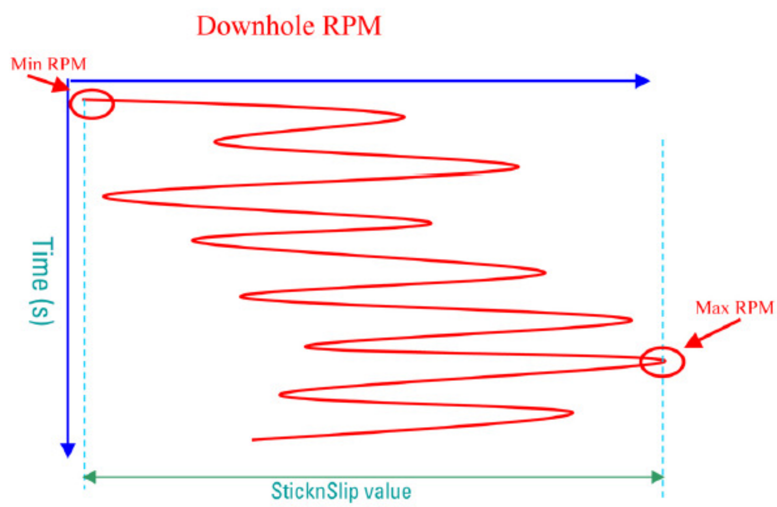


Figure 76 Stick and Slip due to change in RPM

During a User Defined period (25 seconds default) the tool measures the minimum and maximum Instantaneous RPM values. The Stick Slip is computed as a Percentage with the equation below:

$$Stick\ Slip\ \% = \left(\frac{Max\ Instantaneous\ RPM - Min\ Instantaneous\ RPM}{2 *\ String\ RPM}\right) X100\%$$

Equation 18 Stick & Slip computation

Thresholds are set for the Stick and slip values as follows. The Maximum and Minimum values for the instantaneous RPM are given in the Table below.

Stick Slip%	Stick Slip Risk	Risk Level	Time Limit (Yet to be implemented)
0-40	0	None	None
40-80	1	Low	Mitigation Recommended
80-100	2	Med	Mitigation requested
>100	3	High	30 minutes

Table 6 Stick & Slip Risk level

When Level 2 & 3 stick and Slip risk levels are seen it is advisable to change the drilling parameters including changing the RPM to reduce the shock levels. Typically Stick and Slip is seen with low RPM and High Weight on Bit.

STALL THRESHOLD

Due to severe Stick and Slip conditions the instantaneous RPM falls considerably below the normal RPM and is considered as a stall value. A user defined Stall threshold (normally set 15 rpm) is used. If the instantaneous RPM falls below this value due to stick and slip it is considered a stuck event.

NEGATIVE RPM THRESHOLD

This instantaneous RPM is used to detect “negative rotation” events ie when the tool, likely in a stick slip situation, has turned too much forward that it turns in reverse. This results in backed off tool joints and PDC bit cutter loss. If the instantaneous value falls below a threshold set by the user (normally set at - 5 rpm) it is considered as negative RPM.

ROTATION FLAG

The tool uses the cycle rpm for a rotation flag. This flag is used for the tool to distinguish between rotation and sliding conditions. This allows the Tool to send Gamma ray values at a higher update rate

(The rotation threshold will be + 5, if the Negative RPM threshold described above is - 5).

4.4. DYNAMX DISPLAYS AND MONITORING

DYNAMX curves providing Shock and Vibration, Stick and Slip and reverse flags can be enabled and monitored to improve the Rate of penetration.

An Example from an Air Drilling job is provided below. In the first part of the job

- The DYNAMX Shock Lateral Risk level is 3.
- The DYNAMX Stick and Slip Risk level is 2.
- The Rig was drilling with Low RPM & High Weight on Bit.

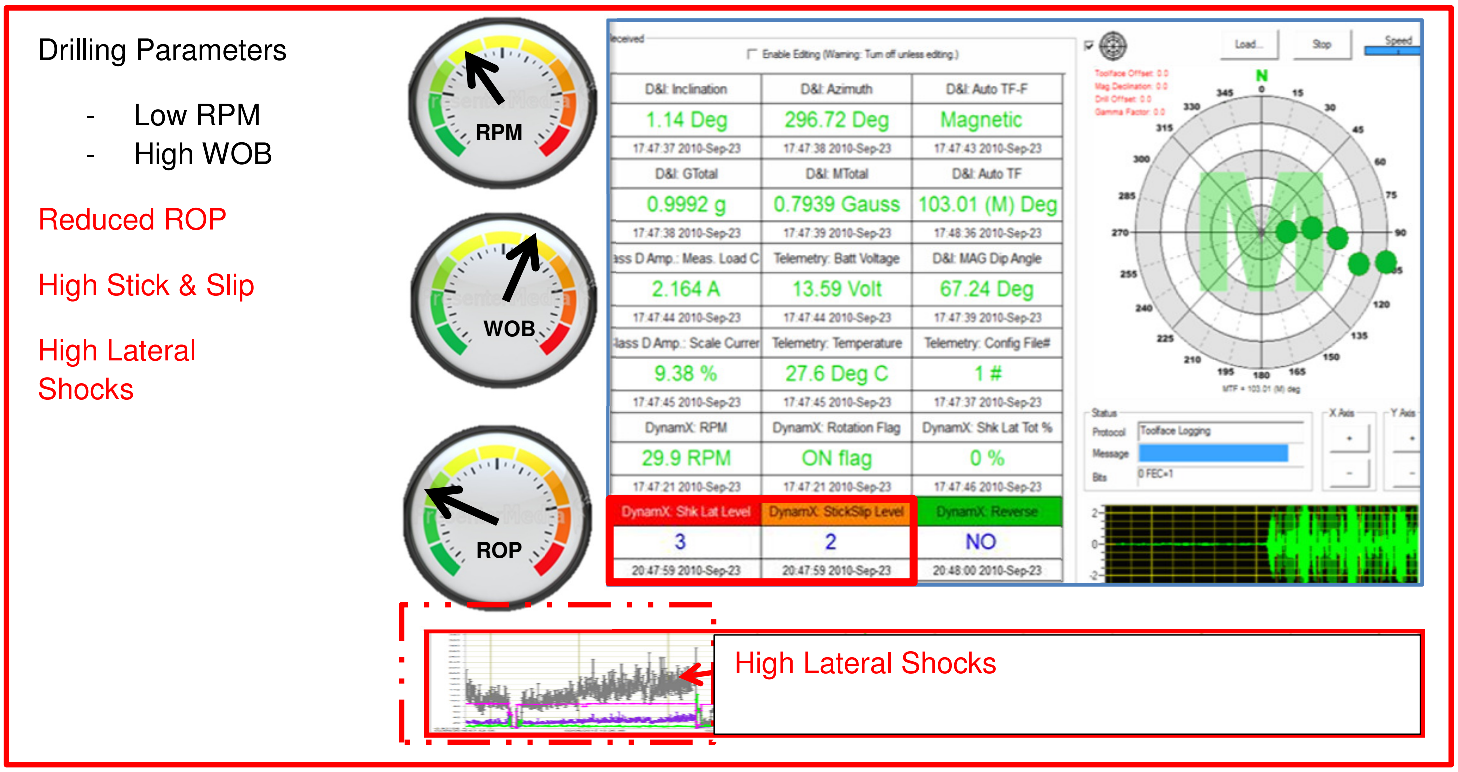


Figure 77 High Shock Risk Level while Drilling in Real Time

After seeing the high shock levels with the DynamX probe the Drilling parameters were adjusted

- Increased the RPM
- Reduced the WOB.

This reduced the shock level and improved the ROP.

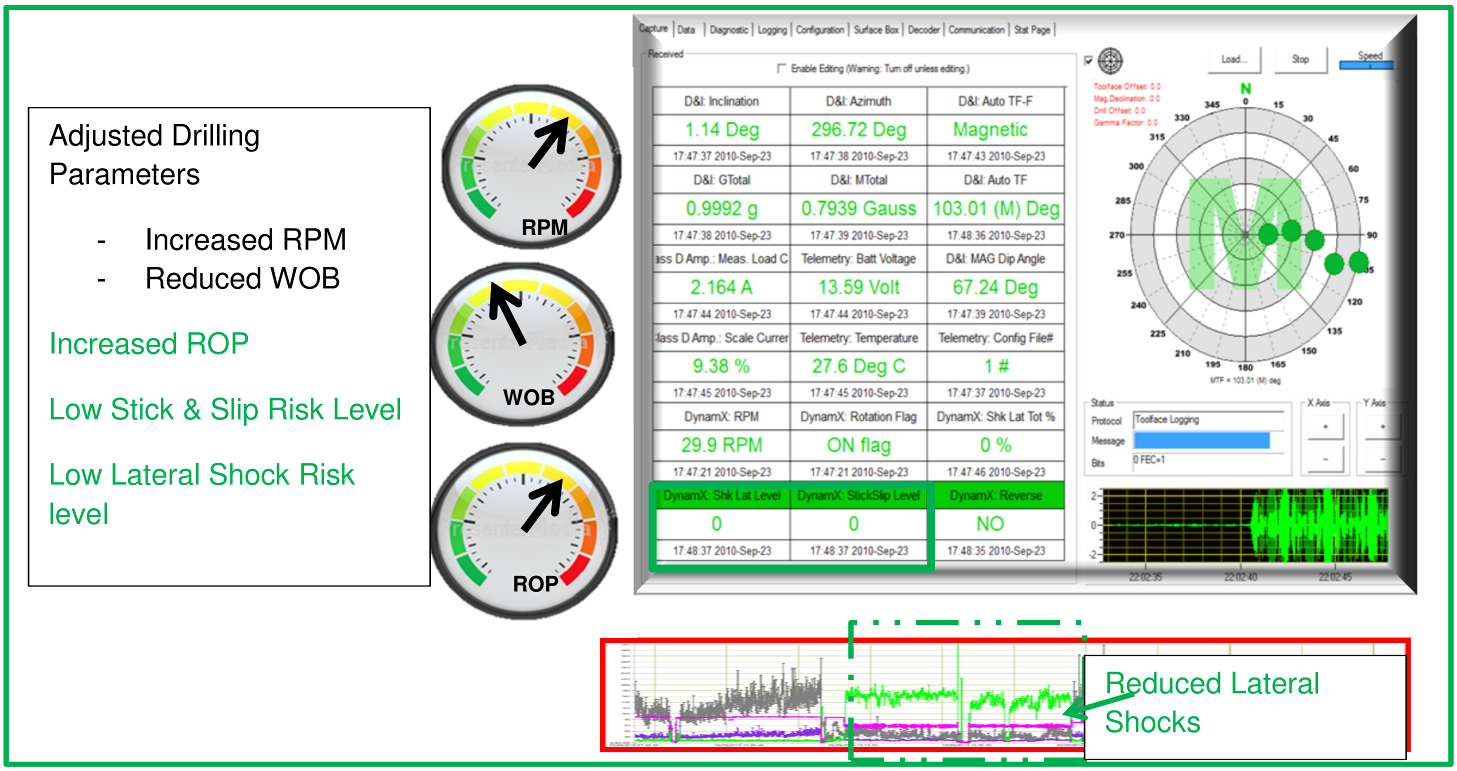


Figure 78 Low Shock Risk Level after improving the drilling parameters

Reacting in Real time to Shocks can improve the Drilling efficiency as well as reduce the chances of Drill string failure.

Shock information can be sent across WITS and displayed with other curves to make informed judgments about the Drilling parameters including Weight on Bit, RPM, Flow Rate and mud properties. This information is useful for the Drilling operator, Bit Company and the Drilling Engineer.

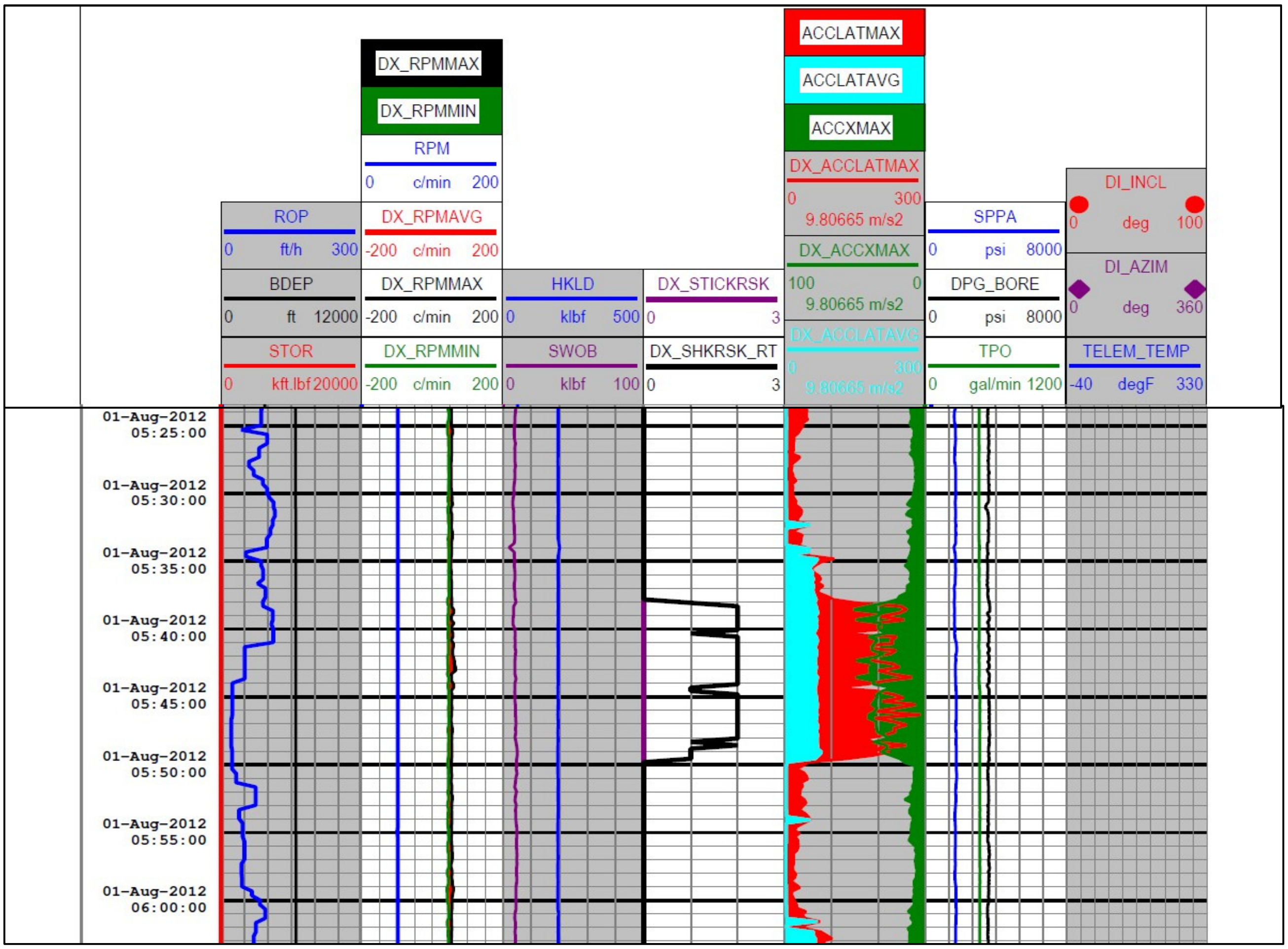


Figure 79 Shock & vibration Monitoring

At the end of every run after the Tool Memory is Dumped, Time- Based Logs are generated using the Perform tool kit. These allow the Command center to identify issues with Logs and see if the tools are fit for the next run. They can also be used to optimize the Drill string and select the appropriate Bit that will be used in subsequent runs and wells.

DynamX Memory from 2 jobs are shown in the Figures below:

- The 1st Log was generated from a run where a slick BHA (BHA with no stabilizer) was used with Air Drilling on a vertical well
- The 2nd Log was generated from a Horizontal well.

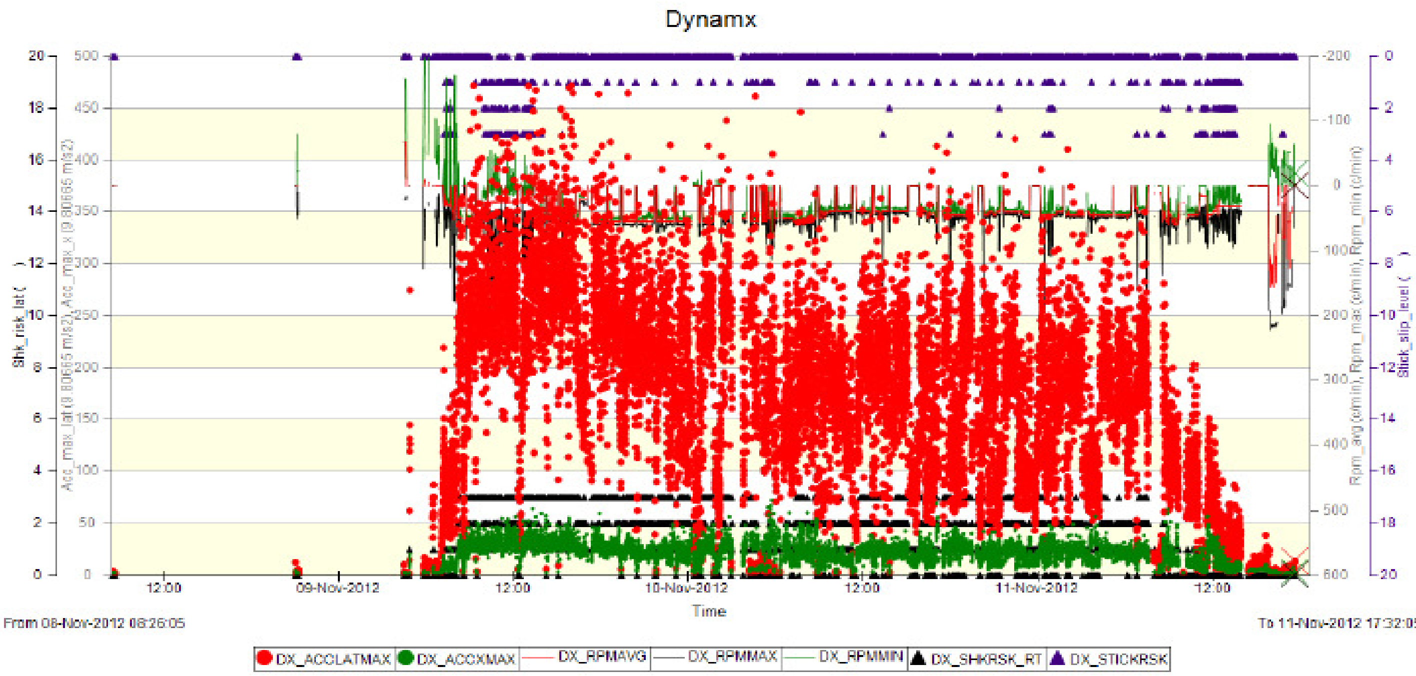


Figure 80 High Shocks Un-Stabilized BHA/Vertical Hole

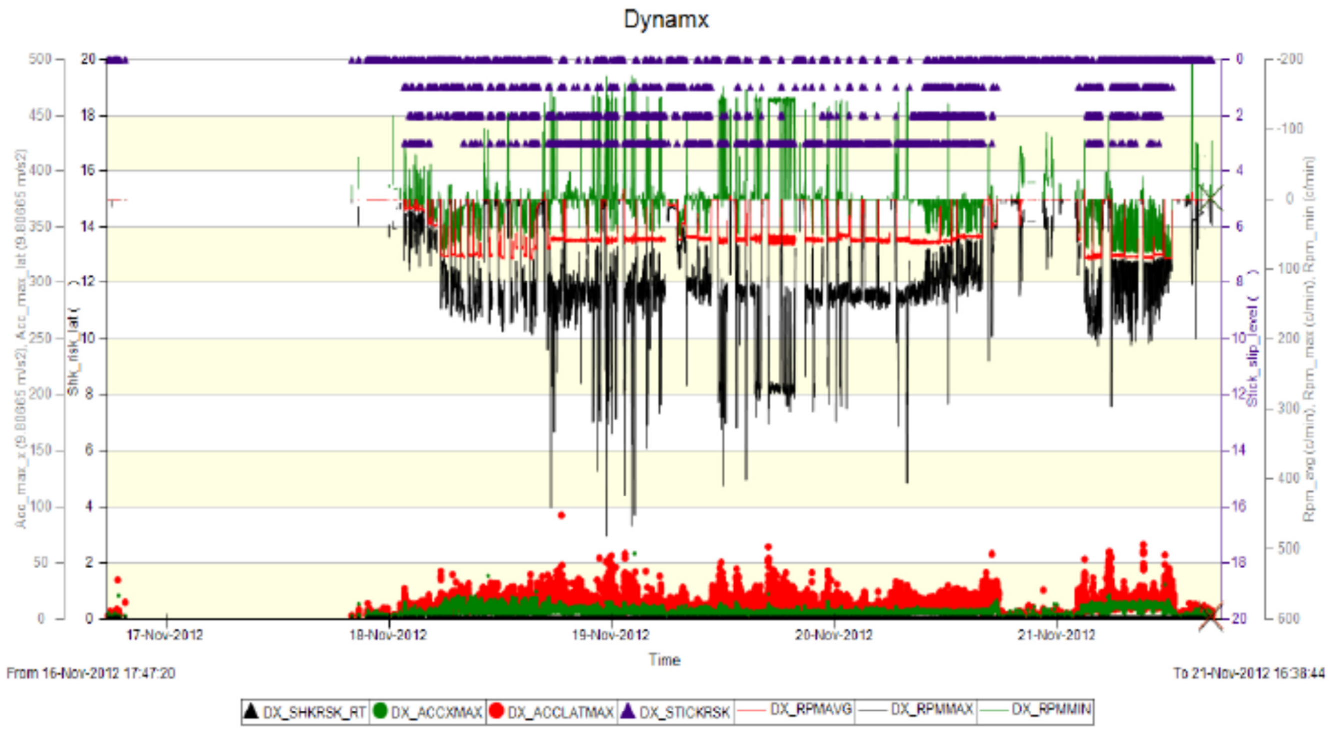


Figure 81 Low shocks -Stabilized BHA

4.5. SUMMARY

The following table summarizes the Shock measurements that are available from the DYNAMX.

Index	Signal	Command	Min	Max	Bits	Units	WITS ID	Flag
215	Shk Lat Total	263	0	1E +09	32	Count	8918	Int 32
216	Shk Lat Max	265	0	10	10	g	8919	Int 32
217	Shk Axl Total	269	0	32	32	Count	8920	Int 32
218	Shk Axial Max	271	0	10	10	g	8921	Int 32
219	Stick Slip level	294	0	2	2		8922	Int 32
220	Shk Lateral Level	295	0	2	2		8923	Int 32
221	RPM	296	0	9	9	Rpm	8924	IEEE Float
222	Rotation Flag	34	0	1	1	flag	8925	Flag
223	Reverse	298	0	1	1		8926	Flag
227	Shk Lat Total %	302	0	7	7	%	8927	Int 32
228	Shk Axial Total %	303	0	7	7	%	8928	Int 32

Table 7 S&V Measurements

- *Shock Lateral Total* is the total number of lateral shocks after the last reset.
- *Shock Lateral Max* is the maximum value of lateral shocks during an interval selected in the user configuration.
- *Shock Axial Total* is the total number of axial shocks after the last reset.
- *Shock Axial Max* is the maximum value of axial shocks during an interval selected in the user configuration.
- *Stick and Slip Risk Levels* from 0-3 based on stick and slip values above the threshold value.
- *Shock Lateral Risk Levels* from 0-3 based on Lateral shock counts above the threshold value.
- *RPM*: Rotation speed measured by counting the number of Sinusoids per minute.
- *Rotation flag* set to true when the RPM exceeds a threshold. When the RPM falls below the rotation threshold the Rotation flag is set to False.
- *Reverse Flag* for reverse or negative rotation.

- *Shock Lateral %* since the last reset, using 200 000 shocks as being 100%. The signal maximum value is set to 128%.
- *Shock Axial %* since the last reset, using 200 000 shocks as being 100%. The signal maximum value is set to 128%.

5. GAMMA RAY

5.1. INTRODUCTION

Gamma radiation is the electromagnetic radiation from atomic nucleus during radioactive decay. These atomic nucleuses transform from one isotope to another while decaying giving off Gamma rays in the process. This phenomenon normally occurs naturally, gamma rays can also be generated from artificial sources.

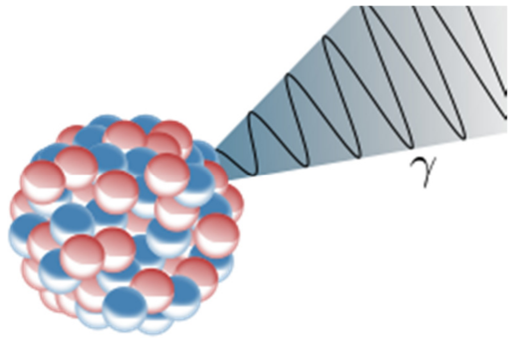


Figure 82 Nucleus Decay giving of Gamma rays

Natural sources of gamma rays on earth include gamma decay from naturally occurring radioisotopes. The following isotopes produce gamma that can be detected by the gamma ray detector in the XEM Gamma module.

- Potassium
- Uranium
- Thorium

Among the different types of rocks encountered while drilling, Formations with high Shale emit more gamma rays than others because radioactive potassium is a common component in the Shale clay content. Shales are also able to adsorb uranium and thorium. Pure Sands stone, Carbonates (Limestone, Dolomite) have low gamma ray counts as such it becomes easy to distinguish between different zones with shale and Sand or Shale and carbonates from Gamma Logs.

Gamma counts are measured in counts per second but are converted to **API** units, an arbitrary scale set up by the American petroleum Institute. This is based on an artificially radioactive concrete block at the University of Houston that has a radioactivity of 200 API. All gamma ray Logging tools are required to present the value in API units to facilitate comparison

A sample gamma Ray Log is given in the following Page which provides guidelines on qualitative comparison in different formations. In reality the gamma ray will vary from place and may read differently in formation depending on the radioactivity of the formation.

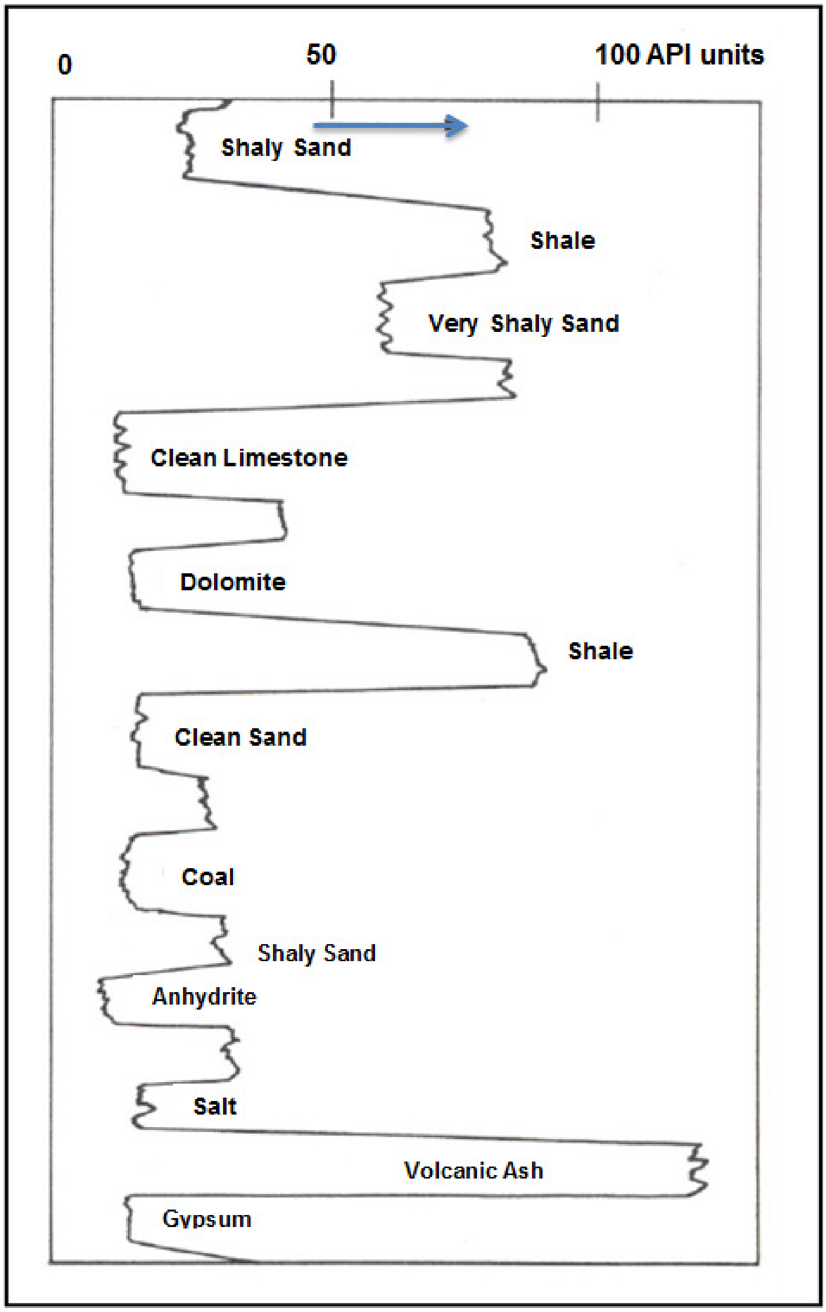


Figure 83 Gama Ray Value

The following are applications of the gamma ray measurement

I. *Zone Identification and Log Correlation*
By looking at Logs and comparing them with offset Logs from nearby wells we can identify the zone in which we are currently drilling and predict when the next zones will be encountered.

II. *Estimation of Shale volume*
The volume of Shale in any zone can be calculated with the value of the gamma ray in the Zone, the value of gamma ray in a clean zone and Shaly zone with the equation below:

$$Volume\ of\ Shale\ in\ Zone = \frac{(Gamma\ Ray\ in\ Zone - Gamma\ Ray\ in\ Clean\ Zone)}{(Gamma\ Ray\ in\ Shale - Gamma\ Ray\ clean)}$$

Equation 19 Volume of Shale

III. *Geo-steering*
When drilling highly deviated or horizontal well applications, based on the gamma ray value the geologist may be able to decide the direction in which the well has to be steered.

IV. Depth Determination
The depth recorded with Wire line differs from the depth used by the driller which is based on the pipe tally. The Drillers Depth which uses the pipe tally can be matched and corrected by applying an offset to match it to the wire line depth

V. Through Casing Logs
The gamma ray logs acquired when the tool is inside casing are useful (Some other logs are affected by gamma ray). The absolute value of the gamma ray may be different when the gamma ray passes through casing however the trend may be the same.

5.2. MEASUREMENT THEORY

The XEM gamma detector is a plateau type scintillation detector. It has a Sodium Iodide crystal doped with thallium. The crystal is coupled to a photomultiplier (PM) tube. The body of the PM tube is held at high voltage and has some dynode stages, each of the dynode stage is held at a higher stage than the preceding one.

Gamma ray travels from the formation through the collar, into the body of the probe and on to the crystal in the detector. Once reaching the crystal a flash of light is given off; this flash of light causes the photocathode to eject an electron by means of Photo-Electric effect.

The electrons are attracted towards the Dynode plates due to the High voltage in the process amplified by each dynode stage before eventually reaching the anode.

The light appears as a single pulse at the output of the PM tube due to high luminous period of the photocathode. The number of pulses is proportional to the gamma rays absorbed. Pulse height at the anode is proportional to the energy of the incident gamma ray (for a given reference PM voltage bias, High voltage HV, setting). The plateau sensor is thus named the number of counts registered by the device does not change with changes in the value of the high voltage.

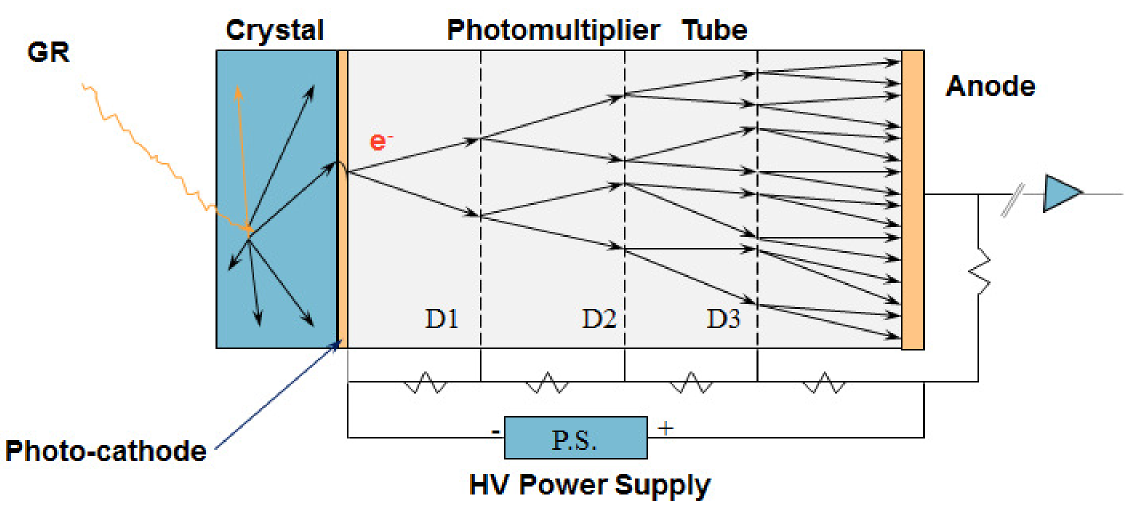


Figure 84 Sodium Iodide crystal Detector

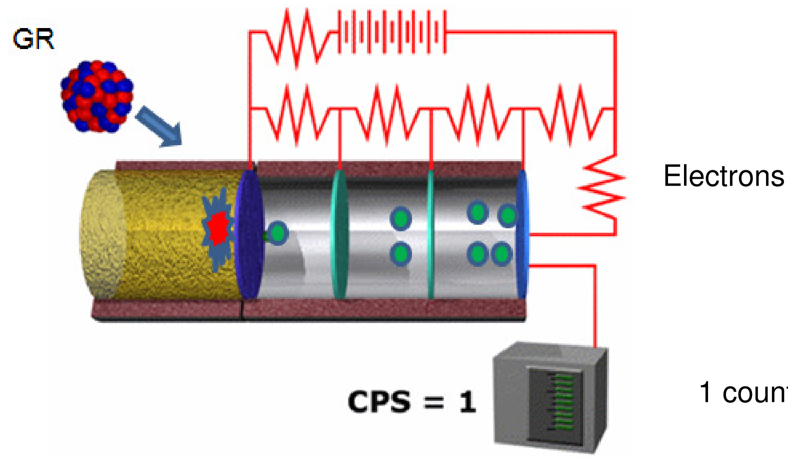


Figure 85 Gamma ray transformed into counts

5.3. ENVIRONMENTAL CORRECTIONS

The gamma ray is given in counts per Second from the Detector. This is corrected into API units automatically by the calibration factor in the tool. Each tool has its own API calibration factor which is provided by the manufacturer and permanently programmed into the tool during manufacturing.

A gamma correction factor is applied on surface to compensate for the collar /probe thickness and the Mud weight. This can be calculated using a spread sheet “FST Templates” available on the Extreme Intranet or calculated by the user with the steps below.

Step1: The following information has to be obtained before the Gamma correction factor can be calculated:

- Drill Collar OD
- Drill Collar ID
- Mud Weight
- Gamma probe OD = 1.75”

The Collar Wall thickness is calculated as follows

$$Collar\ Wall\ Thickness = 0.5 * (Collar\ OD - Collar\ ID)$$

Equation 20 Collar Thickness

The Mud Annulus thickness is calculated with the formula

$$Total\ Annulus\ Mud\ Thickness\ =\ 0.5 * ((Bit\ Size\ -\ Collar\ OD)\ +\ (Collar\ ID\ -\ 1.75''))$$

Equation 21 Mud Annulus Thickness

Step2: Using the Collar Wall Thickness and the NGT-T Collar Correction Chart below, look up the corresponding Collar/Barrel Correction Factor for the Probe (BeCu housing) thickness closest to 0.150" (approximately half way between the 3/16" and 1/8" curves). There are 2 separate curves for both Steel and NM Collars

Step3: Using the Total Annulus Mud Thickness and the NGT-T Mud Correction Chart, look up the corresponding Mud Correction Factor for the mud weight being used.

Step4: Calculate the Gamma Correction Factor:

*Gamma Correction Factor = Collar/Barrel Correction Factor * Mud Correction Factor*

Equation 22 Gamma Correction factor

This Value is entered as a parameter for Gamma ray on the surface Receiver Box.

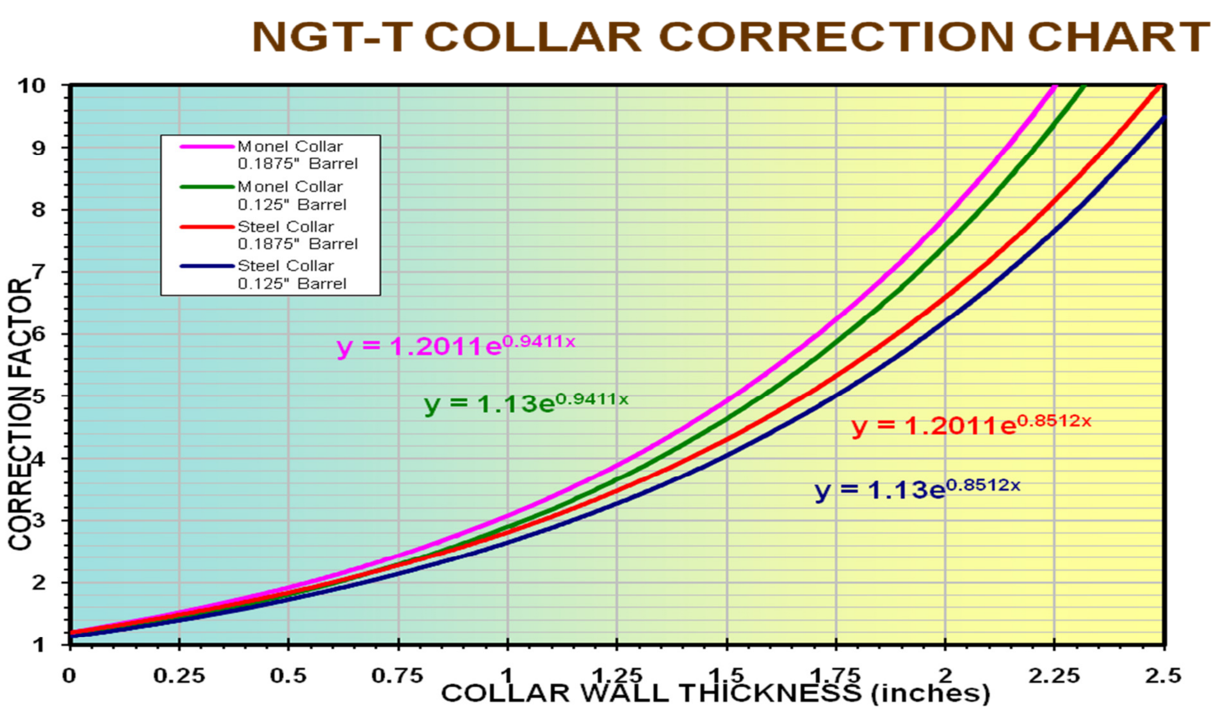


Figure 86 Collar Correction Chart

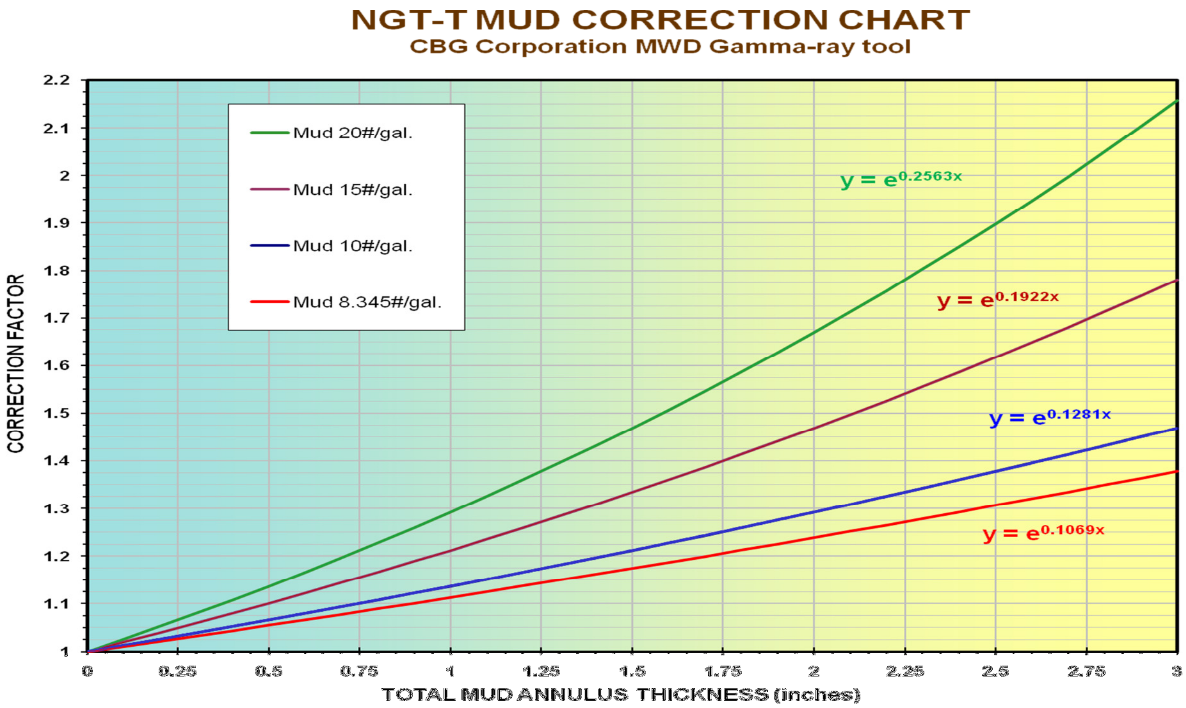


Figure 87 NGT Mud correction chart

5.4. UPDATE & COMPRESSION

Gamma Logs are provided in both Real times on surface and recorded in the tool memory. While the Memory logs have a much better quality they are only available at the end of the run when the tool is on surface.

Real time Logs are affected by the quality of the signal as well as update rate which in turn is affected by the number of variables that have to be transmitted up hole. Gamma Ray data points need to be spaced in a configuration so that the gamma ray Logs have a good resolution. The Spacing on the Logs in feet is given by the equation below:

$$Spacing\ on\ Logs\ (feet) = \frac{ROP * Update\ Period\ From\ Tool}{3600}$$

Where ROP is the Rate of Penetration in feet/hour, Update from Tool is in Seconds

Equation 23 Spacing on Logs

As an example if the Tool provides an update every 30 Seconds and the ROP = 150 ft./hour

$$\text{Spacing on Log} = \frac{150 * 30}{3600} = 1.25\text{ft}$$

This implies that one value of Gamma Ray will be plotted every 1.25 ft. It is recommended to have a spacing of 1ft between Gamma samples to have a good resolution. Sometimes when drilling deep and at low frequencies the update rate is low. In these cases at high ROP it may not be possible to get 1 sample per feet.

In such cases the Gamma values can be zipped or compressed by the tool and decompressed or unzipped by the receiver software to generate a log. The XEM uses the "Discrete Cosine transform" technique for gamma compression. Here 20 successive gamma data points are converted into coefficients of a Cosine function. The representative coefficients are transmitted up hole with the EM signal and decompressed back to gamma values by the surface software. These are then time referenced in order to be updated on a Log.

The following chart provides guidelines on spacing versus ROP. The Horizontal axis has ROP, the vertical axis has the spacing for the compressed data point. The chart is divided into several compression quality zones Red, Green, Yellow and Orange.

Red (R1 and R2 zones) = When the Update rate < 20 seconds or when update rate >200 seconds. GR Compression will not work. **Green (G Zone)** = Excellent quality of Data. In this Zone the following conditions apply

- 20 seconds ≤ Update rate ≤200 seconds
- 0ft <Update spacing ≤ 3ft

The logs provided in this zone are comparable with Memory Logs.

Yellow (Y Zone) = Good Quality

- 20 seconds ≤ Update rate ≤200 seconds
- 3ft <Update spacing ≤ 6ft

The Logs provided in this Zone will have sufficient resolution for qualitative interpretation. The geologist will be able to make decisions based on the data

Orange (O Zone) = Good Quality

- 20 seconds ≤ Update rate ≤200 seconds
- 6ft <Update spacing

The Logs provided in this zone will have poor quality and may not be useful

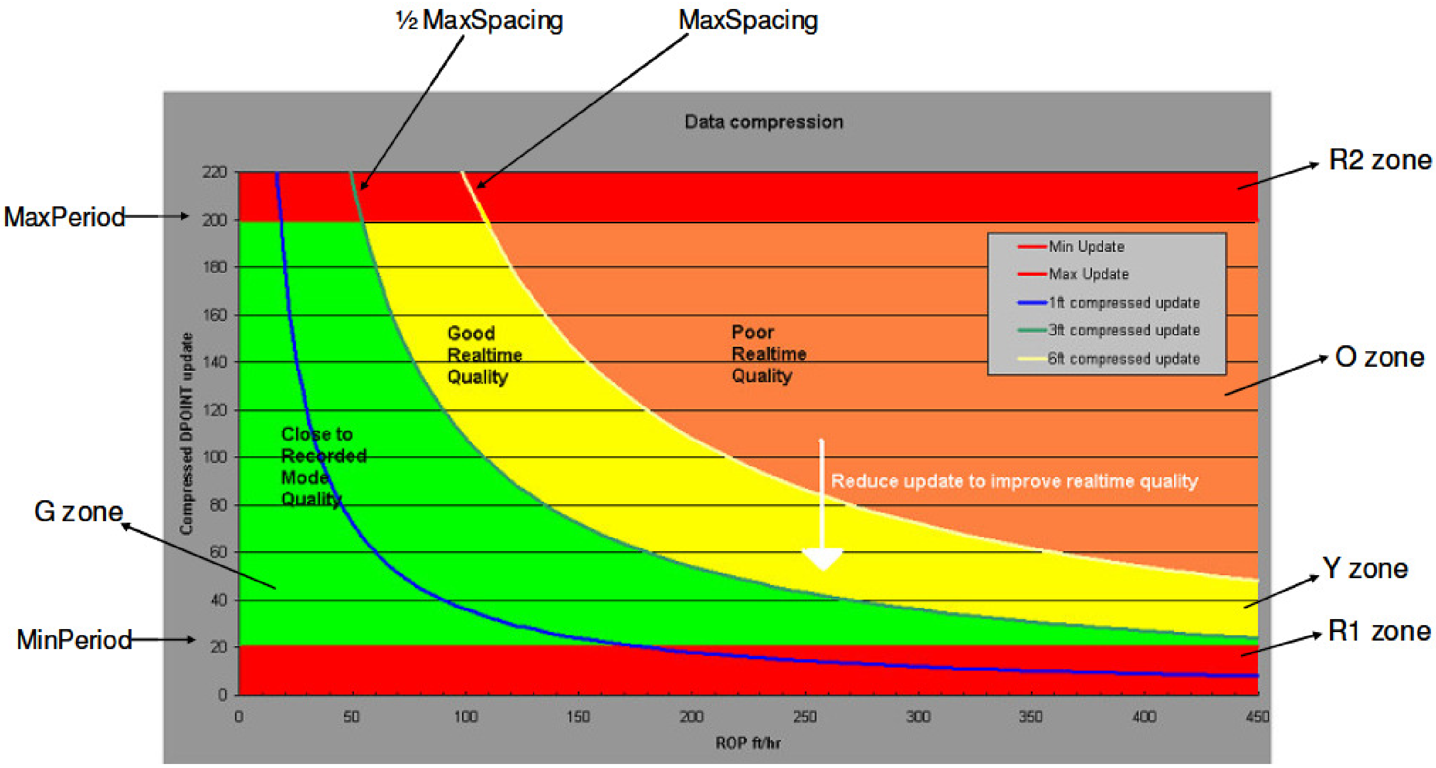


Figure 88 Spacing versus ROP for Compressed gamma Ray Data

In general the following important rules apply:

- The spacing between consecutive gamma values in time is REQUIRED to be at least 20 seconds and NO MORE than 200 seconds apart.
- At any Rate of Penetration the data quality using compressed gamma is better than normal gamma.
- The Spacing Depth is recommended but not required to be less than 6ft.
- The Surface software will output a gamma value 3 seconds on surface; for example if 2 x compressed Gamma values are spaced 30 seconds apart then the SW will output 10 x uncompressed gamma values.
- The Compressed Gamma Data points do not need to be evenly spaced
- The Effective data rate when using Compressed Gamma as opposed to Gamma without Compression can be x2,x3 or higher depending on the configuration file.

As an Example

If the ROP = 360 ft/hour and gamma ray (Normal without compression) is given every 30 seconds from the tool

- Spacing on Log = $\frac{360 * 30}{3600}$ = 3 ft

The Logs will have a poor resolution and quality as the requirements is to have 1 sample per foot for good quality logs

If compressed Gamma ray is used instead (every 30 seconds from the tool) the Logs would still be at the border of the green zone on the 3 feet compressed update line, this represents a 3x improvement in the rate, there is also room to increase the ROP even further in the yellow zone.

6. REFERENCES

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