University of the Highlands and Islands
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ISCWSA

# ISCWSA: WELL INTERCEPT SUB-COMMITTEE EBOOK

Wellbore Ranging Technologies, Intercept Applications and Best Practices

VERSION 11.02.28

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## Revisions

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 intension 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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All comments on this publication, submissions or amendments should be directed 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.

I would like to take this opportunity to recognize Benny Poedjono, Schlumberger and Pete Schiermeier, Halliburton for their hard work and dedication to help with the updates to the ISCWSA Well Intercept Sub-Committee eBook. The 1st version of this eBook was well received and there were over 15,000 downloads. Some users did provide feedback and wanted additional explanation and better graphics, so we did just that. Our hope is that this guide continues to evolve with feedback and learnings from the industry.

Roger B. Goobie

ISCWSA

Chairman Well Intercept Sub-Committee

2015 - 2019

# Well Intercept Sub-Committee eBook

Complied and co-written by

Members of the ISCWSA

Well Intercept Sub-Committee

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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 (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 (SAGD) Drilling, 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 previously 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. An emergent Resistivity Ranging technology is covered briefly. 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 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 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 into 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 from 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 of 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 side-tracks 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 greater 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 Plug and Abandon (P&A) of the target well.

From 1934 to 1990, almost all 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 Measurements While Drilling (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 common practice for detecting offset wellbores, although, recent technological advances have increased interest to acoustic ranging, 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 earth's and target pipe magnetic field. The induced field is analysed 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 into 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 the direction that the sound is propagated, the distance and accurate 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 depend upon injecting current into the formation to magnetize (light up) the offset well can only occur at relatively 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 Resistivity Ranging Technique

Due to the complexity of some ranging objectives additional ranging techniques beyond existing acoustic and magnetic may be needed. Active resistivity ranging is an emerging ranging technology whereby conductive objects such as a cased wellbore can be located using deep directional LWD resistivity tools. Resistivity ranging uses directional second order propagation measurements from deep directional resistivity tools to detect and estimate the position and direction of conductive objects. Ranging applications include well intervention, relief well drilling, wellbore avoidance, and SAGD casing tracking. Since the measurements are made using a tool already in the drilling BHA, additional AMR or AAR could possibly be completed with fewer wireline runs, thereby improving ranging confidence and time to drill for interception.

## 1.5 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. Improved wellbore survey accuracy is the key to timely well intercepts/paralleling.

Ranging technology 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, thus 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 several applications for ranging technology, with 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. Ranging technologies need to be considered and understood during the initial planning stages when relief well contingencies are included in license applications.

## 1.6 Wellbore Intercept Applications

### 1.6.1 Relief Wells

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

### 1.6.2 Intervention Wells

Intervention wells are drilled to perform some type of remedial operation, such as a P&A or a re-entry into a wellbore. These wells are similar to relief wells 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 or counties. 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 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 past 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 depicts some typical relief and well intervention and intersection designs which have been utilized in the industry.

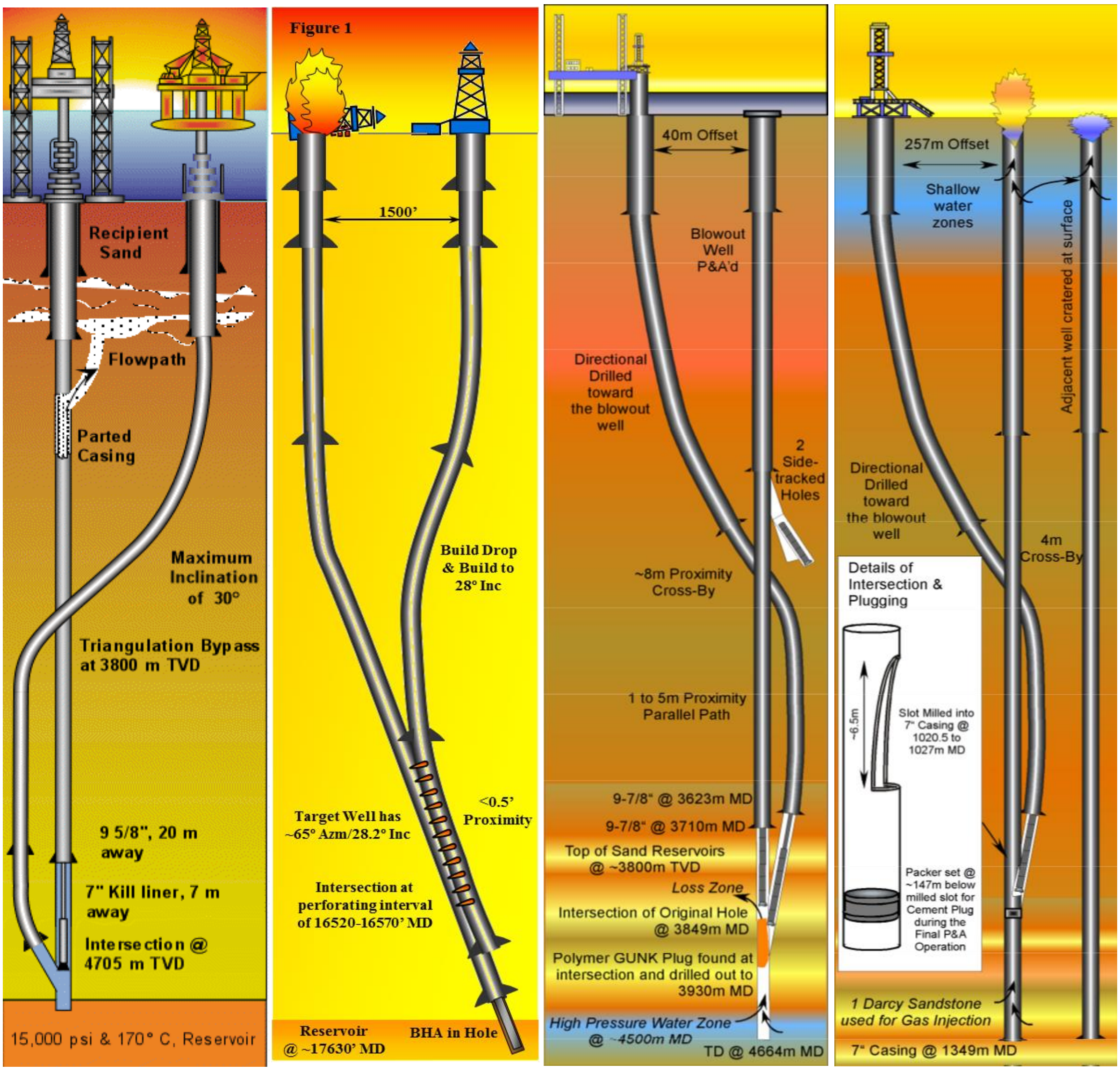


**Figure 1—Relief and well intervention and intersection**

### 1.6.3 U-Tube Wells

The first feasibility study for connecting two wells together end to end was developed in 2000. 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).

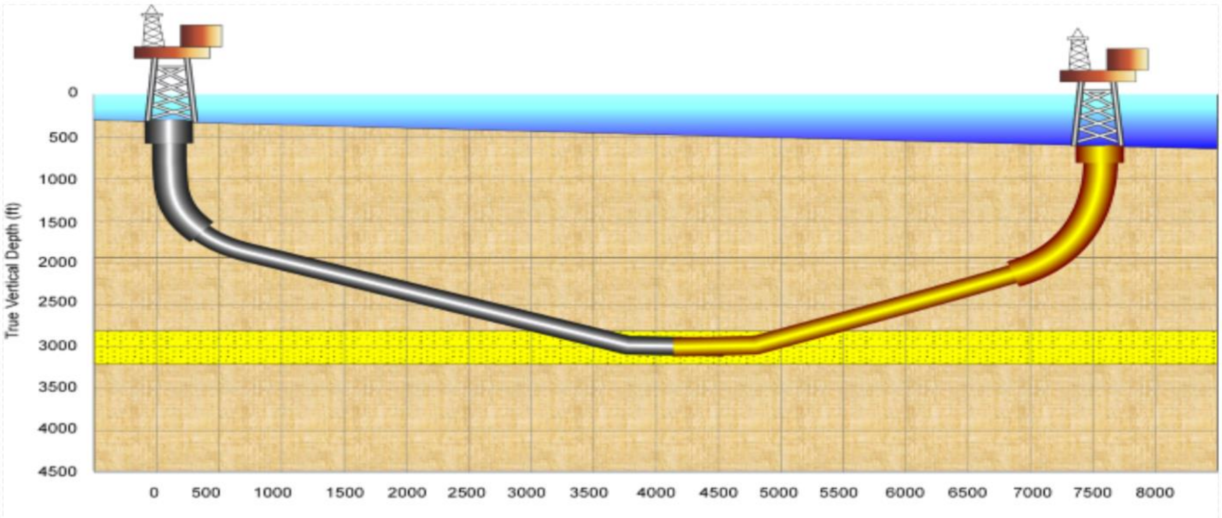


Figure 2—Example of a u-tube well connected end-to-end to convey a pipeline

### 1.6.4 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).

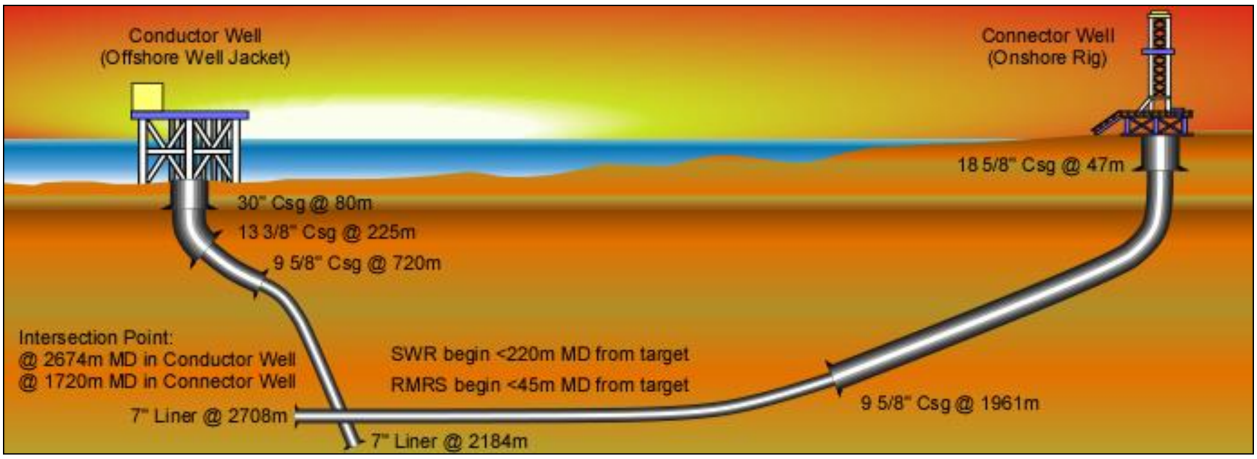


Figure 3—Conductor connector well drilled in 2007, Single Wire Ranging (SWR), Rotating Magnet Ranging System (RMRS)

### 1.6.5 Steam Assisted Gravity Drainage wells

Well twinning, where a producer and a steam injector are drilled in close proximity, and normally parallel 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.

### 1.6.6 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.

### 1.6.7 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.

### 1.6.8 Horizontal Directional Drilling (HDD)

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

### 1.6.9 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 to around 50m, depending on the current loop used.

# 2. Passive Magnetic Ranging (PMR)

## 2.1 Introduction to PMR

The PMR method uses surface 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 it is technically incorrect. This assertion is supported by SPE 17255, which elaborates on this topic by comparing various magnetic models for casing. 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 neighbouring 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 vicinity 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. 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.

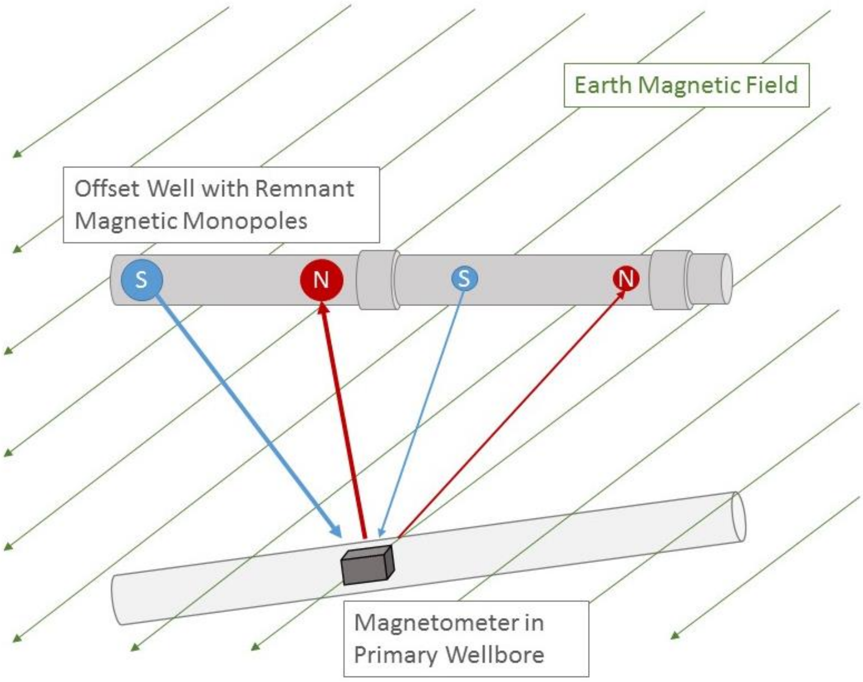


**Figure 4—Superimposition of magnetic fields emanating from multiple magnetic monopoles on top of the magnetic field of the Earth**

## 2.1 When to 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 normally can be an economical ranging option as it utilizes the existing MWD Hardware found within a typical drilling BHA. However, each situation is unique and needs to be evaluated to assure the risk is understood and the technology is fit for purpose.

## 2.4 Insensitivity to Formation and Hole Conditions

PMR does not depend on formation, such as salt. Instead it relies on the remnant magnetic field of steel equipment or casing in a target well whereas active magnetic ranging injects current into the formation and is dependent on formation conductivity. 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 undertaken.

EM-MWD increases the transmission rate of the data from downhole to surface by decreasing the acquisition time, while possibly increasing the data density for analysis. Higher density data along the string increases confidence in the results.

## 2.5 High Inclination and Incidence Angles

High incidence angles can limit PMR if native MWD is used due to the distance between the sensor and the bit when combined with the limited range. PMR can be used at all hole inclinations including horizontal. High incidence angles between the drilling and offset well can affect PMR.

## 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. Published 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 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 magnetic dipoles out.
- Detection is not typically dependent on the survey instrument as any 6 axis MWD/wireline tool can provide readings that can be utilized for PMR. – Detection range is a function of the sensitivity of the sensors and their calibration residuals due to the variation in the measured field as a function of change in attitude.
- 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 ± 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 ± 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. Inaccuracy in 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 magnetic pole strength as an input. However, the estimation of distance is heavily dependent on the modelling of the magnetic poles (with more or less complex functions and distribution of magnetic poles). It is this sensitivity on the modelling 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.), as described in the next section.

### 2.6.4 Magnetized Casing to Improve PMR

Casing can be intentionally magnetized prior to placing downhole with the purpose of increasing the range and accuracy of planned (well twinning or SAGD for example) or unplanned (relief well) future PMR work. When steel is made the magnetic domains generally cancel each other out giving no external magnetism. If the steel is exposed to a strong external magnetic field the domains in alignment to the externally applied magnetic field grow while others shrink. The change remains after the external field is removed, making the steel itself an external magnetic source (Fig 5). Casing can be magnetized offsite or on site just prior to running in hole with a variety of patented methods.

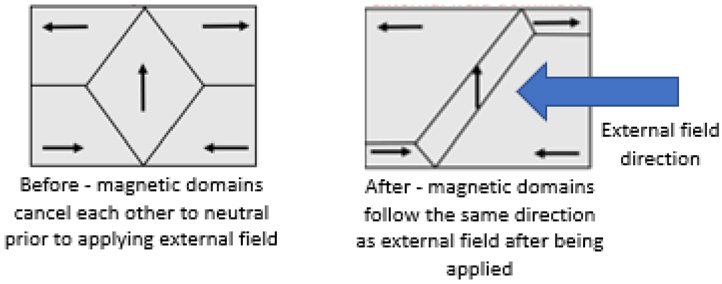


Figure 5—The left shows virgin steel with no magnetic field. The right shows the same steel after being exposed to an external magnetic field with the magnetic domains aligned to the external field growing creating a magnetic field in the metal

There is often residual magnetization at the threads as part of the magnetic particle inspection process. This residual magnetism left in the casing tends to be at the joint ends with not much magnetism in the middle of the casing joint (Fig 6). Purposeful casing magnetization creates known field strength and patterns along the casing string, called a "designer magnetic pattern". An example of a designer magnetic pattern is shown in Figure 7 with a series of opposing magnetic poles (i.e. NN, SS, NN, SS, etc.) which throw the magnetic flux out perpendicular from the casing axis. This known pattern eases the challenge of PMR in separating out the offset well from the background field and then determining its relative distance and direction. Designer magnetic patterns increase the maximum range and the distance to target accuracy as compared to non-designer patterns.

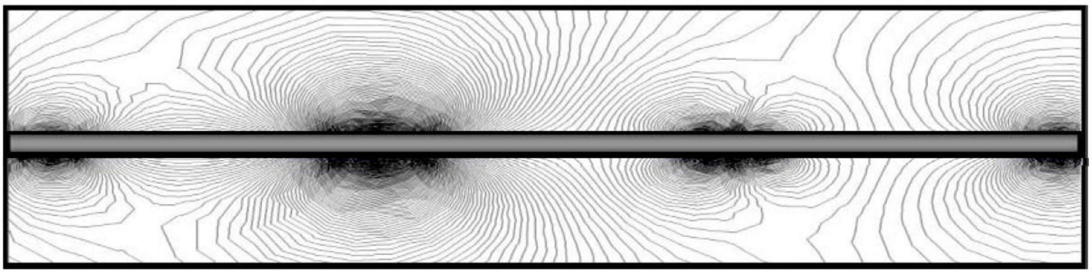

Figure 6—Example of residual casing magnetism from magnetic particle inspection showing erratic amplification and dampening of the magnetic signature along the casing string.

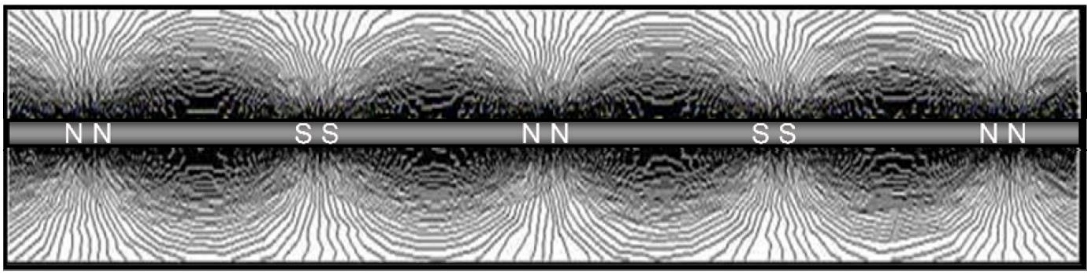


Figure 7—Magnetically saturated casing with a designer pattern.

## 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 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. For 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 60,000 nT. Therefore, considerations should be given to ensure the MWD can sustain the expected level of magnetization without saturation in certain specific cases.

Some PMR techniques require knowledge of the Earth magnetic field 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 Interpolated in-Field Referencing (IIFR/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. Notwithstanding, IIFR/IFR2 is not necessary but local magnetic diurnal variation monitoring is. Absolute measurement is not essential; compensation of variation is a simpler option. There is a requirement for vector as well as total field monitoring in order to back out the change in the magnetic vector (which is what PMR measures).

### 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 the 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, however this rather reduces the advantage of using inherent MWD sensors and may sway the economic/precision balance towards AMR.

### 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. 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 to range to an offset well while using PMR when another offset well is 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 (AMR)

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 measured and analysed to define a proximity vector between the two wellbores. Magnetic fields are generated by several methods, passing a current through wire or pipe, passing current through a coil of wire, or permanent magnets, as shown in Figure 8.

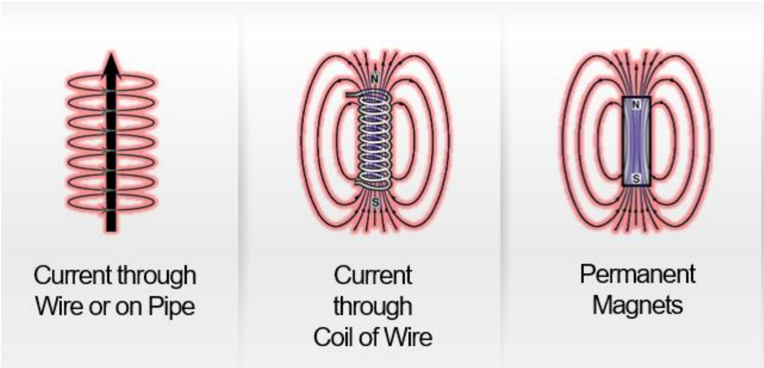


Figure 8—Different ways to create a magnetic field. The two shown on the right are considered point sources.

The AMR technology is separated into two categories based on accessibility of the target well, Access-Dependent and Access-Independent:

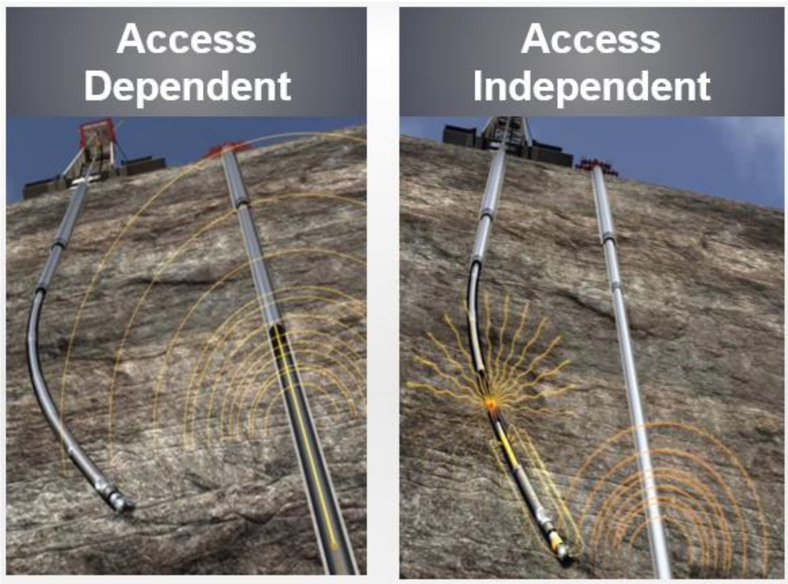


Figure 9—Access independent does not require access to the existing target wellbore

- **Access-Dependent Active Magnetic Ranging (AD-AMR)** - Access-dependent active magnetic ranging services are used when it is possible to position a magnetic source in one of the wells under examination. Such techniques 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 Drainage (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 (AI-AMR)** - When there is no access to the existing target 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 (AD-AMR)

### 3.1.1 Magnetic Solenoid Systems

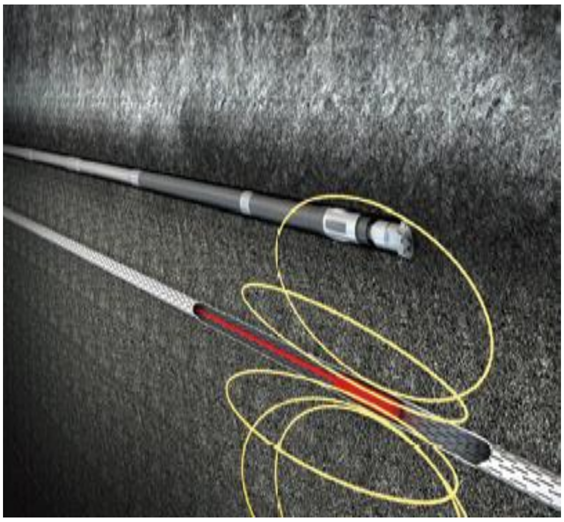

**Figure 10—Typical magnetic solenoid AMR system diagram. The magnetic field generating wireline carried solenoid is displayed in red, which is placed in the target well**

The system consists of a solenoid, approximately 5m (16 ft.) in length, which is placed in the target well on mono conductor wireline at a specific depth relative to the current bottom hole depth in the drilling well. A 6-axis MWD Directional Probe is placed in the drilling BHA. A single large magnetic field is generated by the solenoid via 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 generated magnetic field is then measured by the 6-axis MWD Directional Probe and analysed to determine a distance and direction to the solenoid in the target well.

The AMR engineers are in communication with the Wireline engineers moving the Magnetic Solenoid to new depths in the target well as drilling progresses. When the radial separation between the target well is 15 – 23m (50 – 75 ft.) the accuracy of the Magnetic Solenoid AMR system is within ± 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 ± 2 – 4% of the radial distance.

> **Note:** There are commercially proven solenoid systems that offer the following:
>
> When the target well is 20 – 30m (65 – 100 ft.) accuracy is between ± 1.5 - 5% (2 sigma) in the radial direction. When between 4.5 – 20m (15 – 65 ft.) accuracy is between ± 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

#### *3.1.1.1 Typical Magnetic Solenoid System Protocol*

- Follow normal drilling practices until a regular survey depth is reached
- Confirm Magnetic Solenoid is at desired depth with Wireline Engineer in the target well
- Has 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 target 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 target well
- Repeat steps 2 – 9 until well is completed or AMR is no longer needed

### 3.1.2 Rotating Magnet System

**Figure 11—Typical rotating magnet AMR system diagram showing the rotating magnet sub near the bit and the wireline conveyed directional sensor in the target well.**

The system consists of a Rotating Magnet Sub (RMRS), 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. The magnetic field is monitored by a 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; it 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 wellbores to an accuracy of approximately ± 5% of the wellbore separation. This equates to wellbore position accuracy of less than a foot from the target 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.

#### *3.1.2.1 Rotating Magnet 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)

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

- The 6 axis Directional Sensor Probe (Conveyed via Wireline in target well)
- A bottom weight bar
- The tool foot

- Optional above tool weight bar with feed-through wire
- Rotating Magnet Sub (Drilling Well)

The tool and weight or extension bars are 1.75 inch O.D for 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.

#### *3.1.2.3 Typical Rotating Magnet Operation Protocol*

1. Follow normal drilling practices until approximately 90m (300 ft.) from the pass by of the Offset Well
2. While drilling and approaching the 90m (300 ft.) distance, data monitoring begins. 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.
3. Steps involved with taking a Recorded Rotary Magnet AMR Shot:
    a. At any new hole depth, a bottom hole survey will be taken.
    b. The Directional Driller on tour will make an extrapolation to the bit based off the survey information received and provide that extrapolation to the Ranging Specialist.
    c. Data is typically acquired in 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 ≈ 1.5m/min (5ft/min). It is important that the section is wiped at a consistent speed in rotary 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.
    d. 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.
    e. At this time the Ranging Specialist will process and analyse the recorded Rotating Magnet AMR Data.
4. Depending on the results from any given recorded RMRS determination the Ranging Specialist will determine whether or not more RMRS data is needed to be taken at a given hole depth.
5. Once enough data has been acquired at a given point, the Ranging Specialist will advise the Company Representatives on the status of 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.).
6. Steps 3-5 will be repeated until the objective has been completed.

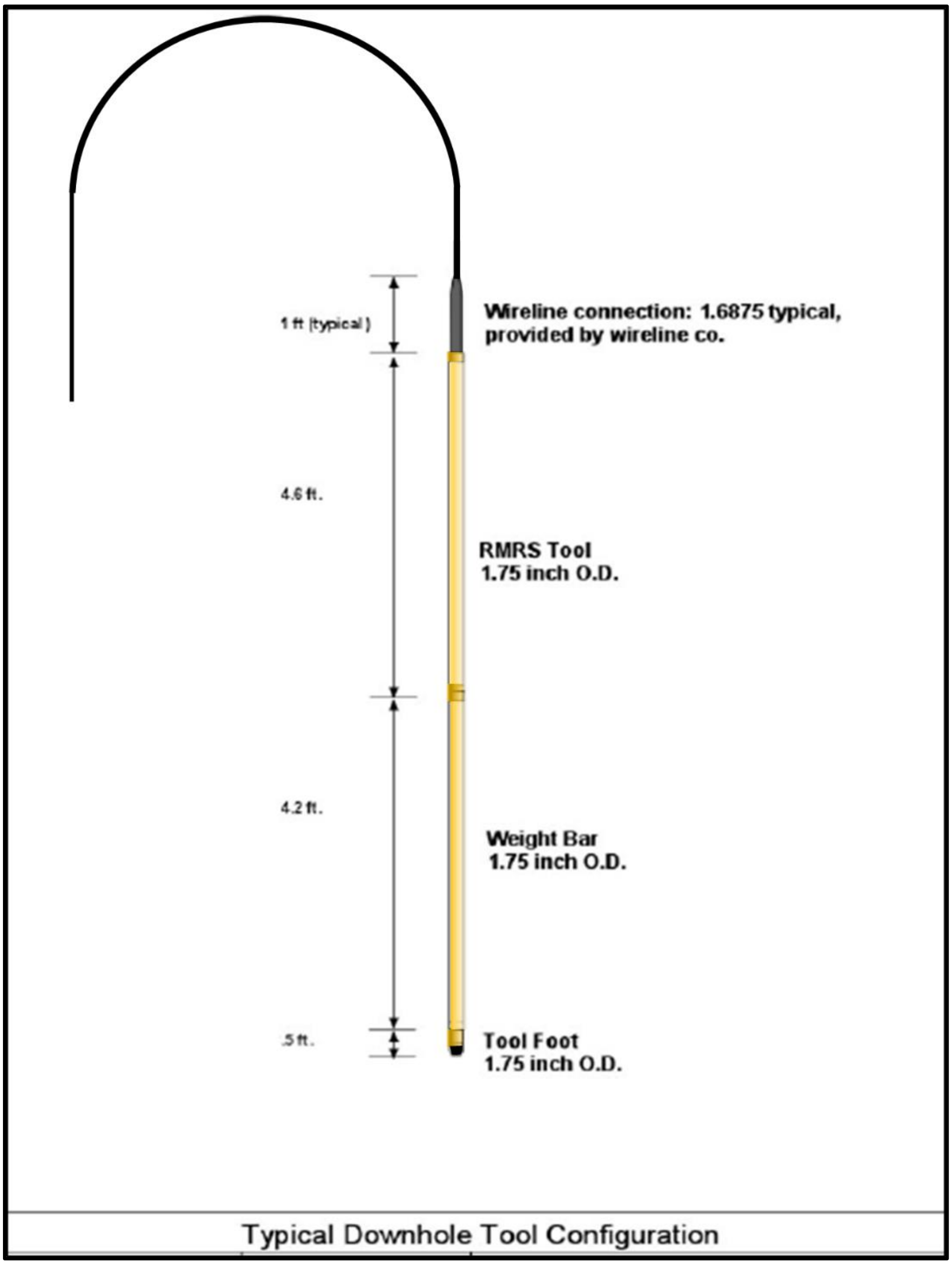


Figure 12—Typical RMRS tool configuration

### 3.1.3 Energized Wire Systems

Figure 13—Energized wire AMR system. Current in the wire in the target wellbore, sensors in the BHA

The energized wire active magnetic ranging system consists of an electric wireline being placed in the target well. A known A/C current is then applied to the wireline. A large magnetic field is generated along the length of the wire by the applied A/C current. Unlike the two AMR methods described above, the magnetic field generated is not a point source. A magnetometer array in the intercept wellbore BHA is used to analyse the created magnetic field in the target well to determine a distance and direction.

### 3.1.4 Surface Access System

The Surface-Access Active Magnetic Ranging system (SA-AMR) is a no target wellbore access active magnetic ranging technology that utilizes surface excitation to determine a ranging distance and direction relative to the drilling wellbore. Other Access Dependent ranging systems require downhole access to the target wellbore for deployment of a magnetic source as described in earlier sections. This SA-AMR technology requires only surface access to the target wellbore equipment, i.e. wellhead or casing, for use as a connection point for excitation. SA-AMR typically has applications in well paralleling or SAGD type wells. An alternating current field is generated by passing a current between the target well and the remote return through ground stakes or other production wells. With sufficient current generated a measurable magnetic field along the target well at depths downhole is created. A downhole sensor (receiver) utilizes an array of magnetometers in the drilling well to analyze the magnetic field to calculate distance and direction to the target well.

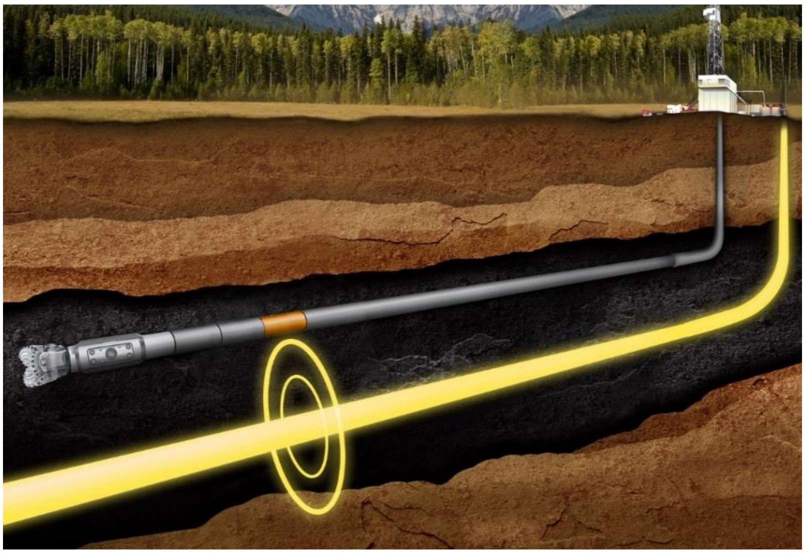

**Figure 14—SA-AMR uses well-head access to induce a magnetic field in the target well (shown in yellow above) which is then utilized by a downhole sensor in the drilling BHA**

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

**Figure 15—AI-AMR system diagram. No target well access. A wireline conveyed AMR tool injects the formation with AC current creating an induced magnetic field in the target well casing.**

AI-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. No access to the target wellbore or well head is required.

### 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 side-track.
- Works equally well on steel and non-magnetic tubulars.
- Detection range not significantly impacted by the target well tubular size.
- 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 dedicated kit and personnel onsite.

### 3.2.3 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:

- The three phases of relief well 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 analysed by the ranging specialist and any infill data will be taken on a 2$^{nd}$ 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.

### 3.2.5 Tool and Wireline Assembly (Bridle)

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

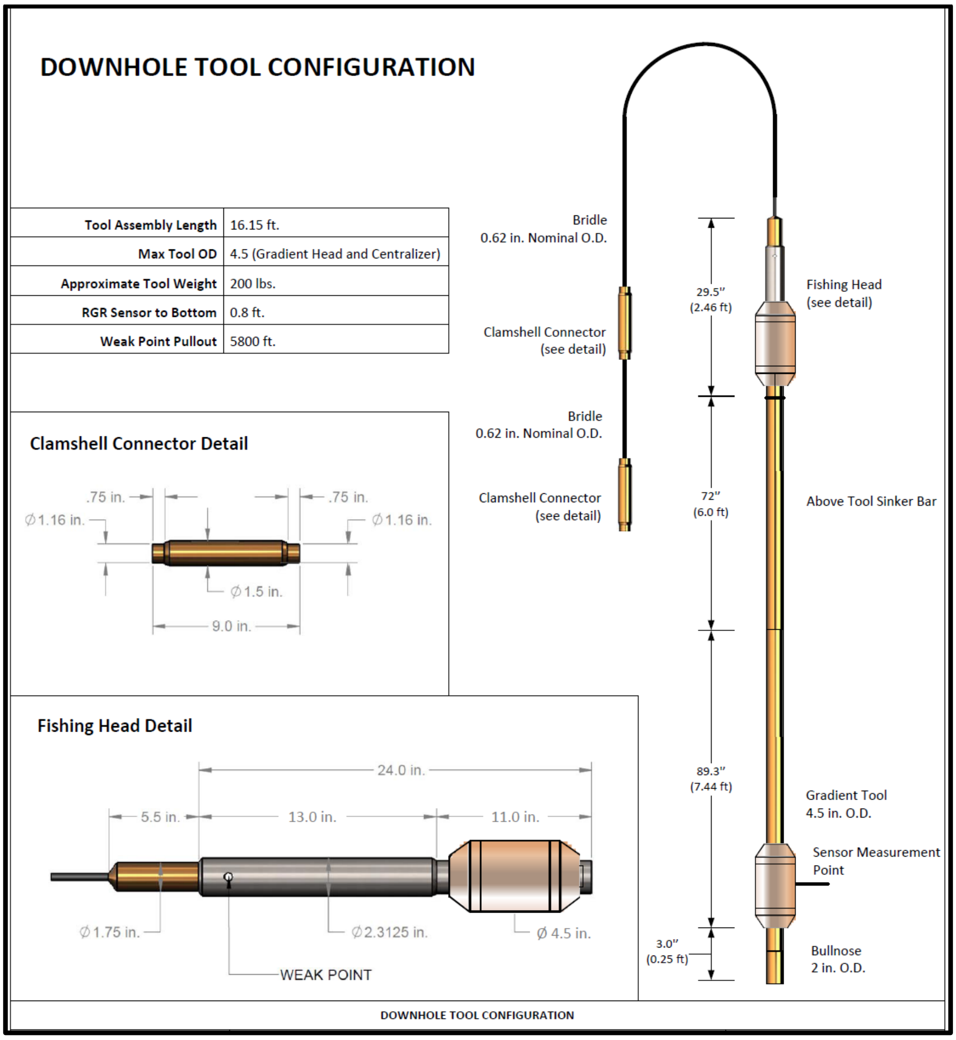


Figure 16—AI-AMR downhole tool configuration

#### *3.2.5.1 AMR Wireline Cable 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.

### 3.2.6 Detection Range

The detection range for the AMR tool is dependent on the following factors: Relief Well (RW) trajectory, size of Target Well (TW) tubulars, 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 modelling software used to determine the detection range are the Signal Intensity (uA\m\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 17 and Figure 18),

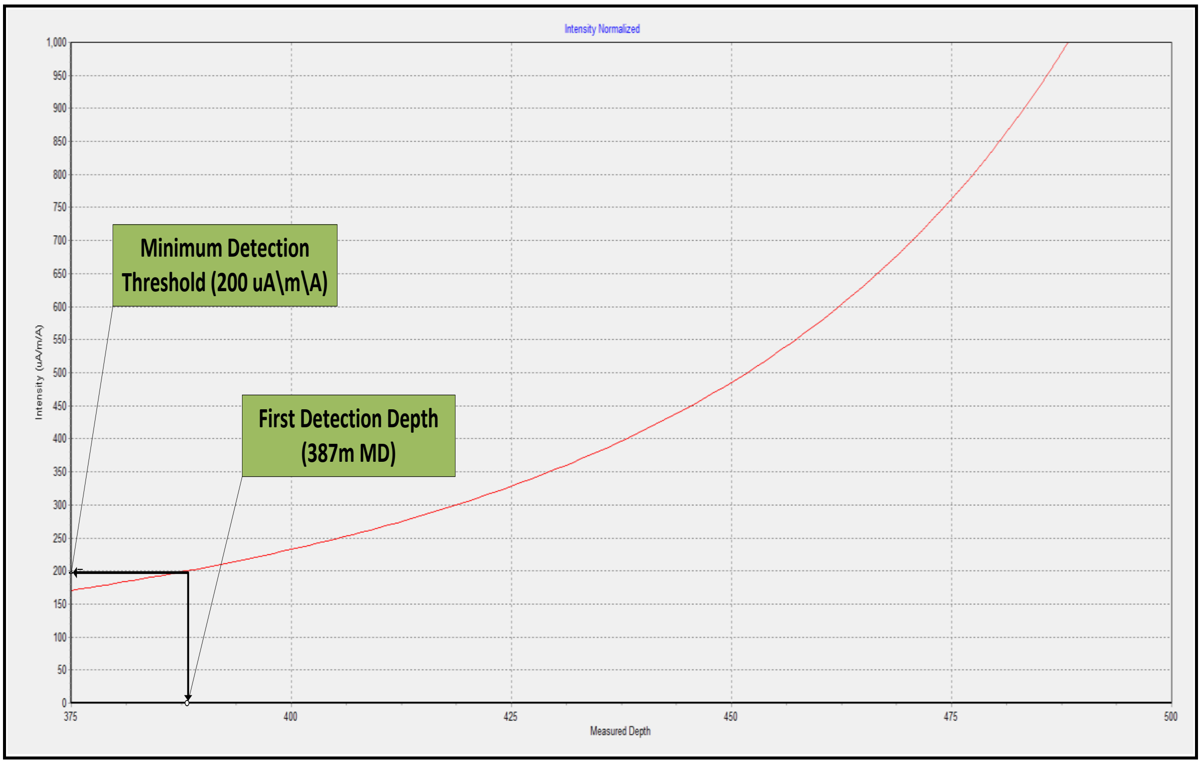


Figure 17—Typical AI-AMR detection threshold

**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 a typical AMR detection threshold plot. This is project specific and needs 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 48uA/m.

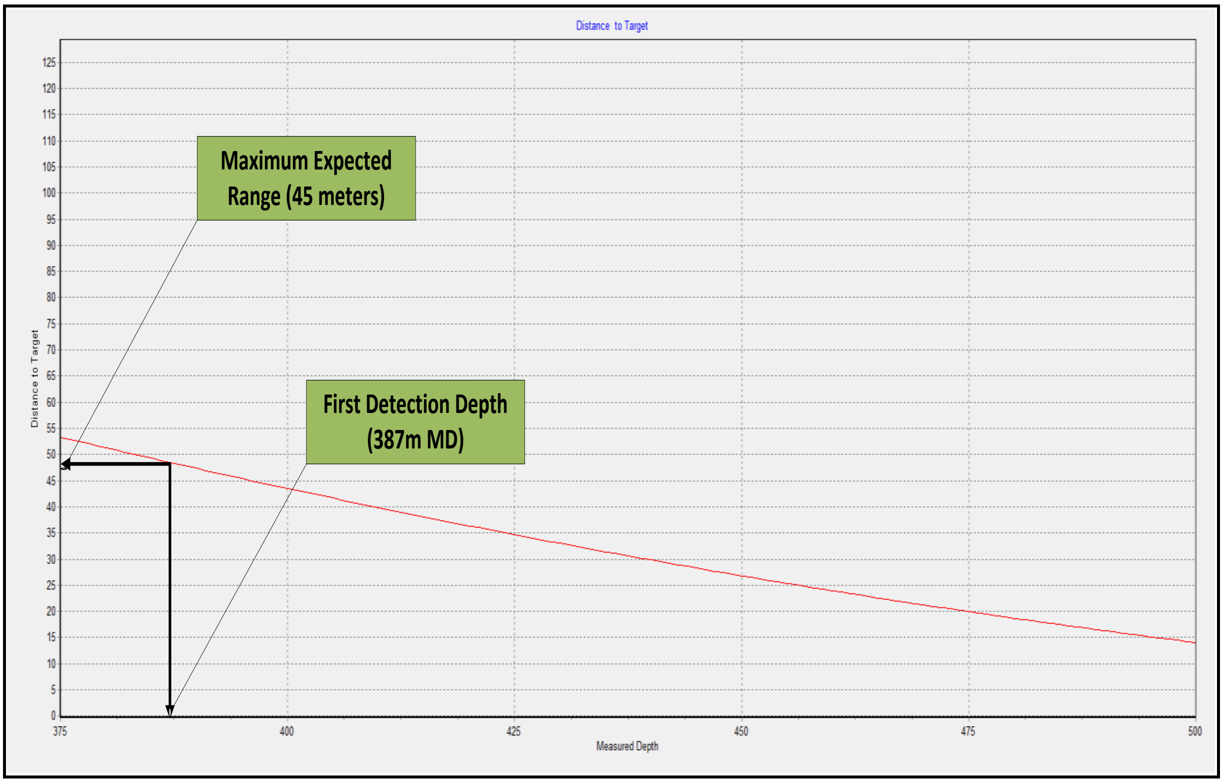


Figure 18—AI-AMR maximum expected range

## 3.4 Crowded Ranging Environment

The ability to distinguish a target well from any offset wells is an ability unique to some AMR tools. Identifying a single well in a crowded field can be accomplished in two ways:

- Surface location selection – pre-planning the relief well so the vertical section direction will place the target well in the same direction as the offset well.
- Vector subtraction – This is the process of identifying the vector component of a ranging signal that is generated by an offset well. This is not available for any PMR service as the direction and distance accuracy are not sufficient and the measurements from both wells must be taken at the same depth. The vector component of an offset well can be determined by:
  - Direct excitation of the offset well– This is the most accurate method as the vector component of the offset well is measured separately. While this method is limited by depth it's likely that any offset well inside detection range will only be inside the detection range in the upper section of the hole.
  - Downhole excitation of both wells – This method requires a survey of the offset well be included in its calculated position. The combined model vector position of each well should match the measured vector when exciting both wells. As this depends on the survey accuracy of both wells the accuracy when both wells are at equal distance from the relief well is reduced. As the relief well is drilled toward the target well the offset well vector component of the overall ranging measurement is reduced until it is made irrelevant in the calculation of the target well location.

## 3.5 Impact of Incidence Angle on Detection

Approaching a target well at a high incidence angle has an impact on the detection for AMR, like PMR. Drilling towards a target well at a high approach angle should only be done when it is necessary. The high incidence angle for an AMR ranging measurement will mean that the excitation source will be farther away from the target well, thus reducing the signal intensity. The reduced signal intensity will require shorter drilling intervals to avoid drilling outside the tool's detection 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 analysed 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. 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 is generated by the drilling bit as shown in Figure 19. The strength of the noise generated is varied by the bit type and the distance from the source. A fixed-cutter bit, which drills with scraping and shearing, will create a weaker signal compare to a Roller-cone bit, which drills by scraping and gouging.

Figure 19—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 higher frequency acoustic noise. When the drill bit approaches an existing well, this noise penetrates the well structure, and may propagate over long distances within the well as shown in Figure 20.

Figure 20—Illustration of drill bit closing in on an existing well

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

Figure 21—Illustration of sensors mounted on conductor of the well

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 analysed. Depending on the analysis and comparison to predicted calculations, steering decisions can be made to avoid a collision or drilling can resume with confidence that a collision has been avoided, as shown in Figure 22.

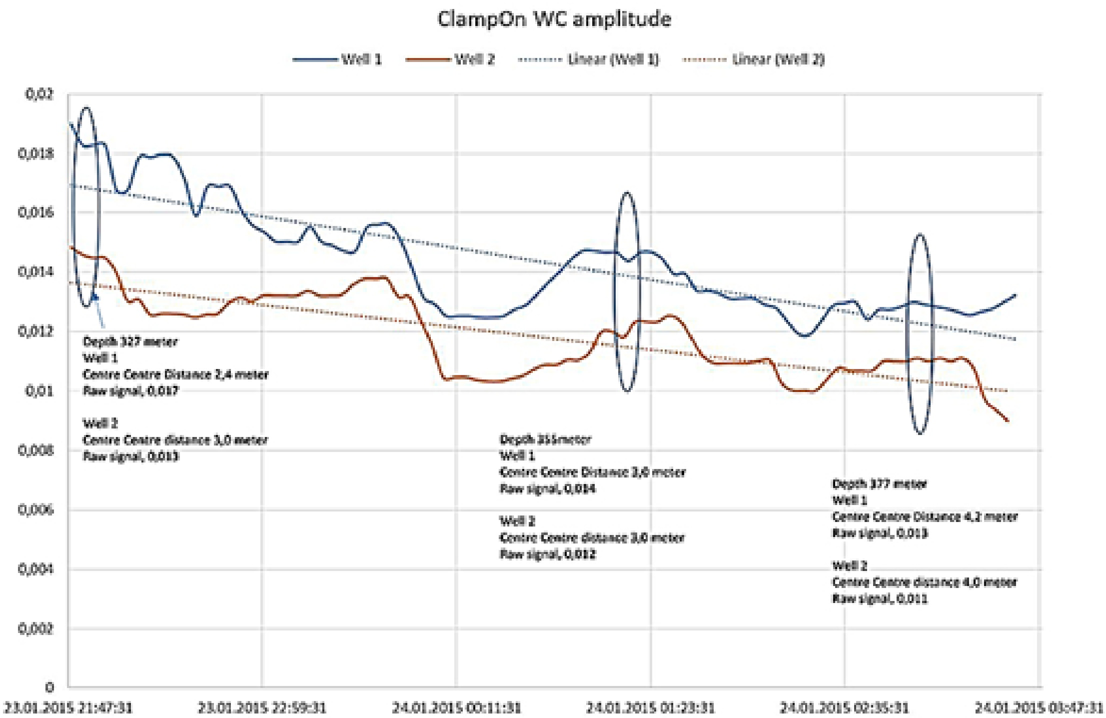


Figure 22—Signal strength recorded at 2 different well conductor locations in collision avoidance situation, increasing centre to centre distance

# 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 acoustic source to initiate signal that travels and reflects as it encounters a contrast in acoustic impedance. Those reflected waveforms are recorded as time events and are later 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. Seismic is an essential process needed by oil companies to make valuable decisions. Both land and offshore use the same principle and slightly different setups to map the layers underneath the surface.

Active Acoustic Ranging (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).

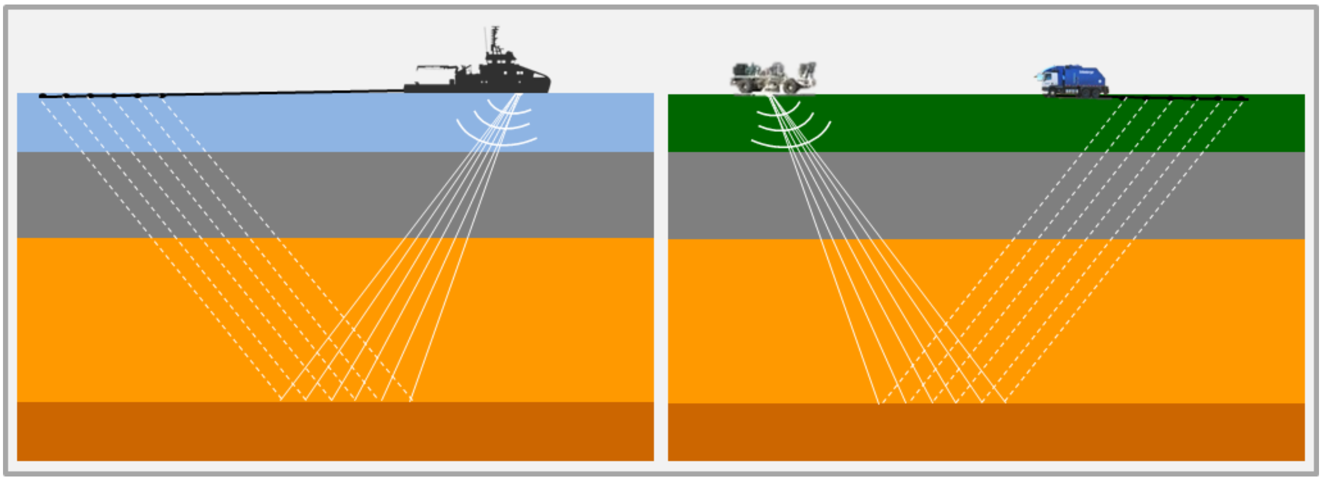

Figure 23—Seismic setup offshore (left) and land (right)

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.

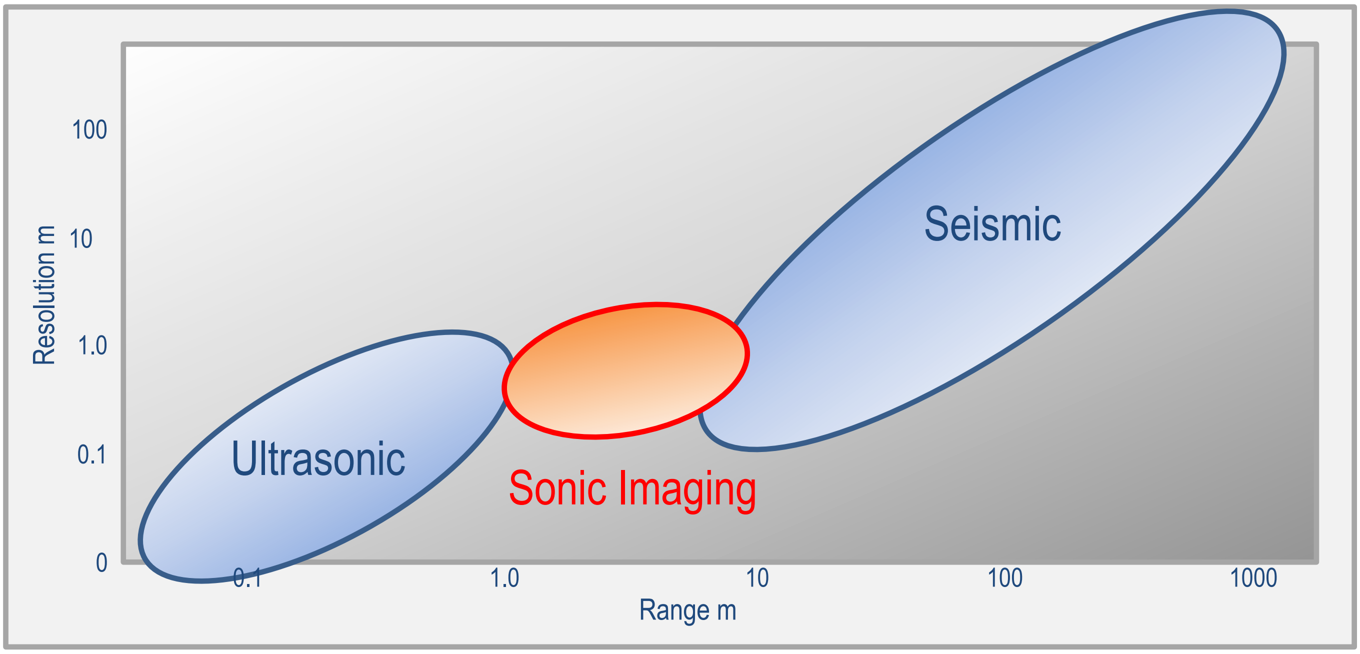


Figure 24—The resolution of sonic imaging range in between ultrasonic and seismic ranges

## 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, **B**orehole **A**coustics **R**eflection **S**urvey (BARS) evolved. Micro resistivity, ultrasonic, and Stoneley methods of fracture and mobility detection are all limited to the area immediately surrounding the borehole. BARS use 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 are to be acquired in a minimum of 8 sectors.
- Recording of tool orientation is to be done at the same time as waveform acquisition to determine the azimuth of waveforms.
- Ensure enough waveforms are recorded to cover the expected target well location.

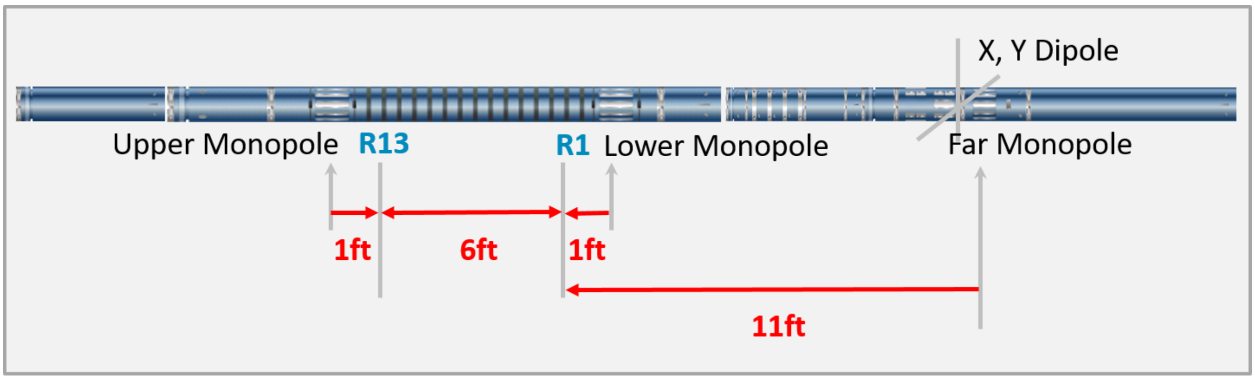


Figure 25—Illustration of the Advanced Sonic Logging (ASL) tool with various transmitters and receivers spacing's; total of 13 receiver stacks with 8 receivers azimuthally arranged for every stack

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 analysed. 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 collision or ensure interception with the target well. Until recently, the only options were active electromagnetic and passive magnetic methods to locate a nearby well. Both methods required the target well be a cased hole, and both perform best when the two wells are parallel. Active acoustic ranging has been successfully deployed to locate both cased hole and open hole in North America and Gulf of Mexico, USA (Poedjono et all, 2017, SPE 187313). In addition, active acoustic ranging can be used in conjunction with other ranging technique, PMR or AMR, to improve the chances of success. Figure 26 displays the geometry of the wave paths to target wellbore and general processing steps to determine the ranging distance, direction and direction uncertainty improvement.

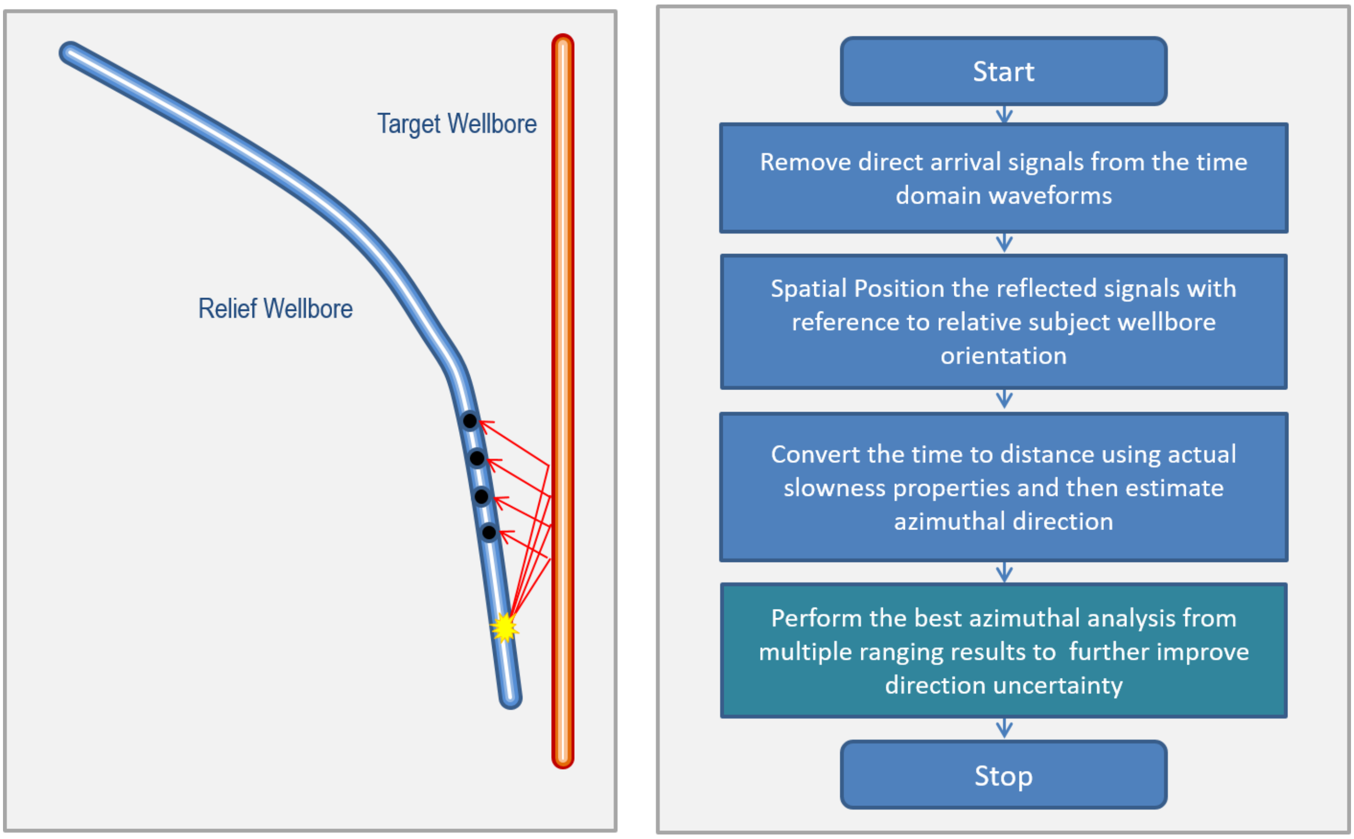


Figure 26—Illustration of AAR to detect target wellbore using acoustic source and receivers (left) and illustration of general processing steps to determine the ranging distance and direction (right)

### 5.2.2 Acoustic Source

There are two common types of sources used to generate the acoustic signal that propagate through the rocks.

***Monopole***

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.

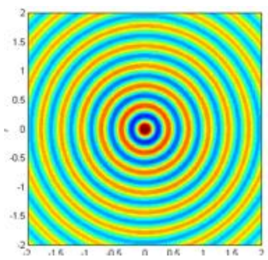

Figure 27—Shows monopole generated acoustic signal pattern

### *Dipoles*

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

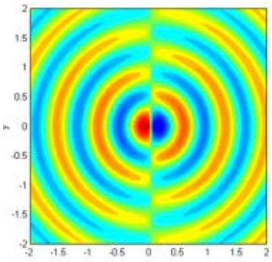

Figure 28—Shows dipole generated acoustic signal pattern

### 5.2.3 Acoustic Propagation

Acoustic 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 29. 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 in Figure 29. 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. Acoustic waveforms produced by logging tools are shown in Figure 30.

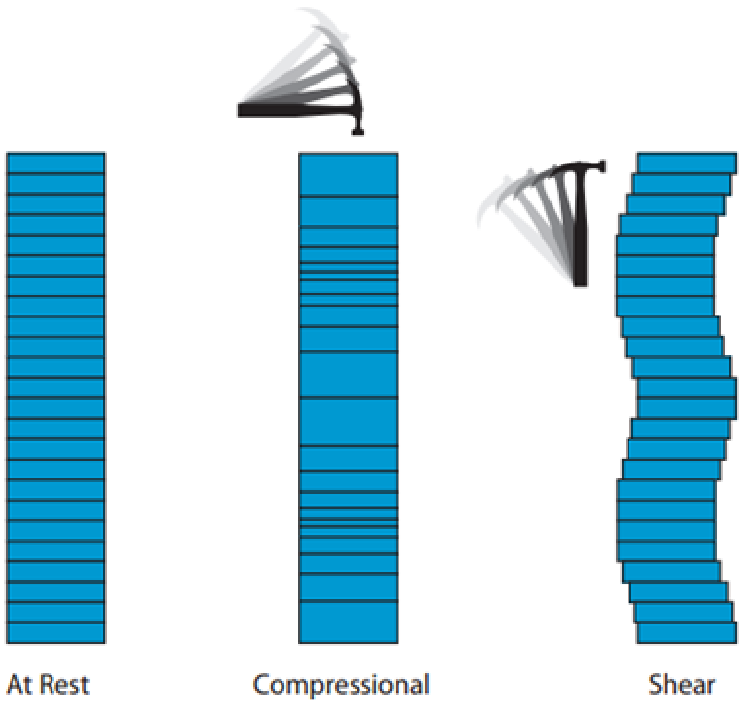


Figure 29—Particle motion in formation at rest versus wave propagation direction, compressional and shear

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 30 and how the waveform is presented as colour scale in Figure 31.

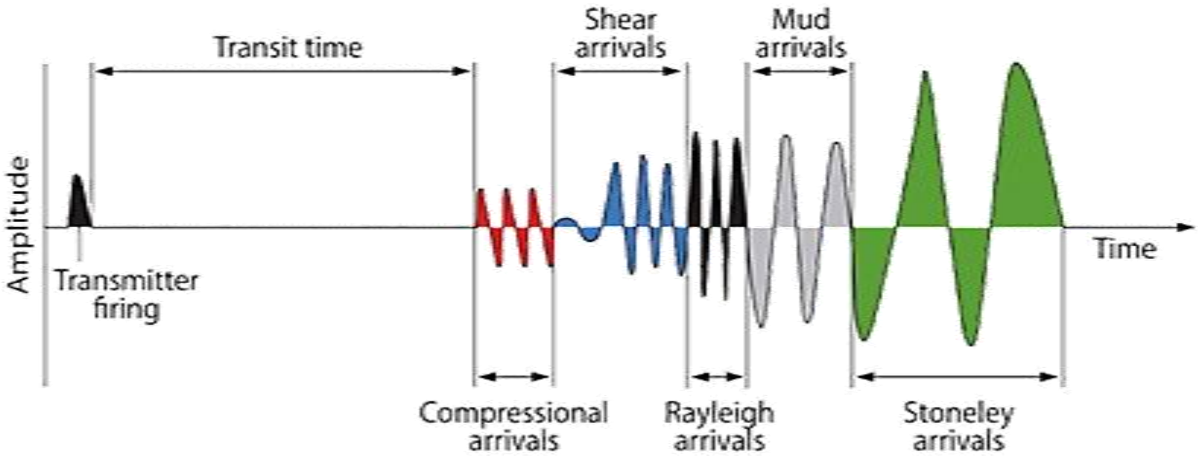


Figure 30—Various waveforms as reflected and refracted in time

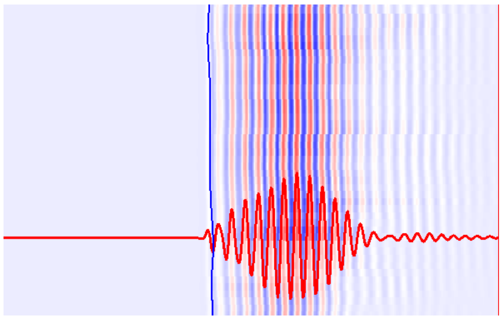

Figure 31—How the waveform is presented with the colour scale as peak in red and trough in blue

## 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 distance. Knowing the slowness of the formation, the speed of sound in the rock, that is acquired during the ranging run it is possible to define the distances. Currently the best ranging detection distance is in fast formations such as salt due to the use of commercial Advanced Sonic Logging, ASL, tool that has limits in recording time. The recording time limits result in shorter ranging distances in slow formations 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 Least Distance, the distance which is normal to the target well rather than normal plane, which is perpendicular to the subject well or travelling cylinder distance as shown in Figure 32.

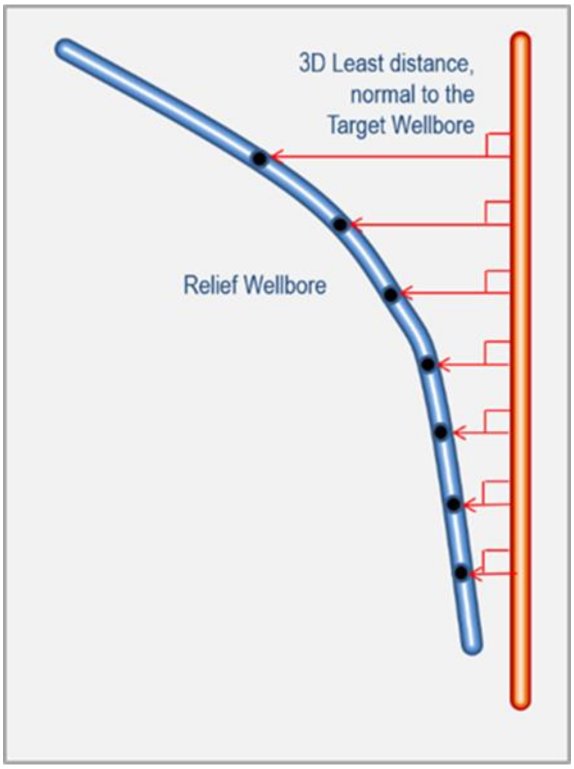


Figure 32—3D least distance illustration

### 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 are positioned 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 Figure 26 and 33.

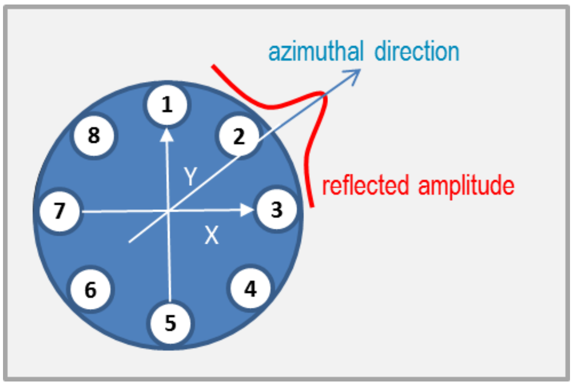


Figure 33—Particular azimuthal receiver locations to detect the direction of reflected signal

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 Figure 34. Ranging direction can be further improved by performing multiple data acquisition passes during the run. The ranging distance can be plotted along with the survey centre-to-centre distance as illustrated in Figure 35.

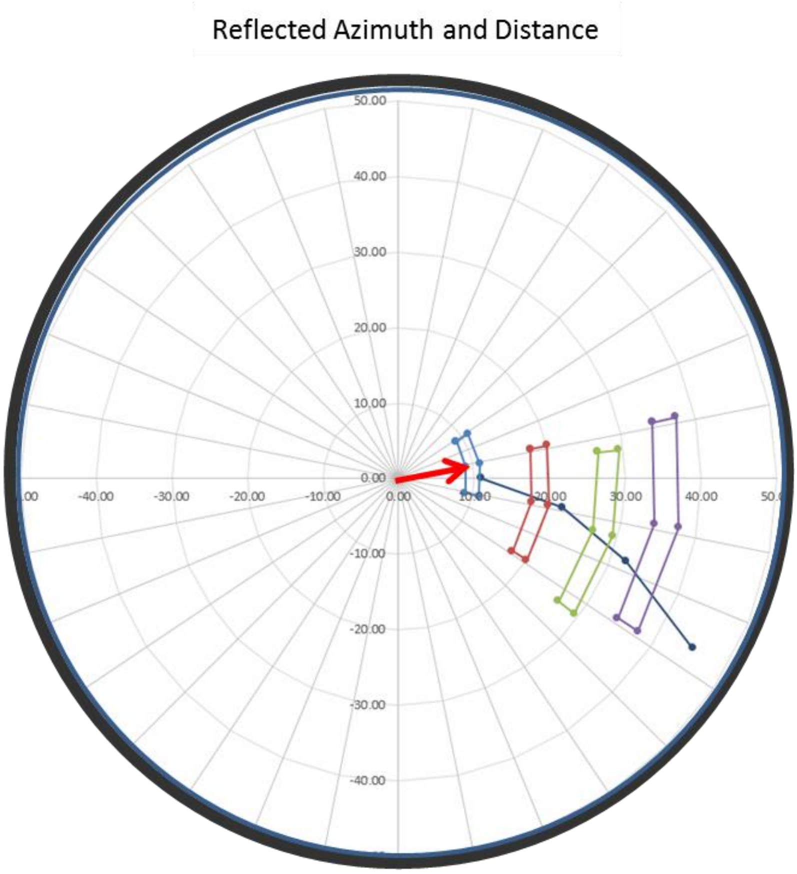


Figure 34—Travelling cylinder where the distance and direction are plotted at each ranging depth

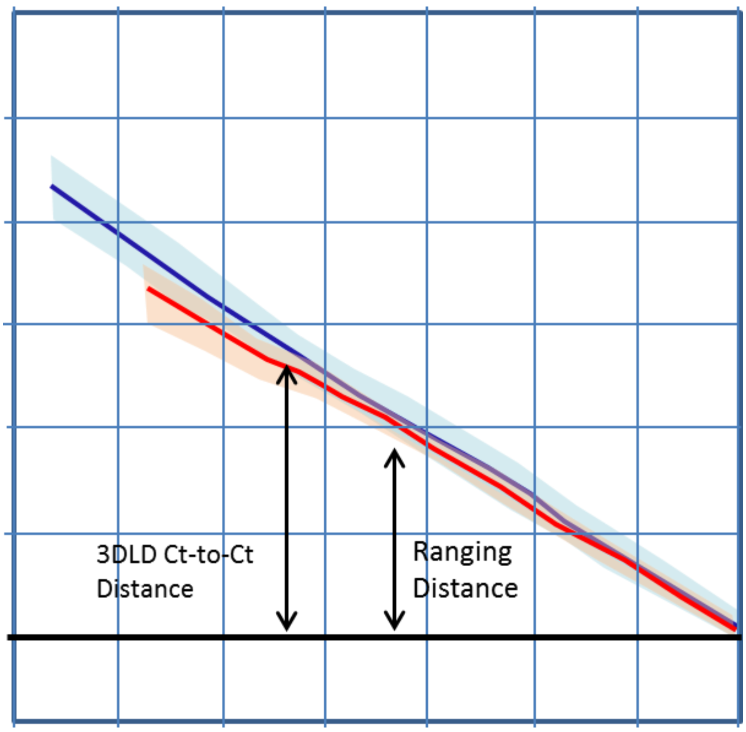


Figure 35—Ct-to-ct distance and ranging distance are plotted against the measured depth

## 5.4 Application

Active acoustic ranging technique is versatile with many ranging applications such as the ability to provide ranging in open or cased hole inside a 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.

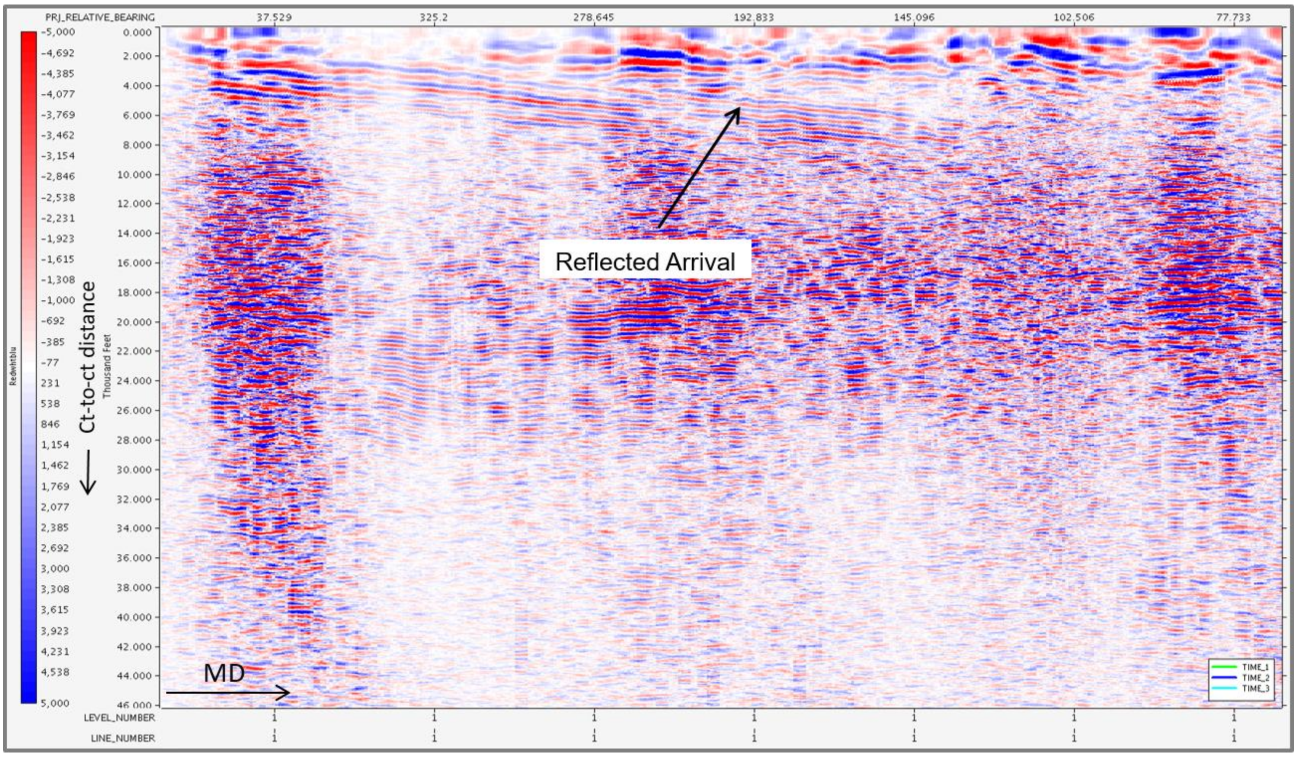


Figure 36—Reflected compressional image arrival from the target wellbore

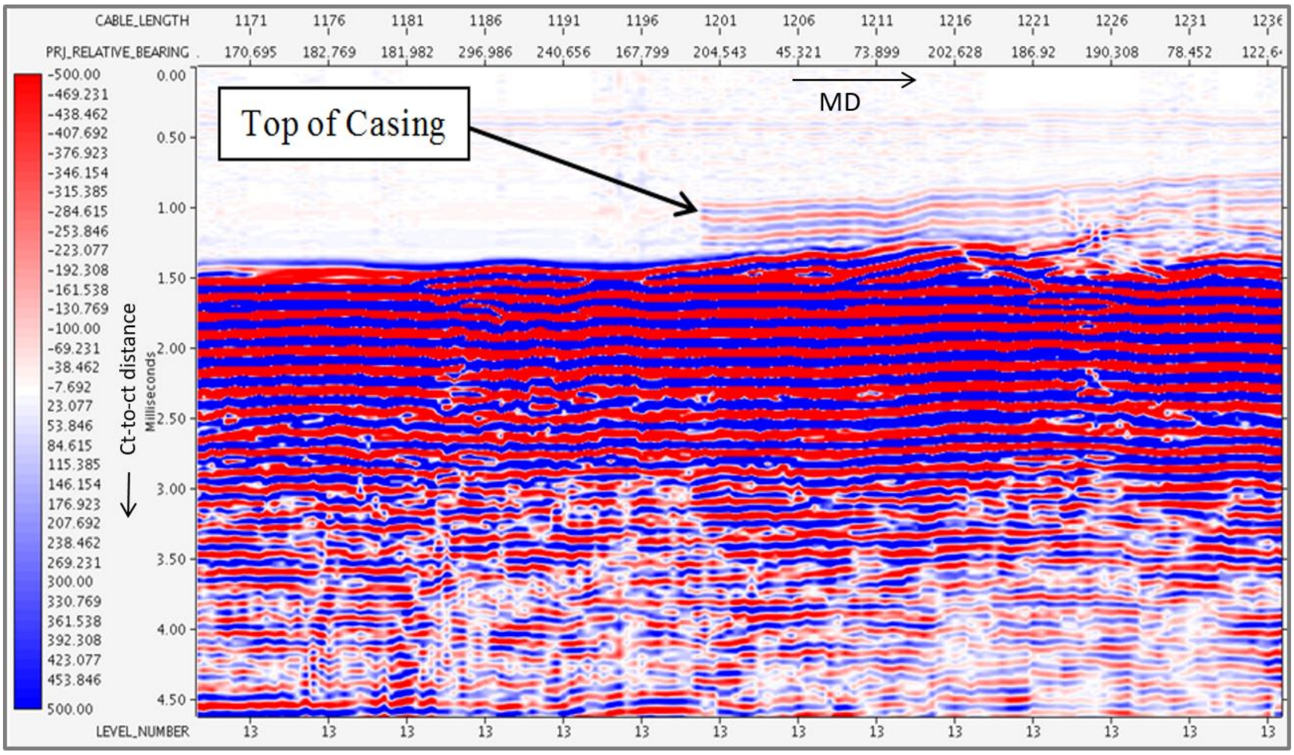


Figure 37—The image shows the reflected compressional arrival from the open hole (top of casing) and cased hole target wellbore

## 5.5 Modelling

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 wells relative trajectory, formation slowness and tool configuration is optimum to detect the nearby target wellbores as shown in Figure 38 and Figure 39.

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 minimum, centre to centre, and maximum distance between wellbores for each scenario.
- Designing tool setup and acquisition parameters to optimize chances for success (If modelling shows it is possible to image the target over the desired range).

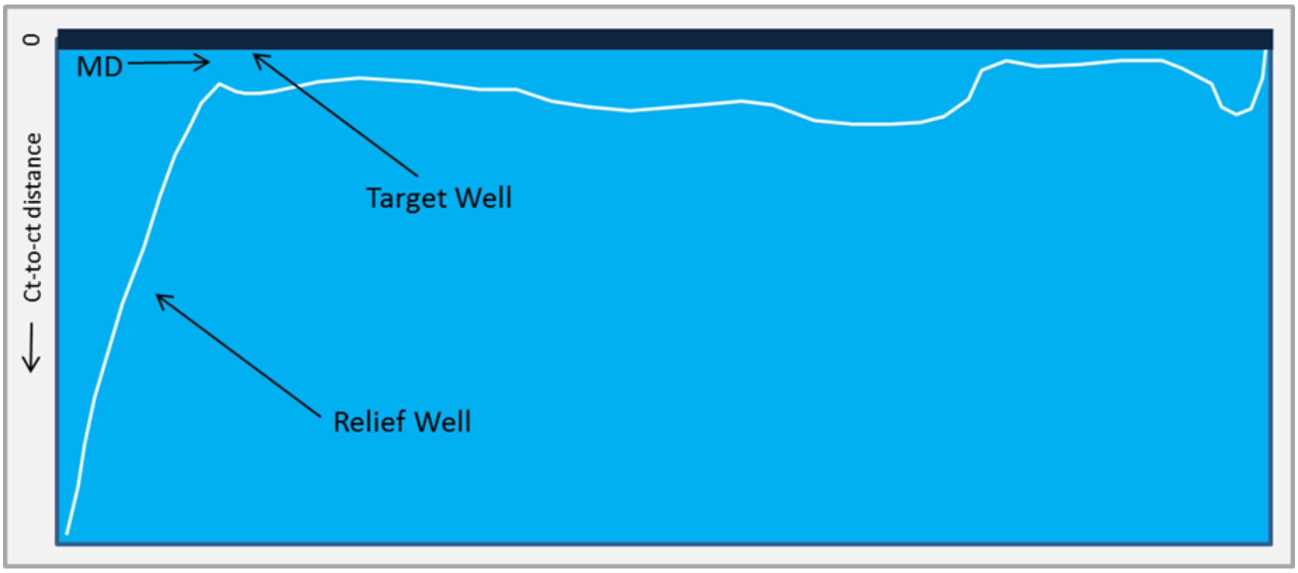


Figure 38—Ct-ct distance between the subject and target wellbore

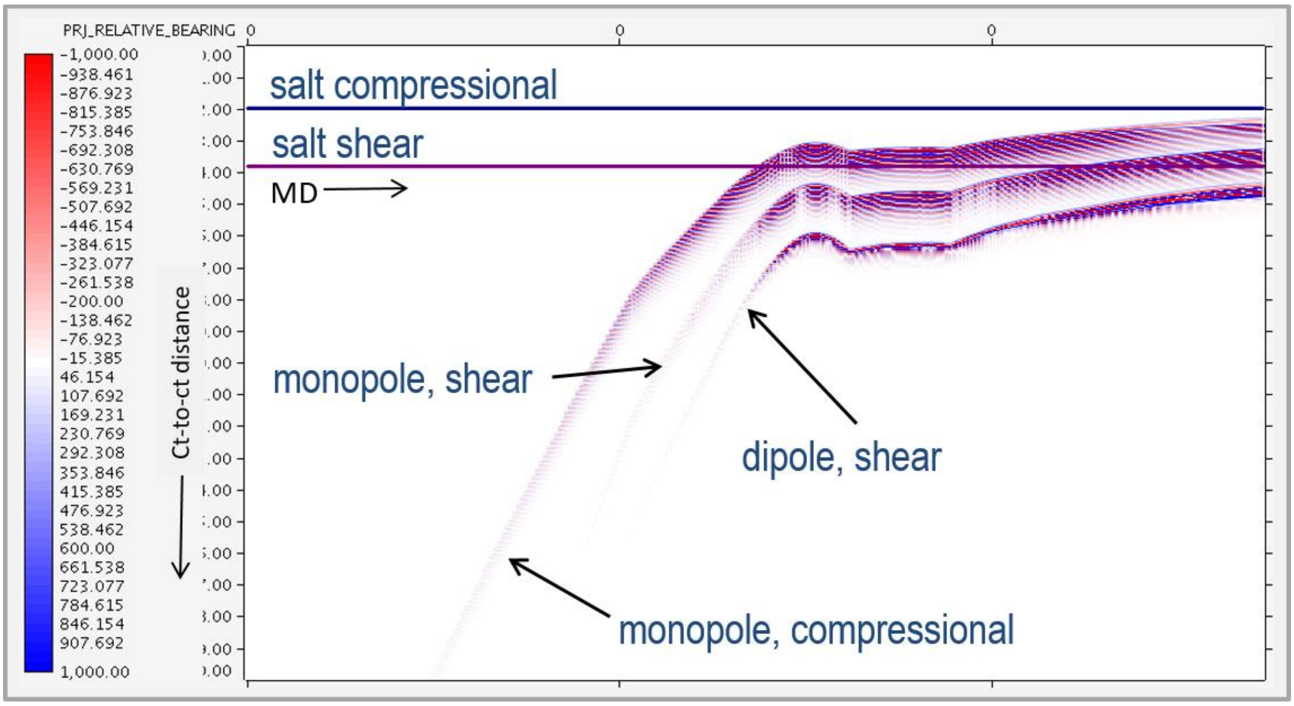


Figure 39—The simulated various sources vs reflected and signals as a function of signal strength, centre-to-centre distance and measured depth

# 6. Active Resistivity Ranging

## 6.1 Introduction

Resistivity ranging is an emergent ranging technology that utilizes deep directional LWD resistivity tools for detection of nearby conductive objects, such as casing. Due to the complexity of some ranging objectives additional ranging techniques beyond existing acoustic and magnetic are needed. The addition of resistivity ranging could provide redundancy and a complimentary solution while drilling since one single ranging technology might not provide a complete solution. Deep directional resistivity was recently developed to provide reservoir scale measurement for geosteering and reservoir mapping using an oriented electromagnetic induction transmitter and variably spaced oriented receivers in the drilling BHA. The low frequency induction style measurements are sensitive to changes in the induced current paths, which can be due to casing. The ranging applications include well intervention, relief well drilling, wellbore avoidance, and SAGD casing tracking.

## 6.2 Basic Theory

Resistivity ranging uses directional second order propagation measurements from deep directional resistivity tools to detect and estimate position and direction of cased wells. At specific tool orientations relative to the casing, generally near parallel, the transmitter induced currents pass through the casing of the offset wellbore and a measurable signal is detectable by the receiver antenna component that is coplanar with the transmitter. Shallow resistivity measurements are then used to find the equivalent background resistivity of the formation. It is then possible to estimate the distance and azimuth to the casing using the measurements, the background resistivity and the orientation of the transmitter and receivers.

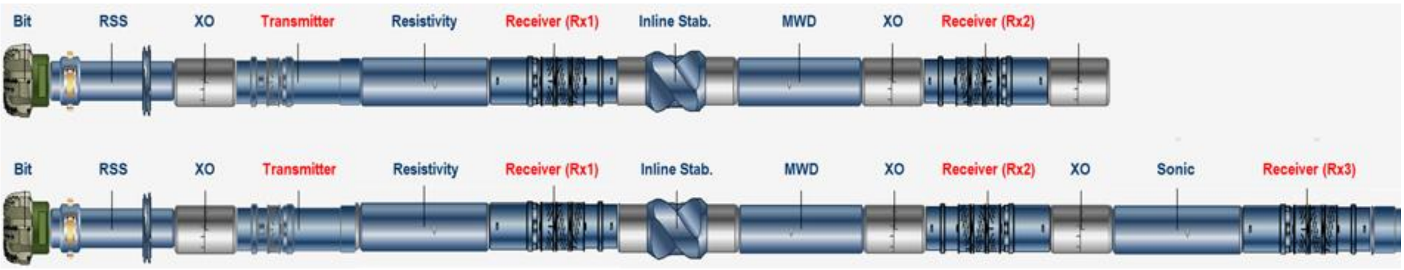


Figure 40—The location of the resistivity transmitter and receivers in the two different example BHAs

## 6.3 Distance and Direction

The ranging distance for resistivity ranging is comparable to the tool spacing and can be adjusted as fit based on specific well and formation details, some examples are shown in figure 40. Spacing is typically between 40, 80 and 120 ft with ranging distances generally half the spacing or more, see figure 41 and figure 42 for typical responses. In addition to determining spacing requirements, the optimal frequency used will depend on the formation resistivity and is lower than the frequency used for boundary detection and geosteering. Pre-job modelling is a critical aspect of the pre-job preparation in successful deployment of the tool.

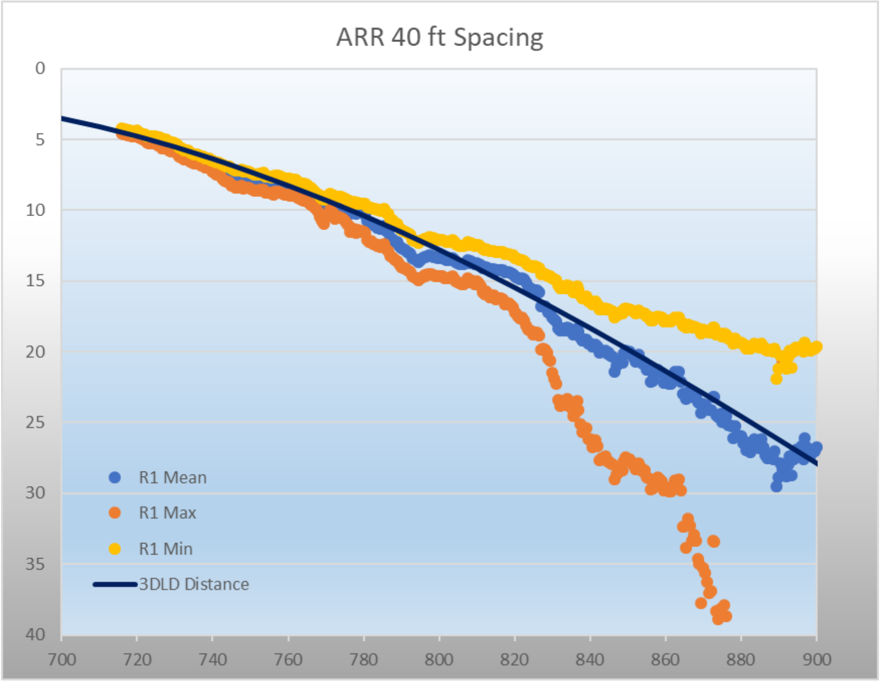


**Figure 41—Comparison of the resistivity ranging distance using 40 ft spacing to ct-ct distance**

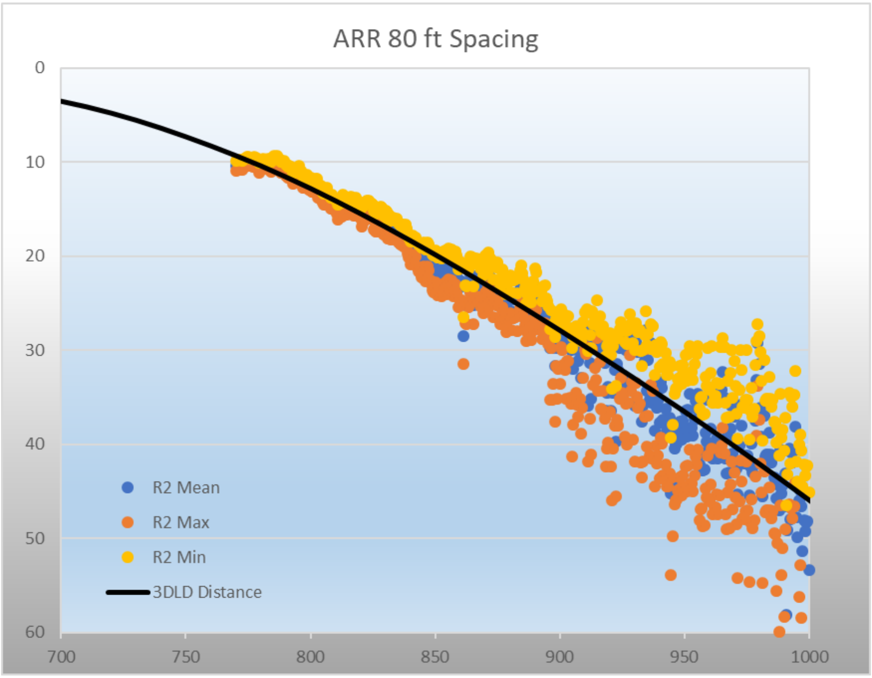


**Figure 42—Comparison of the resistivity ranging distance using 80 ft spacing to ct-ct distance**

## 6.4 Application

Resistivity ranging can be used to detect conductive material such as casing in OBM, WBM, and salt saturated muds, providing flexibility for while drilling applications. Since the measurements are made using a tool already in the drilling BHA, additional AMR or AAR could possibly be completed with fewer wireline runs, thereby improving ranging confidence and time to drill for interception.

The measurements are most sensitive when the incidence angle is less than 15 degrees, or near parallel, but anything steeper than that will cause a loss in measurement sensitivity. The second harmonic measurements used are also sensitive to any asymmetry in the formation and not just to nearby casing. Higher frequency responses are more sensitive to the formation heterogeneity, so it is generally preferable to use low frequency responses that are primarily sensitive to nearby casing. The asymmetry sensitivity leads to certain situations where a nearby boundary or formation anisotropy can induce a signal similar to a casing signal. This issue will also affect the azimuth angle measured, pointing to a different orientation from either the boundary or casing. In these situations, it is necessary to first find the formation resistivity profile locally to be used as background for the calculations. Pre-job modelling will help determine if resistivity ranging is a viable option for each specific situation.

# 7. Ranging Techniques Comparison

Previous chapters describe different available ranging technologies in the market:

- Chapter 2 describes the Passive Magnetic Ranging Technology (PMR)
- Chapter 3 describes the Active Ranging Technology (AMR)
- Chapter 4 describes the Passive Acoustic Ranging Technology (PAR)
- Chapter 5 describes the Active Acoustic Ranging Technology (AAR)
- Chapter 6 describes the Active Resistivity Ranging Technology (ARR)

All techniques presented have their own specific applications (Table 1), strengths and limitations. This chapter compares different available technologies, to assist in the selection of an 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, PAR, AAR, and ARR 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 modelled 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 is the correct tool for a relief well application is to complete an analysis that considers all the relevant inputs.

The table below gives an overview of different ranging techniques, that are described in Chapter 2 to 5; it only considers comparable 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.

## 7.1 Ranging Comparison Table

| DESCRIPTION | PASSIVE RANGING | ACTIVE RANGING | ACTIVE ACOUSTIC RANGING |
|---|---|---|---|
| **Technique** | 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. |
| **Best Case Performance** | Wells are parallel | Wells are parallel | Wells are at the same plane |
| **Worst Case Performance** | Wells are perpendicular | Pure Salt Formation<br>Wells are perpendicular | Wells are perpendicular at large c-c distance |
| **Detection Range Estimate** | 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 |
| **Definitive Detection Range** | 5 – 15m | 20 – 60m<br>40 – 100m with Direct Excitation on TW | 1 – 55m |
| **Detection Along Body of The Target Well** | Detection range up to 5m<br>(1/2 joint length), 6m on 12m casing | Up to 60m | Up to 55m |
| **Detection Near Break or End of Pipe** | Detection Range Up to 15m | Limited range within 1m of top and bottom of pipe ends | Up to 55m. Can detect Open Hole |
| **Deployment - Wireline Required** | 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 |
| **Data Acquisition Time** | 6 to 30 hours<br>For MWD Logging | 30 hours (8 hours in TPR BHA)<br>(assuming 4500m well) | 6 to 15 hours depending on the logging intervals<br>(assuming 4500m well) |

| | | | |
|---|---|---|---|
| **Distance Accuracy** | 10% of detection Range. To be considered 1 standard deviation. Depends on the quality of the Target Well Magnetization strength and Signal/Noise ratio level. | Non Gradient Tool : 5-20% Depends on High Side to Target variation<br>Gradient Tool: Depends on distance. Less than 5% | ~0.3m at 1 standard deviation |
| **Direction Accuracy** | ~5° at 1 standard deviation | ~5° at 1 standard deviation | ~22.5° at 2 Standard deviation |
| **Target Well detection** | Casing, Fish, Packer, completion, all steel equipment | Casing, Fish, Packer, completion, all steel equipment | Casing, Fish, Packer, completion, all steel equipment and Open hole |
| **Case Histories** | Widely used in the industry | Widely used in the industry | New technology recently developed |
| | Mainly used for P&A and collision avoidance<br>Very Few Successful Relief Well Intercept | Relief Well & Re-Entry Wells | Only few case histories are available |
| **Sensor Measurement Point** | 15m – 20m from Bottom hole | On Bottom | On Bottom |
| | On Bottom if WL Deployed. | 25 – 35m from Bottom Hole if deployed in BHA | |
| **Non Magnetic Target Pipe** | Detection not possible | No Effect same as steel pipe | No Effect same as steel pipe |
| **Target Casing Corrosion** | Detection may not be possible | Minimal impact on detection range | Minimal impact on detection range |
| **Presence Of Breaks Or Discontinuities In Target Pipe** | 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 |
| **Effects of Different Casing Sizes and Weight** | 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<br>40 Lbs./Ft has an expected max range of 3m along the body | | |
| **Effects of Other Nearby Wellbores** | 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 |
| **Effects of Highly Insulating Formation** | No Effect | Minimal impact up to 300m MD into the formation. Beyond 300m detection range is largely reduced | Negligible Effect |
| **Effects of High Incidence Angle Between Target And Drilling Well** | 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 |
| **Is The System Effected By Poor Hole Conditions in Drilling Well** | No Effect | Potential to add additional ranging run time for open ended drill pipe runs | Negligible Effect |
| **Effects of Different Mud Types** | No Effect | OBM may slightly reduce the detection range | Negligible Effect |

Table 1— Ranging comparison table

## 7.2 Impact of Incidence Angle on Detection

Incidence angle describes the angle of approach between the target well and the subject well. This angle will influence the detection distance for different ranging tools. Approaching a target well at a high incidence angle has an impact on the detection for all ranging techniques. Drilling towards a target well at a high approach angle should only be done when it is necessary. As an example, to avoid the AMR operates outside the tool's detection range, the trajectory must be modelled to verify the proposed incident angle provides an optimum detection possible. For PMR using MWD, due to the position of magnetometers away from the bit, this could pose a risk of interception. Therefore, a wireline survey method or dedicated ranging BHA with the MWD positioned at the bottom could be required.

To illustrate the difference the following diagram (Figure 43) considers a locate phase with a 30° pass by that is intended come within 3 meters of the target well.

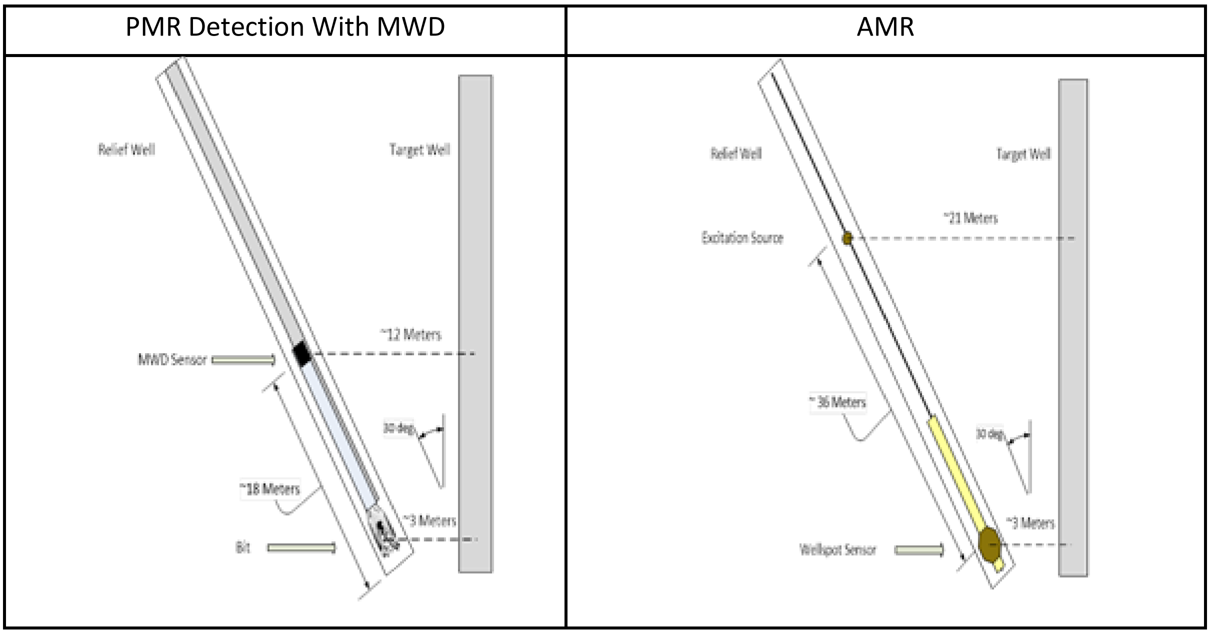


**Figure 43—Illustration of PMR and AMR incident angle**

### 7.2.1 PMR

The high incidence angle for a PMR measurement means that the sensors are much farther from the target well than the bit. In the case above, it can increase the possibility of an unintended collision as a PMR determination at 12 meters may be of reduced accuracy, or in many cases unattainable.

### 7.2.2 AMR

The high incidence angle for an AMR measurement will mean that the excitation source will be farther away from the target well thus reducing the signal intensity. While this may cause some possible detection issues when at greater distances from the target well, in the case illustrated above, the ARM tool sensor is only 3 meters from the target well which reduces the signal intensity requirements for a ranging determination. Ranging with AMR at this well geometry does not pose an unintended collision risk.

### 7.2.3 AAR

Higher incidence angles for AAR will reduce the amount of acoustic signal received by the tool. This reduction in acoustic signal in turn reduces the ranging distance possible for AAR. Figure 44 below illustrates the difference in a high incidence angle and a low incidence angle.

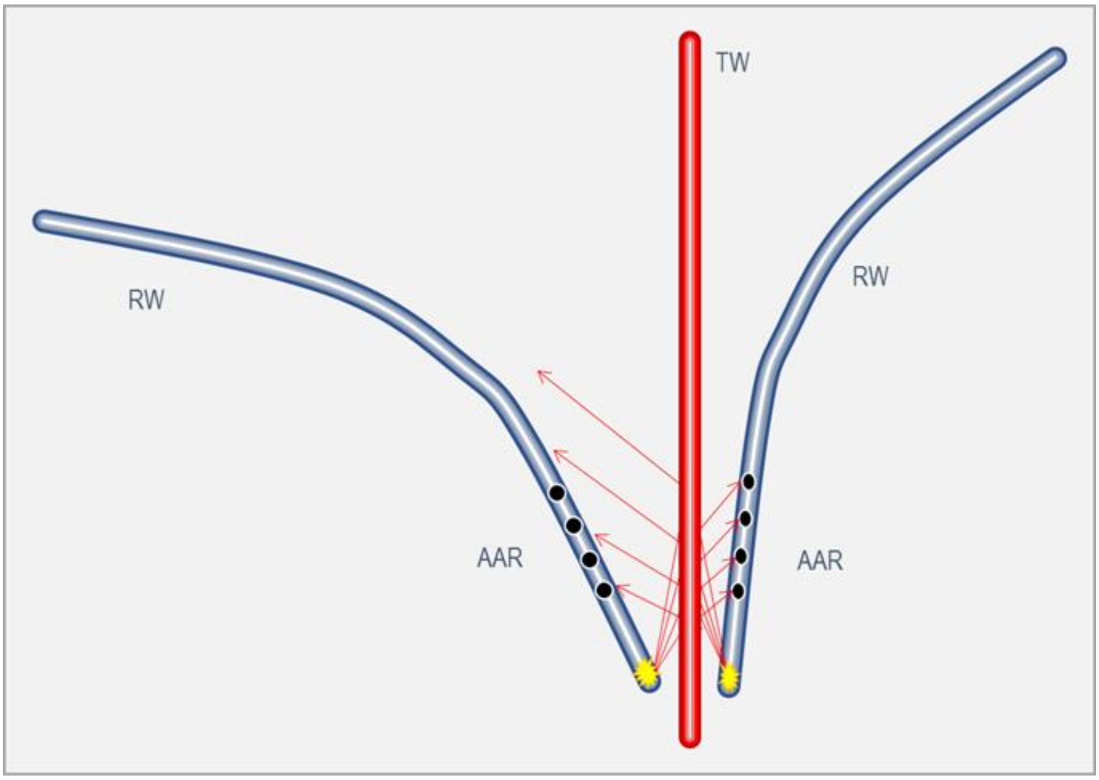


**Figure 44—Incidence angle effects on AAR. The left wellbore has a high incidence angle which reduces the acoustic signal (red arrows) received by the tool which in turn reduces the detection distance. The right wellbore shows a smaller incidence angle which allows all the acoustic signals to be received by the tool.**

# 8. Relief/Interception Well Ranging Operations

## 8.1 Relief Well Overview

Drilling a relief well is a unique operation that provides an emergency response to uncontrolled well incidents, such as minor well-control events with only financial effects, to major blowout situations with catastrophic repercussions to human lives and the environment. These incidents can occur in unpopulated areas, sensitive populated zones, or at deep offshore locations.

Every situation is different and requires a specific intervention response. When compared with standard wells, drilling a relief well is very different, particularly from a wellbore positioning perspective. Because the objective in drilling a relief well is to intercept a very small target, and even occasionally re-enter the uncontrolled well casing, an elevated level of accuracy is required. Achieving this goal can be especially challenging when the operation is in the presence of adjacent offset wells where the high density of wells makes collision avoidance a high priority.

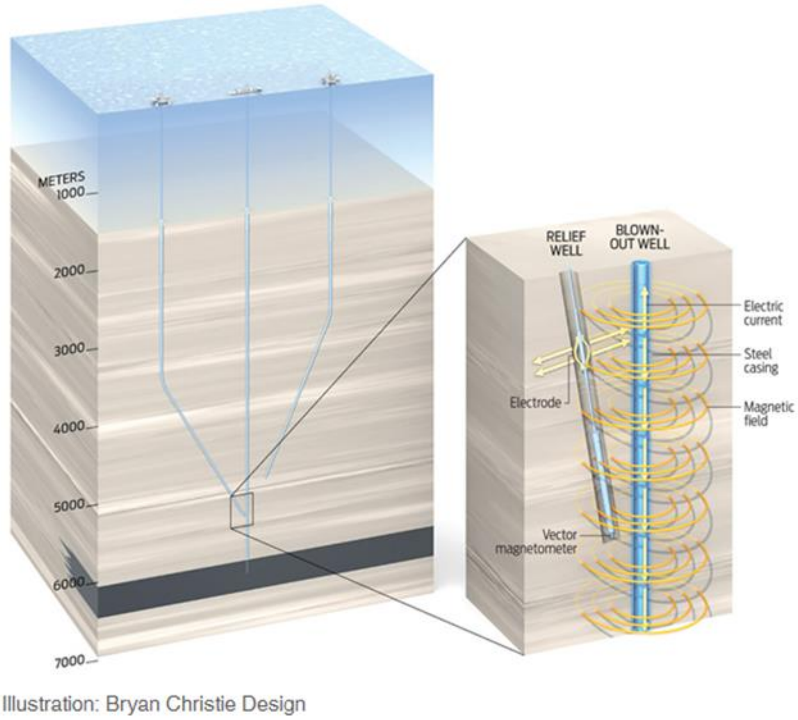


Figure 45—Example of two relief wells directional design utilizing active magnetic ranging

A relief well is usually planned to be a last resort option in the event the blowout 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 45), to intercept the original flowing well as deep 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 considered “killed” when the blowout well is controlled and brought back to a state of static condition.

Although a highly complex drilling operation, drilling relief wells requires optimum control and organized planning. A systematic approach significantly increases the chances of success and avoids failing to implement the solution that solves the uncontrolled well incident.

A surface intervention or capping operation is often the first response to a well out of control. These operations frequently take time with no guaranteed success; therefore, the planning of the relief well typically begins in parallel with the surface operations to avoid any loss of time in the event the surface intervention is unsuccessful. The objective of the relief well is to establish communication with the target well (see Figure 46) and to be able to pump a kill fluid, such as heavy drilling mud that could be followed by cement for plug and abandonment. This operation should stop the flow at the surface and control the target well. Communication with the target well can be established by:

- Performing the kill operations through highly permeable or fractured formation

- Perforating the target well casing
- Milling a penetration in the target well casing through direct intercept
- Performing a re-entry through a window milled in the target well casing

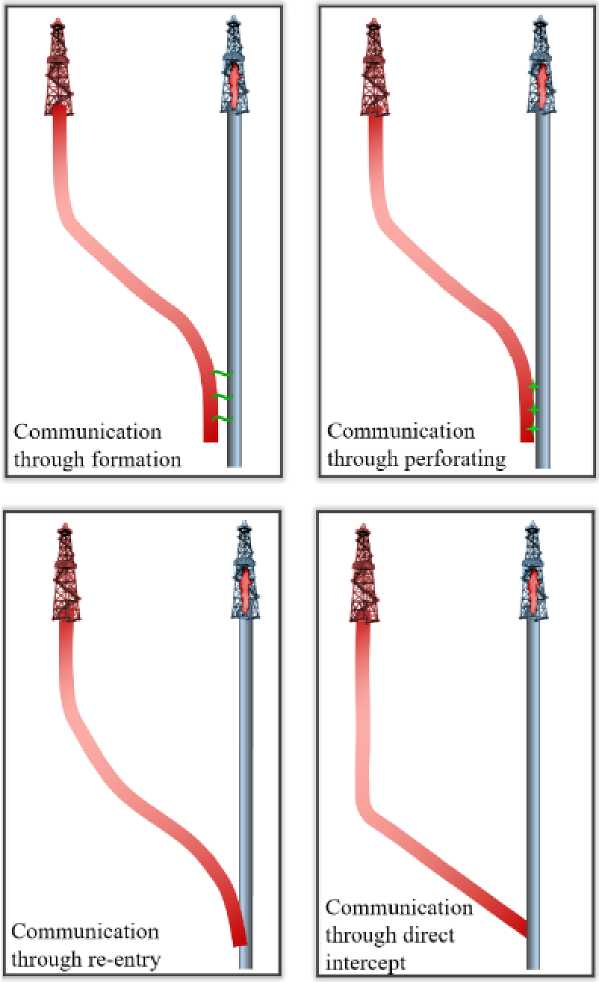


Figure 46—Establishing communication with the target well and allow for pumping a kill fluid can be accomplished in different ways

In conventional drilling operations, the goal is to reach the final reservoir targets while avoiding collision with nearby wells. For the relief well, the final objective is to intercept the blowout well. Standard collision avoidance rules based on absolute positioning can be applied when the wellbores are approaching each other; however, at a certain point in time, the envelopes of uncertainty will be so close that these rules must be broken.

Ranging techniques such as those contained in the Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA) error model (Well Intercept Sub-Committee eBook: Wellbore Ranging Technologies, Intercept Applications and Best Practices) are applied to determine the relative positioning between wellbores by measuring the distance and the direction of the uncontrolled target well. This unconventional approach requires a set of rules that are specific to the relief well and are only applied if all prevention and mitigation actions are in place to ensure the residual risk is non-HSE, and that it has been reduced to an acceptable and reasonably practical level.

### 8.1.1 Management System

The challenges faced in relief well operations require a robust and reliable management system to accurately assess, prevent and reduce potential risks, and ensure consistent execution of the relief well operations. The management system also takes into consideration the lessons learned from experience and integrates the methods and techniques already in place for standard drilling operations.

The management system defines the principles and guidelines for conducting the drilling operations, which should be shared, communicated, and adopted by all parties involved in the project, either in the office or in the field. This approach reinforces the leadership, optimizes the resources, prevents and mitigates the risk, and keeps all personnel focused on their task. Figure 47 shows how the management system provides a continuous iterative loop for operations control, corrections, and improvement.

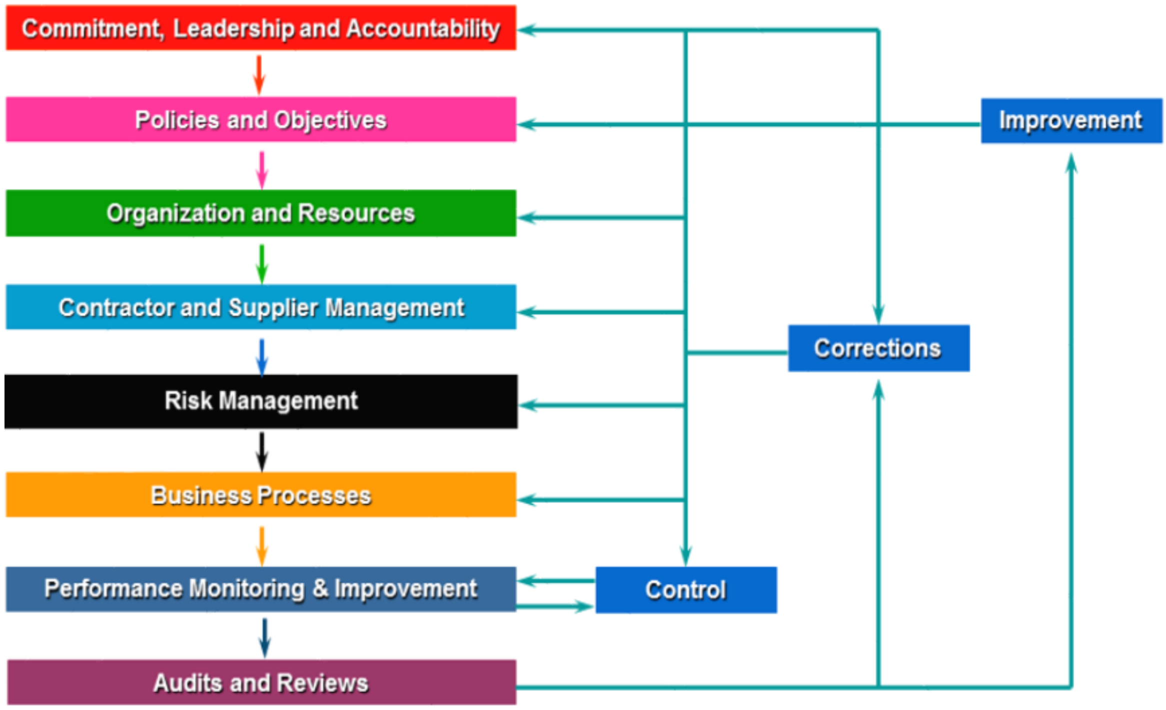


Figure 47—A robust and reliable management system ensures consistent execution of relief well operations, takes into consideration lessons learned, and integrates methods and techniques already in place for standard drilling operations

The management system dictates how the relief well drilling should be conducted. Figure 48 shows an example of components needed for relief well drilling and how they relate to other activities. For example, the use of Collision Avoidance Standard (Poedjono et al. 2009, SPE 121040), Hazard and Risk Control (HARC), and STOP program are components for a systematic approach to stop the operation and ensure no lapse(s) in safety and quality.

Comprehensive risk assessments with preventive and mitigation actions must be in place prior to drilling below the Separation Factor (SF) of 1.2 (Figure 51), which ensures the residual risk of accidental interception is non-HSE; i.e., without losing control of the relief well.

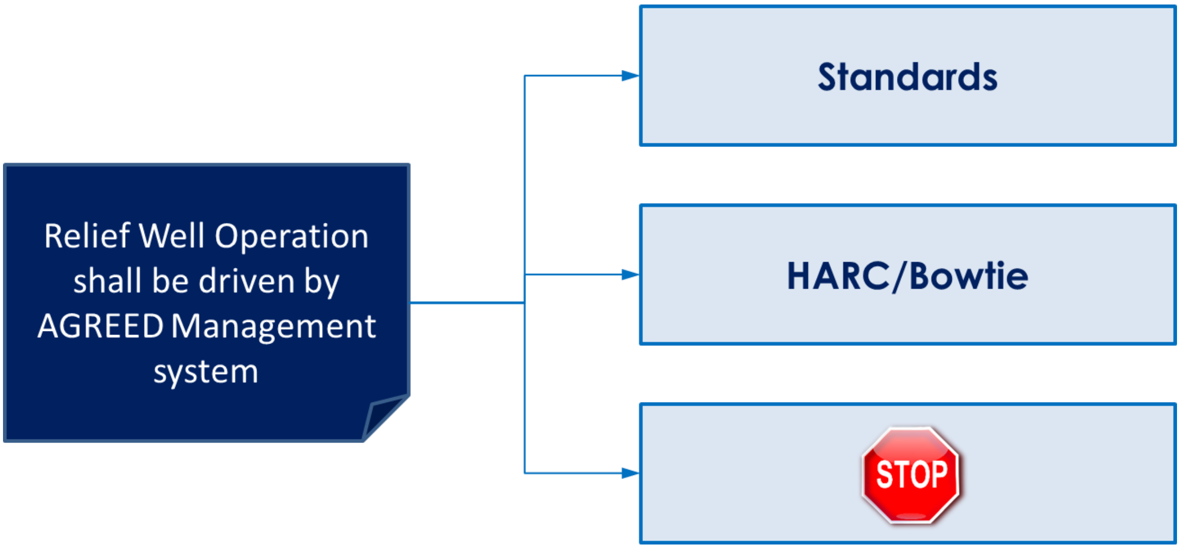


Figure 48—Examples of components needed for relief well and how they relate to other activities and the management system

### 8.1.2 Communication

Clear communication protocols are a key cornerstone of the management system because they are the only way to ensure the best use of the expertise and experience of all team members. Additionally, to ensure that all team members have the same understanding of the workflow process, especially in terms of task assignment and responsibilities, it is important to perform drilling simulation on paper, including operation sessions during the planning phase. This approach allows for improving and validating all action items that are to be carried out by the team during actual drilling operations.

All seven phases of the workflow process, shown in Table 2, are separated into a sequence of consecutive tasks that need to be undertaken. The workflow process manual regroups all identified tasks into a logical and chronological sequence throughout all phases. These key elements, shown in Table 1, are listed as non-exhaustive examples of how a task should be carried out and are described as follows:

- What—Task or activity name
- When—Time when the task should be carried out and results sent to relevant personnel
- Who— Person responsible for executing
- Review—Responsible person to review proper achievement of task
- Where—Location of the team member or relevant person
- Why— Objective of the task
- Input—Inputs needed to perform the task
- Means— Resources to carry out the task
- Output—Task or activity results
- Send to—Individuals who should receive the results

| Action | Description |
|---|---|
| ***What*** | *Target well definition*<br>• *Precise target well surface position*<br>• *Specify target well position*<br>• *Specify target well position uncertainty* |
| ***When*** | *During phase 1: Planning phase*<br>• *Results provided as soon as possible, and updated after every completed process* |
| ***Who*** | *Primary service company* |
| ***Review*** | *Independent third-party survey management company* |
| ***Where*** | *Relief well operation centre at oil company office* |
| ***Why*** | • *Objective: Provide reference data to all parties*<br>  ◦ *Geodetics and geomagnetics references*<br>  ◦ *Target well surface positioning*<br>  ◦ *Target well corrected survey listing*<br>  ◦ *Target well optimized positional uncertainty*<br>  ◦ *Survey program used for target well*<br>• *All parties should rely on same valid data and update their well trajectory*<br>• *Database consequence to regulate different software packages for collision avoidance computation*<br>• *Reduce the target well uncertainty to a minimum to increase chance of target well detection with ranging techniques.*<br>• *To define reliable relative RW to TW surface uncertainty and to define target well EOU size to establish ranging strategy* |
| ***Input Data*** | • *Historical TW surface location coordinates report(s)*<br>• *New (if possible) TW surface coordinates measurement*<br>• *Historical geomagnetic mapping*<br>• *New (if possible) geomagnetic mapping*<br>• *Target well definitive survey data*<br>• *Target well raw survey data*<br>• *Target well bottomhole assembly (BHA) description and sliding or steering sheet*<br>• *Target well survey program report (survey tools and quality assurance and quality control*<br>• *Target well end of well report* |

| | |
|---|---|
| ***Means*** | • *Geomagnetic and geodetic equipment and expertise*<br>• *Geomagnetic data processing*<br>• *Referenced relief well planning software*<br>• *Wellbore positioning uncertainty expertise* |
| ***Output Data*** | • *Geodetic references*<br>• *Geomagnetic references*<br>• *Definitive target well surface location coordinates reference*<br>• *Target well surface location uncertainty*<br>• *Target well reprocessed and corrected survey listing*<br>• *Survey tool type and error tool code for target well*<br>• *Error models customized for target well in easy-to-import format type*<br>• *Target wellbore positional uncertainty for the chosen confidence level* |
| ***Send To*** | • *Oil company*<br>• *All relief well team members* |

**Table 2— Action steps and descriptions for performing a task**

## 8.2 Ranging Decision Matrix

Ranging technology selection is critical to successfully achieving the goals of each phase of relief well activity (Figure 50). Ensuring the technology is fit for purpose for approaching, locating, following, intercepting and establishing communication with the target well for the killing and plug and abandonment requires careful and detailed planning. Each relief well strategy differs from one case to another and the choice of the ranging technologies may rely on different aspects: access to the target well, environment, deployment methodology, required expert personnel, cost, effectiveness, objectives, performances, hole conditions, etc.

One single ranging technology may be chosen for a specific relief well case, but most of the time a combination of different ranging techniques will 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 7: Ranging Technologies comparison to identify and select the appropriate ranging technology for the specifics of the relief well project.

## 8.3 Categories of Relief Well Designs

The three categories of Relief Well Trajectory Design are shown in figure 49.

### 8.3.1 Simple Intercept

This Design is typically a J-shaped well that intercepts the target well at a specific depth. Such intersects usually requires three phases: A data gathering phase, drilling phase and intercepting phase. Simple intercepts are typically the most difficult to execute without the use of a side-track(s).

### 8.3.2 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.

### 8.3.3 Oriented Intercept

This Design is typically an S-shaped 2D or 3D well that is designed to initially locate and then relocate and intercept the blowout well at deeper depth. This type of well usually requires five phases: A planning phase, approaching phase, locating phase, following phase, and Intercepting phase.

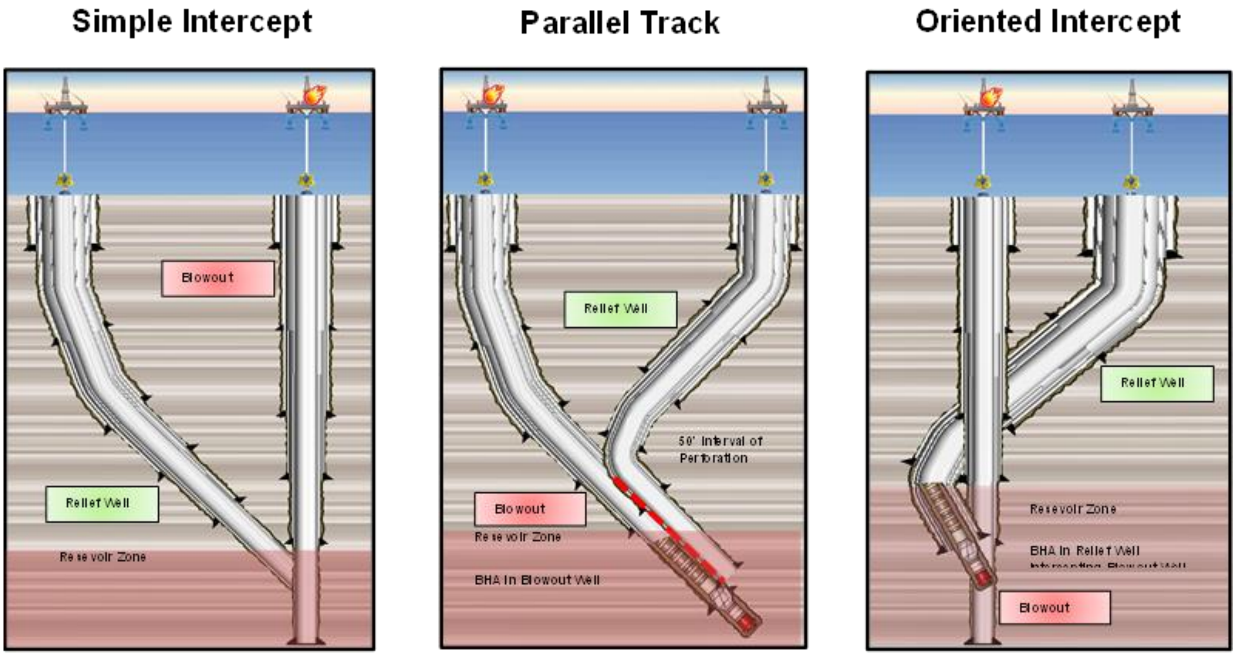


Figure 49—Various examples of relief well designs

## 8.4 Relief Well Phases

At the core of the relief well process is the workflow, which consists of seven phases, as shown in Figure 50. Each phase consists of specific tasks that must be planned, communicated, performed, and executed properly prior to moving on to the next phase. These phases make the relevant experts focus on their given tasks without interfering with other team members and provide an effective way to communicate and disseminate information to all relevant stakeholders (Poedjono et al., 2017, SPE-186901).


Figure 50—The core of the relief well process is the workflow, consisting of seven phases

### 8.4.1 Planning Phase

The planning phase is key to a successful relief well operation (Goobie et al. 2015, SPE 173097). The goal for this planning phase is to produce a comprehensive project plan, which defines all processes and activities required to meet the final objective. Incomplete planning is generally the root cause of significant issues encountered during execution. The relief well team, a multidisciplinary team with roles and responsibilities clearly defined at each phase, should undertake live simulation drills to identify any gaps and implementation redundancies. An example of one of these exercises is to simulate a successful ranging run and then analyse the performance.

All risks must be identified during the planning phase, along with the necessary detailed preventive and mitigation actions. Incorporating this standard process eases the go/no-go decision-making process during the execution.

Relief well planning starts with the planned interception locations (requires intensive dynamic fluid modelling) and goes back up to surface. Designing the optimum relief well trajectory (Goobie et al. 2015) requires going from the interception window to the surface location while respecting the directional constraints, the well architecture constraints, taking into consideration the surface exclusion zone, and incorporating a selection of ranging technologies through single or multiple technologies deployment.

The relief well planning requires an advanced and optimum survey program to identify the best wellbore position possible. This position determines the safe operation envelope as shown in Figure 51 by following the collision avoidance standard, such as an SF = 1.2. Actions must be in place prior to operating below an SF of 1.2., which will ensure safe drilling and prevent losing control of the relief well due to an unintentional wellbore collision.

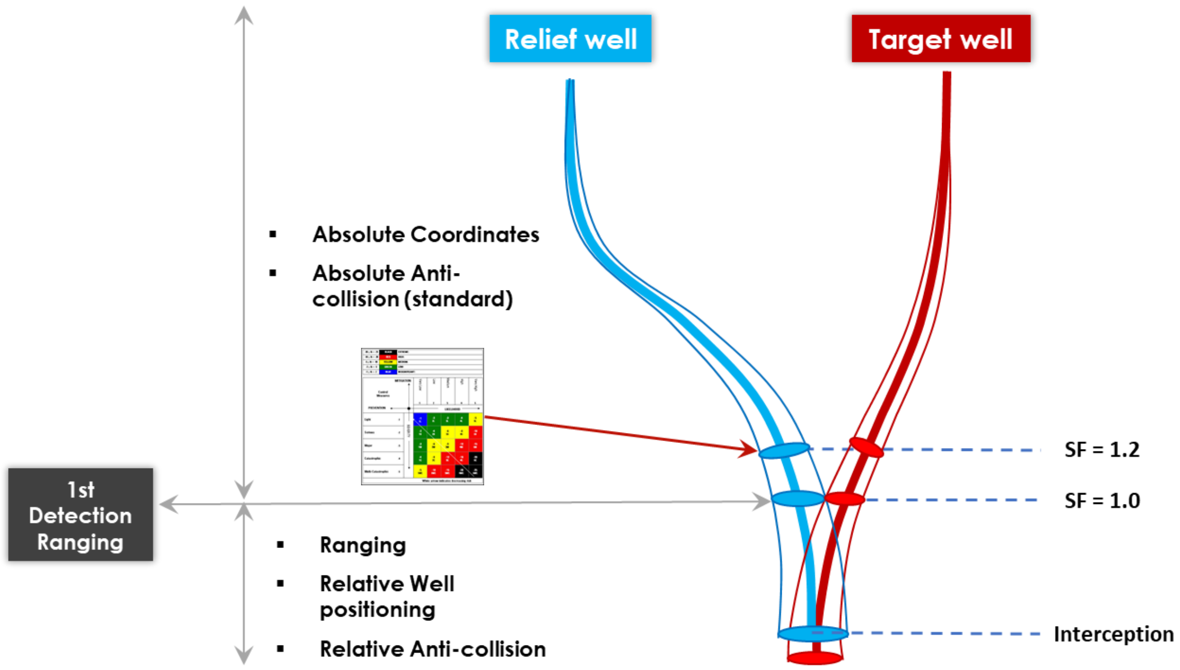


**Figure 51—The relief well planning requires an advanced and optimum survey program to obtain the best wellbore position possible. This, along with HARC, determines the safest operation envelope following the collision avoidance standard, such as a separation factor of 1.2, and ensures the risk of early interception shall be managed to non HES prior to the first ranging run.**

#### *8.4.1.1 Regulatory requirements*

To meet new regulatory requirements, many oil and gas companies are looking for ways to produce reliable relief well plans without generating intercept plans for every casing section. These regulations require that the operator has the financial capability to drill a relief well and conduct other emergency well control operations. In the event of a blowout, the regulations also require that you know the estimated time it will take to drill the relief well. They require that a least two relief well surface locations are verified for use, and that a rig is available and identified for use in relief well operation. These items must be supported by a clear process for execution and plans for how to kill the well. Example of the requirements to meet the US Government and operator's standards are highlighted below:

US Government BSEE, Regulations TITLE 30 CFR 250 - MINERAL RESOURCES (Division: Minerals Management Service) Revision Date - 06/03/2010.

(e) Bonds, oil spill financial responsibility, and well control statements. Note that you have or will have the financial capability to drill a relief well and conduct other emergency well control operations.

(g) Blowout scenario. A scenario for the potential blowout of the proposed well in your EP that you expect will have the highest volume of liquid hydrocarbons. Include the estimated flow rate, total volume, and maximum duration of the potential blowout. Also, discuss the potential for the well to bridge over, the likelihood for surface intervention to stop the blowout, the availability of a rig to drill a relief well, and rig package constraints. Note that you have to estimate the time it would take to drill a relief well.

An example of an operator's planning expectations under BP IG 11/09/2010, in conjunction with planned drilling operations a documented relief well plan and includes the following regarding relief wells:

1. At least 2 identified relief well surface locations that have been verified for use offshore
    a. Location verification may include things like shallow hazard surveys, seabed surveys, and cores to ensure the sites are acceptable.
    b. For multi-well development sites, consideration should be given regarding whether more than 2 relief well locations are advisable in order to intersect all the planned wells at the site
2. Rig availability for use in relief wells shall be identified
    a. Recognizing that rig share agreements may be needed in SPUs where a capable rig is not under operator contract
3. Identification of required tangible items
    a. Confirmation that such items can be made available in the timeframe needed
4. High level view of dynamic kill requirements shall include:
    a. confirmation that required hydraulic horse power can be made available as needed
    b. confirmation that required volumes and weights of kill fluid can be adequately mixed/shipped/stored
5. Identification of a clear process
    a. Enables the SPU D&C VP to sign off that the above requirements have been met

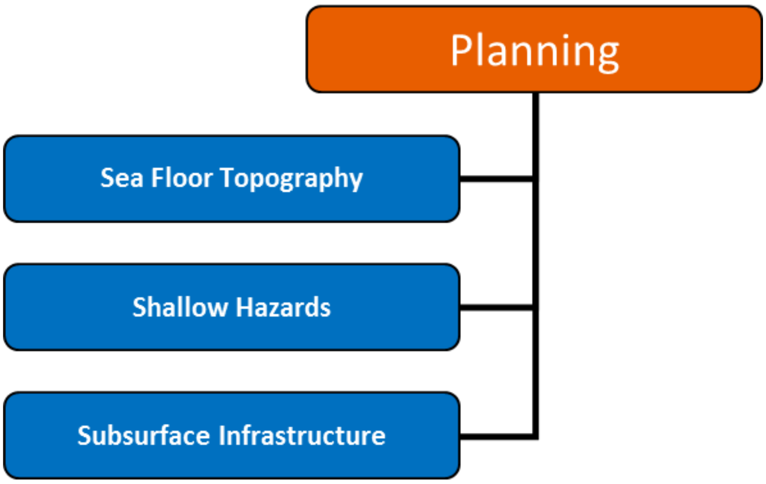


Figure 52—Planning, initial data gathering requirements

An example of Phase 1, planning data gathering steps in GOM offshore environments. A cross-functional team of geoscientists and engineers gather, and quality check all subsurface models, seafloor topography and shallow hazard data, required to plan a relief well. The objective of this phase is to define possible surface locations, and avoid steep or unstable slopes, faults, and no-go zones, such as offset wells, pipelines and shipping lanes.

An example of key element tasks and responsibilities in Phase 1, Planning phase.

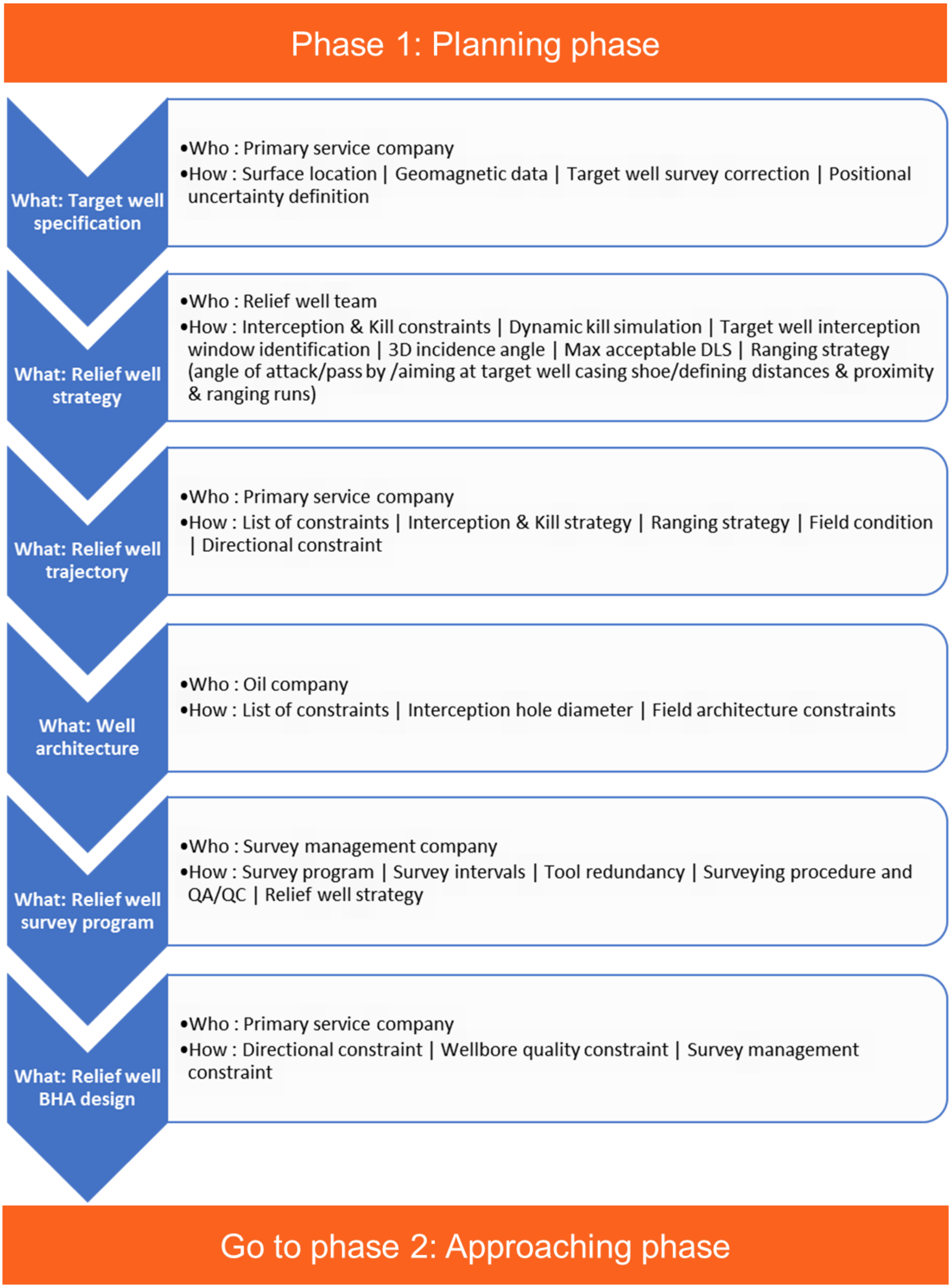


**Figure 53—Phase 1: Planning phase key tasks and responsibilities**

#### 8.4.1.2 Robust Crosscheck Methodology.

To reduce the risk of gross errors, the relief well phases from planning to intercepting are designed with continuous crosscheck methodology using independent tools available for all tasks as shown in Table 3.

| Task | Primary Solution | Backup or Crosscheck |
|---|---|---|
| **Well planning** | Primary contractor | Secondary contractor |
| **Ranging techniques** | Primary contractor (acoustic), (Poedjono et al. 2017, SPE-187313) | Secondary contractor (magnetic) |
| **Survey management** | Primary contractor | Secondary contractor |
| **Hydraulic simulations** | Primary contractor | Secondary contractor |

Table 3—Tasks assigned to primary and secondary, back-up contractors

#### 8.4.1.3 Use of Hazard and Risk Control (HARC).

The objective of the HARC shown in Figure 54, is to set standard process and tools for identifying hazards, assessing associated risks, and defining required control measures. The scope of the HARC process is to address service quality, health, safety, security, and environmental risks as applicable on a task or process basis and applies at all times to the entire relief well project where management control is expected. HARC also allows considerable improvements or changes to the plan in an organized and controlled manner. Poedjono et al. (2009), SPE121040 describes one such process using HARC and a management of change process.

During the planning phase, the HARC process identifies and isolates all potential hazards and relates them to the risk of occurrence in addition to their potential impact on the relief well drilling. The same hazard might result in multiple impact variations depending on the specific uncontrolled well circumstances (population, environment). Addressing these hazards might require modifying the plan, adapting the process, or changing equipment. The objective is to reduce the risk to an acceptable level that can be managed throughout contingency plans during the entire drilling process.

From the HARC perspective, it should be noticed that the ability to kill the uncontrolled target well requires performing and establishing communication at the expected kill window; therefore, it is essential to avoid any unintended interceptions that could be difficult to manage. The best relief well plan allows for succeeding on the first attempt. For that reason, it is important to ensure that after each ranging run, the relief well plan still allows for intercepting the target well at the intended kill depth under the constraints defined in the planning phase. All measures need to be in place to reduce the risk of side-tracking or even worse, losing the well.

The relief well requires breaking the collision avoidance rule, and specific relief well drilling rules must be applied. It is important to analyse all specific solutions using the HARC process to reduce the risk of misusing the specific techniques. It is also important to keep in mind that the main results of HARC is to make certain that all prevention and mitigation actions are in place prior to any decision making. It is only by making all the teams adhere to this process that they will be able to successfully drill the relief well safely and efficiently.

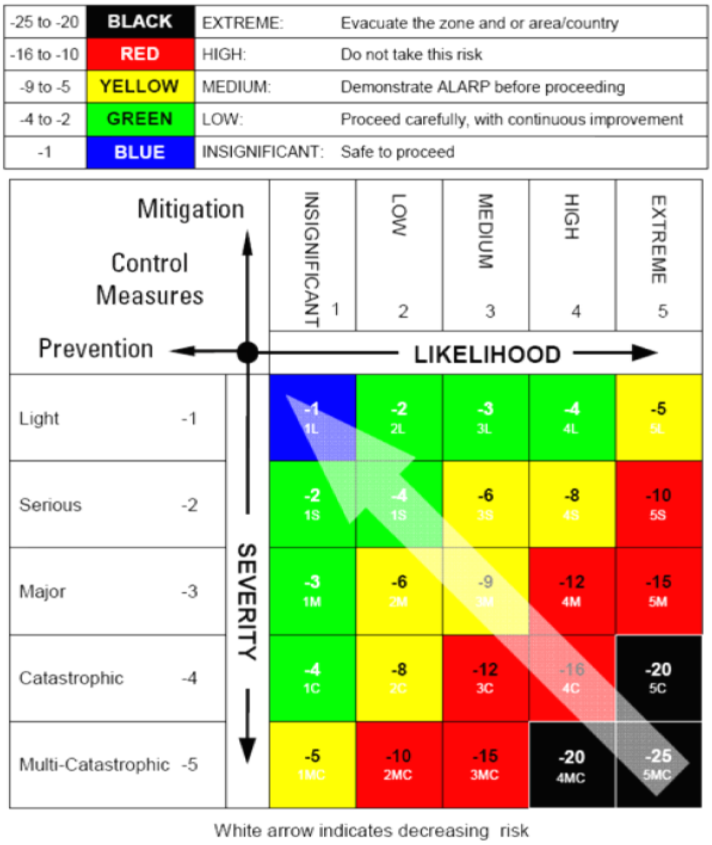


Figure 54—The HARC process identifies and isolates all potential hazards and relates them to the risk of occurrence in addition to the potential impact on the relief well drilling

#### *8.4.1.4 Preventive and Mitigative Risk Mapping*

Another method of risk mapping that gained recent popularity is the bowtie method (Rowe et al. 2015, SPE 173565) as shown in Figure 55. This bowtie diagram visualizes the risk in a single image, creating a clear differentiation between the preventive and reactive mitigation risk management process prior to drilling. These diagrams are especially helpful with identifying systems, processes and equipment, which are essential to the drilling operation.

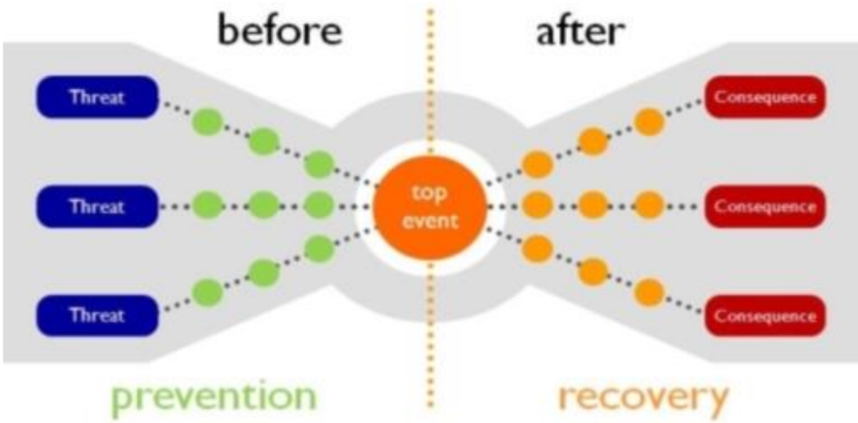


Figure 55—The bowtie method is a diagram that visualizes the risk in a single image, creating a clear differentiation between preventive and reactive mitigation risk management process prior to drilling

### 8.4.2 Approaching Phase

Relief well operations present substantial challenges starting with the approach phase as shown in Figure 56**.** This phase aims to approach the target well until reaching the detection range using available ranging tools. One might consider this initial drilling phase to be conventional and not critical, but that is not correct. This key phase places the relief well in the most optimal position to detect the target well, while avoiding collision with potential offset wells; therefore, collision avoidance monitoring while drilling is required.

During this phase, it is essential not to deviate from the planned trajectory because this increases the chances of success in the locate phase. Special attention must be given to the smoothness of the borehole, to optimize the torque and drag features, and minimize potential hole issues. The relief well team must be proactive with directional drilling analysis by performing bottom hole assembly (BHA) pre- and post-analysis to assess performances and improve drill-ahead projections. By doing so the relief well team reduces the risk of potentially large local doglegs.

The approach phase requires a rigorous survey program to be followed. Advanced survey management processes are necessary to drill an accurate well path with the smallest positional uncertainty. This process includes real-time sag correction, multi-station analysis, in-field referencing, raw data crosscheck, and multiple survey tools redundancy.

This approach phase verifies that all workflows and communication protocols are well understood by all team members and are being implemented correctly and efficiently.

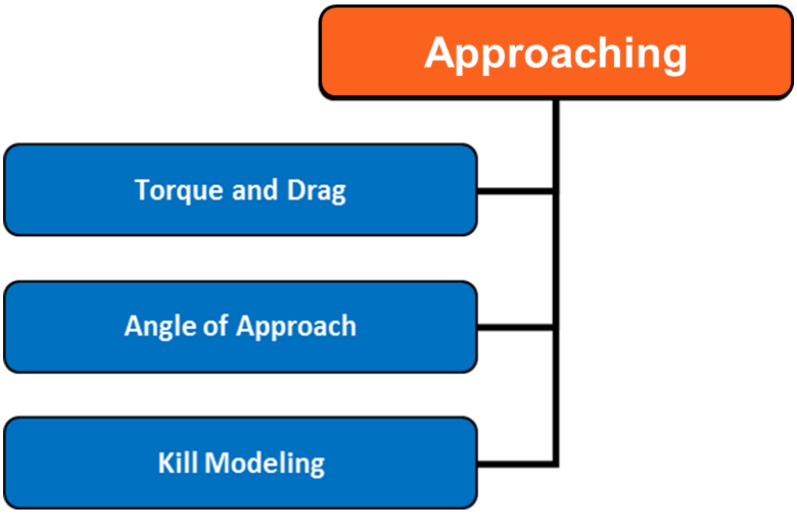


Figure 56—Approaching, initial data and modelling requirements

After addressing the planning phase, Phase 2 looks at the drilling feasibility of the well design. Surface location positional accuracy, torque and drag, sail angle, angle of approach, tangibles, and kill modelling are all items that are considered. This phase is typically representative of the drilling operations on the target well. The spud location of the relief well is surveyed to a high level of accuracy and precision, and sources of error associated with the well positional accuracy are considered and accounted for prior to drilling commencement.

An example of key element tasks and responsibilities in Phase 2, Approaching phase.

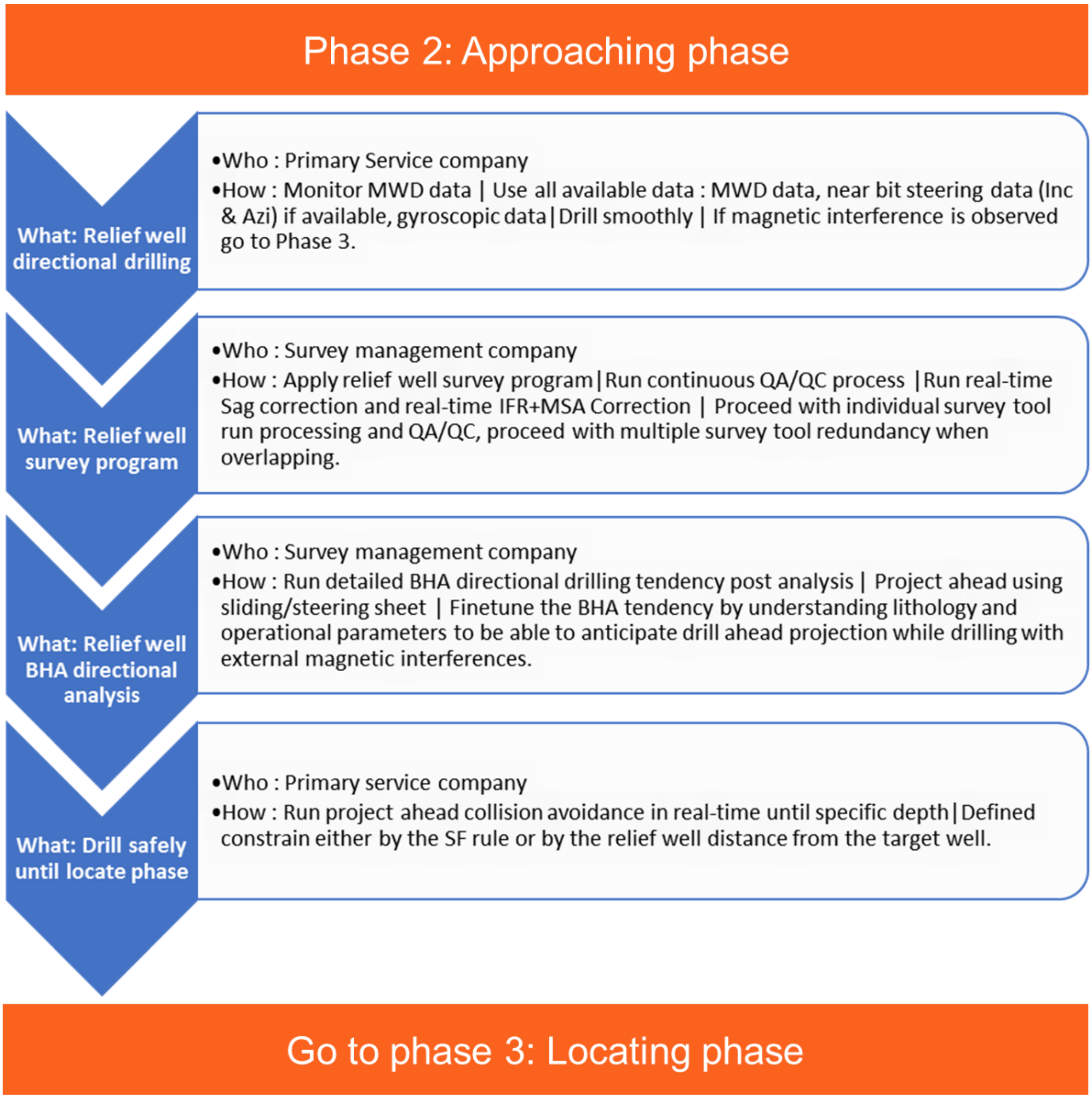


Figure 57—Phase 2: Approaching phase key tasks and responsibilities

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 target well. Figure 58 shows an example of well intersection process cycle.

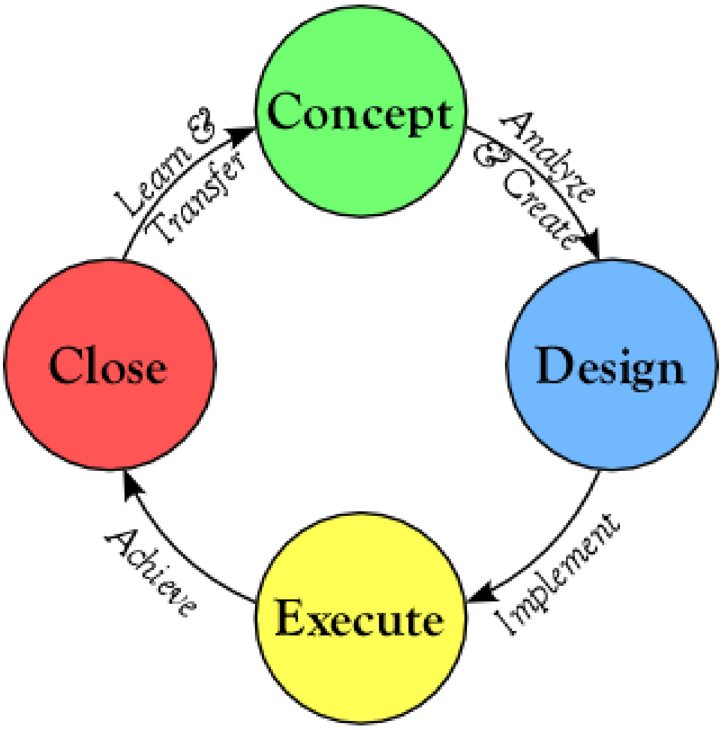


Figure 58—Well interception process cycle

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 process is an iterative where each new input, whether it is data or the findings from an investigation, must be analysed 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 59 and Figure 60).

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

- Gather relevant data
- Make onsite assessment
- Perform diagnostics to define the problem
- Define relief well/intervention well constraints
- Define the relief well/intervention well project objective(s)
- Define the intersection/kill point(s)
- Define the hydraulic communication method/intersection strategy
- Evaluate the position uncertainty
- Evaluate the geologic conditions
- Define the attack angle
- Develop the ranging strategy
- Determine the surface location(s)
- Develop the relief well trajectory
- Define the relief well casing program
- Define the survey program
- Evaluate the kill/P&A hydraulics
- Determine the number of required relief wells/intervention wells
- Define the kill/P&A/remedial equipment and kill/P&A/remedial procedures

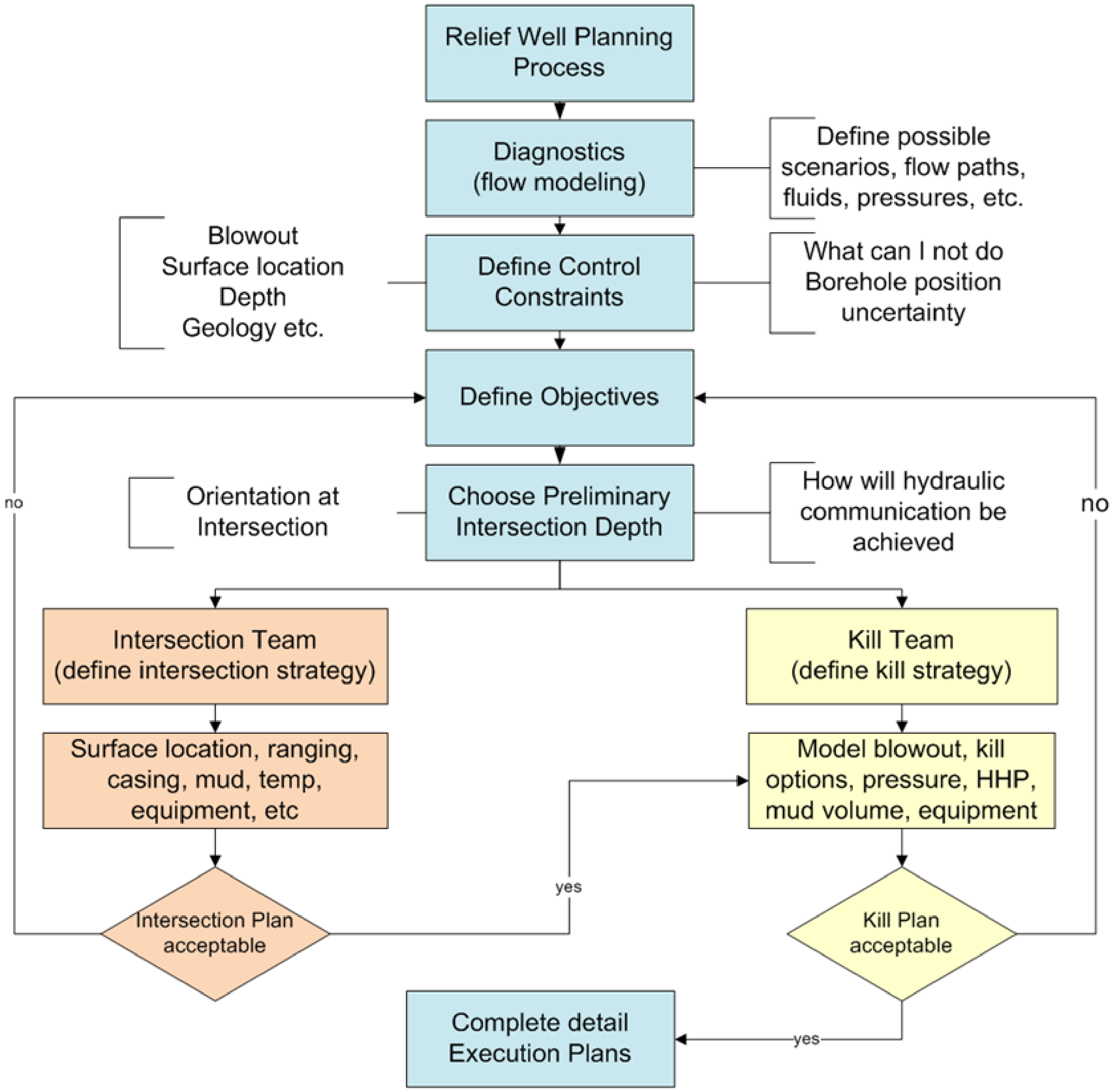


Figure 59—Summarized wellbore interception planning steps

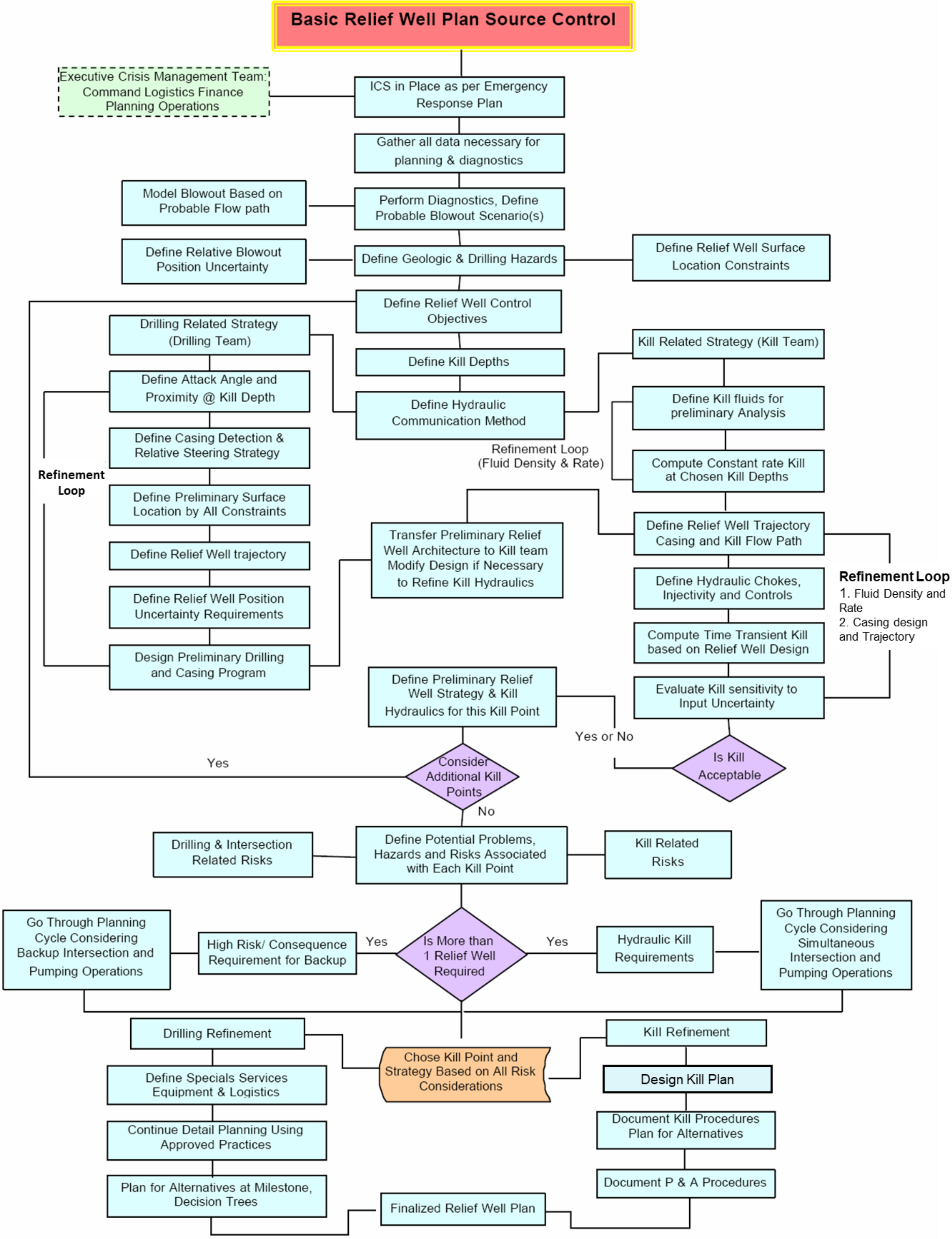


**Figure 60—An example of detailed relief well planning process**

### 8.4.3 Locating Phase

Locating the target well requires the use of suitable ranging techniques. Positive detection requires deriving the relative position between the relief well and the target well by measuring the distance and direction from the relief well to the target well. The Phase 3, Locate phase, as shown in Figure 61, is based on a strategy that allows for investigating the total area of the potential detection zone. The range of this zone mainly depends on the size of the combined Ellipsoid of Uncertainty (EOU) and the expected ranging detection distance. In the worst-case scenario where the target well has not been detected as expected, a new zone for investigation is defined and a new plan is developed accordingly.

It is only by having positive detection of the target well that the ranging technique capabilities can be confirmed. Thus, it is important to monitor closely the potential magnetic interferences by analysing the available raw data (near-bit direction and inclination packages, measurement while drilling MWD), to ensure a safe approach toward the target well until the positive detection of the target well exists.

The positive detection of the target well allows for reinitializing the relative uncertainty between the target well and the relief well and is likely to require a new relief well plan to comply with the ranging results. This procedure needs to be performed under the relief well constraints as defined in the planning phase (directional and ranging considerations, interception constraints, etc.).

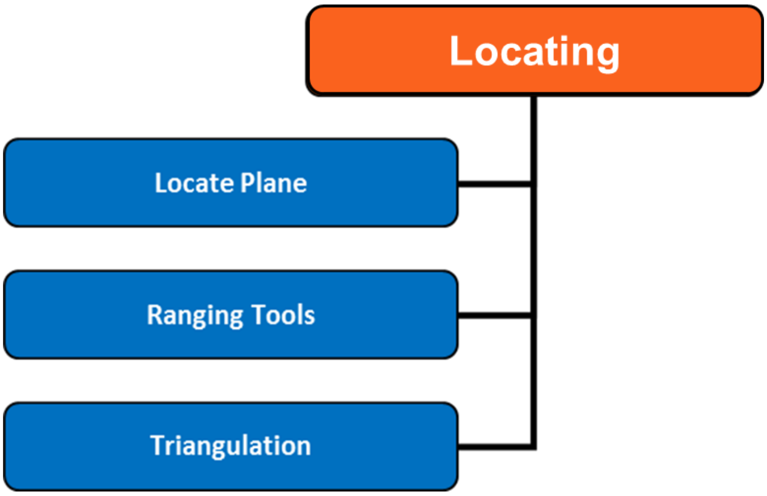


Figure 61—Locating, ranging technology selection for optimizing target wellbore detection

Phase 3, the Locating phase, defines the directional drilling parameters and an initial well trajectory, such as using magnetic ranging technology. This locates and “fly’s by” the target wellbore at a specified distance (+/-1,000-ft MD) above the intended intercept point, taking precautions to avoid an unintended collision.

An example of key element tasks and responsibilities in Phase 3, Locating phase.

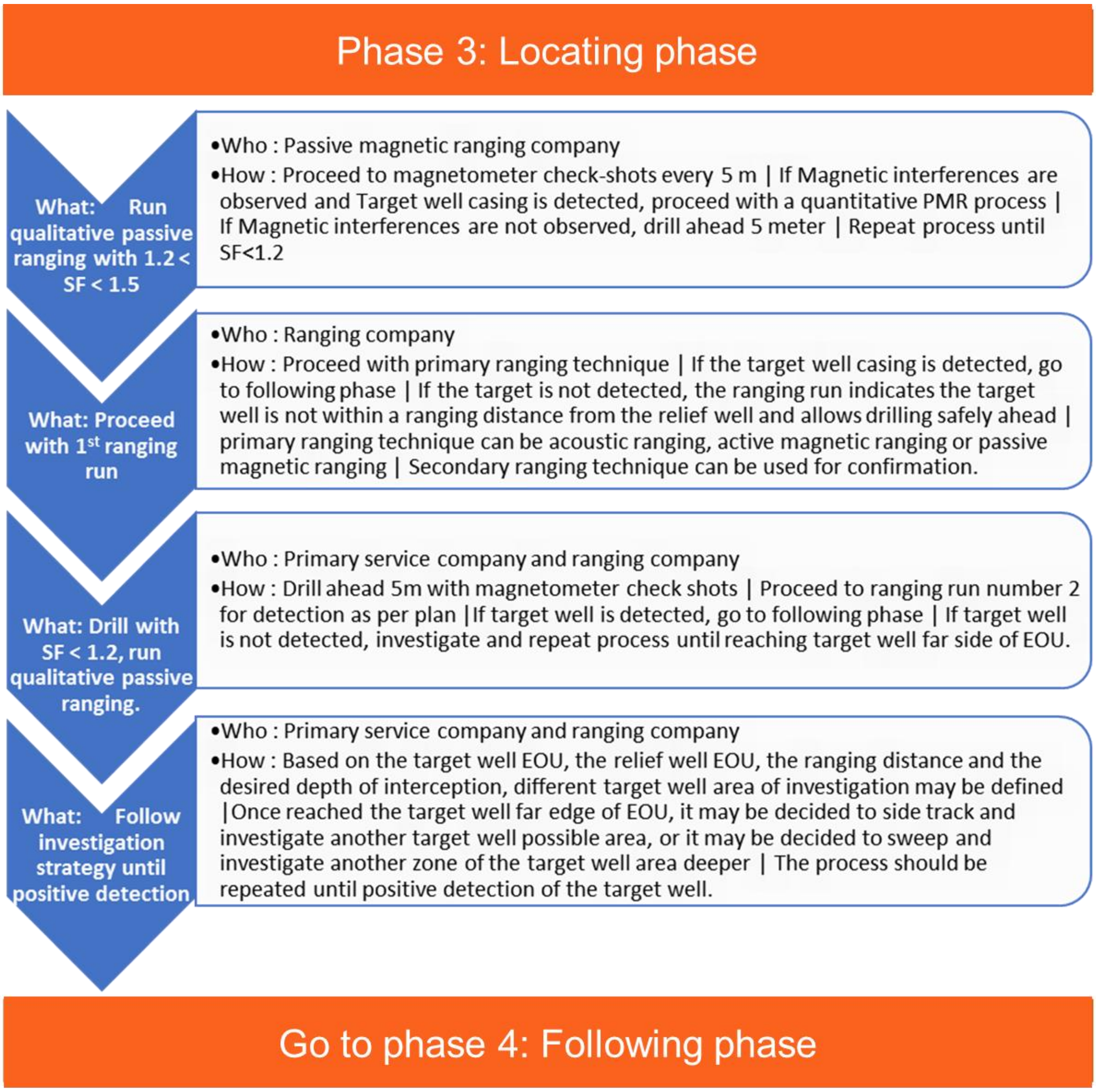


Figure 62—Phase 3: Locating phase key tasks and responsibilities

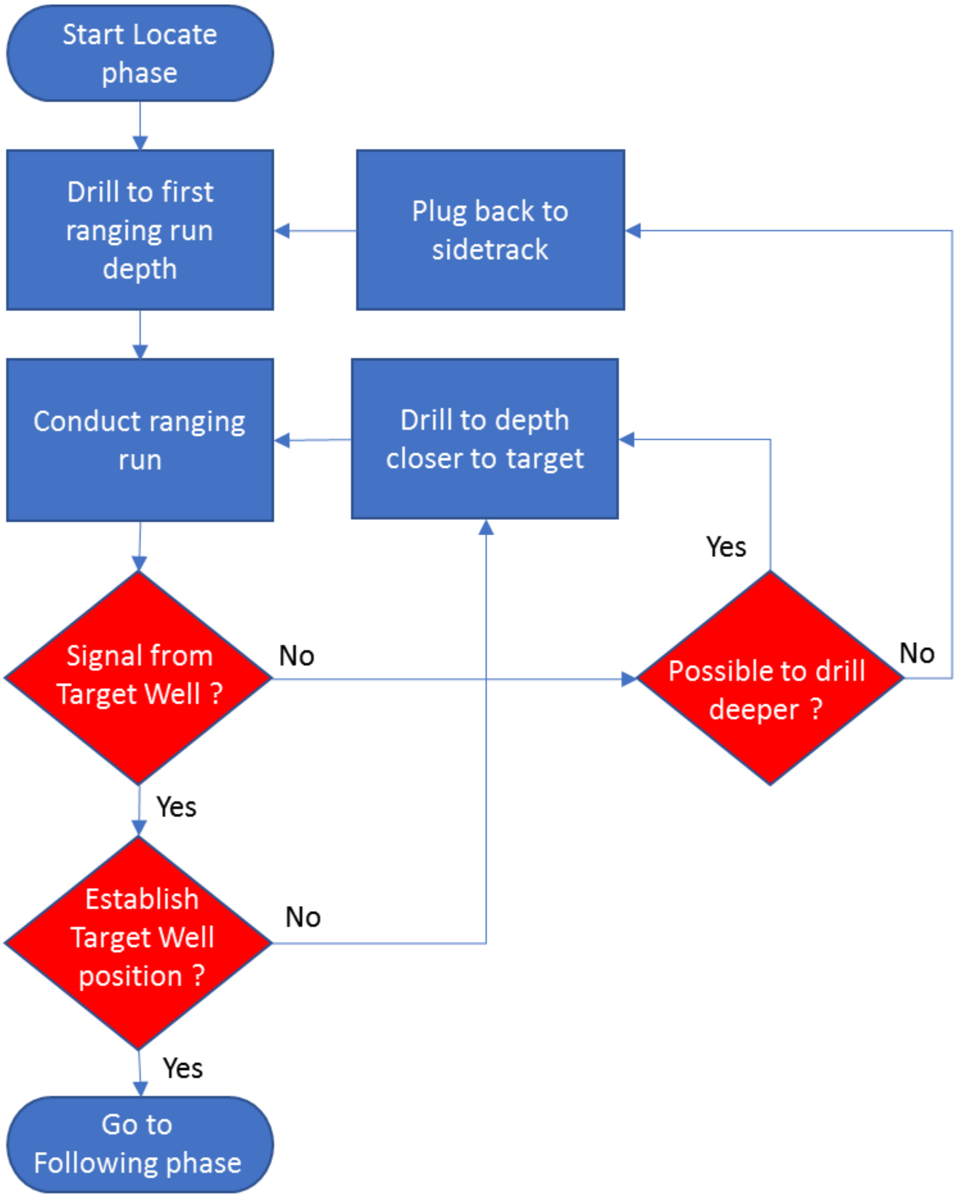


Figure 63—Locating phase ranging decision flow chart

The depth of the first ranging run will depend on:

- The detection range of the selected ranging tool as modelled 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 modelled detection range. This can be safely done if the separation factor remains higher than 1.

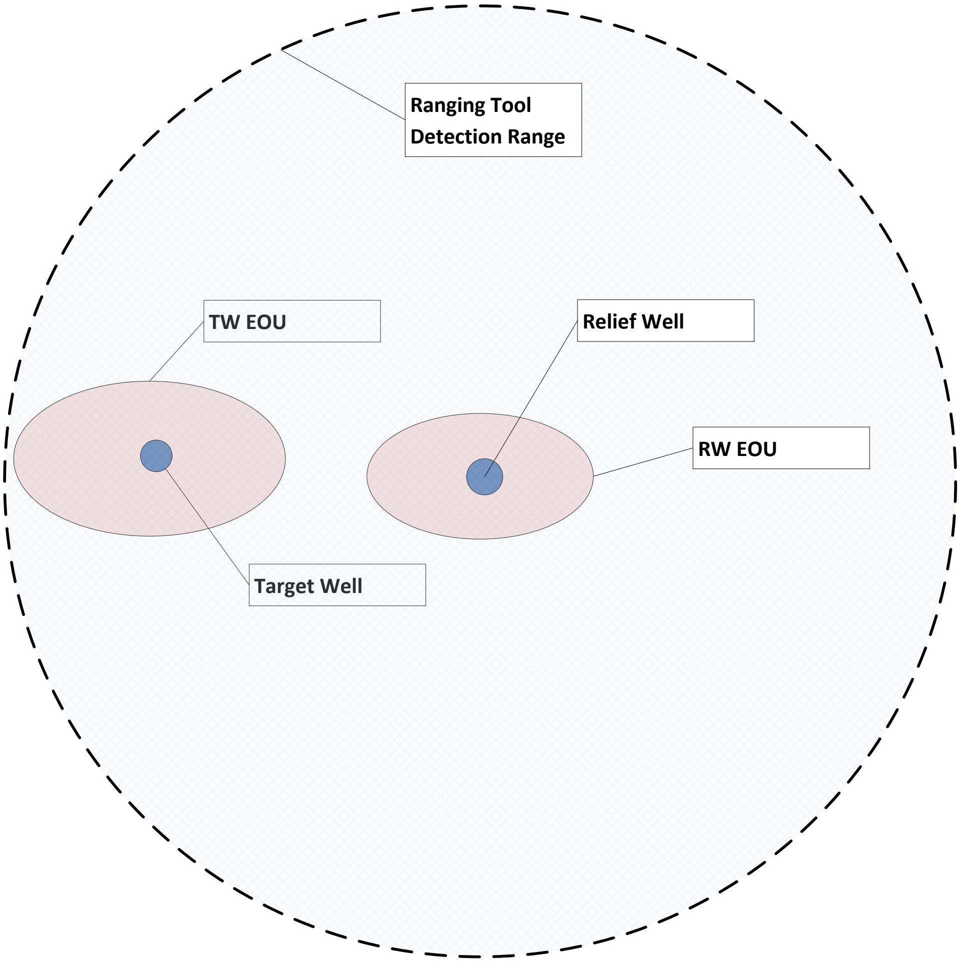


Figure 64—Ranging tool detection range

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 centre of their ellipses and detection is less than the centre to centre (c-c) separation of the wells.

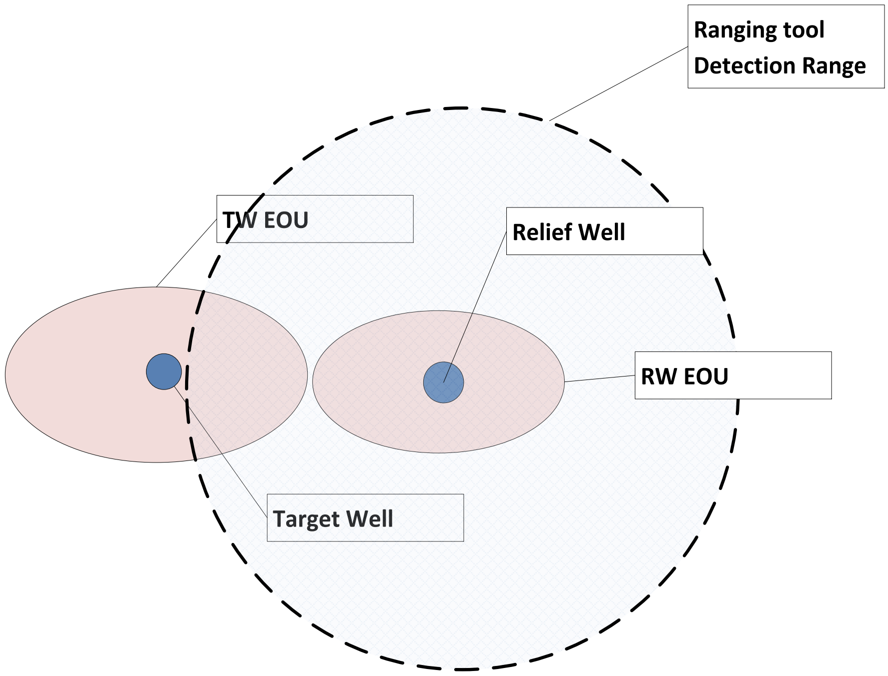


Figure 65—Anti-collision run

Once a ranging determination is complete, the results are reported in the ranging report as a direction and distance that have an associated ± ambiguity.

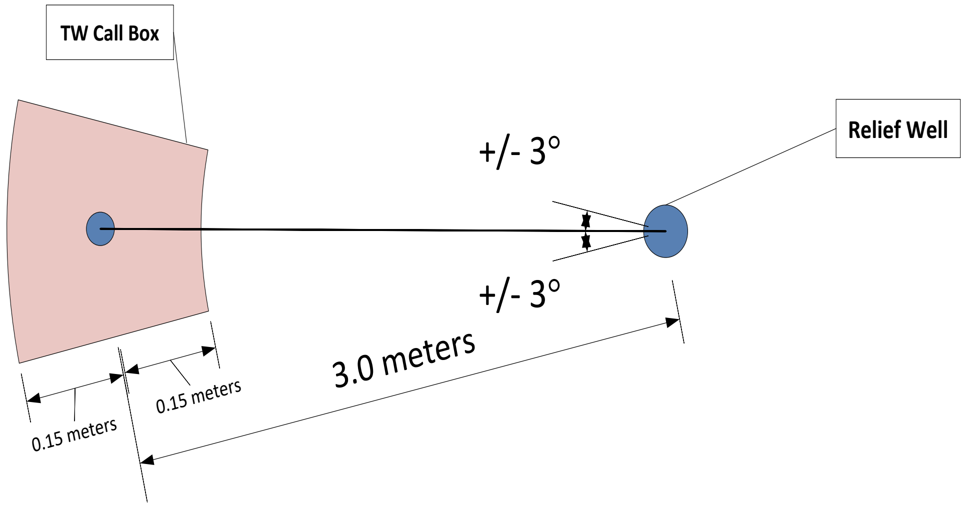


Figure 66—Ranging call with a direction of 270° + 3° and a distance of 3.0 meter + 0.15m

### 8.4.4 Following Phase

The objective of the Phase 4, Following phase, shown in Figure 67, is to track the target well by monitoring its relative positioning with the relief well. It is important at this stage to stay within the detection distance of one of the available ranging techniques. Being at such a close distance from the target well can even allow combining passive and active ranging techniques; hence, optimizing the ranging strategy.

However, the close proximity means that the relief well can suffer from the magnetic interference of the nearby casing, especially in case no Gyro MWD tool is used. To overcome this obstacle, the deviation of the relief well can be assessed based on directional analysis, taking into consideration the bottomhole assembly (BHA) description, sliding or steering sheets, and drilling parameters.

In addition, given that the close proximity can raise some sensitive risks, which could result in either losing the well or having to plugback and sidetrack, it is essential to make the best use of the multiple ranging runs that are performed during the following phase. In fact, the trajectories of the relief well and the target well are to be optimized to meet the successive ranging outputs. Such enhanced interpretation of the ranging results allows for constantly reducing the uncertainty on the next target well ranging position, which minimizes the directional corrections that must be applied to the relief well trajectory.

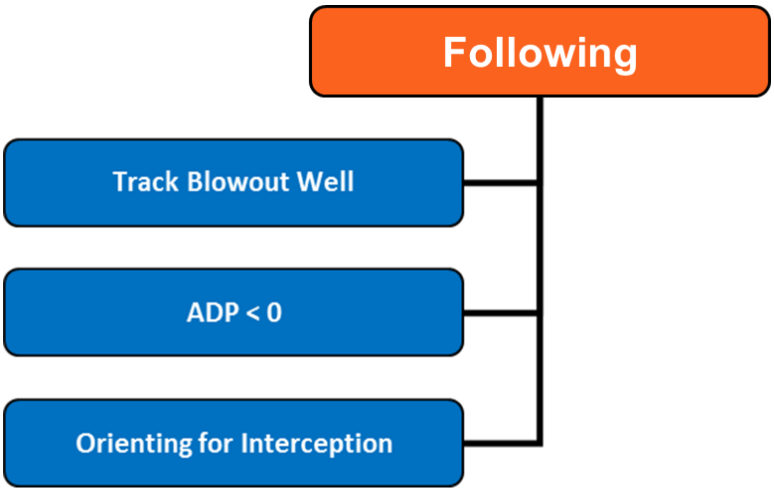


Figure 67—Following, ranging techniques selection & methodology for tracking to the required interception depth

During Phase 4, the Following phase, the well trajectory is designed so the target well can be tracked using simple MWD magnetic ranging in cased hole. A second “fly by”, this time much closer to the ultimate interception depth, kill point, can be considered before lining up for the intercept, usually within +/-100-ft MD above it.

An example of key element tasks and responsibilities in Phase 4, Following phase.

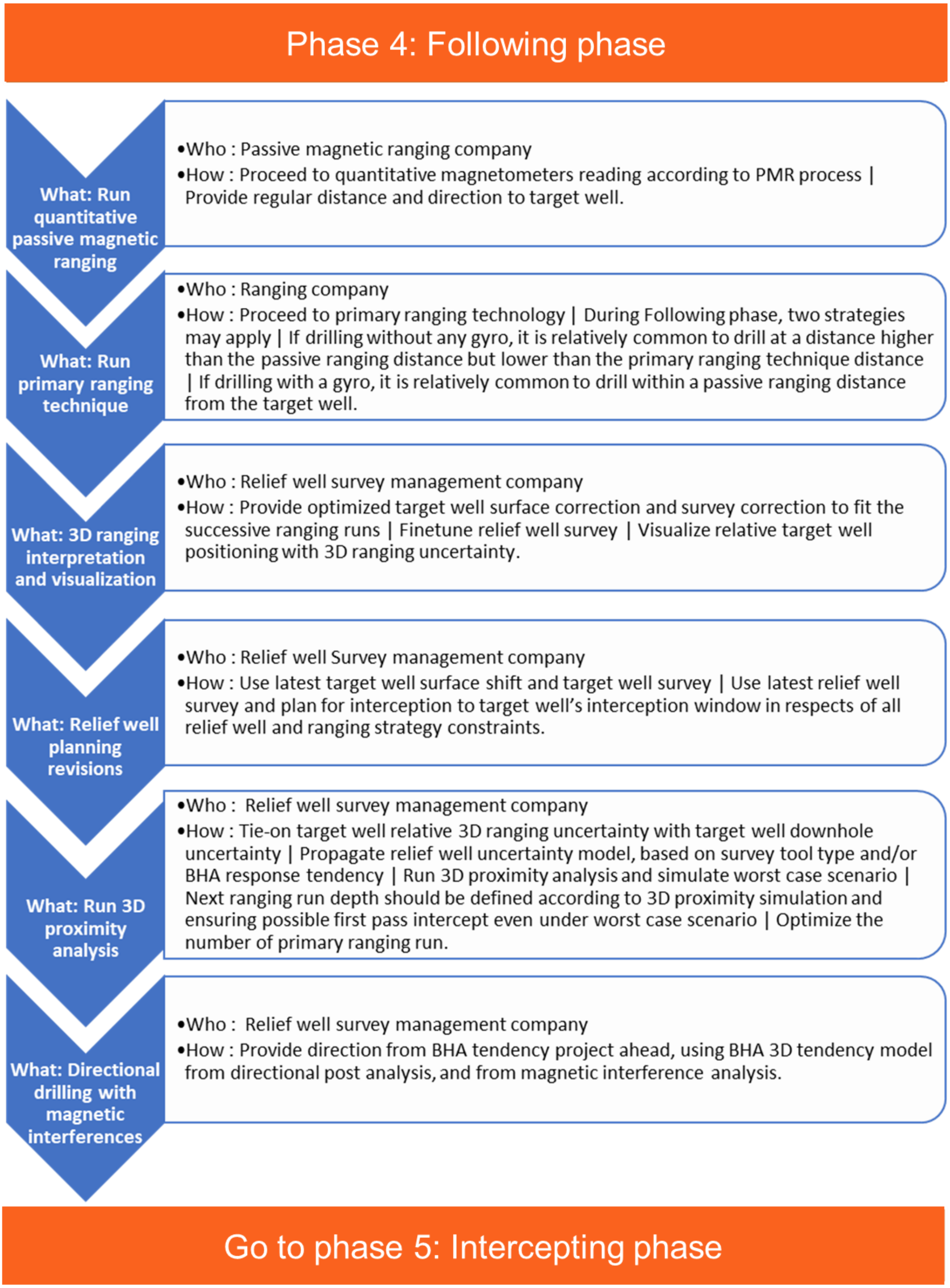


Figure 68—Phase 4: Following phase key tasks and responsibilities

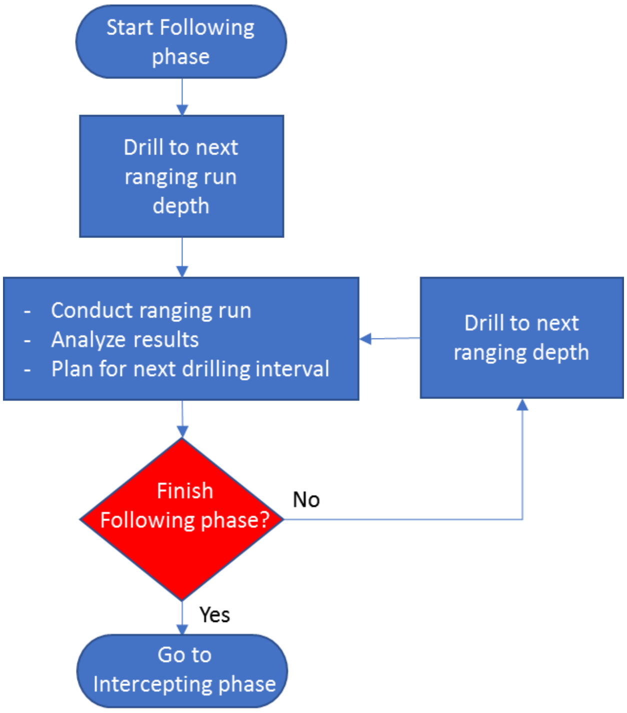


Figure 69—Following phase ranging decision flow chart

### 8.4.5 Intercepting Phase

The Phase 5, the Intercepting phase, shown in Figure 70, is the final objective in drilling a relief well; i.e., intercepting the target well. The interception angle depends on the communication option chosen; either parallel positioning between the target and relief well in the case of perforating, high-incidence angle in the case of direct intercept, or low-incidence angle in the case of re-entry into a milled window.

At this stage, the distance between the relief well and the target well is very small, which certainly does not mean that successful interception should be taken for granted. Therefore, it is important to use advanced 3D simulation tools to model the interception, considering the relative positioning between the wellbores and all possible scenarios for the final approach until the soft touch.

3D reverse ranging engineering process allows to modify the target well surveys to correspond to the ranging calls and improve the relative positioning between the intercepting well and the target well. Understanding the directional behaviour of the target well from the 3D reverse ranging process is key to ensure a successful intercept on the first attempt.

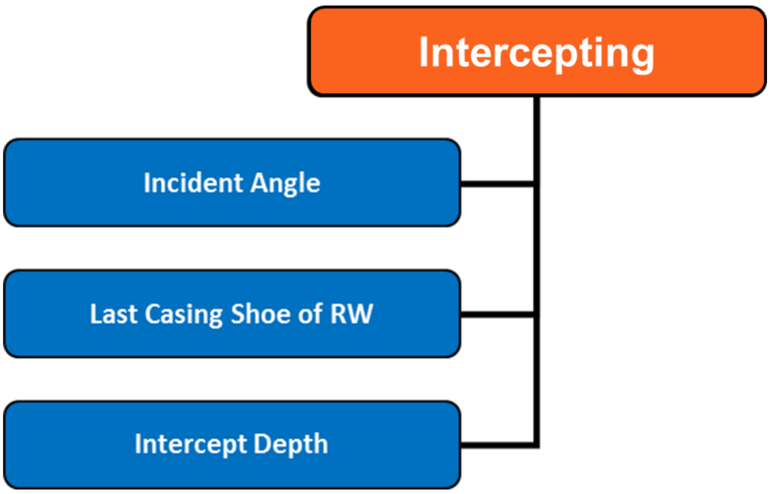


Figure 70—Intercepting, techniques and methodologies to allow positive interception

In Phase 5, the final relief well trajectory is normally designed so that it can intercept at a low angle of incidence (< 5°). This will successfully allow a breach to the blowout well near the last casing shoe, above the target hydrocarbon-bearing zone.

An example of key element tasks and responsibilities in Phase 5, Intercepting phase.

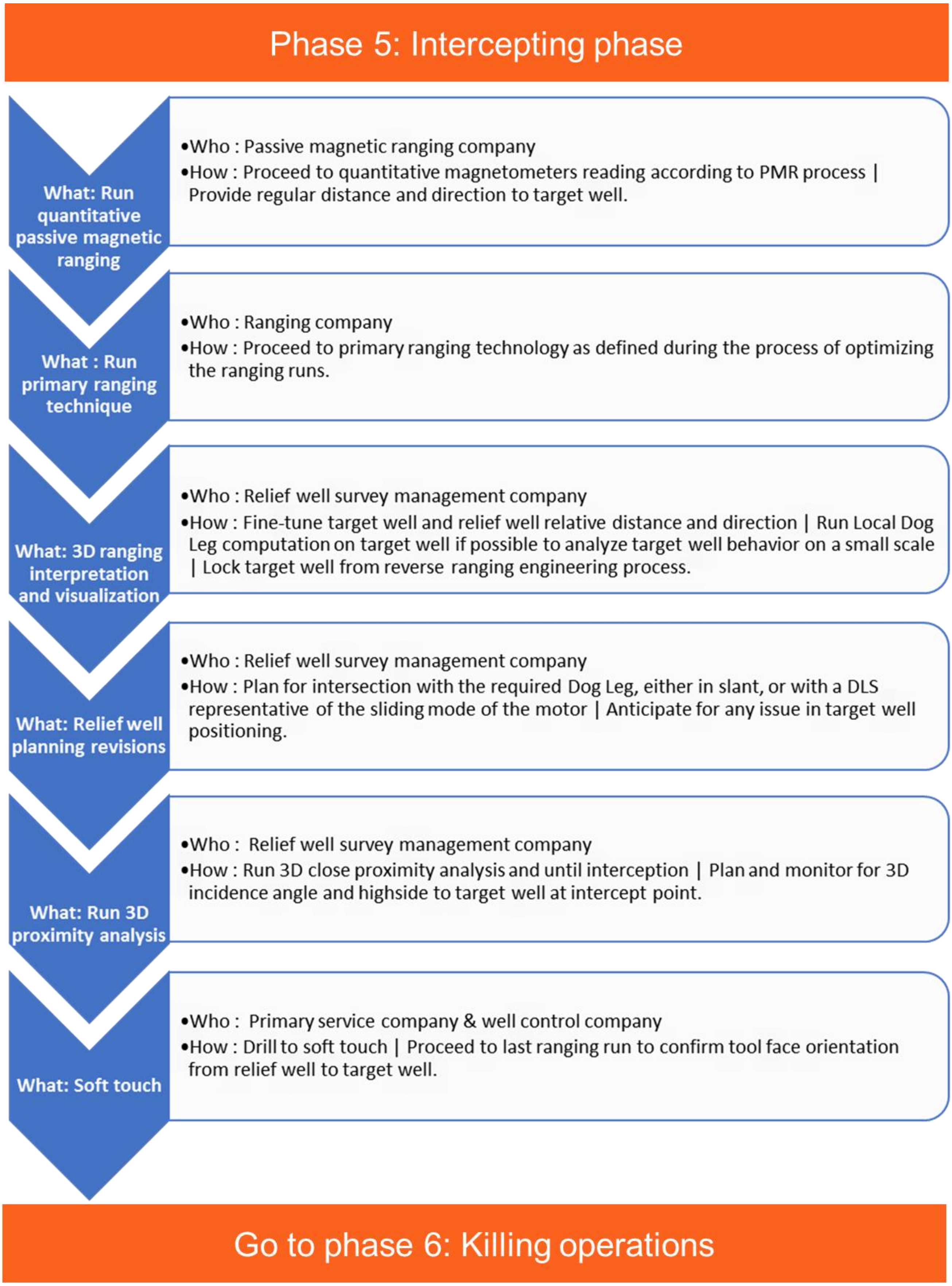


**Figure 71—Phase 5: Intercepting phase key tasks and responsibilities.**

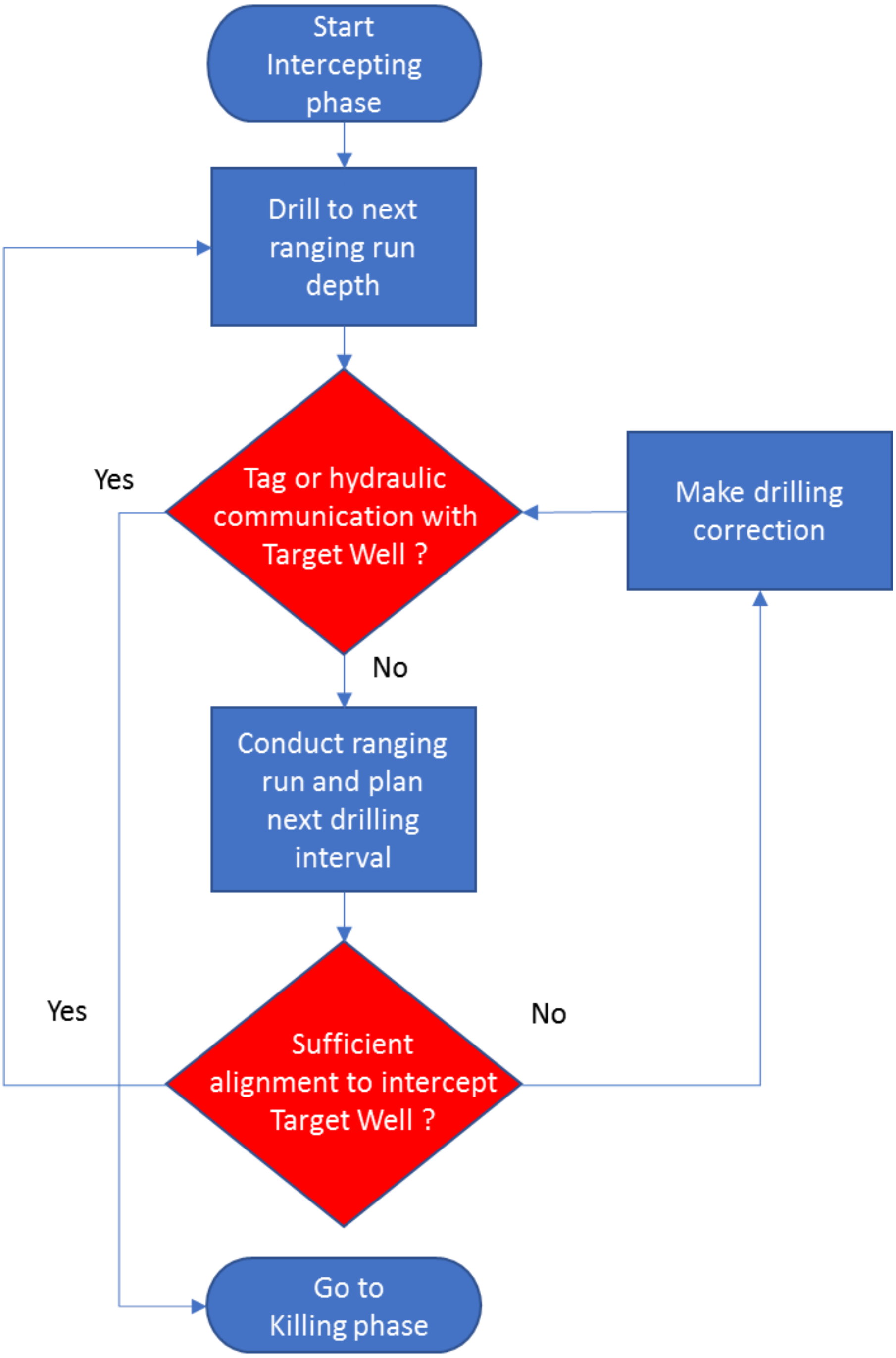


**Figure 72—Intersecting phase ranging decision flow chart**

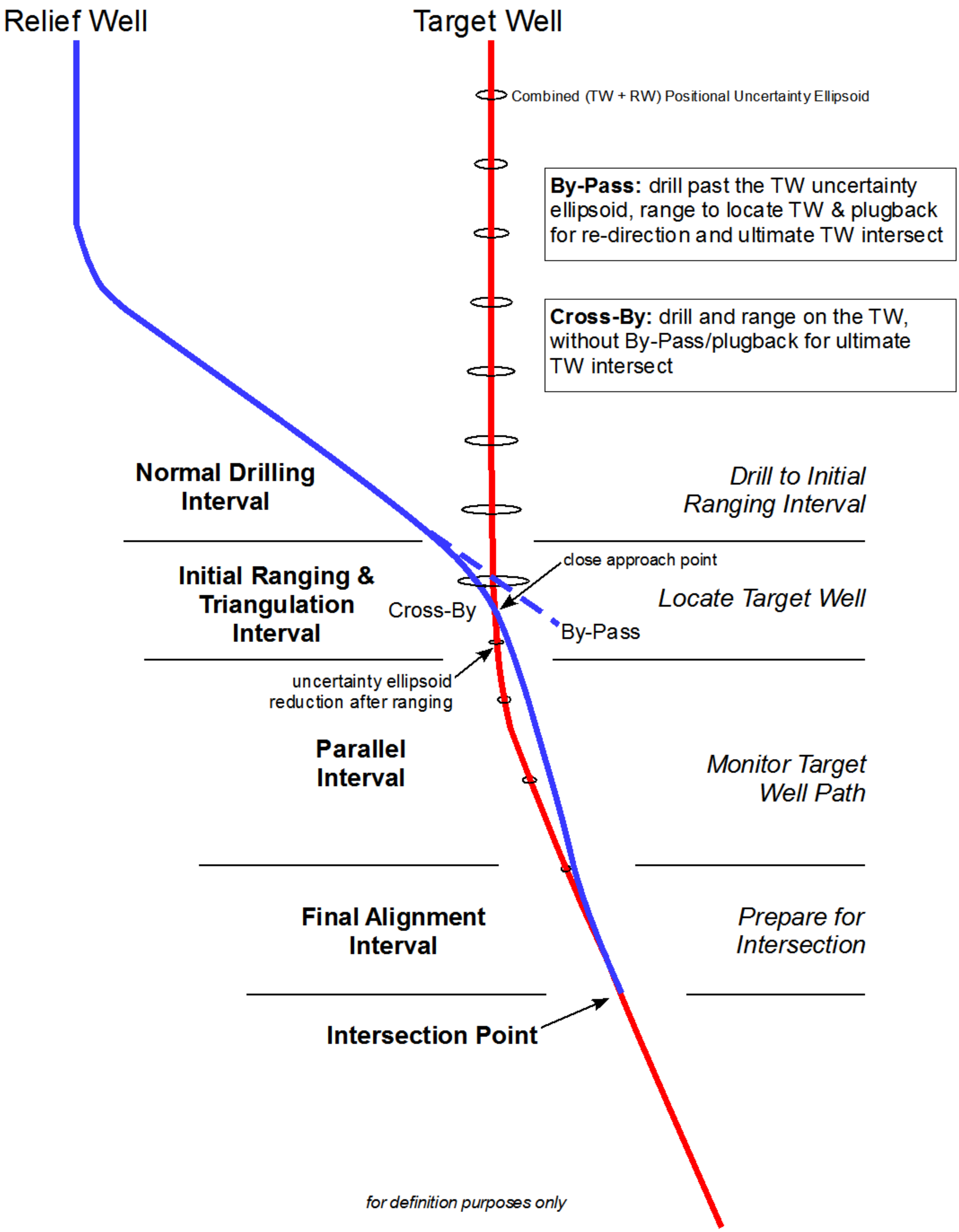


Figure 73—A diagram depicting a general breakdown of relief well elements

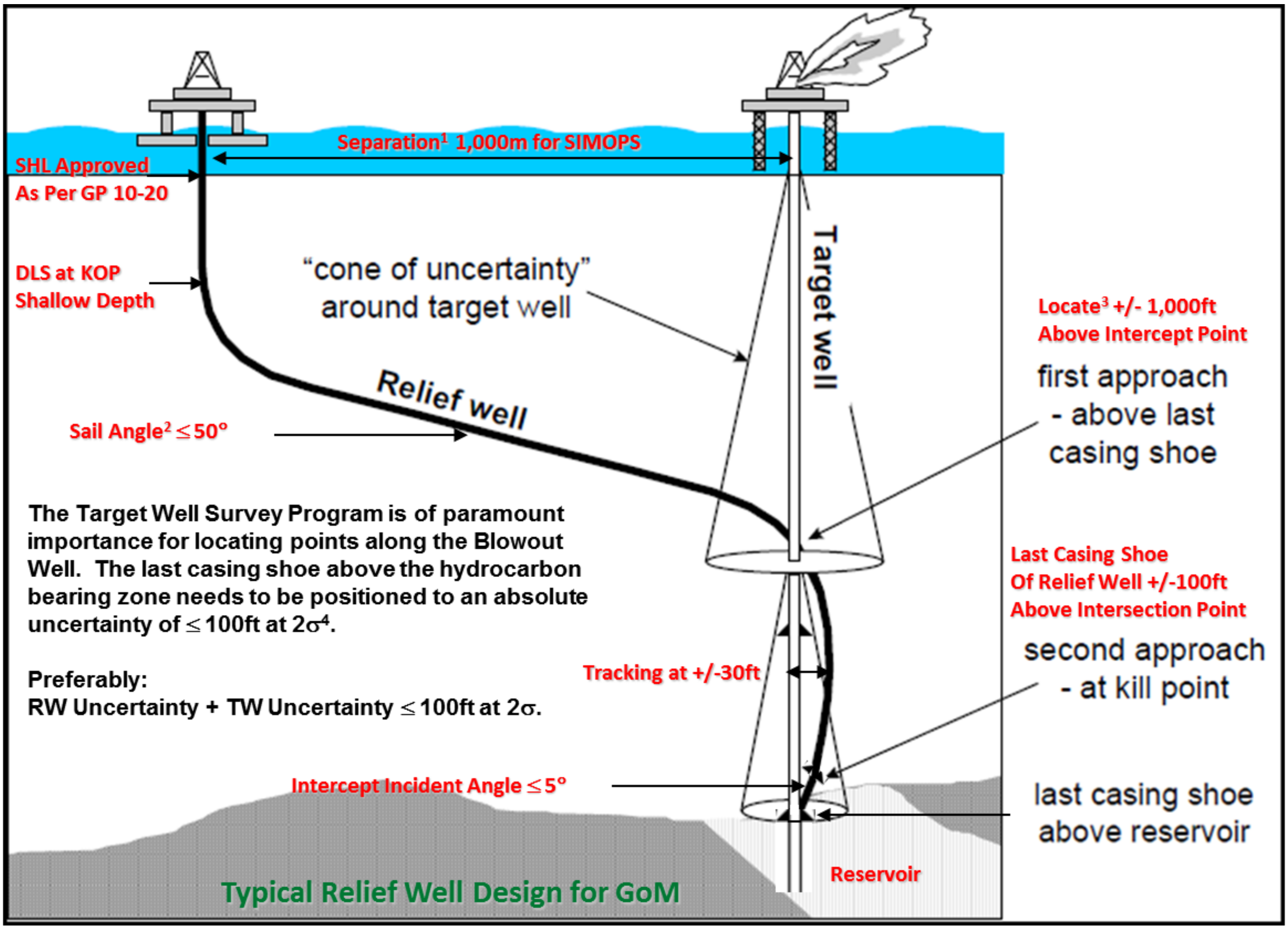


Figure 74—A typical example of relief well trajectory in GOM

An example as shown in Figure 73, following the Locate phase using magnetic ranging technique, a "pass-by" (also known as a "flyby"), is performed for triangulation to reduce the well-to-well distance uncertainty and maintain the 2D profile.

Triangulating from the relief well to the target well is essential for fixing the target well in relative 3D space. Following the Locate and "triangulate" phases, pass-by or not, it is advisable to "track" the target well to the intercept depth.

The well interception planning process starts with the last phase, the Intercept. Not all well interceptions are meant to provide pipe-on-pipe contact. The objective may be to hydraulically communicate near the target wellbore rather than a direct hit or re-entry. These outcomes require working from the final objective back to Phase 1. This Quick Guide begins at the well intercept (Phase 5) and continues to the start of the well drilling (Phase 2).

In well intercept strategies, planning for less complex 2D profiles is often preferred. Figure 74 above depicts a typical relief well design for the Gulf of Mexico wells based on the Oriented Intercept technique. The diagram captures minimum inputs and boundaries to lead to an optimum design.

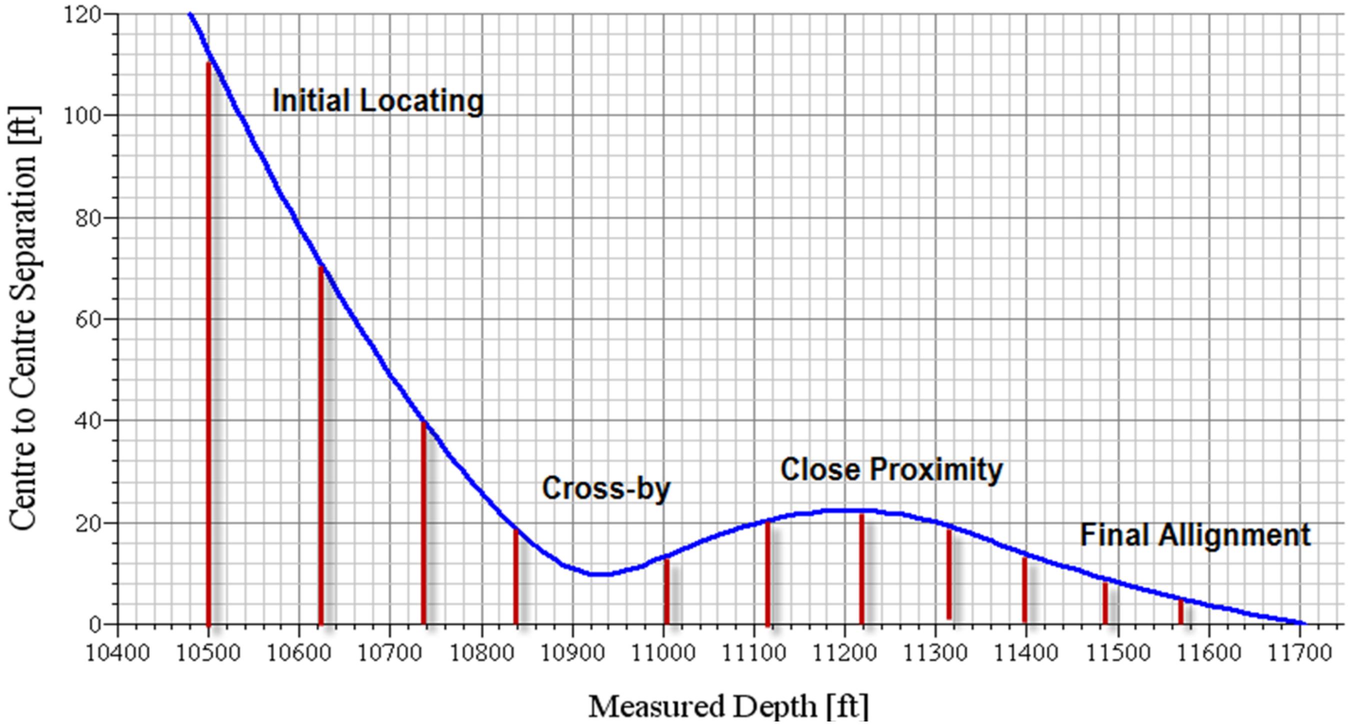


Figure 75 - An example of relief well centre-to-centre distance to the target well plotted by measured depth

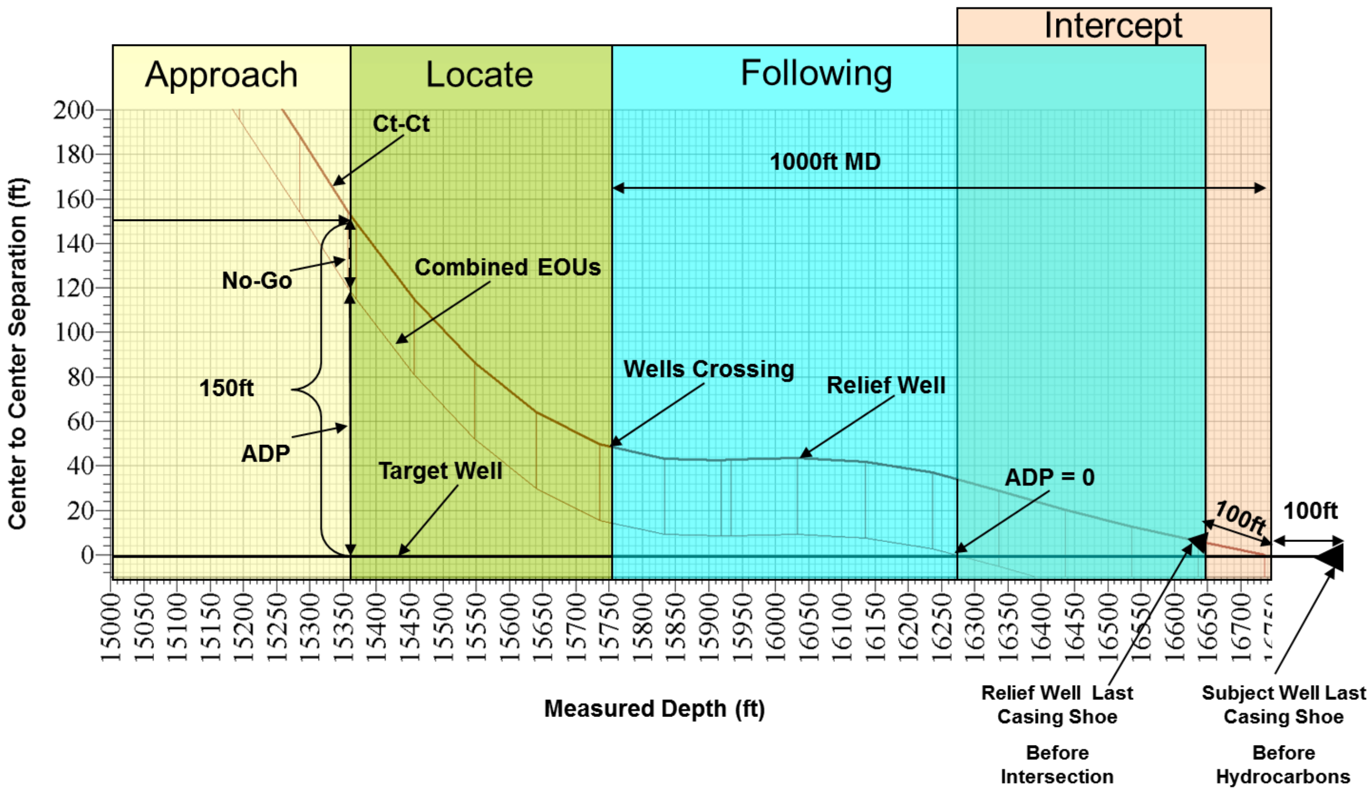


Figure 76—An example of GOM relief well ladder plot, centre-to-centre distance to the target relative to the relief well. Based on MWD + IFR + MS Surveys and BP Major Risk Criteria for the EOU calculation

The Figure 75 shows four of the five major phases associated with the relief well plan and can be used to perform quality control (QC) on the relief well trajectory design. As current active magnetic ranging technology is not capable in the salt body, therefore the plot shall also include markers indicating the top of salt (TOS) and base of salt (BOS).

Additional information from the data gathering and while drilling can also be included in this plot for completeness, for example:

- TOS and BOS – to determine ranging interval

- Sail angle of the Relief Well < 50˚ unless intercept point is shallow
- By Pass angle at the Locate Point
- EOU at the last casing shoe prior to intersection
- Intersect Angle < 5˚

## 8.5 Relief Well Survey Management

Relief well Survey Management (SM) is 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. SM may also include IFR2 services or localized magnetic field variometer monitoring to exclude diurnal “noise” from extended PMR operations.

## 8.6 Relief Well Planning Personnel

In today’s drilling environment, successful relief well drilling is dependent on teamwork between the oil company, drilling contractor, and service and other secondary contractors. The oil company is the sole responsible party to make final decisions based on the recommendations and conclusions of the relief well team experts.

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 considering 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
- Survey Management Specialist
    - Assist in analysis of existing target well data to refine target potential
    - Analyse all survey data as acquired, both geometric and ranging to confirm relative locations
    - Assess congruency of actual ranging data to predicted target trajectory to advise on ranging frequency or allowable drilling intervals
    - Assist Well Planner, Interception Specialist and Ranging Specialist in formulating further safe drilling operations
    - Monitor local magnetic field conditions through the monitoring station, especially if extended PMR operations are undertaken
- 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

## 8.7 Reporting

As relief well operation progresses, a relevant and unique report shall be issued. These reports can be summarized into three categories:

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

### 8.7.1 Ranging Plan

This “Ranging Plan” is the initial pre-job study developed for the operator. This study encompasses all relevant information and challenges that the operator 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 relief well challenges and the solution to be provided
- Analysis - A modelled analysis based on the Well plans, Formation Type, Casing Models, and Resistivity.
- Modelled Results - Simulated results based on the initial analysis
- Phases of Ranging- Provides a predictive 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

### 8.7.2 Ranging Report

The Ranging Run Report is a key tool in keeping the operator 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 – List all personnel 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 centre 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 of 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 and should include a revised relative position of the target well to the relief well position

### 8.7.3 Project Summary

The project summary report is a brief report containing an executive summary of the current relief well operation and operations in the next 6 hours or less, plan versus results and the plan of actions. The reports purpose is to fully inform everyone involved on the progress as well as update them as to when their expertise will be required in the operations.

# 9. Well Intersection Design Fundamentals

Typically, 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 Target Well (TW). 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.

## 9.1 Types of Well-to-Well Intersections

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

### 9.1.1 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 open hole or casing, or in a remedial operation where a mechanical and/or hydraulic operation is necessary to meet the project's objectives.

### 9.1.2 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.

## 9.2 Establishing Hydraulic Communication

After achieving the intersection, whether open hole, 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.)

### 9.2.1 Geometric

The geometric method of establishing hydraulic communication can occur instantaneously as in the case of a direct open hole intersection, or it may require additional equipment or methods. The geometric method includes direct open hole, 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 open hole intersections are the most simplistic and quickest to gain hydraulic access to the target well, with open hole or annulus intersections as the most common.

### 9.2.2 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 77).

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 Interception Well (IW) can be built to test the actual perforating results.

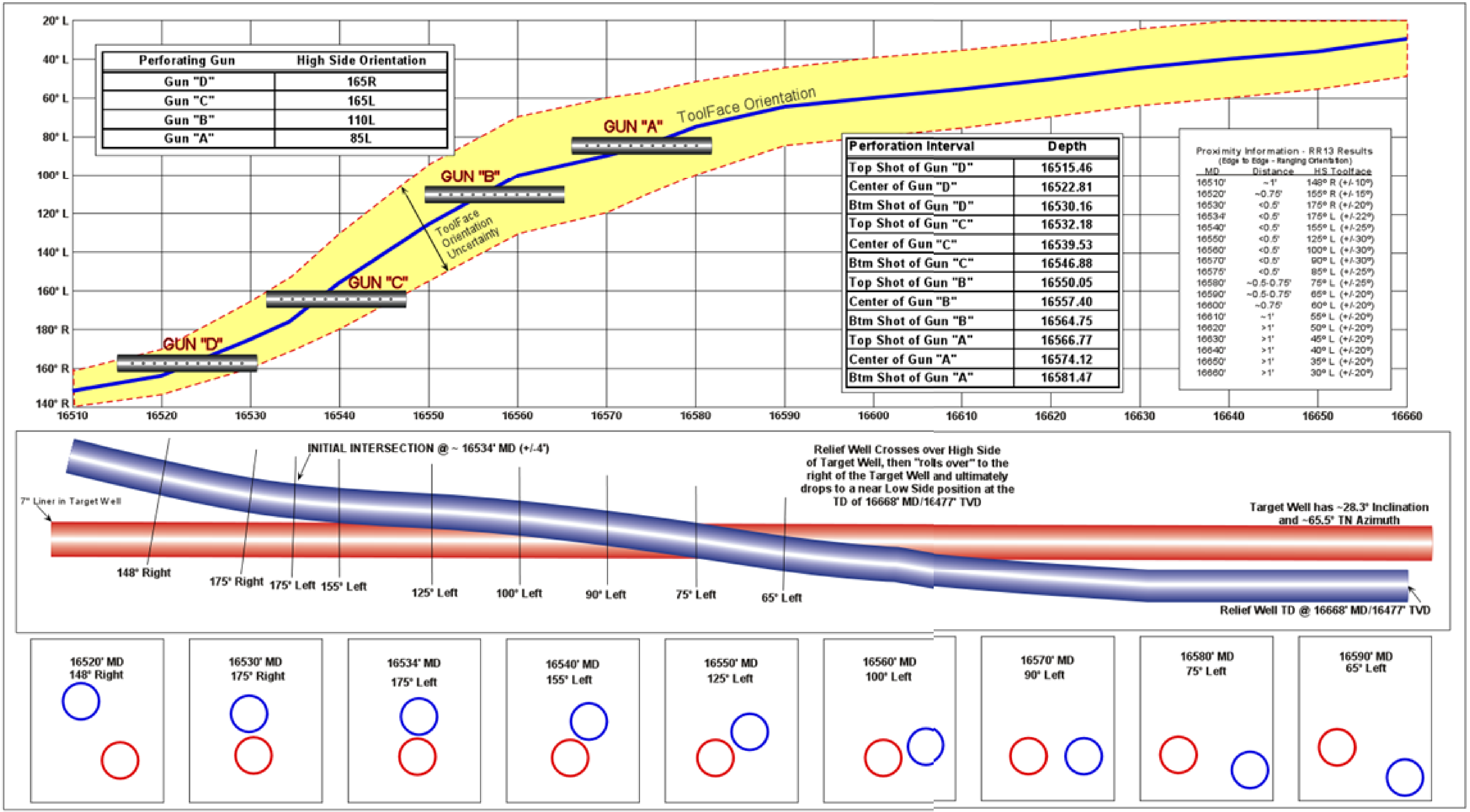


Figure 77—Example perforating method to establish hydraulic communication

### 9.2.3 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 centreline 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 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 78). 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 (Figure 79).

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

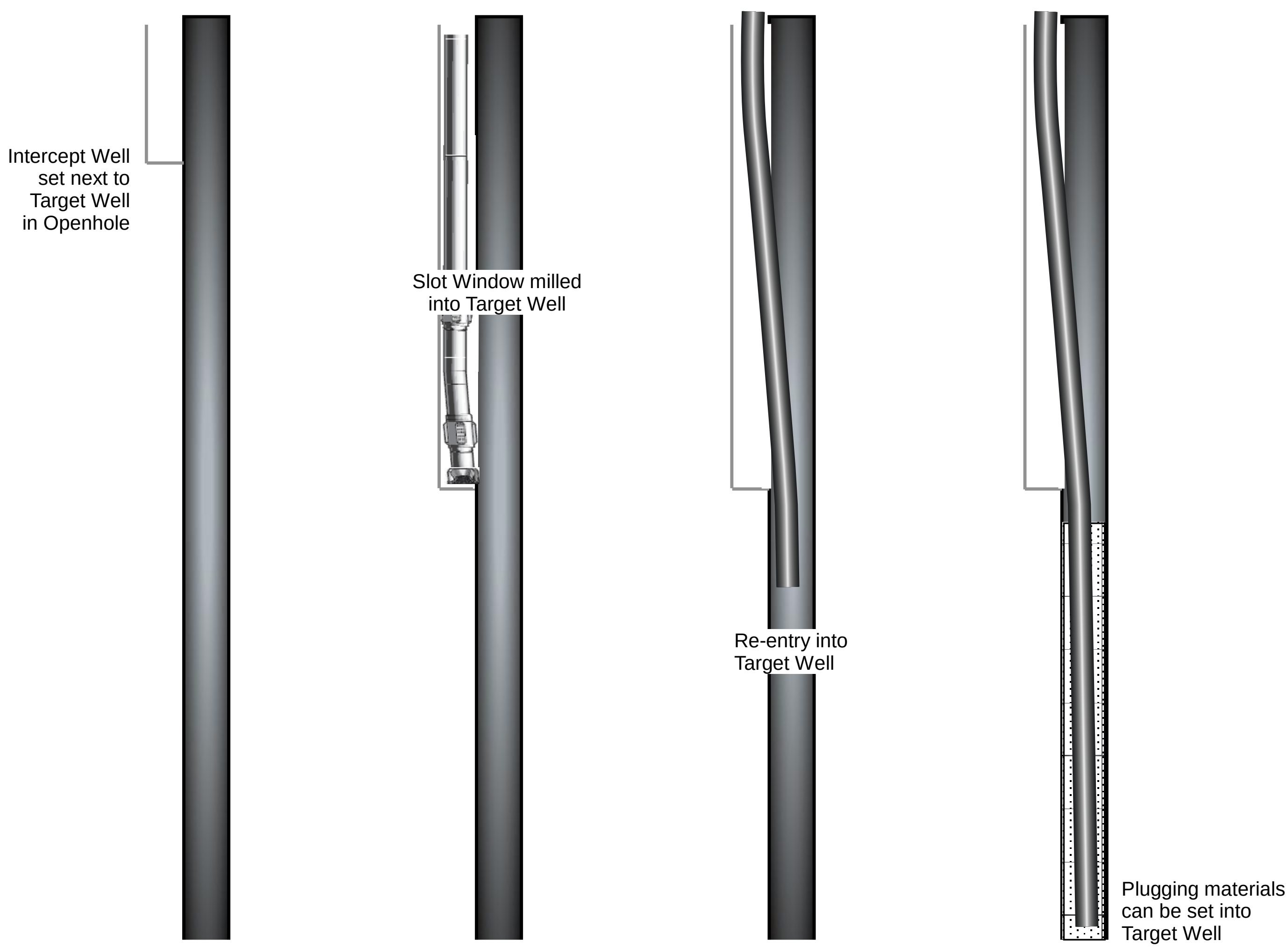


**Figure 78—Slot milling method concept**


Figure 79—Cased hole whipstock milling method concept

### 9.2.4 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, can 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 tool string). 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.

## 9.3 Typical Equipment and Methods

### 9.3.1 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.

### 9.3.2 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.

### 9.3.3 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, fracing, and well killing operations
- Specialized milling equipment, whip-stocks, etc.

## 9.4 Killing Operations Phase

Following the successful intercepting phase, the first step of Phase 6, killing operation phase, shown in Figure 80, is to successfully establish communication between the relief well and the target well by hydraulic communication, milling, or perforating. In this latter case, performing perforating simulations is recommended to select the perforating gun size, density, orientation, and the resulting penetration diameter into the target well casing. In addition, for a high-profile relief well, it is recommended that surface tests be performed to validate the final option.

If the milling option is selected, modelling the milling operation is important, including the detailed description of the milling assembly, the relative positioning between wellbores, and the completion dimensions. The milling modelling allows for assessing the milled window characteristics (shape, length, width, flow area, etc.) in different possible scenarios, with the objective being to simplify the decision making in selecting the best operational milling parameters.

An example of key element tasks and responsibilities in Phase 6, Killing operation phase.


Figure 80—Phase 6: Killing operation phase key tasks and responsibilities

### 9.4.1 Pump to Kill

During this phase, kill mud is pumped into the target well to stop the flow. The kill mud properties are defined at the planning phase based on the killing simulations (density, volume, flow rate, etc.).

### 9.4.2 Stabilize Well

The objective of stabilizing the well process is to allow for reducing the high-pumping rate used in the Pump-to-Kill step to a reasonable level until the target well is stable. Kill mud continues to be injected while carefully monitoring the pressure and mud volume.

## 9.5 Plug and Abandonment Phase

This final phase of the relief well process, Phase 7, the plug and abandon phase as shown in Figure 81, aims to properly plug and abandon the target well in a secured manner. The plugging requirements depend on the local regulatory bodies, but the general objective is to inject cement into the target well to ensure that the productive zone is permanently isolated. Bridge plugs could be required in addition in some cases. Pressure tests are undertaken to ensure target well integrity.

An example of key element tasks and responsibilities in Phase 7, Plug and abandon phase.

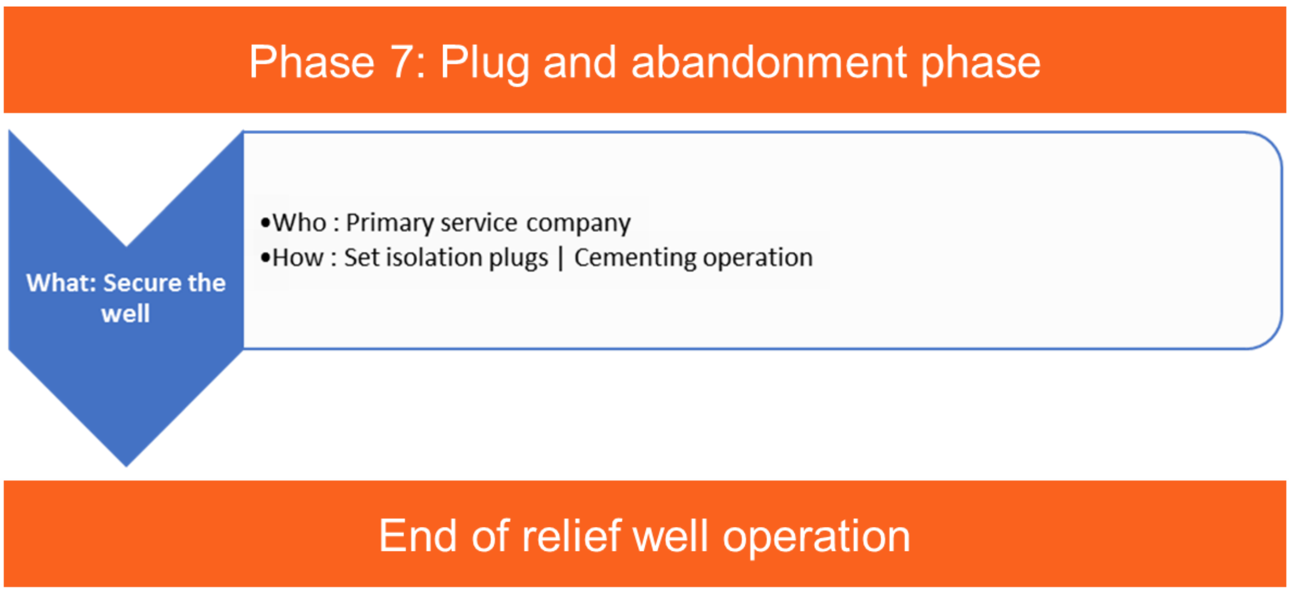


Figure 81—Phase 7: Plug and abandonment key tasks and responsibilities

## 9.6 Organization

With an average of only two to three 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.

Intersection well planning and execution 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 wells 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.

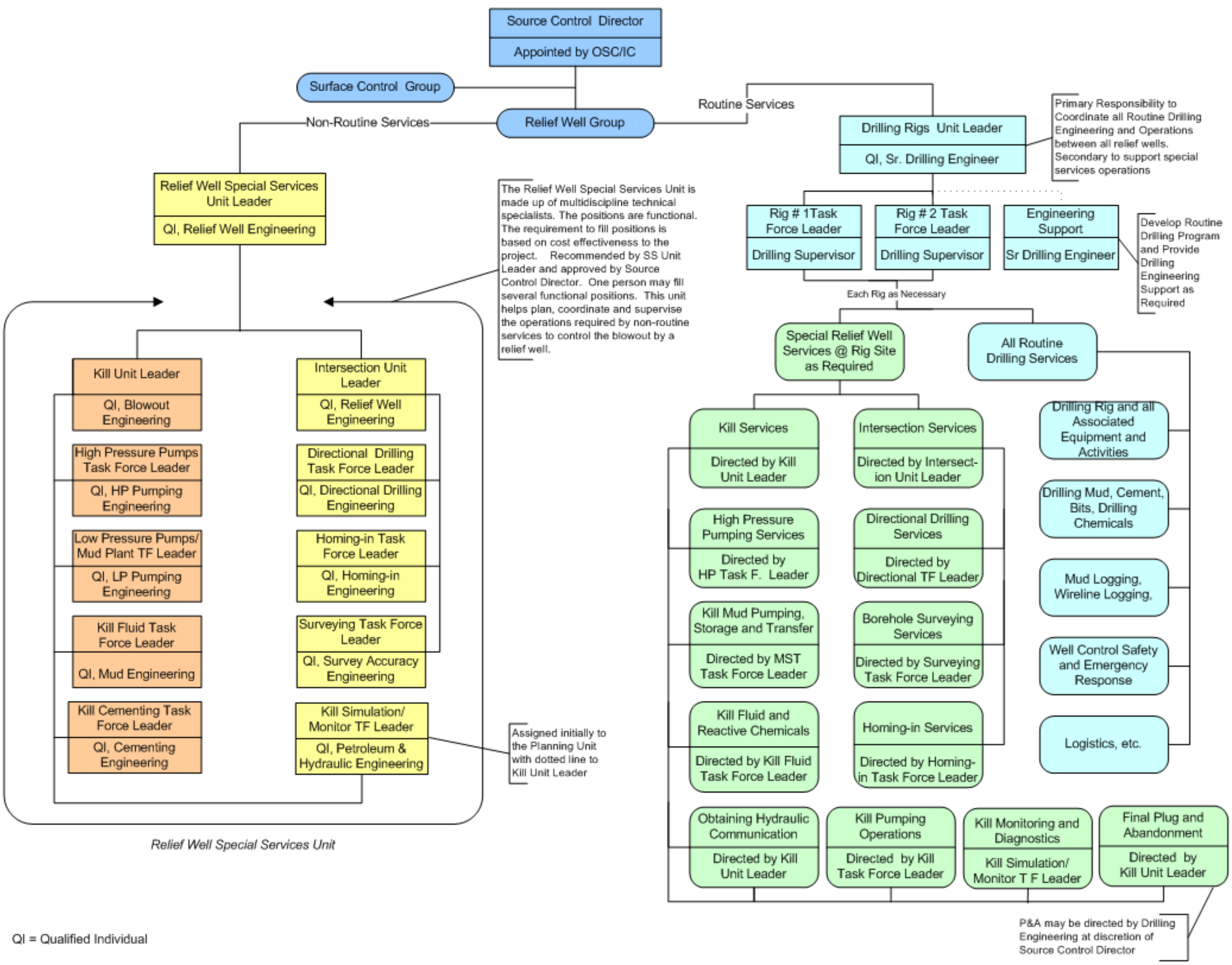


**Figure 82—Example of relief well team organization**

# Well Interception Lexicon

| 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. |
| Approach, Approach phase | A drilling stage where the trajectory objective is to get closer to the target well until reaching the desire detection range. |
| Attack Angle | See Angle of Incidence |
| Angle of Incidence | The relative angle between two wells, expressed in degrees (°), 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. |
| Bowtie, Bow tie | A risk mapping method that visualizes the risk in a single image, creating a clear differentiation between the preventive and reactive mitigation actions. |
| Bxy | 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. |

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| ct-ct | Centre to Centre distance, is the measured distance between the centre of two offset wellbores. |
| Degaussing | 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 dipole source is a directional source that generates an acoustics signal that excites the media in a direction perpendicular to the propagation direction. |
| 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 represents 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 represents 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. |

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| Follow, Following phase | A drilling stage after locate phase where the trajectory objective to follow the target well to ensure positive detection at all time until reaching the desired intercept depth |
| 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. |
| Hazard and Risk Control (HARC) | A standard process and tools to identify hazards, assessing associated risk and defining required control measures. |
| 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 drilling 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 Chapter 9. |
| Intercept Point | The point along the subject wellbore where the relief well intersects the subject well. |
| Killing, Killing phase | The operation after intercepting phase with the main objective to perform killing operations then will be followed with stabilize prior plug and abandonment operations |
| 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 centres or positional uncertainty ellipses. |
| Locate, Locate Phase | 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 Dipole | A steel component having both a North and South magnetic pole. It is also defined as |

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| 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 Monopole | A single North or South magnetic pole. Does not actually exist in nature but can be a useful mathematical construct. |
| 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 type of source that 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. |
| 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 |

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| | 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 close 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. |

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| 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 an 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. Also known as Energized Wire Active Magnetic Ranging. |
| STOP | A safety program that required all relevant personnel to think, identify risk (s) and authorized to stop the operations to ensure no lapse (s) in safety and quality. STOP can be applied anytime, anywhere, by following the proper procedure |
| 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. |
| Twinning | 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. |

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| 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. |

# Well Interception Bibliography


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|---|
| World Oil December 2001, pgs 61-64; "Relief Well Drilling Operations Allow Re-Entry and Control of a Blowout Well"; David Barnett |
| Well Logging and Formation Evaluation, Chapter 12; "Homing in Techniques"; Toby Darling |
| SPE/IADC 092685; "U-Tube Wells – Connecting Horizontal Wells End to End Case Study: Installation and Well Construction of the Worlds First U-Tube Well"; Dean Lee, Richard Hay, Fernando Brandao |
| SPE 187313; "Active Acoustic Ranging to Locate Two Nearby Wellbores in Deepwater Gulf of Mexico"; Benny Poedjono, Samer Alatrach and Albert Martin, SPE, Schlumberger; and Roger B. Goobie, William T. Allen, and Eugene Sweeney, SPE, BP |
| SPE 186901; "Managing Risks in Relief Well Operations: From Planning to Execution"; Poedjono, B., SPE, Schlumberger; and Macresy, L. and Sikal, A., SPE, PathControl |
| SPE 174479; "Thinking Beyond the Conventional – A Case Story of Using a Surface Read out Wireline Device while Ranging to Reduce Risk of Failure During Drilling of a Sagd Well in Hot Zone"; Jeremy Ray, Welltec |
| SPE 173160; "Multiple Relief Well Planning for an HPHT Blowout in Southern Mexico"; Rodrigo Varela, Schlumberger; Freddy Iturrizaga, Schlumberger; Diego Patino, Schlumberger; Nixklafe Atencio, Schlumberger; Daniel Romero, Schlumberger; Oscar Buitrago, Schlumberger; Javier Pineda, Pemex |
| SPE 173135; " High Speed, Continuous Single Well Magnetic Ranging"; F. Chad Hanak, Intuitive Machines; Robert Estes, Baker Hughes |
| SPE 173097; "A Guide to Relief Well Trajectory Design using Multidisciplinary Collaborative Well Planning Technology"; Roger B. Goobie, BP; William T. Allen, BP; Barbara M. Lasley, BP; Kent Corser, BP; Jose Patino Perez, Halliburton |
| SPE 171275; "Improvement of Drilling Technology for the Yarega Heavy Oil Field Development by SAGD Method With Counter Producing and Injecting Wells"; Denis S. Loparev, Lukoil-Engineering; Mikhail V. Chertenkov, Lukoil; George V. Buslaev, USTU Oil and Gas R&D Institute; Asif A. Yusifov, Scientific Drilling International; Aleksey V. Klyavlin, Scientific Drilling International |
| SPE 168051; "Combining MWD Ranging Technology And Gyro While Drilling (GWD) In High Inclination Wellbores Deliver Reduced Drilling Costs And Complexity Without Compromising Safety"; C. H. Duck, Sperry a Halliburton company; K. Beattie, Gyrodata Inc.; R. Lowdon, Schlumberger; G. McElhinney, Solutions 52 Ltd |
| SPE 168029; "Relief Well Planning"; Vanessa Flores, Penny Dailey, David Todd, Rohit Mathur and Brian Donadieu, Baker Hughes; Presented at the IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas, USA, 4–6 March |
| SPE 167994; "Relief Well Drilling Using Surface Seismic While Drilling"; Kristoffer Evensen, Sigbjorn Sangesland, Staale Emil Johansen, Espen Birger Raknes, Borge Arntsen, Norwegian University of Science & Technology |
| SPE 167984; "Directional Challenges and Planning of Relief Well to Resolve an HP/HT Well Blowout"; M Al-Muhailan, Kuwait Oil Company; Ali Al-Saleh, Kuwait Oil Company; A K Al-Shayji, Kuwait Oil Company; Arun Rajagopalan, Kuwait Oil Company; D C McKinnell, Total Kuwait; |

| |
|---|
| SPE 163411; “Well Bore Collision Avoidance and Interceptions – State of the Art”; John P. de Wardt, De Wardt and Company; Steve Mullin, Gyrodata; John L. Thorogood, Global Drilling; John Wright, Bearco; Robert Bacon, BP |
| SPE 159405; “New Logging-While-Drilling Ranging Technique for SAGD; Theory and Experiment”; Michael Bittar, Hsu-Hsiang Wu and Shanjun Li, Halliburton |
| SPE 159404; “Well Planning Based On Passive Magnetic Ranging and Magnetized Casing”; Roger van Noort, SPE, Shell International Exploration and Production Inc, William Abrant, SPE, James Towle, SPE, Scientific Drilling International |
| SPE 159404; “Well Planning Based On Passive Magnetic MWD Ranging And Magnetized Casing”; Roger H. Van Noort, (Shell Intl. E&P Co.; Chip Abrant, Scientific Drilling; James N. Towle, Scientific Drlg Ltd |
| SPE 156119; “The First Relief Well Drilled in Qatar to Intersect, Kill, and Abandon an Underground Blowout”; Talib A. Al-Murri, Qatar Petroleum; Fawzi El-Faghi, Qatar Petroleum; Khalid Ahmad Al-Meer, Qatar Petroleum |
| SPE 155892; “One New Needle Technology of Remote Intersection between Two Wells and Applications in Chinese Coalbed Methane Basis”, Tian Zhonglan, Shen Ruichen and Qiao Lei, Research Institute of Drilling Engineering, CNPC |
| SPE 138287; “Field/Well Integrity Issues, Well Abandonment Planning and Workover Operations on an Inadequately Abandoned Well: Peace River Alberta Case Study”; Chris Diller, Shell Canada Ltd. |
| SPE 133129; “An Innovative Approach To Heat Heavy Oil Formations by Means of Two Horizontally Interconnected Wells”; Roberto Poloni, ENI E&P; Giuseppe Sassi, ENI E&P; Pietro Valente, ENI E&P; Antonio Di Campli, Baker Oil Tools; Daniele Bianchella, Baker Hughes |
| SPE 121040; “Anti-Collision Risk Management Standard for Well Placement”; Poedjono B., Lombardo J. Guy, and Phillips W., SPE, Schlumberger |
| SPE 119420; “Rotating Magnetic Ranging Service and Single Wire Guidance Tool Facilitates in Efficient Downhole Well Connections”; Ray Tommy Oskarsen, John Wright Co.; John Wayne Wright, John Wright Co.; David Winter, Vector Magnetics LLC; Don Fitterer, Vector Magnetics LLC; Anthony G. Nekut, Vector Magnetics; Jed E. Sheckler, Vector Magnetics |
| SPE 119420; “Rotating Magnet Ranging Service and Single Wire Guidance Tool Facilitates in Efficient Downhole Well Connections”; Ray Oskarsen and John Wright, John Wright Company and Donal Fitterer, Dave Winter, Anthony NeKut and Jed Sheckler, Vector Magnetics Inc |
| SPE 116274; “Successful Relief Well Drilling Utilizing Gyroscopic MWD (GMWD) for Re Entry into an Existing Cased Hole”; Juergen Maehs, Baker Hughes; Douglas Robert MacAfee, Apache Corp.; Steve Renne, Baker Hughes; Gregory L. Cellos, Baker Hughes; Ananth Srinivasan, Baker Hughes |
| SPE 079005; “Magnetic Ranging Technologies for Drilling Steam Assisted Gravity Drainage Well Pairs and Unique Well Geometries – A Comparison of Technologies”; Tracy Grills Sperry-Sun Drilling Services |
| SPE 049059; “Makarem-l Relief Well Planning and Drilling”; V.C. Roes, Petroleum Development Oman; R.A. Hartmann, Shell Intl. Research and Technical Services; J.W. Wright, John Wright Company |
| SPE 039396 - "Stopping a Water Cross Flow in a Sour Gas Well Producer", 1998, LeHello, Y., Ghesquiere, P. and Woodruff, J. |

| |
|---|
| SPE 039389; "Collision Avoidance Using a Single Wire Magnetic Ranging Technique at Milne Point, Alaska"; C.R. Mallary,' ARCO Alaska Inc.; H, S, Williamson, * BP Exploration Operating Co. Ltd.; R. Pitzer, Vector Magnetics Inc.; and James Robertson,* ARCO Alaska Inc. |
| SPE 037667; "Case Histories Demonstrate a New Method for Well Avoidance and Relief Well Drilling"; Graham McElhinney, Halliburton; Roar Sognnes, Halliburton; Bob Smith, BP Norge UA |
| SPE 029859; Case History: Relief Well Control of Underground Blowout In Bahrain"; Larry H. Flak, Wright Boots & Coots L.L.C.; Ghassan A. Muhanna, Bahrain National Oil Company; Mohamed Al-Qassab, Bahrain National Oil Company |
| SPE 028319; "A Magnetostatic Well Tracking Technique for Drilling of Horizontal Parallel Wells"; C.K. Pratt, Shell Canada Ltd.; R.A. Hartman, Koninklijke/Shell E&P Laboratorium |
| SPE 027466; "New Electromagnetic Surveying/Ranging Method for Drilling Parallel Horizontal Twin Wells"; A.F. Kuckes, SPE, Vector Magnetics Inc; RT Hay, SPE and J McMahon, Sperry-Sun Drilling Services of Canada; AG Nord and DA Schilling, SPE, Amoco Canada; Jeff Morden, Sperry-Sun Drilling Services of Canada |
| SPE 021997; "Relief Well Contingency Drilling Plans for Remote Areas"; G.A. Pidcock, Gulf Canada Resources Ltd.; D.R. Fowler, Gulf Canada Resources Ltd. |
| SPE 020915; "Relief Well Breakthrough at Problem Well 2/4-14 In the North Sea"; B.S. Aadnoy, Rogaland U.; P. Bakoy, Saga Petroleum A/S |
| SPE 020446; "Use of New Ranging Tool To Position a Vertical Well Adjacent to a Horizontal Well"; B.A. Tarr, SPE, Mobil E&P Services Inc.; A.F. Kuckes, SPE, Vector Magnetics Inc.; M.V. Ac, Mobil Oil Canada |
| SPE 020420; "Relief-Well Planning and Drilling for a North Sea Underground Blowout"; Frode Leraand, Saga Petroleum A/S; J.W. Wright, John Wright Co.; M.B. Zachary, Eastman Christensen Inc.; B.G. Thompson, Vector Magnetics Inc. |
| SPE 018717; "Enchova Blowout: Record Relief Time"; W.P. Maduro, Petrobras; Jim Reynolds, Smith Intl. Inc. |
| SPE 018059; "Operations at a Deep Relief Well: The TXO Marshall"; by R.D. Grace, GSM & A W. Kuckes, Vector Magnetic; J, Branton, TXO Production |
| SPE 017820; "Relief Well Drilling Technology"; Xiu Yu, Dagand Petroleum Admin. Bureau; Jinling Jie, Dagand Petroleum Admin. Bureau |
| SPE 017255; "Improved Detectability of Blowing Wells"; John I. de Lange and Toby J. Darling, SPE, Koninklijke/Shell E&P Laboratorium |
| SPE 016677; "Relief Well Planning and Drilling for SLB-5-4X Blowout, Lake Maracaibo, Venezuela"; J.A. Voisin, Lagoven S.A.; G.A. Quiroz, Lagoven S.A., R. Pounds, Eastman Christensen; J. Wright, Eastman Christensen; K. Bierman, Shell Intl. Petroleum Mij. B.V. |
| SPE 014388; "Improved Magnetic Model for Determination of Range and Direction to a Blowout Well"; Douglas L. Jones, * Rice U., Gus L. Hoehn,* * Mobil R&D Corp.; Arthur F. Kuckes, Cornell U. |
| SPE 014047; "Ulsel Interpretation In Blowout Well Location From Relief Wells"; Runge, Richard J., Chevron Oil Field Research Co. |

| |
|---|
| SPE 011996 - 1983; "Successful ELREC Logging for Casing Proximity in an Offshore Louisiana Blowout"; C.L. West, Shell Offshore Inc., A.F. Kuckes, Cornell U., H.J. Ritch, Shell Offshore Inc. |
| SPE 010946; "An Electromagnetic Survey Method for Directionally Drilling a Relief Well Into a Blown Out Oil or Gas Well"; Arthur F. Kuckes, Cornell U.; T. Lautzenhiser, Amoco Production Co.; A.G. Nekut, Amoco Production Co.; R. Sigal, Amoco Production Co. |
| SPE 010946; "An Electromagnetic Survey Method for Directionally Drilling a Relief Well Into a Blown Out Oil or Gas Well"; Arthur F. Kuckes, Cornell U., T. Lautzenhiser, Amoco Production CO., A.G. Nekut, Amoco Production CO., R. Sigal, Amoco Production Co. |
| SPE 006781; "A New Method Of Determining Range And Direction From A Relief Well To A Blowout Well"; F.J. Morris, Tensor, Inc.; R.L. Waters, Tensor, Inc.; G.F. Roberts, Tensor, Inc.; J.P. Costa, Houston Oil and Minerals, Research and Development, Inc. |
| SPE 003963; "Gas-Blowout Control by Water Injection Through Relief Wells-A Theoretical Analysis"; F. Lehner, Koninklijke/Shell Exploratie; A.S. Williamson, En Produktie Laboratorium; |
| SPE 003511; "A New Approach in Relief Well Drilling"; Bruist, E.H., Shell Oil Co. |
| SPE 003496; "Magnetostatic Methods for Estimating Distance and Direction from a Relief Well to a Cased Wellbore"; J.D. Robinson, Shell Development Co.; J.P. Vogiatzis, Shell Development Co. |
| PETSOC, 2004-176 "A Comprehensive Comparison Between the Magnetic Guidance Tool and the Rotating Magnet Ranging Service"; B. VANDAL, T. GRILLS, Halliburton / Sperry-Sun, G. WILSON, Husky Energy |
| JPT SPE Journal Paper – 2009, 0509-0075; "Downhole Well Connections By Use of Rotating-Magnetic- Ranging-Service and Single-Wire-Guidance Tool"; Karen Bybee, JPT Assistant Technology Editor |
| John Wright Co, Technical Library: http://www.jwco.com/technical-litterature/lib_abs.htm |
| JCPT May 1988 Volume 37, No. 5; "Emerging Technologies for SAGD Drilling and Production"; Tracy Grills |
| JCPT March-April 1983; "Use of Magnetic Ranging Logging Tool to Direct Amoco et al. Steep A7-26-66-07 W6M Drilling"; Alan T. Duguid |
| 2013-065 OMC Conference Paper – 2013; "New Logging While Drilling Ranging and Formation Evaluation Technique"; M. Bittar, Halliburton; H. Wu, Halliburton |

# VERSION & SUBMISSION INFORMATION

## 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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