



University of the  
Highlands and Islands  
Oilthigh na Gaidhealtachd  
agus nan Eilean

## ISCWSA: WELL INTERCEPT SUB-COMMITTEE EBOOK

Wellbore Ranging Technologies, Intercept  
Applications and Best Practices



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The authors of this publication are fully aware the nature of the subject matter covered will develop over time as new techniques arise or current practices and technologies are updated. It is, therefore, the intention of the authors to regularly revise this eBook to reflect these changes and keep this publication current and as complete as possible.

Anyone who has expertise, techniques or updates they wish to submit to the author for assessment for inclusion in the next revision should email the data in the first instance to:

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# Preface

The subject of Well Intercept has frequently been dealt with in best practice manuals, guidelines and check sheets, this eBook will attempt to capture in one document the main points of interest for public access through the Society of Petroleum Engineer (SPE) Wellbore Positioning Technical Section (SPE WPTS or otherwise commonly referred to as the, Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA).

This eBook was written by the SPE WPTS (aka ISCWSA) Well Intercept Sub Committee (WISC) and is intended to develop good practice in wellbore intercept applications and promote its understanding within the oil and gas wellbore construction industry.

The intent of this document is to help engineers determine the appropriate ranging methods and technologies for a given positioning objective. Depending on the objective complexity, there may not be a silver bullet or one technology on its own that may provide a complete solution. In many applications, a combination of ranging technologies and methods, involving multiple industry expertise may be required to achieve the desired objectives.

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2015 - 2017

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## Well Intercept

Compiled and co-written by

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# 1. Introduction

A planned well intercept, as related to the oil and gas industry, can be defined as one or more boreholes that are directionally drilled with the intention of geometrically intersecting a second or multiple boreholes to achieve a specified objective. The subject of Well Intercept has frequently been dealt with in best practice manuals, guidelines and check sheets, this eBook will attempt to capture in one document the main points of interest for public access through the Society of Petroleum Engineer (SPE) Wellbore Positioning Technical Section (SPE WPTS or otherwise commonly referred to as the, Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA). This eBook was written by the SPE WPTS (aka ISCWSA) Well Intercept Sub Committee and is intended to develop good practice in wellbore intercept applications and promote its understanding within the oil and gas wellbore construction industry.

Wellbore Intercept is a broad topic which covers a range of technologies, methods and domain expertise to deliver desired objectives. The topic covers a wide range of industry application from Steam Assisted Gravity Drainage Drilling (SAGD), River Crossing, Re-Entry Drilling, Plug and Abandonment Operations, Well Salvage Operations, Horizontal Directional Drilling, controlling a blowout with a relief well, and connecting boreholes end to end for pipeline production fluid conveyance.

The objective for making the intersection, the local operational conditions, and available technology and expertise will dictate the well intersection design process. Each of the examples listed above can be quite different from each other as well as from the basis of design for a typical production well. Although there are many similarities, such as the basic geometric design and drilling equipment used, designing and executing these wells requires expertise in the various specialized methods and equipment used to achieve the objective.

The intent of this document is to help engineers determine the appropriate ranging methods and technologies for a given positioning objective. Depending on the objective complexity, there may not be a silver bullet or one technology on its own that may provide a complete solution. In many applications, a combination of ranging technologies and methods, involving multiple industry expertise may be required to achieve the desired objectives.

The main ranging technologies to meet these challenges, which are currently available to the industry as of the time of this publication, can be summarized into two groups, Magnetic and Acoustic Ranging. Both technologies may be deployed with active or passive operations modes. This document outlines the characteristics and capabilities of both Magnetic and Acoustic methods of ranging. Also included in this document are sections on Relief Well (RW) Ranging operations which are intended to provide a general overview of the planning and processes required when developing a RW ranging plan.

## 1.1 History of Ranging

Prior to 1933, if a well blowout could not be controlled from the surface, multiple vertical wells were drilled around the blowout into the reservoir and produced at maximum rate to relieve the pressure. These wells were called relief wells. The name stuck when controlled directional drilling was used after that time to control blowouts even though the objective changed to pumping fluid into the blowout rather than producing the reservoir. The first documented case of intentionally drilling a well to intersect another wellbore in the reservoir occurred near Conroe, Texas in 1933 when traditional relief wells and other conventional well control methods failed to stop the flow from Standard Oil's Madely #1 blowout. Prior to this Incident, relief wells were normally drilled vertically near the blowout well in order to relieve reservoir pressure through additional production, by flowing them at higher rates. However, it was conceived that if a wellbore could be drilled close enough to the blowout well to establish hydraulic communication, then water could be pumped through the relief well and into the blowout well, thus equalizing the formation pressure and killing the well. This proved to be an effective method on the Madely #1 blowout and became the standard strategy for relief well drilling until 1970. (Gleason, 1934)

Before the advent of magnetic ranging, there were no reliable methods for detecting the location of a wellbore in the subsurface. This was particularly frustrating when drilling relief wells because uncertainty in wellbore surveying methods made it extremely challenging to accurately place a relief well close enough to a blowout well in order to establish hydraulic communication and prevent an accidental collision. As a result, drillers often had to drill multiple relief wells in an attempt to land one or more close enough to effectively kill the blowout. This was an expensive, time intensive, and a relatively uncertain technique which often required trial and error.

On March 25, 1970, a relief well was needed when a Blowout occurred at the Shell Corporation Cox No. 1 well in Piney Woods, Mississippi (Bruist, EH., Shell Oil Co., 1970). A conventional relief well, Cox No. 2, was drilled on May 3, 1970 with a plan of reaching the bottom of Cox No. 1 at 6,400m (21,000 ft.) However, there was reasonable doubt about the effectiveness of this method as it required steering the well accurately to the bottom of Cox No. 1. The

positional uncertainties associated with drilling a conventional relief well were known and this motivated the company to explore new techniques to place the relief well accurately. The operator formed a taskforce of engineers and scientists, and they developed a method for determining the relative distance and direction to a target casing near the planned intersection depth. Their primary approach was to analyze the remnant magnetic poles located on the target casing using new magnetometer and accelerometer technology to acquire the data. This method was later called “passive ranging.” A secondary method was also used to help determine distance using an ultra-long spaced electric log. Using these methods, the first recorded planned geometric intersection was made and was close enough for perforating between the two wells. The pioneering work on this method was performed by J.D. Robinson and J.P. Vogiatzis of Shell Development Company. A United States Patent #3,725,777 was issued in recognition of the work.

Charles A Schad also contributed significantly towards this method. He developed highly sensitive magnetometers to be used in the directional guidance system. His work led to the development of magnetometers sensitive enough to measure small magnetic field disturbances in the presence of the Earth’s powerful magnetic field. Schad also envisioned the use of an artificial magnetic field to be produced in the target wellbore which would provide a much stronger and predictable magnetic signal to guide the well for interception. This idea later developed to be active magnetic ranging.

The first commercial service using magnetic ranging techniques was developed by Tensor, INC and was called MAGRANGE Services. It was based on the United State Patent #4,072,200 issued to Fred J. Morris on February 7, 1978. The development of this service was in response to a call by Houston Oil and Minerals when they experienced a blowout in 1975. This technology also used highly sensitive magnetometers to measure distortions in the natural magnetic field due to the presence of ferromagnetic bodies. However, this method differentiated itself by measuring the change in the magnetic gradient along a wellbore. MAGRANGE Services was designed to make continuous measurements along the relief well path to analyze the change in the magnetic gradient in order to determine the distance and direction of the intercept point. The rationale behind this technique was that a small magnetic field by the ferromagnetic body changes the small and uniform gradient of the natural magnetic field. This technique was used to drill many relief wells. However, it was eventually phased out as it was not accurate enough to consistently locate blowout wellbores and was also limited by its detection range.

Within a few years, a wireline conveyed commercial passive ranging service was available to the industry and was used on dozens more relief wells from the mid-1970s through the early 1990s (SPE 6781). During this period, some geometric intersections were made, but in most relief well cases, the technology was used to get close enough to make hydraulic connection. A significant factor in not taking the effort to make geometric intersections during this period was the lack of precision directional drilling technology as well as uncertainty in the ranging techniques. Typically, multiple sidetracks using mudmotors and bent subs were required and became more complicated in open hole as this technique requires steel to be in the target well to range on.

In the early 1980s, electromagnetic ranging became commercially available (SPE 11996). This method is often referred to as “active ranging” because electrical current is injected into the formation. If an electrically conductive target tubular (or even wireline) is within range, the injected current will flow on the target steel creating a radial magnetic field vector that can be measured to determine a distance and direction. In most situations, this method can sense the target at a farther distance than passive techniques and produces a signal along the target tubular. This technology increased the reliability of locating and tracking the target well, however, it was not until the late 1980s with the introduction of new directional drilling technologies—e.g., MWD, steerable motors and north seeking gyroscopes—that geometric intersections began to become more practical. A geometric intersection greatly increased the chance of efficiently killing a blowing well and/or achieving a permanent P&A of the target well.

From 1934 to 1990, almost all of the well intersections (close enough to gain hydraulic communication down hole) were relief wells drilled to control blowouts. After 1990, with the advent of better ranging and well placement technology, more geometric well intersections were being made for purposes other than controlling a blowout. The most common use was the P&A of wells that could no longer be re-entered from the surface. Once the intersection was made, the remediation might include perforating into the target casing in one or more places, cutting a hole with a mill, or cutting a slot for re-entry into the target casing.

Other uses included re-entry into a borehole below a casing shoe or fish that could no longer be accessed from the surface. During the 1990s, most geometric well intersections were made using active ranging technology, which was enhanced with the addition of gradient sensors that allowed for the direct measurement of distance when the proximity to the target well was less than 4 meters or so. Most of these intersections were made without access to the target well. However, a few were made when access was possible using a powered solenoid in the target well as

a ranging beacon. While not used for making intersections, a similar technology was extensively used for drilling parallel Steam-Assisted Gravity Drainage (SAGD) wells at a fixed proximity during this period (SPE 27466).

Starting in the early 2000s, more applications for well intersections developed, particularly in situations where the operator has access to the target well and can convey wireline tools to the intersection depth. New technologies aided in these projects, particularly the rotating magnet technique, which uses a bit sub containing strong permanent magnets in the drilling assembly and a sensor in the target well that can measure the distance and direction directly to the bit, in real time, during drilling (SPE-CIM-01-01-MS). The most common intersection application for this technology was the guiding of horizontal wells to intersect vertical wells for coal bed methane production. It has also been used for connecting boreholes end to end to create a pipeline under surface and/or subsea obstacles. Another example was the use of the method to drill a horizontal well from a land rig to make a perpendicular intersection of a well offshore (SPE 119420).

As magnetic ranging technologies have matured into more robust and reliable services, the oil and gas industry has adapted many of these technologies to provide other technical solutions. Even though ranging techniques were designed for well intersection, the capability to determine relative distance and direction to an offset wellbore makes ranging suitable for applications that require close proximity drilling without intersection. In some applications such as fracture salvage and SAGD, the goal is to drill a well closely parallel to an offset wellbore in the form of twinning. Another application of ranging is collision avoidance. In many cases of multi-well pad drilling, the vertical segments of wellbores are planned very close to offset wellbores. Ranging can be used to maintain a safe distance from these offset wellbores in order to prevent costly and/or hazardous collisions.

A revival in the use of passive magnetic ranging techniques began in the early 2000s using the raw MWD magnetometer and accelerometer data. This was primarily driven by cost and time savings over using electromagnetic ranging, which normally required tripping the BHA to make wireline conveyed ranging runs. It was mostly used on P&A and well avoidance projects where the budgets were low and re-entry is not required. It has also been considered for ranging in thick salt sections where typical electromagnetic ranging does not work. In some offshore wells, the casing that is run through the salt is pre-magnetized, as a contingency, to assure a strong magnetic pole for passive ranging if a relief well intersection is required.

Passive and electromagnetic ranging methods both require some type of metal in the target well for ranging. There are currently field tests being run to determine the practicality and constraints of using active sonic-based measurements to range on open hole.

## 1.2 Magnetic Ranging Techniques:

Magnetic ranging is a method of detecting nearby offset wellbores in the subsurface for the purpose of collision avoidance, twinning, and/or intersecting. Magnetic ranging technologies are based on the measurements of magnetic field disturbances attributed to the steel in the offset wellbore casing or tubing. By interpreting downhole magnetic field distortions, the relative distance and direction of the offset wellbore, which is the source of the magnetic disturbance, can be determined. This technique has become the industry standard for detecting offset wellbores, although, recent technological advances have increased interest to acoustic ranging, especially in fast formations, like salt.

Magnetic Ranging Techniques can further be subdivided in to two sub categories:

- Passive Magnetic Ranging (PMR) – uses existing MWD sensors to measure the magnetic signature of the remnant magnetic field on the target well to determine distance and direction to the target.
- Active Magnetic Ranging (AMR) – generates its own alternating magnetic field on the target well which is distinct from both the earths and target pipe magnetic field. The induced field is analyzed to determine a distance and direction to the target.

## 1.3 Acoustic Ranging Techniques:

Like magnetic ranging methods, an acoustic signal can be used to locate the target wellbore, or to complement the current technique which relies on magnetic properties. By knowing the time required for the sound to travel in the formation and which direction the sound is coming from, the ranging distance and direction can be determined.

Acoustic Ranging Techniques can further be subdivided in to two sub categories:

- Active Acoustic Ranging (AAR), this technique relies on sound from a transmitter being measured at the receivers. The sound waves traveling through the formation will be reflected by the target well and then bounce back to the receivers. By utilizing similar two way time surface seismic processing technique, the distance and direction can be established.
- Passive Acoustic Ranging (PAR), this technique relies on the detection of the acoustic signal generated by the bit or fluid noise. By knowing the slowness or the speed that sound travels in the formation and from which direction the sound is propagated, the distance and direction of the noise can be determined.

Acoustic Ranging helps solve the ranging challenges associated with Magnetic Ranging in salt formations. Since the salt formation is conductive, active magnetic ranging techniques which depends upon injecting current into the formation to magnetize (light up) the offset well can only occur at relative close proximity to the offset well. This results in the inability to make informed steering decisions early enough without entering the ellipse of uncertainty or avoiding having to plug back, if the objective was to intersect in the salt formation.

## 1.4 Well Intercept/Paralleling Technology

Well intercepts are becoming a more common technology in the Oil and gas industry. The main uses are listed below, but all of them rely on one key fact, the better you understand the position of the well you want to intercept/parallel the easier this will be to achieve. The improved wellbore survey accuracy is the key to timely well intercepts/paralleling.

Ranging technology in itself is not going to answer all well intercept needs. These situations often involve some form of navigation and geometric challenges before the ranging process starts, so the positional accuracy of the offset well is key to enabling this.

In PMR and AMR there is some form of target, such as drill pipe or casing in order to range. Magnetic parameters define the performance limits of this ranging technique and will be discussed further in this document.

There are a number of applications for ranging technology, the main three being Plug and Abandonment, SAGD drilling and Coal bed methane. The most notable of all applications is relief well drilling but this continues to be relatively rare. However, as a result of HSE consequences the high visibility of relief wells drives public interest and recognition.

## 1.5 Wellbore Intercept Applications

### 1.5.1 Relief wells

A well drilled to re-establish well control of a well in which containment is lost. Relief wells can be very complex. Each Relief Well is a unique event requiring study and analysis. Understanding all four techniques PMR, AMR, PAR and AAR, and their capabilities and limitations is necessary to design a relief well which satisfies the specific objectives.

### 1.5.2 Intervention Wells

Intervention wells are drilled to perform some type of remedial operation, such as a P&A or a re-entry into a “lost” wellbore. These wells are similar to a relief well in design but without the kill objectives and many of the complications and constraints caused by the blowout. Intervention wells are a product of the success from recent relief well operations and are the primary type of well intersections being drilled today.

Milling a hole or a slot for re-entry into the target well tubular(s) or perforating or intersecting the open hole or annulus or another well are routinely performed to resolve various downhole issues. Most intervention wells require a specific orientation relative to the target well to achieve the desired objectives.

- **Plug & Abandonment** – The use of ranging technology to intercept wells, allowing pressure relief and or flow barriers to be put in place. Plugging regulations in the early 1900s were much generalized and lacked many standard requirements across states. Regulations changed significantly in the 1970s in order to drive greater environmental protection. These stricter requirements described that cement plugs had to be placed at specific depth intervals in order to prevent formation fluids from migrating to other strata. However, since steel casing is susceptible to corrosion and collapse, often times these depths can become obstructed and

not reachable through traditional means. This led to the methodology of using ranging technologies to intersect the subject wellbore at the necessary depths to set the required plugs. (Plugging and Abandonment of Oil and Gas Wells, 2011)

- **Well salvage** – twinning an existing well from which reservoir access has been lost in order to recover the production. One specific example of this is fracture salvage. In certain fields, the cost to drill a wellbore is significantly less than the cost to hydraulically fracture the reservoir. In these situations, when a wellbore collapses from corrosion or other environmental conditions, ranging is used to drill a new wellbore in close proximity to the existing well in order to penetrate the existing fractured zone for continued production.
- **Well Recovery** – re-entering a well below a fish or casing damage.
- **Fish & By Pass - a variation of Well recovery.** When a portion of the BHA is separated from the drill string and creates an obstruction within the wellbore, ranging may be used to navigate a side-track passed the fish and back into the original wellbore by detecting the magnetic signature from the steel in the BHA components. This enables the recovery of an already drilled hole which can result in significant cost savings.
- **Completion recovery** –The use of ranging technology to parallel or re-enter a well to the reservoir, run a completion and drain the area where a previous completion has failed.

Figure 1 below depicts some typical Relief and Well Intervention and Intersection designs which have been utilized in the industry.

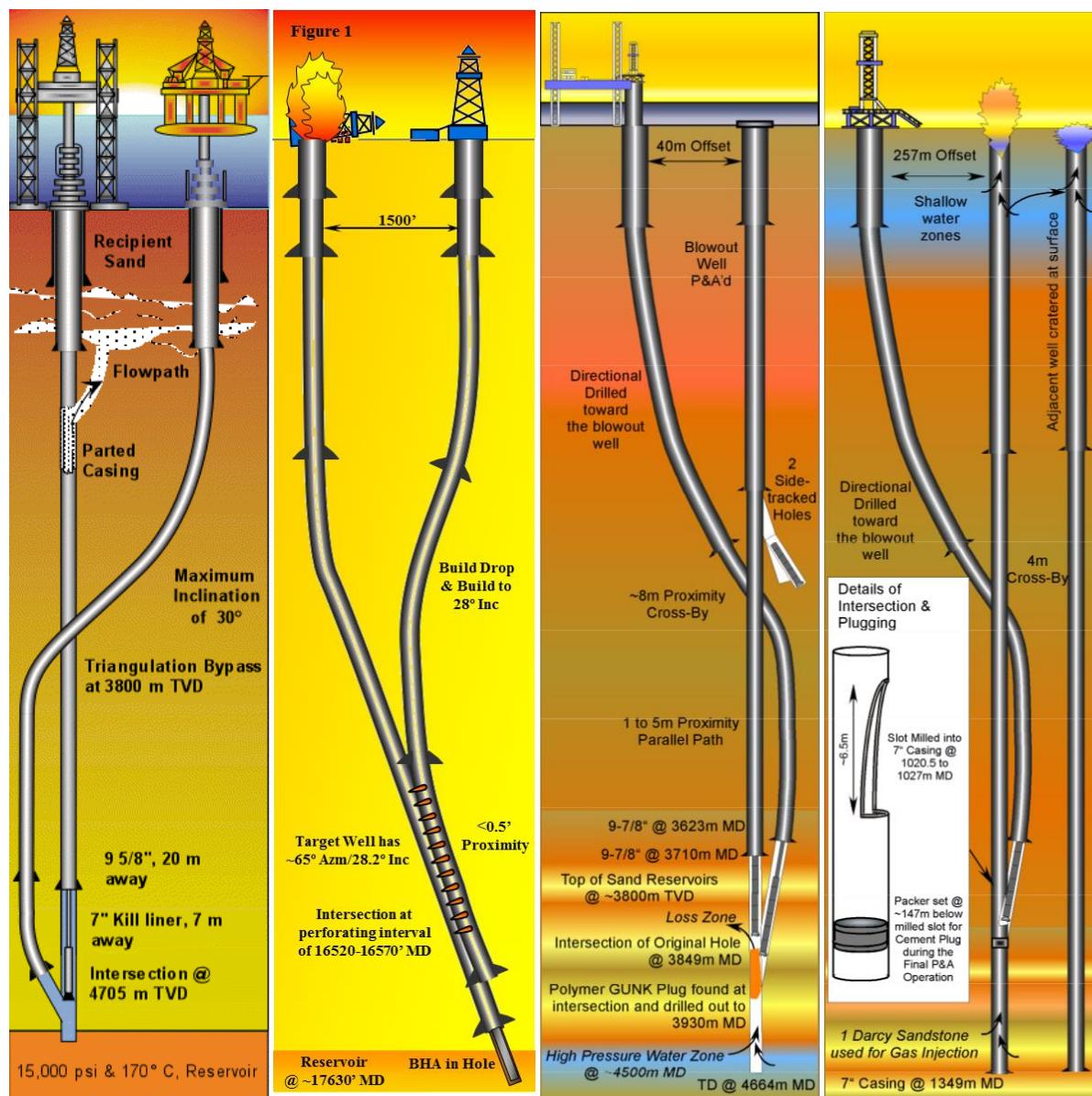


Figure 1 Relief and Well Intervention and Intersection

### 1.5.3 U-Tube Wells

The first feasibility study for connecting two wells together end to end was developed in 2001. The objective was to assess connecting two offshore platforms together using two connected wells versus laying a pipeline on the seabed to mitigate the associated permitting and environmental risk. The first implementation of the method was made a few years later in the successful connection of two wells under a canyon to convey a pipeline (New Technology Magazine, December 2004). While this operation has been attempted only a few times, they all have been completed successfully.

These types of projects will normally have access to both wells and would typically use dual-well ranging technologies, e.g., rotating magnet, single wire ranging, solenoid techniques, or combinations, for making the intersection (see Figure 2).

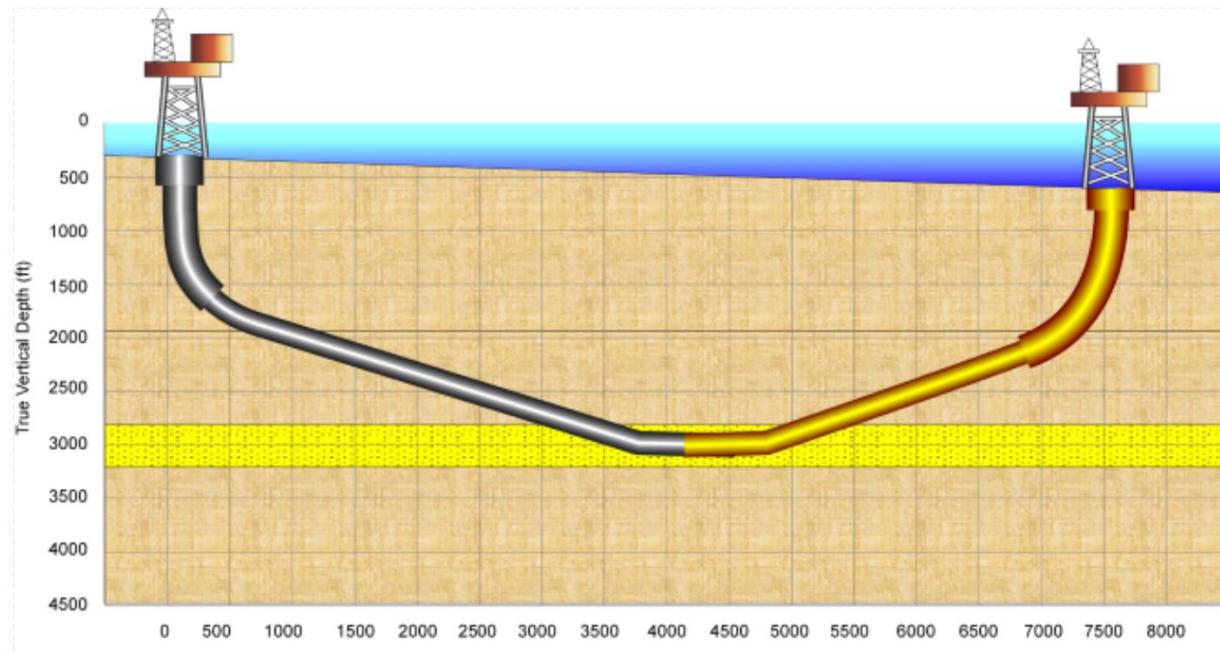


Figure 2 Example of a U-Tube Well Connected End to End to Convey a Pipeline

### 1.5.4 Conductor Connector Well (CC)

Intersect two or more wells at any incidence angle for production purposes. An example is the perpendicular intersection of a horizontal well into a vertical well for coal bed methane production.

- Normally there is access to the target well when drilling this type of borehole. Ranging will typically consist of a rotating magnet, single wire, solenoid, or combinations.
- Modern well intersection technologies are opening new opportunities for well designs and production enhancements. As the industry's experience increases with well-to-well intersections, then it could be expected that new applications will be found for this unique type of well. An example of connecting a producing offshore well to a horizontal land well is reviewed in SPE 111441. These types of projects will normally have access to both wells and would typically use dual-well ranging technologies, e.g., rotating magnet, single wire ranging, solenoid techniques, or combinations, for making the intersection (see Figure 3).

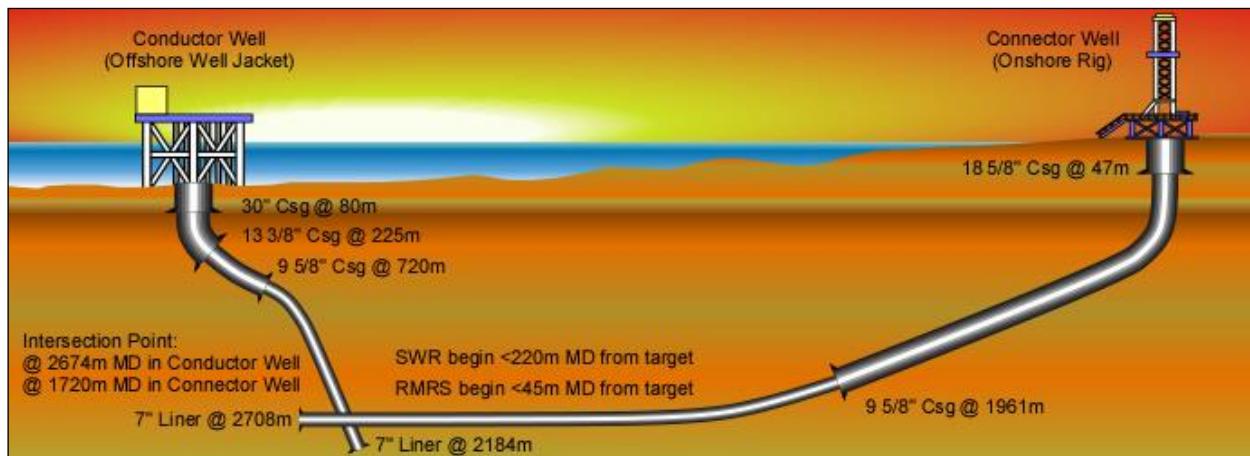


Figure 3 Conductor Connector Well drilled in 2007

### 1.5.5 Steam Assisted Gravity Drainage wells

Well twinning, where a producer and a steam injector are drilled in close proximity to each other to optimize thermal transfer and therefore production. Ranging technology is used to ensure the relative placement of the two wells is achieved. SAGD was conceptualized by Dr. Roger Butler of Imperial Oil in the 1970s for application in the Canadian oil sands.

### 1.5.6 Well avoidance

Well avoidance is the use of ranging technology to avoid other wells, where conventional survey techniques may not be adequate. In certain applications, ranging to a nearby offset wellbore is used as a mechanism to reduce the relative uncertainty of the offset wellbore position for the purpose of collision avoidance. This practice has become more common in recent years as multi-well pad drilling has become prolific. This method is especially advantageous when the combined positional uncertainty of the two wells exceeds an acceptable risk threshold. (Expand wellbore crossing Benny P)

### 1.5.7 Subsurface connected wells

Using ranging technology to allow two wells to meet or parallel each other in a reservoir, both wells are drilled from different locations but are positioned in the zone of interest relative to each other.

### 1.5.8 Horizontal Directional Drilling (HDD)

Generally used for running pipelines under villages/towns/rivers. It is an adaptation of previous applications and technologies.

### 1.5.9 Ranging to Surface

Technologies for ranging to surface do exist, and generally consist of generating a magnetic field with a current at the surface that is sensed by sensors downhole. The effective TVD range of such systems is limited.

## 2. Passive Magnetic Ranging (PMR)

### 2.1 What is PMR?

The passive magnetic ranging (PMR) method uses up-hole software methods to analyze the magnetic “interference” measured by the MWD or other magnetic surveys that may be caused by a casing string, stuck fish, or other steel in an offset wellbore. The magnetic “interference” is used to estimate the range and direction to the offset well from the active well.

Most steel casing possesses some degree of remnant magnetism. There are several events in the life of a steel tubular that will cause it to become magnetized, including cooling in the presence of a strong magnetic field after being formed, magnetic inspection, and being in close proximity to other magnetized objects. Usually attempts are made to demagnetize the steel tubulars after inspection, but the magnetism is almost never completely erased. The remaining magnetism on a steel tubular after all magnetizing and de-magnetizing events have concluded is called remnant magnetism. It is this remnant magnetism that can be sensed downhole during PMR operations. Note that it is possible to purposely magnetize casing prior to putting it downhole. Such an operation can greatly increase the detection range and accuracy of PMR.

The magnetism along a steel tubular is often conceptualized as a bar magnet, with a North Pole at one end, and a South Pole at the other. It is common to treat each end of this conceptual bar magnet as a separate magnetic monopole (also called a magnetic charge), even though magnetic monopoles are not thought to exist.

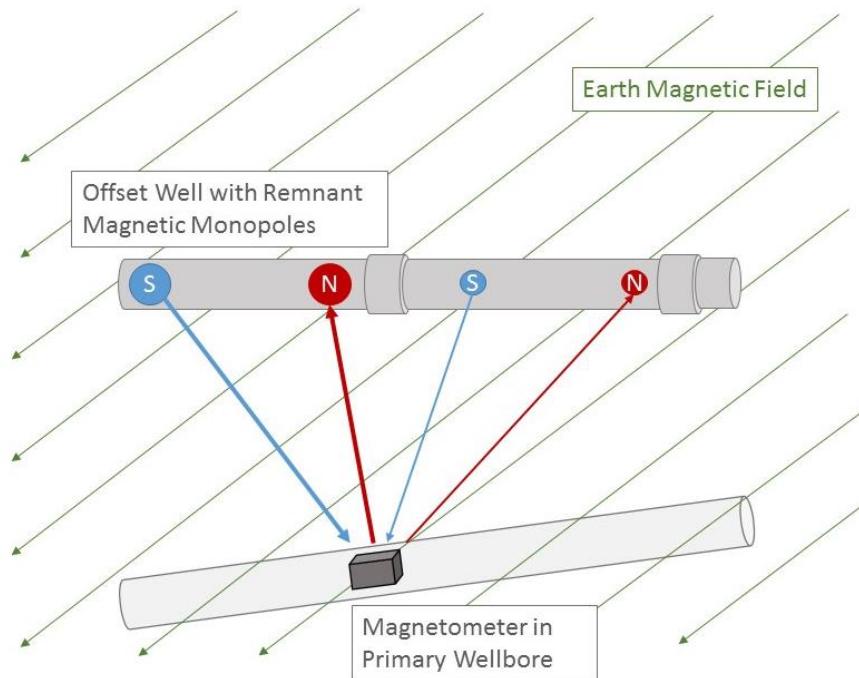
Mathematically, there is nothing wrong with this approach (indeed there are many advantages to it), even though physically it is incorrect. This assertion is supported by SPE 17255, which elaborates on this topic by comparing various magnetic models for casing. In order to simplify the explanation as much as possible, the point source magnetic monopole paradigm will be adopted in what follows. It should be noted, however, that some techniques model the magnetic monopoles as with an exponential decay rather than as a point (SPE 14388).

As the joints of casing are joined together and placed downhole, they can be visualized as a string of bar magnets as a first approximation. The bar magnets may all be aligned in the same direction as they go down the hole, but more than likely some of the joints will be magnetized in the opposite direction, meaning two North poles or two South poles may abut, generating a much stronger magnetic field than the neighboring North + South pole combinations (which will cancel each other to a degree).

The magnetic field originating from each magnetic monopole is superimposed upon (added to) to the magnetic field due to the Earth at any location in the neighborhood of the casing. Thus, when a magnetometer is experiencing interference from nearby casing, the interference is likely due to many magnetic monopoles of unknown strength, located at unknown positions along the casing in the offset well, as illustrated in Figure 4.

This is a challenge of PMR: Identifying the location of a distributed source (as opposed to a point source) in the presence of a background field of unknown strength and relative orientation. In order to begin to discern the effect of one magnetic monopole vs. another, multiple magnetometer readings are required along a length of the active wellbore. Proprietary methods are then used to separate remnant magnetism from the background field, and to estimate the relative range and direction of the offset well.

PMR is classified as an Access-Independent ranging technique, meaning that ranging can occur without access to the offset well. It is known as a passive magnetic ranging because the magnetic source (the steel casing, stuck fish, or any other steel downhole equipment) is not altered in real-time during the ranging process.



**Figure 4: Superposition of Magnetic Fields Emanating from Multiple Magnetic Monopoles on Top of the Magnetic Field of the Earth.**

## 2.1 Why Use PMR?

PMR can be used anytime magnetic interferences occur owing to the presence of the necessary MWD hardware in the wellbore. For example, PMR can be used either for collision avoidance purposes, when offset wellbores are relatively parallel in trajectory to the drilling wellbore or in a top hole environment with nearby multiple wells; it can also be used for complex wells such as paralleling a target well with the objective to perform a P&A operation, or with the objective to perforate the target well.

## 2.3 Economics

PMR is always an economical ranging option as it utilizes the existing MWD Hardware found within a typical drilling BHA.

## 2.4 Insensitivity to Formation and Hole Conditions

PMR does not depend on formation, as it relies on offset well steel equipment remnant magnetic.

PMR does not depend on formation, as it relies on offset well steel equipment remnant magnetic.

However we should not mention “resistive” or compare to any other ranging techniques.

PMR is an economic option, without comparing to any other ranging techniques, since it only uses the existing MWD Hardware within the drilling assembly. However, each situation is unique and needs to be evaluated to assure the risk in understood and the technology is fit for purpose.

The process requires the collection of 8 to 15 discrete MWD directional survey Measurements anytime an estimation of the range and direction to the target well needs to be done.

EM-MWD increases the transmission of the data from downhole to surface increasing the PMR process during operations.

## 2.5 High Inclination and Incidence Angles

PMR can be used at all hole inclinations including horizontal. High Incidence angles between the drilling and offset well can affect PMR. PMR can be effective for any Inclination range without comparing to any other ranging techniques.

## 2.6 Accuracy and Detection Range

Detection range differs from one project to another due to the initial remnant steel casing (which may be an unknown), the quality and the evolution of the casing with time, and the random arrangement of the distributed North/South poles. However, at the planning stage, Expected and maximum PMR detection range can be estimated using the weight/length characteristics of the target tubular and from a field strength chart. Publicized accuracy and

detection ranges will vary somewhat from vendor to vendor. It is good practice to assume that accuracy numbers for any ranging technique represent 1 standard deviation in the absence of further clarification by the PMR provider. Note that quoted accuracy levels assume a good signal-to-noise ratio (SNR). As the sensor gets further from the offset well, SNR decreases which will impact accuracy. Key points about the PMR detection range include:

- Expected and Maximum detection Range are an estimation based on a theoretical remnant magnetic field.
- Range to a physical break or end of tubular or casing shoe is approximately twice of that along the body of the tubular.
- No minimum range exists however it is physically possible that a tubular may have little or no remnant magnetic field. It is also possible that the arrangement of the tubulars (north/south magnetic poles) minimize each other's dipoles out.
- Detection range is not typically dependent on the survey instrument as any 6 axis MWD/wireline tool can provide readings that can be utilized for PMR.
- Generally the resolution of the MWD tool has no impact on the detection range as the typical MWD tool with a resolution of 6nT is well below the typical earth field noise.
- Care should be taken not to plan detection ranges based on an externally magnetized casing model, unless the operator has specifically stated that the casing has been intentionally magnetized prior to the blowout.

### **2.6.1 Direction Accuracy**

PMR is generally able to produce accurate estimates of the direction of an offset well. This is because the PMR relies on vector measurements of the magnetic field signal. Commonly quoted accuracies are on the order of  $\pm 5$  degrees. This number should assume to be a 1 standard deviation number in the absence of further clarification by the PMR provider.

### **2.6.2 Distance Accuracy**

The commonly quoted number is up to  $\pm 10\%$  of the well-to-well distance. PMR is typically less accurate in determining a distance to an offset wellbore than a direction, because the strength of the remnant magnetic field for any casing string is estimated and is based on a maximum theoretical value for each casing string for a specific weight and size. This estimated value is treated as a known variable when calculating the distance to the offset target for PMR. The less accurate the estimated strength of the remnant magnetic field for any given casing string directly relates to the accuracy of the distance to target determination, and currently there is no means of independently measuring the remnant magnetic field strength for a casing string while it's downhole.

Note that some PMR methods do not use the pole strength as an input. However, the estimation of distance is heavily dependent on the modeling of the poles (with more or less complex functions and distribution of poles). It is this sensitivity on the modeling that also typically results with the distance determination being less accurate than the direction determination.

### **2.6.3 Detection Range**

Publicized PMR detection range is usually between 6 – 10m (19 – 33 ft.). However these detection ranges are maximum theoretical values as the detection range is entirely dependent on the amount of remnant magnetism in the offset well, which is highly dependent on the weight of the casing, and is significantly reduced if the casing itself becomes corroded. Pre-magnetizing a section of casing can increase the detection range of PMR up to 15m (50 ft.).

## **2.7 Limitations of PMR**

Some of the more significant limitations of PMR are outlined below.

### **2.7.1 Reliability/Repeatability**

PMR relies on the residual magnetism in the casing of the offset well as a source signal. If a section of the casing has little to no residual magnetism, the well will not be detectable via PMR. This makes ranging to corroded casing

potentially difficult. However, a break in otherwise un-corroded casing can actually improve the PMR detection range but the irregular field will potentially degrade the accuracy of the ranging.

As with any service offered by various providers not all PMR techniques will yield the same result. For non-automated methods, the human performing the fit can cause results to vary from individual-to-individual. Furthermore, the quality of MWD sensors and telemetry used to gather the MWD information can vary from vendor to vendor. Care should be taken to ensure the MWD tool being used meets the expected accuracy requirements of the PMR vendor. Example, tool saturation is possible when at close distances to the target well.

Note:- A possible limitation is the saturation level of the magnetometers. When drilling very close to the target well <0.5m (1.5 ft.) and the remnant magnetization level are observed up to 100 000 nT, typical MWD sensors can be saturated at 60 knT. Therefore considerations should be given to ensure the MWD can sustain the expected level of magnetization without saturation in certain specific cases.

Lastly, some PMR techniques require knowledge of the Earth magnetic field in order to range. These techniques can be affected by how accurately the Earth magnetic field is known and how accurately azimuth can be determined from the corrupted MWD measurements. All PMR techniques can be affected by large changes in the Earth magnetic field as a function of time during the collection of the ranging measurements. Use of IFR2 is a way to mitigate the effect of Earth magnetic field variations when ranging. In the absence of real-time background field monitoring, care should be taken to check for space weather which can cause such magnetic variations.

### **2.7.2 Sensor Location**

MWD-based PMR utilizes the sensors in the MWD directional tool. As such, they are usually 15 – 20m (45 – 65 ft.) behind the bit. If offset from bit is an issue, an EMS tool can be run on a wireline to get a PMR ranging shot closer to the bottom or the hole.

### **2.7.3 Interference from the Casing Shoe in the Drilling Well**

Using PMR immediately after exiting a casing shoe can result in unreliable results. This is because the PMR can pick up the magnetism of the casing shoe, which decays with distance. The casing shoe signal makes it difficult to isolate the magnetic signature of the casing in the offset well.

### **2.7.4 Multiple Offset Wells**

It is increasingly difficult ranging to an offset well while using PMR when there is another offset well a similar distance away. While there are techniques for dealing with such scenarios, the complexity of the situation can result in decreased accuracy of the ranging solution until a closer proximity is established to the target wellbore.

## **2.8 Applications for PMR**

There are many applications where PMR is useful. A few are

- Collision Avoidance
  - When magnetic interference is detected
  - During planned close approaches with relatively similar wellbore trajectories
- Well Twinning
- Passing Over/Under a Perpendicular Well (When accidental collision is not a safety concern)
- Wellbore Intercept
- Well Re-Entry

### 3. Active Magnetic Ranging

Active magnetic ranging (AMR) is used to reduce the uncertainty of wellbore position when surveys are not enough. AMR technology is comprised of two main components: the generation of a magnetic field and a method to detect that magnetic field. This generated magnetic field, which is distinct from the earth's' magnetic field, is then measured and analyzed to define a proximity vector between the two wellbores. AMR technology is separated into two categories:

- **Access-Dependent Active Magnetic Ranging** - Access-dependent active magnetic ranging services are used for the precise measurement of distance and direction between two or more wellbores, accomplished by using magnetic field sources of known strength and orientation. Access-dependent active magnetic ranging systems allow two or more wellbores to be positioned within extremely tight tolerances, such as:
  - Drilling stacked horizontal well pairs for steam-assisted gravity design (SAGD)
  - In-fill drilling and collision avoidance
  - Wellbore intersections for well control or pipelines
  - Observation well placement
  - Coalbed methane degasification wells
- **Access-Independent Active Magnetic Ranging** - When there is no access to the existing wellbore, access-independent active magnetic ranging systems precisely position wellbores with no cumulative surveying error, allowing wellbores to be placed much closer together than is possible using surveys alone, greatly optimizing wellbore placement. This technology is used for:
  - Relief well operations
  - Complex plug and abandonment
  - Collision Avoidance
  - Wellbore recovery

#### 3.1 Access Dependent Active Magnetic Ranging

##### 3.1.1 Magnetic Solenoid AMR Systems

Consists of a solenoid, approximately 5m (16 ft.) in length, which is placed in the reference well on mono conductor wireline at a specific depth relative to the current bottom hole depth in the drilling well. A single large magnetic field is generated by the solenoid by sending a direct current in a positive polarity through it, followed by reversing that current to a negative polarity. The magnetic field is generated only during a special Magnetic Solenoid AMR Survey. The AMR engineers are in constant communication with the Wireline engineers moving the Magnetic Solenoid to new depths in the reference well as drilling progresses. When the radial separation between the reference well is 15 – 23m (50 – 75 ft.) the accuracy of the Magnetic Solenoid AMR system is within  $\pm$  5% of the radial distance. When within 4.5 – 15m (15 – 50ft.) of radial distance the accuracy of the Magnetic Solenoid AMR system improves to  $\pm$  2 – 4% of the radial distance.

Note:- There are commercially proven solenoid systems that offer the following:

When the reference well is 20 – 30m (65 – 100 ft.) accuracy is between  $\pm$  1.5 - 5% (2 sigma) in the radial direction. When between 4.5 – 20m (15 – 65 ft.) accuracy is between  $\pm$  0.5-1.5% ( 2 sigma) in the radial direction. It should also be noted that errors are dependent on relative geometry of the wellbores, magnetic interference and error coordinate direction.

Magnetic Solenoid AMR Systems are used in a variety of Directional Drilling applications including:

- Drilling stacked horizontal well pairs for Steam Assisted Gravity Drainage (SAGD)
- Infill and collision avoidance
- Observation well placements

Magnetic Solenoid AMR Systems Downhole typically consists of the following components:

- 6 axis MWD Directional Probe (Sensor in Drilling Well)

- 5m (16 ft.) Magnetic Solenoid (Conveyed via Wireline in Reference Well)

### **3.1.1 Typical Magnetic Solenoid AMR Systems Protocol**

- Follow normal drilling practices until a regular survey depth is reached
- Confirm Magnetic Solenoid is at desired depth with Wireline Engineer in the reference well
- Have the Magnetic Solenoid energized with a positive direct current using the Magnetic Solenoid's power supply
- Begin taking Magnetic Solenoid survey with Magnetic Solenoid software
- When indicated by the Magnetic Solenoid survey software, reverse the polarity of the Magnetic Solenoid
- When the Magnetic Solenoid survey is completed, demagnetize the Magnetic Solenoid and turn off direct current
- Ranging Engineer QC's the Magnetic Solenoid survey, and provides the Directional Driller with a relative position to the reference well (Typically High-Low / Left-Right distances are provided)
- Begin drilling down to next survey station in the drilling well
- Move Magnetic Solenoid to the next desired depth in the reference well
- Repeat steps 2 – 9 until well is completed or AMR is no longer needed

### **3.1.2 Rotating Magnet AMR Systems**

Consists of a Rotating Magnet Sub, approximately 0.5m (1.6 ft.) in length, which sits between the bit and the motor. This sub contains stacks of powerful rare earth magnets that create an A/C magnetic field when rotating with the bit. This magnetic field is monitored by the 6-axis directional sensor located in a nearby well on wireline, with a useable range of up to 46m (150 ft.) in Casing, and 80m (262 ft.) without casing, and provides a distance and direction from the sensor to the drill bit. Data is processed in real time to generate distance and directions between each of the well bores to an accuracy of approximately  $\pm 5\%$  of the wellbore separation. This equates to wellbore position accuracy of less than a foot from the reference well.

Note: There are commercially proven rotating magnet systems that have a usable range of 91m (300 ft.) in a cased well and 128m (420 ft.) in open hole.

#### ***Rotating Magnet AMR Systems are used in a variety of Directional Drilling applications including:***

- Intersecting an existing well
- Steering past an existing well at a controlled separation
- As a guidance tool in Civil Engineering River Cross operations
- To provide controlled separation of parallel wellbores (typically in heavy oil production)

#### ***Rotating Magnet AMR Systems Downhole Tool strings typically consists of the following components:***

- The 6 axis Directional Sensor Probe (Conveyed via Wireline in Reference Well)
- A bottom weight bar
- The tool foot
- Above tool weight bar with feed-through wire (optional)
- Rotating Magnet Sub (Drilling Well)

The tool and weight or extension bars are 1.75 inch O.D Standard Temp applications or 2.0 inch O.D for High Temp applications (up to 200°C), with an approximate length of 1.4m (4.6 ft.) for the tool, and 1.3m (4.2 ft.) for the weight or extension bars, making the typical tool assembly of wireline head, tool, weight bar, and foot approximately 3.1m (10.3 ft.) in length. The connection between tool and wireline is made with a Go connector.

#### ***Typical Rotating Magnet AMR Systems Protocol***

- Follow normal drilling practices until approximately 90m (300 ft.) from the pass by of the Offset Well
- While drilling and approaching the 90m (300 ft.) distance data monitoring will begin, if the RMRS Probe is detecting a flux in the AC field data will be recorded and an RMRS determination will be made at the next survey point

- Steps involved with taking a Recorded Rotary Magnet AMR Shot:
  - At any new hole depth a bottom hole survey will be taken
  - The Directional Driller on tour will make an extrapolation to the bit based off of the survey information received and provide that extrapolation to the Ranging Specialist
  - Data is typically acquired real-time while drilling. Dependent on the quality of data collected while drilling, the ranging specialist may require the data be collected after a section has been drilled by having the driller wipe the section at a speed of  $\approx 1.5\text{m/min}$  (5ft/min). It is important that the section is wiped at a consistent speed and not fluctuating between the given parameters. Each wiped section will be 3 – 5m (10 – 15 ft.) in length, and is determined on a case by case basis by the Ranging Specialist

Note:- This step may not be required in some cases. All data can be taken at the survey station on bottom while circulating the hole prior to making connection. Wiping the hole may be optional depending on the situation.

- Once the determined section has been wiped the Driller will take necessary precautions to maintain hole integrity by reducing parameters to what is deemed appropriate by the Company Representative(s) on site

Note: In certain circumstance this step can be eliminated, hole integrity issues may be avoided by not wiping the hole.

- At this time the Ranging Specialist will process and analyze the recorded Rotating Magnet AMR Data
- Depending on the results from any given recorded RMRS determination the Ranging Specialist will determine whether or not more RMRS data is need to be taken at a given hole depth
- Once enough data has been acquired at a given point, the Ranging Specialist will advise the Company Representatives on the status of the where the drilling well is relative to the offset well. The Ranging Specialist will also recommend a distance to drill ahead, typically 3 – 10m (10 – 33 ft.)
- Steps 3-5 will be repeated until the objective has been completed.

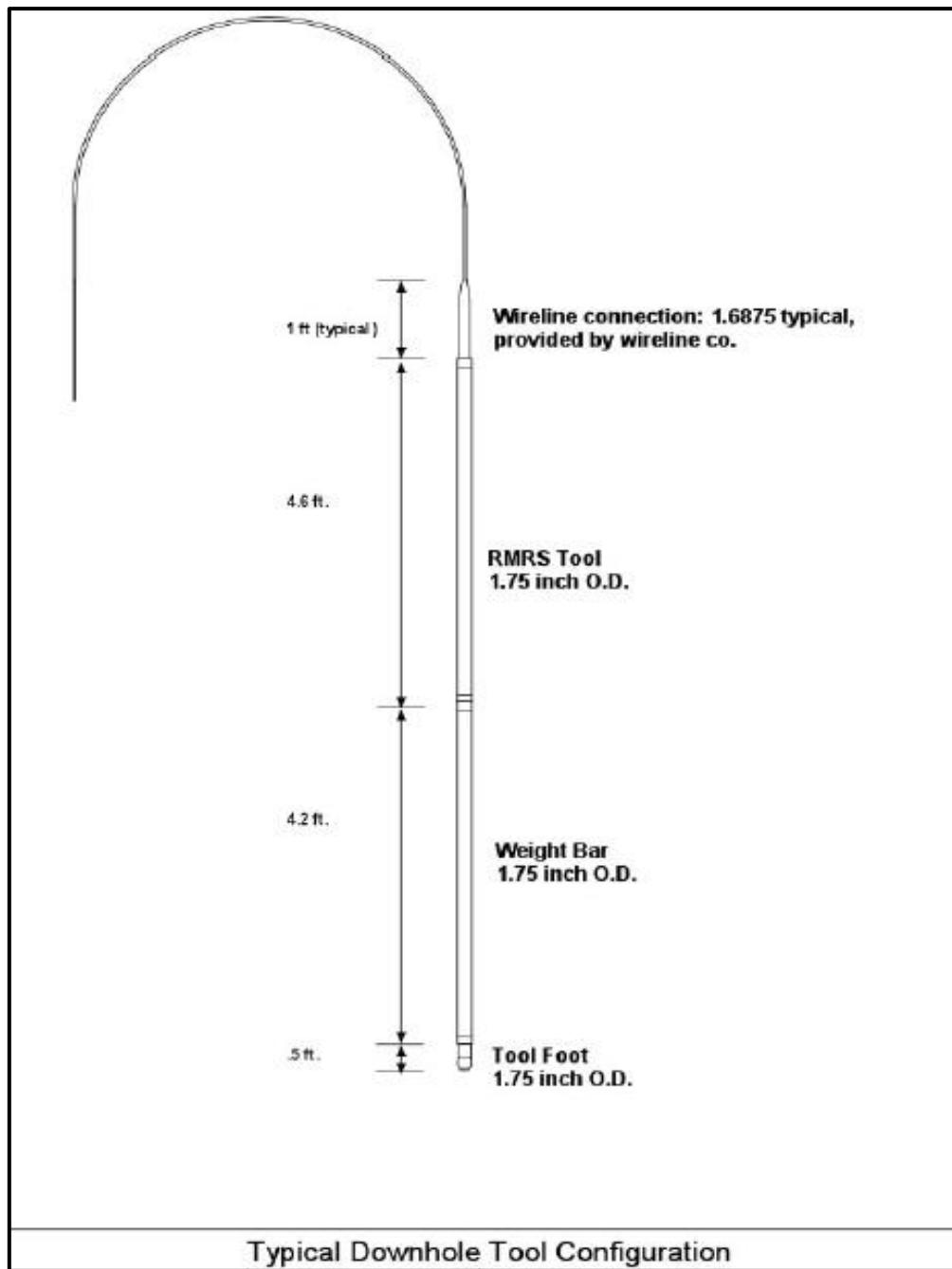


Figure 5 Common Tool Configuration

Typical Magnetic Solenoid & Rotating Magnet AMR Systems Tool Specifications		
	Magnetic Solenoid AMR	Rotating Magnet AMR
Nominal Tool OD	2.0 in / 44.5 mm	1.75 in / 44.5 mm
Hole Size Range	NA	3-7/8 in & Up
Minimum Tubing ID	2-7/8 in / 73 mm	2-7/8 in / 73 mm
Length	8.2 ft / 4.9 m	8.2 ft / 2.5 m
Weight	20 lb / 9.1 kg	20 lb / 9.1 kg
WL Connection	1-3/16 inch – 12 GO-head	NA
BHA Connection	NA	2-3/8 inch Reg & Up
Maximum Operating Temperature	302°F / 150°C	392°F / 200°C
Maximum Operating Pressure	15,000 psi / 103.42 MPa	25,000 psi / 103.42 MPa
Accuracy 16 to 49 ft / 5 to 15 m	2-4%	5%
Accuracy 49 to 82 ft / 15 to 25 m	5%	5%
Accuracy Beyond 82 ft / 25 m	NA	5%
Maximum Range	82 ft. / 25 m	262 ft. / 80 m

Figure 6 Typical Magnetic Solenoid & Rotating Magnet AMR System Tool Specifications

### 3.2 Access-Independent Active Magnetic Ranging (AI AMR)

AMR works by injecting an AC current into the formation and then onto the target well, which in turn creates a magnetic field. From this induced magnetic field, both distance and direction can be determined.

#### 3.2.1 Advantages

- Detection is based on a signal that is generated by the AMR assembly.
- Detection range is typically an order of magnitude greater than PMR.
- Planning can be developed around a calculated detection range significantly reducing the likelihood of a sidetrack.
- Works equally well on steel and non-magnetic tubulars.
- Detection range not significantly impacted by the target well tubular size.
- Industry's only ranging service that can take a direct distance measurement.
- Lowest risk of an accidental collision as the ranging is taken on bottom with the greatest depth of investigation.

#### 3.2.2 Disadvantages

- While the ability to perform AMR exists in a directional drilling BHA, the service is not appropriate for all applications. On a typical relief well the majority of ranging runs will require an open hole wireline trip.
- Service may not work when run in ultra-high resistivity (UHR) formations such as pure salt. This constraint is generally not an issue when ranging in close proximity of the target well. This issue may also be mitigated by the design of the ranging assembly that has the excitation source above the UHR formation.
- Service requires a dedicated kit and personnel onsite which increases the cost.

#### 3.2.3 AMR Data Collection

For each ranging run, a unique data collection plan is designed to ensure the data requirements are met while also making the overall logging time as short as possible. Factors that impact the overall data collection time include:

- Phase of the relief well. The three phases of ranging operations are Locate, Follow, and Interception. The respective goal of each phase is to determine the location of the target before ellipsoids overlap, to safely converge on the target, and to guide the relief well into the target well. Ranging determinations in the locate and interception phase require a higher data density to tightly map the trajectory. In the follow phase the proximity between the relief and target well is typically large enough so any deviations from the expected position of the target well have limited impact on the overall drilling plan.
- Survey quality of the target well – For a target well with limited or no available surveys the ranging determinations must be made from high density data. This data is used to both determine the proximity between the relief and the target well and to predict the deeper trajectory of the target well.
- Physical limitations – The AMR tool has a temperature gradient limitation that will impact the available logging time. For wells with temperatures in the higher limits of the tool, the shortened logging time may limit the available data collection time increasing the size of the call box. In extreme cases this may increase the overall ranging runs required to intersect the target well.

Under normal operating conditions the data collection plan will require high data density for the deeper sections of the ranging interval. This data will typically be taken at 0.3m (1 ft.) intervals for the bottom 3 – 6.6m (10 – 20 ft.) feet and increased to 1.5m (5ft.) foot intervals up to 15m (50 ft.) off bottom. Any subsequent data points in unlogged sections will be taken at 7.5 – 15m (25 – 50 ft.) intervals. This data will be analyzed by the ranging specialist and any infill data will be taken on a 2<sup>nd</sup> descent if required.

The estimated time for a ranging run is as follows:

- 30 minutes for tool and wireline handling
- 45 m/min (150 ft./min) descent time to deploy the tool to the logging interval
- 3 hours of data collection
- 45 m/min (150 ft./min) ascent time
- 30 minutes of tool and wireline handling time

Under challenging logging conditions, deploying the AMR tool inside a ranging BHA will increase this time. An additional 30 minutes of surface handling for deploying the tool via a side entry sub should be added for deploying and retrieving the tool. Additional time for circulating cooling mud through the ranging BHA may also be required.

### **3.3.1 Reasons to Select AMR**

- AMR offers the highest success rate for intersections. If minimizing time is critical to the operation, using the AMR system offers less risk of additional sidetracks.
- With the trip time included, it is generally quicker to complete a relief well intersection with AMR as the increased range and accuracy eliminates the sidetrack risk of PMR.

### **3.3.2 AMR Tool and Wireline Assembly (Bridle)**

AMR is deployed into an open hole via a 7 conductor wireline. The bridle assembly contains the tool assembly, isolation section, and excitation components.

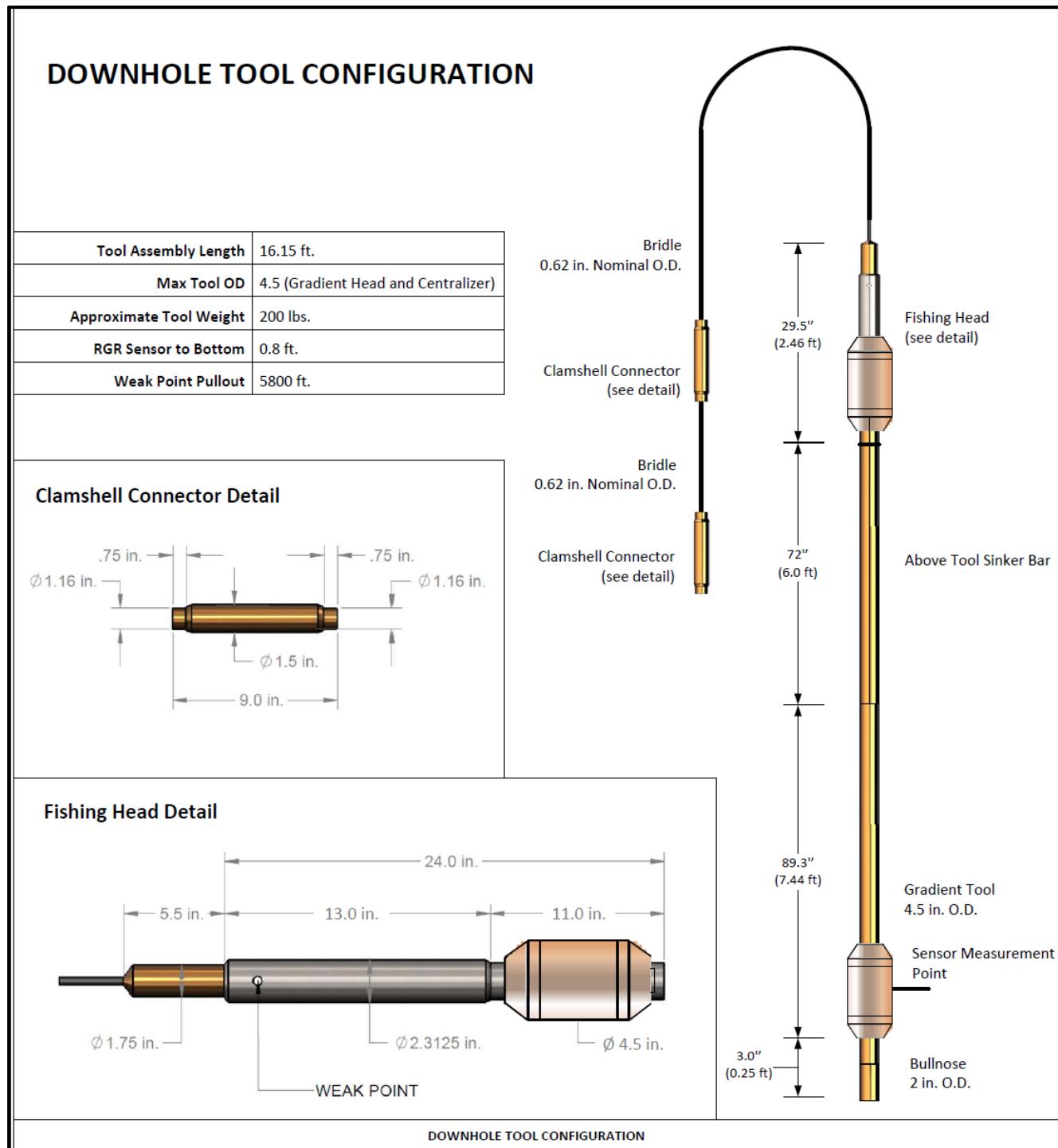


Figure 7 Downhole Tool Configuration

### AMR Wireline Requirements

The AMR kit is fully equipped to connect to a Halliburton, Baker Hughes, or Schlumberger 7 conductor logging unit. Connecting to other units is possible but will require detailed pre-planning to ensure the correct crossovers are sourced.

### Shipping Details

- The AMR kit comes complete in a 2.67m x 1.32m x 1.32m (8.76 ft. x 4.33 ft. x 4.33 ft.) box.
- The shipping weight is approximately 950 kg (2100 lbs).
- Kit contains no hazardous chemicals or radiation.
- Kit is air transportable.

### 3.3 Detection Range

#### 3.3.1 AMR Active Magnetic Ranging (AMR)

The detection range for the AMR tool is dependent on the following factors: RW trajectory, size of target well tubulars, target well tubular top/bottom, formation resistivity, bridle configuration, and excitation method. Expected detection range is determined by a model of an induced magnetic field. This induced field is an AC magnetic field that exists only when the target well is being excited by the AMR ranging assembly. *Accurate estimation of the range of detection is a key component in creating an effective relief well ranging plan.*

Two key plots from the modeling software used to determine the detection range are the Signal Intensity ( $\mu\text{A}/\text{m}/\text{A}$ ) and the distance to target. The following graphs are examples of the custom analysis that are included in the relief well ranging plan. [Figure 8 & Figure 9]

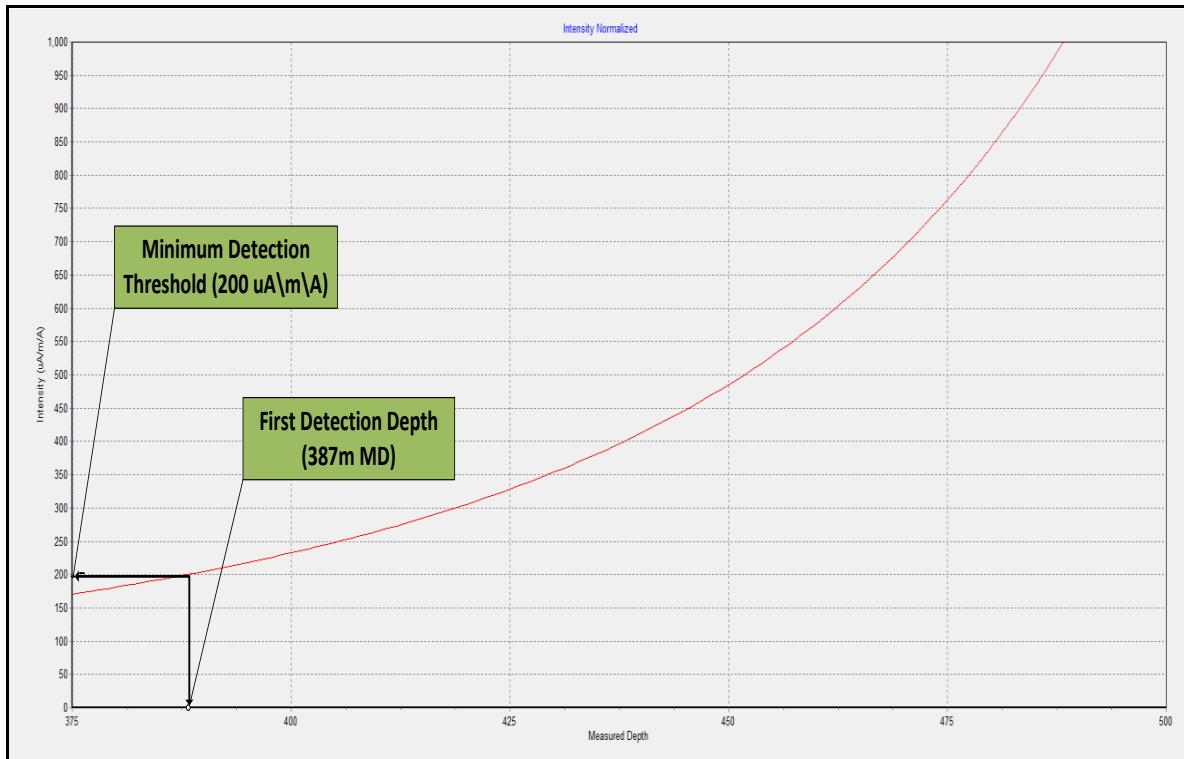


Figure 8 Typical AMR Detection Threshold

Note:- The signal detection is independent of the current injected therefore this detection threshold is not quoted normalized by injected current. The detection threshold also directly relates to maximum detection range. The diagram above shows typical some Typical AMR Detection Threshold. This is project specific and need to be updated as the estimation of detection distance is a key component in creating an effective relief well plan. There are commercially proven systems with a minimum detection threshold of 48 $\mu\text{A}/\text{m}$ .

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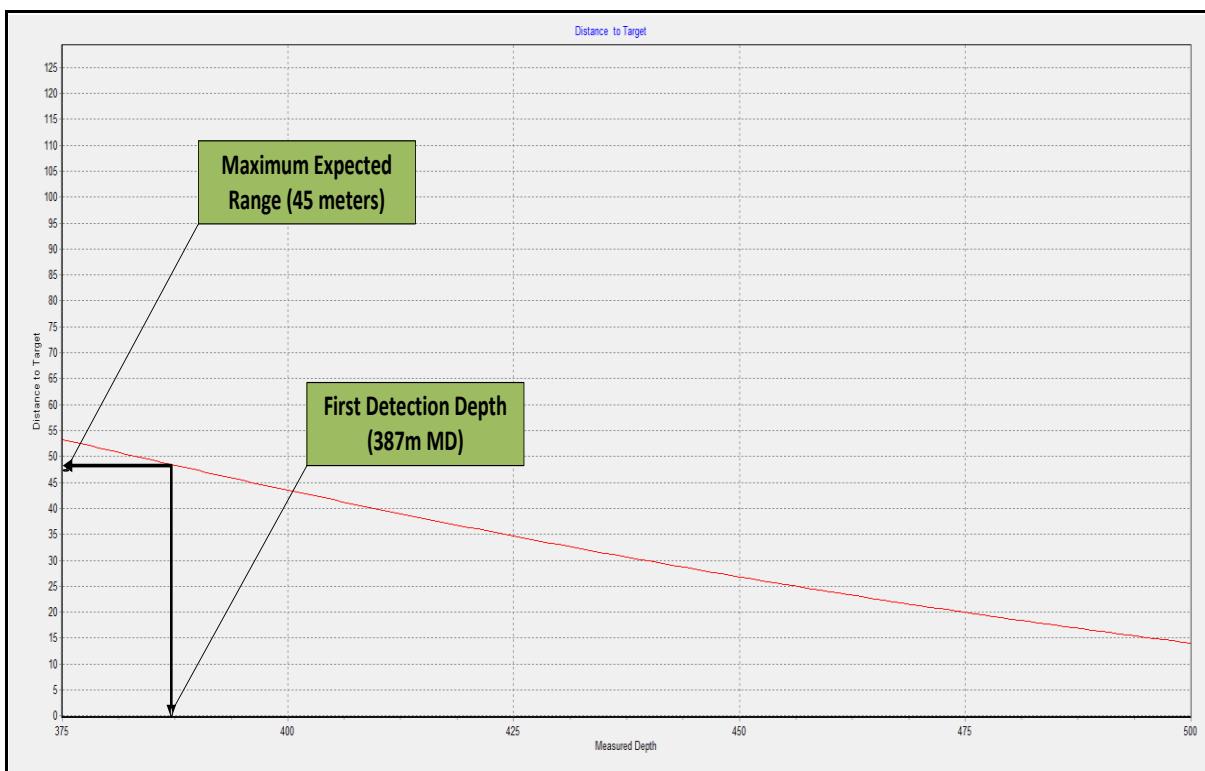


Figure 9 Maximum Expected Range

## 4. Passive Acoustic Ranging

### 4.1 Introduction

PAR involves the detection of sound or vibration created by the object being detected, which is then analyzed to determine the location of the object in question.

The sources generate an acoustic signal that travels in all directions and travels in the media in the same direction as the excitation direction. These monopole signals can either be high frequency generating a compressional signal.

Acoustics waves can propagate in a media in multiple modes that are based on the way the particles in the media react to the disturbance introduced. When listening for passive acoustics, the sound is propagated as a compressional wave. In compressional waves, the displacement of the particles occurs in the same direction of wave propagation. Compressional waves can be generated in liquids as well as solids because the energy travels through the atomic structure by a series of compressions and expansion (rarefaction) movements.

The common passive acoustic source is the noise that generated by the drilling bit as shown in **Error! Reference source not found.**. The strength of the noise generated is varied by the bit type and the distance from the source. Fixed-cutter bit, which drill with shearing and scraping will create weaker signal as compare to Roller-cone bit, which drill by scraping and gouging.



Figure 10 Various bit type to produce acoustic source for passive acoustic ranging detection

### 4.2 Application

Within the oil and gas industry, one application that can use passive acoustic ranging is well collision avoidance. The acoustic source in this case is the drill bit, which when in operation generates strong vibration and also higher frequency acoustic noise. When the drill bit approaches an existing well, this noise penetrates into the well structure, and may propagate over long distances within the well.

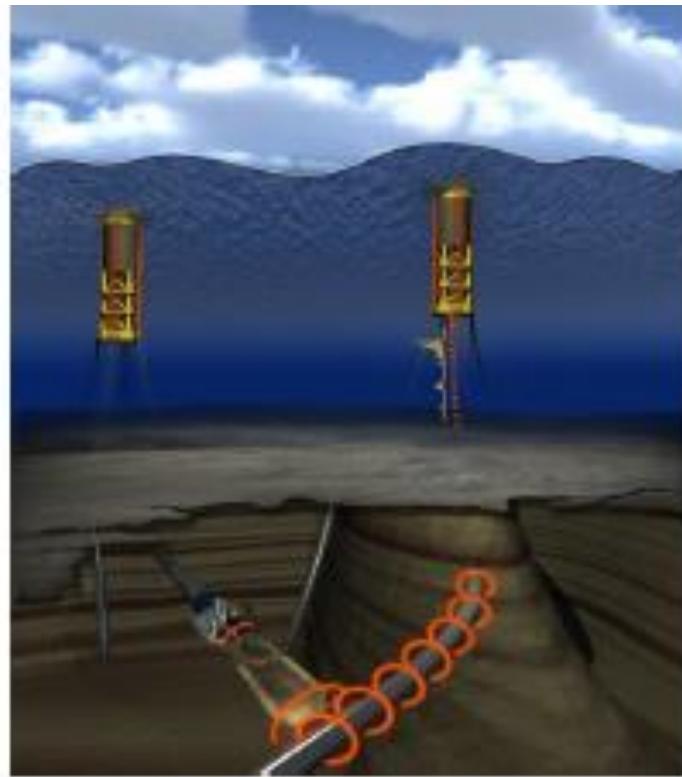
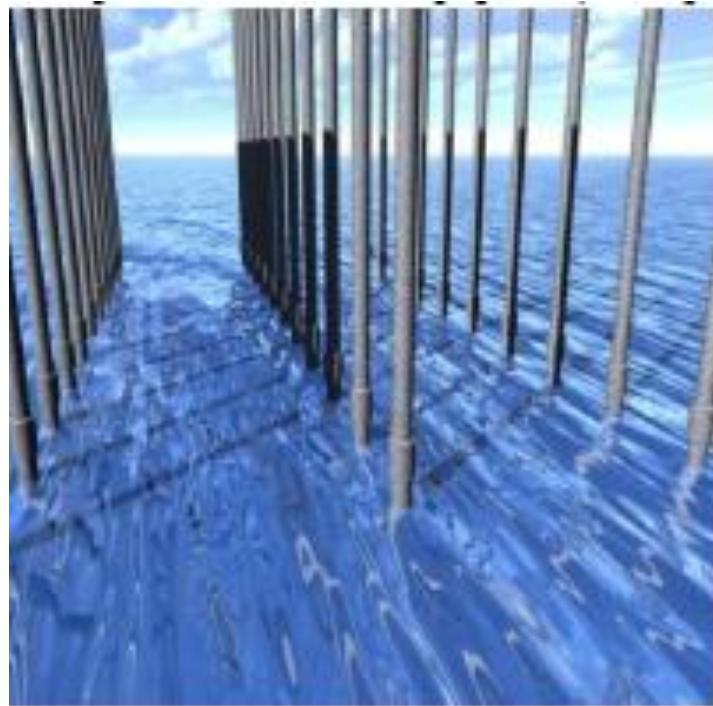


Figure 11 Illustration of drill bit closing in on an existing well

Non-invasive sensors are clamped topside on wells adjacent to the drilling operation in order to pick up such propagated drilling noise. Spectrum analyses of all sensor data are presented during the drilling operation in real time.



Figure 12 illustration of sensors mounted on conductor of the well



**Figure 13 Well conductors, acoustic wave guides transporting information back from drilling operation.**

Any change in the acoustic conditions on the well heads is readily available for scrutiny as the operation commences and may provide early warning of the drill bit approaching an existing well. Upon observations of strongly increasing ultrasonic signal levels, drilling can be halted and data from available sources analyzed. Depending on the analysis, the drill string may be diverted or drilling can resume with confidence that a collision has been avoided as shown in **Error! Reference source not found.** or that predictive calculations have been confirmed.

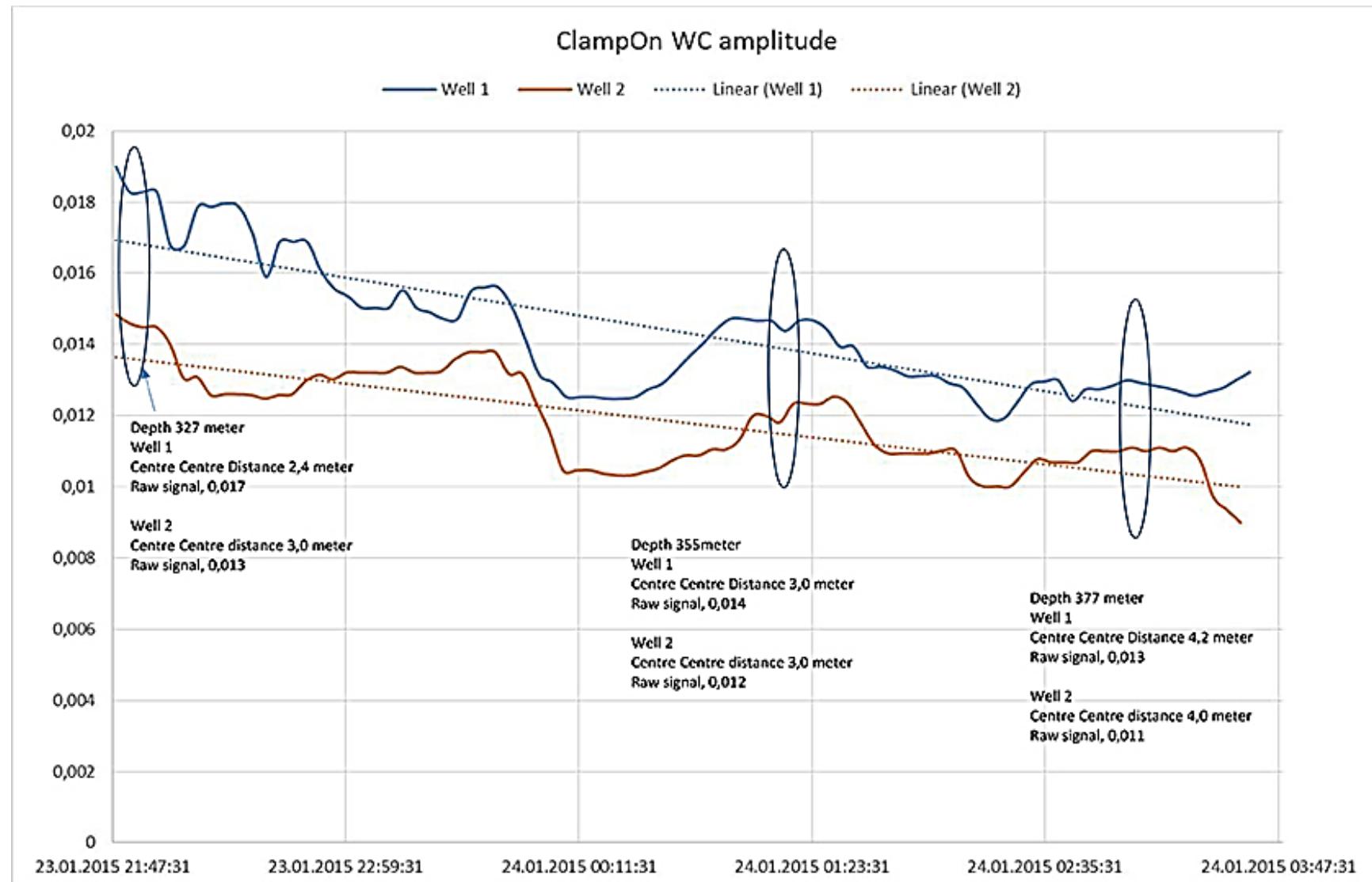


Figure 14 Signal strength recorded at 2 different well conductor locations in collision avoidance situation, increasing ct-to ct distances

# 5. Active Acoustic Ranging

## 5.1 Introduction

Geophysicists use surface seismic data to map and interpret potential petroleum reservoirs as well as hazardous drilling events that affect the drilling process. Seismic surveys use a powerful source represented in **Error! Reference source not found.** as a cluster of air-guns to initiate a signal that travels and reflects as it encounters a contrast in acoustic impedance. Those reflected waveforms are recorded as time events and are later on converted to an image that represents the rocks and structures underneath. Geologists use those maps to identify potential hydrocarbon reservoir traps and determine location of drilling wells. Surface seismic is an essential process needed by oil companies to make valuable decisions. Both on land and offshore uses the same principle and slightly different setup to map the layers underneath the surface.

AAR utilizes surface seismic processing methods to determine azimuthal direction and distance of compressional and shear acoustic signals, reflected from around the borehole. After processing the reflected signals, the distance and direction of nearby wellbores can be determined. This can be effective in salt formations, where resistivity inhibits use of active electromagnetic ranging tools.

Interest in reflected signals was limited in the beginning to detecting fractures crossing the wellbore. The idea of using sonic-waveform data to generate high-resolution seismic surveys around the borehole was first discussed in 1984 (Utard, et al) and in 1989 (Hornby, 1989). Later, in the 1990s, this method was used to image fractures away from the borehole (Yamamoto et al., 1999).

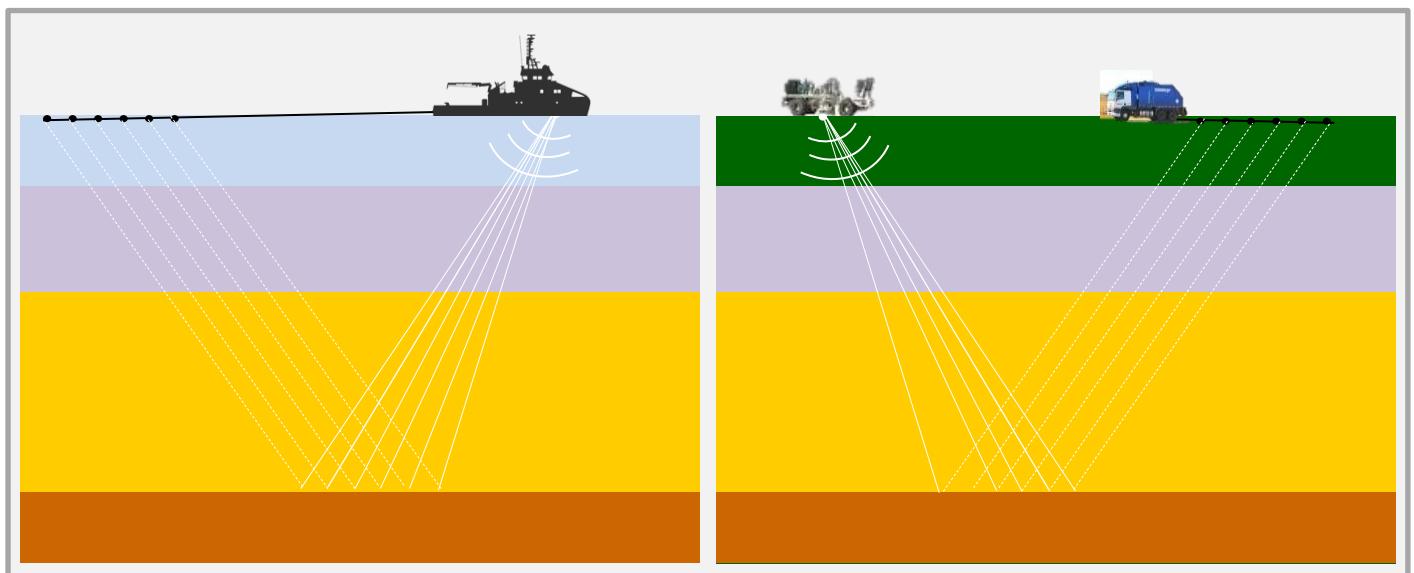


Figure 15: Seismic Setup Offshore (Left) and Land (Right)

Most of the surface seismic sources generate a relatively low frequency signal capable of traveling thousands of feet deep in the rock. Due to the low frequency nature of those signals, the resolution of surface seismic is so low that it is only able to detect events larger than 100 m (328 ft) in deep wells.

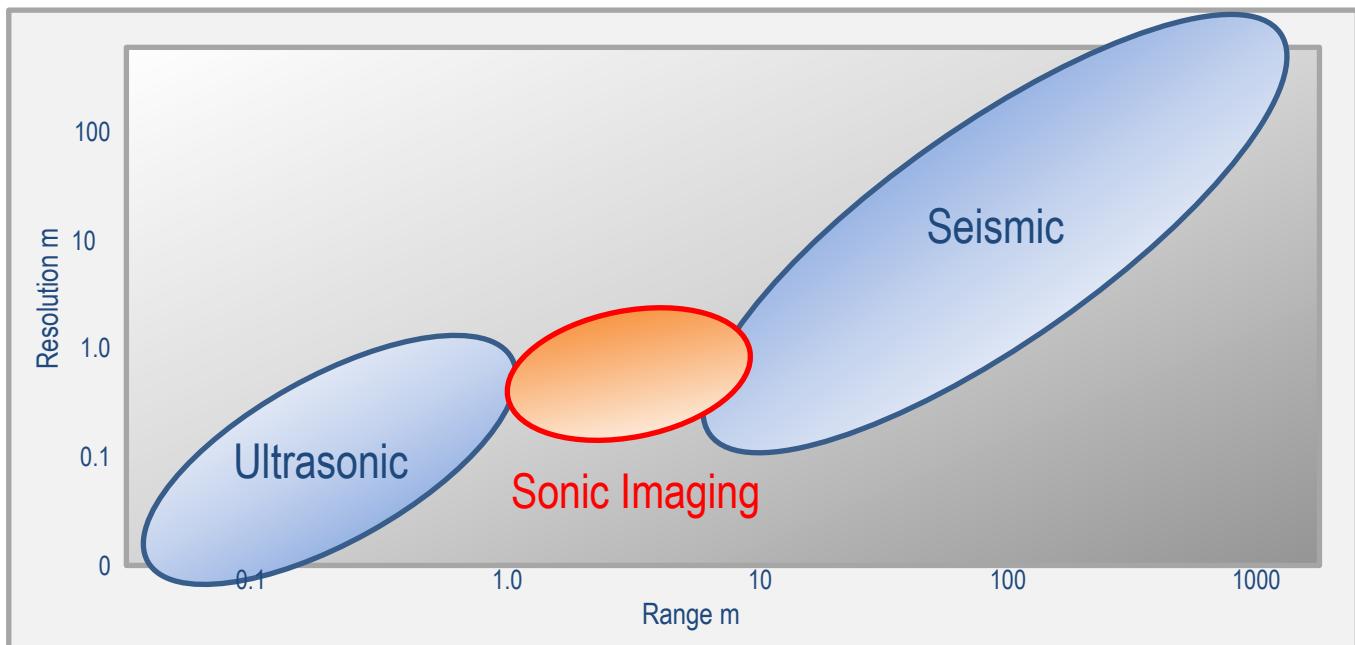


Figure 16 the resolution of sonic imaging range in between ultrasonic and seismic ranges

## 5.2 Basic Theory

The idea of using sonic-waveform data to generate high-resolution seismic surveys around the borehole was first discussed in 1989. Later, in the 1990s, this method was used to image fractures away from the borehole [Yamamoto et al., 1999]. Since then, Borehole Acoustics Reflection Survey (BARS) evolved. Micro resistivity, ultrasonic, and Stoneley methods of fracture and mobility detection are all limited to the area immediately surrounding the borehole. BARS uses reflected acoustic waveforms to penetrate deeper into the formation, resolving features away from the wellbore and providing a better understanding of the reservoir. The quality of the data acquired is very important for its processing. The quality of the image produced is a function of the acoustic platform used in the acquisition.

### Acoustic Acquisition:

- Acoustic acquisition is to be done using both Monopole as well as Dipole transmitters.
- Monopole and dipole data is to be acquired in a minimum of 8 azimuths.
- Recording of tool orientation is to be done at the same time as waveform acquisition in order to determine the azimuth of waveforms.
- Ensure enough waveforms are recorded to cover the expected target well location.
- Ensure enough waveforms are recorded to cover the expected target well location.

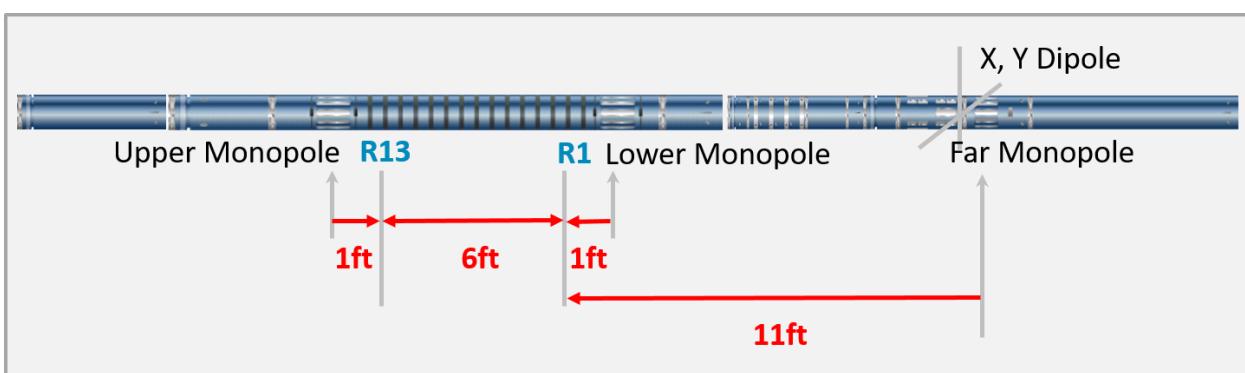


Figure 17 Illustration of the ASL with various transmitters and receivers spacing's, total of 13 receiver stacks with 8 receivers azimuthally arranged for every stack

Active acoustic ranging is one of many applications of the Borehole Acoustic Reflection Survey that uses reflected waveforms (compressional and shear) rather than refracted waveforms to detect events that lie in the range of the acoustics tool used. This measurement has a higher resolution than the surface seismic due to the frequency used and analyzed. Its objective is to detect nearby wells and determine their location accurately.

### 5.2.1 Fundamental Principle

Acoustics waveforms propagate in a media in different forms that vary dependent on the source of the acoustic excitation and disturbance and the frequency as well as the properties of the media. The velocity of propagation of acoustic signals in a media is a function of the media properties as well as the mode of excitation.

Knowing the distance and direction to a nearby wellbore can be critically important—either to avoid or ensure collision with the other well. Until recently, the only options were active electromagnetic and passive magnetic methods to locate a nearby well, but both methods require the target well be a cased hole, and both perform best when the two wells are parallel. Active Acoustic Ranging has been successfully applied, along with the passive magnetic method, to locate a cased hole and standalone to locate an open hole. For example, Active Acoustic Ranging can be run in an open hole, highly deviated well to determine the distance and direction to a cased vertical well. Figure 18 displays the geometry and wave paths used to image bedding (top) and a nearly perpendicular well (bottom).

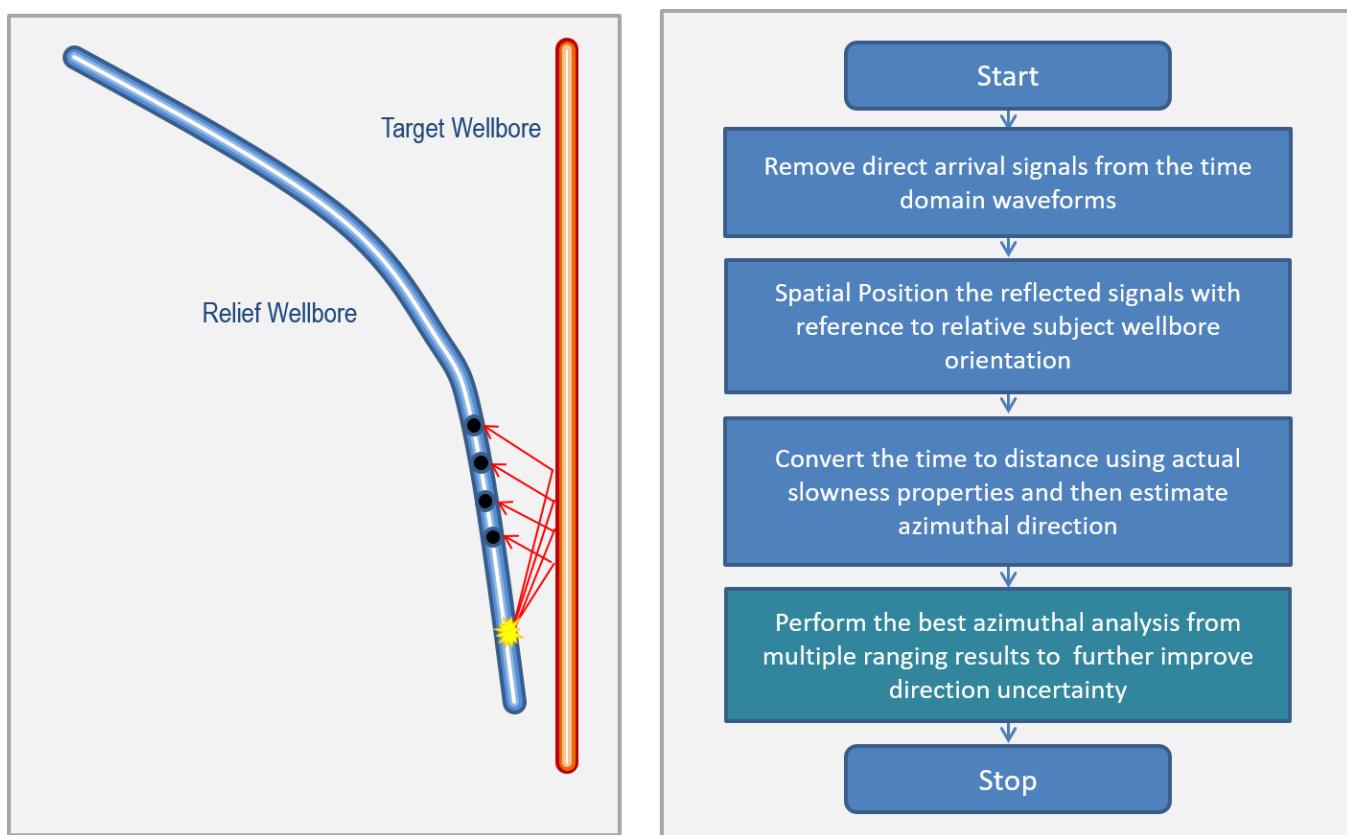


Figure 18 Illustration of AAR to detect the target wellbore using acoustic source and receivers (left) and illustration of general processing steps to determine the ranging distance and direction (Right)

### 5.2.2 Acoustic Source

There are two commonly type of sources are used to generate the acoustic signal that would propagate the signal through the rocks.

- Monopole (see

)

This type of source generates an acoustic signal that travels in all directions and travels in the media in the same direction as the excitation direction. Monopole signals can either be high frequency generating a compressional signal or a low frequency generating a Stoneley signal. Stoneley is a boundary wave (or interface wave) that typically propagates along a solid-solid interface or at a liquid-solid interface.

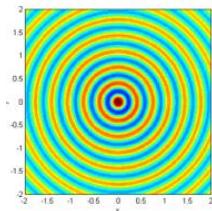


Figure 19 Shows Monopole generated acoustic signal pattern

- Dipoles (see Figure 20)

Dipole source is a directional source that generates an acoustics signal that excites the media in a direction perpendicular to the propagation direction.

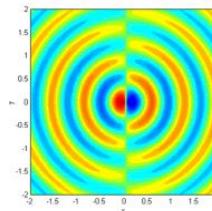


Figure 20 Shows Dipole generated acoustic signal pattern

### 5.2.3 Acoustic Propagation

Acoustics waves can propagate in a media in multiple modes that are based on the way the particles in the media react to the disturbance introduced. Sound can propagate as compressional waves, shear waves and some other modes. Some of the modes of propagations are listed below.

- Compressional

In compressional waves, the displacement of the particles occurs in the same direction of wave propagation as shown in Figure 21. Compressional waves can be generated in liquids as well as solids because the energy travels through the atomic structure by a series of compressions and expansion (rarefaction) movements.

- Shear

In shear waves, the displacement of the particles is transverse to the direction of propagation as shown Figure 21. Shear waves require an acoustically solid material for effective propagation and therefore are not effectively propagated in materials such as liquids or gasses. Shear waves are slower than compressional waves. Acoustics waveform produced by logging tools appears as attached in the Figure 22.

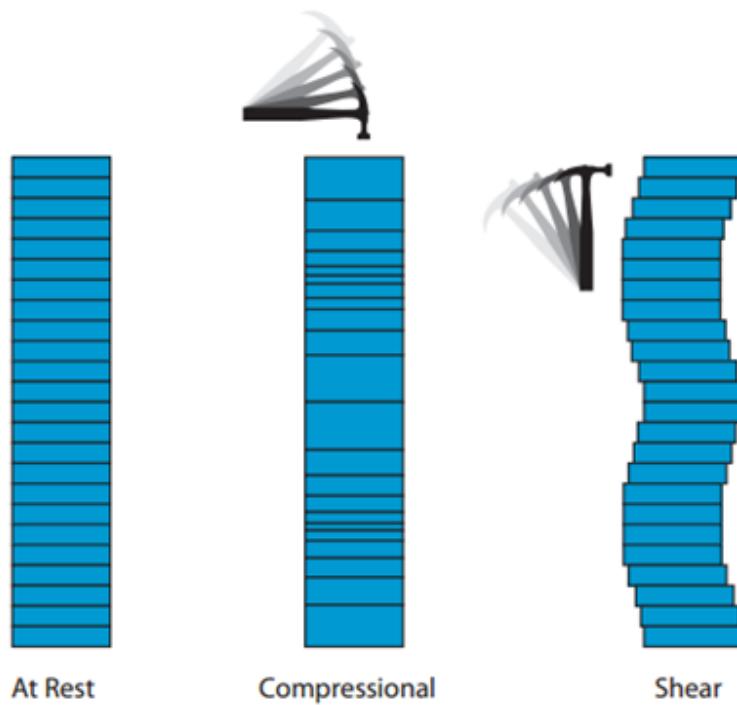


Figure 21 Particle motion in formation at rest versus wave propagation direction, compressional and shear

Compressional and shear waves are stress-velocity fields that propagate in formation rock by acoustic excitation. These waves are also known as bulk waves (or body waves). The complete waveform from the start of firing to the reflected waves is shown in Figure 22 and how the waveform is presented as color scale in Figure 24.

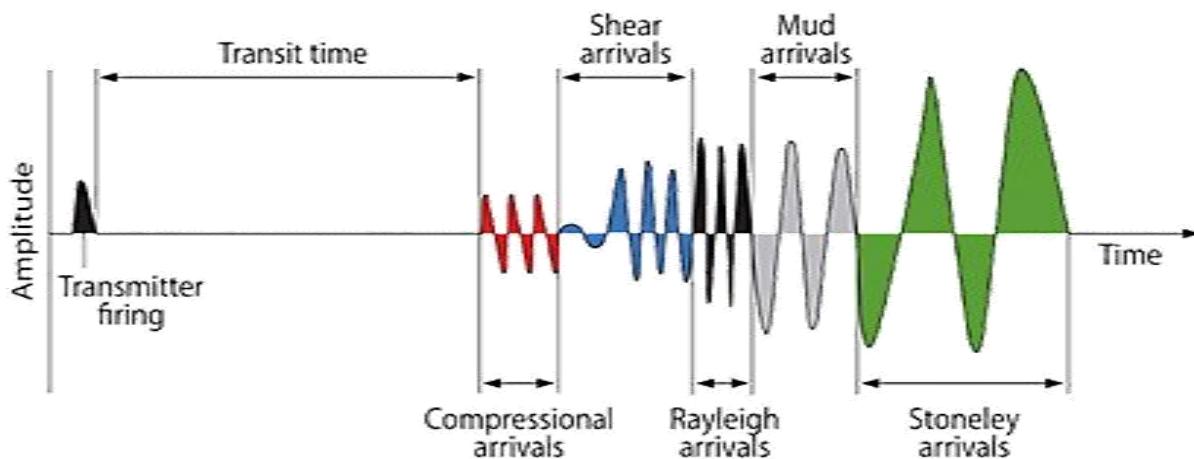


Figure 22: various waveforms as reflected and refracted in time

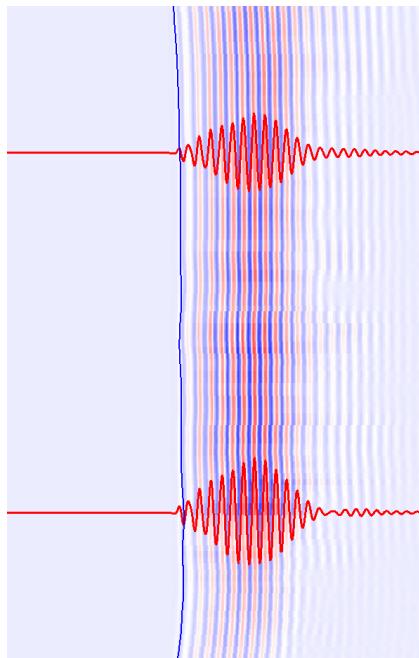


Figure 23 how the waveform is presented as color scale as peak in red and trough in blue

### 5.3 Acoustic Distance and Direction

The acoustic distance is a result of migration processing. This is the process by which the events are geometrically re-located in time to the location the event occurred as reflected by the target wells rather than the location that it was recorded. This creates a more accurate image of the target well location. This process is necessary to overcome the limitations of geophysical methods imposed by areas of complex geology, such as faults, salt bodies, folding etc.

The time is then converted to the distance. By knowing the slowness of the rock, speed of sound travels in the rock that measures during the acquisition; therefore, the distance can be defined. The best ranging detection distance is defined better at fast formation such as salt due to the current limitation of recording time that resulted in shorter distance at slow formation such as shale.

Since the acoustic distance is relying on the signal reflected from the target well to the receivers,; the acoustic distance is closer to the 3D Lease Distance, the distance which is normal to the target well rather than normal plane, perpendicular to the subject well or travelling

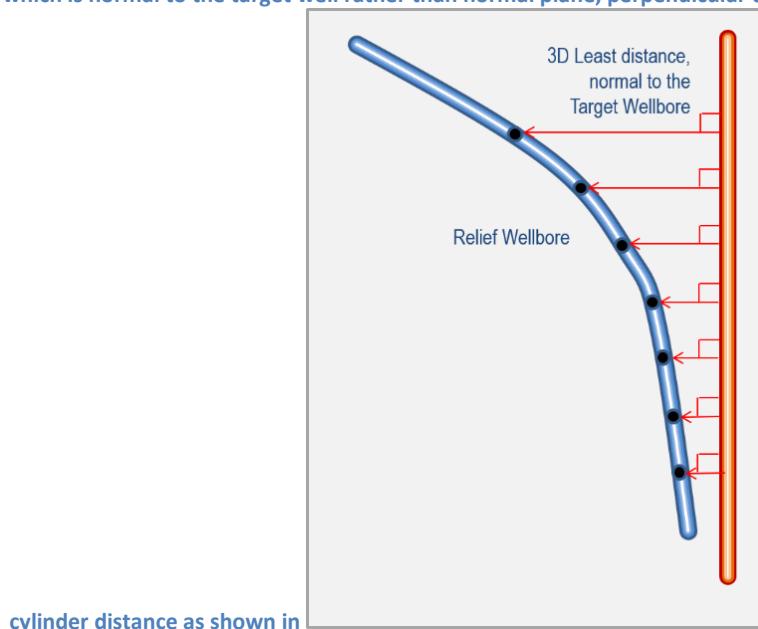


Figure 24.

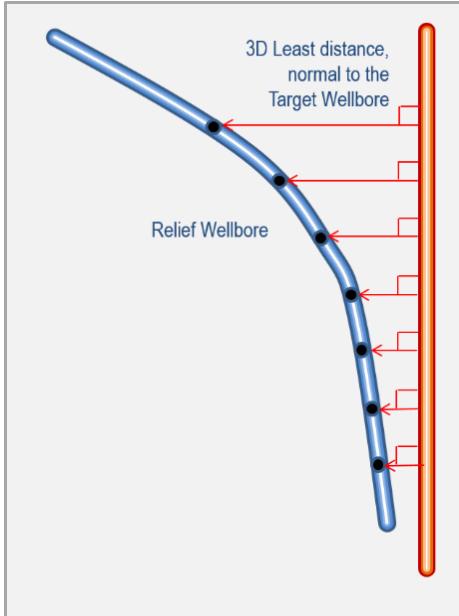


Figure 24 3D Least Distance Illustration

### 5.3.1 Ranging Direction

The ranging direction is currently limited by the design of a particular wireline acoustic tool. The current commercial tool is utilizing 8 azimuthal receivers that position at 45 degrees apart which provides 22.5 degree resolutions. The direction of the target well is interpolated using the maximum reflection strength with the adjacent receivers as illustrated in **Error! Reference source not found..**

Figure 25 Particular azimuthal receivers location to detect the direction of reflected signal

The ranging direction uncertainty is reduced by reducing the distance from the target well. Both ranging distance and direction are plotted using a travelling cylinder as illustrated in the Figure 26. Ranging direction can be further improved by performing multi passes data acquisition run. The ranging distance can be plotted along with the survey ct-to-ct distance as illustrated in the Figure 27 below.

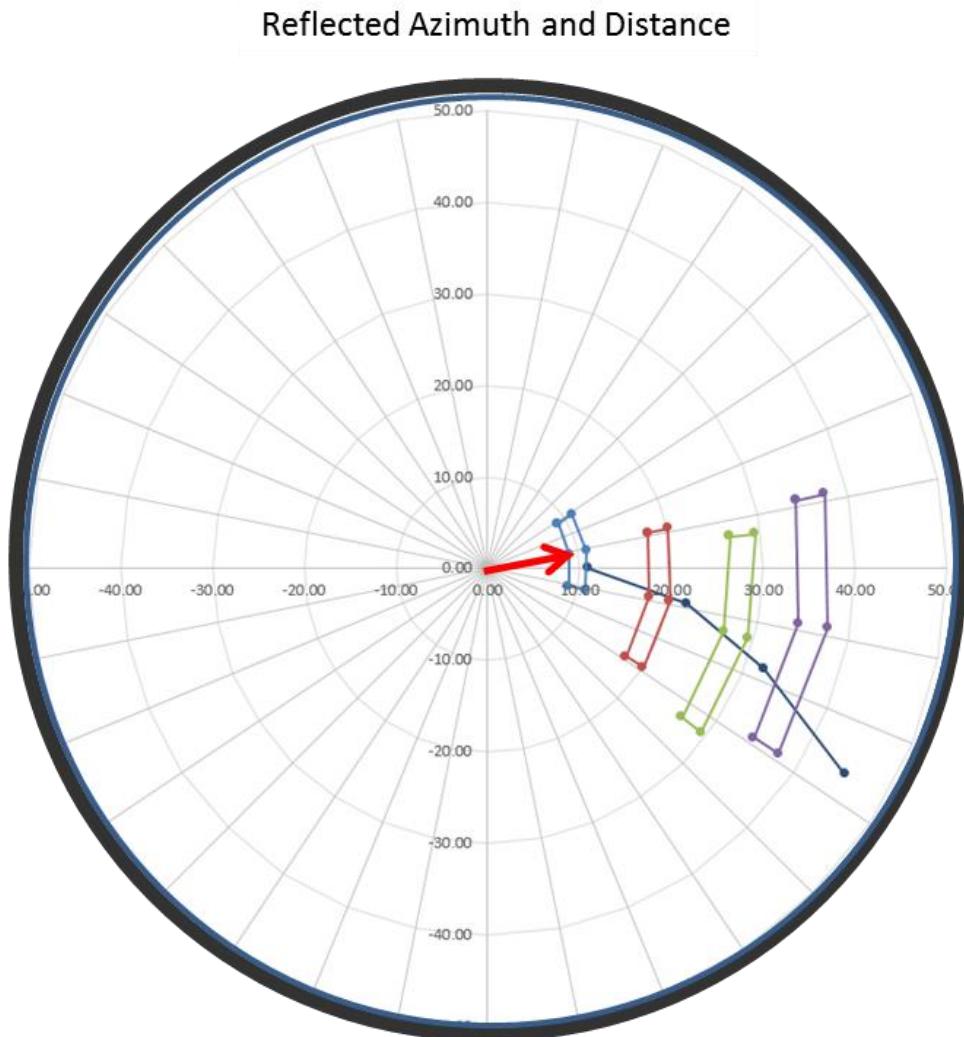


Figure 26 Travelling cylinder where the distance and direction are plotted at each ranging depth

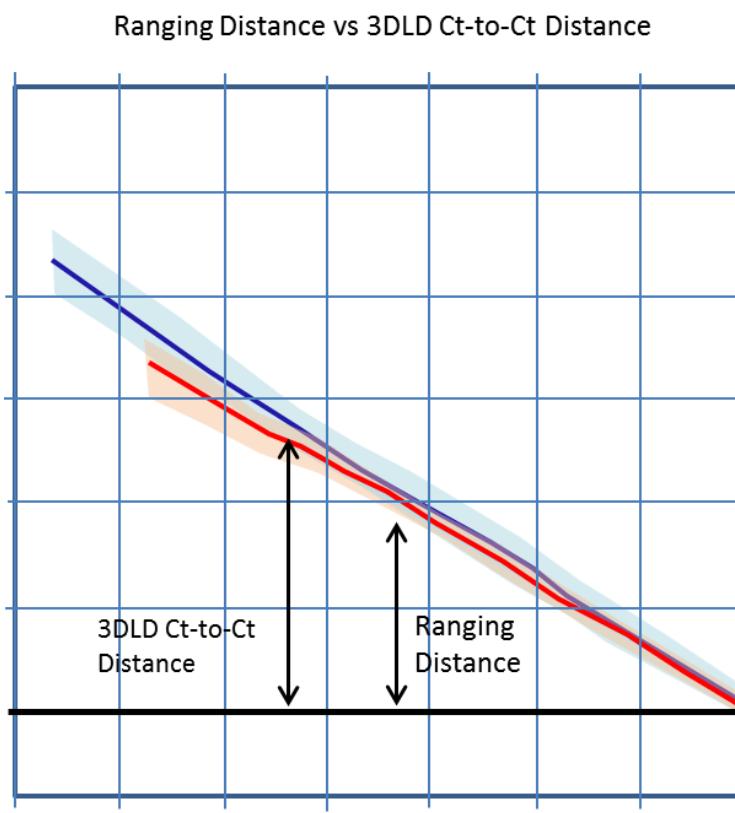


Figure 27 ct-to-ct distance. The ranging distance is plotted against the measured depth

## 5.4 Application

The Active Acoustic Ranging technique is very versatile with many ranging applications such as the ability to provide ranging in the open or cased hole inside the salt body. It can also be used to evaluate the salt quality at the same time in order to provide information about where the best location would be to intercept the target wellbore, to provide maximum hydraulic strength for a well control situation.

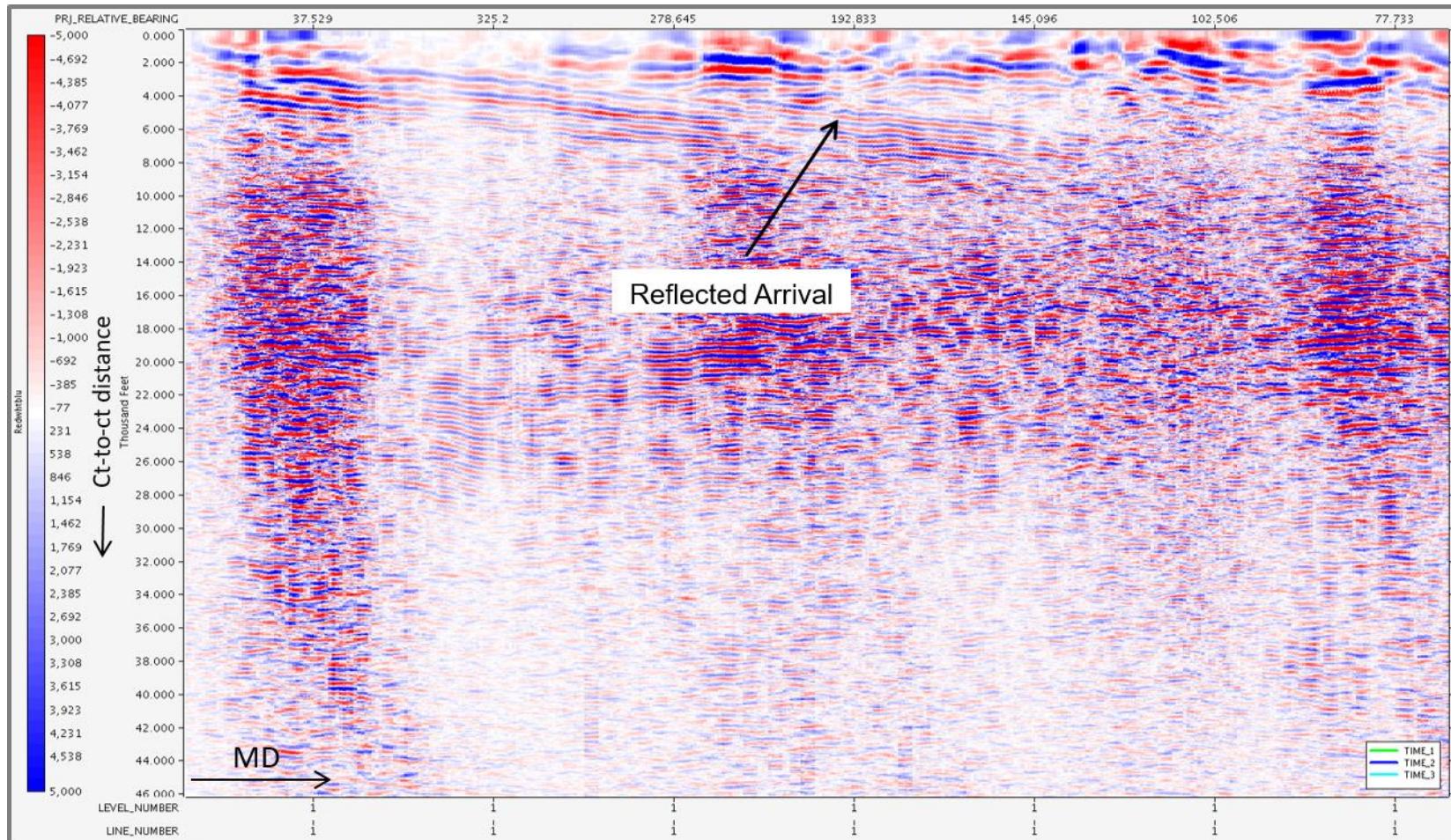


Figure 28 reflected compressional image arrival from the target wellbore

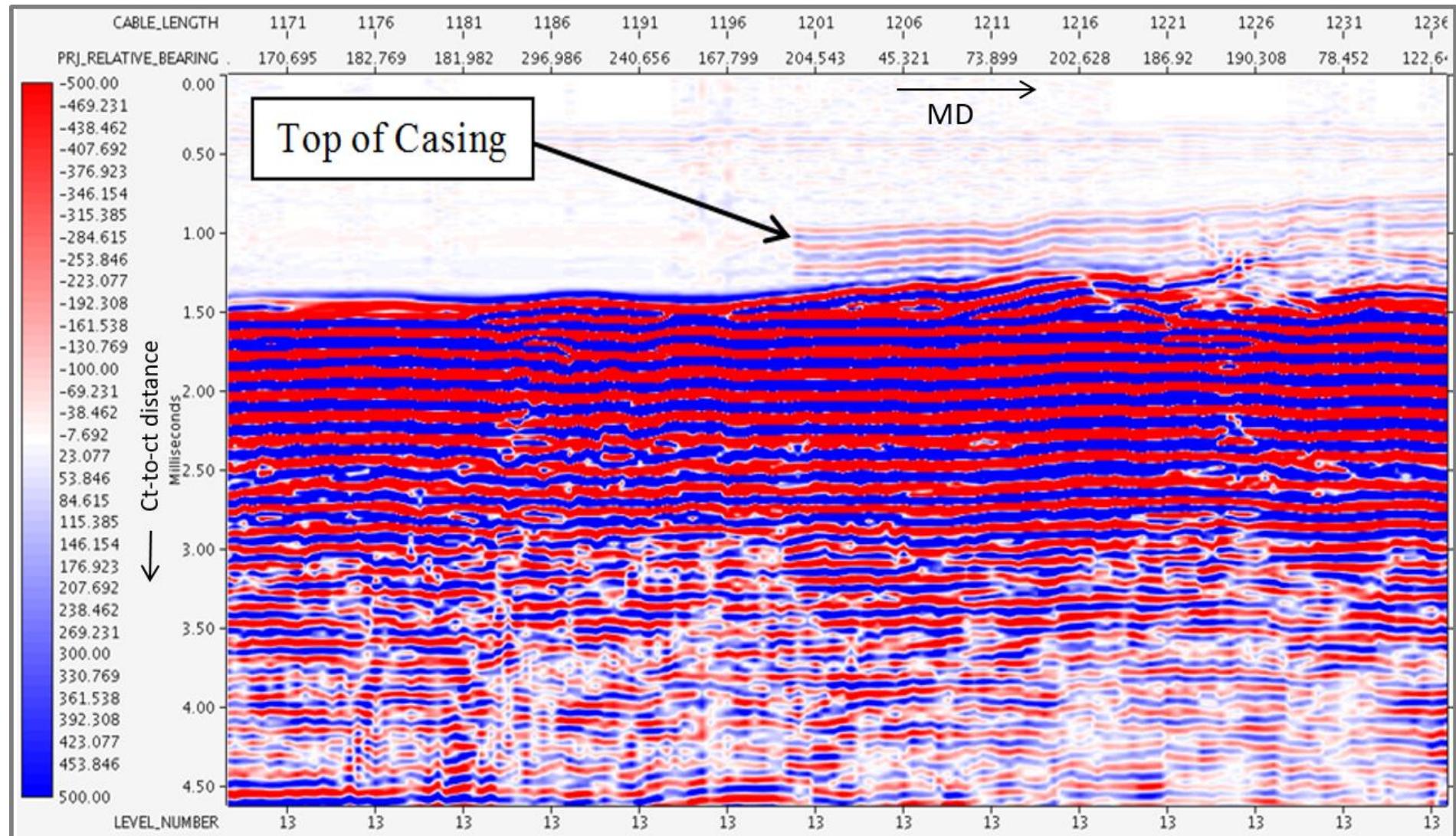


Figure 29 The image shows the reflected compressional arrival from the open hole (top of casing) and cased hole target wellbore

## 5.5 Modelling

In order to understand the acoustic ranging performance in the environments where the tool is operating, it is critical to model the relative position of the subject well to the target trajectory for the maximum and minimum acoustic ranging detection distance. As part of the job planning, modelling is required in order to program and configure the wireline acoustic tool to increase the chances of success.

Modelling for specific ranging scenarios is required in order to determine if the subject well relative trajectory, formation slowness and tool configuration is optimum to detect the nearby target wellbores as shown in Figure 30 and Figure 31.

The modelling covers the following:

- The predicted wave field generated in the subject wellbore and its interference with both potential reflected and refracted waves from the target well at sidewall to sidewall distance range from 2.2 – 0.5m (7.2 – 1.6 ft.) or even touching.
- Varying transmitter receiver spacing and transmitter types determine the best acquisition setup by taking the wellbore ellipse of uncertainties and calculating the distance for each scenario, minimum, center to center and maximum distance between wellbores.
- Designing tool setup and acquisition parameters to optimize chances for success (If modelling shows it is possible that we would be able to image the target over the desired range).

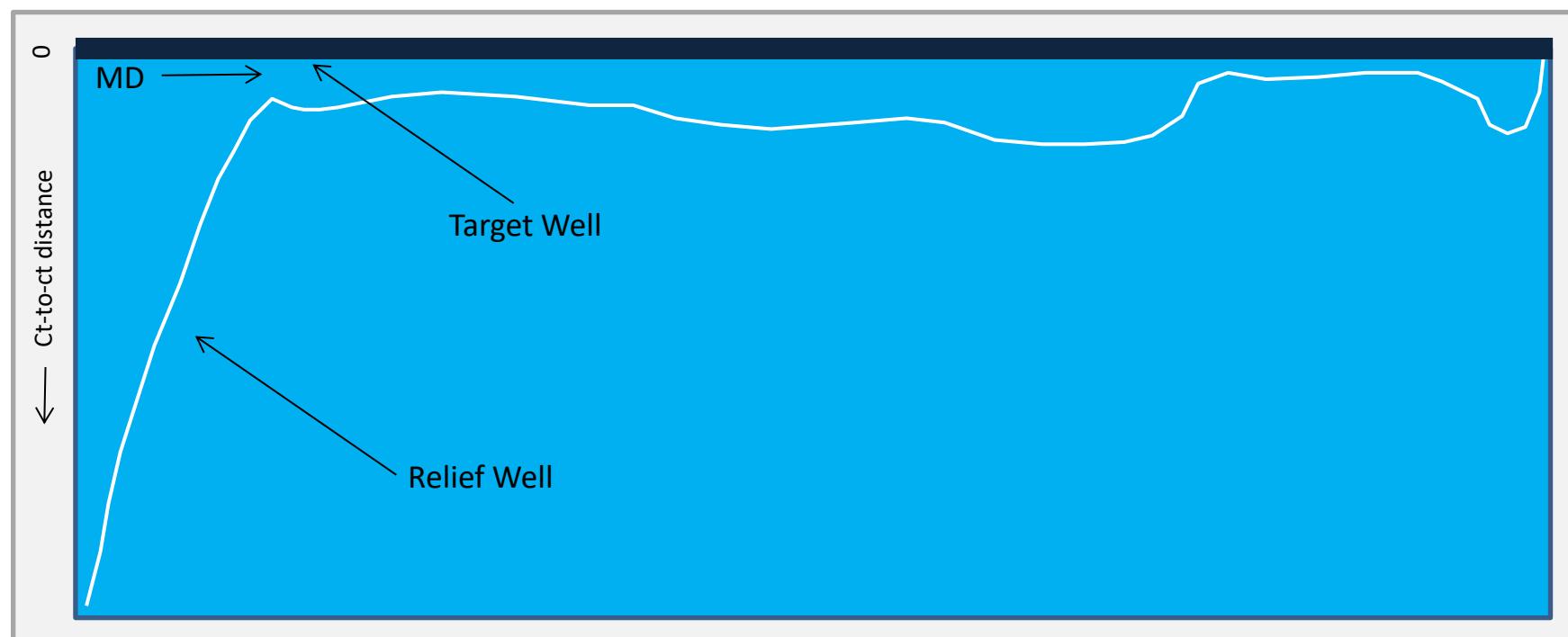


Figure 30 c-c distance between the subject and target wellbore

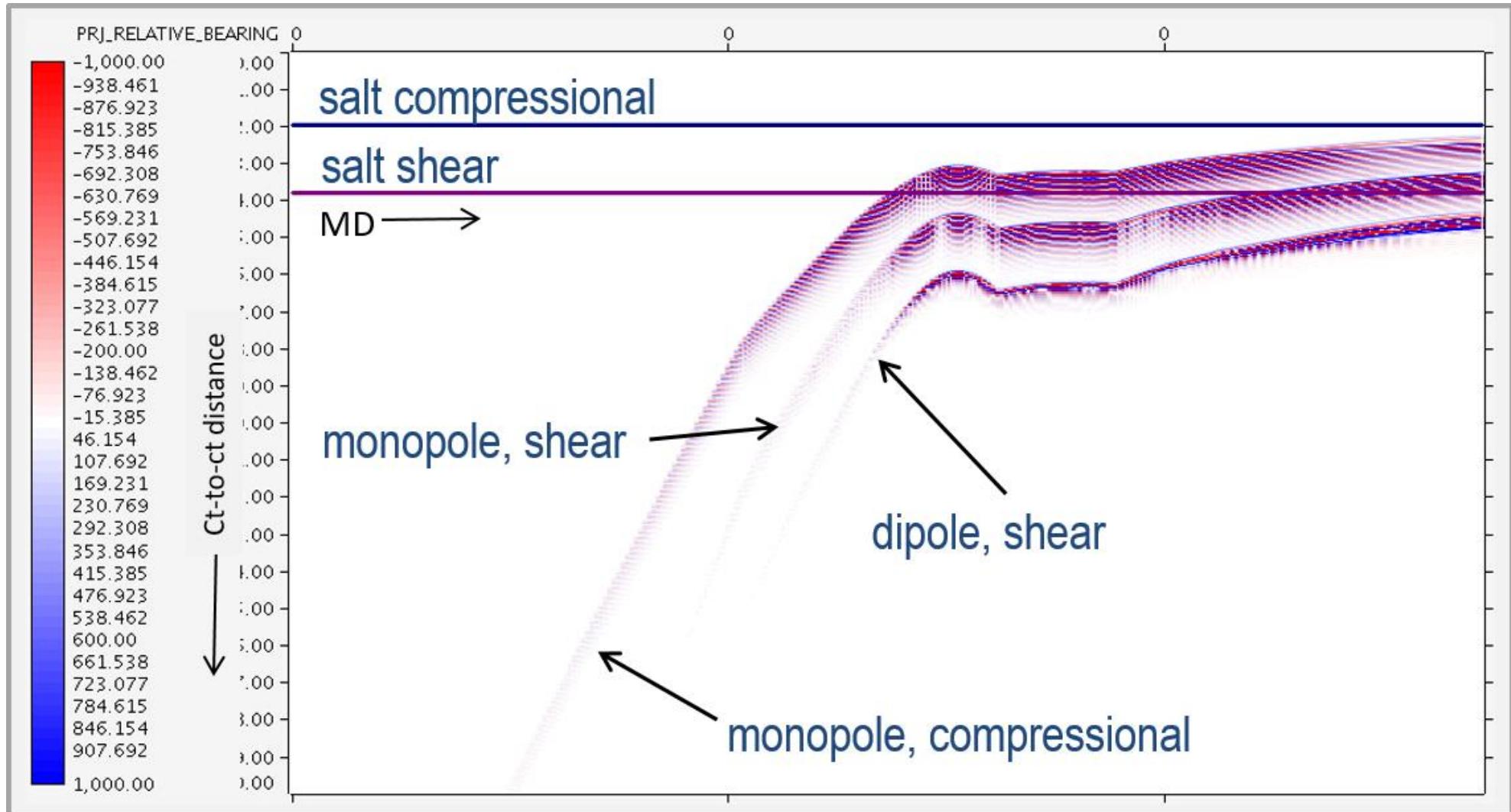


Figure 31 the simulated various sources vs reflected and signals as a function of signal strength, ct-to-ct distance and measured depth.

## 6. Ranging Techniques Comparison

Previous chapters describe different available ranging technologies in the market:

- Chapter 2 describes the Passive Magnetic Ranging Technology
- Chapter 3 describes the Active Ranging Technology
- Chapter 4 describes the Passive Acoustic Ranging Technology
- Chapter 5 describes the Active Acoustic Ranging Technology

All techniques presented have their own specificities, their strength and their limitations. This chapter intends to compare different available technologies, to ease the selection of the most appropriate technique for a given project. It should be mentioned that not only one technique is suitable for a given project. The selection of the ranging technique should be done on a case by case feasibility study, by taking into considerations the Pros and Cons of each technique together with the technical, economical, timing and risk environment aspects. It should also be mentioned that the overall ranging strategy can be optimized by the use of a combination of ranging techniques which can be complementary on certain aspects.

Consequently, comparing the detection range capabilities between PMR, AMR and AAR is only possible on a case by case basis, and only when considering the entirety of the inputs and factors involved for each method. It is also important to note that in all cases the PMR has considerably more room for variation in the modeled detection range than that of the detection range calculated with AMR or AAR. Typically the expected detection range for PMR will be significantly less than the AMR, unless the ranging is to take place under conditions that impact the AMR signal intensity such as ranging in pure salt. The only certain way to determine what the correct tool for a relief well application for example is to complete an analysis that takes in account all the relevant inputs.

*Table below gives an overview of different ranging techniques, that are described in Chapter 2 to 4; it only considers comparable Access-independent (AI) ranging techniques which can be deployed in case there is no access to the target well : Passive Magnetic Ranging, AI Active Magnetic ranging and Active Acoustic Ranging.*

*The table does not include Access-dependent ranging techniques such as magnetic Solenoid AMR Systems, Rotating Magnet AMR Systems and Passive Acoustic systems.*

DESCRIPTION	PASSIVE RANGING	ACTIVE RANGING	ACTIVE ACOUSTIC RANGING
<b>Technique Principle</b>	Depends on Target well casing magnetization / Earth Magnetic field variations / Magnetic noise. Take multiple surveys from MWD Tool	Inject Current into formation from electrode. Receptor at bottom. Multiple shots along the MD	Based on Sonic Waves propagation. Analyze the reflected sonic Waves. Transmitters and receivers are on the same logging tool.
<b>Best Case Performance</b>	Wells are parallel	Wells are parallel	Wells are at the same plane
<b>Worst Case Performance</b>	Wells are perpendicular	Pure Salt Formation	Wells are perpendicular at large c-c distance
		Wells are perpendicular	
<b>Detection Range Estimate</b>	Selected from a chart representing the possible max magnetic field	Calculated using geometry and magnetic model	Calculated using geometry and actual sonic wave propagation property as measured during the run
<b>Definitive Detection Range</b>	5 – 15m	20 – 60m	1 – 55m
		40 – 100m with Direct Excitation on TW	
<b>Detection Along Body of The Target Well</b>	Detection range up to 5m  (1/2 joint length), 6m on 12m casing	Up to 60m	Up to 55m
<b>Detection Near Break or End of Pipe</b>	Detection Range Up to 15m	Limited range within 1m of top and bottom of pipe ends	Up to 55m. Can detect Open Hole
<b>Deployment - Wireline Required</b>	No. However WL can be required for high density or for on bottom data collection	Yes. However, It can also now be deployed in Non Mag BHA behind MWD	Yes. It is a logging tool
<b>Data Acquisition Time</b>	6 to 30 hours	30 hours (8 hours in TPR BHA)	6 to 15 hours depending on the logging intervals
	For MWD Logging	(assuming 4500m well)	(assuming 4500m well)
<b>Distance Accuracy</b>	10% of detection Range. To be considered 1 standard deviation.	Non Gradient Tool : 5-20% Depends on High Side to Target variation	~ 0.075m at 1 standard deviation

	Depends on the quality of the Target Well Magnetization strength and Signal/Noise ratio level.	Gradient Tool: Depends on distance. Less than 5%	
<b>Direction Accuracy</b>	~5° at 1 standard deviation	~5° at 1 standard deviation	~ 22.5° at 2 Standard deviation
<b>Target Well detection</b>	Casing, Fish, Packer, completion, all steel equipment	Casing, Fish, Packer, completion, all steel equipment	Casing, Fish, Packer, completion, all steel equipment and Open hole
<b>Case Histories</b>	Widely used in the industry	Widely used in the industry	New technology recently developed
	Mainly used for P&A and collision avoidance	Relief Well & Re-Entry Wells	Only few case histories are available
	Very Few Successful Relief Well Intercept		
<b>Sensor Measurement Point</b>	15m – 20m from Bottom hole	On Bottom	On Bottom
	On Bottom if WL Deployed.	25 – 35m from Bottom Hole if deployed in BHA	
<b>Non Magnetic Target Pipe</b>	Detection not possible	No Effect same as steel pipe	No Effect same as steel pipe
<b>Target Casing Corrosion</b>	Detection may not be possible	Minimal impact on detection range	Minimal impact on detection range
<b>Presence Of Breaks Or Discontinuities In Target Pipe</b>	Potential to increase detection range from the magnetic signature	Detection range reduced for short sections (~1m) of the target well	Minimal impact on detection range
<b>Effects of Different Casing Sizes and Weight</b>	Casing weight has a direct impact in range:	Negligible Effect	Negligible Effect
	20 Lbs./Ft has an expected max range of 2m along the body		

	40 Lbs./Ft has an expected max range of 3m along the body		
<b>Effects of Other Nearby Wellbores</b>	Eliminates possibility of using service	Direct excitation of OW method removes impact. If direct excitation not possible vector subtraction mitigates effect	Under special process, can detect multiple wells from different azimuthal positions
<b>Effects of Highly Insulating Formation</b>	No Effect	Minimal impact up to 300m MD into the formation. Beyond 300m detection range is largely reduced	Negligible Effect
<b>Effects of High Incidence Angle Between Target And Drilling Well</b>	High Incidence angle increases sensor to target thus greatly reducing the effective detection range	AMR signal reduced by increasing distance between excitation source and target well	Increases the quality of the wave propagation signal analysis
<b>Is The System Effected By Poor Hole Conditions in Drilling Well</b>	No Effect	Potential to add additional ranging run time for open ended drill pipe runs	Negligible Effect
<b>Effects of Different Mud Types</b>	No Effect	OBM may slightly reduce the detection range	Negligible Effect

## 7. Relief Well Ranging Operations

### 7.1 Relief Well Overview

A relief well provides a means to intercept and kill a blowout well when surface intervention or capping requires an extended period of time or when that may not succeed. [<http://dx.doi.org/10.2118/168029-MS>.] A relief well should be faster to drill than the original well due to the knowledge already gained about the geology and pressure in the reservoir. However, drilling a well of this nature presents many technical challenges, from locating the offset blowing well to verifying that the flowing well can be intercepted in the right position and that the fluid pumping operations may be effective.

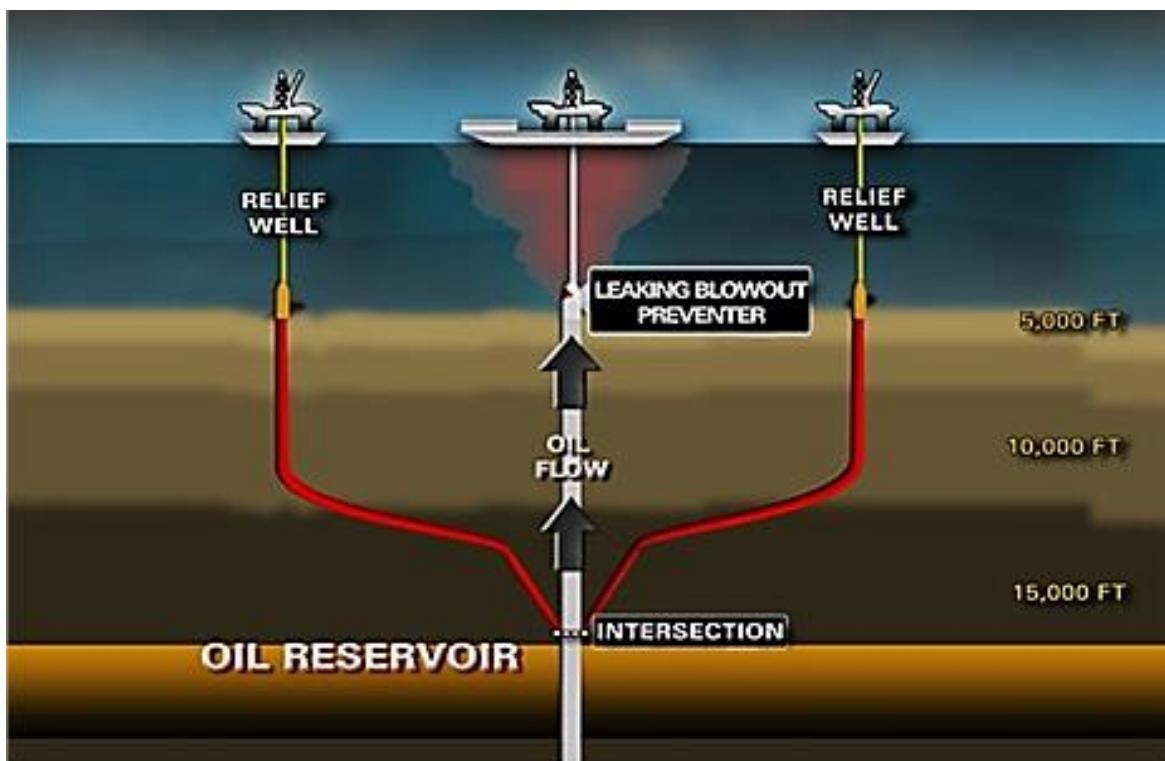


Figure 32 Relief well directional design

A relief well is usually planned to be a last resort option in the event the blowing wellbore is inaccessible and the rates required to kill the well are too large for normal surface intervention methods to be applied. A drilling rig drills the relief well, or second well, (see illustration in Figure 32) to intercept the original flowing well as deeply as necessary; or to intercept at the last casing shoe before the hydrocarbon bearing zone is encountered. Heavy drilling mud is then pumped into the flowing well at a predetermined flow rate to bring it under control. This heavy mud is denser than oil and thus exerts hydrostatic pressure to stem the flow of oil. Once the flow is stopped, the well can be returned to a safe condition. The well is killed when the blowout well is controlled and brought back to a state of static condition.

### 7.2 Ranging Decision Matrix

Ranging technologies is necessary to ensure the success of the execution of a planned Relief Well, and in particular when the objective is to parallel and perforate the blow-out well, or to intercept and mill inside the blowout casing or to mill and re-enter a stinger into the blow-out casing or completion equipment. Each Relief Well strategy differs from one case to another and the choice of the ranging technologies may rely on different aspect : access to the blown-out well, environment, deployment methodology, Required expert personnel, cost, effectiveness, objectives, performances, hole conditions, etc...One ranging technology may be chosen over another for a specific relief well case, but most of the time a combination of different ranging techniques may be chosen to improve the overall efficiency of the ranging strategy for a given project. Therefore an optimization between the utilization of different ranging techniques will have to be conducted. One should refer to Chapter 5 : Ranging Technologies comparison to identify and select the appropriate ranging technology for the specifics of the relief well project.

## 7.3 Categories of Relief Well Designs:

The three categories of Relief Well Trajectory Design are shown in Figure 33:

### 7.3.1 Simple Intercept

This Design is typically, a J-shaped well that intercepts the target well at a specific depth. Such intercepts usually requires three phases: A Data Gathering Phase, Drilling Phase and Intercept Phase. Simple intercepts are typically the most difficult to execute without the use of a sidetrack(s).

### 7.3.2 Parallel Track

This Design requires an S-shaped two-dimensional (2D) or three-dimensional (3D) well design which tracks the blowout well once located and can be used to perforate and establish communication with the blowout well. This type of well usually requires four phases: A Data Gathering Phase, Drilling Phase, Locate Phase, and Tracking Phase.

### 7.3.3 Oriented Intercept

This Design is typically an S-shaped 2D or 3D well that is designed to locate and intercept the blowout well at two distinct points. This type of well usually requires five phases: A Data Gathering Phase, Drilling Phase, Locate Phase, Tracking Phase, and Intercept Phase.

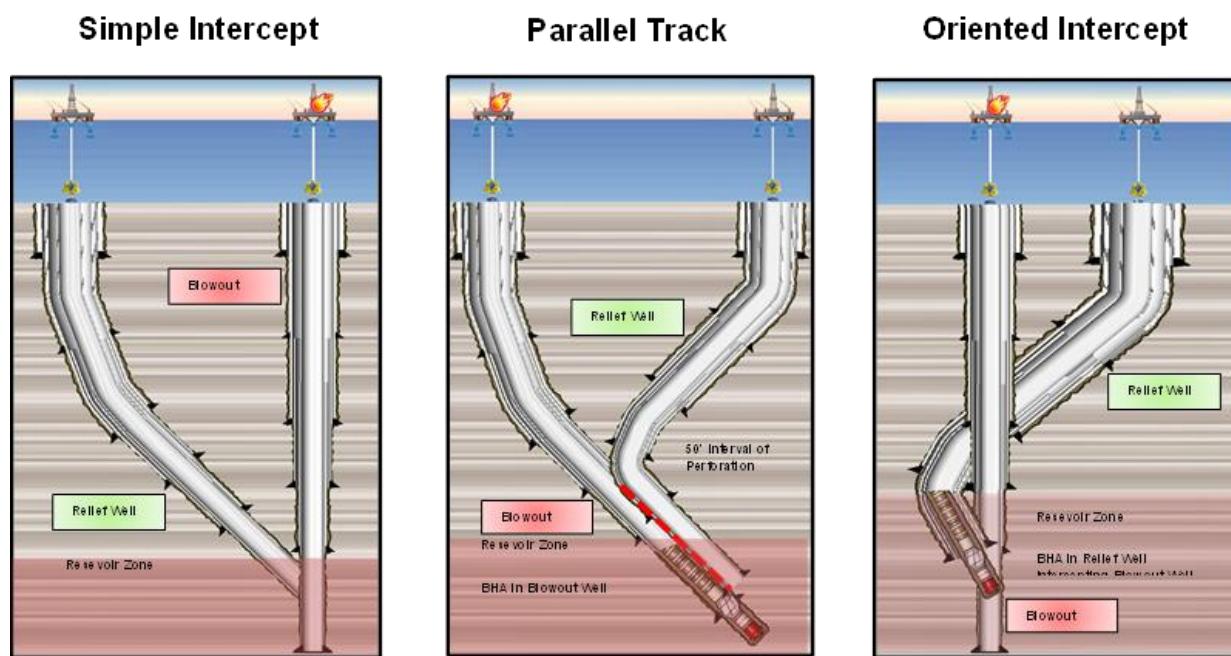


Figure 33 Relief Well Designs

## 7.4 Relief Well Phases:

The five phases of Relief Well Trajectory Design are in Figure 34

1. Data Gathering (*Planning*) Phase.
2. Drilling Phase.
3. Locate Phase.
4. Tracking (*Follow*) Phase.
5. Intercept Phase.

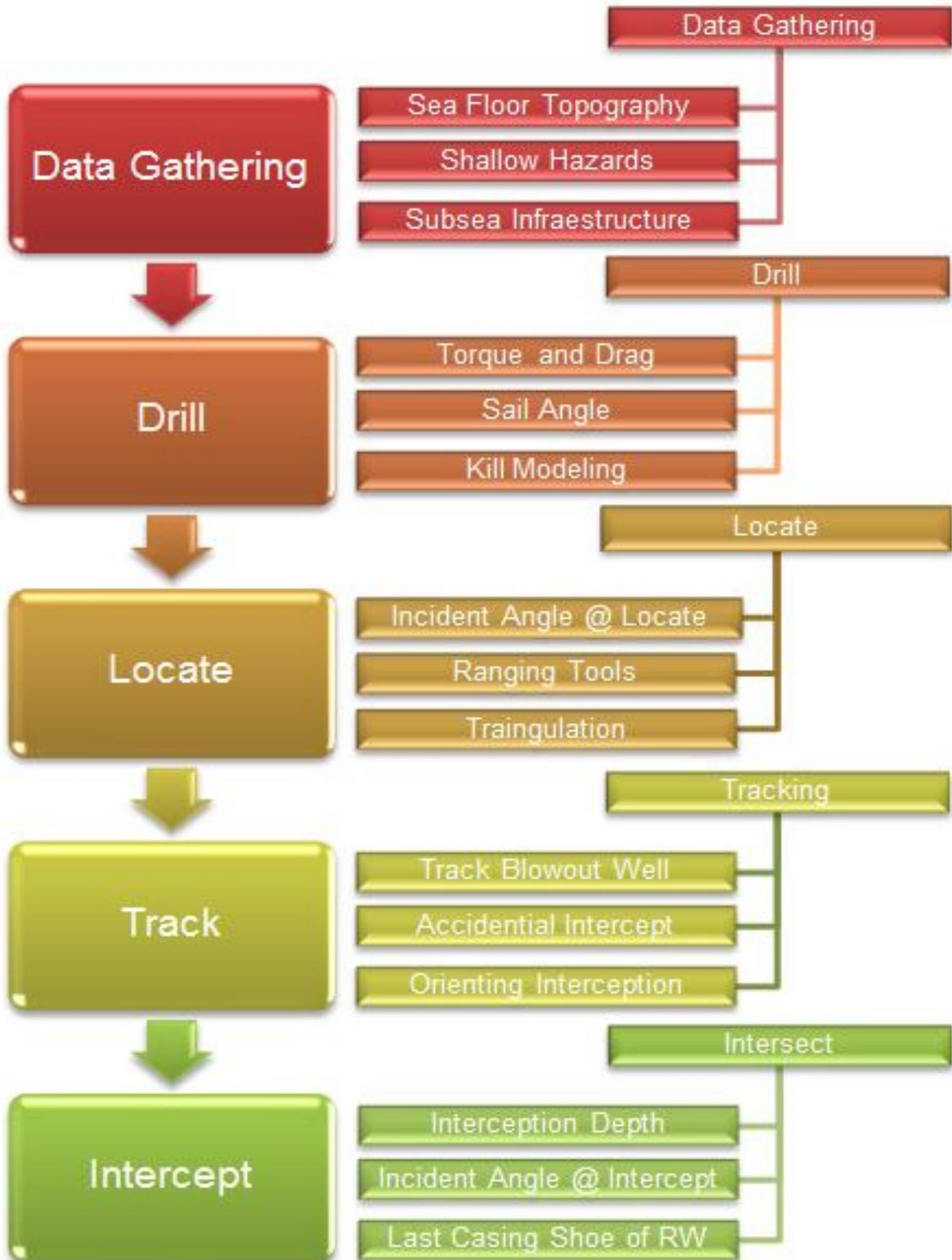


Figure 34 Five-Phase systematic methodology of relief well planning process

### **7.4.1 The Data Gathering (*Planning*) Phase:**

This is the first phase of the process which defines the Surface Location of the Relief Well. It requires a cross-functional team of geoscientists and engineers, who gather data and assess the subsurface models, wind direction, sea currents, seafloor topography, and shallow hazard data required to plan the relief well.

The objective of this initial phase is to define the possible surface locations for the relief well, by avoiding steep or unstable slopes, faults and no-go zones such as shallow hazards, environmental considerations, offset wells, pipelines, sub-sea facilities, obstructions or other physical hazards on the sea floor. Insurance carriers for drilling contractors typically stipulate that the relief well be at least 500m (1640 ft.) equivalent from the surface location blowout. However, shipping lanes and possible marine traffic contingencies due to the blowout situation should also be factored in. The relief well rig location is a major contributor to the measured depth of the relief well design and has an impact on the sail angle, angle of approach for locating the well and the torque and drag associated with the design.

### **7.4.2 The Drilling Phase:**

This second planning phase of the process initiates when the primary and secondary surface locations have been identified and selected, this phase requires creating a directional path to drill towards the interception target and the evaluation of the drilling feasibility for the well design. It is important to consider and evaluate at this stage: The surface location positional accuracy, torque and drag analysis, trajectory design, survey and ranging program and the kill simulation models.

Typically, this phase is representative of the drilling operations on the original well. It is an important requirement that the spud well reference point (WRP) of the relief well be surveyed to a level of accuracy to confirm the surface hole location viability before spud. The WRP uncertainty is a systematic error that adds to the wellbore uncertainty and if large, may complicate the locate phase, hence consideration is given to all possible sources of error associated with the well positional accuracy. Key consideration here is to establish the bearing between the relief well spud location and the target well.

### **7.4.3 The Locate Phase:**

The purpose of the Locate phase is to determine that active ranging has identified the target well. The initial ranging runs are designed to locate the target well by seeing an increase in active magnetic signal strength and direction that can be positively identified to be emanating from the target tubular.

The “pass-by” should (1) verify location of the target casing, and (2) reduce the relative borehole uncertainty of the target well due to ranging tool uncertainties. It is advisable to locate the target well at least  $\pm$  300m (1,000 ft.) measured depth (MD) prior to the intercept point (or more depending on the position uncertainty) to allow sufficient distance for course corrections prior to the Interception point.

Note that the first ranging run should be determined by the error of uncertainty (EOU) ellipse sizes of both the target and drilling wells. This is to prevent an unplanned intersection.

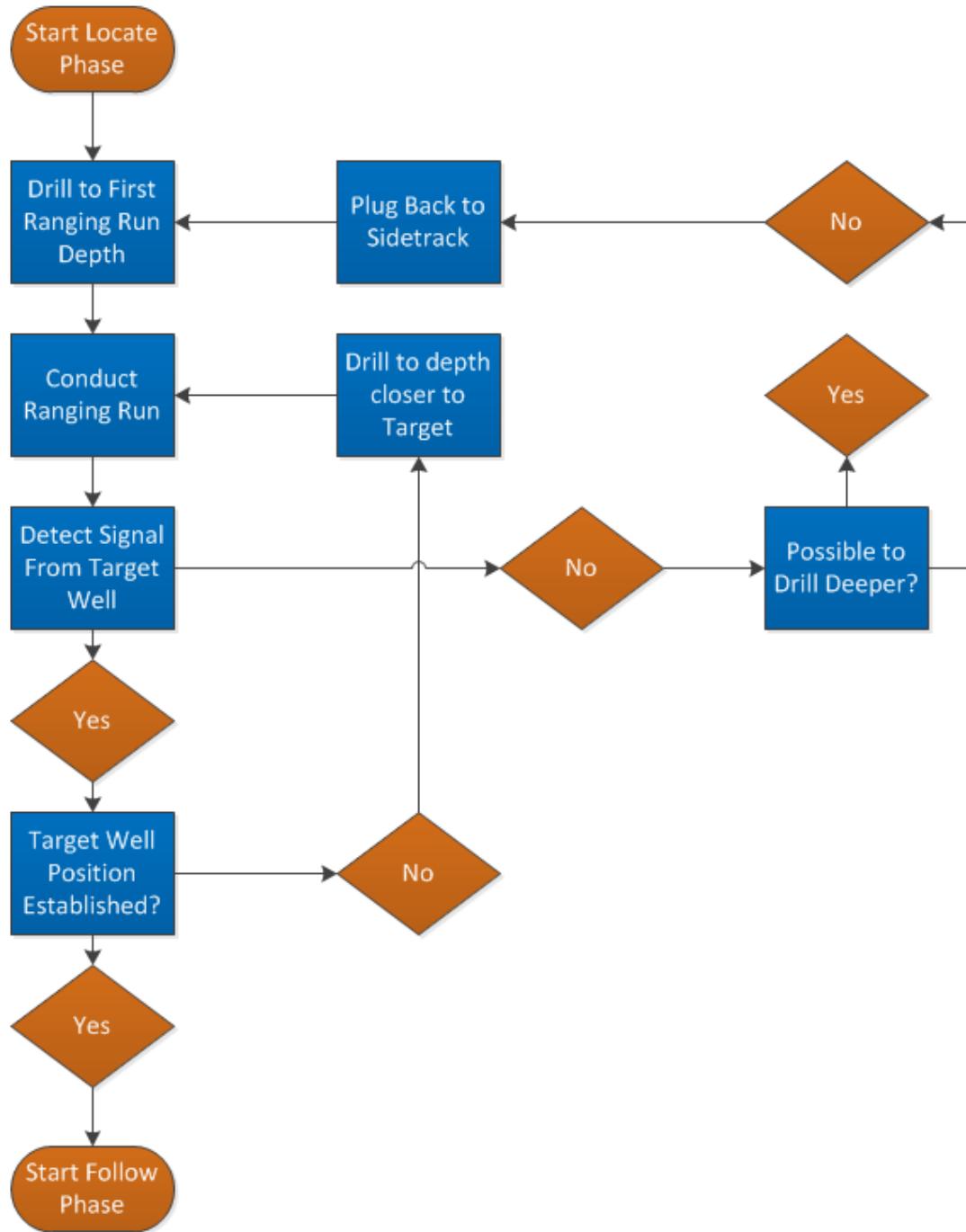
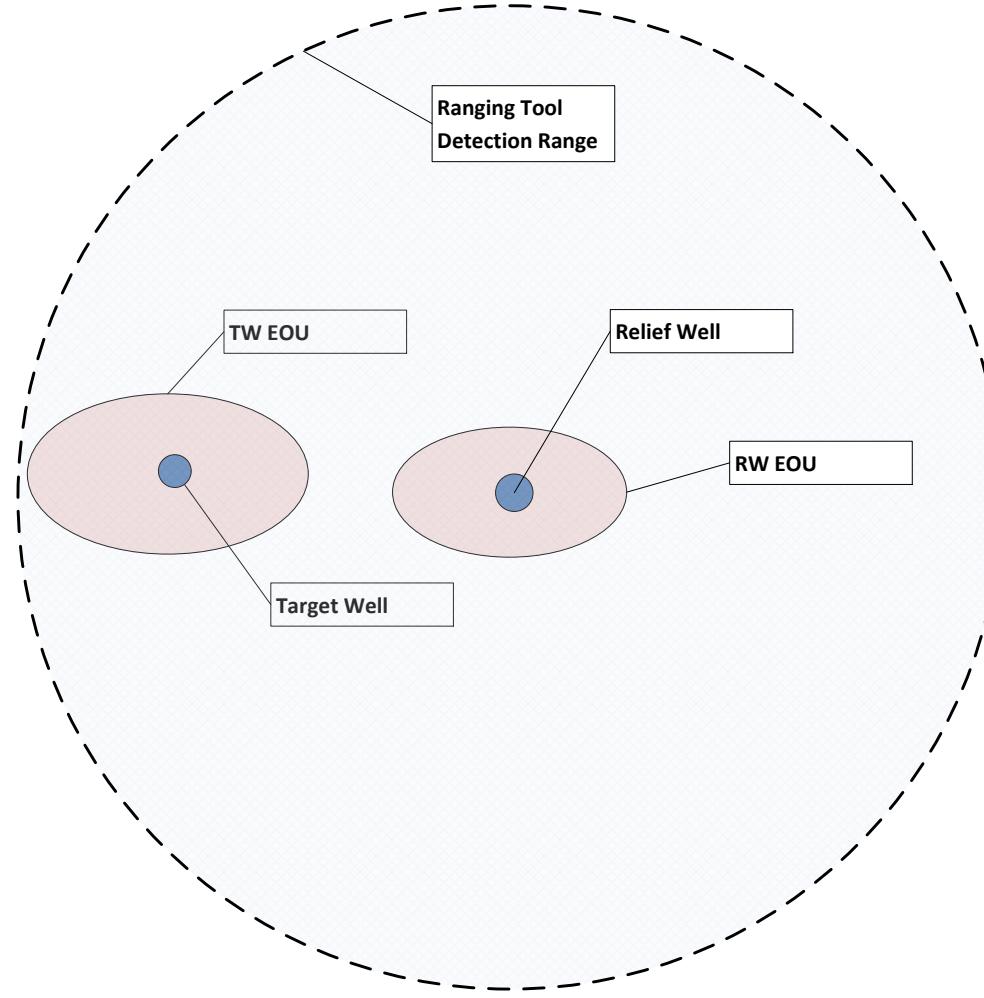


Figure 35 Locate Phase

The depth of the first ranging run will depend on:

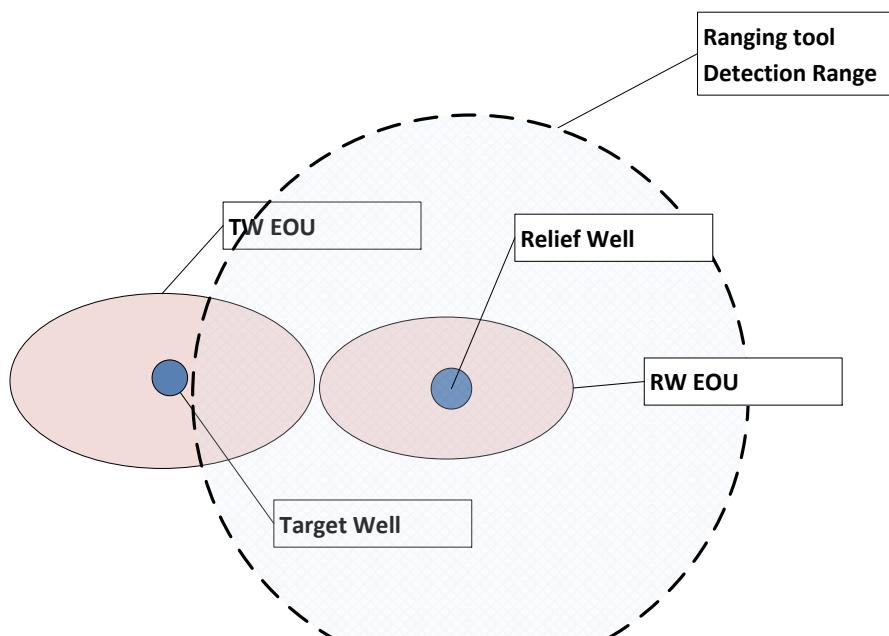
- The detection range of the selected ranging tool as modeled on a case by case basis.
- Ellipse of Uncertainties of the target well and relief well.

Typically the first ranging run will take place just as the entire Ellipse of Uncertainty (EOU) of the target well falls inside the modeled detection range. This can be safely done as long as the separation factor remains higher than 1.



**Figure 36 Ranging Tool Detection Range**

The first run may be used as an anti-collision run that will take place outside expected detection range. Ranging at this instance will determine if the target well falls within the ellipse of the drilling/relief wellbore error of uncertainty (EOU), which could potentially cause an accidental interception. Completing this ranging run will allow drilling to continue without the risk of accidental collision. The diagram below illustrates an anti-collision run with the target well and relief well in the center of their ellipses and detection is less than the center to center (c-c) separation of the wells.



**Figure 37 Anti-collision Run**

Once a ranging determination is complete, the results are reported in the ranging report as a direction and distance that have an associated  $\pm$  ambiguity. Figure 38

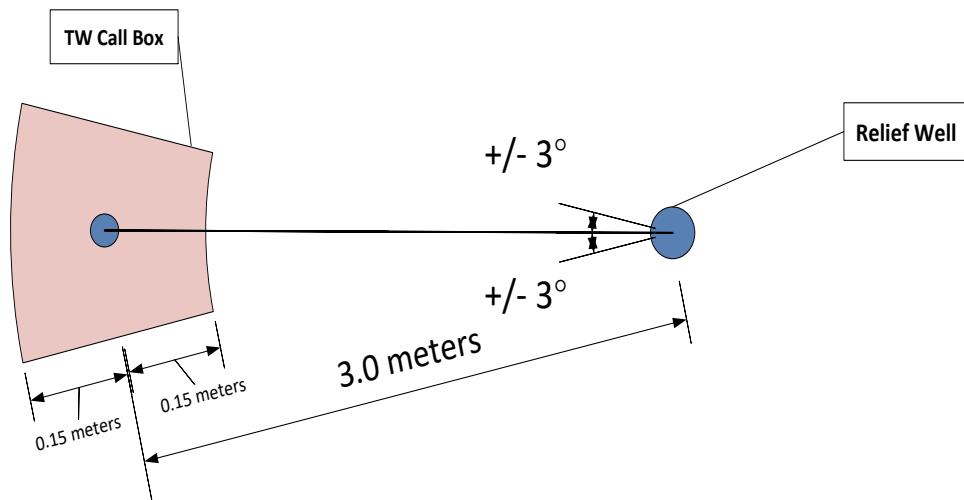


Figure 38 Ranging call with a direction of  $270^\circ \pm 3^\circ$  and a distance of 3.0 meter  $\pm 0.15m$

#### 7.4.4 The Tracking (*Follow*) Phase:

In the fourth phase, the well trajectory is designed to track (or follow) the target well, again using ranging techniques. The Tracking Phase is initiated after the target well has been located and preferably fixed in 3D space.

The objective of this phase is to position the final casing shoe at depth and in the desired trajectory to permit a target intercept with the least amount of corrective steering and less than one stand from shoe to planned intercept point (to enable pulling the bit back into casing in one stand when the dynamic kill operations commence). The Track phase consists of following the well and iteratively re-planning the relief well to the new target location. The uncertainty of ranging measurements will be reduced as the target well and relief well get closer. Each ranging run results will determine the length of the next drilling interval and will require a new well plan. A pass by with a significant angle change or triangulation to the target well at the beginning of the track phase will further reduce uncertainties and allow for longer distance between ranging runs.

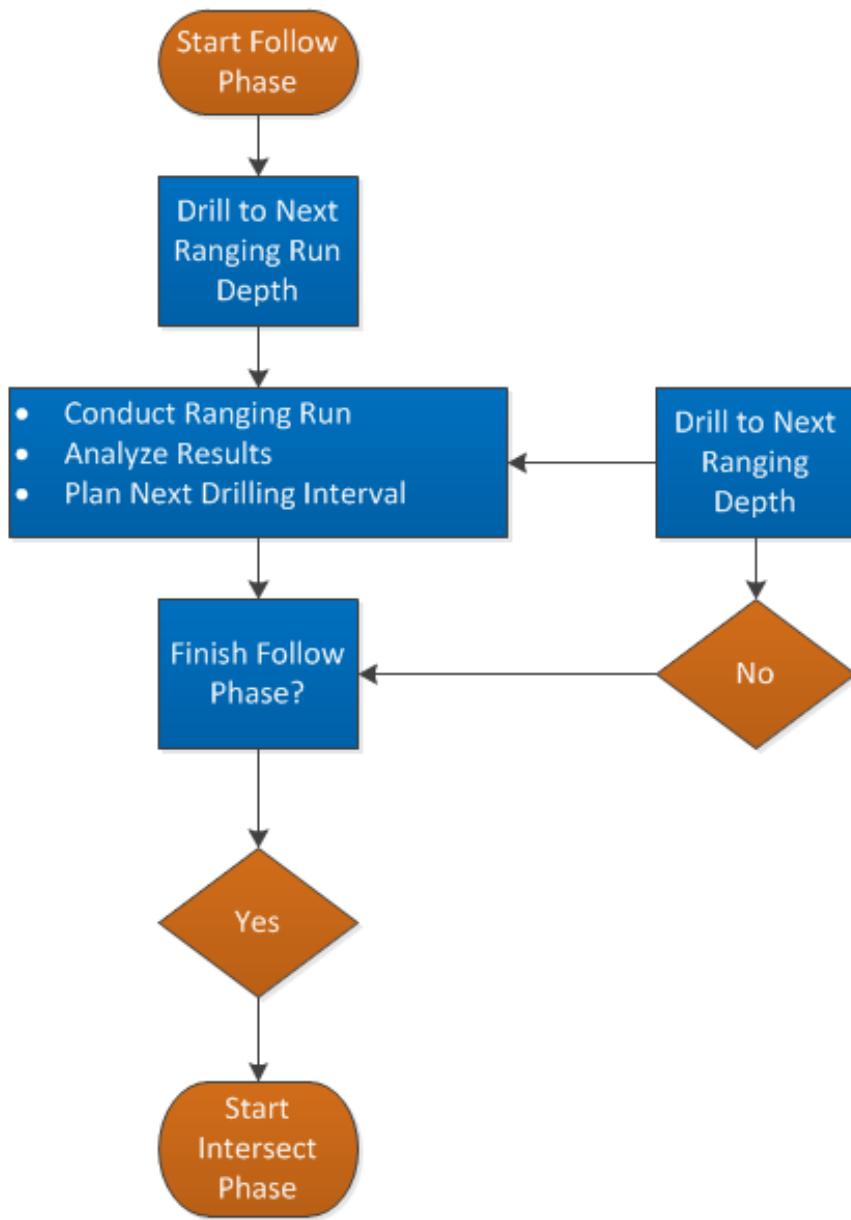


Figure 39 Follow Phase

#### 7.4.5 The Intercept Phase:

In the fifth planning phase, we design a final relief well trajectory that can intercept at a low angle of Incidence ( $< 5^\circ$ ) to successfully range and mill into the blow out well once contact is made at the intercept point at the last casing shoe above the target hydrocarbon-bearing zone.

The objective of this phase is for the relief well to be within close proximity of the target well and to gain hydraulic communication.

The diagram below is a depiction which gives a high level summary of the five-phase to relief well planning and some of the main points to consider during the design.

The Intercept phase consists of the final alignment of the relief well for the intended operation whether re-entry, milling or perforating. The Ranging/Drilling intervals in this phase are progressively shortened to verify proximity. Wireline or surveying BHA is used to get on bottom surveys. At intersection, the recommended Incidence angle is  $3^\circ$  to  $8^\circ$ .

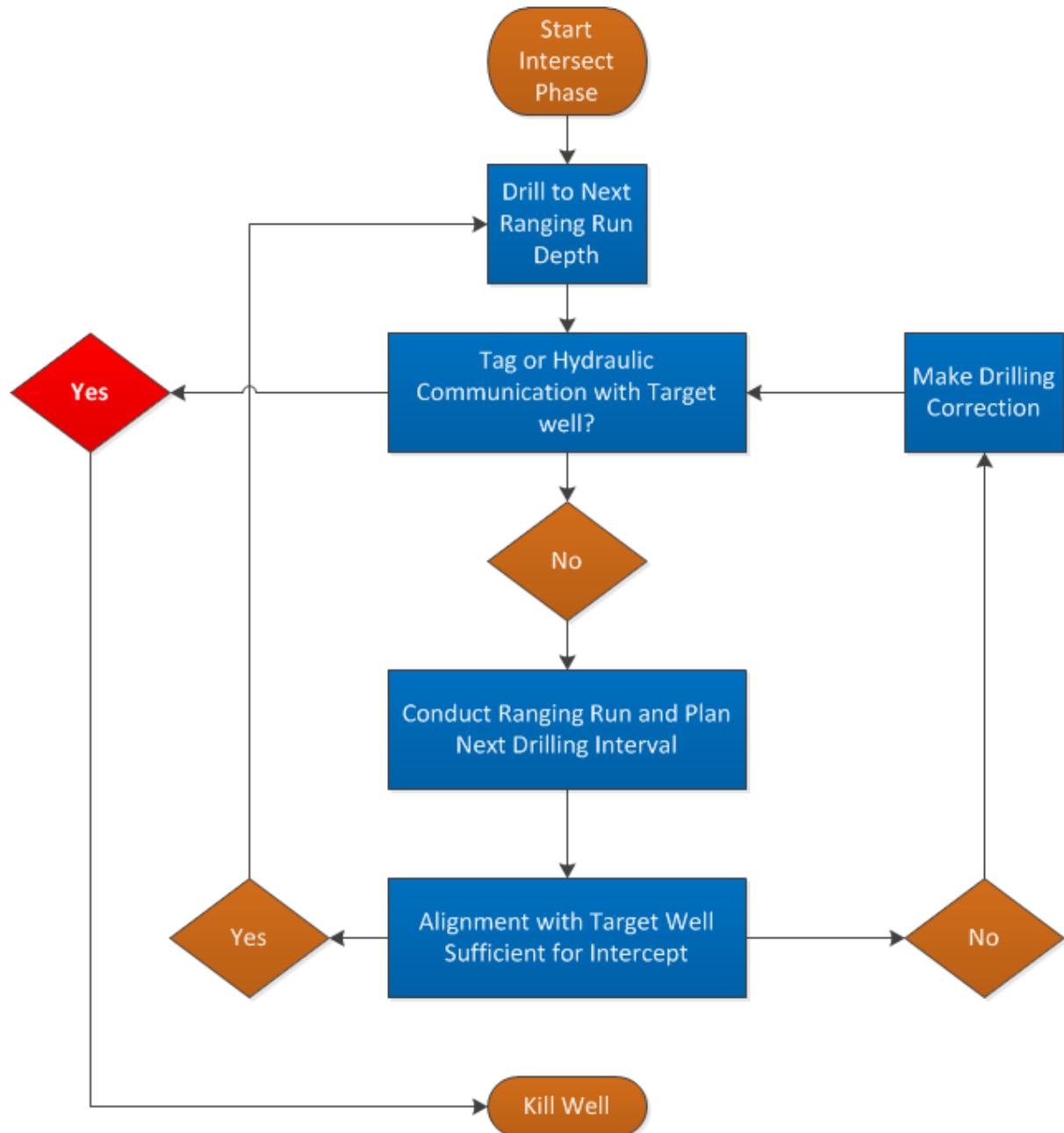


Figure 40 Intersect Phase

## 7.5 Relief Well Survey Management

Relief well survey management (SM) is often a key component of a successful ranging and intersection plan. SM services include ground shots to correct local declination errors and multi station analysis (MSA) used to increase the accuracy of the surveys by the mitigation of instrument biases. Improving survey quality will reduce the ellipse of uncertainty (EOU) which in turn will reduce number of required ranging runs. For the locate phase of the relief well plan, having SM will extend the depth the drilling can continue before starting the first ranging run.

## 7.6 Relief Well Planning Personnel

One of the most effective methods for creating a relief well ranging plan is for the customer to host a planning meeting with the stakeholders. While it is possible for this planning to be completed remotely the recommended method is to have all the stakeholders meet at one location and collaboratively plan the relief well taking into account each stakeholders requirements and limitations. *It should be noted that relief well planning/ operations is composed of two teams: Intersection and Well Control. This section is focused solely on the Intersection.* The following is a list of the personnel required and the key responsibilities of each:

- Drilling Engineer
  - Preferred and alternate interception methods
  - What is required as proof of interception for regulatory board
  - Surface location options and limitations
  - Geology and casing depths
  - Contingency casing options
- Interception Specialist
  - Assist drilling engineer with surface location selection
  - Designing approach and intersection phases of the well plan
  - Coordinate hydraulic communication with well control engineer
  - Estimate drilling intervals / ranging runs required
  - Recommend primary and alternate interception methods
  - Leads operations once drilling commences until hydraulic communication is made with the target well, works cooperatively with Ranging Specialist
- Ranging Specialist
  - Model the depth of investigation
  - Using the ellipse of uncertainty (EOU) of both the target well and relief well, develop the Anti-Collision (accidental interception) plan
  - Recommend changes to the well plan to improve the ranging
  - Provide recommendations on the type of ranging tools required
  - Assist the Interception Specialist with planning the drilling intervals / ranging runs required
- Well Control Engineer
  - Assist Interception Specialist with the interception depth selection
  - Create contingency plans in case of premature hydraulic communication
  - Leads operations after hydraulic communication has been made with target well
- Directional Driller
  - Provide knowledge of the local drilling environment which is key to developing a workable plan
  - Recommend changes to the well plan to meet local drilling environment
  - Recommend BHA to accomplish relief well planned trajectory
- Well Planner
  - Build the requirements from all the stakeholders into a preliminary relief well plan.
  - Distributes the well plan designed by the interception specialist into the appropriate format for the directional drillers to import into their directional software programs

## 7.7 Project Communication

As each project progresses, a relevant and unique report is issued. These reports can be summarized into three categories:

1. Ranging Plan
2. Ranging Report
3. Project Review

### 7.7.1 Overview of the Ranging Plan

The “Ranging Study” is the initial pre-job study developed for the client. This study encompasses all relevant information and challenges that the customer may have, and is able to provide a concise overview of each ranging method. Key features included in this report are:

- Summary - An overall understanding of the clients challenge and the solution to be provided
- Analysis - A modelled analysis based off of Well plans, Formation Type, Casing Models, and Resistivity.
- Modelled Results - Simulated results based off of the initial analysis
- Phases of Ranging- Provides a predicitive overview of each ranging run interval throughout the course of the project
- Ranging Runs Operational Outline - A concise overview on how a ranging run takes place, Include details such as necessary equipment as well as additional, beneficial services recommended

Provided below is an example of a few sections from a Ranging Plan. Note a ranging study can be in excess of 20 pages

### 7.7.2 Overview of the Ranging Report

The Ranging Run Report is a key tool in keeping the client fully informed on the progress of a relief well project. The objective of this report is to both present the current ranging results with the substantive data, and to provide a basis for the client to understand the ranging techniques used to achieve an interception.

- Well Information – Lists general information about the relief well including the geodetic values used.
- Crew – Lists all crew that is at rig-site that will be involved with the ranging runs
- Summary
  - Ranging call including the dimensions of the call box.
  - Surface shift of the target well surveys required to place the well in the center of the call box.
  - May contain a short summary of the ranging results in achieving the current run objective
- Analysis
  - An explanation of the ranging data quality.
  - Outline of which surveys were used for the relief well and target well
- Technique
  - Overview of the wireline run Including any issues with reaching TD or depth tracking
- Recommendations –
  - Length the next drilling interval
  - Alignment to the target well
  - Changes required to improve ranging signal intensity
- Attachments
  - Tool Diagram – Fishing diagram of the ranging assembly.
  - Proximity Diagram – A scaled map view of the well positions at the ranging call depth. This shows the position of the ranging tool inside of the relief well and the resulting orientation and edge to edge separation.
  - Map View – Plots the progressive ranging run call boxes
  - AMR Raw Data Plots

- High Side to Target – Raw data plot of the High Side to Target as measured by the ranging tool. Used as a positional direction reference between the target well and relief well when the relief well has an INC above 3°
  - Apparent North to Target Direction – Raw data plot of the magnetic direction between the target well and relief well. Used as a direction reference when the relief well has an INC of less than 3°
  - Normalized Intensity – The active magnetic signal strength measured by the ranging tool. Used to qualify the ranging data and for wellbore proximity. This measurement is independent of the earth's field or the remnant magnetic signature of the target well pipe.
  - Distance to Target – Plot of the raw gradient data. High data scatter will occur outside of the ranging tool gradient range.
  - Cross Axis Magnetic Field – Plot of the earth's field in the ranging tools XY axis. This is measurement is used to track perturbations in the expected earth's field to provide a qualitative analysis of the Apparent North to Target reference.
  - Inclination and Azimuth – Plots of the INC and AZI as measured by the ranging tool which are used to correlate the ranging tool data with the relief well surveys. Discrepancies between the relief well survey data and these plots indicate depth or survey positional errors which may skew the ranging results.
- Definitive Surveys – target well and relief well surveys used in the calculation of the ranging results.

## 7.8 Summary

Both passive and active magnetic ranging have been successfully used to guide a relief well interception. While similar in their end product, they employ different methods in determining proximity between two wellbores. When deciding which method to use, the operational parameters, characteristics, limitations, and costs of each type of ranging must be considered.

In terms of technological capability, AMR has proven to be the most reliable method for accuracy and detection range. For PMR, the lower range and reduced accuracy must be accepted if an intersection is required in a zone that is not accessible to AMR.

Using AMR is most appropriate for jobs where there is one or more of the following factors to consider: Low tolerance for sidetracks, a large ellipse of uncertainty, mounting environmental damage, or increasing political impact. While PMR may be attractive based on the lower daily cost, caution must be taken as the limitations of the service may lead to costly sidetracks.

The ideal solution in most cases is to use the following ranging methods in the below phases:

- Locate Phase - AMR is used for the initial ranging, making the most of the detection range capabilities.
- Follow Phase - AMR is utilized in a specialized tool push ranging (TPR BHA that allows for proper separation required between the relief well and target well (for safety purposes as recommended by the Well Control Engineer) while providing the same time/costs savings as PMR as ranging data is not required to be taken on bottom during this phase.

Note: Although the principal thought behind this concept is great, being close enough to the Target Well to utilize PMR in the follow phase is typically not practical because the chance of accidental interception is significantly increased. This method is more commonly used in P&A situations where the consequences for accidental collision are minimal.

- Intercept Phase – AMR is used to complete the intersection, taking advantage its ability to: directly measure distance, take on bottom data, and range at any depth.

## 8. Well Intersection Design Fundamentals

After the initiation of a project data collection process, there are several key components and steps in the design of an intercept/intervention well project.

### 8.1 Project Objective(s)

Designing a well intersection begins with clearly defining the well objectives—especially what is required after the intersection is made. In some cases, the objectives will be obvious, but some projects may require more complex statements. For example, in a relief well, the first objective may be to control the blowout, but secondary objectives may require that the blowout well be plugged and abandoned from the relief well and, furthermore, require a detailed plan of how it will be confirmed. In any case, it is important to define not only objectives, but also operational milestones that define progress and achievements.

### 8.2 Drilling and Remedial Operations Plan

A well construction and operations plan to meet the project objective(s) includes the simultaneous development of both a drilling plan and a remedial operations plan. These are created concurrently within the team organization, and the details are highly dependent on the complexity of the project and requirements to meet the objective(s). This is a process that may require several iterations before an acceptable plan is developed

### 8.3 Intersection Strategy

The initial process of an intersection strategy is to assess and select appropriate intersection point(s) along with the required orientation to the target well. The ability to successfully establish and then maintain a robust hydraulic communication path required for a kill and/or P&A operation will be important during the intersection strategy development.

### 8.4 Ranging Strategy

Development of the ranging strategy will be based predominantly on the available ranging methods and tools, positional uncertainties, wireline access to the target well, and operational constraints, e.g., intersection depth, surface location, blowout related factors, adverse formations, pipe length, end of pipe effects, adjacent wells, and the incidence angle between the TW and the IW at key intervals in the operations.

### 8.5 Directional Trajectory

Directional trajectories are typically 3D wellpaths with distinct intervals. A suitable surface location is determined after defining and evaluating all constraints and becomes the starting point for the well. The end point is defined by the intersection point(s) with a relative orientation to the target well. The path in between must allow for the implementation of the ranging strategy to efficiently locate and intersect the target.

### 8.6 Intersection Project Complexities

The design of a well intersection can be a very complex undertaking and requires a team approach with many disciplines and specialty services. The complexity of a well intersection project is dependent on many variables. Some of these complexities include the following (for a relief well):

- General blowout rate and HSE consequence
- Relief/intervention well objective(s) complexity
- Environmental and operational complexity
- Hydraulic communication establishment complexity
- Well intersection complexity
- Hydraulic kill complexity
- Target Well (TW) P&A complexity

Risk evaluation will be predominant during the planning process, and reliance on previous experience of the team members will be important. New ideas, methods and tools may be required to increase project success and reduce intervention time. Many of the tools, processes, and services available today for well intersections were developed out of necessity during previous intervention projects.

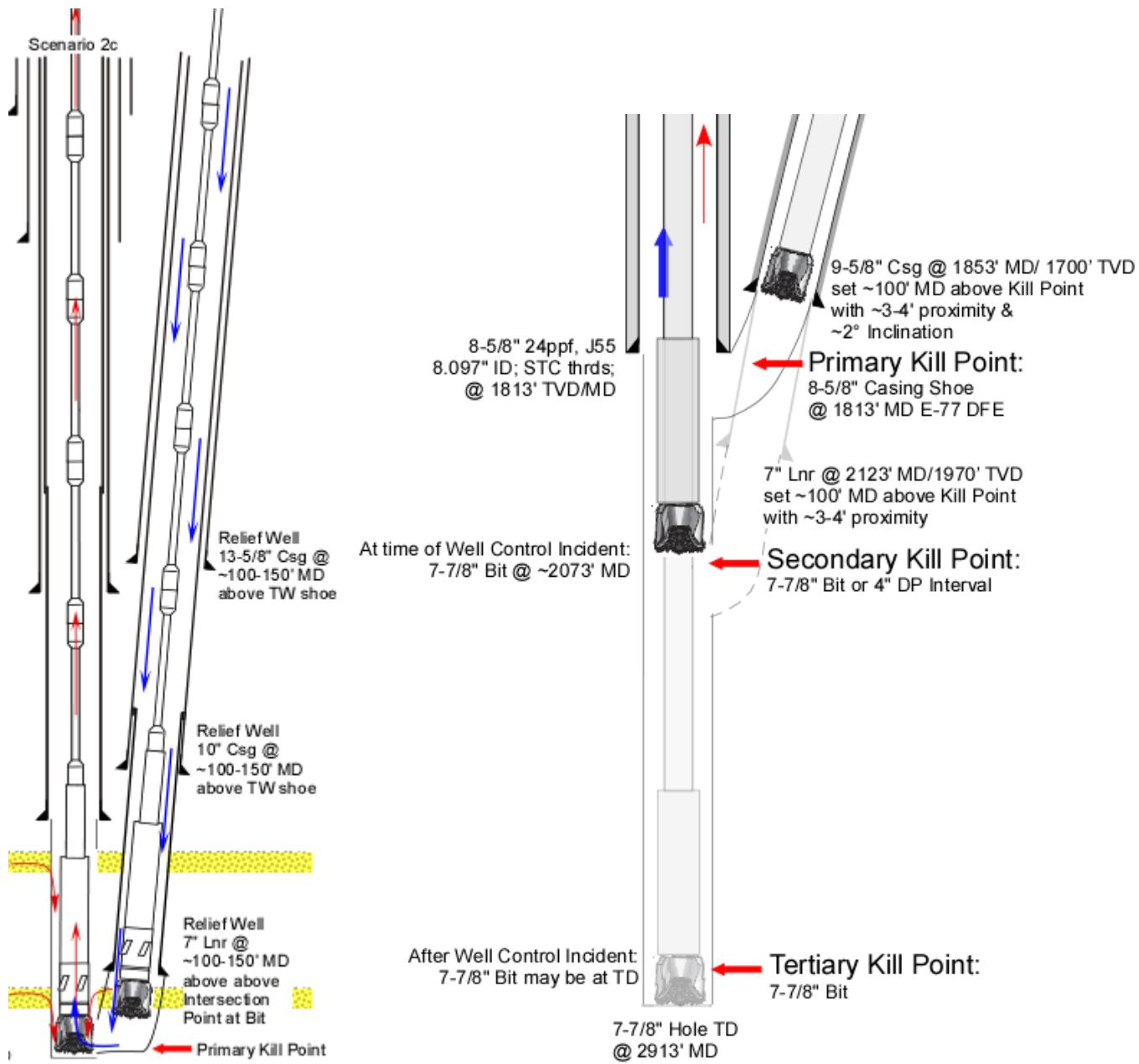


Figure 41 Intersection Strategy Diagrams

## 8.7 General Planning Process

The design of an intercept/intersection project follows the basic four components of a typical project life cycle:

1. Develop concept
2. Develop design
3. Execute the project plan
4. Close the project

During the initial phase of the project, the problem is presented and all of the data is gathered, objectives are defined, teams are outlined, and a conceptual project plan is approved by the project owner.

The design phase of the project entails the development of the project plan, which is based on all of the inputs and evaluations from the team members. Once the project plan is approved, the project can move forward.

Drilling, intersecting, and performing the required kill and/or P&A or other remedial operations are completed to the satisfaction of the project owner during the execution phase.

After achieving the project objective(s), the project is closed. All final documents are completed and submitted, including lessons learned, final status diagram, and end of project reports.

### 8.7.1 Well Intersection Planning Process

Typically, two distinct, simultaneous, and interdependent planning processes and associated teams are required during the planning of an intersection project. A drilling team will plan the strategies and tactical details of making the intersection a reality and a well kill/P&A team will be responsible for the well kill operation (in the case of flow being present) as well as the P&A of the TW. Figure 44 shows a typical well intersection planning process cycle.

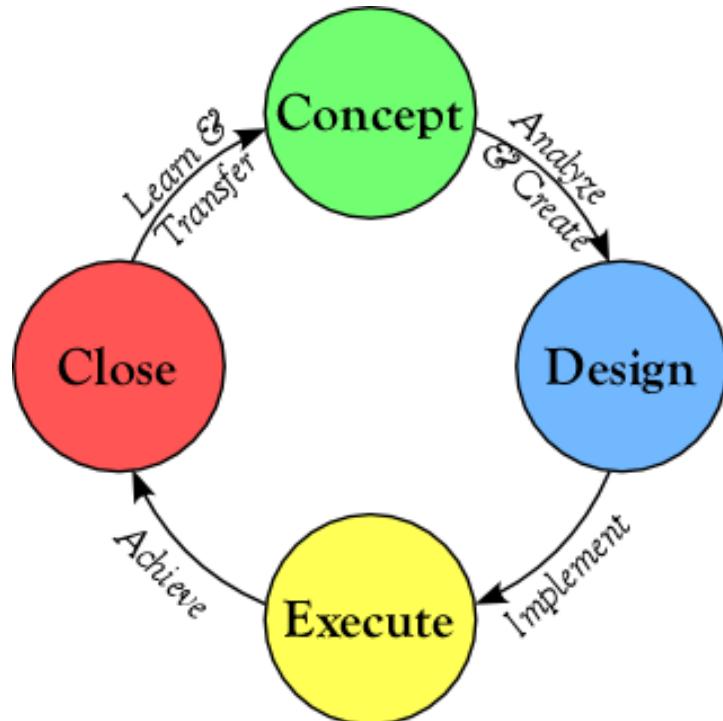


Figure 44 Well Intersection Planning Process

Depending on the project's complexity, the team members may have multiple roles and some responsibilities may be shared. In the case of a less complex project, some responsibilities may be unnecessary. Good communication between team members is imperative during the planning and execution phases as the developed strategies and tactics are interdependent and can create operational conflicts.

The planning process is an iterative process where each new input, whether it is data or the findings from an investigation, must be analyzed and evaluated to ensure the plan continues to be one that creates success. Ultimately, a comprehensive and robust project plan is produced for the execution phase of the project (see Figure 45 and Figure 46).

The planning or design process steps for a relief well in generic terms, includes the following as a minimum:

1. Gather relevant data
2. Make onsite assessment
3. Perform diagnostics to define the problem
4. Define relief well/intervention well constraints
5. Define the relief well/intervention well project objective(s)
6. Define the intersection/kill point(s)
7. Define the hydraulic communication method/intersection strategy
8. Evaluate the position uncertainty
9. Evaluate the geologic conditions
10. Define the attack angle
11. Develop the ranging strategy
12. Determine the surface location(s)
13. Develop the relief well trajectory
14. Define the relief well casing program
15. Define the survey program
16. Evaluate the kill/P&A hydraulics
17. Determine the number of required relief wells/intervention wells
18. Define the kill/P&A/remedial equipment and kill/P&A/remedial procedures

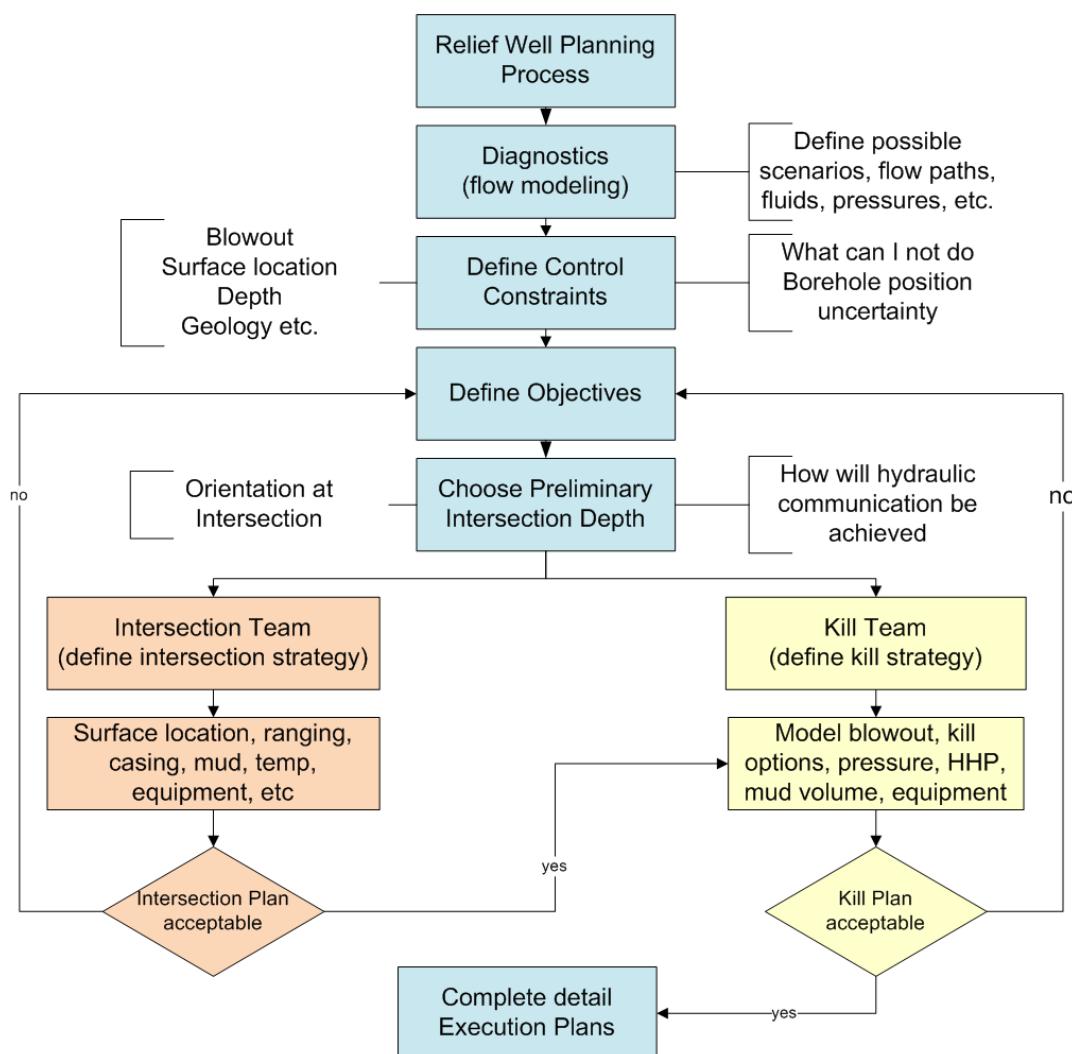


Figure 45: Summarized Intersection Well Planning Process

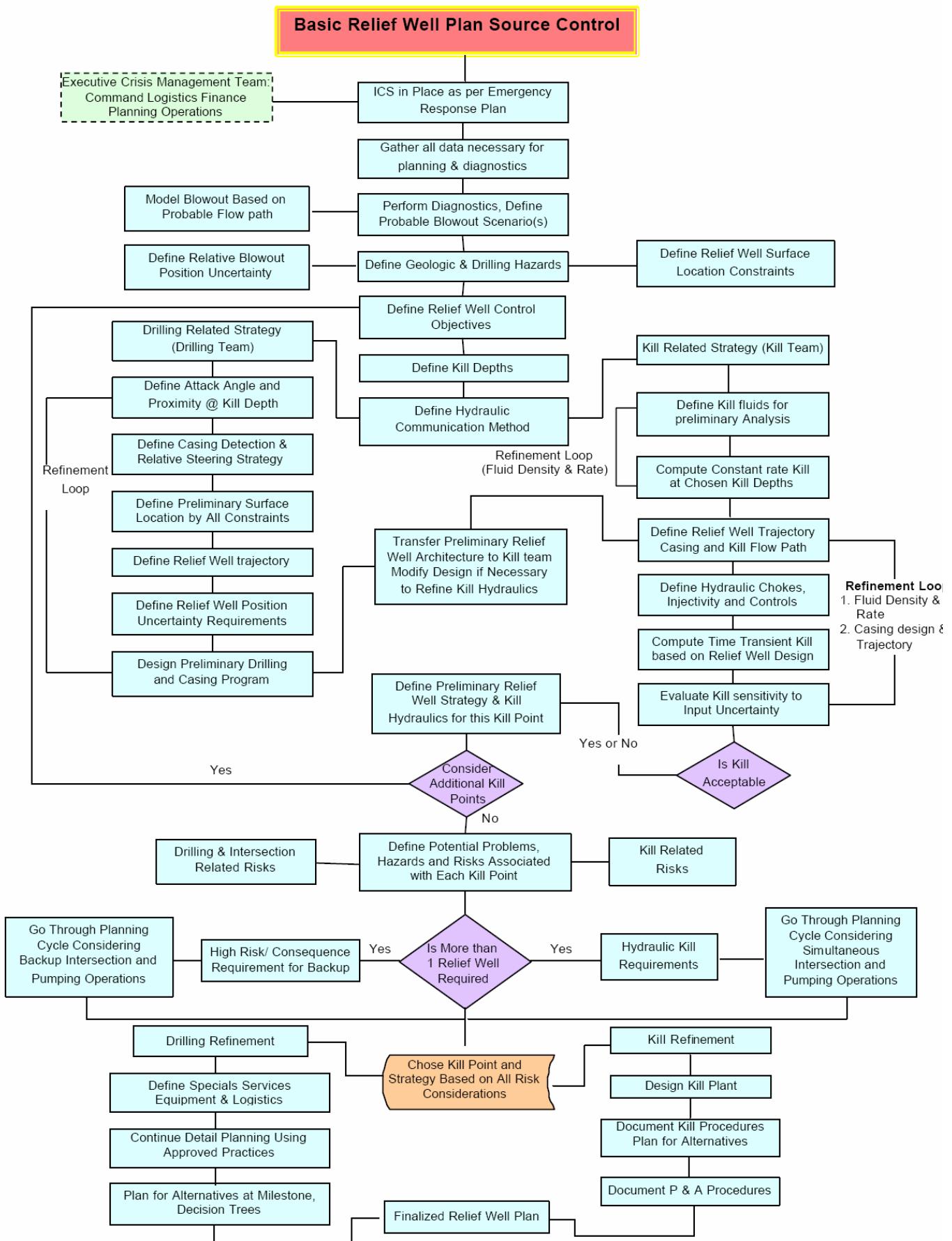


Figure 46: Detailed Relief Well Planning Process Example

## 8.8 Drilling Intervals of an Intersection Well Project

The following discussion relates primarily to the drilling of a typical relief well or intervention well. Based on the situation, U-tube, conductor connector wells, and other intersection wells where access to the target well is available may have different intervals.

### 8.8.1 Normal

During this interval, “normal” drilling operations occur while the distance between the two wells is reduced to allow for the next interval where ranging operations commence. The well is spudded and the required vertical drilling, with the setting of appropriate casing strings, are completed as per the plan.

The relief well/intervention well is kicked off according to the directional program and drilled adhering to the guidance and BHL requirements set forth in the program. Additional surveying operations and other controls may be specified. The objective in this interval is to efficiently drill and place the intersection wellbore at a required location, within a specified positional uncertainty area, that will provide for the locating of the Target Well with the ranging tools.

### 8.8.2 Initial Locating/Ranging

Ranging operations begin and continue in this interval to provide an accurate location of the TW with respect to the relief well/intervention well. Typical electromagnetic ranging operations, when practical, incorporate a cross-by and/or pass-by to positively identify the target well location (see Figure 47 and Figure 48).

After positively identifying the target well location and reducing the total positional uncertainty to an acceptable level, a protective casing string may be set to preserve the intervention well wellbore, which may have been open for some time due to the ranging operations. The two wells may be as close as a few feet at the cross-by, but typically the two wells are within less than 30 to 50 feet proximity prior to the next interval.

### 8.8.3 Monitor/Parallel

In the monitoring or parallel interval, the two wells are drilled having a close proximity in preparation for the final alignment required for the intersection. The length of this interval is dependent on available TVD, quality of the TW survey, results of the directional drilling, and ranging plans and difficulty associated with the project.

### 8.8.4 Final Alignment & Intersection

The intersection(s) and remedial operations (re-entry, plugging, etc.) are performed in the final alignment and intersection interval. The intersection may be an open hole or cased hole type of intersection. One or two intersection points may have been specified in the project plan and will have been achieved in this interval.

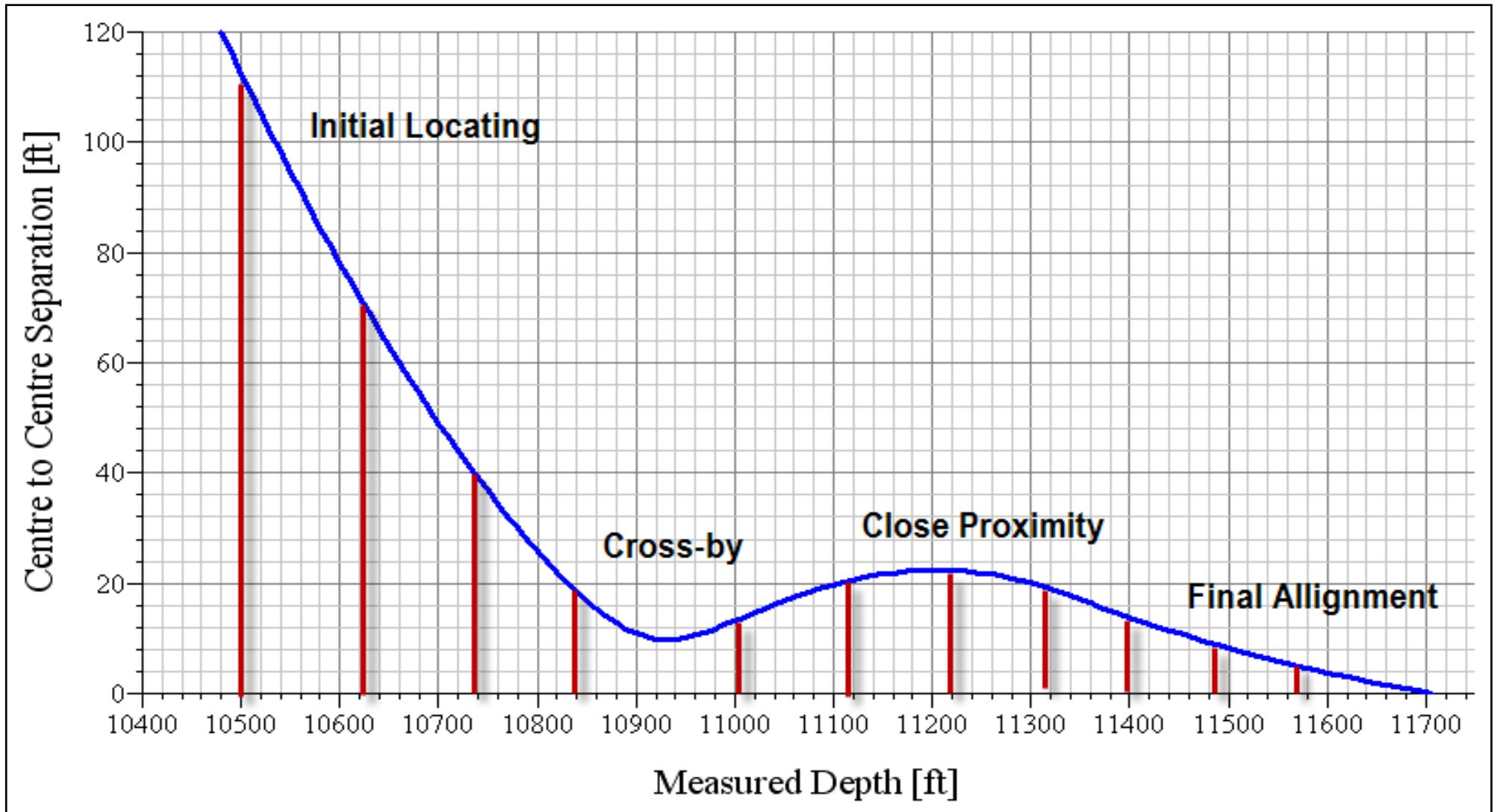


Figure 47: Example Ranging Program

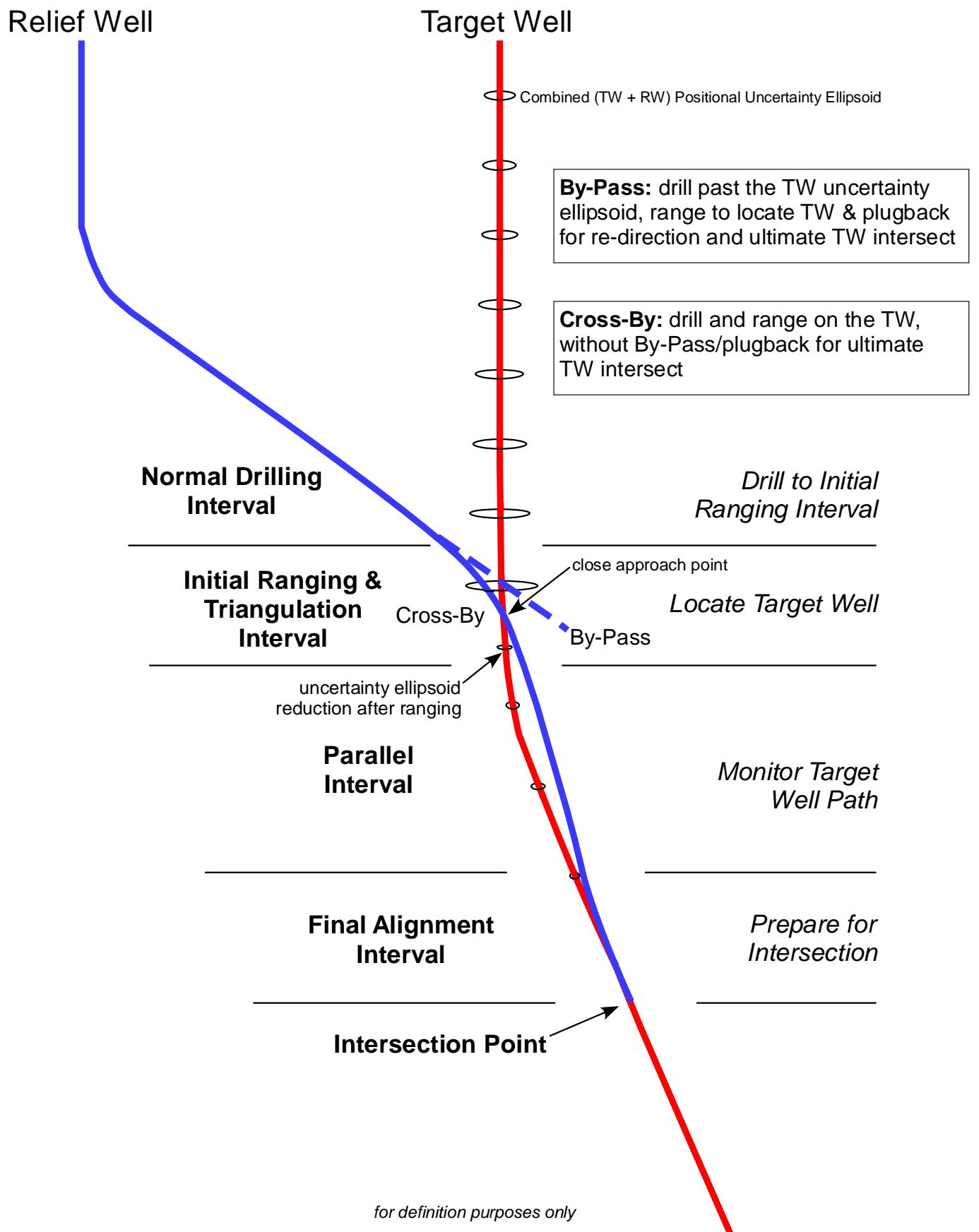


Figure 48: Drilling Intervals of an Intersection Well Diagram

## 8.9 Types of Well-to-Well Intersections

Well-to-well (WTW) intersections can be categorized into two types: either direct/geometric or indirect/proximity.

### 8.9.1 Direct/Geometric

A direct or geometric type of intersection is one that makes direct and physical contact with the target well. A direct or geometric intersection is used during wild well killing operations, re-entry into a target well openhole or casing, or in a remedial operation where a mechanical and/or hydraulic operation is necessary to meet the project's objectives.

### 8.9.2 Indirect/Proximity

An indirect or proximity type of intersection does not require a mechanical contact with the TW and may mandate that a minimum or maximum distance between the two wells is necessary. Examples include a relief well that would water-flood within the blowing reservoir, drilling into washout zones or acid soluble formations where only hydraulic communication is required, or an intersection where the two wells should not touch, but maintain some pre-determined separation.

## 8.10 Establishing Hydraulic Communication

After achieving the intersection, whether openhole, cased or within a proximity target boundary, hydraulic communication usually follows. Several types and techniques are available and include:

- Geometric (OH, porosity, washout, etc.)
- Perforating/explosive
- Milling (mills, whipstock, etc.)
- Hydraulic (sand cutting, acid, water, etc.)

### 8.10.1 Geometric

The geometric method of establishing hydraulic communication can occur instantaneously as in the case of a direct openhole intersection, or it may require additional equipment or methods. The geometric method includes direct openhole, hydraulic connection through the porosity of a formation, and the ultimate washing out of formation between two wellbores with water and/or acid. Typically, direct openhole intersections are the most simplistic and quickest to gain hydraulic access to the target well, with openhole or annulus intersections as the most common.

### 8.10.2 Perforating/Explosive

When target well tubulars or formation prevent an instantaneous hydraulic communication from occurring, perforating or the use of other explosives may be appropriate. Limiting success factors include formation, steel thickness, multiple tubulars, orientation, contact interval, and the distance between the two wells. Perforating in high BHP, high mud density, elevated temperature environments, and multiple tubular targets can dramatically reduce penetration success with perforators (see Figure 49).

In the past, there have been specifically designed relief well perforating guns, but at this time no suppliers are offering a dedicated relief well type perforating system. So, when planning a WTW perforating operation, a full-scale layout of the TW and IW can be built to test the actual perforating results.

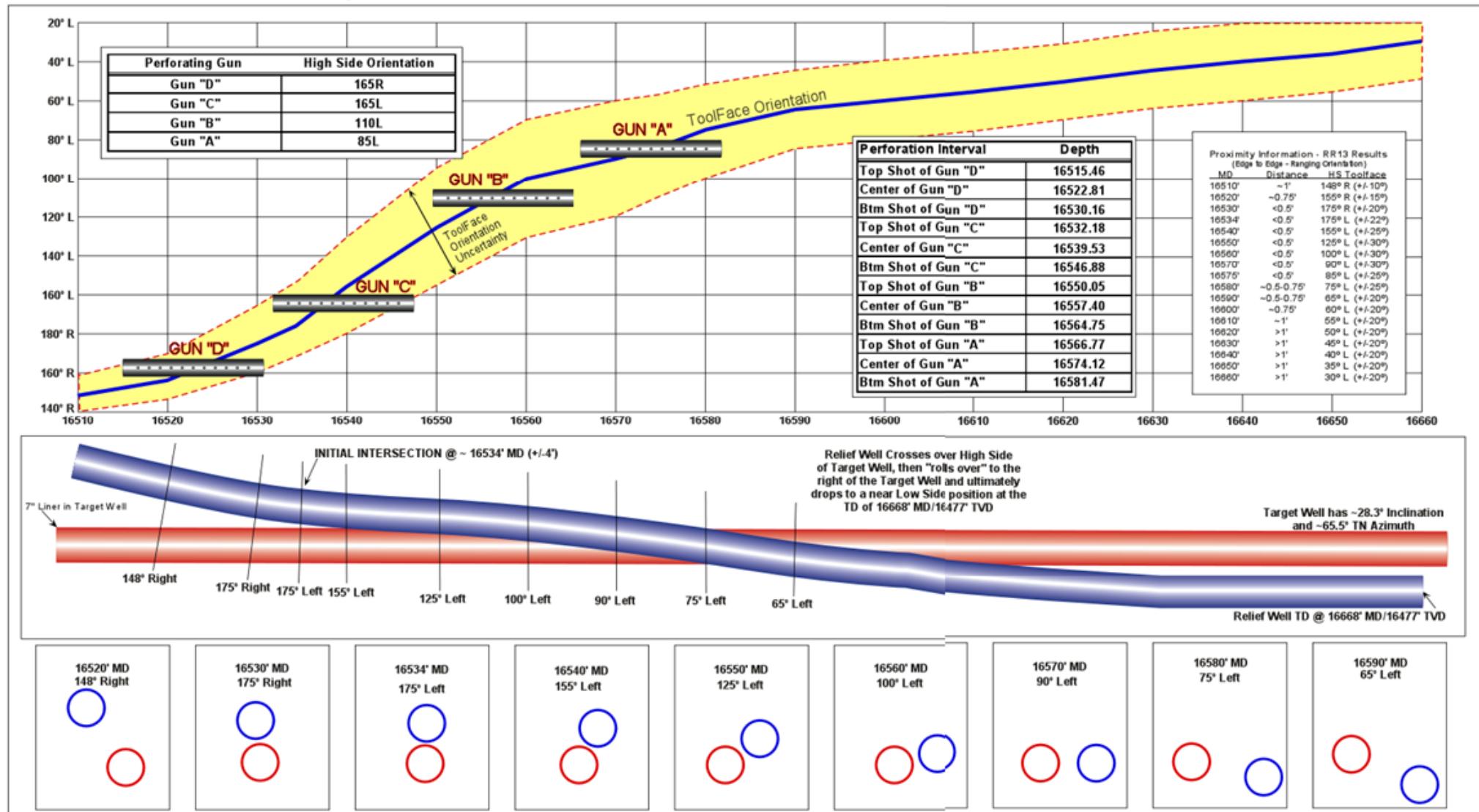


Figure 49: Example Perforating Method to Establish Hydraulic Communication

### 8.10.3 Milling

Another method used to penetrate casing or other tubulars is milling with a mud motor, rotary BHA, or by using a whip-stock. Specially designed mills aid in efficient tubular penetration and milling operations. Project objective(s) may require a small hole of sufficient TFA for well killing and/or plugging, or it may mandate that a “slot” is milled to allow for re-entry into the casing to set or pull packers, plugs, etc.

Exacting well alignment is imperative for a successful WTW milling operation. Incidence angle and centerline alignment become very critical to prevent “rolling off” the TW tubular. The presence of soft formations, centralizers, and high dogleg trajectories further complicate these operations. Accurate bottomhole surveying and ranging techniques at the final alignment interval are critical to ensure an imminent intersection.

Slot milling with a motor and mill have been performed on previous projects with good success (see Figure 50). Whip-stock methods have had some success but can be hindered by several factors, including whip-stock rotation, milling BHA rolling off the whip-stock, target/hole size ratios, high-strength casing grade, deep intersection point(s), and formation strength between the two wells (see Figure 51).

When planning a milling operation at an intersection, consider the following:

- Wellbore inclination and incidence angle
- Formation integrity and washout potential
- Side-force loading and cutting capabilities of tools
- Effect of hole and tubular diameter differences
- Ability to maintain effective alignment during final drilling and milling operation

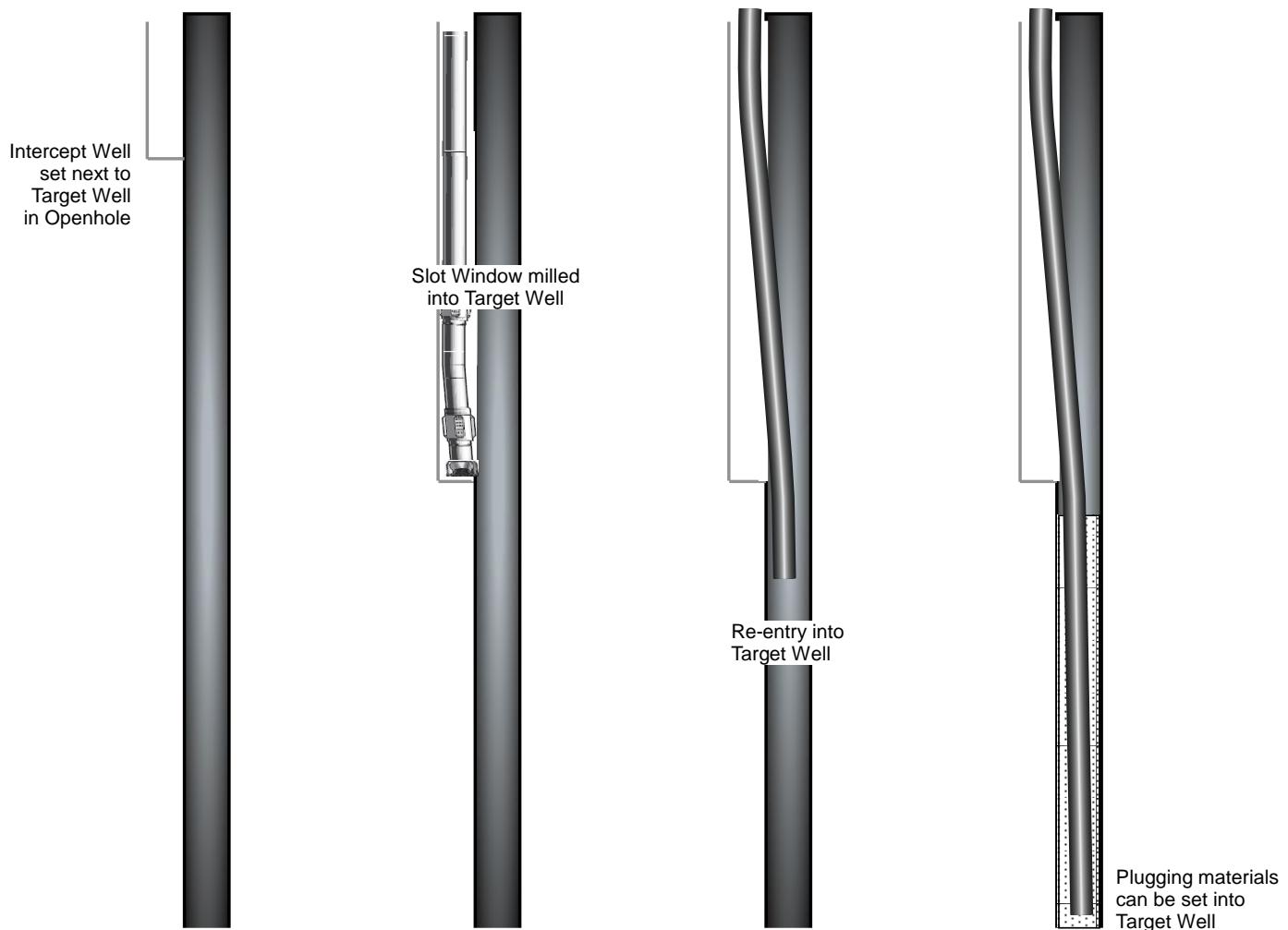


Figure 50: Slot Milling Method Concept



**Figure 51: Cased Hole Whipstock Milling Method Concept**

### Hydraulic (sand cutting, acid, water, etc.)

In some instances, hydraulic cutting techniques are employed to complete the hydraulic communication process. A high-pressure pumping system, with sand-laden fluid, has been used to penetrate drillpipe and/or casing if very close (usually <6-inch proximity).

Hydro-jetting is a method that can produce good results to create an adequate TFA for the pumping of the plugging materials. This method requires a hydro-jet tool, configured with small diameter jet nozzle(s) and a high-pressure pumping unit, and can be run either oriented or rotated with a high-pressure rated swivel.

In the oriented mode and pointed towards the target casing with a surface readout north-seeking gyroscope, the hydro-jet tool can be reciprocated a short distance to efficiently create a slot into the target well. When rotated, the entire target casing can be severed, but the intervention well casing or hole is also cut/washed circumferentially.

Hydro-jetting is advantageous when a very limited intersection contact distance is present and the communication path must be made at a particular point (cutting nozzles are very close to end of toolstring). This method is considered as a secondary method in some situations where previous attempts were unsuccessful.

Also, acids can be pumped down hole to develop the final hydraulic channel in acid-soluble formations and connect with the TW. And, large volumes and high rates of water to "wash out" a formation have been employed in the past, especially on relief wells drilled into reservoirs when supposedly "close" to the TW. This type of final hydraulic connection method was used extensively prior to the invention of modern ranging equipment.

## Typical Equipment and Methods

### Directional Drilling Equipment

To complete a well intersection project, various directional drilling tools and techniques may be necessary, which include those normally used in the drilling area and specialized tools. Specialized tools may include rotary steerable, steerable mud motor, and even older style tools that may be more appropriate for the conditions.

Making the final intersection should be performed with tool(s) that are not affected by the presence of magnetic tubulars, target well casing centralizers, or other adverse drilling environment conditions when drilling without proximity to the target well.

### Surveying Equipment and Methods

Accurate surveying tools and methods are key to minimizing positional uncertainty and accurately recording the intersection well trajectory and BHL. Typically, increased survey interval frequency, multiple surveys, establishment of downhole survey benchmarks, and other borehole surveying methods are employed.

North-seeking gyroscopic systems, both wireline and drilling/MWD deployed, have been instrumental in achieving success on many past projects and are a necessity when drilling within a magnetic anomalous environment.

### Special Kill and Plugging Equipment

Some of the specialized well killing and plugging equipment required on relief well/intervention well projects include:

- Enhanced well control equipment, e.g., larger diameter lines, additional BOP rams, drilling spool(s), RBOP, etc.
- Large diameter, deep-penetrating perforation equipment
- Specialized plugging materials, e.g., GUNK, sodium silicate, polymer LCM, etc.
- High-pressure pumping equipment for hydro-jetting, fracturing, and well killing operations
- Specialized milling equipment, whip-stocks, etc.

## Operational Information

With an average of only 2 to 3 relief wells completed per year, experience may be difficult to obtain. Where experience in blowout complexity is not necessary, intervention wells are drilled more routinely and more experienced personnel for this type of intersection is available. Typically, personnel with the knowledge and special skills to efficiently intersect another well are found at ranging tool services and at professional well control response companies that have relief well engineering teams.

When planning and undertaking a well intersection project, it would be prudent to include those with recent experience and having a broad range of skills to assist in managing the required special, non-routine services.

As stated previously, intersection well planning and the execution of the plan can be complex. Many disciplines within a team organization are required, with the team size based on the complexity of the project and ultimately the availability of personnel.

For example, how should a relief well team be organized? Following the premise that a relief well is similar to an exploration well having a different objective, the overall team should be led by the operator's well construction leader or similar designate.

Under the team leader, there are two operational branches. One branch will be responsible for all of the routine services for well construction design and delivery tasks. This branch would typically be led by one of the operator's senior well construction engineers.

The second branch is responsible for the design and delivery of the non-routine tasks that are unique to the relief well objectives. This "special services" branch should be led by a relief well specialist with experience in both well intersection and hydraulic kill design and delivery.

The special services branch is divided into a hydraulic kill team and a well intersection team. The leaders of both of these teams should be relief well specialists with relevant experience to lead their respective groups.

The intersection team leader is tasked with the design and delivery of the well intersection at the specified depth. This will include gaining hydraulic communication between the relief and target wells. The initial design tasks are iterative and include: defining well construction constraints and hazards, surface location(s), ranging strategy, intersection geometry and position uncertainty, trajectory, casing size and depths, surveying, drilling tool requirements, and documenting the special services plan.

Example services and specialists that would typically be led by this team are: directional drilling, MWD, borehole and surface/subsea surveying, ranging, any related wireline, perforating, whip-stocks, mills, downhole tools, etc.

The kill team leader is tasked with the design and delivery of the hydraulic kill at the specified intersection depth. The initial design task is to work with a hydraulic simulation specialist and the operator's technical staff to define the kill requirements. This is an iterative process to arrive at a workable solution.

If a secondary objective is the P&A of the target well through the relief well, then the same teams, with additions and deletions as required, will plan and execute the P&A.

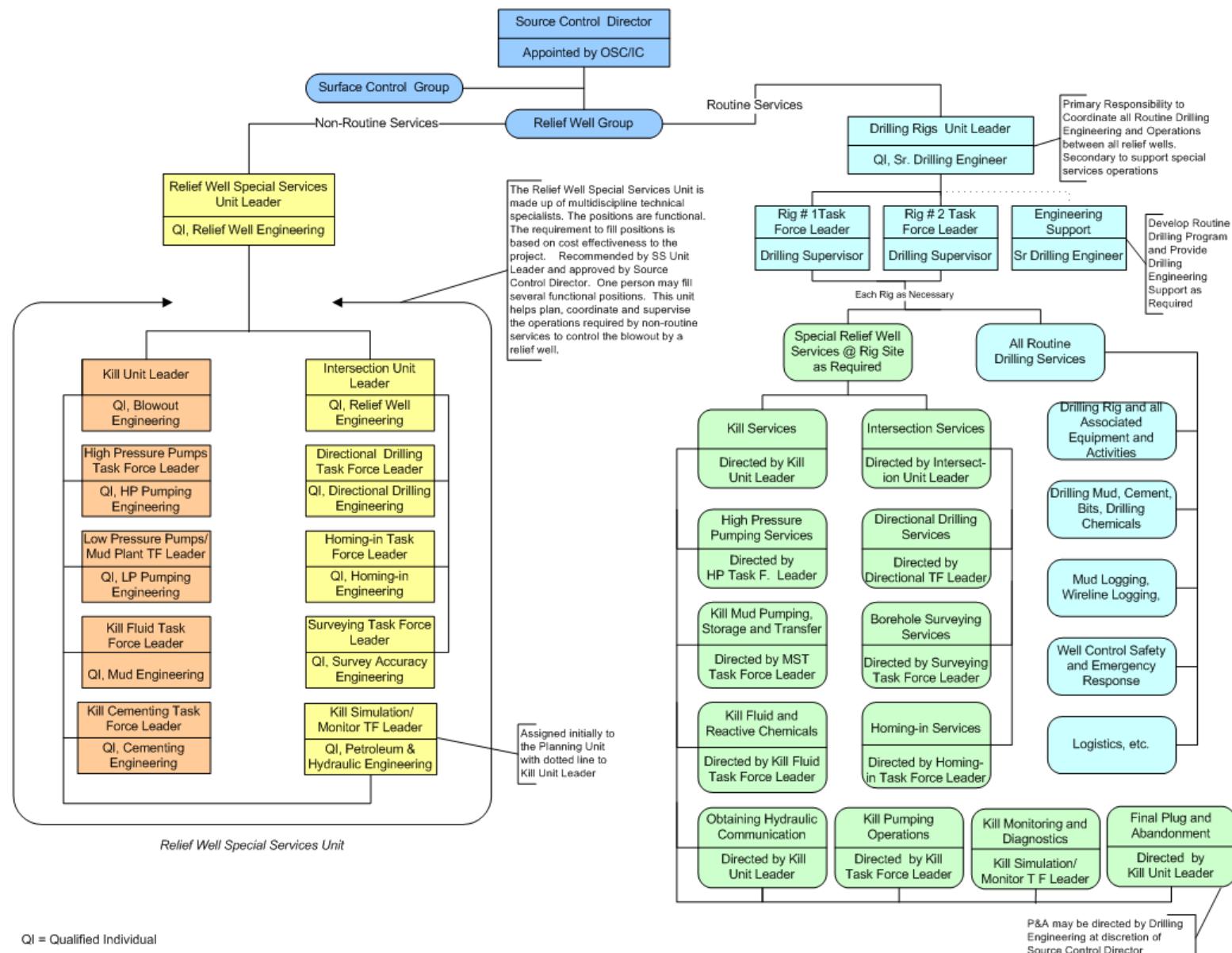


Figure 52: Example of Relief Well Team Organization

## Well Intercept

Word/Phrase/Symbol	Definition
Absolute Positional Uncertainty	Three dimensional position uncertainty with respect to a defined local reference point.
Active Acoustic Ranging	A technique that utilizes direct bursts of acoustic energy toward an acoustic reflector generally an open hole or cased hole wellbore. The reflected signal time is measured to determine the distance. The direction of the reflected signal is determined by the reflected azimuth relative to the tool position or the surface seismic source and receiver arrangements.
Active Magnetic Ranging	Any well-to-well ranging technology that requires the induction and detection of a magnetic field between two wellbores.
Allowable Deviation from Plan (ADP)	The maximum distance in 3D space that an as drilled wellbore may deviate from the directional well plan.
Attack Angle	See Angle of Incidence
Angle of Incidence	The relative angle between two wells, expressed in degrees ( $^{\circ}$ ), which defines the total angular difference in the well trajectory vectors. Can be expressed as a two or three dimensional difference(s) and having either converging or diverging vectors. Typically used to describe the angle present between the RW and the TW during ranging operations and when attempting to make the final intersection.
Blowout Well	A wellbore that may be completed or is being drilled in which hydraulic control has been lost resulting in a need to kill the well. Also referred as Target Well or Subject Well.
B <sub>xy</sub>	Magnitude of the magnetic field measured perpendicular to the relief wellbore direction.
Call Box	The distance and direction to a target, projected in the plane normal to the RW or IW on a horizontal (TVD) plane that incorporates best estimates of the ranging result and its uncertainty.
Capping	A surface intervention technique which allows the blow out well to be capped and brought under control without the need to drill a relief well.
Completion Recovery	The use of ranging technology to drill a new wellbore that communicates with a target wellbore for the purpose of gaining further utilization of the completion of the target well (for instance, the fracture job of the target well).
Cone of Uncertainty	A 3 dimensional area of positional uncertainty in the form of a cone where the central axis of the cone aligns with the downhole axis of the wellbore and the base is located at the deepest measured depth of the wellbore. Cones of uncertainty are typically defined by degrees per distance or lateral error per distance.
Contingency Relief Well Plan	A document which describes the plan of implementing a relief well project to solve an uncontrolled blowout well condition. Plans may be required by corporate guidelines and/or by a regulatory entity prior to the drilling of the subject well which could blowout or create an uncontrolled effluent release.

Cross Axial Interference	Magnetic interference along the magnetometer axes perpendicular to the tool axis.
Cross-By	A relief well planning technique to reduce positional uncertainty which requires the RW to be geometrically drilled past the TW with a close proximity (usually <50') to allow for triangulation between the two wells, and without a side-track or plug-back operation. See Diagram 1.
De-Gaussing	Applying an external magnetic field to a steel component for the purpose of reducing magnetism in the steel.
Detection Range	Maximum well-to-well distance over which ranging signals can be detected. Usually refers to a modelled vendor specification.
Dipole	A steel component having both a North and South magnetic pole.
Direct Intercept	A well intercept technique that does not require a pass-by to locate the blow out well. Also see Simple Intercept.
Dogleg Severity (DLS)	A measure of the amount of change in the inclination and/or direction of a borehole, usually expressed in degrees per 100 ft. or per 30 m of course length.
Dynamic Kill	When a blowout occurs, the well unloads a mixture that can include hydrocarbon liquid, gas or water flowing at a high rate due to a pressure imbalance at the exposed interval. This imbalance/differential can result in a pressure thousands of psi below reservoir pressure. A Dynamic kill is the process of stopping this imbalance and as a result the influx. This is accomplished by pumping heavy mud into the wellbore at high rates to suppress the flow. The process introduces kill mud into the blowout well to raise the density of the blowout stream. Acting in combination with the increased density, the flow rate of the kill mud creates considerable friction pressure which further decreases the pressure imbalance. The combination of these two forces stops the blowout by increasing the bottom hole pressure above that of the exposed interval.
Edge to Edge Distance	Distance between the ellipses of uncertainty of the offset well and the target well along the direction of closest approach.
Effective Detection Distance	Detection range specific to the formation and geometries in the ground.
Electromagnetic	Refers to magnetic fields generated by electric currents. Can be used as a source or for sensing. Also can be used for magnetization or degaussing.
Ellipse of Uncertainty (EOU)	The area produced by projecting an ellipsoid of uncertainty onto a defined plane.
Ellipse Major Axis	The larger of the two principal axes of the ellipse formed when an ellipse is projected onto a defined plane (e.g. horizontal or perpendicular to wellbore). A mathematical construct it represent the largest dimension of the ellipsoid
Ellipse Minor Axis	The smaller of the two principal axes of the ellipse formed when an ellipse is projected onto a defined plane (e.g. horizontal or

	perpendicular to wellbore). A mathematical construct it represent the smallest dimension of the ellipsoid
Ellipsoid Major Axis	The largest of the three axes of an ellipsoid
Ellipsoid Minor Axis	The smallest of the three axes of an ellipsoid
Fish Bypass	Technique of drilling around an obstruction in a wellbore and re-entering said wellbore.
Ghost Wells	Cased wells that are missing from the survey database used for anti-collision calculations.
Gyro Survey	A directional survey comprising of measured depth, inclination, and azimuth where the azimuth is determined using gyroscopes which either measure the Earth's horizontal turn rate or the change in relative direction from an initialized orientation.
Hand Railing	Using ranging technology to "follow" an existing well. Commonly used in operations such as SAGD where only the first well has an absolute positional survey, and the additional well position is calculated relative to the existing well.
Homing in	The iterative process of deploying ranging techniques to establish a relative position between the RW and TW, with each successive iteration, reducing the relative uncertainty between wellbore positions. The homing in process continues until the goal of the RW has been achieved i.e. the RW intersects the TW and hydraulic communication has been achieved.
Homing in Point	This is the point in the wellbore that you will initially range too. It is the point in the target well where you establish its relative position to the interception well. It is both shallower and quite different to the well interception point.
Injector	See SAGD description.
Intersection Angle	The actual angle of closure between the relief well and the target well, defined as the angle between the along-hole vectors of the target and relief wells.
Intercept Phase	The final phase of a relief well project where the two wells are intersected, either mechanically or having a specified proximity. A geometric intersection has the two wells having a convergent trajectory, with an actual contact point or interval present. A proximity intersection has two wells maintaining a parallel proximity path or a diverging incidence angle. Precision directional drilling and ranging operations are critical during this project phase. See Diagrams 1 and 2.
Intercept Point	The point along the subject wellbore where the relief well intersects the subject well.
Kill Point	Point at which desired hydraulic communication is established between the target and relief wells.

Lateral Distance (LD)	The horizontal distance between two wells to define the positional difference between well centers or positional uncertainty ellipses.
Locate Phase	Signal acquisition phase of relief well drilling during which position of relief well is established via ranging measurements. Prior to tracking phase. Anti-collision criteria will be violated for the first time during this phase.
Magnetic Guidance	An induced magnetic field is utilized in a ranging process to correlate wellbore relative locations/separation between a drilling well and a reference well.
Magnetic Hot Spot	Location of unusually high residual magnetism in a steel component.
Magnetic Signature	Magnetic field induced by either the remnant magnetism in a steel component or an electromagnetic source.
Magnetic Survey	Would normally constitute a survey comprising "measured depth, Inclination and a direction derived from a magnetic sensor". Sensor can be an analogue device of which a "picture" is taken (Camera based data", or solid state magnetometers deriving a hole azimuth from the ratio of the defined horizontal cross tool and along tool magnetic measurements. Direction is normally corrected using some measured or modelled value of the local magnetic field to adjust to Grid or true North.
Magnetized Casing	Is a technique where casing has a known or predictable magnetic profile, resulting from a controlled magnetization of wellbore tubulars. This increases the radius investigation of passive magnetic ranging, enhances signal strength, ranging distance and predictability of detection.
Magnetometers	Sensors for measuring the strength, and possibly direction, of a magnetic field.
Minimum Allowable Separation (MAS)	This is the minimum distance calculated between a subject and offset well (also known as the no-go distance), before the drill ahead anti-collision rules is violated or the tolerance line is crossed.
Measured Bearing	Toolface angle defining the measured direction to the target well, as determined by ranging data.
Minimum Pass-by Distance	Minimum well-to-well separation distance during a pass by or triangulation. Used to assess risk of collision during tracking phase.
Monopole	A single North or South magnetic pole. Does not actually exist in nature but can be a useful mathematical construct.
No flyby Intercept	See Direct Intercept definition.
Observation Well	A (typically) vertical well used to measure parameters relative to other nearby wells in a field.

Oriented Intercept	An S-shaped two dimensional or three dimensional well that is designed to locate and intercept the blowout well at two distinct points. This design requires a pass-by for triangulation to confirm the position of the blowing well and to reduce the positional uncertainty.
Parallel Track	An S-shaped two-dimensional or three-dimensional well design which tracks the blowout well once located which can be perforate and establish communication with the blowout well. In this design a pass-by to triangulate the position of the blowing well is not performed, if the confidence in the survey position of the well is considered to be high.
Pass-by	Drilling past an existing wellbore for the purpose of locating the target well.
Passive Magnetic Ranging	Utilizing measurements of the magnetic anomaly arising from remnant magnetism in the casing of the target well over a range of measured depths to estimate the location and orientation of the target well relative to the BHA.
Passive Acoustic Ranging	A non-invasive technique that listens to the acoustic noise generated either by the drill bit or flowing fluids. Utilizing a triangulation method, incorporating spectrum analysis, the noise source distance and direction can be estimated.
Piggy Backing	The use of Gyro While Drilling tools in conjunction with an MWD to provide accurate azimuth when in near proximity to offset well casing. This reduces the number of magnetic ranges necessary to provide the desired offset from the target well.
Polarity	Refers to the magnetic polarity (North to South) of drill string or casing which can change at joints.
Producer	A well that is producing returns under pressure.(natural or induced flow)
Ranging Phase	The section of the well where ranging is to be used.
Ranging Run(s)	The cessation of drilling activities when ranging operations occurs.
Ranging Uncertainty	Relative position uncertainty which is normally described in terms of a distance and bearing uncertainty.
Reference Well Translation	Translation of the target well to pass through the measured position derived from the ranging observation. This is an iterative process.
Relative Position	Offset well position described as a distance and bearing to the point of closest approach.
Relative Positional Uncertainty	The uncertainty associated with the distance and bearing.
Relief Well	This refers to the well drilled to intercept the target well for the purpose of restoring well control.

Remnant Magnetism	This refers to the residual magnetization of steel components after degaussing.
Reverse Survey	Adjustment of the survey of the target well so that it is consistent with the range and bearing of the latest ranging measurement.
Rotating Magnets	Radially-oriented permanent magnets located in a sub that rotates with the BHA.
Rotation Shots	This is the acquisition of at least 4 magnetic surveys in at least 3 different quadrants at the same measured depth (+/-1 m). It is often employed to ensure that a MWD tool does not have tool face-dependent errors.
Safe Separation	The minimum distance at which you would want to pass or parallel a well without the risk of intercepting it. The distance varies based on the acceptable consequential risk of intercept, the relative positional uncertainty of the associated wells and the capabilities of the technologies and techniques used to ensure a safe separation is possible.
SAGD	A thermal production method for heavy oil that twins a high-angle injection well with a nearby production well drilled along a parallel trajectory. The pair of high-angle wells is drilled with a vertical separation of about 5 m [16 ft.]. Steam is injected into the reservoir through the upper (injector) well. As the steam rises and expands, it heats up the heavy oil, reducing its viscosity. Gravity forces the oil to drain into the lower well where it is produced.
Sail Angle	A wellbore trajectory segment where the inclination angle is held constant.
Sensor	Mechanical or electronic devices for measuring various properties in the well such as: temperature, pressure and wellbore direction. There are a huge number of measurements made by sensors some are permanent in a wellbore and some temporary.
Simple Intercept	A two dimensional J-shape well, designed to intercept the blow out well at a specific depth and does not require a pass-by to locate the blow out well. Also see Direct Intercept.
Simultaneous Operations (SIMOPS)	Simultaneous execution of two or more operations conducted under common operational control in which the activities of any one operation may impact the safety and success of the other(s).
Single Wire Guidance	Active ranging technique in which current is transmitted across a wire in the target well for the purpose of inducing a magnetic field measurable from the well being drilled.
Surface Location	This refers to the point at which a well originates. This may be a wellhead on a platform, on a land pad or a wellhead positioned on the sea floor.
Surface Location Uncertainty	The error associated with the measured surface location relative to the reference point. This is dependent on the techniques used to position the wellhead such as GPS. (Check Anti-Collision)

	documents for parallel definition.) Reference SPE 67616 for more details.
Target Well	This is the well which you want to range too, for either interception or twinning.
Track Phase	The phase of drilling after the homing point and prior to intersection.
Triangulation	Taking ranging shots from multiple azimuths during the track phase for the purpose of calibrating the magnetic model. May involve performing a well bypass.
Twining	The act of paralleling an existing cased wellbore while maintaining a specified distance.
Well Avoidance	Observing anti-collision rules for the purpose of maintaining an accepted safe distance between wells.
Well Reference Point	A point on the ground level or at the mud line which defines the initial starting point of the well. It defines the X-Y surface coordinates of the well which the surveys are tied into. It is a permanent, recoverable, fixed point in the well.
Wellbore Geometry	The geometrical description of the wellbore in 3 dimensional space as defined by a measure of inclination with respect to the vertical plane and a measure of azimuth (direction) with respect to a specific north reference. Wellbore geometry at each survey point is used to interpolate the wellbore trajectory using minimum curvature.
Worst Case Discharge (WCD)	The maximum flow rate of produced fluid during an uncontrolled wellbore flow event—that is, the average daily flow rate on the day that the highest rate occurs, under worst-case conditions (a blowout). It is a single value for the expected flow rate calculated under worst-case wellbore conditions using known or expected formation properties. In assessing WCD, “worst case” pertains to the loss of pressure containment in the well with a wellbore configuration terminating at surface; and no equipment present in the well (BHA, drill string, testing assembly, wireline etc.). Formation properties if unknown should be selected as best technical estimates for the WCD calculation.

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## Submissions for Assessment

The authors of this publication are fully aware the nature of the subject matter covered herein will develop over time as new techniques are arise or current practices and technologies are updated. It is, therefore, the intension of the author to regularly revise this eBook to reflect these changes and keep this publication current and as complete as possible.

Anyone who has expertise, techniques or updates they wish to submit to the author for assessment for inclusion in the next revision should email the data in the first instance to:

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