

WELL INTERCEPT SUB-COMMITTEE eBOOK R4

Wellbore Ranging Technologies, Intercept, Applications and Good Practices

REVISION 4 (2026)

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Revision

The authors of this publication, WISC team is 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.

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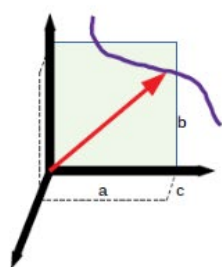
On the cover: Graphic illustrates a plan to intercept and control a target well (red) with two Relief Wells (yellow and blue). The plan for a third Relief Well (green) is included as a contingency well should the need arise.

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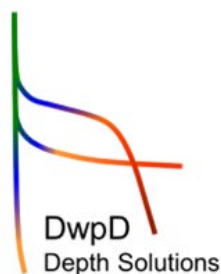
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Well Intercept Sub-Committee eBook



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Preface

The subject of Well Intercept has frequently dealt with local best practices, published and non-published technical papers, local guidelines, and check sheets.

The Wellbore Intercept Sub Committee (WISC) eBook attempts to capture industry knowledge and “good” practices in one document with the objective of increasing public awareness and understanding of well intercept applications. Note, when addressing practices, we intentionally moved away using the term “best” because the term holds unintentional negative meaning for younger generations, regulatory references, and regulation. A practice may be best in certain environments, but certainly not for all conditions.

The WISC eBook was part of the Society of Petroleum Engineer (SPE) Distinguished Lecture Program 2021-2022, Good Practices in Well Control Intervention via Relief Well Subsurface Interception. The eBook can be accessed through [FlippingBook](#), the SPE WPTS, website ([spe.org](#)) and ISCWSA, website ([iscwsa.net](#)).

This eBook was compiled from various sources, re-written, and updated by WISC team and is intended to continue developing wellbore intercept good practices and to promote a better understanding of its complexity within the industry and academia. Most of the figures and texts in the eBook are based on original documents provided by the contributors and therefore may include different terms for similar concepts. For example, depending on context, the term “relief well” may be more accurate than “intercept well”.

The intent of this knowledge-sharing document is to help line management, decision makers, and engineers and academia determine appropriate well intercept actions, beginning with not accepting excessive risk-taking and operating only under “As Low As Reasonably Practical (ALARP)” conditions, and selecting appropriate ranging methods, technologies and wellbore surveying techniques, and operation contingencies for a given interception objective. Depending on the objective complexity, a “silver bullet”, or single technology that provides a complete solution, may not exist. 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 thank Roger B. Goobie, 2015-2019 WISC Chairman, for his leadership and expertise in bringing the companies and industry experts together to make the eBook reality. Also, thanks to fourth revision team members for their hard work and dedication to helping with the updates.

The first, second, and third revisions were well received with over 33,000 downloads along with requests to use the eBook as reference in academia and to translate it to different languages for internal use.

With good feedback from the industry, academia and the Distinguished Lecture program, we were able to complete the Fourth Revision by January 2026. We sincerely hope that the WISC eBook continues to evolve with feedback and learnings from the industry.

Benny Poedjono, Jamie Dorey

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Chairman and Co-Chairmen, 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. This definition has been expanded to include juxtaposition of wells. The subject of Well Intercept has frequently been dealt with in good-practice manuals, guidelines, and check sheets.

This eBook attempts to capture, in one document, the main points of well intercept good practices and to make them available to the industry and academia through the Wellbore Positioning Technical Section (WPTS) of the Society of Petroleum Engineer (SPE) and through the Industry Steering Committee for Wellbore Survey Accuracy (ISCWSA). This eBook is intended to share and develop good practices in wellbore intercept applications and to promote an understanding of those practices within the wellbore construction industry.

Wellbore Intercept is a broad topic covering a range of technologies, methods, and domain expertise, to deliver desired objectives. The topic includes a wide range of industry applications from Steam Assisted Gravity Drainage (SAGD) Drilling, River Crossing, Re-Entry Drilling, Plug and Abandonment Operations, Well Salvage Operations, Horizontal Directional Drilling (HDD), blowout control through relief wells, connecting boreholes end-to-end for pipeline production fluid conveyance, and recently in Advanced Geothermal Systems (AGS).

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

Depending on the objective complexity, there may not be a “silver bullet”, or a single technology, that may alone 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.

To meet these challenges, the main ranging technologies available to the industry as of the time of this publication can be summarized into two groups: Magnetic and Acoustic. Both technologies may be deployed in active or passive modes. An emergent Resistivity Ranging technology (ARR) is covered briefly. Also included are sections on Relief Well (RW) Ranging operations, which are intended to provide a general overview of the overall process and planning 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 downhole pressure. These wells were called relief wells. The name stuck when later controlled directional drilling was used to control blowouts even though the objective changed to pumping fluid into the blowout rather than through the producing 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 and flowing them at higher rates than the blowout.

However, it was conceived that if a wellbore could be drilled close enough to the blowout well to establish hydraulic communication, 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 while simultaneously preventing an accidental collision. As a result, drillers often had to drill multiple relief

wells to land one or more close enough to the target well to effectively kill the blowout. This was an expensive, time intensive, and relatively uncertain technique that often require 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 to reach the bottom of Cox No. 1 at 6,400m (21,000ft). 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 conventional relief wells were known, which motivated the company to explore new techniques for accurately placing relief wells. The operator formed a taskforce of engineers and scientists that developed a method for determining the relative distance and direction to a target casing near the planned intersection depth. The group's 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 that could be produced in the target wellbore, which would provide a much stronger and predictable magnetic signal with which to guide the well for interception. This idea was 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 from earlier techniques 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 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 before it was eventually phased out because it was not accurate enough to consistently locate blowout wellbores and was 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 a 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 mud motors and bent subs were required and became more complicated in open hole as this technique requires steel in the target well.

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 an orthoradial 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. Although this technology increased the reliability of locating and tracking the target well, it was not until the late 1980s with the introduction of new directional drilling technologies, such as 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 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 to P&A 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 about 4m (13ft). 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 when the operator had access to the target well and could 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 while drilling (SPE-CIM-01-01-MS).

The most common intersection applications for this technology was to guide 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 subsea obstacles. The method was also used to drill a horizontal well from a land rig to make a perpendicular intersection of an offshore well (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 ability 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 and prevent costly and hazardous collisions.

A revival in the use of passive magnetic ranging techniques began in the early 2000s, using the raw Measurement-While-Drilling (MWD) magnetometer and accelerometer data. This was primarily driven by cost and time savings over 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 for which the budgets were low and re-entry was not required. Passive magnetic ranging 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. Currently field tests are 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 intersecting. Magnetic ranging technologies are based on the measurements of magnetic field disturbances attributed to the steel in the offset wellbore casing or tubing. Interpreting downhole magnetic field distortions helps determine the relative distance and direction of the offset wellbore (the source of the magnetic disturbance). The magnetic ranging technique has become common practice for detecting offset wellbores.

Magnetic ranging techniques can be divided into two categories—Passive and Active Magnetic Ranging.

- 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 the target pipe’s joint magnetic field. The induced field is analyzed to determine a distance and direction to the target.

1.3 Acoustic Ranging Techniques

Like magnetic ranging methods, an acoustic signal can be used to locate the target wellbore, either Open Hole (OH) or Cased Hole (CH). Acoustic ranging can also be used to complement other ranging techniques as it works on different principles from magnetic ranging. The ranging distance and direction can be determined by knowing the time required for the sound to travel in the formation and the direction from which the sound is coming.

Acoustic ranging techniques can be divided into two categories—Active and Passive Acoustic Ranging.

- Active Acoustic Ranging (AAR) relies on sound from a transmitter being measured at the receivers. The sound waves traveling through the formation are reflected by the target well back to the receivers. By utilizing similar two-way time surface seismic processing techniques, the distance and direction can be established. When drilling in homogenous salt formations, AAR solves ranging challenges due to the formation’s conductive property.
- Passive Acoustic Ranging (PAR) relies on the detection of the acoustic signal generated by the bit or fluid noise. By knowing the slowness or the speed that sound travels in the formation and from which direction the sound is propagated, the distance and accurate direction of the noise can be determined.

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 Logging-While-Drilling (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 industry. The main uses are listed below but they all rely on one key fact; the better the position of the target well to be intercepted or paralleled is understood, the easier the goal will be to achieve. Therefore, improved wellbore survey accuracy is key to timely well intercepts and 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, making the positional accuracy of the offset well key to enabling this method.

In PMR and AMR applications, some form of metal target, such as drill pipe or casing, must be present 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 four being plug and abandonment, SAGD drilling, coal bed methane and Advanced Geothermal Systems (AGS). The most notable of all applications is relief well drilling but this continues to be relatively rare although because they incur health, safety, security, and environmental (HSE) consequences, they are highly visible, which 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

Relief wells are drilled to re-establish control of a well in which containment has been lost. Each relief well, which can be very complex, is a unique event requiring study and analysis. Understanding the five ranging techniques of PMR, AMR, PAR, AAR, and ARR, and their capabilities and limitations, is necessary to design a relief well that satisfies the specific objectives of the operation.

1.6.2 Intervention Wells

Intervention wells are drilled to perform remedial operations, such as a P&A or wellbore re-entry. These wells are like relief wells in design but do not have the kill objectives, complications, and constraints associated with a blowout. Intervention wells are a product of the successes from recent relief well operations and are the primary type of intersection wells being drilled today.

Milling a hole or a slot for re-entry into the target well tubulars or perforating or intersecting the open hole or annulus of another well, is routinely performed to resolve various downhole issues. Most intervention wells require a specific orientation relative to the target well to achieve the desired objectives. Intervention well types include:

- Plug & Abandonment—Ranging technology is used to intercept wells and allow pressure relief and or flow barriers to be put in place. Plugging regulations in the early 1900s were generalized and lacked standard requirements across states or counties. Regulations changed significantly in the 1970s to drive greater environmental protection. These stricter requirements mandated that cement plugs must be placed at specific depth intervals to prevent formation fluids from migrating to other strata. However, since steel casing is susceptible to corrosion and collapse, these depths often become obstructed and unreachable through traditional means. This has led to the use of ranging technologies to intersect the subject wellbore at the necessary depths to set the required plugs (SPE-138287).
- Well salvage—Through well twinning, production can be recovered from an existing well in which reservoir access has been lost. One example of this objective 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 near the existing well to penetrate the existing fractured zone for continued production.
- Well Recovery—This technique is used to re-enter a well below a fish or casing damage that has blocked flow from the formation.
- Fish & Bypass—Similar to 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—Ranging technology may be used 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 that have been utilized in the industry.

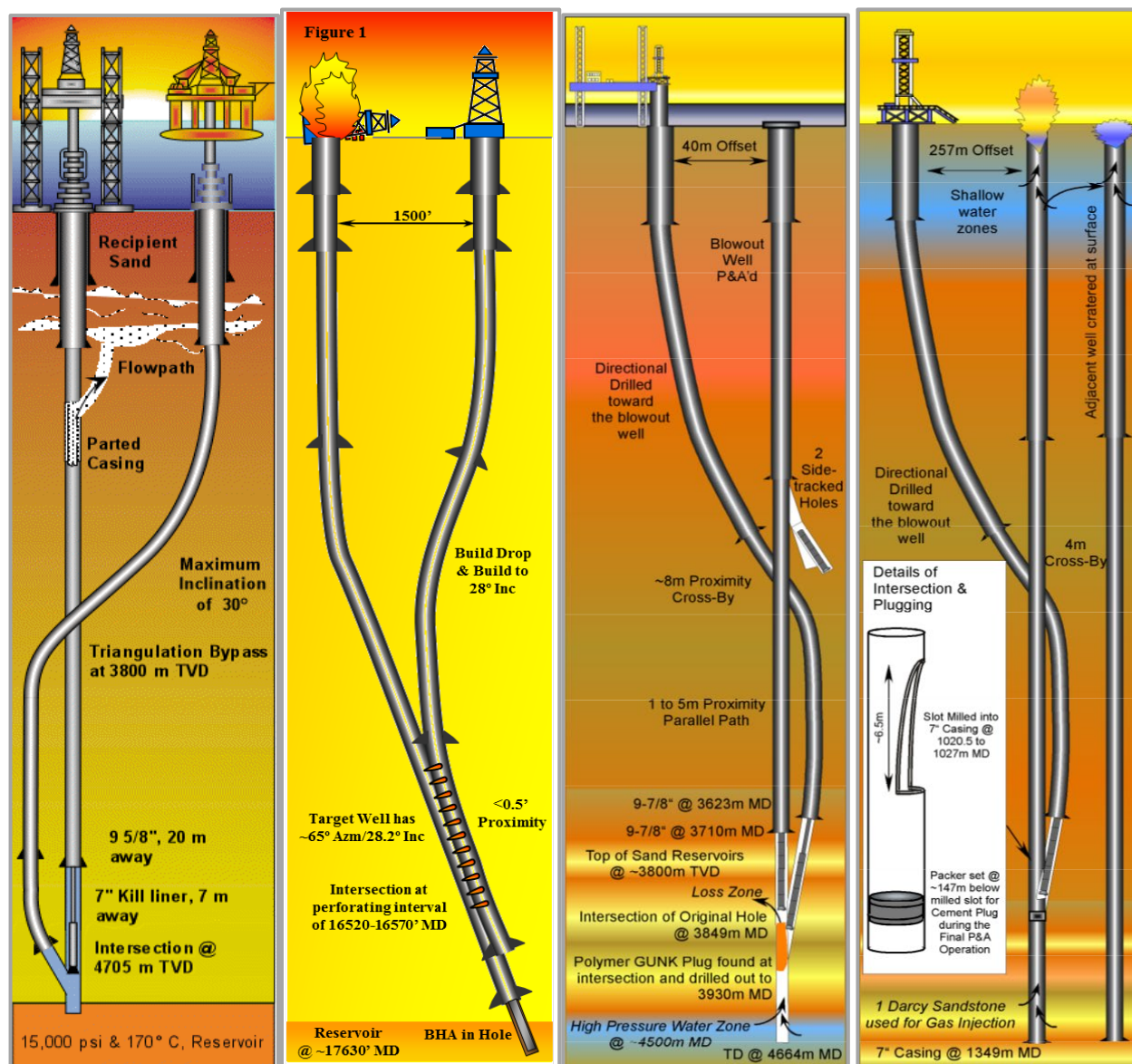


Figure 1—Relief and well intervention and intersection

1.6.3 U-Tube Wells

The first feasibility study for connecting two wells end-to-end was developed in 2000. The objective of the study was to assess connecting two offshore platforms using two connected wells, which would mitigate the permitting and environmental risks associated with laying a pipeline on the seabed. The method was first implemented a few years later in the successful connection of two wells beneath a subsea canyon to convey a pipeline (New Technology Magazine, December 2004). While it has been attempted only a few times, all such U-Tube Wells have been completed successfully. These types of projects will normally have access to both wells and typically make the intersection using dual well ranging technologies, such as x, y, z, or combinations thereof (Figure 2).

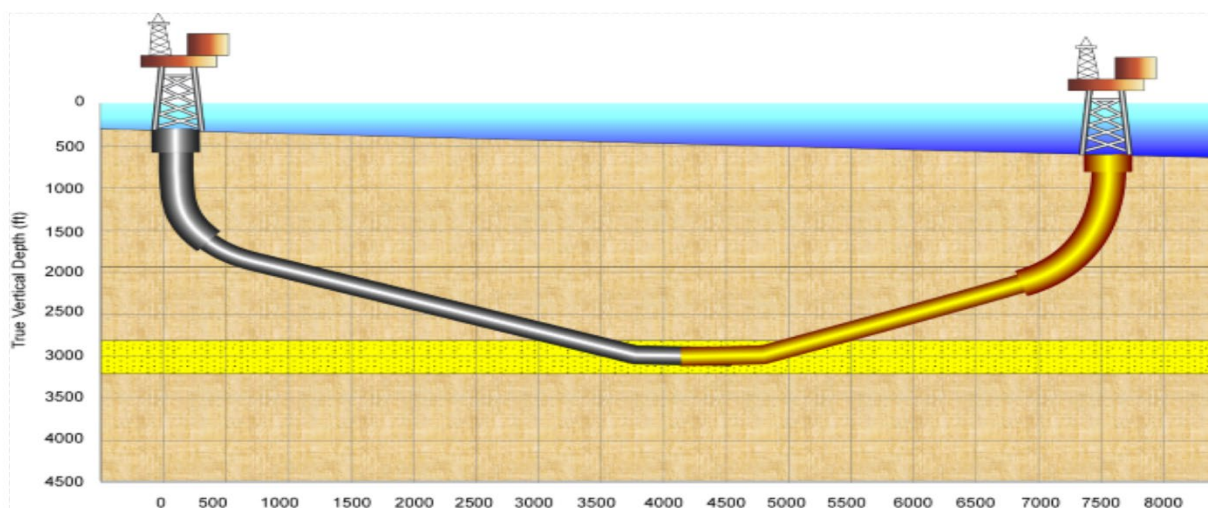


Figure 2—Example of a u-tube well connected end-to-end to convey a pipeline

1.6.4 Conductor Connector Well

Conductor Connector (CC) wells 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 coalbed methane production.

Typically, there is access to the target well when drilling this type of borehole and ranging usually consists of a rotating magnet, single wire, solenoid, or combinations thereof.

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, 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 normally have access to both wells and typically use dual-well ranging technologies, such as rotating magnet, single wire ranging, solenoid techniques, or combinations thereof for making the intersection ([Figure 3](#)).

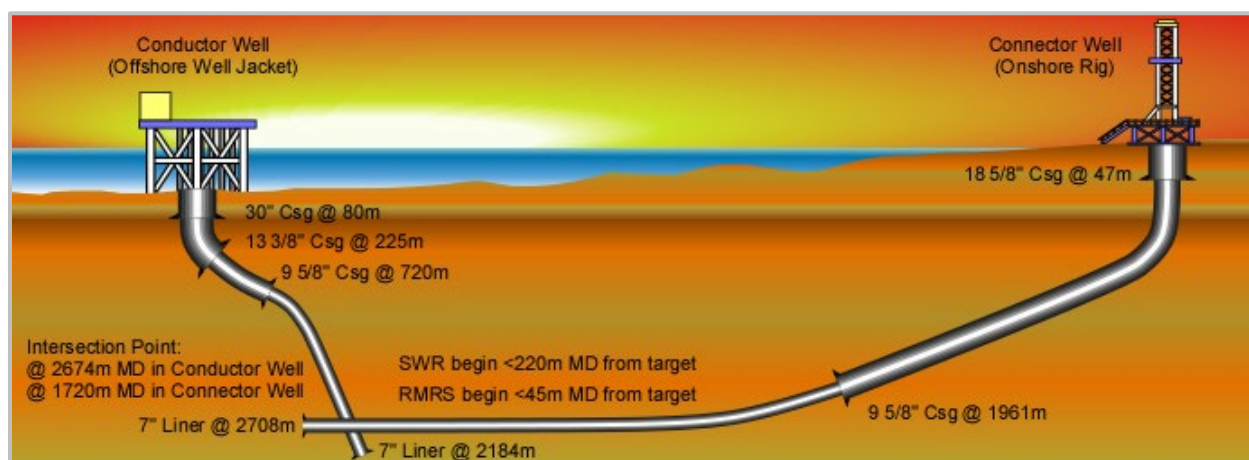


Figure 3—Conductor connector well drilled in 2007, Single Wire Ranging (SWR), Rotating Magnet Ranging System (RMRS)

1.6.5 Steam Assisted Gravity Drainage wells

In Steam Assisted Gravity Drainage (SAGD) well twinning, producer and steam injector wells are typically drilled in close proximity and parallel to each other ([Figure 4](#)). First conceptualized by Dr Roger Butler of Imperial Oil in the 1970s for application in the Canadian heavy oil sands, SAGD maximizes thermal transfer to the reservoir, which optimizes production. Ranging technology is used to ensure appropriate relative placement of the two wells.

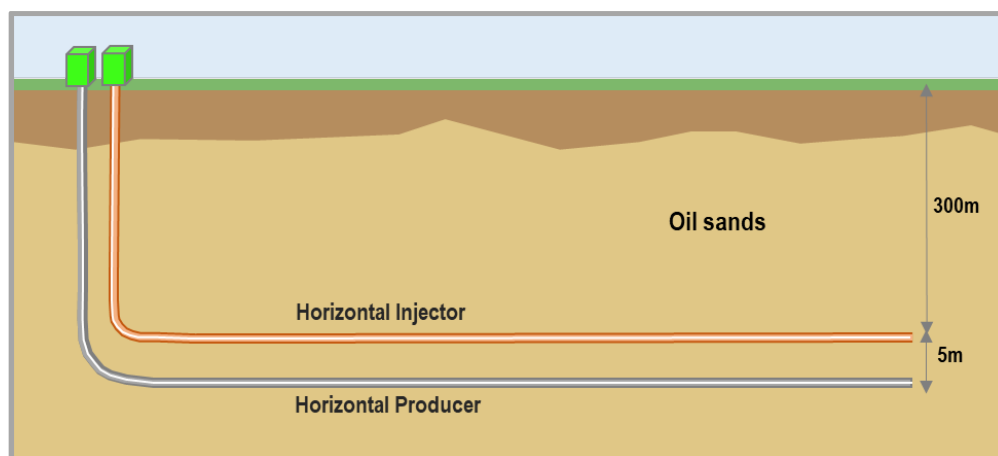


Figure 4—Illustration of Steam Assisted Gravity Drainage, SAGD well pairs

1.6.6 Well Avoidance

Well avoidance is the use of ranging technology to avoid other wells when 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 increasingly common in recent years with the proliferation of multi-well platform or pad drilling. 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

Ranging technology may be used to allow two wells to meet or to parallel each other within a reservoir when the wells are drilled from different locations and are positioned relative to each other within the zone of interest.

1.6.8 Horizontal Directional Drilling

Horizontal directional drilling (HDD) is typically used for running pipelines under villages, towns, and rivers, HDD is an adaptation of previous applications and technologies.

The drilling process is similar to oil and gas style operations with a few notable variations in rig design and design requirements. As opposed to traditional draw works-based rigs, HDD rigs are commonly hydraulically driven to provide the higher force rating necessary to pull product pipe through a reamed borehole. HDD wellbore construction requires several stages from first drilling a small pilot, to reaming and enlarging the hole to accommodate product pipe installation. Rig size varies, from highly mobile smaller rig units that perform utility work, to maxi rigs that are designed to perform extended reach operations. The coordinated system used for planning and directionally drilling the bore is based on an Away/Right/Elevation referenced from bore entry to exit along a baseline azimuth, which is the magnetic north direction from entry to exit as measured by the survey tool.

1.6.9 Ranging to Surface

Horizontal directional pilot hole drilling is typically performed in environments with high levels of magnetic interference, which necessitates use of a gyro-while-drilling system or magnetic ranging methods.

Magnetic ranging methods utilize a downhole steering tool and surface sources that may include wire layouts, point beacon sources, and active downhole tools detected by surface-based receivers known as “walkover systems”. It is a common and cost-effective practice to place a wire on surface across a section of the borehole path and apply DC or AC current that is then detected by the downhole tool.

The ranging wire layouts vary based on the surface environment, the type of current applied, and any obstacles in the way. It is also possible to place a wire inside an adjacent pipeline or drill pipe, which is a common practice when trying to remain inside designated rights of way while attempting parallel crossings within tight spacing.

The limitation of HDD ranging is the effective TVD. The detection range of a surface ranging systems is typically up to 40m (130ft). Technology also exists to perform horizontal-to-horizontal interceptions and hundreds of successful interceptions in river crossing applications have been performed since the early 2000s.

Typically, ranging shots are taken frequently along the borehole while drilling and are used to adjust the baseline azimuth to enable the borehole survey to match the ranging data. In areas of high magnetic interference, it may be necessary to collect ranging data along the entire borehole, which can be used to produce an as-drilled survey of the borehole.

1.6.10 Advanced Geothermal Systems

An Advanced Geothermal Systems (AGS) is a closed-loop heat exchange system created by connecting two parallel wellbores. Fluid pumped through an injection well is heated by sub-surface rocks through conductive heat transfer and returned to the surface through a producer well. AGS is part of the unconventional geothermal systems (UGS) that is considered a more efficient and cleaner alternative to Enhanced Geothermal Systems (EGS) because it eliminates the need for complex operations, such as hydraulic fracturing, which requires large volumes of fresh water. EGS and AGS are artificial, human-engineered techniques designed to provide heat-generated energy anywhere at any time, which is different from conventional hydrothermal systems (CHS), which must rely on the presence of natural fractures and underground fluid to bring geothermal heat to the surface.

In an AGS, the rock fractures' role in creating a hydrothermal closed-loop system is achieved by constructing a grid of lateral wellbores (multilateral wells) drilled from the surface (injector mother bore). These are connected at the toe of an identical grid of lateral wellbores drilled from a second well (producer mother bore) in a nearby location. The final arrangement of wellbores gives the impression of a gigantic underground car radiator loop system. They may be horizontal or deep closed-loop systems depending on the depth of the target sub-surface heat source rocks ([Figure 5](#)).

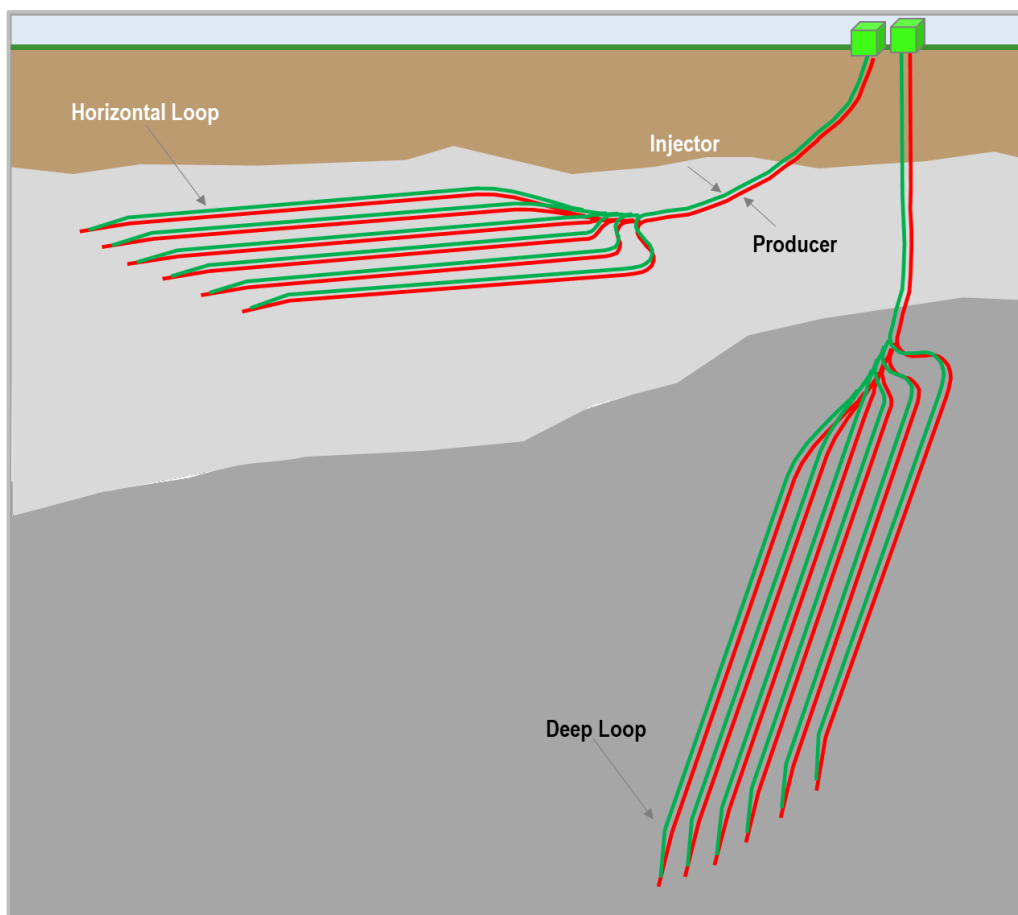


Figure 5—Illustration of Advanced Geothermal Systems (AGS); horizontal or deep closed loop systems dependent on the depth of the target sub-surface heat source rocks

Various AGS designs have been proposed based on borehole geometries and multilateral arrangements have been proposed to maximize heat production. Common factors among these configurations are the substantially longer wellbores to increase the surface area for heat transfer, many parallel laterals on top of each other at close center-to-center distances of 40m to 70m for effective heat exchange, and optimum location of hot source rocks to enable long-

term electrical power generation. This requires high temperature equipment rated to above 150°C, factory directional drilling, advanced wellbore positioning, simultaneous ranging and directional steering, and interception techniques.

2. Passive Magnetic Ranging (PMR)

2.1 Introduction

The PMR technique relies on the presence of steel materials in the target or offset wellbore. It uses surface software methods that analyze magnetic “interference” as measured by the MWD or other magnetic sensors. This “interference” may be caused by a casing string, stuck fish, or other steel component in the offset wellbore and is used to estimate the range distance and direction from the subject well to the offset 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 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 thought to not 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 this text. It should be noted, however, that some techniques model the magnetic monopoles as with an exponential decay profile 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 cancel each other to some degree.

The magnetic field originating from each magnetic monopole is superimposed upon the magnetic field imposed by 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 ([Figure 6](#)).

It is a challenge of PMR to identify the location and distribution magnetic monopoles, as opposed to a single point source, in the presence of a background magnetic field of uncertain strength and 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 ultimately 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—steel casing, stuck fish, or other downhole steel equipment—is not altered in real-time during the ranging process.

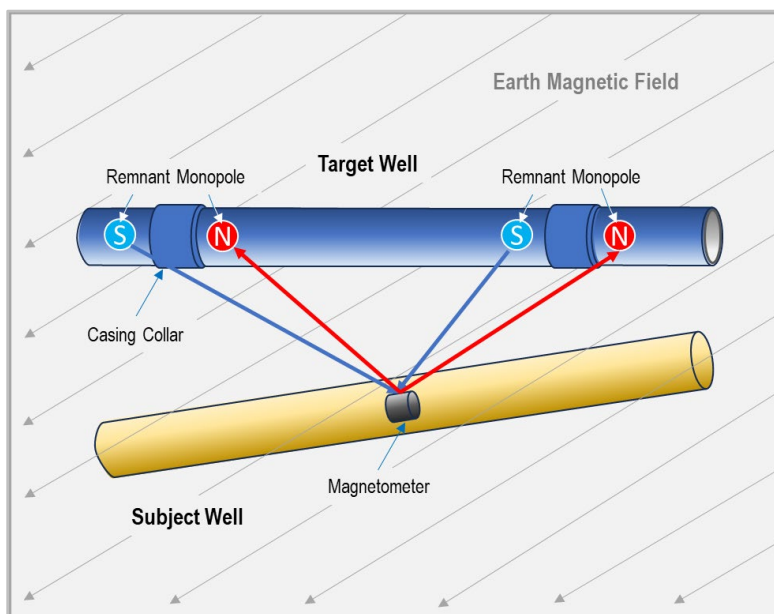


Figure 6—Superimposition of magnetic fields emanating from multiple magnetic monopoles on top of the magnetic field of the Earth

2.2 When to use

Owing to the presence of the necessary MWD hardware in the wellbore, PMR may be used anytime magnetic interferences occurs. 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 may also be used for complex wells such as paralleling a target well with the objective to perform a P&A operation, or to perforate the target well.

2.3 Economics

Normally, PMR is an economical ranging option as it utilizes the existing MWD hardware found within a typical drilling BHA. However, each situation is unique and must be evaluated to ensure that the risk is understood, and that the technology is fit for purpose.

2.4 Insensitivity to Formation and Hole Conditions

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

Electromagnetic data transmission, EM-MWD, increases the transmission rate of the data from downhole to surface by decreasing the acquisition time, while possibly increasing the data density available 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 because of the distance created between the sensor and the bit when combined with the limited range. PMR can be used at all hole inclinations, including horizontal, but high incidence angles between the drilling and offset well can affect PMR (see [Section 7.2](#)).

2.6 Accuracy and Detection Range

Detection range differs from one project to another depending on 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 a field strength chart. Published accuracy and detection ranges

will vary somewhat from vendor to vendor. In the absence of further clarification by the PMR provider, 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), which has a direct impact on accuracy. As the sensor gets further from the offset well, not only will the SNR decrease, but it will also transition from a $1/r^2$ relationship to a $1/r^3$ relationship somewhere between a 7- and 15-m (23- and 49-ft) distance. Key points about the PMR detection range include:

- Expected and maximum detection range are an estimation based on a theoretical remnant magnetic field.
- Detection 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 although measurement density must be increased at close range.
- 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, especially at a distance of 5m (16ft) or more.
- Although most 6-axis MWD/wireline tools can provide readings that can be utilized for PMR, its calibration residuals, whether from the procedure itself or from the passage of time, are just as important as the resolution. These can cause an apparent variation in the measured field with respect to attitude which can imitate the effects of a pole.
- A good understanding of the magnetic reference field is also desirable.
- 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 running in the borehole.

2.6.1 Direction Accuracy

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

2.6.2 Distance Accuracy

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

2.6.3 Detection Range

Publicized PMR detection range is usually 6 to 10 m (19 to 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 by up to 15m (50 ft) as described in the next section.

2.6.4 Magnetized Casing to Improve Detection

Casing can be intentionally magnetized prior to placement downhole with the purpose of increasing the detection range and direction of the planned magnetic ranging work (**Note**; magnetized casing ranging is classified as PMR), such as well

twinning or SAGD, or for unplanned PMR work, such as drilling a relief well. 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 (Figure 7). Casing can be purposefully magnetized offsite or on site just prior to running in hole with a variety of patented methods.

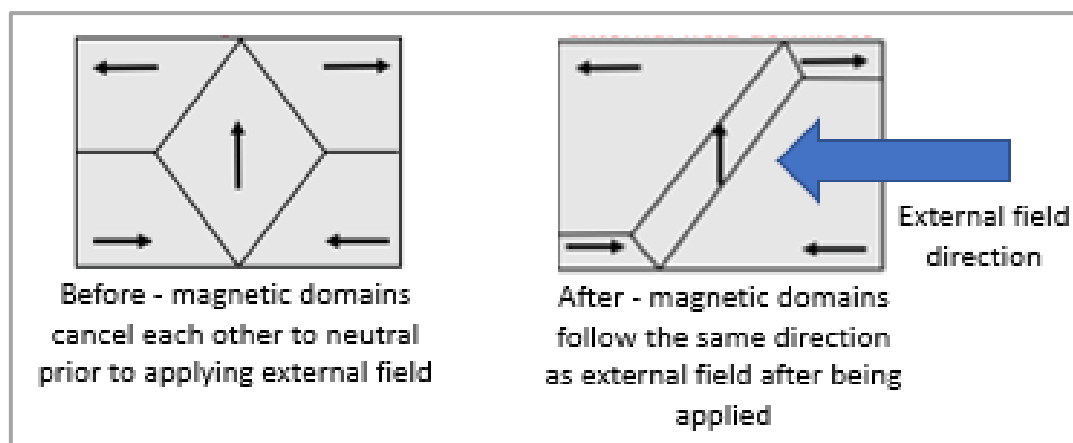


Figure 7—The left shows virgin steel with no magnetic field. The right shows the same steel after being exposed to an external magnetic field with the magnetic domains aligned to the external field growing creating a magnetic field in the metal

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 much less magnetism in the middle of the casing joint, as illustrated in Figure 8. Purposeful casing magnetization creates known field strength and patterns along the casing string, called a “designer magnetic pattern”. Figure 9 illustrates an example of a designer magnetic pattern 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 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 of PMR compared to non-designer patterns.

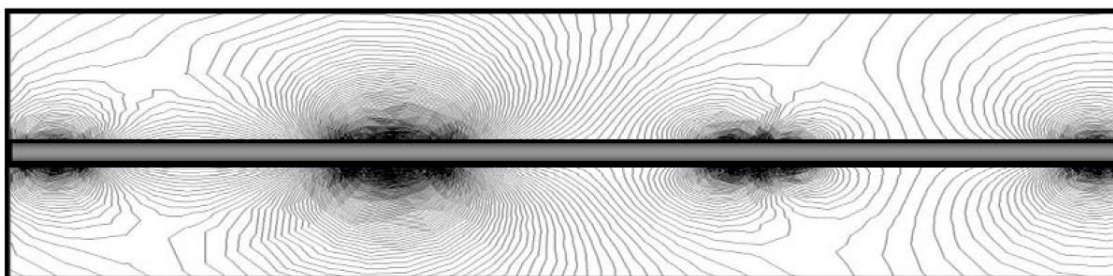


Figure 8—Example of residual casing magnetism from magnetic particle inspection showing erratic amplification and dampening of the magnetic signature along the casing string.

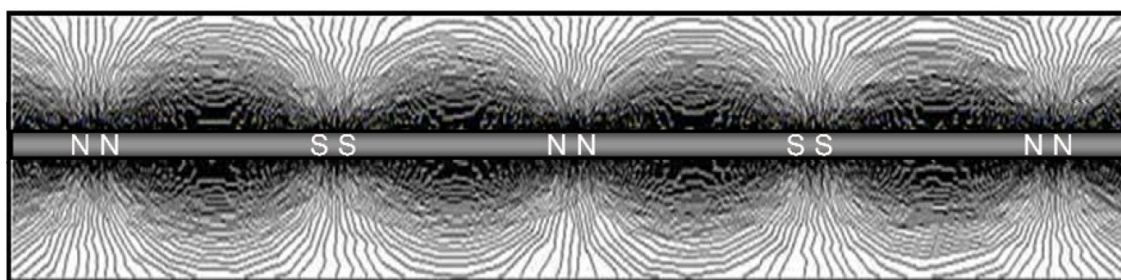


Figure 9—Magnetically saturated casing with a designer pattern.

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, while a break in otherwise un-corroded casing can improve the PMR detection range, 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 at less than 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) or IFR2 corrections is a way to mitigate the effect of the Earth magnetic field variations when ranging. In the absence of real-time background field monitoring or correction, care should be taken to check for space weather, which can cause temporal magnetic variations. Although IIFR/IFR2 is not necessary, local magnetic diurnal variation monitoring is necessary. Because absolute measurement is not essential, compensation of variation is a simpler option. Vector and total field monitoring is required 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 of the hole. However, this reduces the advantage of using inherent MWD sensors and may sway the economic/precision balance towards AMR ([Section 7.2, Figure 63](#)).

2.7.3 Interference from the Casing Shoe in the Subject 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 Wellbores Environment

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 3D Processing Technique

The Passive Magnetic Ranging (PMR) technique is primarily based on the detection and localization of point-like or extended monopoles, which are commonly located on offset well casings or on other metallic components, such as a stuck fish. PMR results are typically expressed in terms of the estimated distance between the subject well and the target well, and the direction from the subject well to the target angle.

The direction term can be provided within two reference frames.

- In the “High Side, Lateral, Along Hole” frame, the direction to the target is specified as an angle relative to the High Side vector within the radial plane.
- In the “East, North, Vertical” frame, the direction to the target is defined by the azimuthal angle from North within the horizontal plane.

Traditionally, PMR measurements yield estimates of both distance and direction accompanied by associated uncertainties. The results are often represented as a distance $d \pm Dd$ and direction $\pm D$. The spatial domain representing the uncertainty surrounding the located position is typically described as a 2D trapezoidal surface, bounded by two circular arcs and two linear segments (Figures 85 and Figure 99, green trapezoid).

A key limitation of this representation is its two-dimensional nature, which inadequately represents spatial uncertainties. Given that spatial uncertainties are inherently three-dimensional, a 3D representation provides a more accurate characterization (Figure 10).

For a given set of ranging surveys, assuming that a reliable model for the PMR data has been developed, various optimization methods may be employed to address the problem created by 2D uncertainty representation. A robust model ensures that the observed magnetic field is accurately described based on the knowledge of the reference field and the magnetic sources distribution. The difference between the observed and the modelled magnetic fields serves as a critical indicator of the model’s accuracy.

Figure 10 is an example of a modelling fit that focuses on both the radial (left) and axial (right) components of the magnetic field after the reference field has been subtracted. The blue line represents the observed data, while the red line denotes the modelled values.

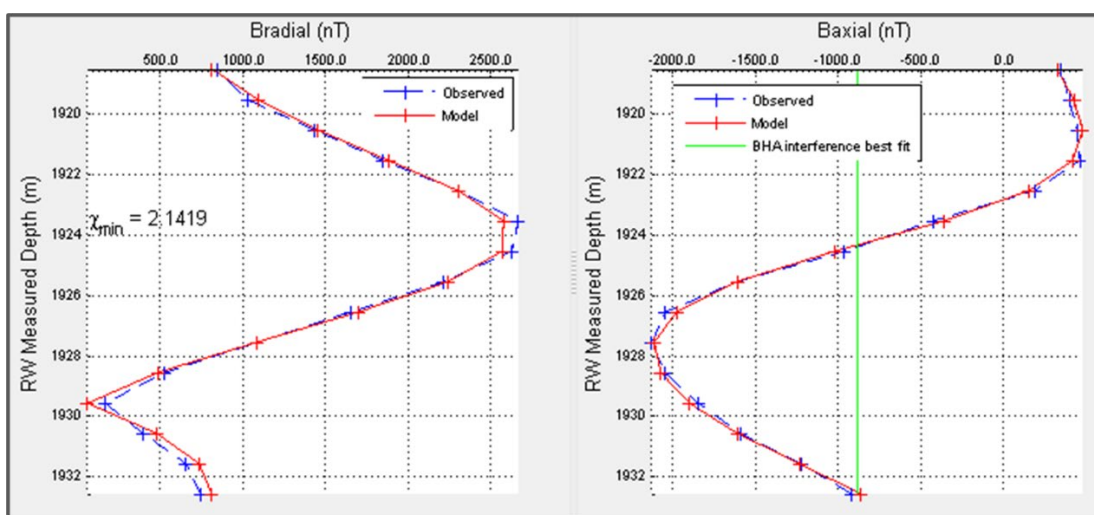


Figure 10—Comparison of observed data and modelled magnetic field data after reference field subtraction. Left: Radial field. Right: Axial field

Key input parameters derived during PMR modelling include the reference magnetic field and the distribution of magnetic sources along the target well. If the magnetic sources are treated as poles, their distribution is characterized by a collection of magnetic strengths (e.g. in μWb) and the 3D coordinates of these poles. The uncertainties of the poles’ positions are represented by a 3D ellipsoid of probability distribution, offering a more accurate representation compared to the previously described 2D trapezoidal surface.

The ranging analysis provided by the Passive Magnetic Ranging technique facilitates the positioning of one or more poles within one or more probability distributions, which are typically assumed to be Gaussian ellipsoids.

Figure 11 shows an example of such ellipsoid determination. The two white ellipsoids represent the uncertainties around two identified poles during a PMR operation used to locate a target well (blue), the re-computed target well (olive green) after surface shift post-PMR analysis from the ranging well or subject well (green). For comparison the 2D trapezoidal uncertainty (yellow) from the traditional determination method is superimposed on the ellipsoids (white).

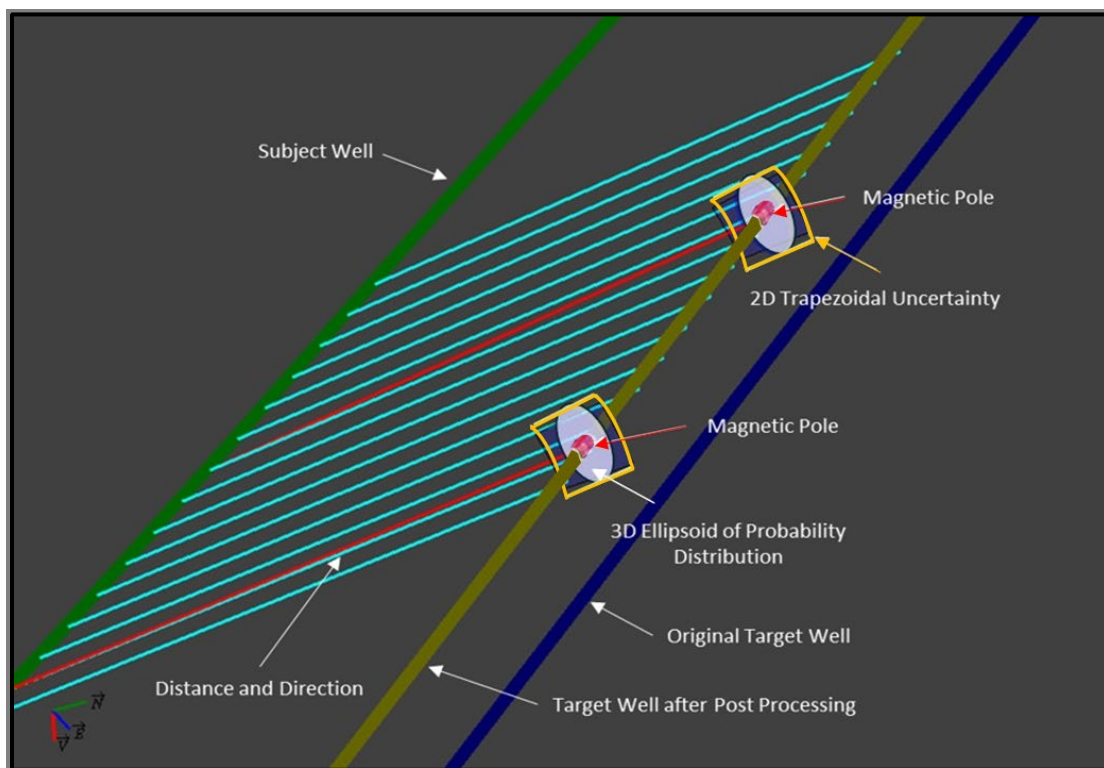


Figure 11—Ellipsoidal and trapezoidal surfaces of uncertainties after 3D PMR processing

2.9 Applications for PMR

There are many applications for which PMR is useful. A few include:

- Collision avoidance
 - When magnetic interference is detected
 - During planned close approaches with relatively similar wellbore trajectories
- "Always on" proximity detection
- Well twinning
- Passing over or under a perpendicular well (when accidental collision is not an HSE concern)
- Wellbore intercept
- Well re-entry

2.10 Modelling

PMR detection range, or distance, can be assessed using a simple monopole model. When moving a 3-axis magnetometer past a magnetic monopole of strength (impulse) M , one can parameterize the response in terms of the closest approach distance (L), and the along-hole depth (S) from the point of closest approach of the well to the magnetometer. The axial (Figure 13, left) and cross axial (Figure 13, right) of the magnetic field are determined from the inverse square law acting on this monopole, or concentrated, pole source (Figure 12). Passive magnetic modelling is discussed in detail in Jones, et al., 1987, SPE-14388.

During the job planning phase, in order to optimize the data acquisition and the chances of success, it is critical to model the relative position of the subject well relative to the target trajectory for the maximum and minimum detection distances (see Section 7.2).

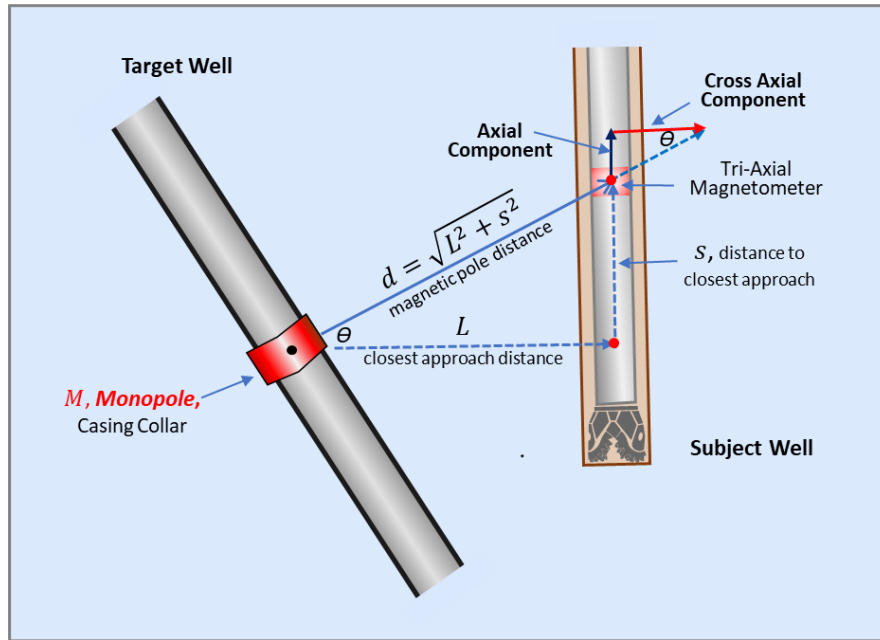


Figure 12—The basic principle of Passive Magnetic Ranging Modelling

2.10.1 Detection Range

The amplitude of the axial and cross axial magnetic fields is dependent on the pole strength, while their shapes are only dependent on L. The range L can be determined from the separation, *l* (Figure 13, left) between the maximum and minimum of the axial magnetic field or half-width of the cross axial magnetic field, *l^{ca}* (Figure 13, right).

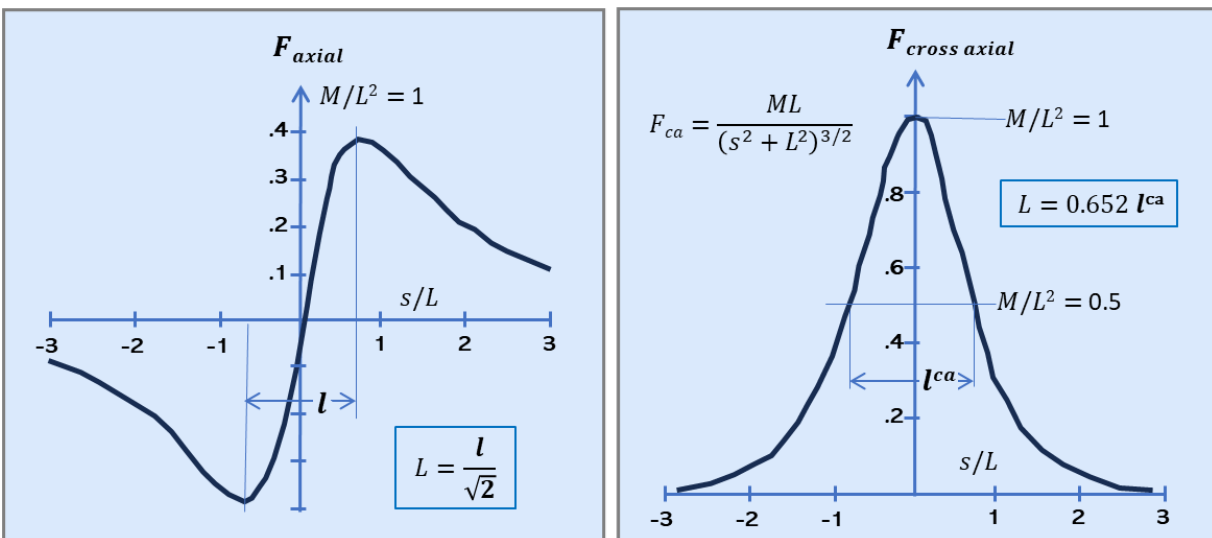


Figure 13—The determination of axial magnetic field component and range equation L (left) and the cross-axial magnetic field component and range equation L (right).

The ranging detection and distance can be challenging to estimate, primarily because it depends on numerous variables, which include:

- **Monopole Strength:** Monopole strength is strongly related to the casing’s weight, age, and condition. To put it simply, the more metal in the casing string, the higher the pole strength. Figure 14 shows the interference associated with typical magnetic pole strength for various casing weights for a continuous casing model. However, for open-end casing or casing shoe, this interference could be 2- to 3-times stronger.
- **Casing age:** The ferromagnetic properties of casing can decline with its age and the length of time it has been in-situ.

- **Environmental Effects:** Casing can degrade significantly, especially in the presence of H₂S or CO₂, which degrades casing integrity, thus weakening pole strength.
- **Polarity:** While the specific polarity of the monopole has little bearing on casing detection, the overall pattern of plus and minus poles along the casing ([Figure 8](#) and [Figure 9](#)) will affect detection distances. Casings with a positive end may be set against another positive end, in which case the dipole distance is on the order of the casing length, while a negative end set against a positive end will yield a dipole of diminished length and strength.
- **Magnetic Ranging tool resolution:** Detection range using survey data alone requires good quality noise reduction in the MWD tool, Multi Station Analysis (MSA) corrections, and a thorough knowledge of the geomagnetic reference field.
- **Data Acquisition rate, Interval:** Standard MWD surveying techniques are generally insufficient in specifying detection ranges because a single point survey every stand (90ft) may miss the interference signature from an offset well. For example, the survey could fall in a position between two magnetic poles and so give the appearance of no detection and, in an anti-collision scenario with larger incidence angles, the survey interval may not be sufficient to detect an offset well before the bit reaches it (see [Section 7.2](#)).

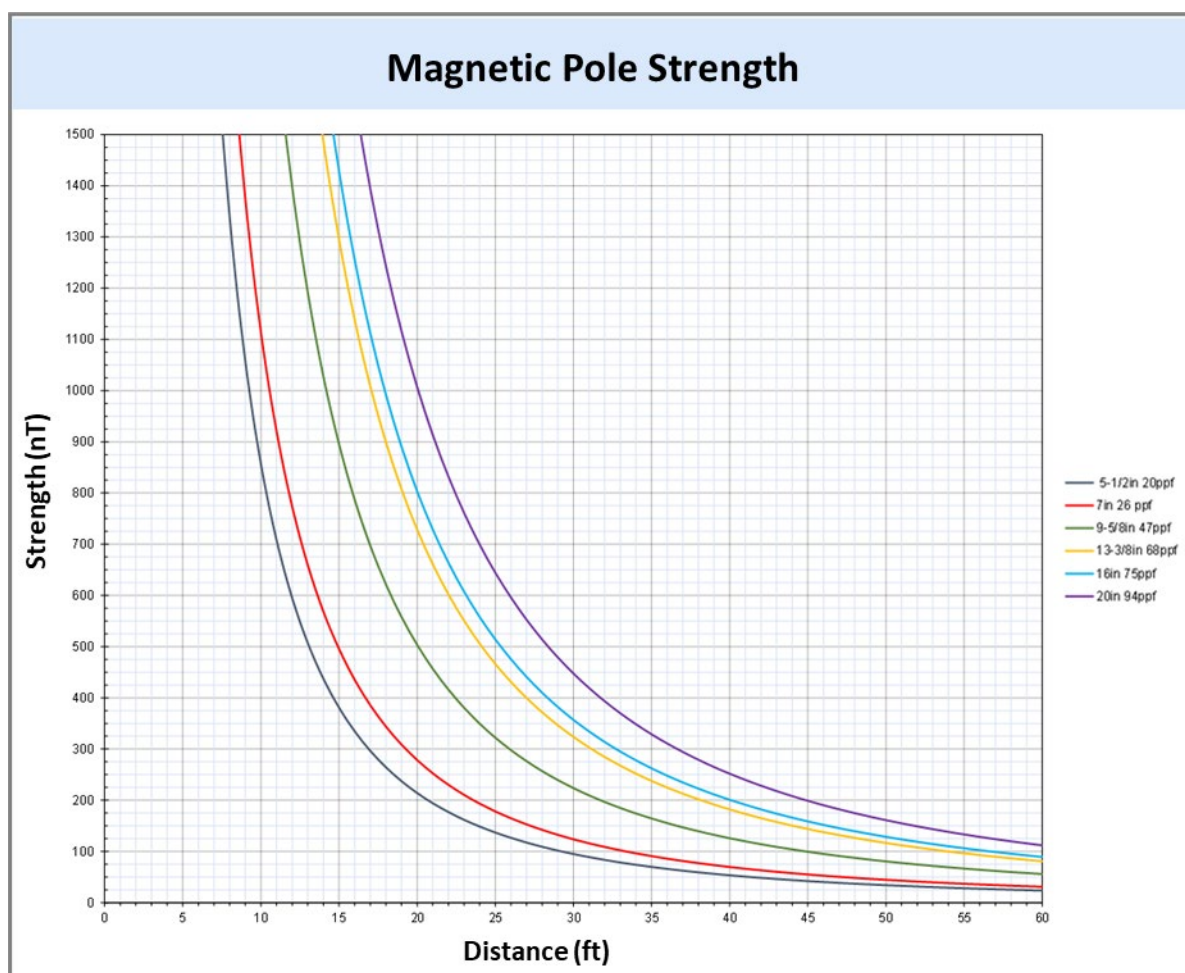


Figure 14—The chart shows the relationship of the estimated monopole strength vs distance for various casing weights.

A more reliable method uses a gradient, the rate of change of the monopole strength to determine detection range ([Figure 15](#)). This requires a much greater data acquisition rate and overlapping intervals, either from continuous monitoring of the magnetic field while drilling, or from continuous surveying techniques. It is possible to do this using the axial magnetometer data, but because this method has the potential to lead to false positive results, continuous monitoring of borehole orientation is still required.

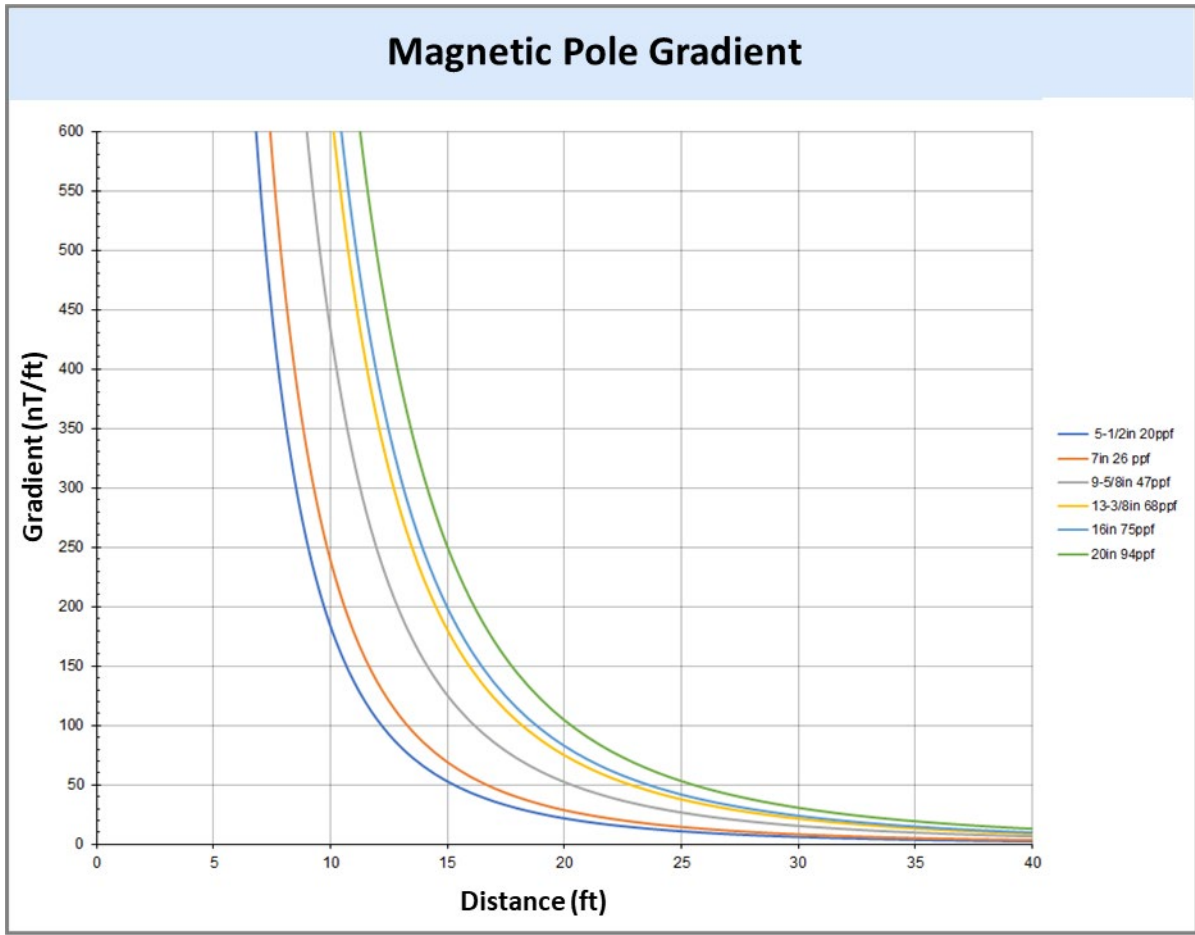


Figure 15—The chart shows the relationship of the estimated monopole gradient vs distance for various casing weights

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 analyzed to define a proximity vector between the two wellbores. Magnetic fields are generated by numerous methods, such as passing a current through wire or pipe, passing current through a coil of wire, or permanent magnets ([Figure 16](#)).

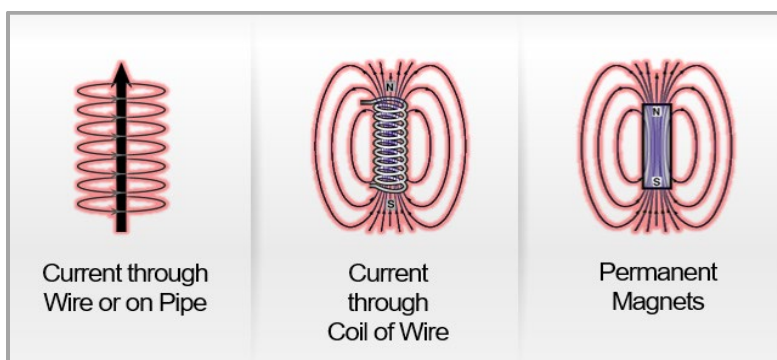


Figure 16—Different ways to create a magnetic field. The two shown on the right are considered point sources.

The AMR technology is separated into two categories based on accessibility of the target well—Access-Dependent and Access-Independent ([Figure 17](#)).

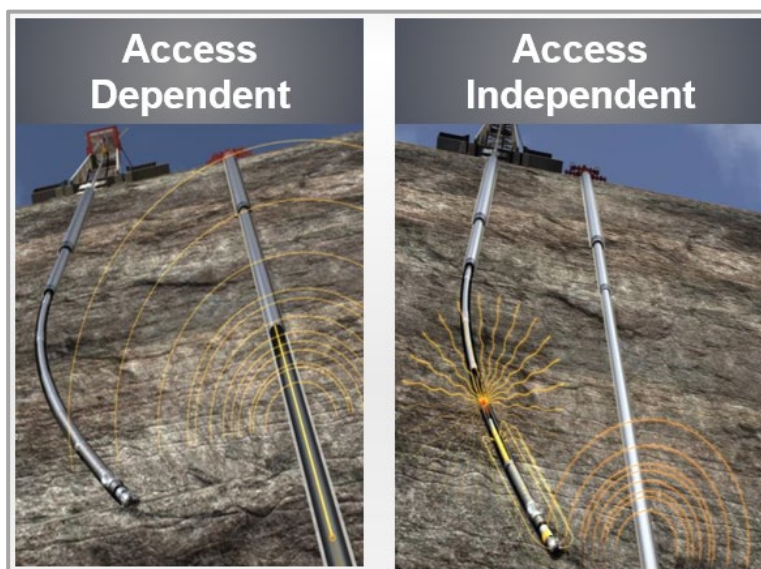


Figure 17—Access independent does not require access to the existing target wellbore

- **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 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 in operations, 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, which optimizes 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

The AD-AMR 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 ([Figure 18](#)). A 6-axis MWD directional probe is placed in the drilling BHA. A single large magnetic field is generated by the solenoid by sending a direct current in a positive polarity through it, followed by reversing that current to a negative polarity. The magnetic field is generated only during a special Magnetic Solenoid AMR Survey. The generated magnetic field is then measured by the 6-axis MWD Directional Probe and analyzed to determine a distance and direction to the solenoid in the target well.

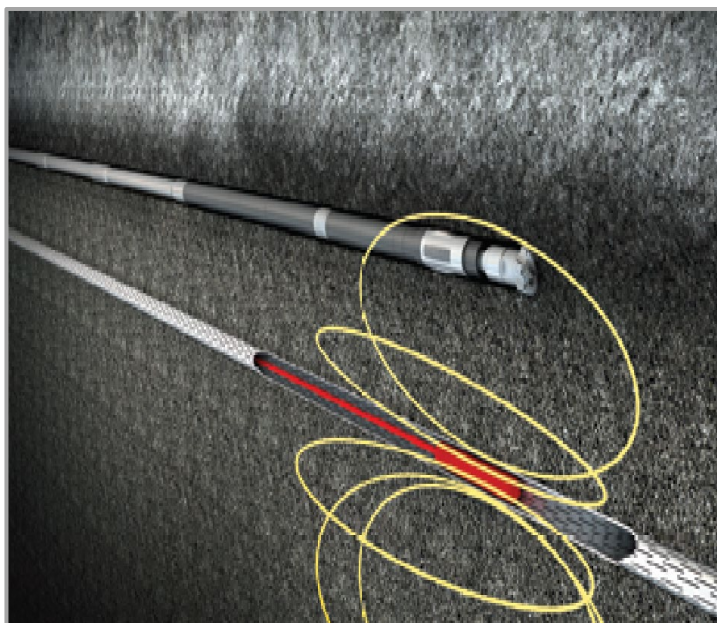


Figure 18—Typical magnetic solenoid AMR system diagram. The magnetic field generating wireline carried solenoid is displayed in red, which is placed in the target well

The 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 $\pm 5\%$ of the radial distance. When within 4.5 – 15m (15 – 50ft.) of radial distance the accuracy of the Magnetic Solenoid AMR system improves to $\pm 2 - 4\%$ of the radial distance.

Note: Commercially proven solenoid systems exist that offer the following:

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

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

- Drilling stacked horizontal well pairs for Steam Assisted Gravity Drainage (SAGD)

- Infill and collision avoidance
- Observation well placements

3.1.1.1 Typical Magnetic Solenoid System Protocol

1. Follow normal drilling practices until a regular survey depth is reached.
2. Confirm with wireline engineer that magnetic solenoid is at desired depth in the target well.
3. Confirm that magnetic solenoid has energized with a positive direct current using the magnetic solenoid's power supply.
4. Begin taking magnetic solenoid survey with magnetic solenoid software.
5. When indicated by the magnetic solenoid survey software, reverse the polarity of the magnetic solenoid.
6. When the magnetic solenoid survey is completed, demagnetize the magnetic solenoid and turn off direct current.
7. Have ranging engineer QC the magnetic solenoid survey, and provide the directional driller with a relative position to the target well (Typically High-Low / Left-Right distances are provided).
8. Begin drilling down to next survey station in the drilling well.
9. Move magnetic solenoid to the next desired depth in the target well.
10. Repeat steps 2 – 9 until well is completed or AMR is no longer needed.

3.1.2 Rotating Magnet Systems

The rotating magnetic system consists of a rotating magnet sub (RMRS), approximately 0.5m (1.6 ft) in length, which sits between the bit and the motor ([Figure 19](#)). This sub contains stacks of powerful rare earth magnets that create an AC 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 $\pm 5\%$ 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.

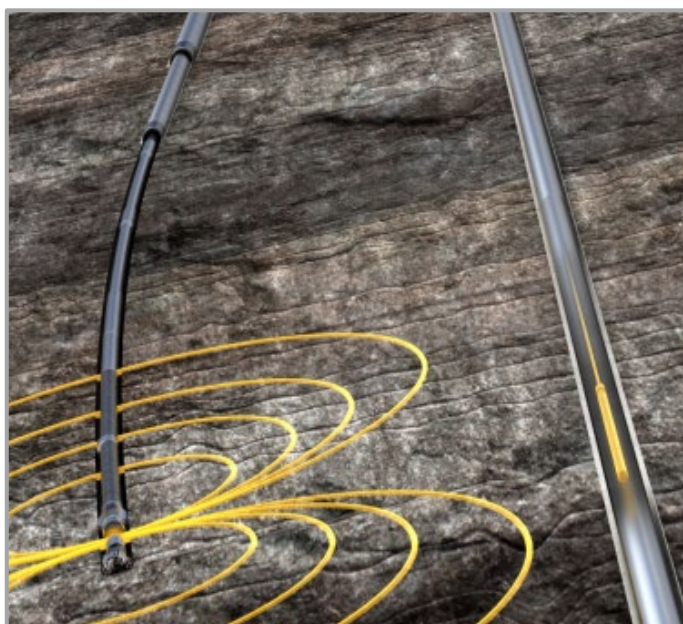


Figure 19—Typical rotating magnet AMR system diagram showing the rotating magnet sub near the bit and the wireline conveyed directional sensor in the target well.

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:

1. The 6-axis directional sensor probe conveyed via wireline in target well ([Figure 20](#)).
2. A bottom weight bar
3. The tool foot
4. Optional above tool weight bar with feed-through wire
5. Rotating magnet sub in subject well while drilling.

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, begin data monitoring. 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 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. Depending on the quality of data collected while drilling, the ranging specialist may require the data be collected after a section has been drilled by having the driller wipe the section at a speed of $\approx 1.5\text{m/min}$ (5ft/min). It is important that the section is wiped at a consistent speed in rotary mode 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 analyze the recorded rotating magnet AMR Data.
4. Depending on the results from any given recorded RMRS determination the Ranging Specialist will determine whether more RMRS data is needed to be taken at a given hole depth.
5. Once sufficient data have been acquired at a given point, the Ranging Specialist will advise the company representatives on the status of the drilling well location relative to the offset well. The Ranging Specialist will also recommend a distance to drill ahead, which is typically 3 – 10m (10 – 33 ft.).
6. Steps 3-5 will be repeated until the objective has been completed.

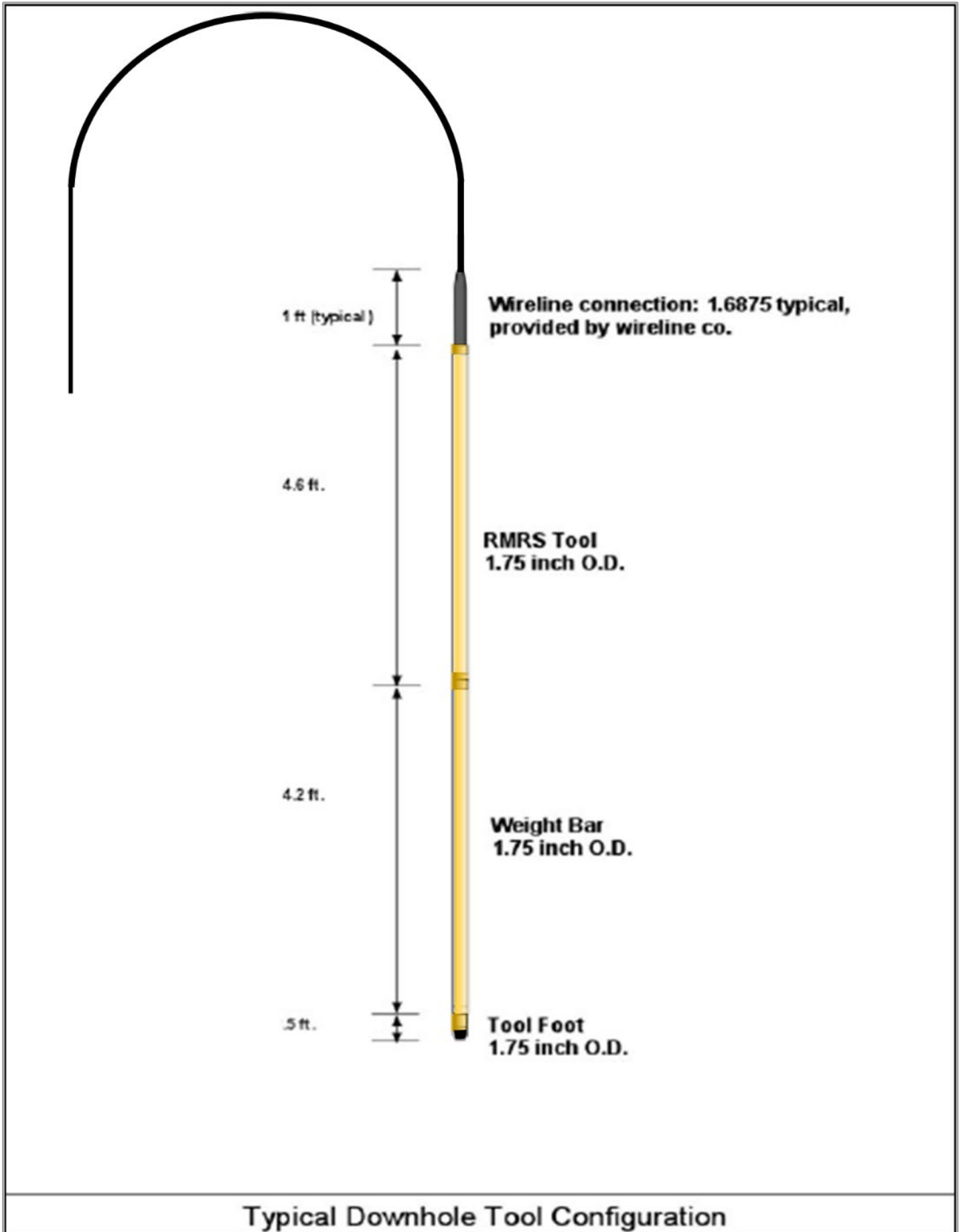


Figure 20—Typical RMRS tool configuration

3.1.3 Energized Wire Systems

The energized wire active magnetic ranging system consists of an electric wireline placed in the target well ([Figure 21](#)). A known AC current is then applied to the wireline. A large magnetic field is generated along the length of the wire by the applied AC 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 analyze the created magnetic field in the target well to determine a distance and direction.

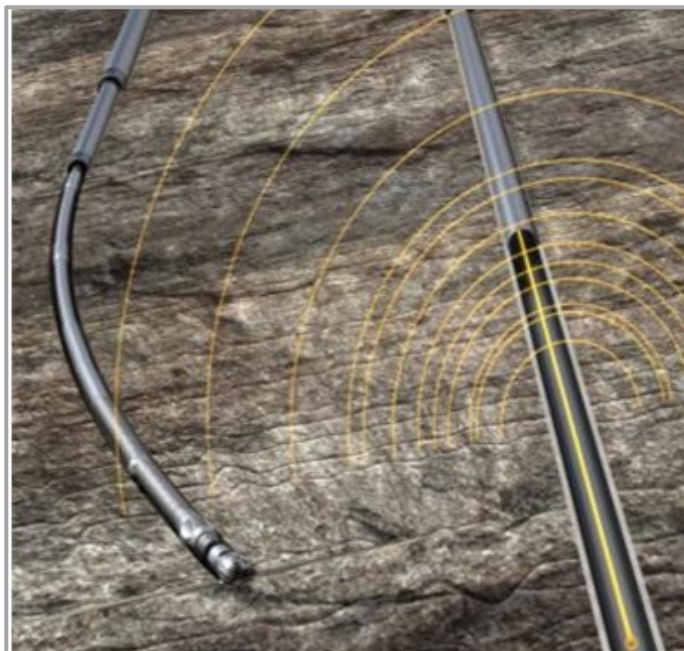


Figure 21—Energized wire AMR system. Current in the wire in the target wellbore, sensors in the BHA

3.1.4 Surface Access Systems

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 ([Figure 22](#)). 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 is created at depths downhole. 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.

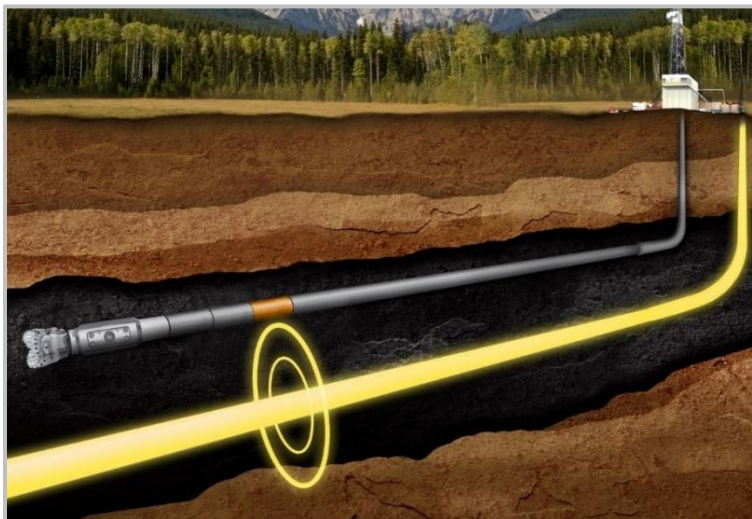


Figure 22—SA-AMR uses well-head access to induce a magnetic field in the target well (shown in yellow above) which is then utilized by a downhole sensor in the drilling BHA

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

AI-AMR works by injecting an AC current into the formation and then onto the target well, which in turn creates a magnetic field (Figure 23). From this induced magnetic field, both distance and direction can be determined. No access to the target wellbore or well head is required.



Figure 23—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.

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, most 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:

- Three phases of RW ranging—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) and increased to 1.5m- (5ft-) intervals up to 15m (50 ft) off bottom. Any subsequent data points in unlogged sections will be taken at 7.5 – 15m- (25 – 50 ft-) intervals. This data will be analyzed by the ranging specialist and any infill data will be taken on a second descent if required.

The estimated time for a ranging run is:

- 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.

3.2.4 Tool and Wireline Assembly (Bridle)

The AMR tool is deployed into an open hole via a 7-conductor wireline. The bridle assembly contains the tool assembly, isolation section, and excitation components ([Figure 24](#)).

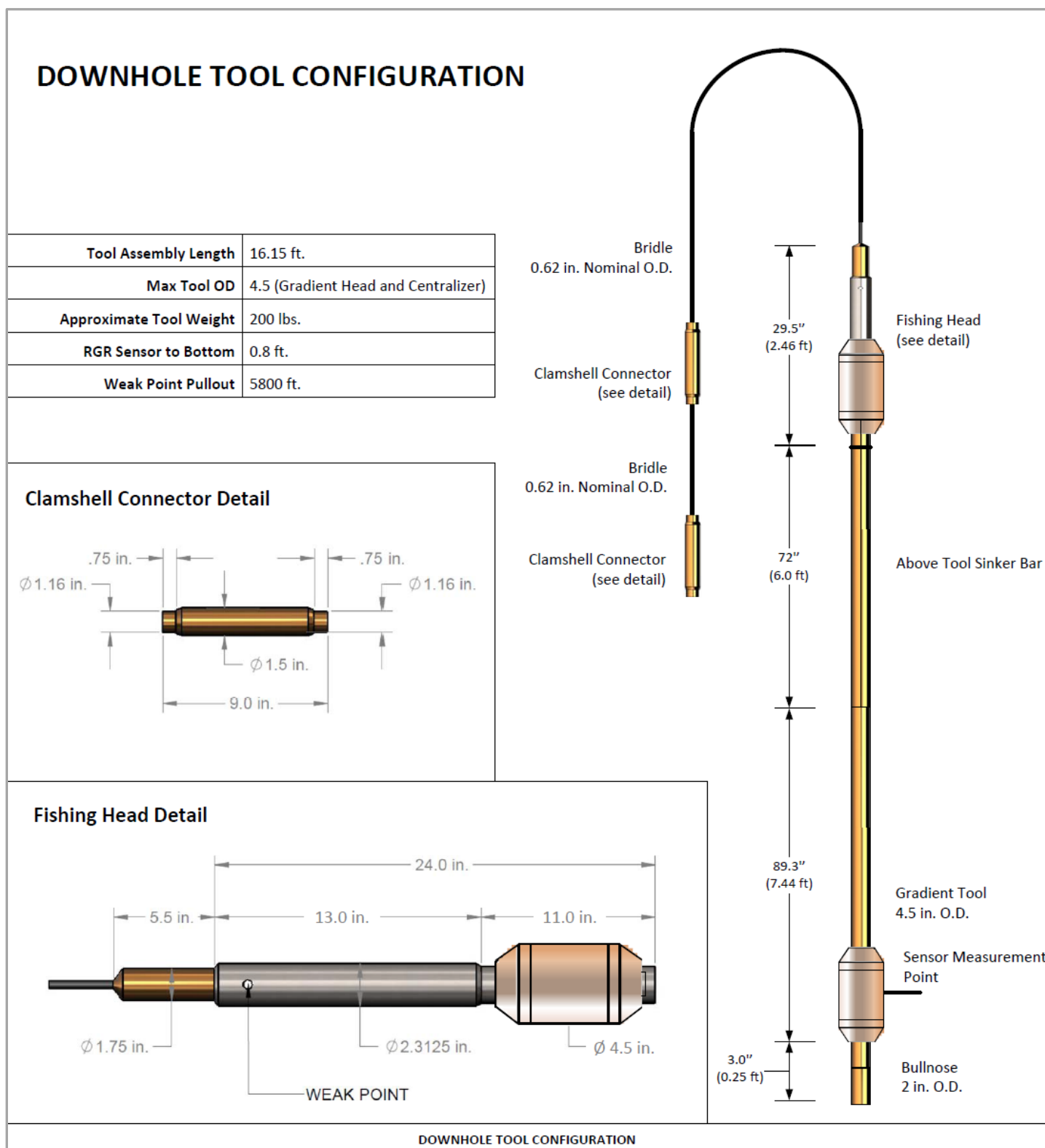


Figure 24—AI-AMR downhole tool configuration

3.2.4.1 Wireline Cable Conveyance

The AMR kit can be run using any major service company wireline logging unit. However, utilizing some providers' units may require detailed pre-planning to ensure that the correct cable and crossovers are sourced.

The preferred wireline cable requirements are 7-conductor heptacables with a 20AWG rating of sufficient length to reach the total operating depth (Figure 25). Typical surface equipment will require at least a 20kVA power supply for the downhole injection power source. The power injection equipment may be run from a single or a 3-phase power source.

The injection input current must be a stable and reliable power source that will not be affected by other equipment on the rig.

Examples of some wireline cables which meet the specification include:

- Camesa 7H47 Series
- SLB 7-42, 7-46, 7-52 and 7-53 Vector Cables
- Rochester 7-H wireline stock including 472, 474, 484, 490 and 550 series.

The wireline cable must have a conductor resistance of less than 35.76 ohm/km (10.9ohm/kft). Regardless of wireline cable type used, a detailed operational assessment must be performed to ensure that the cable meets the current injection requirements.



Figure 25—7-conductors heptacable cross section

[Table 1](#) shows an example of wireline cable resistance for 20,000 ft length.

Table 1—Wireline cable resistance

	Total Resistance	Current at 300 V	Current at 400 V	Current at 450 V	Current at 500 V
5 Conductor Injection	68.6 ohm	4.37	5.83	7.28	8.74
3 Conductor Injection	97.7 ohm	3.07	4.09	5.11	6.14

[Table 2](#) shows an example of Wireline Cable Specification suitable for AI-AMR operations.

Table 2—Wireline cable specification

Wireline Code:	7-46P	Manufacturer:	SLB
Description:	Seven conductor, 20 AWG armored logging cable with TPX and tefzel insulations. The armor wires used are extra high strength galvanized plow steel.		
Conductor Gauge:	#20 AWG	Diameter:	0.9652mm (0.038in)
Conductor Resistance:	35.8 ohm/km (10.9 ohm/kft)	Armor Resistance:	4.3 ohm/km (1.25 ohm/kft)
Insulation Resistance:	4572 M ohm.km	Conductor Capacitance	40pF/m
Voltage Rating	880Vrms at 1.1 A	Temperature Rating	185 degC 1hr 177 degC 8hrs 163 degC 24hrs
Number Inner / Outer	24 / 24	Outer Cable Diameter	11.786mm (0.464in)
Inner Armor OD	0.991mm (0.0390in)	Outer Armor OD	1.245mm (0.0490in)
Cable Breaking Strength	11600 lbf		

[Table 3](#) shows an example of wireline bridle assembly specification for AMR current injection.

Table 3—Wireline bridle assembly specification

Wireline Code:	7-H-550K	Manufacturer:	Rochester
Description:	18x18 Armor ETFE Jacket Coated Special GIPS Steel Wireline		
Conductor Gauge:	#20 AWG	Diameter:	0.97mm (0.038in)
Conductor Resistance:	32.8ohm/km	Armor Resistance:	4.5ohm/km
Insulation Resistance:	15000M ohm.km	Conductor Capacitance	190pF/m
Voltage Rating	1000Vdc	Temperature Rating	260 degC 1hr 246 degC 24hrs
Number Inner / Outer	18 / 18	Outer Cable Diameter	13.97mm (0.550in)
Inner Armor OD	7.95mm (0.313in)	Outer Armor OD	10.95mm (0.431in)
Cable Breaking Strength	81.4kN (18300 lbf)		
Cable Weight (Air)	602 kg/km (404lb/kft)	Cable Weight (Fresh Water)	448 kg/km (301lb/kft)

3.2.5 Coil Tubing

Recently, industry experts developed a coiled tubing-conveyed active magnetic ranging technology that is able to range-while-drilling. The coil tubing drilling (CTD) BHA is connected to wireline cable installed inside the coil tubing for directional control, electric current injection, and to continuously transmit collected ranging data to the surface for analysis. This analysis is then used to take appropriate steering action to drill ahead. The coiled tubing ranging-while-drilling (CT-RWD) BHA consists of an AI-AMR tool in addition to the normal drilling assembly and may provide an alternative to the existing AMR or PMR technologies typically conveyed on drill pipe or wireline cable.

3.2.5.1 AMR Coil Tubing

The CT-RWD kit can be run using any major service company coil tubing drilling package ([Figure 26](#)) and wireline logging unit. However, the CT-RWD BHA may require advanced and detailed pre-planning to ensure that the correct cable, specialized equipment, and crossovers are sourced. The wireline cable specification is the same as in [Section 3.2.4.1](#) and may require additional hardware or adapter.



Figure 26—Mobile Coil Tubing Drilling Package

3.2.6 Wired Drill Pipe

The latest development in braided wired drill pipe (WDP) technology enables bidirectional communications, high speed data transmission, and continual delivery of power downhole (Figure 27). Because this system provides continuous electric current injection and simultaneous data transmission, it can be deployed to perform access-independent active magnetic ranging while drilling without stopping (Figure 29). The WDP system includes a BHA interface to facilitate communication, data transmission, and power distribution to various downhole tools, such as RSS directional control, AI-AMR and MWD/GWD surveys. Continuous current injection allows the AI-AMR tool to transmit collected ranging data to the surface for analyses in real-time at high-speed data rates of up to 56 Kbps. The ranging result is then used to take appropriate steering action to drill ahead. The WDP-RWD provides a real time while-drilling ranging option to current AMR technologies, which are typically conveyed on wireline cable or coil-tubing.

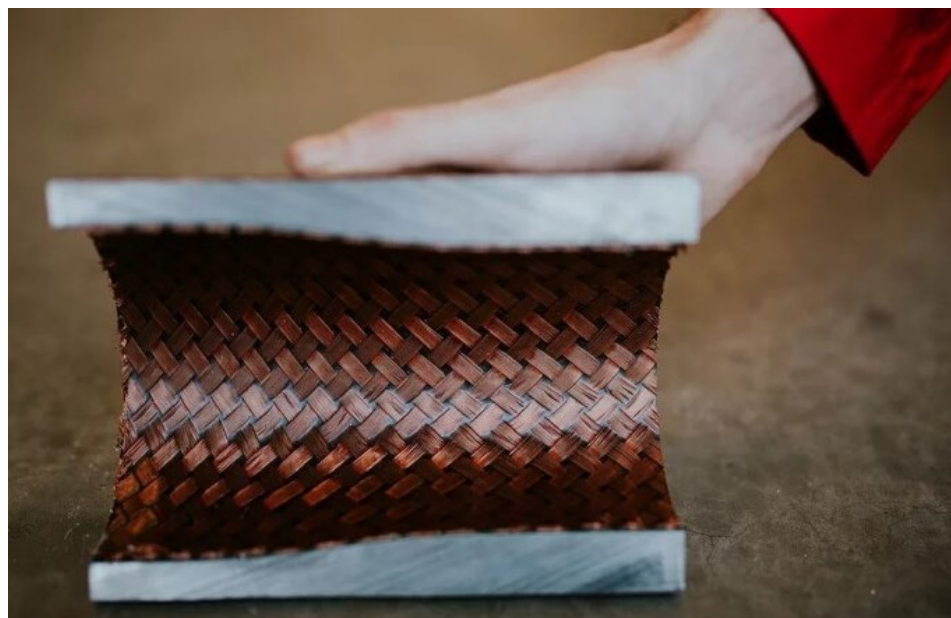


Figure 27—A cutaway exposes the braided wires of WDP, which transfers both power and data to and from a BHA. Source: reelwell.com

3.2.6.1 AMR Wired Drill Pipe

The WDP-RWD BHA (Figure 28) consists of a drill bit, a RSS (rotary steerable system) or motor, or both, AI-AMR, MWD and GWD, non-magnetic spacers and an injector sub, all of which are connected to the WDP/BHA interface to surface.

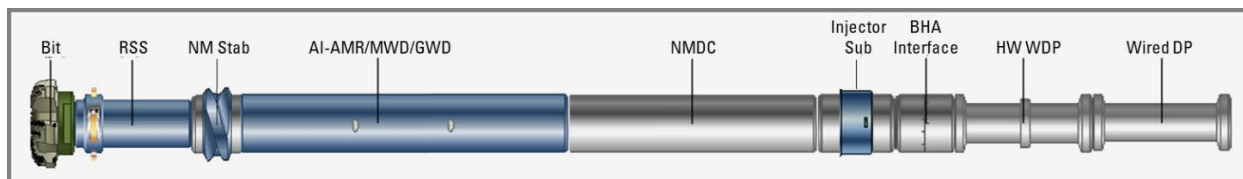


Figure 28—Example of WDP-RWD, AI-AMR BHA with general description of each individual components.

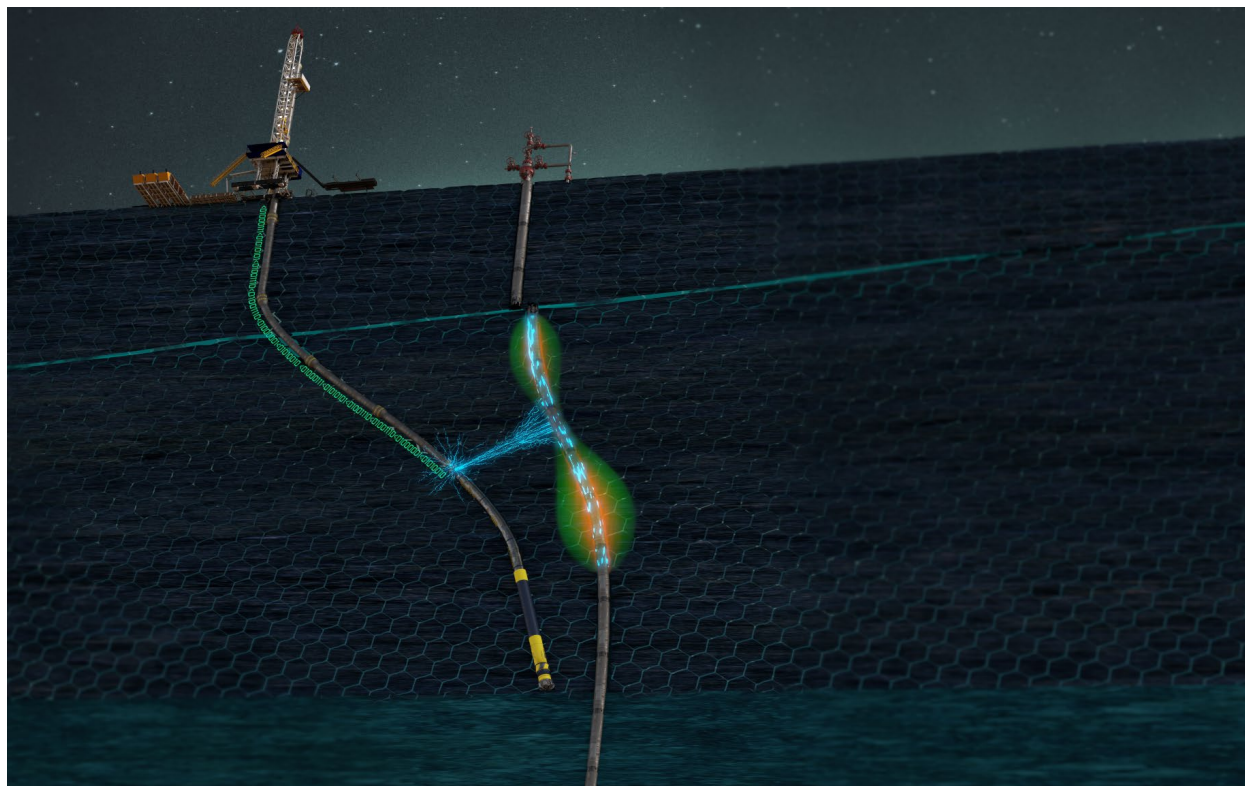


Figure 29—Illustration of the Access-Independent AMR While-Drilling system using braided wired drill pipe for downhole electric current injection and data transmissions (Rassadkin, et al., OTC-35566).

3.2.7 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 ($\mu\text{A}/\text{m}/\text{A}$) and the distance to target. The following graphs are examples of the custom analysis that are included in the relief well ranging plan ([Figure 30](#) and [Figure 31](#)).

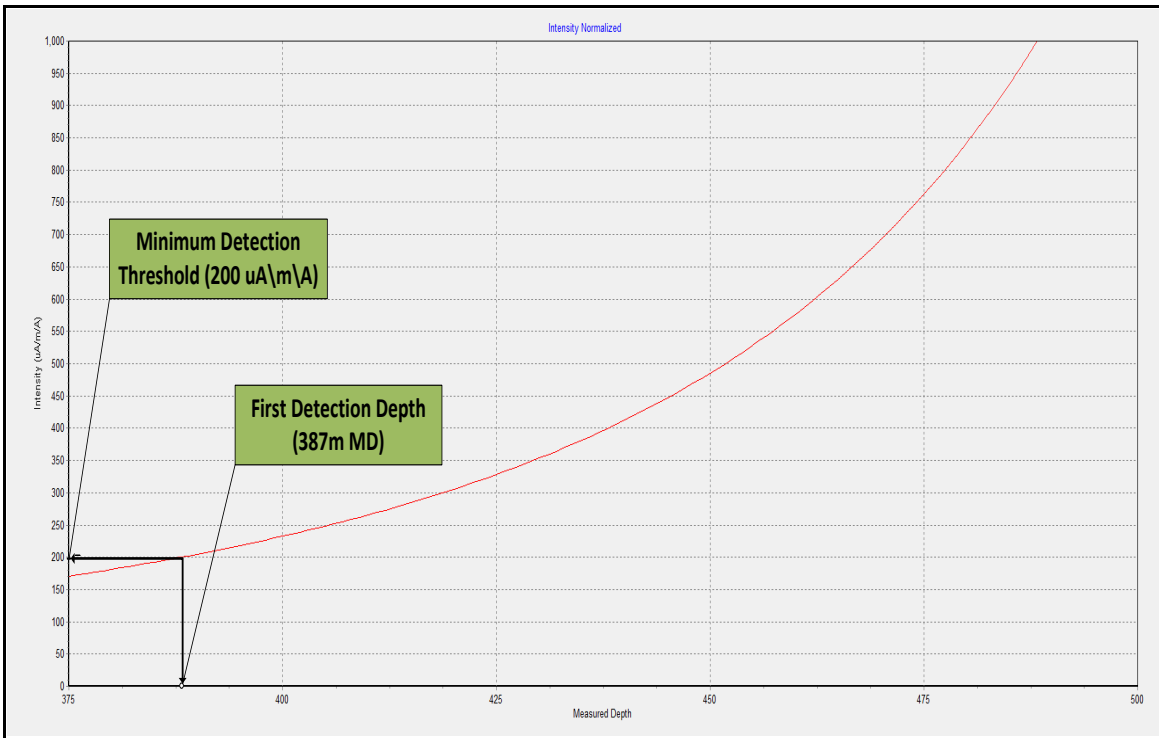


Figure 30—Typical AMR detection threshold

Note: The signal detection is independent of the current injected. Therefore, this detection threshold is not quoted normalized for injected current. The detection threshold also directly relates to maximum detection range. [Figure 30](#) shows a typical AMR detection threshold plot. This is project specific and must be updated as the estimation of detection distance is a key component in creating an effective relief well plan ([Figure 31](#)). Commercially proven systems with a minimum detection threshold of 48uA/m are available.

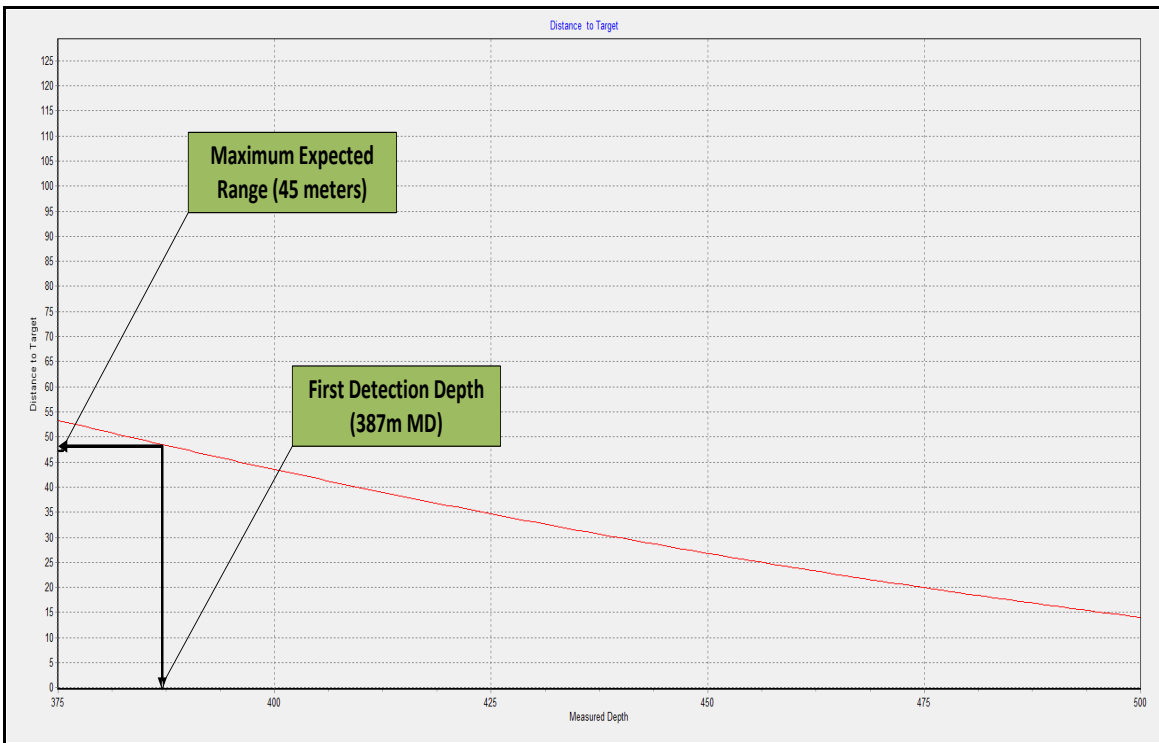


Figure 31—AI-AMR maximum expected range

3.3 Multiple Wellbores Environment

The ability to distinguish a target well from other offset wells is 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 solution is not available using 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 available as the vector component of the offset well is measured separately. While this method is limited by depth, it is likely that any offset well inside detection range will be inside the detection range only 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. Because this method 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.

3.4 Impact of Incidence Angle on Detection

Like PMR, approaching a target well at a high incidence angle impacts the detection for AAR, AMR and ARR. Drilling towards a target well at a high approach angle should only be done when necessary. The high incidence angle for an AMR ranging measurement means 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 (See [Section 7.2](#)).

4. Passive Acoustic Ranging (PAR)

4.1 Introduction

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

The sources generate an acoustic signal that travels in all directions and travels in the media in the same direction as the excitation direction. Acoustic waves can propagate in a media in multiple modes that depend 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, 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 in a series of compression and expansion (rarefaction) movements.

The common passive acoustic source is the noise that is generated by the drilling bit ([Figure 32](#)). 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 than that of a Roller-cone bit, which drills by scraping and gouging.



Figure 32—Various bit type to produce acoustic source for passive acoustic ranging detection

4.2 Application

Within the oil and gas industry, one application for 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 (Figure 33).

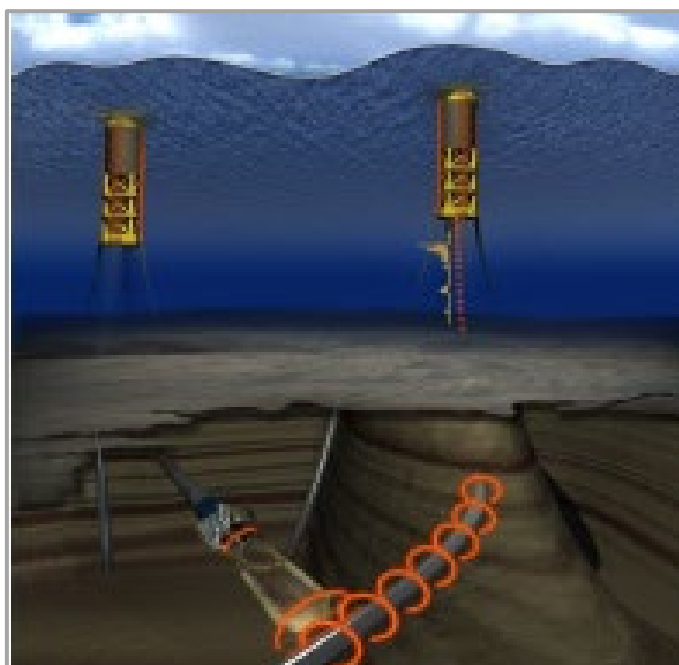


Figure 33—Illustration of drill bit closing in on an existing well

Figure 34 shows non-invasive sensors clamped topside on wells adjacent to the drilling operation pick up such propagated drilling noise.

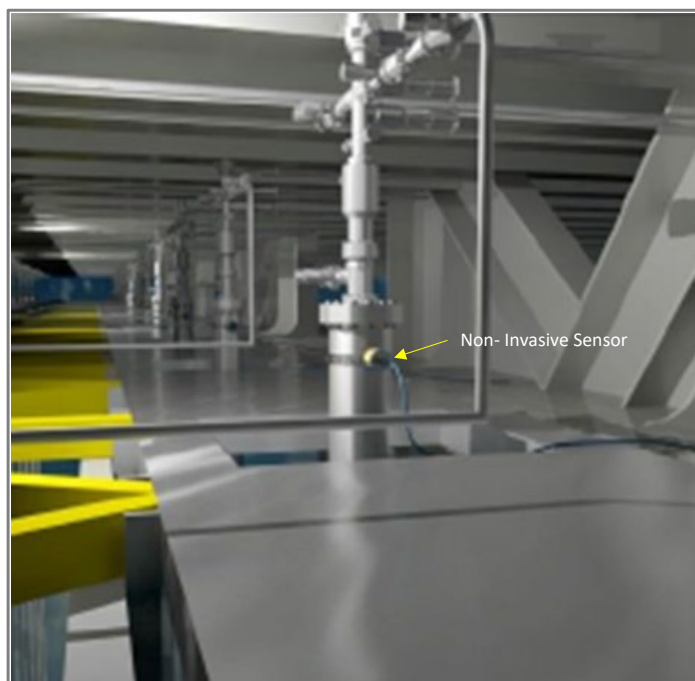


Figure 34—Illustration of non- invasive sensor mounted on the wellhead (yellow arrow)

Spectrum analyses of all sensor data are presented during the drilling operation in real time. Any change in the acoustic conditions on the well heads is readily available for scrutiny when the operation commences and may provide early warning of the drill bit approaching an existing well. Upon observations of strongly increasing ultrasonic signal levels, drilling can be halted and data from available sources analyzed. Depending on the analysis 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 (Figure 35).

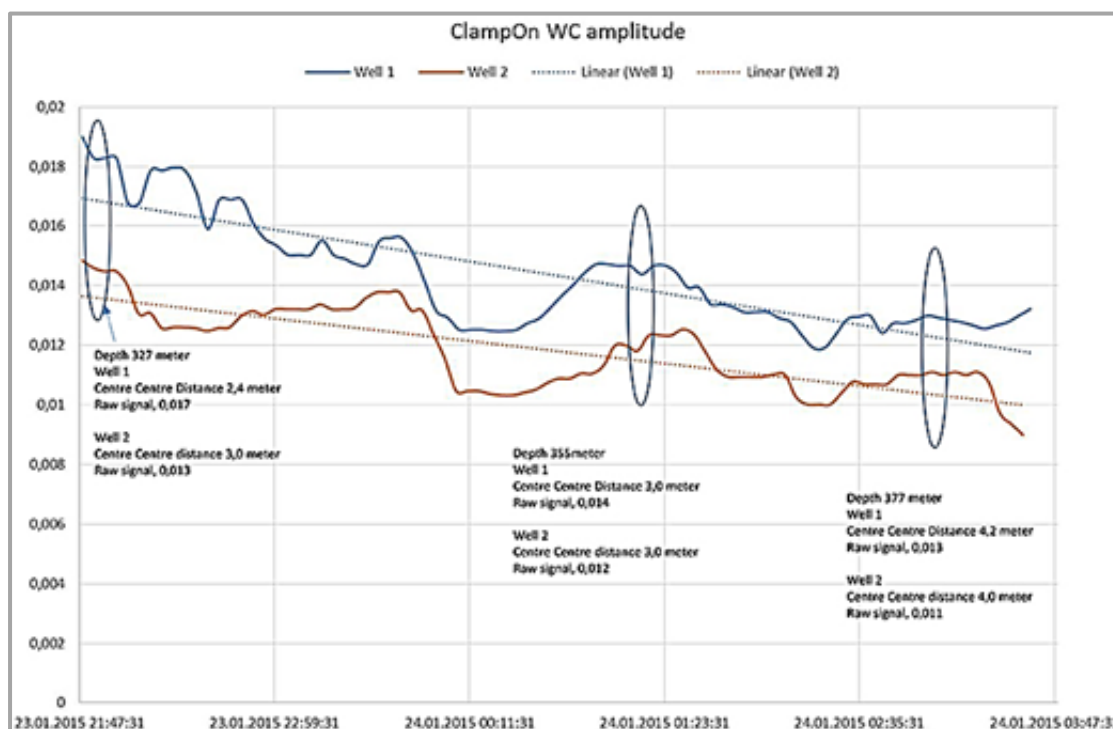


Figure 35—Signal strength recorded at 2 different well conductor locations in collision avoidance situation, increasing center to center distance

5. Active Acoustic Ranging (AAR)

5.1 Introduction

Until recently, options for locating a nearby well were limited to Active Magnetic Ranging (AMR) and Passive Magnetic Ranging (PMR). More recently, Active Acoustic Ranging (AAR) has been successfully deployed to locate both cased-hole and open hole wells in North America and in the Gulf of Mexico (Poedjono, et al., 2017, SPE-187313 and Johansen, et al., 2019, THE LEADING EDGE). Additionally, AAR can be used in conjunction with other ranging techniques, such as PMR, AMR and Active Resistivity Ranging (ARR), to increase chances of success.

AAR utilizes seismic processing methods to determine the azimuthal direction and distance of compressional and shear acoustic signals reflected from the borehole to locate and track a target wellbore. These signals are processed to calculate the distance and direction of nearby wellbores. AAR is particularly advantageous when AMR cannot be used, such as in pure salt formations where resistive rock property prohibits the current injection to excite the target wellbore casing.

In the past, interest in reflected acoustic signals was limited to detecting fractures crossing a wellbore. Land and offshore surface seismic surveys apply the same fundamental principle to map the layers beneath the surface, but each uses slightly different setups and processing techniques ([Figure 36](#)).

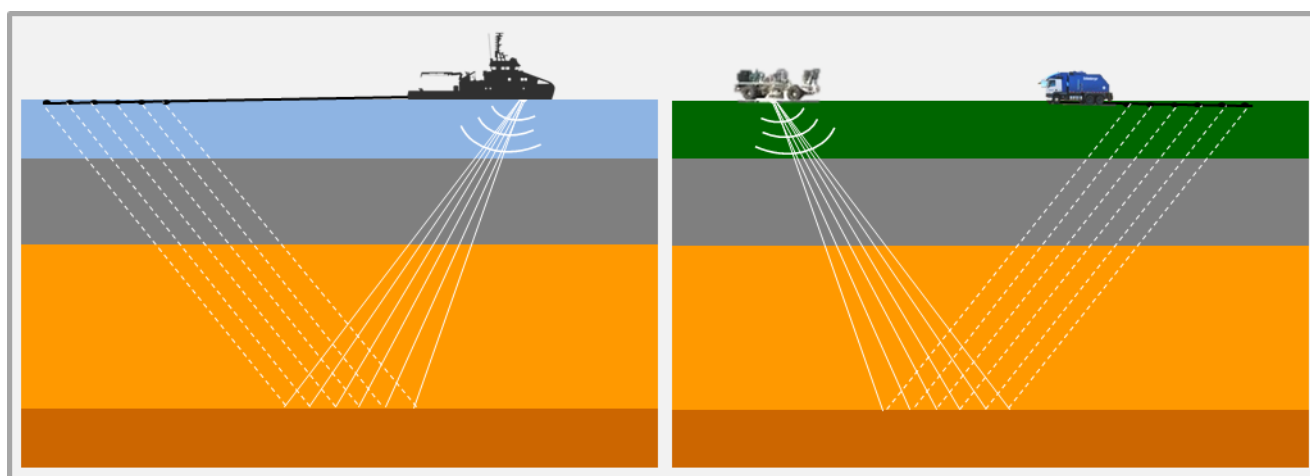


Figure 36—Seismic imaging setups offshore (left) and on land (right).

The concept of using sonic-waveform data to generate high-resolution seismic surveys around a borehole was first discussed in 1984 (Utard, et al) and again in 1989 (Hornby, 1989). In the 1990s, the method was used to image fractures away from the borehole (Yamamoto et al., 1999).

Most surface seismic sources generate a low-frequency signal that can travel thousands of feet through rock. But because of their low frequency, the image resolution produced by these signals can only detect events that are larger than 100m (328ft) in deep wells. In contrast, the sonic imaging AAR frequency lies between ultrasonic and seismic imaging ranges ([Figure 37](#)). This produces a higher resolution image that can detect smaller events, such as nearby wellbores.

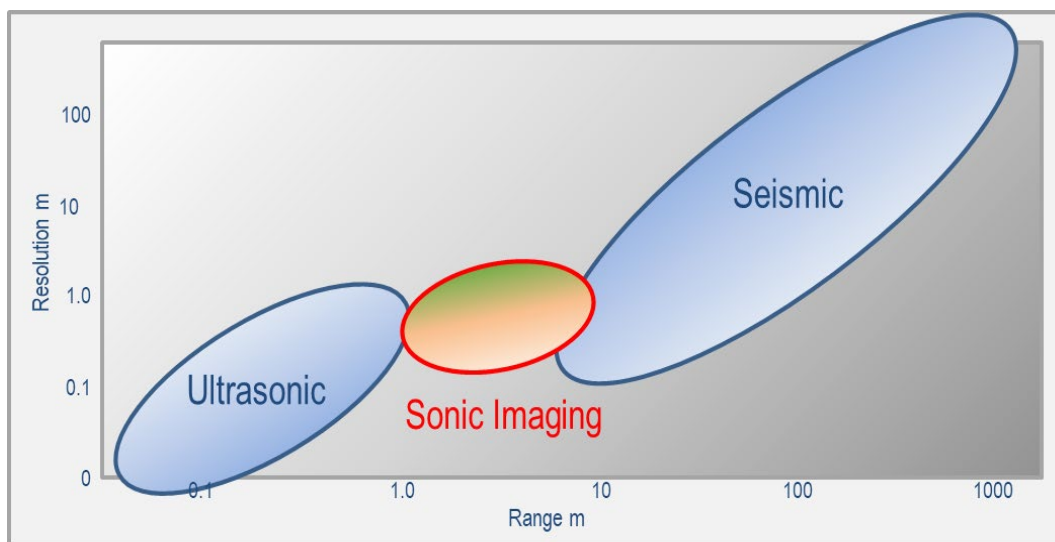


Figure 37—The resolution of sonic imaging range in between ultrasonic and seismic ranges

5.2 Basic Theory

Since the concept of using sonic waveform data to generate high-resolution seismic surveys was first discussed in 1984, the method of Borehole Acoustics Reflection Survey (BARS) has evolved. Earlier fracture and mobility detection methods—micro resistivity, ultrasonic, and Stoneley—are all limited to the area immediately surrounding the borehole. BARS uses reflected acoustic waveforms to penetrate deeper into the formation, which helps resolve features farther away from the wellbore and provides a better understanding of nearby offset wellbores and the reservoir.

5.2.1 Acoustic Acquisition

The quality of the data acquired is crucial for its processing and the quality of the image produced is a function of the acoustic platform used in the data acquisition (Figure 38).

When using acoustic ranging acquisition, both monopole and dipole transmitters are used; monopole and dipole data are acquired in a minimum of eight sectors. Tool orientation should be done at the same time as waveform acquisition to determine the azimuth waveform and confirm that enough waveforms are recorded to cover the expected target.

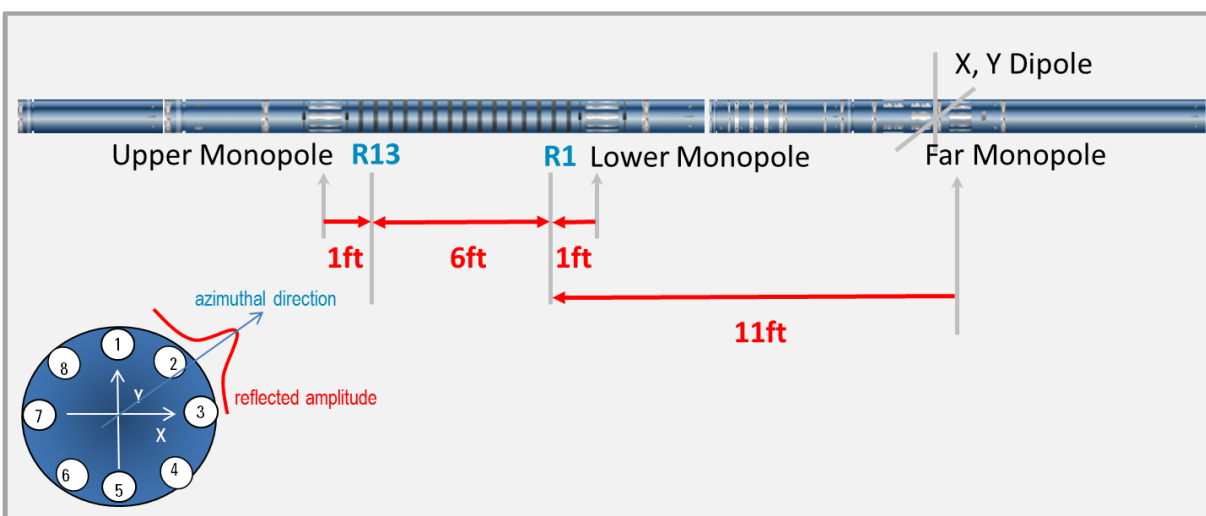


Figure 38—The Advanced Sonic Logging (ASL) includes various transmitters and receiver spacings (top), and a total of 13 receiver stacks with eight receivers azimuthally arranged for every stack (bottom left).

To help make decisions about how to proceed with drilling operations while avoiding, or attempting to intercept, a previously drilled well, it is advantageous to detect the target wellbore as soon as possible. AAR provides a method for determining the azimuth and distance to the target without accessing the target wellbore. This measurement produces a

much higher-resolution image than surface seismic imaging and thus is a better technique to detect and accurately determine the locations of nearby wells.

5.2.2 Fundamental Principle

How acoustic waveforms propagate in a media depends on the source of the acoustic excitation, signal frequency, and the media properties. The propagation velocity of acoustic signals is a function of the media's properties, reflector type (OH or CH or both), and the mode of excitation. [Figure 39](#) displays the geometry of the wave paths from the relief wellbore to the target wellbore (left) along with generic processing steps to determine ranging distance, direction, and direction uncertainty improvements (right).

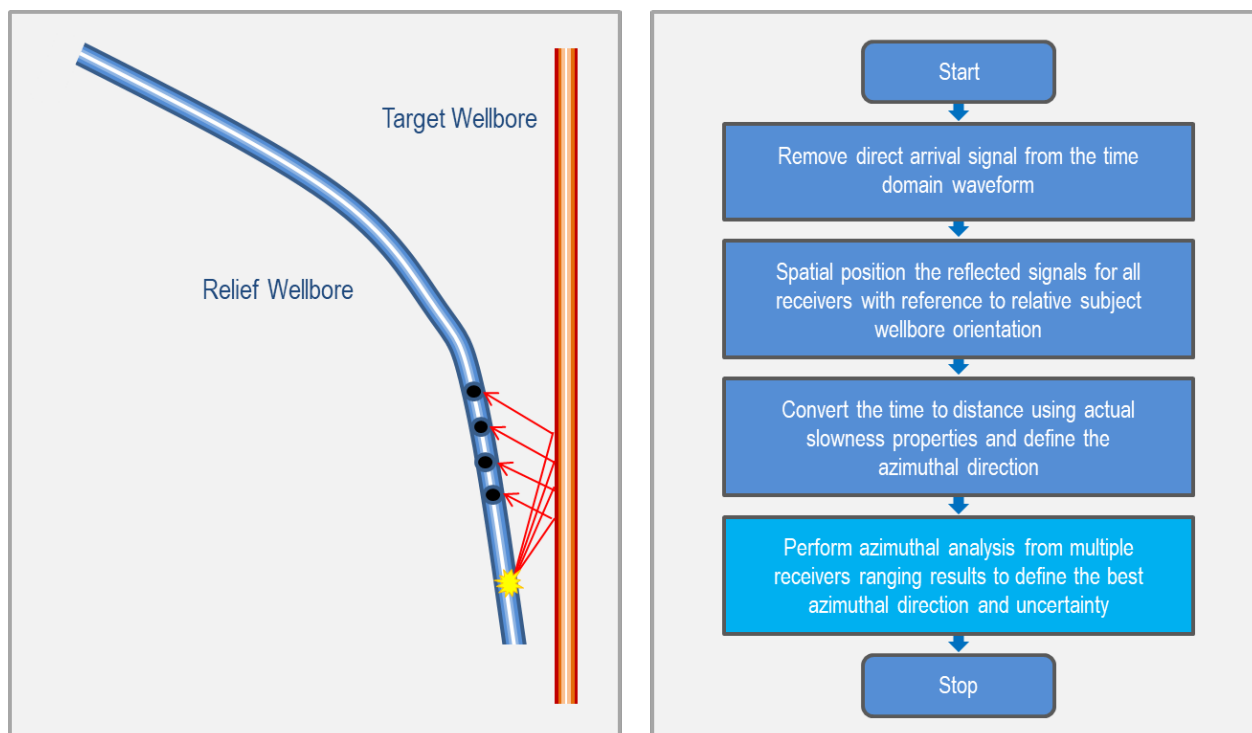


Figure 39—Geometry of wave paths using AAR to detect target wellbore using acoustic source and receivers (left) and general processing steps to determine the ranging distance and direction (right).

5.2.2.1 Automated Processing

In Poedjono et al, 2017, SPE-187313, data collected from the eight azimuthal receivers are treated individually and migrated to form separate images that show the target migrated images from a four-azimuths orientation. The target well reflection can be seen in all four azimuthal images ([Figure 40](#), left). It is then manually interpreted on the third image, which shows the strongest reflection for that specific depth ([Figure 40](#), right).

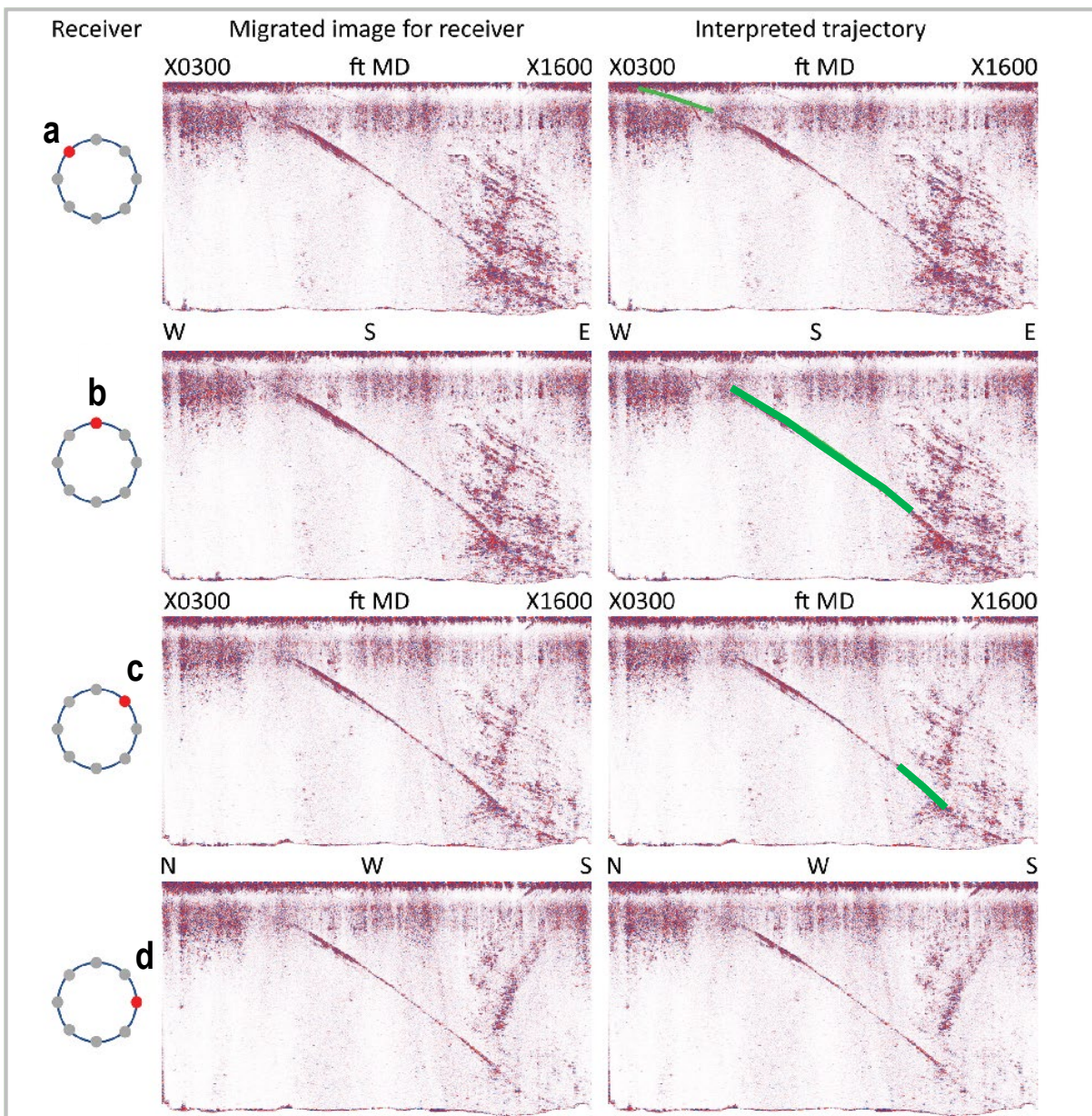


Figure 40—Uninterpreted migrated sections (left) and interpreted sections of the well on the azimuth (right) with corresponding receiver position (a, b, c and d) where it shows the strongest reflection. Target well reflection picks are shown by a green line. The images cover approximately 1,300 ft measured depth along the horizontal axis and out to 150 ft from the observation well on the vertical axis. The observation well is at the top of the image. As the tool rotates and the path of the observation well changes relative to the target, the azimuthal receiver that shows the highest amplitude reflection changes. Four azimuthal images a, b, c and d are shown — three where the target well reflection is interpreted as strongest for that depth plus one in which it is still visible but not the strongest for any depth.

An automated approach, introduced in 2018, builds upon the existing process that reduces manual involvement during the migration and interpretation phase (Bennett et al., 2018, SPWLA 59th Annual Logging Symposium). Automated processing results, using the same data set as Poedjono et al, 2017, were published in Johansen, et al., 2019. The new process improves accuracy, removes interpreter bias, and is especially helpful in situations in which the target well geometry is curved and the logging tool is rotating. The new technique works by identifying linear features as potential reflections in the pre-migrated wavefield using an automated time-pick procedure, which consists of a τ - p transform followed by an event localization procedure. It then characterizes the corresponding reflected arrival events and determines the azimuth and distance to the target well at each measured depth position along the target well (Figure 41).

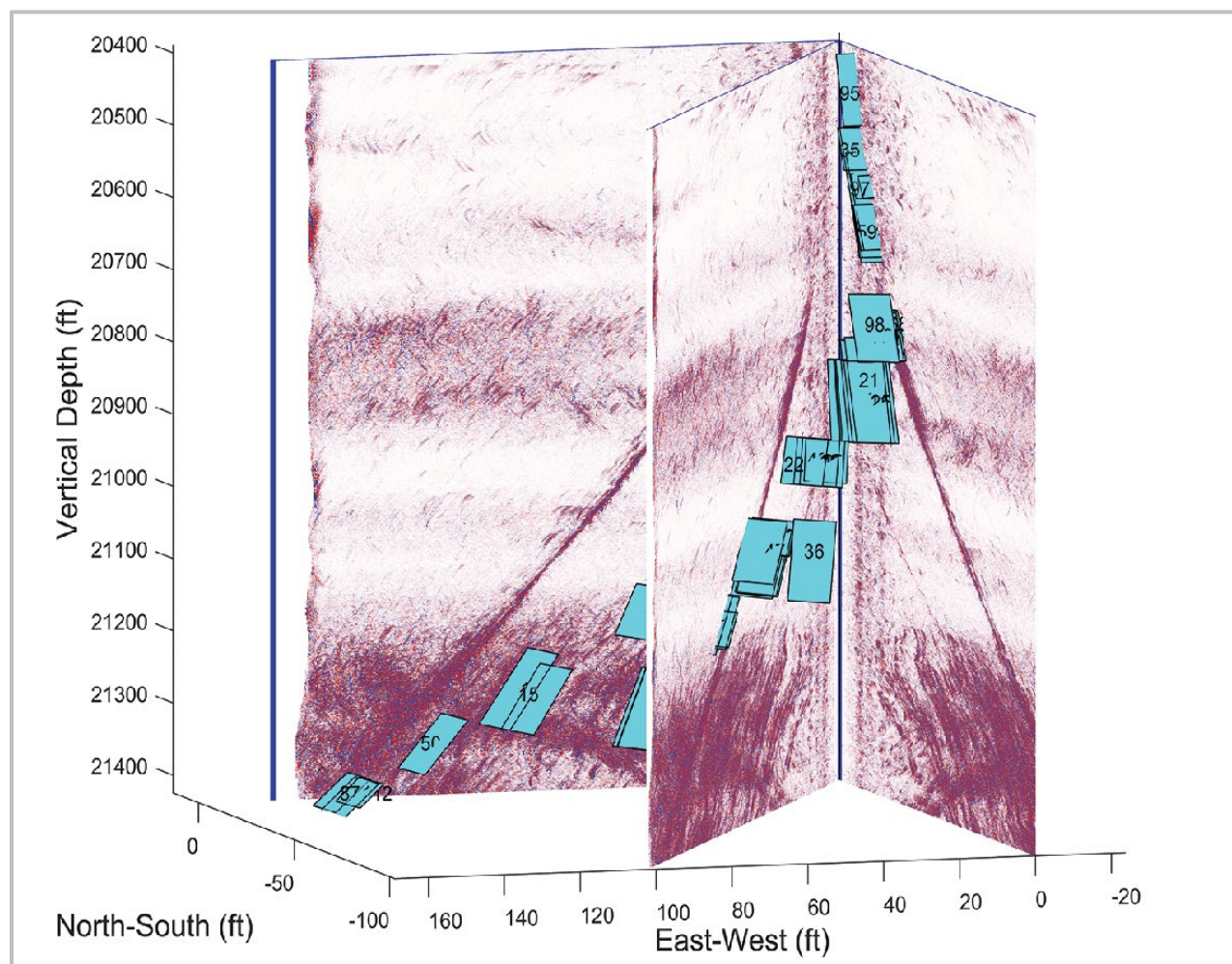


Figure 41—The first three migrated images from Figure 31 are shown in their orientation from the observation well along with the 3D reflectors produced by the new automated method. For clarity, this does not consider the rotation of the tool as it moves up the well and instead projects each 2D image in a fixed orientation.

5.2.3 Acoustic Source

AAR uses two common types of sources—monopole and dipole—to generate the acoustic signal that propagates through the rock.

5.2.3.1 Monopole

The monopole source generates an acoustic signal that travels in all directions through the media (Figure 42). The signal also moves in the same direction as the excitation pole signals, which can be either high-frequency that generates a compressional signal, or low-frequency that generates a Stoneley signal. A Stoneley signal is a boundary, or interface, wave that typically propagates along solid-solid or liquid-solid interfaces.

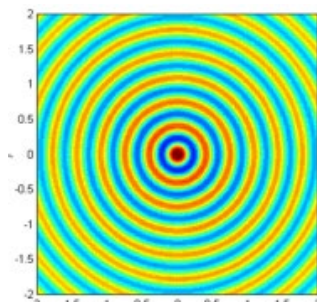


Figure 42—A monopole-generated acoustic signal pattern.

5.2.3.2 Dipole

A dipole source is a directional source that generates an acoustic signal that excites the media in a direction perpendicular to the propagation direction ([Figure 43](#)).

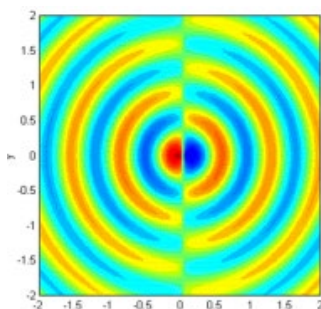


Figure 43—A dipole-generated acoustic signal pattern.

5.2.4 Acoustic Propagation

Acoustic waves propagate through a media based on how particles in the media react to the introduced disturbance. Sound can propagate as compressional waves, shear waves, or other modes. Compressional and shear modes of propagation are discussed below.

5.2.4.1 Compressional

Compressional waves displace particles in the direction of wave propagation ([Figure 44](#), center). Compressional waves can be generated in liquids and solids because the energy travels through the atomic structure in a series of compression and expansion movements, or rarefaction.

5.2.4.2 Shear

Shear waves displace particles transverse to the direction of propagation ([Figure 44](#), right). Shear waves require an acoustically solid material for effective propagation and do not propagate effectively in liquids or gases. Shear waves travel slower than compressional waves.

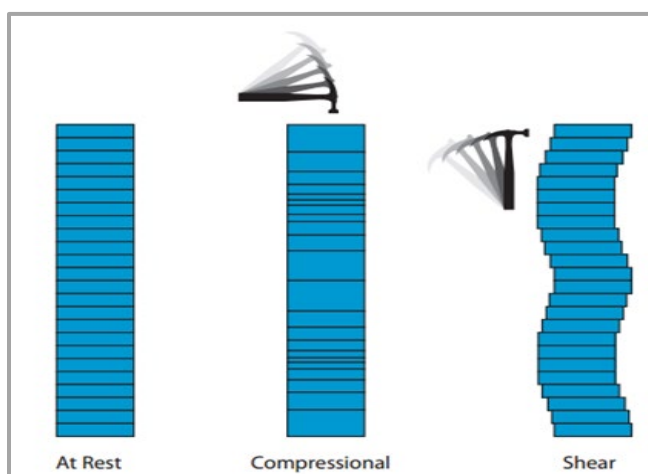


Figure 44—Particle motion in formation at rest versus wave propagation direction for compressional and shear waves.

Compressional and shear waves are stress-velocity fields that are propagated in formation rock by acoustic excitation. These waves are also known as bulk, or body, waves. [Figure 45](#) graphs the complete waveform from the start of firing to the arrival of the reflected waves. [Figure 46](#) presents the waveform in a colour scale.

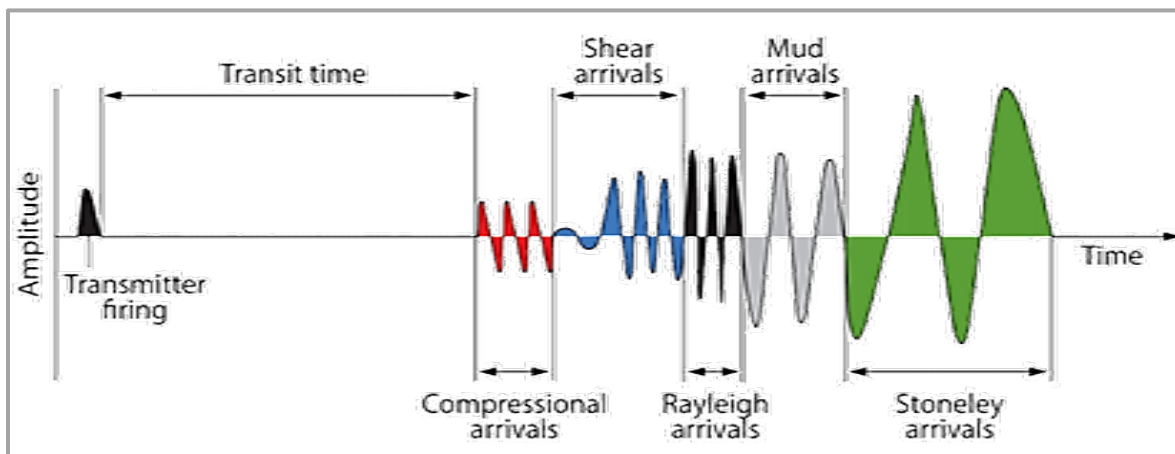


Figure 45—Various waveforms as reflected and refracted in time.

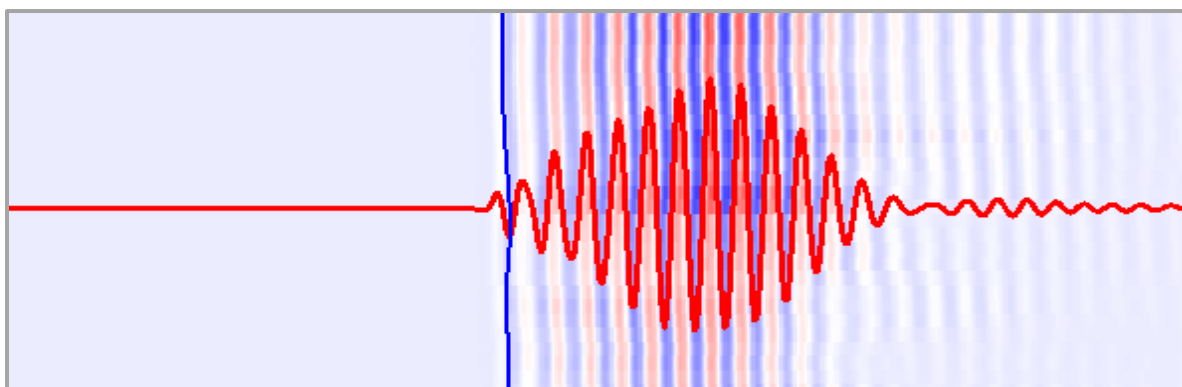


Figure 46—The waveform presented with color scale, Peak (red) and Trough (blue).

5.3 Acoustic Distance and Direction

Acoustic distance is a result of migration processing, during which recorded events are geometrically relocated in time to when the event—the signal being reflected by the target well—occurred, rather than where it was recorded. This creates a more accurate image of the target well's location. This process overcomes the limitations of geophysical methods that are hampered in areas of complex geology, such as faults, salt bodies, folding, etc.

Time is then converted into distance, which may be determined using the slowness of the formation ($\mu\text{s}/\text{ft}$) or the speed of sound (ft/s) through the media, which is acquired during the ranging run. Currently, the best measure of distance in ranging detection occurs in fast formations, such as salt bodies, using a commercial Advanced Sonic Logging (ASL) tool. However, this tool has limits in recording time in slow formations, such as shale, which results in shorter ranging distances.

Since acoustic distance relies on a signal reflected off a target well captured by receivers, it is closer to the 3D Least Distance, which is the distance normal to the target well, rather than to the normal plane, which is perpendicular to the subject well (Figure 47).

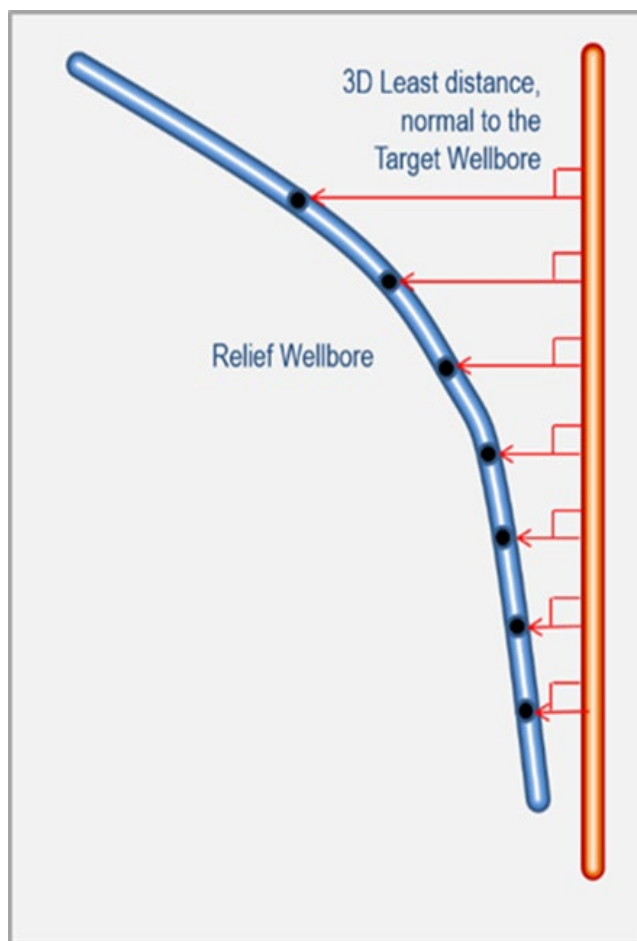


Figure 47—3D least distance.

5.3.1 Ranging Direction

Currently, identifying ranging direction is limited by the design of the commercial ASL, which uses eight azimuthal receivers positioned 45° apart. This provides 22.5° resolutions. The automated process (Johansen, et al., 2019) helps improve accuracy and remove interpreter bias, which simplifies the processing workflow and reduces turnaround time (Figure 48).

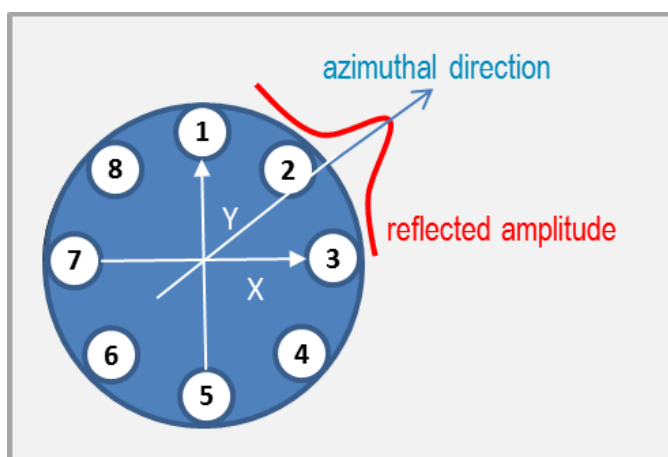


Figure 48—Azimuthal receiver locations to detect direction of reflected signal.

Ranging direction uncertainty can be reduced by decreasing the distance to the target well. Both ranging distance and direction are plotted using a traveling cylinder (Figure 49). Ranging direction can be further improved by performing multiple data acquisition phases during the run.

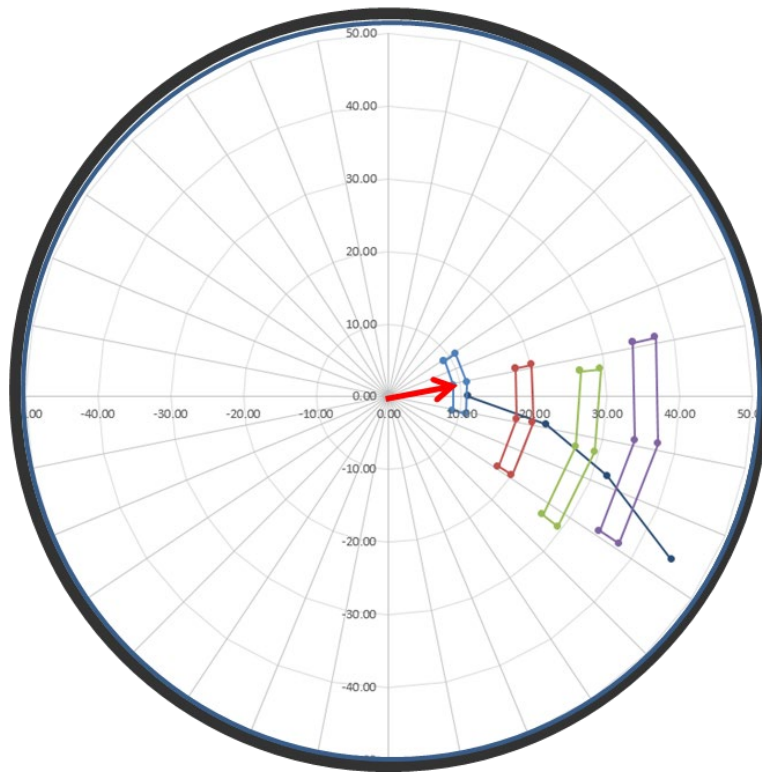


Figure 49—Traveling cylinder where the distance and direction are plotted at each ranging depth.

5.3.2 Ranging Distance

The slowness of the formation which is acquired during the ranging run is then used to convert the reflected time to distance. Ranging distance can also be plotted along the wellbore with the survey center-to-center distance (Figure 50).

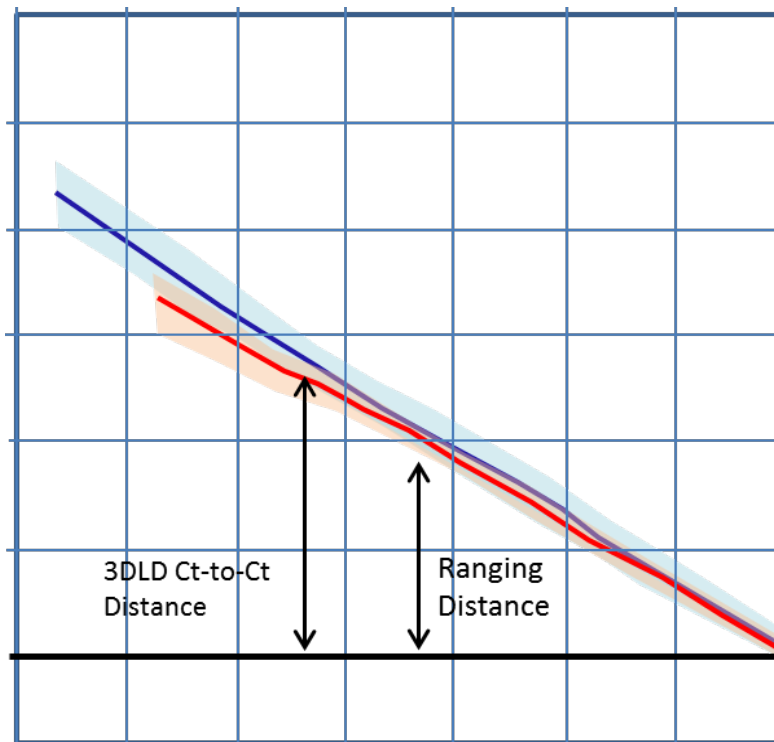


Figure 50—Center-to-center distance and ranging distance are plotted against the measured depth.

5.3.3 Manual vs Automated Processing

[Figure 51](#) shows the comparison of the direction and distance processing results of the same data set. The new processing improves efficiency, accuracy, distance and direction while reducing uncertainty, which also eliminates human bias, especially when the target well geometry is curved and the logging tool is rotating.

For each interpreted segment of the target wellbore, a coloured box illustrates the $\pm 22.5^\circ$ uncertainty associated with the manual method (a). It is clear that a greater accuracy of $\pm 11.25^\circ$ uncertainty is obtained using the automated method (b), which is not constrained by the geometry of the acquisition system.

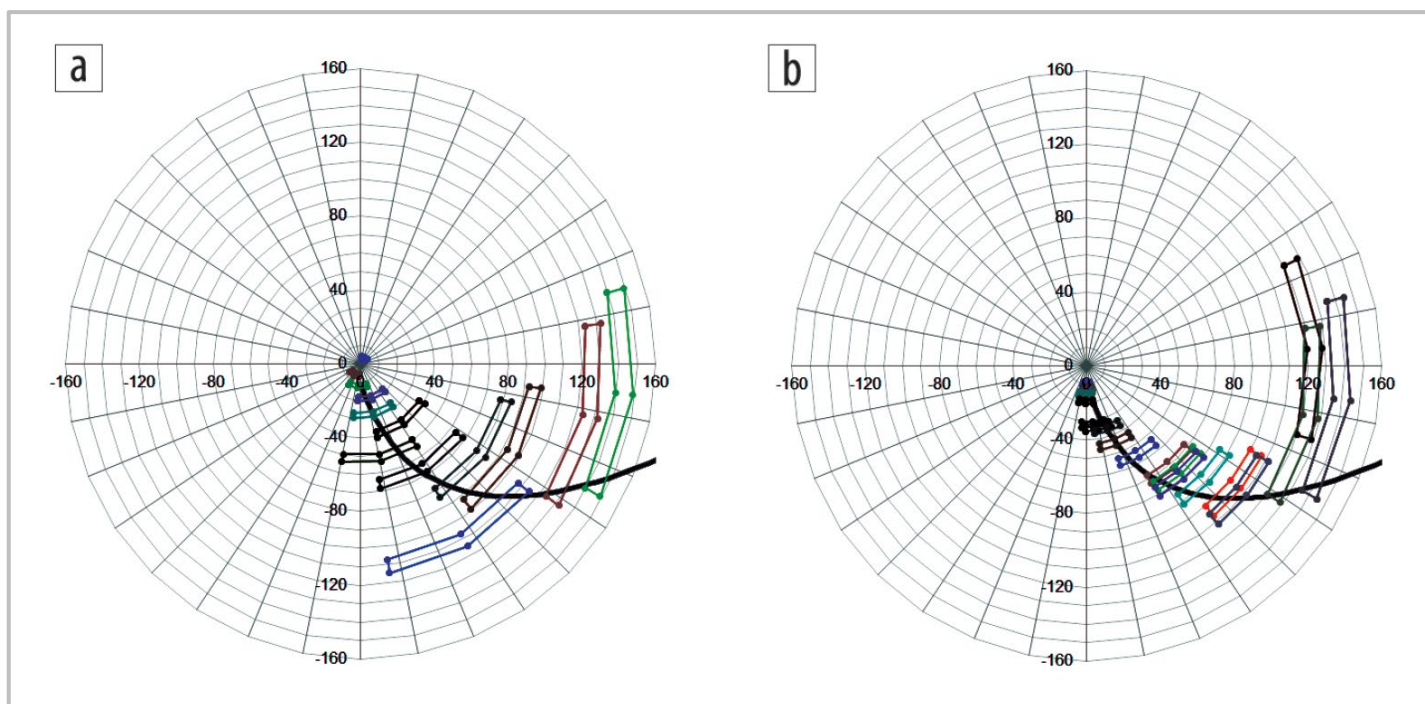


Figure 51—Travelling cylinder of the position of the target well (black line) relative to the subject wellbore (center of plot). Results shown are generated using manual method (a) and the automated workflow (b).

5.4 Multiple Wellbores Environment

The AAR's multiple wellbores detection capability was tested, and the results published under Poedjono et al., 2017, SPE-187313. AAR provides redundancy with two different ranging types—reflected compressional and shear signals from various distances of monopole and dipole transmitters along the subject well—to determine the location of multiple nearby wellbores with a high degree of accuracy.

[Figure 52](#) shows multiple wellbores; two open hole sidetracks labelled ST01BP00 and ST02BP00, and cased hole main bore ST00BP00, where the ranging data was acquired from ST02BP00.

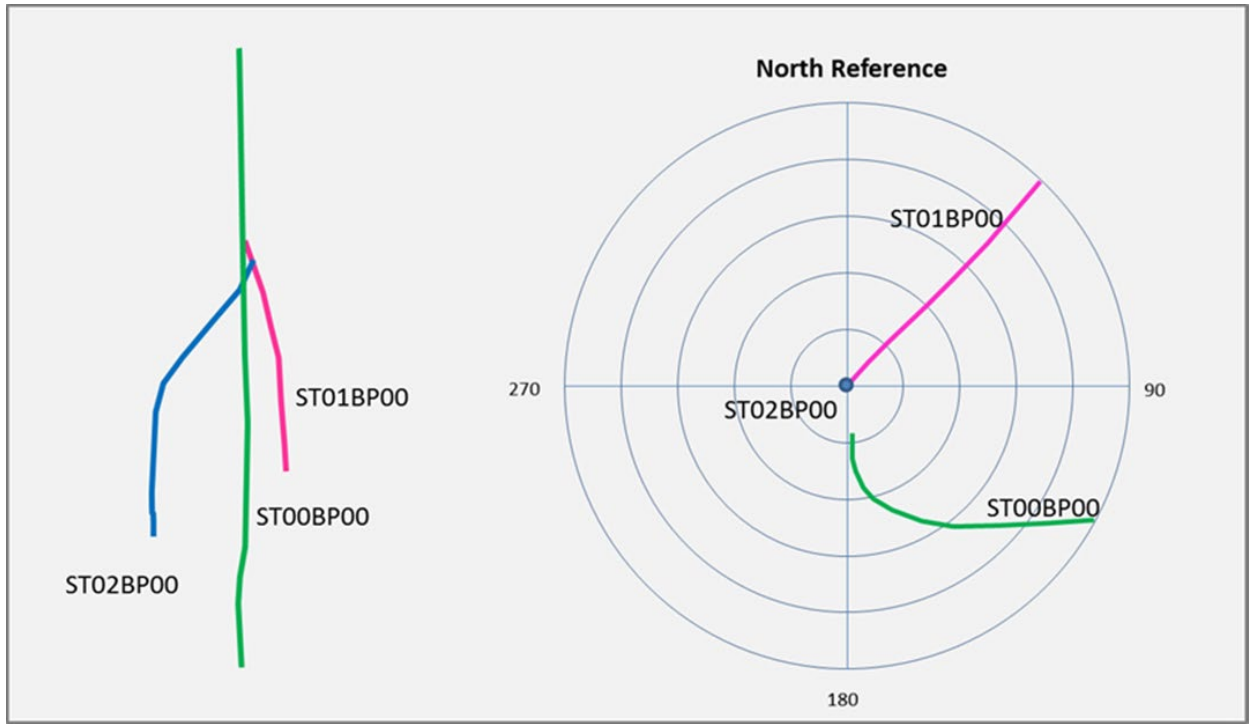


Figure 52—The 3D trajectories based on MWD surveys (left) and travelling cylinder plot (right) with the positions of open hole ST02BP00 as the subject wellbore at the center of the plot and two target wellbores cased hole ST00BP00 in green and open hole ST01BP00 in pink

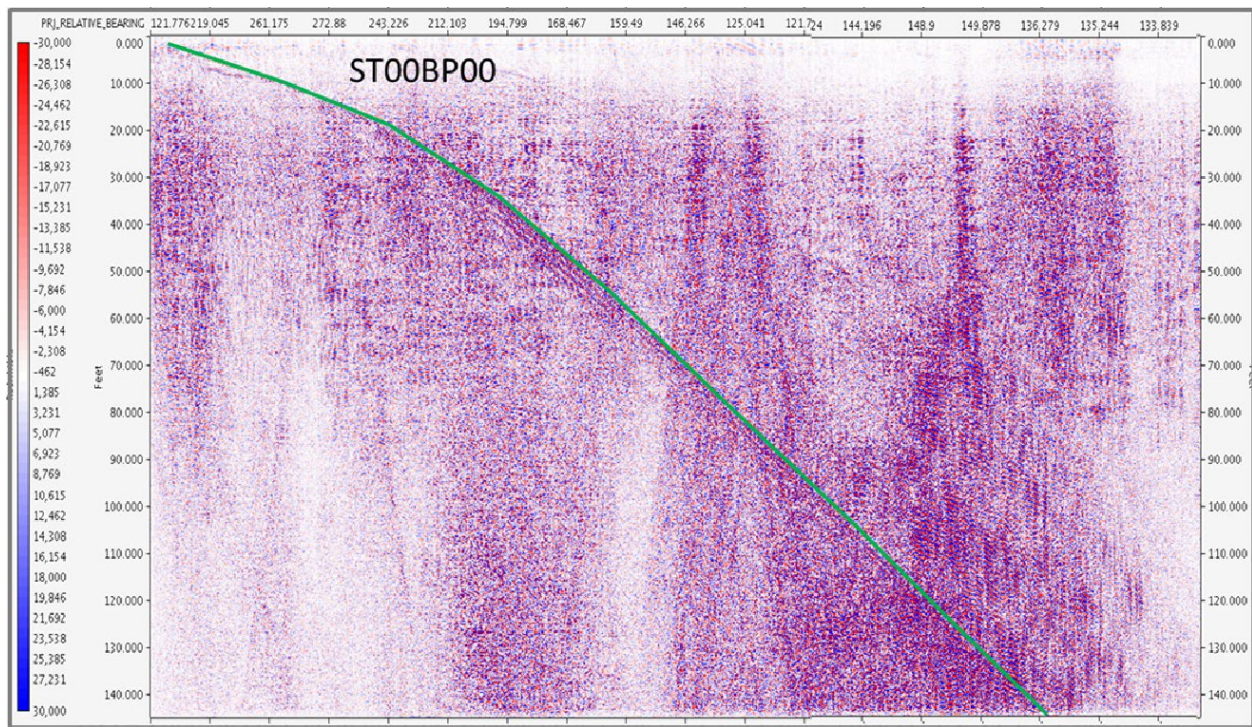


Figure 53—Monopole compression reflected image of the target cased hole ST00BP00 (green), with ct-to-ct distance along Y axis and depth along X axis

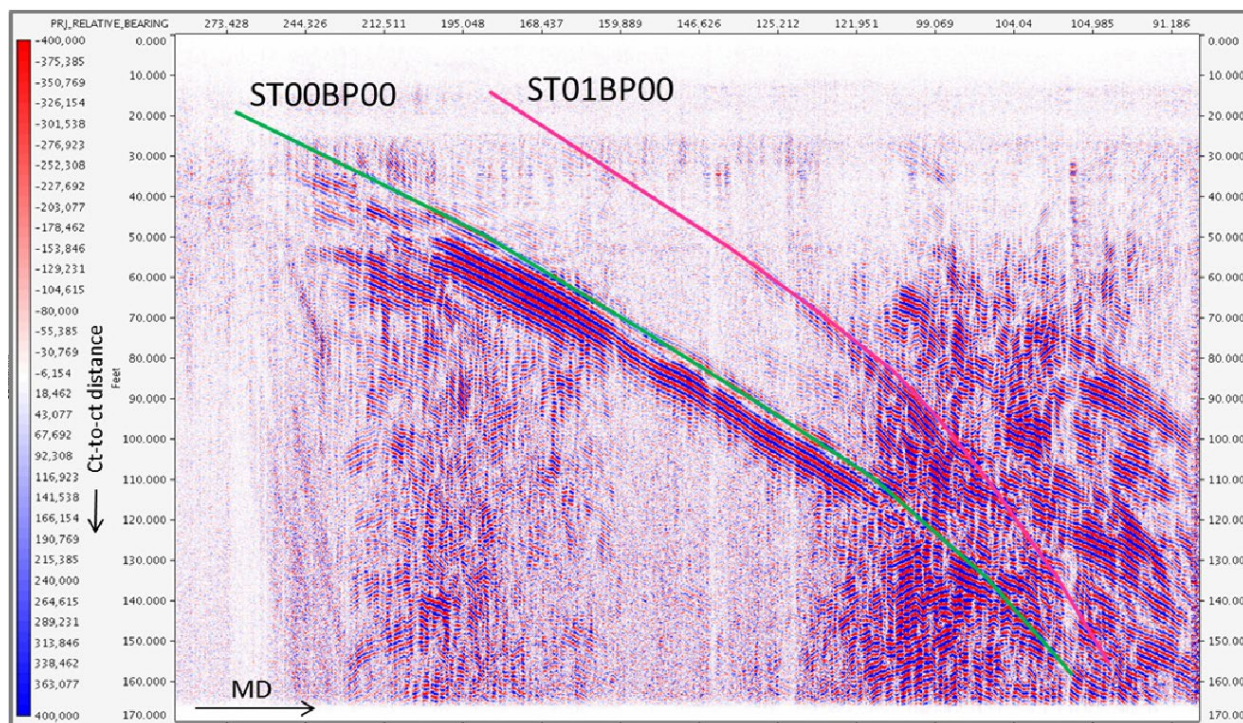


Figure 54—Dipole shear reflection image from the cased hole ST00BP00 (green) and the open hole ST01BP00 (pink), with ct-to-ct distance along Y-Axis and depth along X-Axis

The AAR reflected compression and shear signals were processed to define ranging distance and relative direction. The cased hole ST00BP00 was detected optimally using the monopole as shown in [Figure 53](#) and the open hole ST01BP00 was detected optimally using the dipole as shown in [Figure 54](#). The shear reflection detection was better from the open hole due to the inability of the shear wave to be transmitted into the fluid present in the open hole.

5.5 Other Applications

AAR is highly versatile with numerous ranging applications, including in open or cased holes in salt bodies while simultaneously evaluating the salt's quality. This latter ability provides experts information they may use to select the optimal location at which to intercept the target wellbore to ensure maximum hydraulic strength during well control situations ([Figure 55](#)). This same ranging technique is also able to differentiate between the reflected arrival from the open hole (top of casing) and the cased hole ([Figure 56](#)).

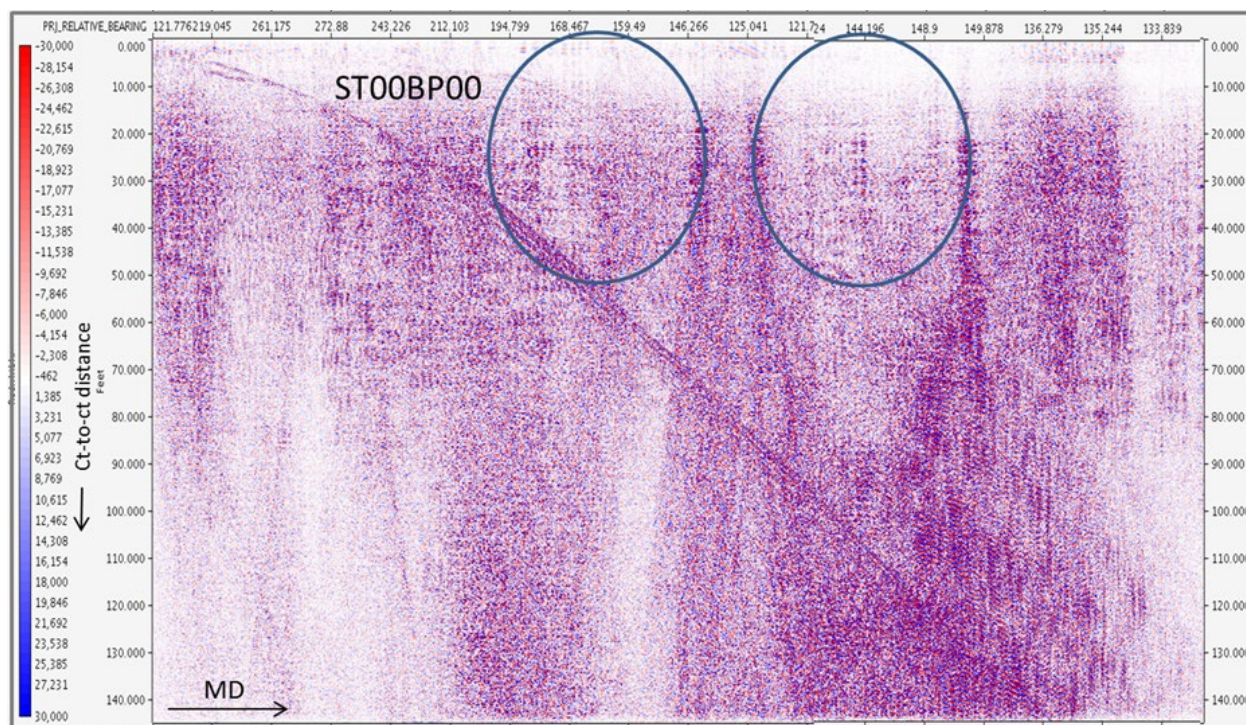


Figure 55—Salt homogeneity may be determined by analysing the formation reflection images as indicated by the blue circle areas. By visually picking highly stable, homogeneous sections of the formation from the images to determine the interception and communication interval of the target well while maximizing hydraulic strength to pump to kill and balance the hydrostatic pressure of the target well.

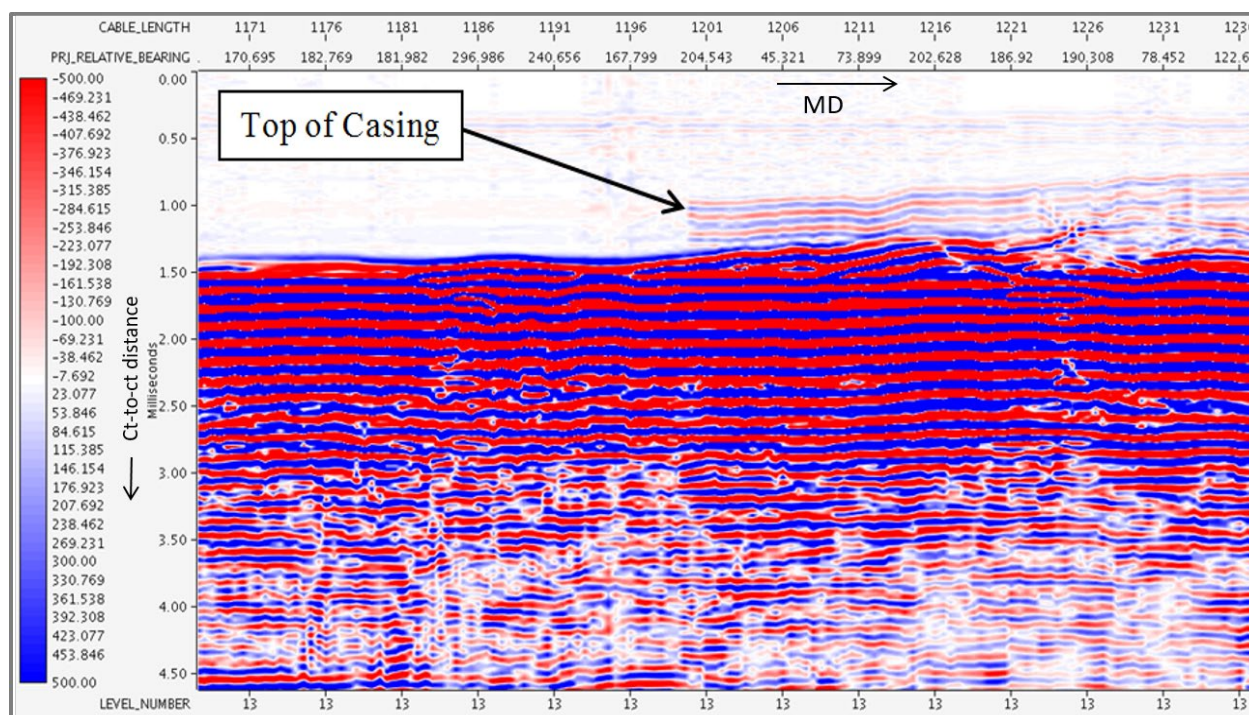


Figure 56—The image shows the reflected compressional arrival from the OH (top of casing) and CH target wellbore.

5.6 Modelling

To understand the performance of the acoustic ranging system for the environment in which the ASL is operating, it is critical to model the relative position of the subject well relative to the target trajectory for the maximum and minimum ranging detection distances. During the job planning phase, modelling is required to program and configure the ASL to optimize the data acquisition and the chances of success.

Modelling for specific ranging scenarios is required to determine if the subject well's relative trajectory, formation slowness, reflector type, and ASL configuration are optimally planned to detect the nearby target wellbores ([Figures 57](#) and [Figure 58](#)). Actual ranging data may be used to compare monopole and dipole generated images where the dipole can provide greater detection distance in salt ([Figure 59](#)).

Modelling:

- Predicts the wave field generated in the subject wellbore and its interference with both potential reflected and refracted waves from the target well at a sidewall-to-sidewall distance range of 2.2–0.5m (7.2–1.6 ft) or touching.
- Varies transmitter-receiver spacing and type to determine the best acquisition setup by using the wellbore ellipses of uncertainties to calculate the minimum and maximum center-to-center distances between wellbores for each scenario.
- Designs tool setup and acquisition parameters to optimize chances for success if the modelling indicates imaging the target over the desired range is possible.

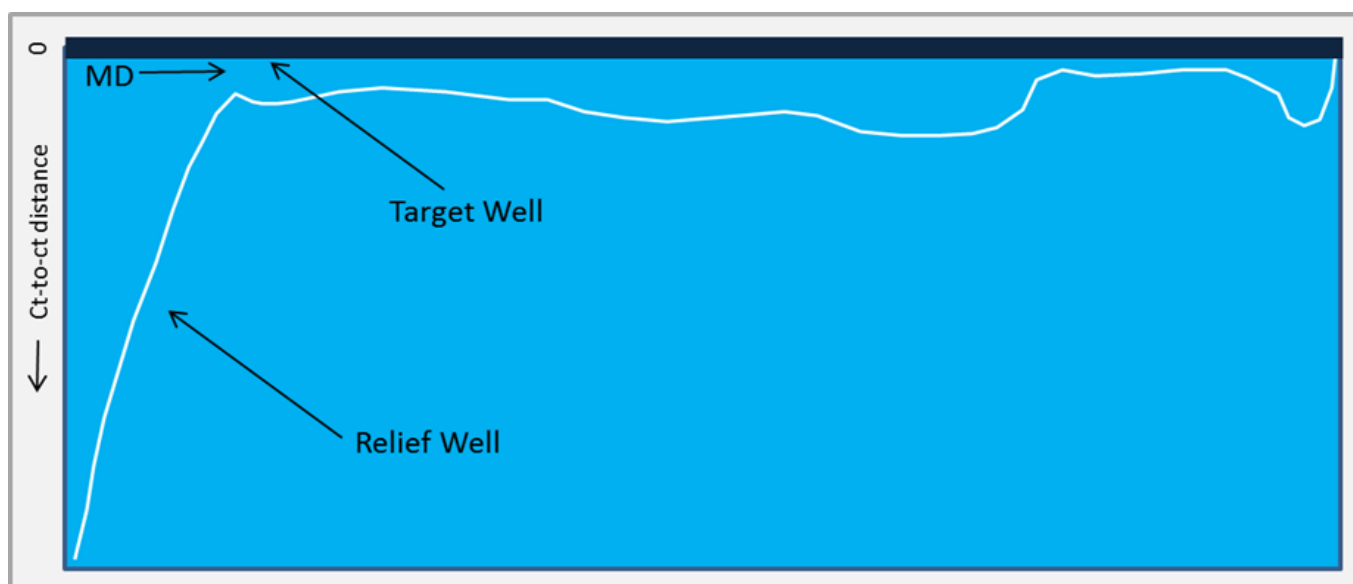


Figure 57—Center-to-center distance between the subject and target wellbore

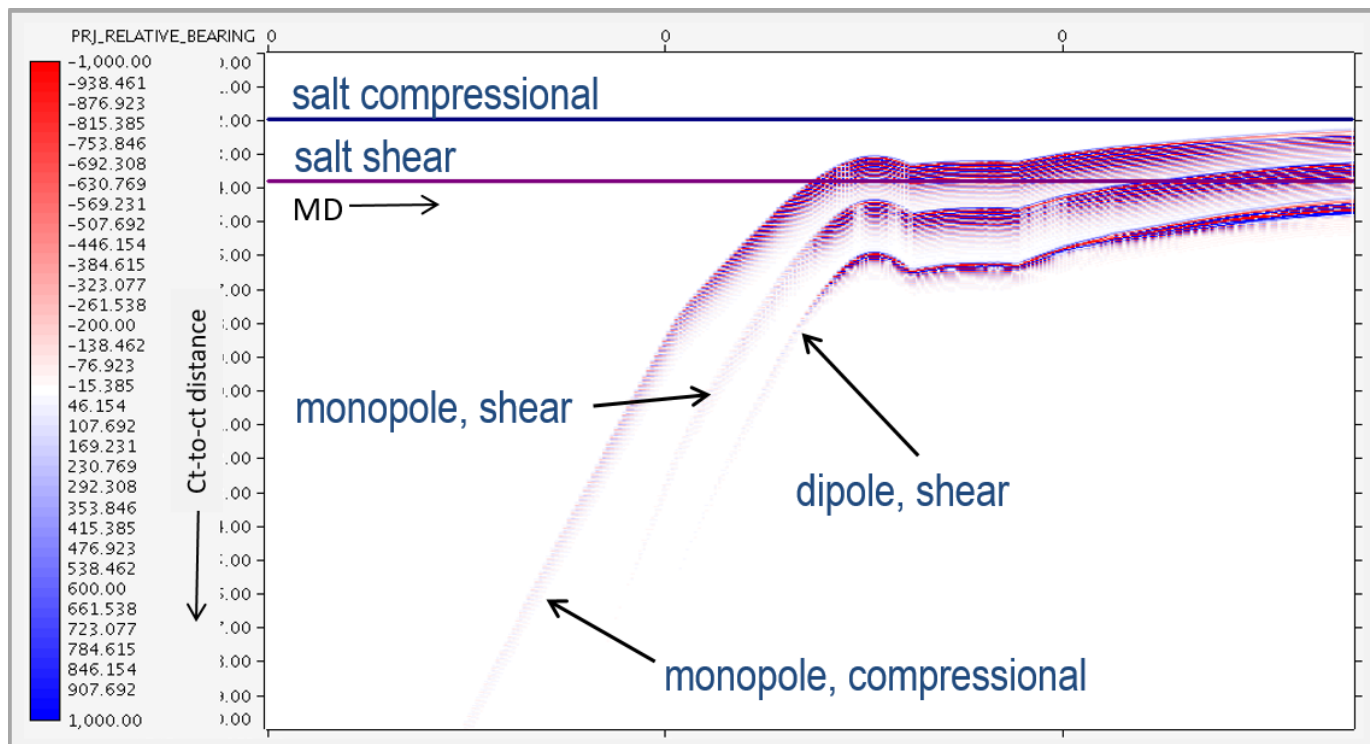


Figure 58—The simulated various sources vs reflected signals as a function of signal strength and center-to-center distance and measured depth

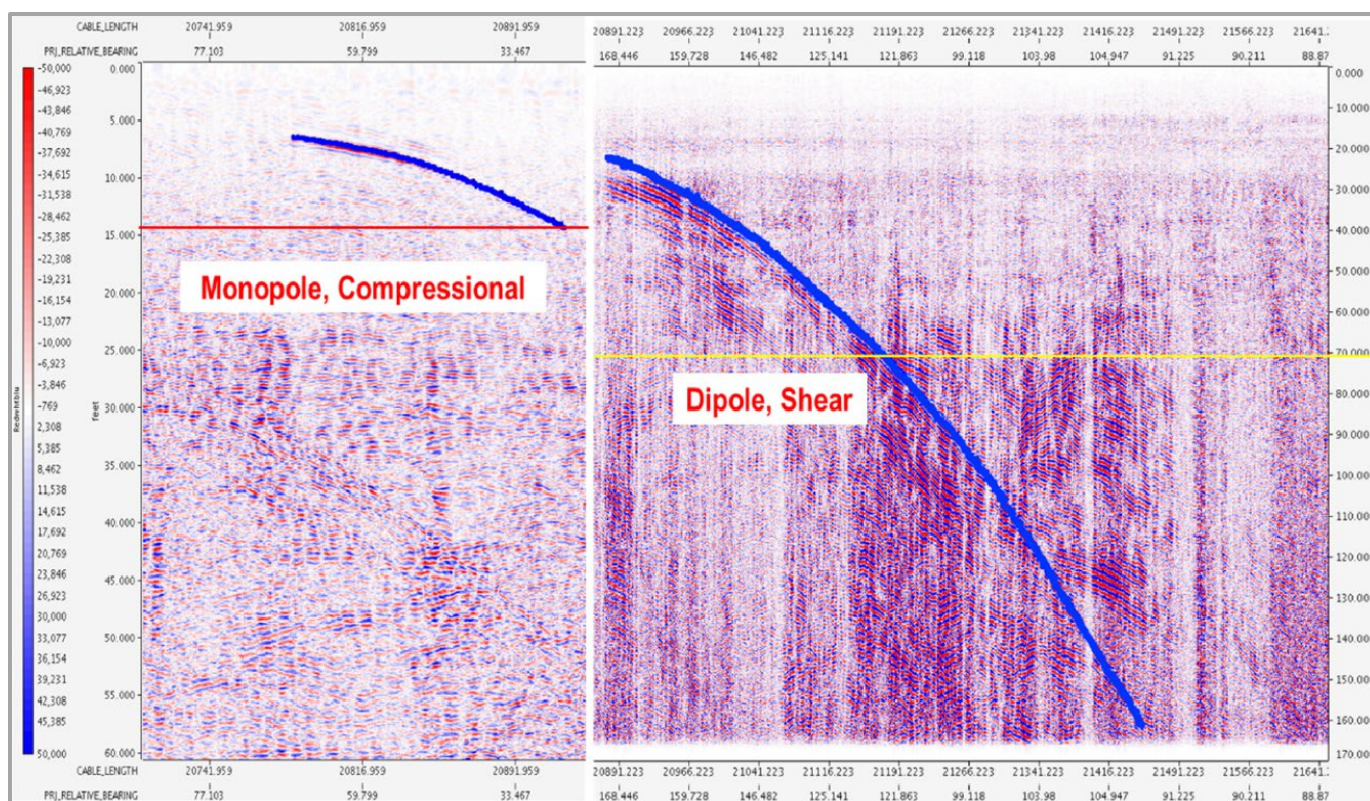


Figure 59—Comparison of actual monopole, compressional detection (left) to dipole, shear detection (right) in OH salt. The dipole can provide greater detection distance because the fluid unable to transmit the shear signal.

6. Active Resistivity Ranging (ARR)

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.

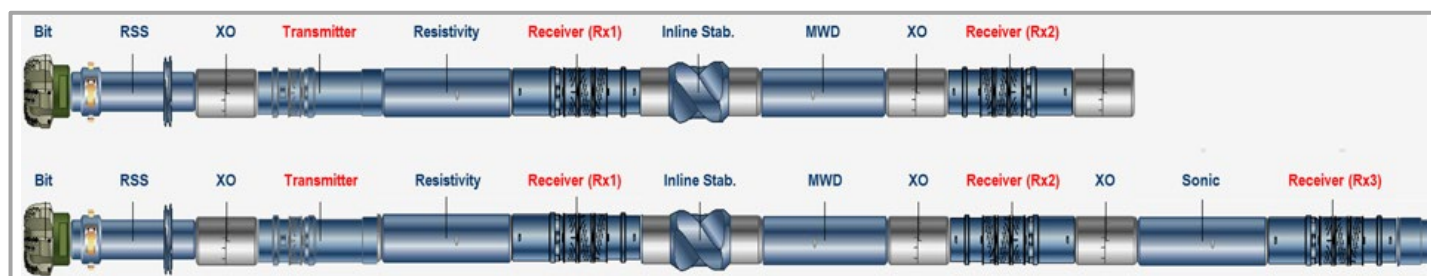


Figure 60—The location of the resistivity transmitter and receivers in the two different example BHAs

6.3 Distance and Direction

The ranging distance for resistivity ranging is comparable to the tool spacing and can be adjusted to fit based on specific well and formation details. Examples are shown in [Figure 60](#). Spacing is typically between 15, 25, and 35 m (40, 80 and 120 ft) with ranging distances generally half the spacing or more. Refer to [Figure 61](#) and [Figure 62](#) 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.

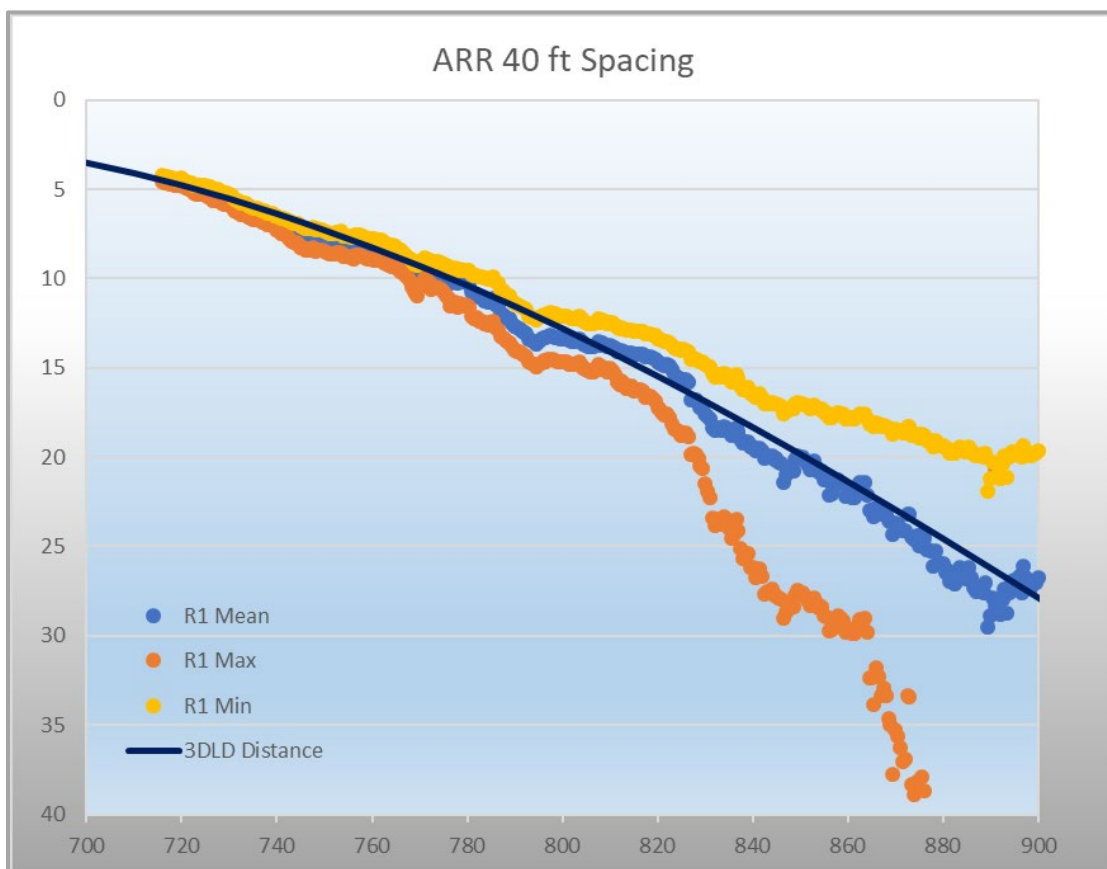


Figure 61—Comparison of the resistivity ranging distance using 40 ft spacing to ct-ct distance

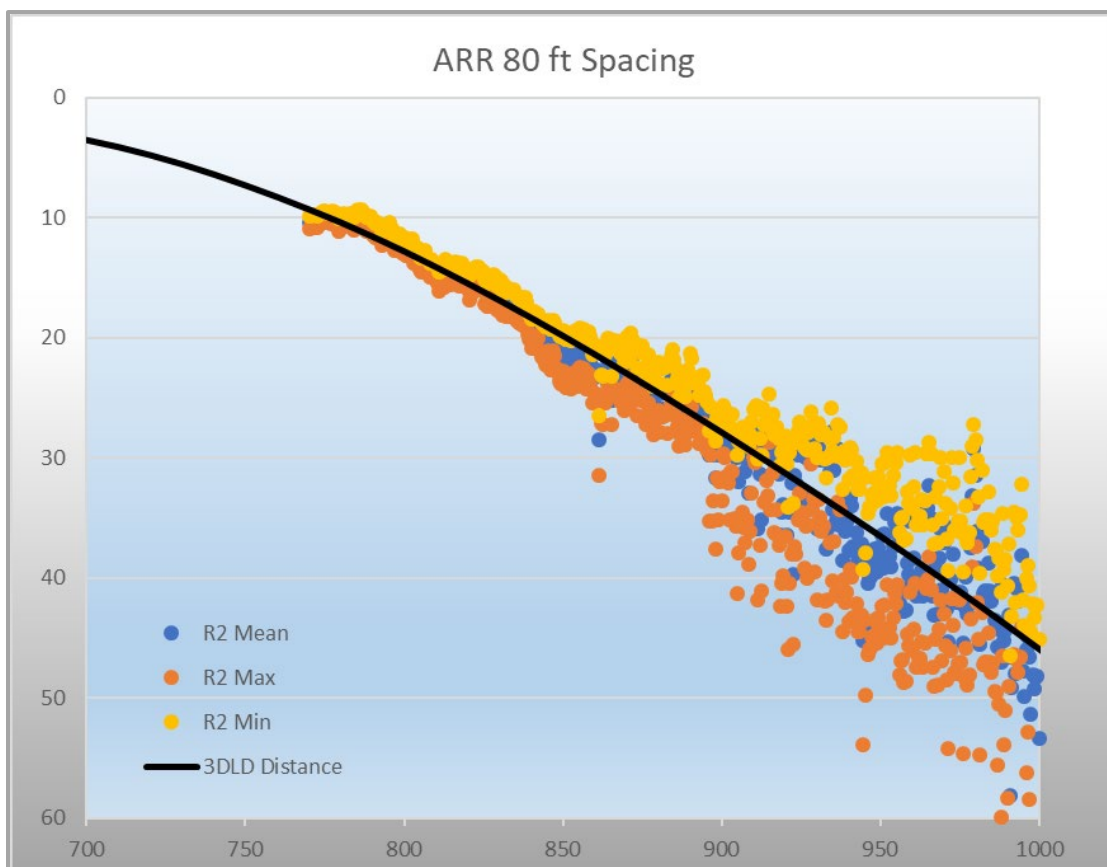


Figure 62—Comparison of the resistivity ranging distance using 80 ft spacing to ct-ct distance

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, 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 in which 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 specific applications, strengths, and limitations. This chapter compares various available technologies to assist in the selection of an appropriate technique for a given project. It should be mentioned that no one technique is suitable for any project ([Table 4](#)). The selection of the ranging technique should be done on a case-by-case feasibility study that takes into considerations the pros and cons of each technique along with its technical, economical, timing, and risk aspects. It should also be noted that the overall ranging strategy can be optimized by using a combination of ranging techniques that can be complementary for certain aspects of the operation.

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 method 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 a pure salt formation. The only certain way to determine 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 through 6](#); it only considers comparable Access-independent (AI) ranging techniques that are deployed when there is no access to the target well, i.e. 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 system.

7.1 Ranging Comparison Table

Table 4—Ranging Comparison table

DESCRIPTION	Passive Magnetic Ranging	Active Magnetic Ranging	Active Acoustic Ranging	Active Resistivity 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 acoustic propagation. Analyze the reflected signals. Transmitters and receivers are on the same logging tool.	Based on the EM ultra-deep azimuthal resistivity measurements. Single EM transmitter and multiple (up to 3) modular receivers that are being positioned in the same BHA.
Conveyance Method	Drill Pipe, MWD or Wireline	Wireline, Coil Tubing and Wired Drill Pipe Drill Pipe; it requires to stop drilling then deploy the tool in Non-Mag BHA above the MWD	Wireline	Drill Pipe
Modelling Ranging Performance	Pole Modelling	Modelling for an optimum current injection	Requires pre-job modelling	Requires pre-job modelling
Best Case Performance	Wells are parallel	Wells are parallel	Wells are at the same plane	Wells are at the same plane
Worst Case Performance	Wells are perpendicular	Pure Salt Formation Wells are perpendicular	Wells are perpendicular at large c-c distance	Wells are perpendicular
Detection Range Estimate	Selected from a chart representing the possible max magnetic field	Calculated using geometry and magnetic model	Calculated using geometry and actual acoustic property acquired during the run	Maximum distance depends on resistivity contrast, spacing, frequency used and relative angle.
Definitive Detection Range	5 – 15m	20 – 60m 40 – 100m with Direct Excitation on TW	0.5 – 55m	Up to 20m

Detection Along Body of The Target Well	Detection ranges up to 5m	Up to 60m	Up to 55m	Up to 20m
	(1/2 joint length), 6m on 12m casing			
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	Up to 20m. Can detect Open Hole
Data Acquisition Time	6 to 30 hours For MWD Logging	30 hours (8 hours in TPR BHA) (assuming 4500m well)	6 to 15 hours depending on the logging intervals (assuming 4500m well)	While-drilling acquisition, on either Wired Drill Pipe or Mud Pulse Telemetry
Distance Accuracy	10% of detection Range. To be considered 1 standard deviation.	Non-Gradient Tool: 5-20% Depends on High Side to Target variation	~0.3m at 1 standard deviation	(a, b) The distance accuracy depends on resistivity contract, spacing, frequency used. The closer to the maximum distance, the higher the uncertainty
	Depends on the quality of the Target Well Magnetization strength and Signal/Noise ratio level.	Gradient Tool: Depends on distance. Less than 5%		
Direction Accuracy	~5° at 1 standard deviation	~5° at 1 standard deviation	~11° at 2 Standard deviation	(c) Direction accuracy depends on resistivity contract, spacing, frequency used and relative angle.
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	Casing, Fish, Packer, completion, all steel equipment and Open hole
Case Histories	Widely used in the industry	Widely used in the industry	Specific applications, can detect multiple wellbores	New technology recently developed
	Mainly used for P&A and collision avoidance			
	Very Few Successful Relief Well Intercept	Relief Well & Re-Entry Wells	Case histories are available for locate, follow and interception	Only few case histories are available

Sensor Measurement Point	15m – 20m from Bottom hole	On Bottom	10-17m from Bottom of the tool	Distance from the bit to each mid-point between transmitter and receiver in the BHA
	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	No Effect same as steel pipe
Target Casing Corrosion	Detection may not be possible	Minimal impact on detection range	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	Minimal impact on detection range
Effects of Different Casing Sizes and Weight	Casing weight has a direct impact in range:	Negligible Effect	Negligible Effect	Negligible Effect
	20 Lbs./Ft has an expected max range of 2m along the body			
	40 Lbs./Ft has an expected max range of 3m along the body			
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	Able to detect multiple wellbores from different azimuthal positions	Under special processing, 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	Positive Effect. The more resistive formation, the higher the max. ranging distance
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	Reduces the chance of the reflect signals being detected by receivers. Effective at low incidence angle.	Reduce the effectiveness of detection range
Is The System Affected by Poor Hole Conditions in Drilling Well	No Effect	Potential to add additional ranging run time for open ended drill pipe runs	Rugosity and non-smooth boreholes will impact quality at closer detection distance.	Minimum Effect

Effects of Different Mud Types	No Effect	OBM may slightly reduce the detection range	Negligible Effect	Minimum Effect
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7.2 Impact of Incidence Angle on Detection

Incidence angle is defined as an angle of approach between the target well and the subject well. The impact of this angle on the detection capability, distance and direction, depends on the type of ranging technology being deployed. Approaching a target well at a high-incidence angle for magnetic ranging may provide a reliable ranging detection, although the same angle would not work at all for acoustic ranging ([Figure 64](#)).

Drilling towards a target well at a high approach angle should be done only when necessary. For example, to avoid the AMR operating outside the tool's detection range, the well trajectory must be modelled to verify that the proposed incidence angle provides optimum detection. For PMR using MWD, because the position of magnetometer measure point (MP) is positioned away from the bit, the bit position must rely on projection from MP while drilling, which could pose a risk of early interception.

Therefore, a dedicated wireline run or cleaning BHA with the MWD positioned closer to the bit may be required to acquire the ranging data closer to the bottom of the hole.

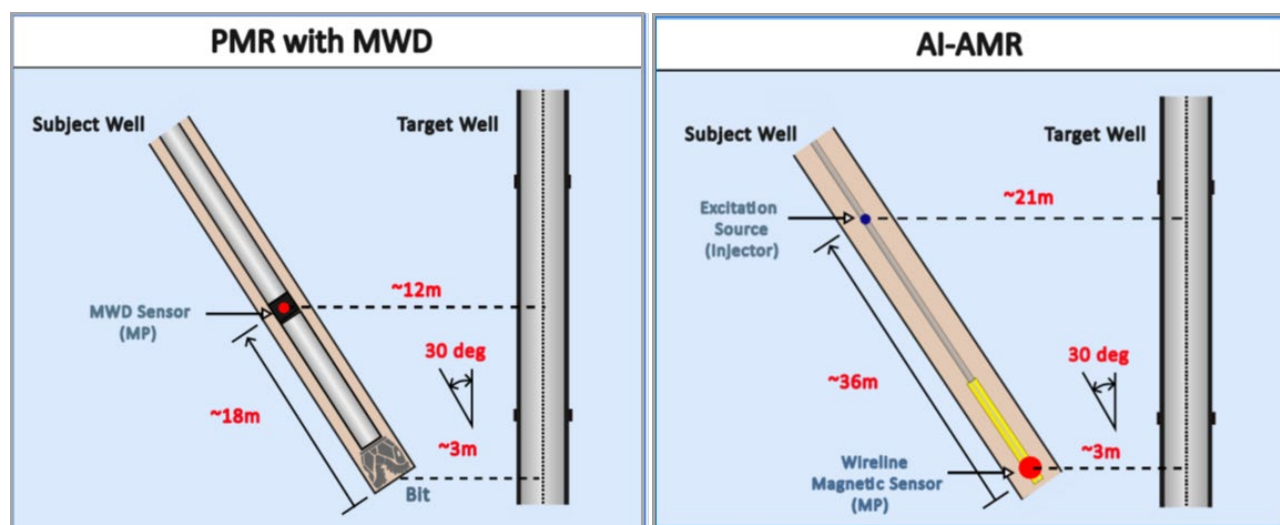


Figure 63—Illustration of PMR and AMR on the effect of the incidence angle selection for pass-by or cross-by

[Figure 63](#) illustrates that while drilling during locating phase with an incidence angle of 30° to pass-by or cross-by within 3m (10ft) from the target well, the difference in measure points (MP) has a significant impact on the detection distance and direction and on the projection to the bit for PMR ([Figure 63](#), left). This is compared to the impact when using an AMR with wireline magnetic sensor ([Figure 63](#) right). In this case, PMR detection is about 12m (40ft). Therefore, the risk of an early interception by relying only on PMR projection to the bit while drilling is significantly increased owing to degrading PMR accuracy. Weaker AMR detection creates a similar situation when the distance of current injection is further from the target well.

7.2.1 Passive Magnetic Ranging

A high incidence angle using a PMR measurement causes an MP to be much farther from the target well than the bit. As illustrated in [Figure 63](#), left PMR may increase the possibility of an unintended collision because a PMR determination at ≈ 12 m may reflect reduced accuracy or, in some cases, may be unattainable. For a summary comparing ranging techniques, refer to [Table 4](#).

7.2.2 Active Magnetic Ranging

A high incidence angle for an AMR measurement means that the excitation source will be relatively far from the target well, which reduces signal intensity. While this may cause some possible detection issues at greater distances from the target well, in the case illustrated in [Figure 63](#), right the ARM tool sensor is only 3 m from the target well, which reduces signal intensity requirements for a ranging determination. Therefore, ranging with AMR in this well geometry does not pose an unintended collision risk. For a summary comparing ranging techniques, refer to [Table 4](#).

7.2.3 Active Acoustic Ranging

Higher incidence angles also reduce the reflected AAR acoustic signals received by the tool. This reduction in acoustic signal reduces the reliability of ranging detection or, in the worst case, completely prevents detection of the target. Reflected signals ([Figure 64](#), red arrows) differ considerably for high incidence angles ([Figure 64](#), left) and low incidence angles ([Figure 64](#), right). For a summary comparing ranging techniques, refer to [Table 4](#).

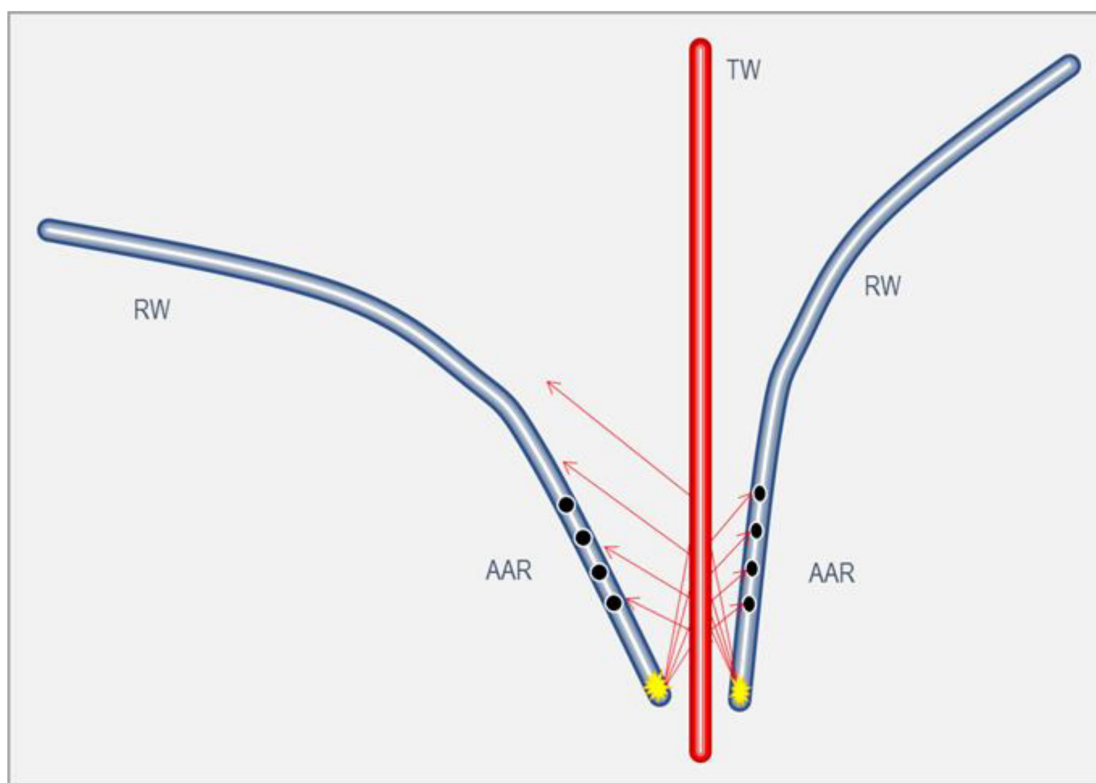


Figure 64—Incidence angle effects on AAR. The left wellbore has a high incidence angle which reduces the number of acoustic signals (red arrows) received by the tool, which reduces the detection. The right wellbore shows a smaller incidence angle, which allows all the acoustic signals to be received by the tool, thus assuring a more ranging detection.

7.2.4 Active Resistivity Ranging

The effectiveness of electromagnetic ranging is reduced at higher incidence angles. The effect is similar to that seen in AAR, which also depends on the transmitter and receiver spacing distances in the BHA. To optimize ARR performance, pre-operations modelling is required because the detection distance and direction accuracy depend on resistivity contact, transmitter and receiver spacing, signal frequency, and incidence angle. The closer the tool is to its maximum detection distance the greater the uncertainty incurred. For a summary comparing ranging techniques, refer to [Table 4](#).

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. These may range from relatively minor well-control events, having only financial effects, to major blowout situations with catastrophic repercussions for 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 each requires a specific intervention response. Drilling a relief well is very different from drilling standard wells, 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 wellbore positioning accuracy is required. Achieving this goal can be especially challenging when the operation is in the presence of multiple wellbores where collision avoidance is a high priority.

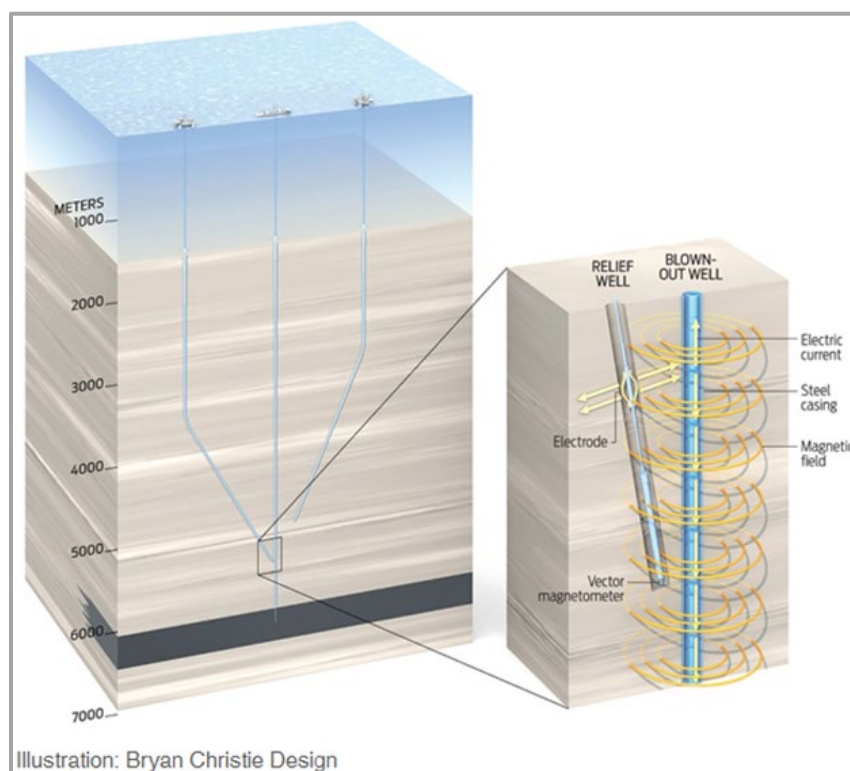


Figure 65—Example of two relief wells directional design utilizing active magnetic ranging

A relief well is usually planned as a last resort option in the event the blowout wellbore is inaccessible, and the flow rates required to kill the target well are too large to apply normal surface intervention methods. A drilling rig drills the relief well, or second well (see [Figure 65](#)), to intercept and establish communication with the target flowing well at a point that is deep enough to intercept it at the last casing shoe above the hydrocarbon bearing zone. Heavy drilling mud is then pumped at a predetermined flow rate to bring it under control. Because this heavy mud is denser than the flowing well fluids, it exerts hydrostatic pressure that stems the flow. 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 returned to a static condition.

Because it is a highly complex 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 guarantee of success. Therefore, planning 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 ([Figure 66](#)) and to be able to pump a kill fluid, such as heavy drilling

mud, that can 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.

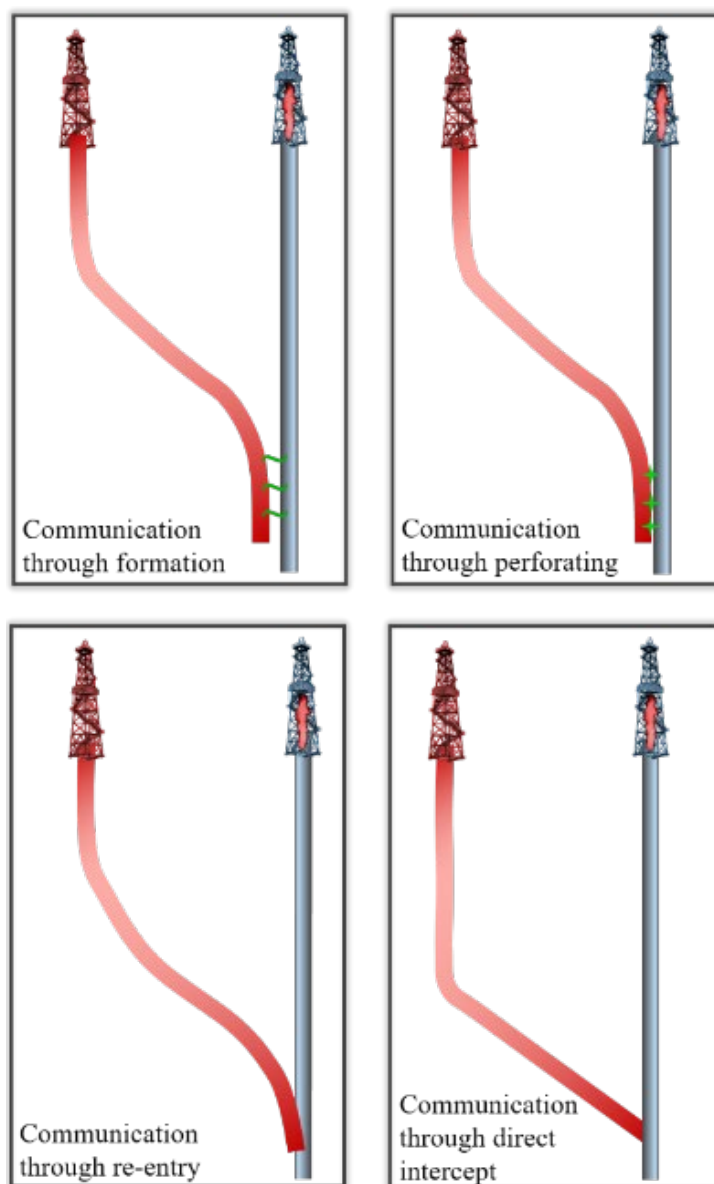


Figure 66—Establishing communication with the target well and allow for pumping a kill fluid can be accomplished in different ways

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 but at a certain point, the envelopes of uncertainty will be so close that these rules must be broken.

Ranging techniques are applied to determine the relative positioning between wellbores by measuring the distance and the direction to 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 has been reduced to an acceptable “As Low As Reasonably Practical (ALARP)” 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 to 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 field- and office-based parties involved in the project. This approach reinforces the leadership, optimizes resources, prevents and mitigates risk, and keeps all personnel focused on their task. [Figure 67](#) shows how the management system provides a continuous iterative loop for operations control, corrections, and improvement.

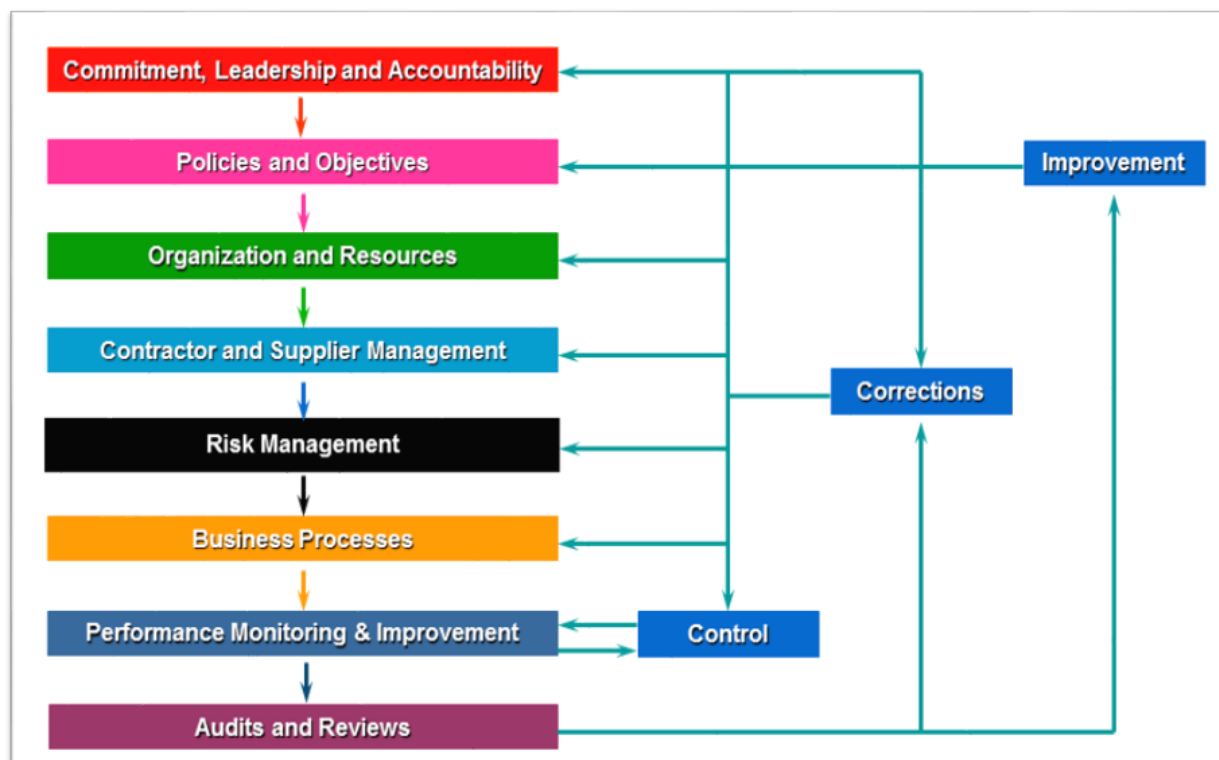


Figure 67—A robust and reliable management system ensures consistent execution of relief well operations, takes into consideration lessons learned, and integrates methods and techniques already in place for standard drilling operations

The management system dictates how the relief well drilling should be conducted. [Figure 68](#) 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 lapses 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 ([Section 8.3, Figure 70](#)), which ensures the residual risk of accidental interception is non-HSE; i.e., without losing control of the relief well.

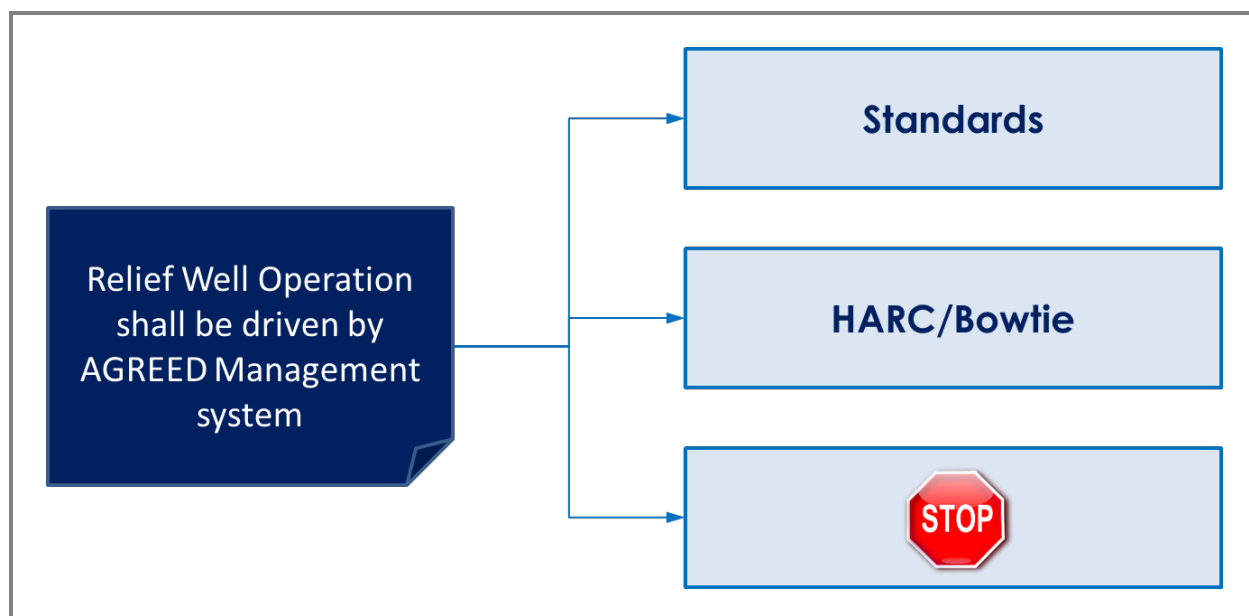


Figure 68—Examples of components needed for relief well and how they relate to other activities and the management system

8.1.2 Communication

Clear communication protocols are a 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 [Figure 69](#) are separated into a sequence of consecutive tasks that must 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 5](#), 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

Table 5—Action steps and descriptions for performing a task

Action	Description
What	<p>Target well definition</p> <ul style="list-style-type: none"> • Precise target well surface position • Specify target well position • Specify target well position uncertainty
When	<p>During phase 1: Planning phase</p> <ul style="list-style-type: none"> • 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 center at oil company office
Why	<ul style="list-style-type: none"> • Objective: Provide reference data to all parties <ul style="list-style-type: none"> • Geodetics and geomagnetics reference • Target well surface positioning • Target well corrected survey listing • Target well optimized positional uncertainty • Survey program used for target well • All parties should rely on same valid data and update their well trajectory • Database consequence to regulate different software packages for collision avoidance computation • Reduce the target well uncertainty to a minimum to increase chance of target well detection with ranging techniques. • To define reliable relative RW to TW surface uncertainty and to define target well EOU size to establish ranging strategy
Input Data	<ul style="list-style-type: none"> • Historical TW surface location coordinates report(s) • New (if possible) TW surface coordinates measurement • Historical geomagnetic mapping • New (if possible) geomagnetic mapping • Target well definitive survey data • Target well raw survey data • Target well bottomhole assembly (BHA) description and sliding or steering sheet • Target well survey program report (survey tools and quality assurance and quality control • Target well end of well report
Means	<ul style="list-style-type: none"> • Geomagnetic and geodetic equipment and expertise • Geomagnetic data processing • Referenced relief well planning software • Wellbore positioning uncertainty expertise
Output Data	<ul style="list-style-type: none"> • Geodetic reference • Geomagnetic reference • Definitive target well surface location coordinates reference • Target well surface location uncertainty • Target well reprocessed and corrected survey listing • Survey tool type and error tool code for target well • Error models customized for target well in easy-to-import format type • Target wellbore positional uncertainty for the chosen confidence level
Send To	<ul style="list-style-type: none"> • Oil company • All relief well team members

8.1.3 Digitalization

Contingency Relief Well (CRW) is increasingly becoming a mandatory practice, particularly in challenging environments, such as deepwater drilling.

Well interception requires experts from multiple disciplines, each of whom are assigned a specific task as outlined in each phase of the operation ([Section 8.4, Figure 71](#)). Therefore, a successful outcome hinges largely on the transparency and availability of information in a timely manner, which must be seamlessly communicated to every person involved in the decision-making and approval process to proceed with or to halt operations.

Traditionally, personnel involved in relief or intercept well operations often work in isolation, using various applications and sharing information through Excel files, PDFs, or hybrid physical and virtual meetings ([Section 9.6, Figure 119](#)). An additional challenge has been the coherence of available data to all parties involved. A mistake as simple as surface location inaccuracy could make a significant difference in trajectory planning, ranging selections, and interception strategy decisions.

From a management perspective, the ability to access all information within the same system, from operations team to vice president to president and CEO, is crucial. Critical approval processes, such as Hazard Analysis and Risk Control (HARC), should be digitally managed and moved away from physical signatures on PDFs or via emails on DocuSign, to more efficient digital approvals in which all data and information are readily available for review by all concerned.

During execution, the challenge of information sharing is even more pronounced; the capability to make immediate virtual changes, obtain necessary approvals, and to pass these on digitally in a controlled manner to the operation team is essential.

Over the decade from 2010 to 2020, numerous service companies and operators developed systems for the storage of centralized data necessary for planning and executing complex operations that is accessible in readable formats across various applications. Since 2020, spurred by the oil and gas industry's acceptance of cloud-based solutions, many service companies have matured their offerings. These solutions now provide central data aggregation from various databases, including surveys, offset well hazards and risks, subsurface models, permits, HARC, downhole tools, and more. This enables multiple stakeholders to collaborate in a single workspace instead of being forced to work separately using their own applications ([Figure 69](#)). These digital solutions facilitate ease of planning and coherence in execution and the decision-making process.

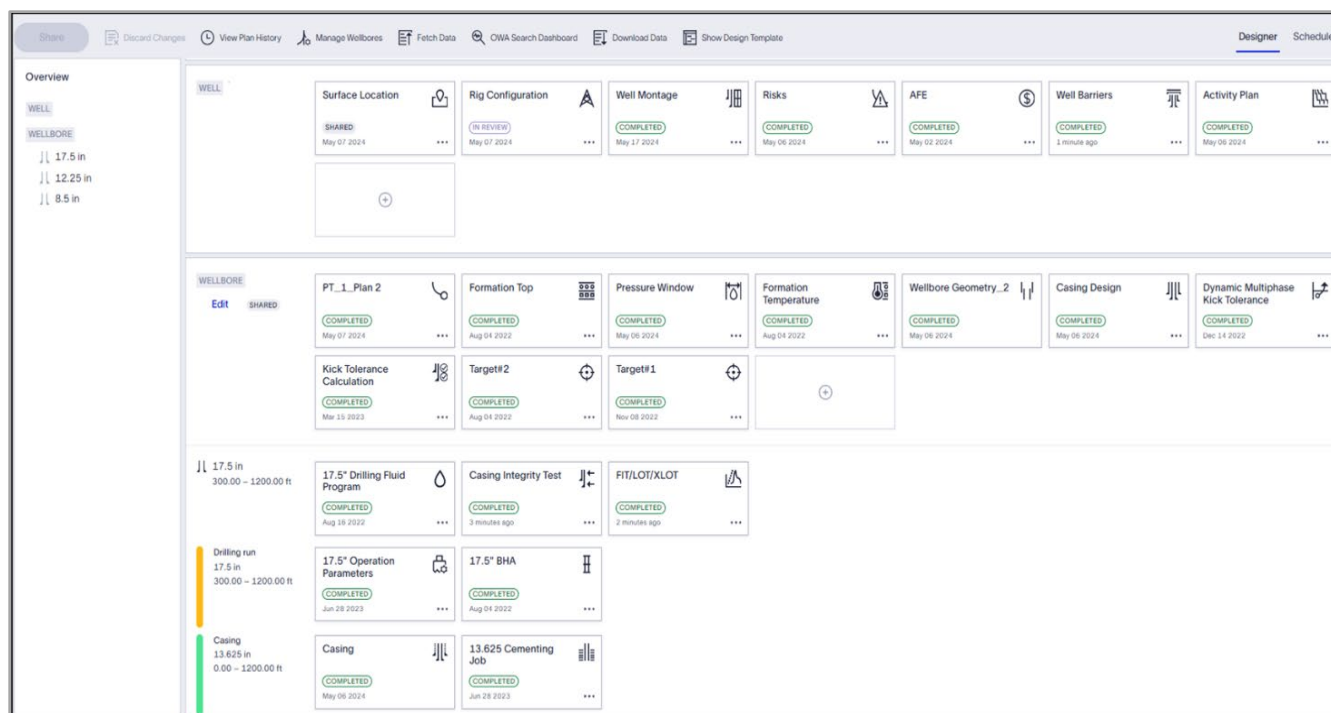


Figure 69—Example of a modern solution with modules and experts from multiple disciplines (well integrity, geologists and geophysicist, reservoir engineer, drilling engineer, directional drilling, ranging team, intercept team, fluids engineer, cementing engineer, well control engineers, etc.) collaborating transparently with information available in a timely manner

Though still in its infancy, a significant player in this digital transformation is the Open Subsurface Data Universe (OSDU), envisioned by operators and service companies as a way to eliminate data silos, reduce data duplication, and enhance data accessibility across disciplines.

Overall, digitalization is enhancing data and information sharing, collaboration, and decision-making across all phases of well interception workflow. Platforms like OSDU and the adoption of cloud-based and automated process minimize gross error and increases the chance of success. The journey to maturity is becoming real and digitalization promises substantial rewards by transforming how CRWs are planned and executed. Cooperation among all operators and service companies is essential to fully realize these digital advancements, which will foster a more connected and efficient industry.

8.2 Ranging Decision Matrix

Ranging technology selection is critical to successfully achieve 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 operations requires careful and detailed planning. Each relief well strategy differs from case to case, and the choice of the ranging technologies may rely on different aspects including access to the target well, environment, deployment methodology, required expert personnel, cost, effectiveness, objectives, performances, hole conditions, and others.

One single ranging technology may be chosen for a specific relief well case, but in most cases 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 must be conducted. One should refer to Chapter 7, “Ranging Techniques Comparison” to identify and select the appropriate ranging technology for the specifics of the relief well project.

8.3 Categories of Relief Well Designs

Over time, relief well experts have developed three categories of Relief Well Trajectory Design ([Figure 70](#)).

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 require three phases: A data gathering phase, drilling phase, and intercepting phase. Simple intercepts are typically the most difficult to execute without the use of side-tracks.

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 after it has been 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.

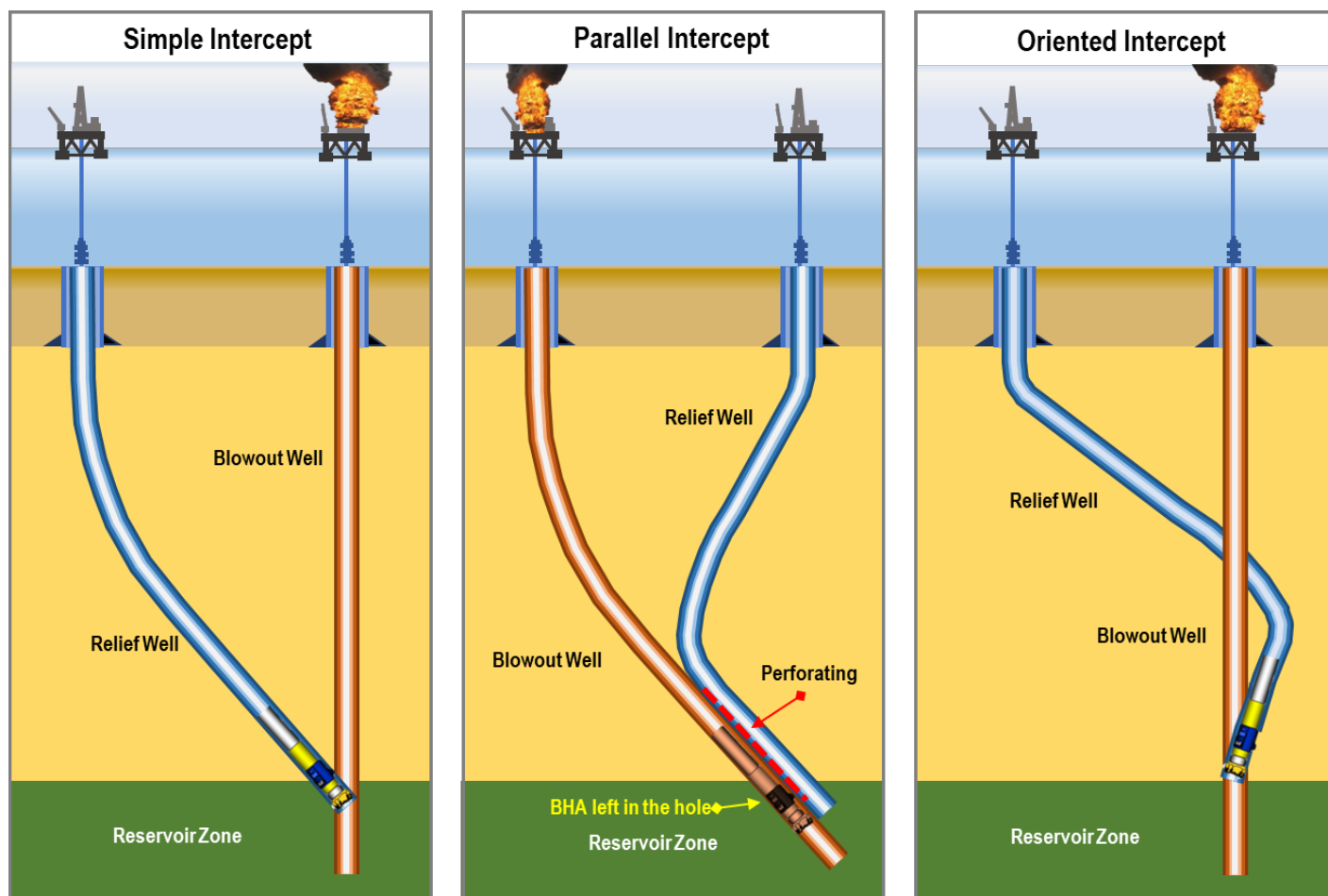


Figure 70—Various examples of relief well designs

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 71](#). Each phase consists of specific tasks that must be properly planned, communicated, performed, and executed prior to moving on to the next phase. These phases force the relevant experts to 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).

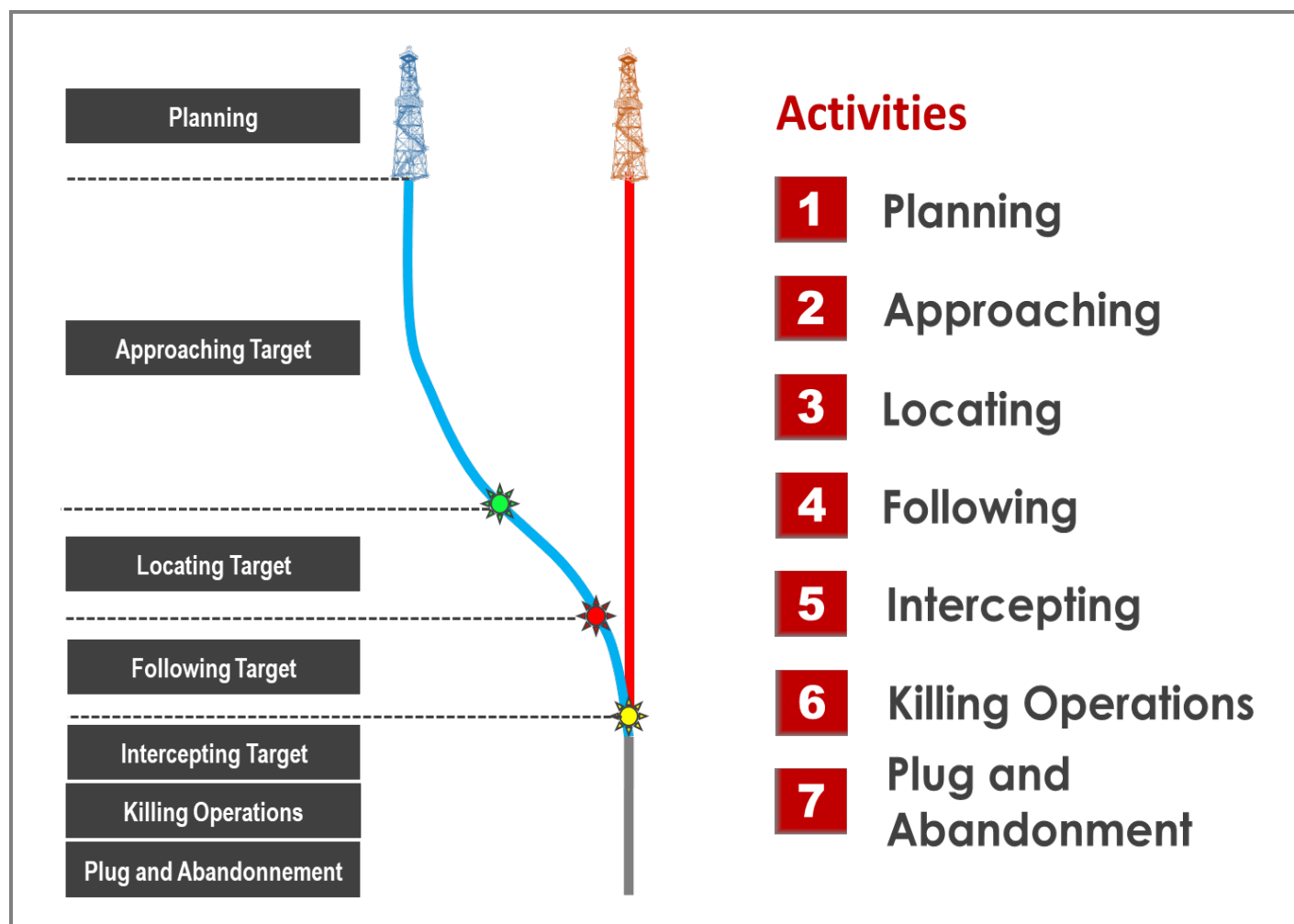


Figure 71—The core of the relief well process is the workflow, consisting of seven phases

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 relief well 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 analyze 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 execution.

Relief well planning starts with the planned interception locations, which requires intensive dynamic fluid modelling, and goes back 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 and well architecture constraints, taking into consideration the surface exclusion zone, and incorporating a selection of ranging technologies through single or multiple technologies deployment.

Due to the unique nature of relief well operations, it is important to define the Target Well as reference in the planning phase. There can be several relief well options with several offset wells to be analyzed, presented, and visualized. All corresponding wells—target well, offset wells and relief well options—must go through robust survey management processes with strict QC/QA to ensure all the wells use the same coordinate reference system (CRS), same TVD reference, known surface locations with high degrees of certainty, and the best possible tool codes. In simple operations, typically the CRS of the Target Well is used. However, for challenging operations with multiple wellbores located in different CRS, then the optimum single CRS must be used.

The use of the same CRS and TVD reference are critical in drilling execution, especially after the first ranging run to analyze the relative positioning of the target well to the relief well and to plan subject well drill-ahead for subsequent ranging runs and following and intercepting phases.

In addition, every effort should be made to minimize the EOU of the Target Well to increase the chances of success in ranging and interception. These positions determine the safe operating envelope, as shown in [Figure 72](#), by following the collision avoidance standard, such as an SF = 1.2. Preventive and Mitigating Actions and HARC must be in place prior to operating below an SF of 1.0 to ensure safe drilling and prevent losing control of the relief well caused by an unintentional wellbore collision.

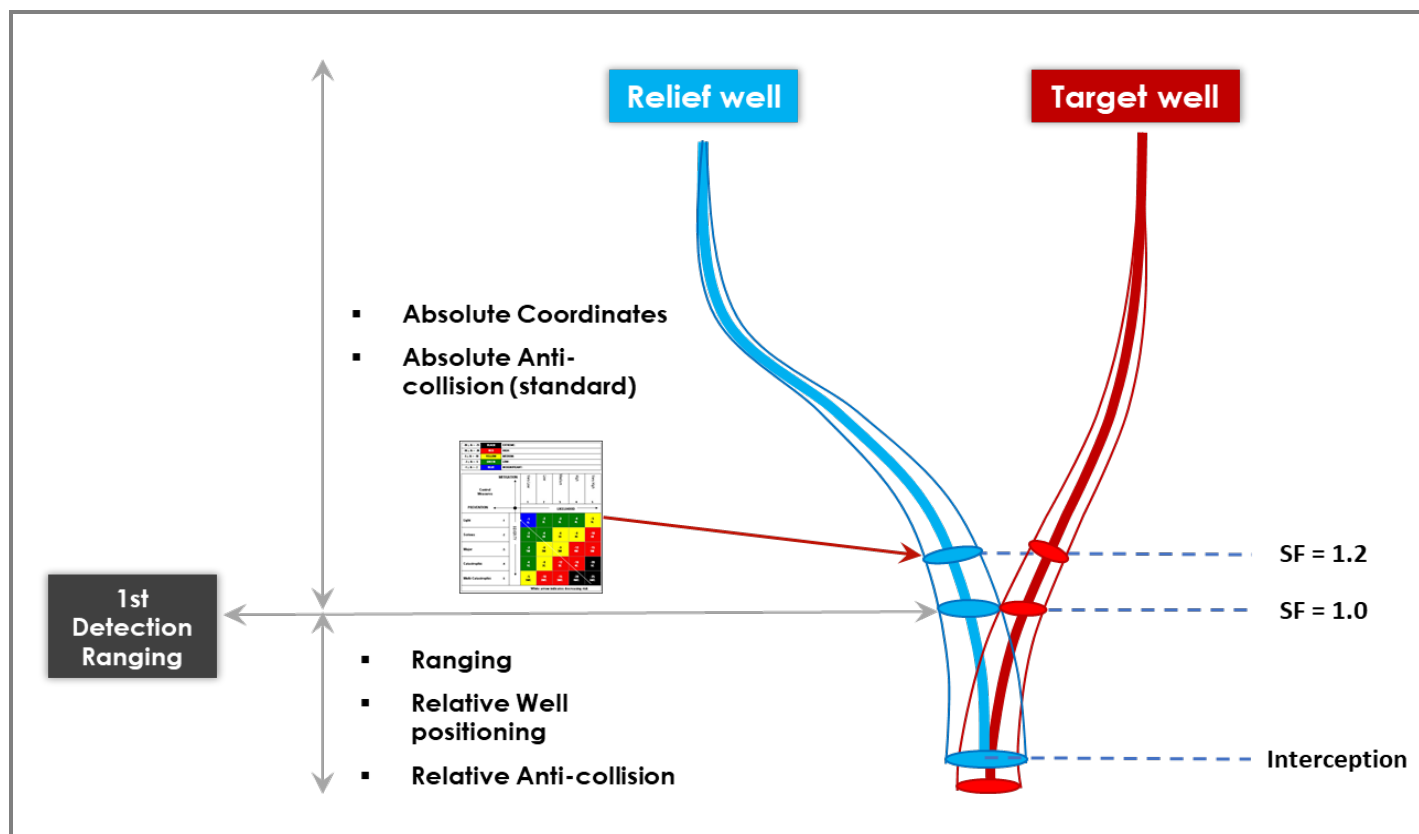


Figure 72—The relief well planning requires an advanced and optimum survey program to obtain the best wellbore position possible. This, along with HARC, determines the safest operation envelope following the collision avoidance standard, such as a separation factor of 1.2, and ensures the risk of early interception shall be managed to non-HSE 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 the operator to have the financial capability to drill a relief well and to conduct other emergency well control operations. In the event of a blowout, the regulations also require that the operator knows the estimated time to drill the relief well. Regulators require that at least two relief well surface locations are verified for use and that a rig is available and identified for use in a 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 include:

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 operators 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 the operator's EP that they 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 the operator must estimate the time required 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 operators must have a documented relief well plan that 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 require documentation, such as 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 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 horsepower can be made available as needed
 - b. Confirmation that required volumes and weights of kill fluid can be adequately mixed, shipped, and stored
5. Identification of a clear process
 - a. Enables the SPU D&C VP to sign off that the above requirements have been met

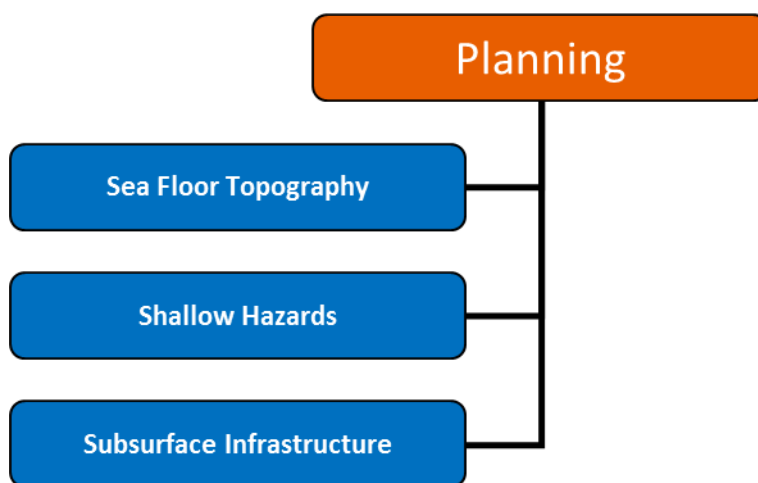


Figure 73—Planning, initial data gathering requirements

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 (Figure 73). 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.

Figure 74 shows an example of key element tasks and responsibilities in Phase 1, Planning phase.

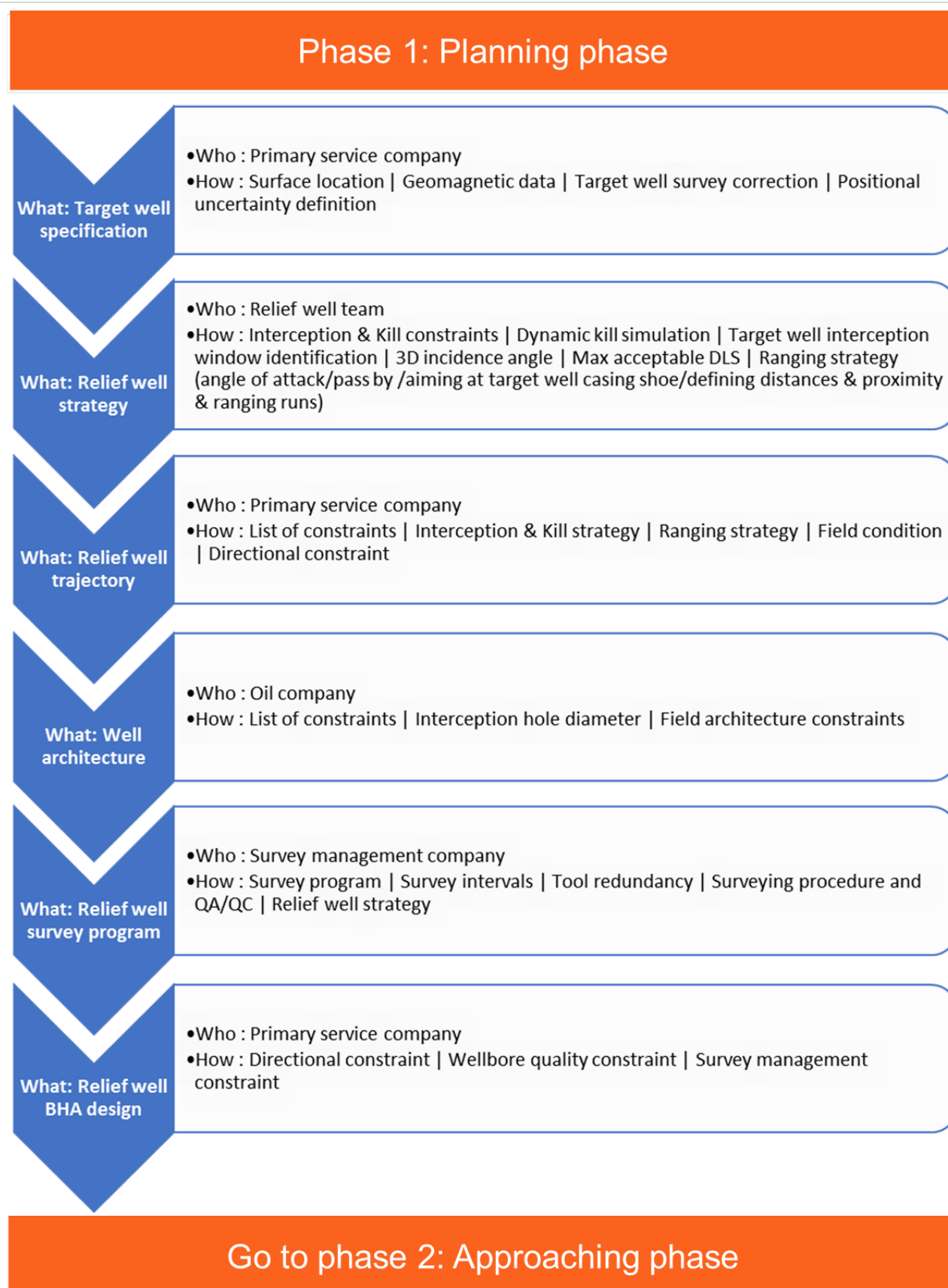


Figure 74—Phase 1: Planning phase key tasks and responsibilities

8.4.1.2 Surface Location Selection

Offshore or land site selection for relief wells are one of the critical aspects of the planning stage. It is necessary to consider the requirement that the relief well be placed a safe distance from the blow-out well but close enough to allow a relief well to be completed successfully and efficiently. In general, insurance requirements and industry guidelines recommend the minimum distance from relief well to target wellbore is at least 500 m (1,640 ft) at surface. For shallow interception, the 500 m could be too great a distance. It may be advantageous to move the surface location closer to the target well if HSE is not compromised and approval is granted from the regulatory authorities, rig contractor, and insurance agencies. For deep slanted wells or for space requirements for clean-up vessels in offshore operations, a further distance is preferable provided drilling conditions allow. Additional distance improves logistics for offshore oil-spill vessels, as well as better protection from the blowout itself. In both cases the exclusion zones around the spill site are based on regulatory authorities, industry experts, and other constraints, such as toxic or explosive gases, noise, smoke, and other circumstances. The following constraints are to be considered in the site selection process and ideally should be investigated in advance as part of the contingency relief well planning.

8.4.1.2.1 General Constraints:

The following constraints are applicable to both on land and offshore relief well surface locations.

- Geology – Understanding of local geology, rock mechanics, and their effects on wells drilled in the area, including but not limited to formation fractures, faults, and shallow gas hazards must be taken into consideration.
- Prevailing Wind Direction – Relief wells should ideally be situated upwind from the prevailing wind directions. This is to help avoid any smoke plumes that could result from the blowout ([Figure 75](#)).



Figure 75—Smoke from blow-out well

- Fire and Heat Radiation – The amount of radiant heat that could be created by a blowout will help determine minimum distance of a relief well. Gas fires burn at approximately 3300° C, Oil fires burn at about 2200° C, and steel melts around 1370° C.
- Oil Plumes or Oil Pooling – It is possible that hydrocarbons could escape using other flow paths than that of the blow-out well due to different geological structures, so it is recommended to avoid placing relief wells up-dip of a fault line or near other potential subsurface pathways.
- Noise – Noise is likely a temporary occurrence on blowouts, but it should be considered to avoid picking locations that are intolerably loud.
- Environmental – Avoid any environmentally sensitive locations such as national parks, reserves, and protected areas as surface locations.

- Positioning Uncertainty – In order to increase the chances of successful detection of the target well during the locate phase, it is important to minimize the uncertainty related to the relief well position. Specifically, it is recommended to avoid drilling in the East/West direction to reduce MWD survey error caused by greater impact of drillstring interference, or GWD/GyroMWD error caused by increased impact of mass imbalance.
- Offset wellbores – The surface location of the relief well must consider the positions of all wellbores in the area. Getting too close from potential offset wells may not only increase the risk of collision, but also may jeopardize the ranging strategy.
- Interception Target – Sub-surface targets of the blowout well also play a key role in the final selection of the surface location. To aid in overall surface location selection, it is suggested that alternative Relief Well-Target Well surface location separations be prepared using a surface location and drilling complexity sensitivity analysis, as shown in [Figure 76](#).

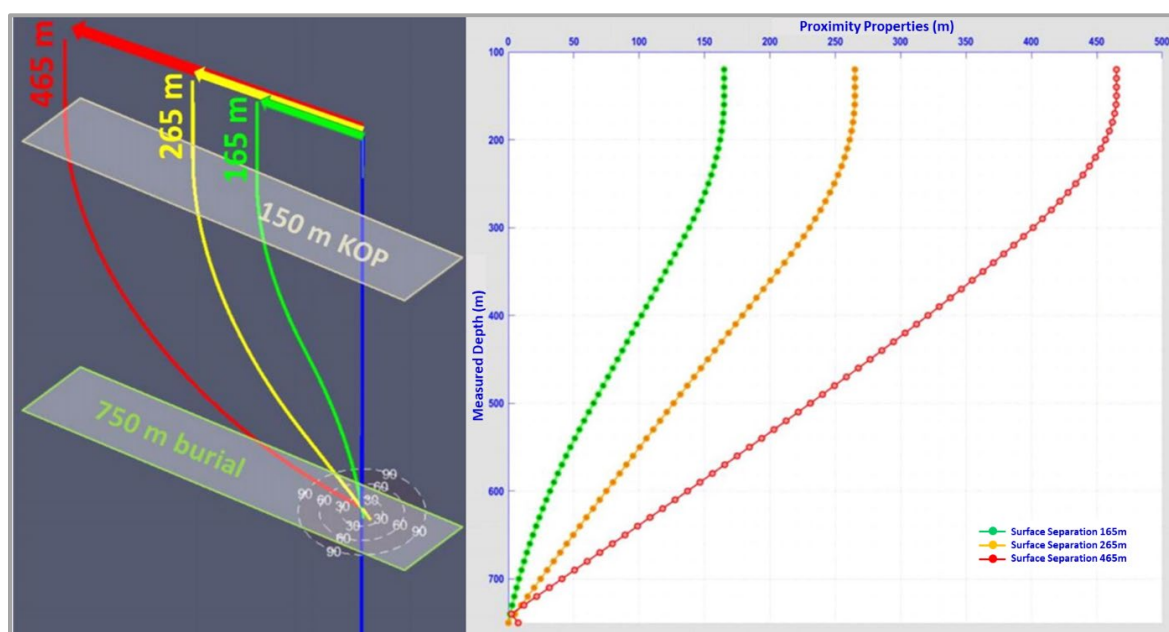


Figure 76—Surface Location and Drilling Complexity Sensitivity Analysis

8.4.1.2.2 Offshore Constraints:

The following constraints specifically pertain to offshore surface locations.

- Seafloor mapping – Having an accurate seafloor map ([Figure 77](#)), which details sub-surface infrastructure ([Figure 78](#)), pipelines, manmade and natural hazards, is ideal to optimise location selection. The bathymetry of the seabed floor also shows potential high slopes or canyons that may complicate the installation of subsea wellheads.

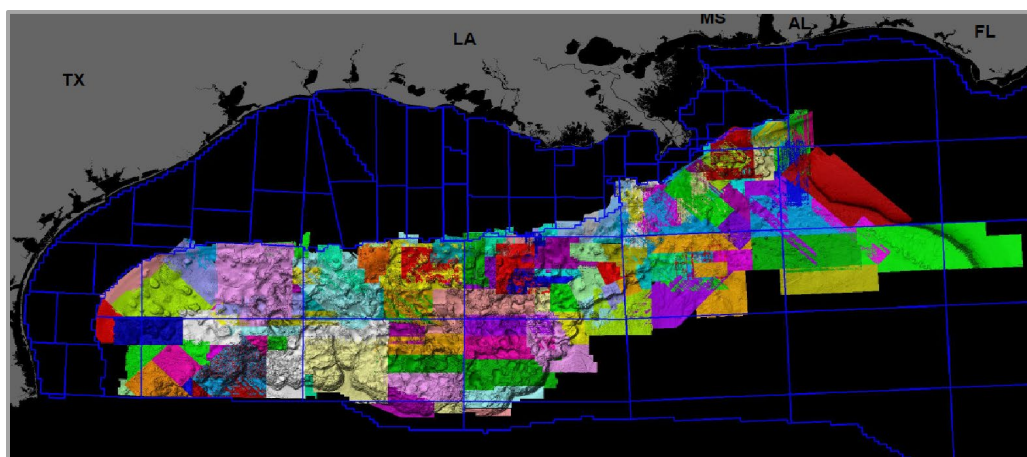


Figure 77—Seafloor grid compiled by BOEM (Bureau of Ocean Energy Management) in the Gulf of Mexico

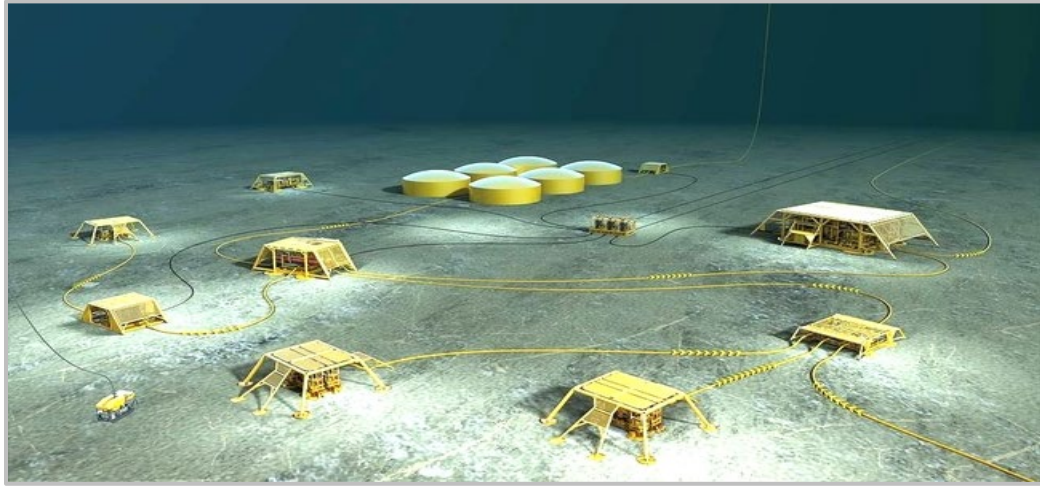


Figure 78—Sub-surface infrastructure examples

- Access consideration – Prohibited air space, general traffic, clean-up activity of surface vessels, ROVs and anchor patterns, and placement of both the near-by floating facilities and relief well rigs that may hinder the operations.
- Oil Plumes or Oil Pooling - the potential size and possible location for subsea plumes needs to be determined, [Figure 79](#).



Figure 79—Subsea plume reaching surface

- Prevailing Current – Prevailing current directions and speed need to be considered. The location should be placed up-current of prevailing area currents to prevent the encroachment of fluids and gas from the blow out well. Because currents can change seasonally, multiple sets of location options might be required ([Figure 80](#)).

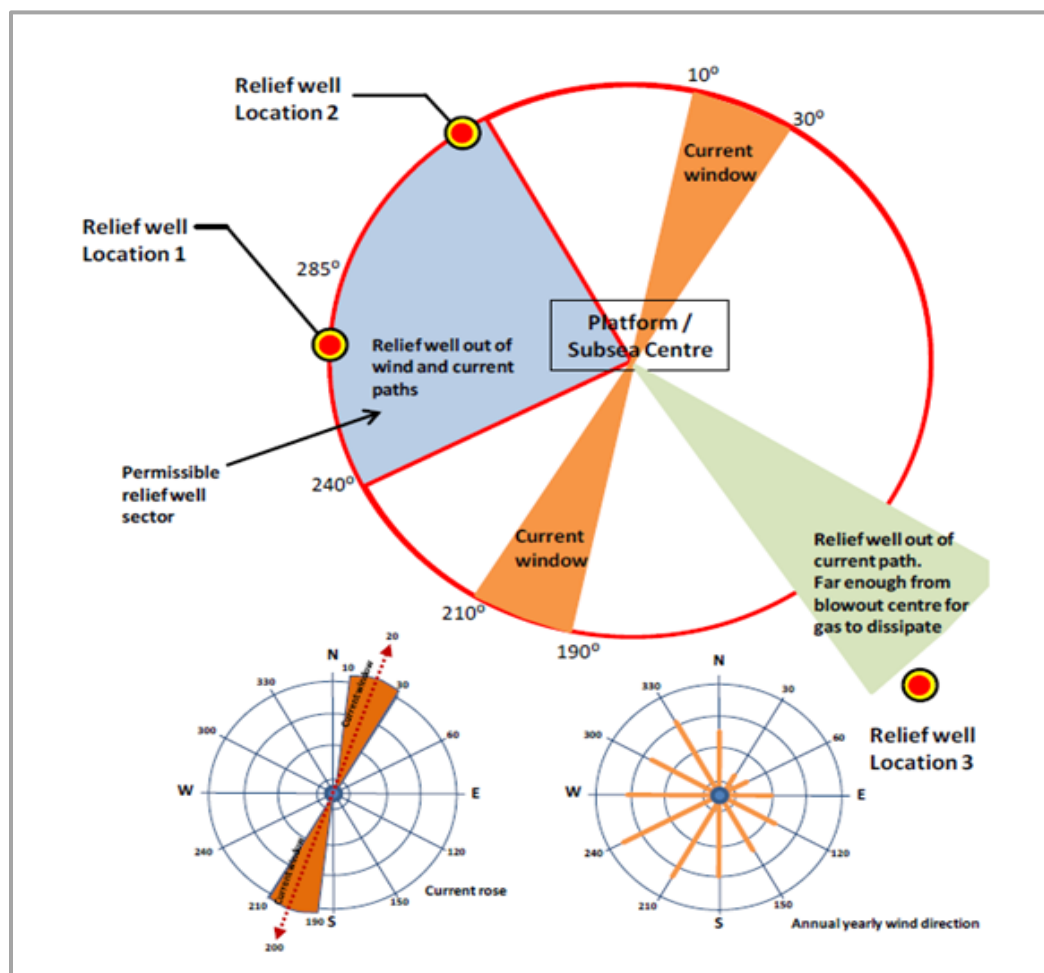


Figure 80—Example of relief well locations based on prevailing wind and current study

8.4.1.2.3 Land Constraints:

The following constraints pertain specifically to land site selection.

- Topographical features— Features, such as road access, cliffs, hills, lakes, rivers, dams, and mountains should be studied when selecting a relief well surface location.
- Site Access – Consideration must be given to prohibited air space, traffic limits, traffic congestions, and multiple road access to both the relief well rigs and the target well, as they may hinder the operations.

8.4.1.2.4 Surface Selection Example:

In addition to the above considerations, the relief well trajectory for locating, following, and intercepting must be considered. A location might be ideal considering only surface information, but the relief well trajectory may be very challenging or extremely difficult to complete. Whereas it may be less than optimal at surface, when interception trajectory is considered, this second location may turn out to be the better position for placement. Therefore, ranging options and simulations need to be studied and become a determining factor when selecting an optimum surface location. What is intended to happen downhole will directly affect what is happening at the surface with regards to surface selection.

[Figure 81](#) shows an example of a surface location study that was completed in South America Land. Three possible sites were selected based on land rules in the area and a wind study that indicated wind direction and speeds headed East Northeast. The client was planning to drill a future well at the northeast location and a pad was in the process of being built on this site, which was the preferred location considering the surface constraints. The northwest location was the second preference because it was upwind and would avoid any smoke plumes.

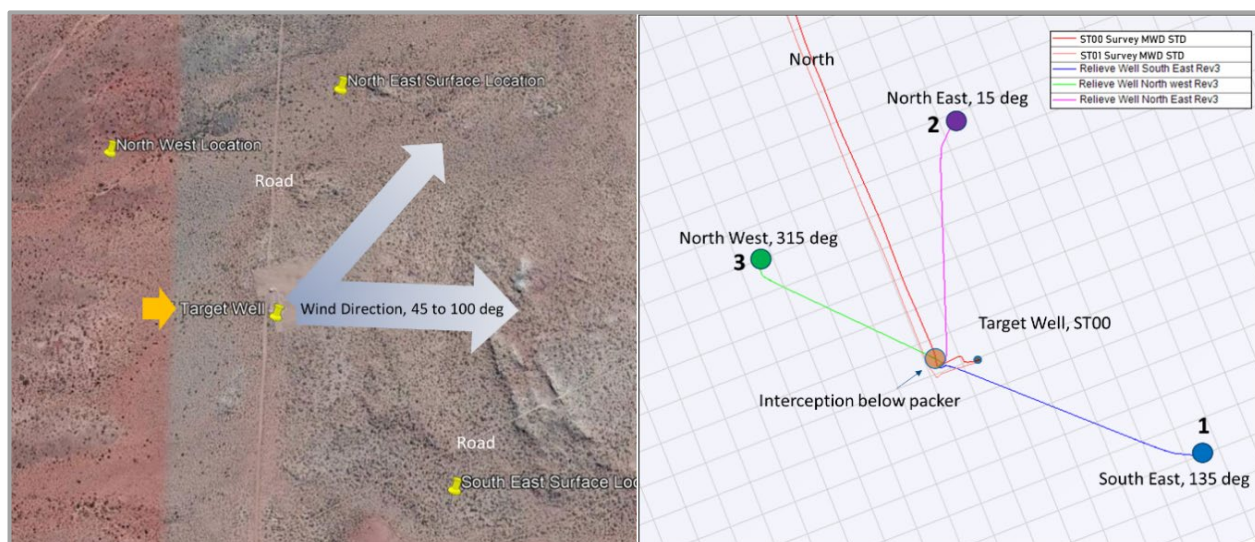


Figure 81—Possible relief well surface locations. The red line is the plan view of the target well trajectory. Based on kill mud modelling the targeted interception point is at 57 degrees inclination in the curve section.

Taking into account the relief well trajectory proved that more than just surface constraints and preferences needed to be considered. The well profile for the NE location would have high tortuosity due to a negative section and high build rates to chase the target well build rates. Other cons to that design included requirement for a larger bit-to-sensor distance because of the need for a motor. In addition, the BHA design needed more flexibility in case the target 7-inch casing was set higher than intended, which would further increase the build rates required to have sufficiently long locating and following phases. The SE relief well profile, on the other hand, would be easier to drill, allowing the use of rotary steerable drilling systems that would get the MWD closer to the bit, lower build rates, and create longer locating and following phases with an expected ranging contact depth of 250 m (820 ft) TVD shallower. Figure 82 below compares the modelled ranging signatures between the two relief well profiles with an expected ability to discern 15 nT of signal.

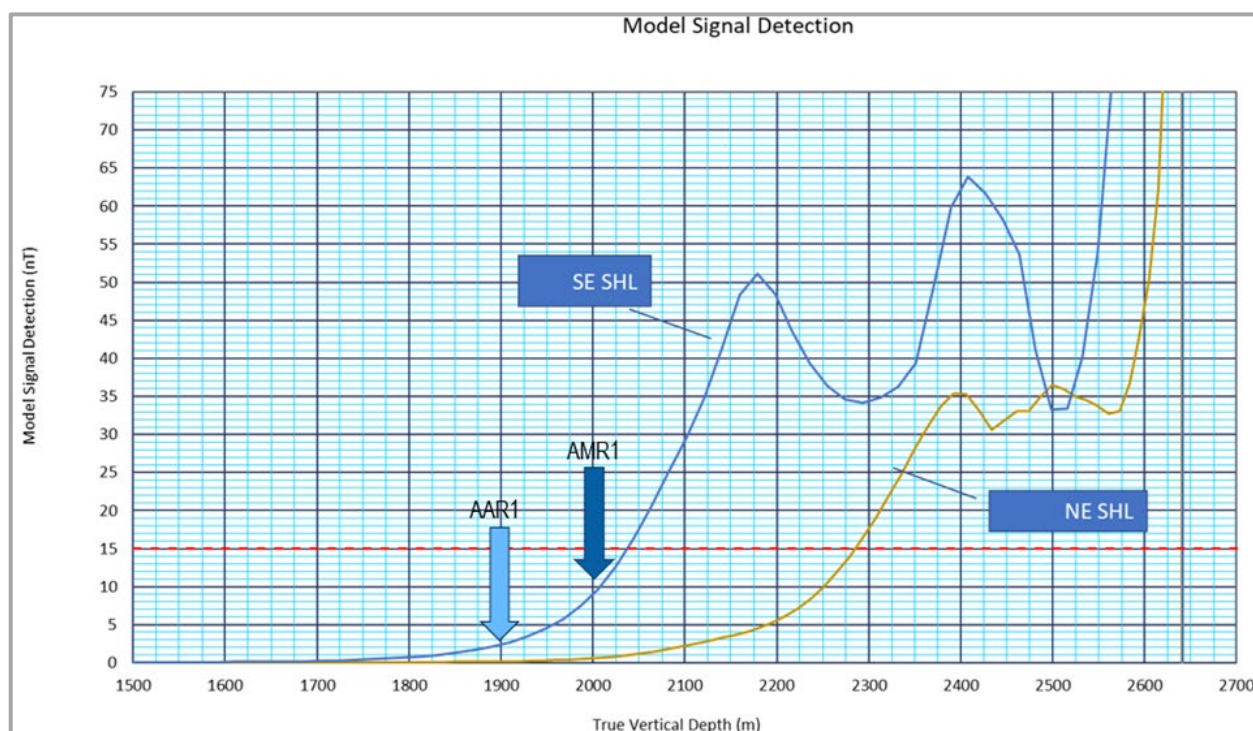


Figure 82—Plot of modelled signal detection in nT versus TVD of the relief well profile. The red dashed line at 15 nT indicates the threshold for detection and it is possible to see that the SE well profile reaches the threshold about 250 meters earlier

8.4.1.3 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 6](#).

Table 6—Tasks assigned to primary and secondary, back-up contractors

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

8.4.1.4 Use of Hazard and Risk Control (HARC)

The objective of the HARC matrix ([Figure 83](#)) is to set standard processes and tools for identifying hazards, assessing associated risks, and defining required control measures. The scope of the HARC process is to address, as applicable, service quality, health, safety, security, and environmental (HSE) risks on a task or process basis and always applies to the entire relief well project where management control is expected.

In HARC, Risk is defined as Severity multiplied by Likelihood; it only operates under “As Low As Reasonably Practical” (ALARP) levels (yellow boxes) and allows management to make considerable improvements or changes to the plan in an organized and controlled manner. Poedjono et al., 2009, SPE-121040 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 their occurrence and 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 (e.g. 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 through contingency plans throughout the entire drilling process.

From the HARC perspective, it should be noted 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 assumes success 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, worse, losing the well.

A successful relief well planning requires breaking the collision avoidance rule ([Section 8.4.1, Figure 72](#)) and applying specific relief well drilling rules. It is important to analyze all specific solutions using the HARC process to reduce the risk of misusing the specific techniques. It is also important to remember that the primary function of HARC process is to make certain that all prevention and mitigation actions are in place prior to making a decision. It is only when all the teams adhere to this process that they will be able to drill the relief well safely, efficiently, and at ALARP levels.

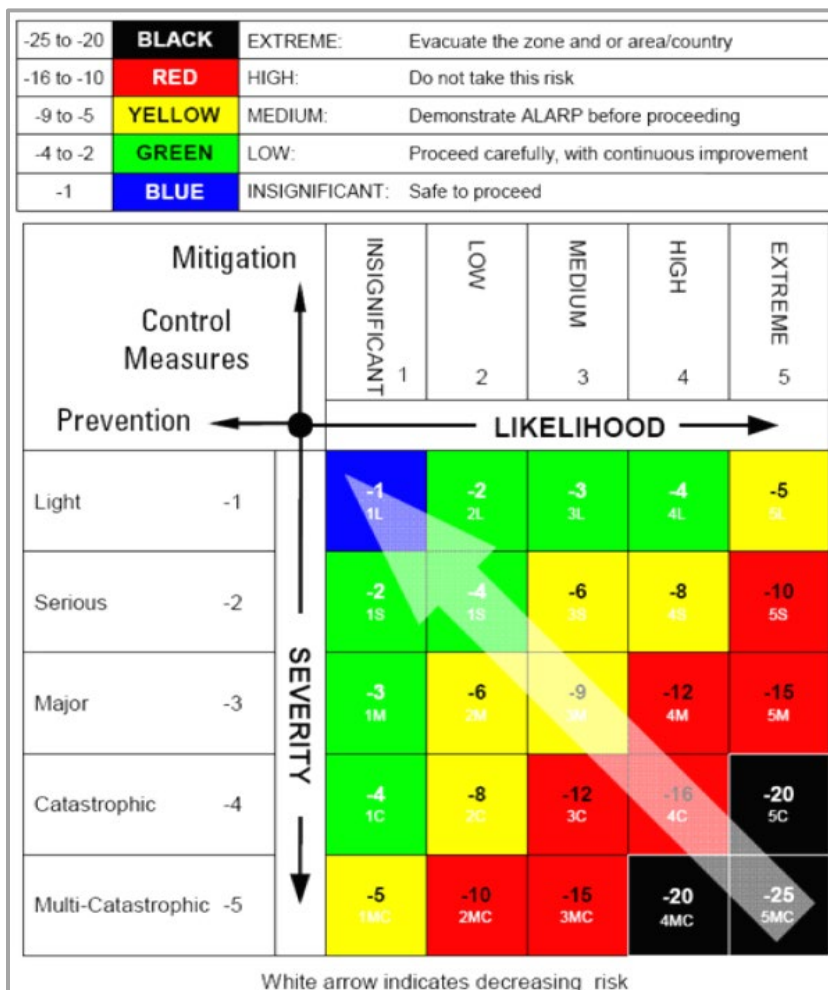


Figure 83—The HARC process identifies and isolates all potential hazards and relates them to the risk of occurrence in addition to the potential impact on the relief well drilling

8.4.1.5 Preventive and Mitigative Risk Mapping

Another of risk mapping method as discussed in Rowe et al., 2015, SPE-173565 that has recently gained popularity is the bowtie method (Figure 84). 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 that are essential to the drilling operation.

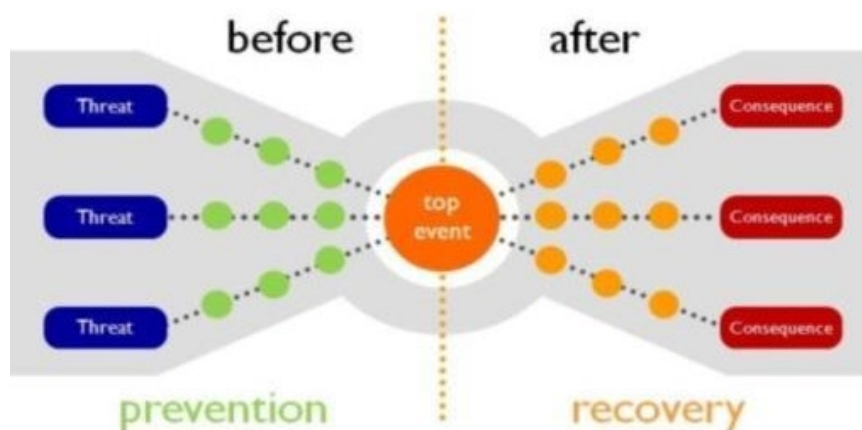


Figure 84—The bowtie method is a diagram that visualizes the risk in a single image, creating a clear differentiation between preventive and reactive mitigation risk management process prior to drilling

8.4.1.6 Managing 3D Positional Uncertainty

To plan a well interception, it is important to understand and manage wellbore 3D positioning and associated positional uncertainties for both the subject and the target well designated laterally in x and y, and vertically in z, which is commonly plotted as North, East, and Vertical (NEV) coordinates ([Figure 85](#)).

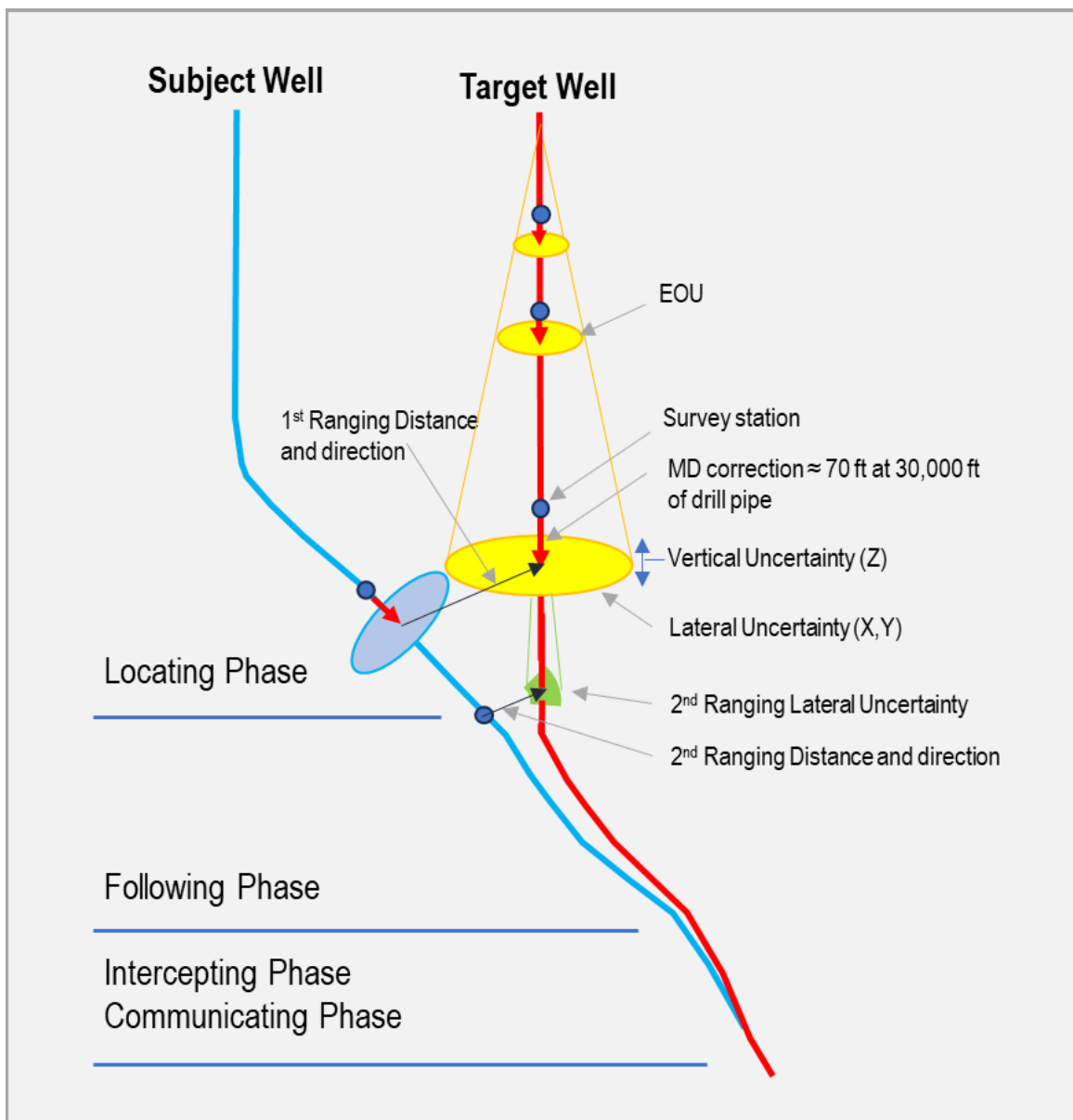


Figure 85—Visualization of target and subject well ellipses of uncertainty (EOUs); lateral and vertical positions with their associated uncertainties before and after successful ranging run.

A survey station is defined as a position from a known well-reference point (WRP) at certain latitude, longitude and elevation from which the measured depth (MD), inclination and azimuth are measured. A wellbore survey will include multiple survey stations that are typically 10 to 30 m (10 to 100 ft) MD apart. The vertical and lateral 3D-position is calculated from the survey stations. To interpolate in between survey station; MD, inclination and azimuth are calculated using minimum curvature or some other geometrical methods, such as slide-rotate, continuous inclination or continuous surveys. Inaccuracies associated with each of the three basic measurements combine to lead to uncertainty in the delivered result. These errors along trajectory are modelled to determine an ellipse of uncertainty (EOU) of the wellbore position. Greater detail on the EOU determination can be found in the ISWISA eBOOK, Introduction to Wellbore Positioning.

An optimal survey program must be designed in-line with the ranging technology selections. It is necessary to minimize the 3D-positional uncertainty for both the target and subject wells. This helps improve chances for a successful ranging

run and to avoid an early intersection that could result in an unplanned well control situation. Therefore, it is important to locate the target well prior to an on-paper collision, where SF=1 and EOUs are touching (Section 8.4.1, Figure 72). Figure 86 is a visualization of the impact that EOU size has on ranging distance.

Survey and EOU improvement can come from survey corrections, combining multiple surveys, combining MWD and Gyro or by using high accuracy surveying techniques (Figure 87). This should enable the most accurate wellbore position possible. However, in blowout situations with no target well access, taking a new survey in the target well is not possible, therefore 3D positional uncertainty mapping should be taken into consideration early prior drilling the target well or in the contingency relief well (CRW) planning.

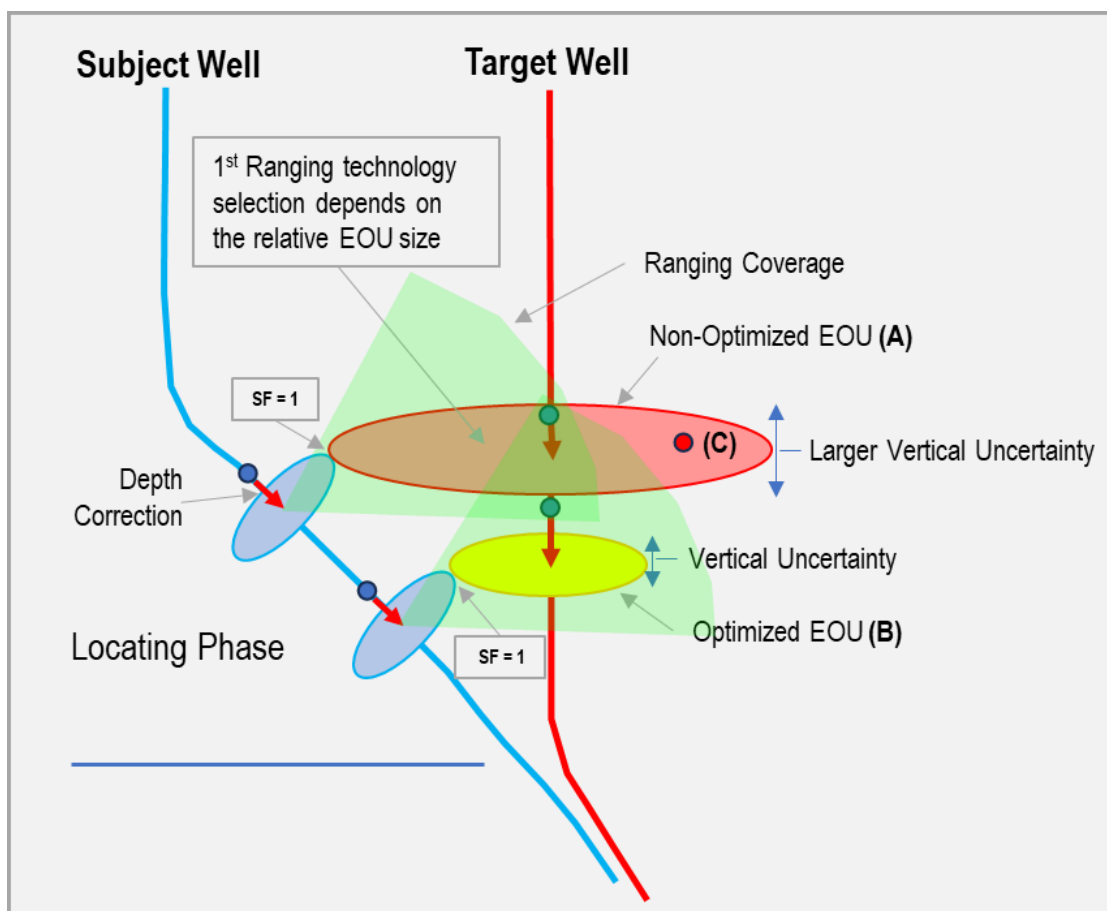


Figure 86—Non-optimized Survey EOU (A) compared to an Optimized Survey EOU (B) and its impact on the recommended first ranging detection. The greater the 3D positional uncertainty based on separation and ranging coverage for the first ranging run (green), the lower the chance of locating the target well at the actual C position.

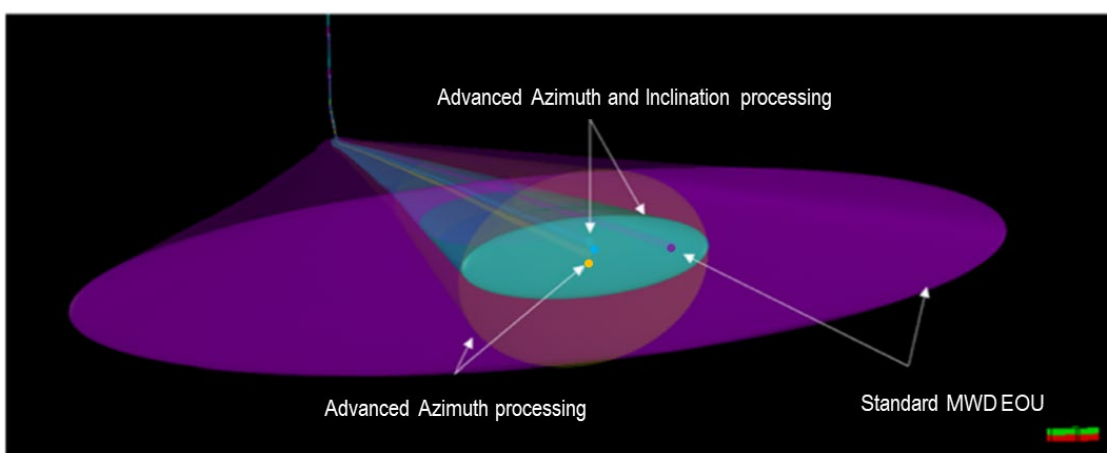


Figure 87—Illustration of various EOU sizes with their corresponding bottom hole location as dots. The smallest EOU corresponds to the highest accuracy survey.

Numerous authors, Poedjono, Bolt and others, have clarified the criticality of accurate depth in downhole activities, including in ranging operations. As part of reconciling and combining multiple surveys to further reduce 3D-positional uncertainty, environmental correction must be applied to each depth measurement, whether the conveyance mode is wireline or drill pipe. The magnitude of the environmental correction is dependent on the wellbore profile, conveyance type, and the rig state during data acquisition. The existence of processing techniques for improving inclination and azimuth underscores the importance of applying depth corrections to enhance the 3D-position and associated uncertainty along the wellbore ([Figure 86](#)).

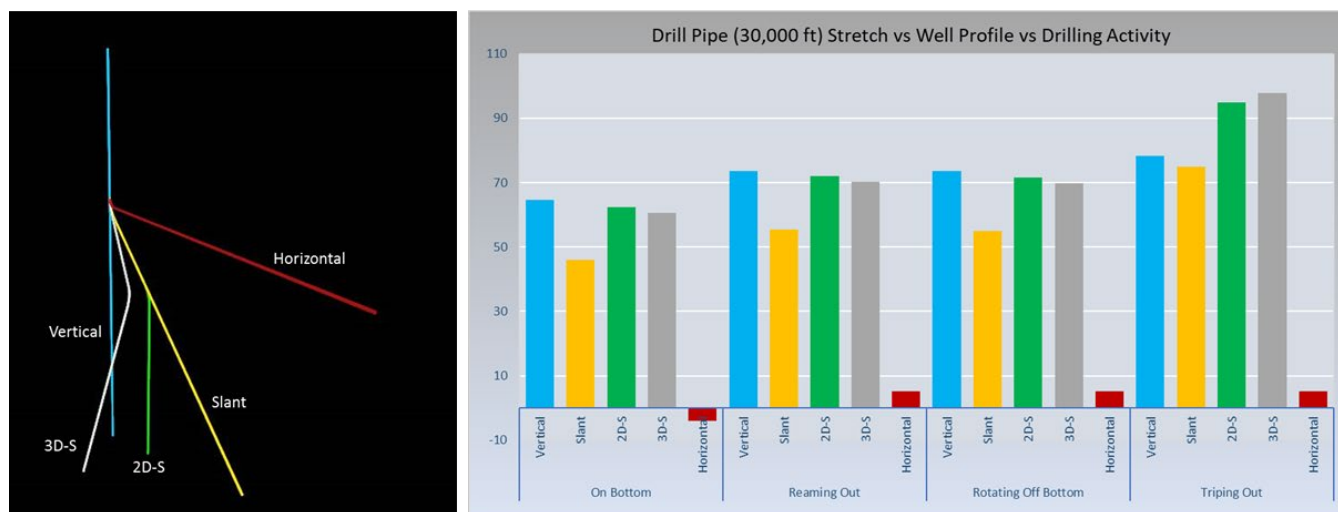


Figure 88—Illustration of the various wellbore profiles vs drilling activities that would affect the measured depth corrections.

[Figure 88](#) shows how well profile and drilling activities affect depth correction. It is challenging to reconcile the ranging results from different ranging runs and types without applying an accurate correction to the survey stations. Defining the relative 3D-positioning of a point in the subject well to a point in the target well is critical in the locating, following, and intercepting phases of the well interception operations. Ranging complexity increases as the wellbore progresses from the vertical, to the 3D-build-and-turn, to the horizontal sections. The most challenging scenario is one in which the subject well must follow the 3D-profile of the target well and then intercept just after the build or turn section. This is further complicated if the target well has been surveyed without adequate consideration of 3D-positional uncertainty, which may compromise the entire interception operation.

8.4.2 Approaching Phase

Relief well operations present substantial challenges starting with the approach phase, as shown in [Figure 89](#). 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. To optimize the torque and drag features and to minimize potential hole issues, special attention must be given to the smoothness of the borehole. 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.

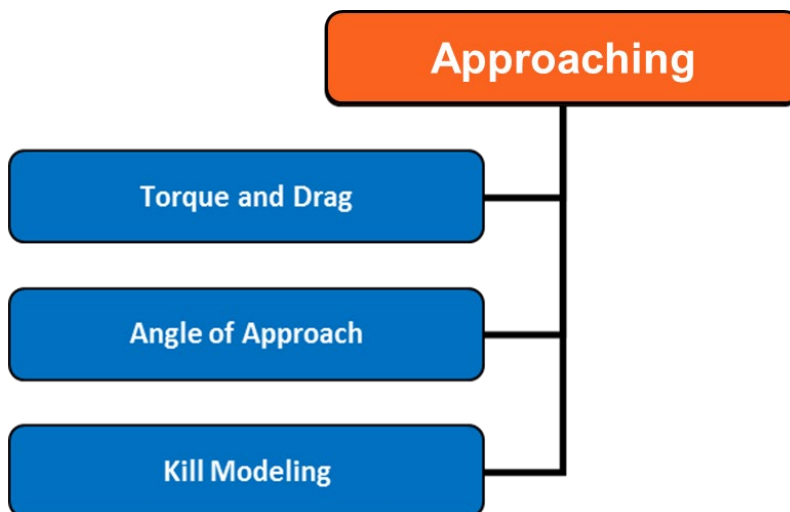


Figure 89—Approaching, initial data and modelling requirements

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 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.

[Figure 90](#) shows an example of key element tasks and responsibilities in Phase 2, Approaching phase.

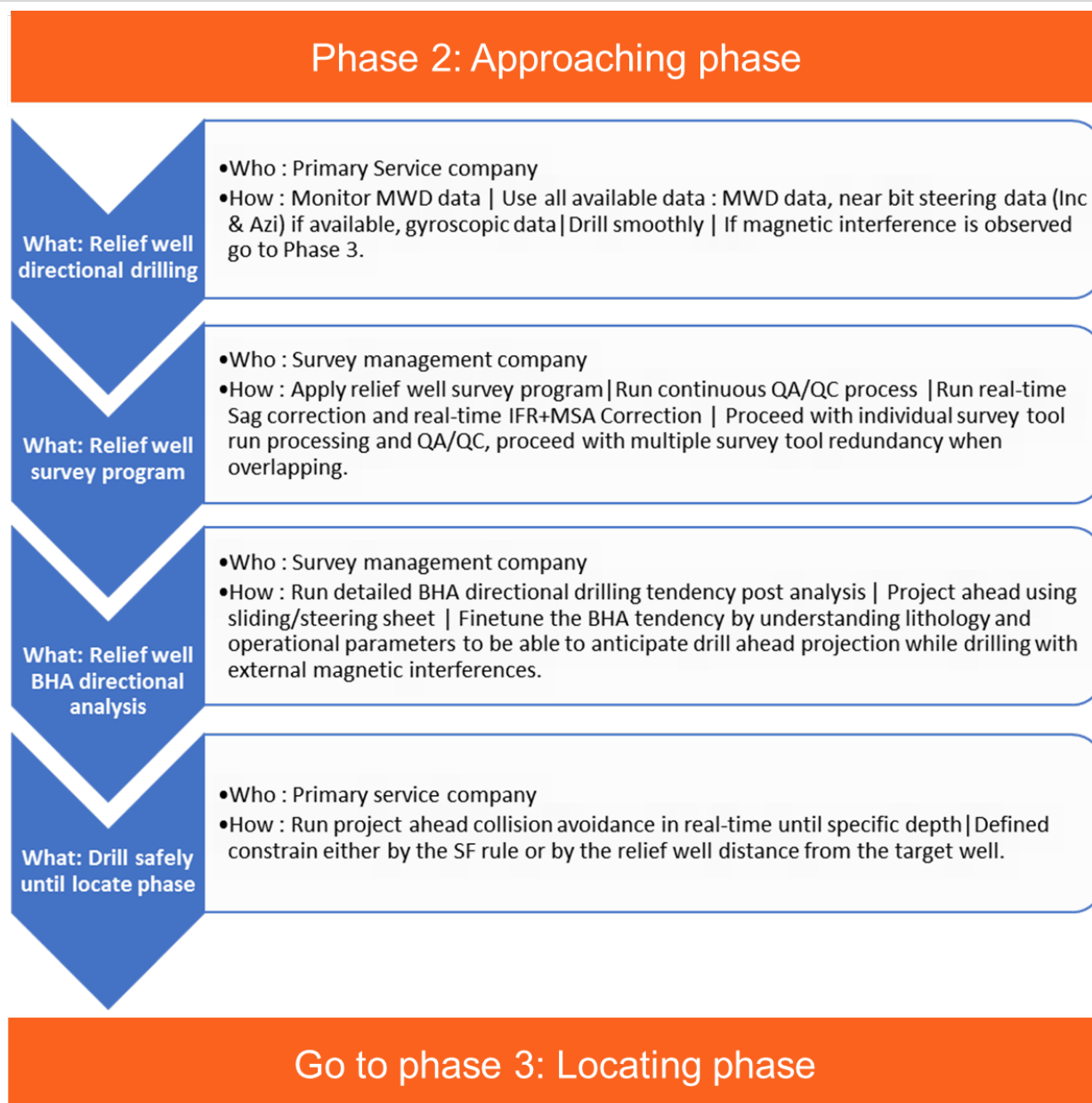


Figure 90—Phase 2: Approaching phase key tasks and responsibilities

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, in the presence of fluid flow, a well kill/plug and abandon (P&A) team will be responsible for the well kill operation as well as the P&A of the target well. [Figure 91](#) shows an example of well intersection process cycle.

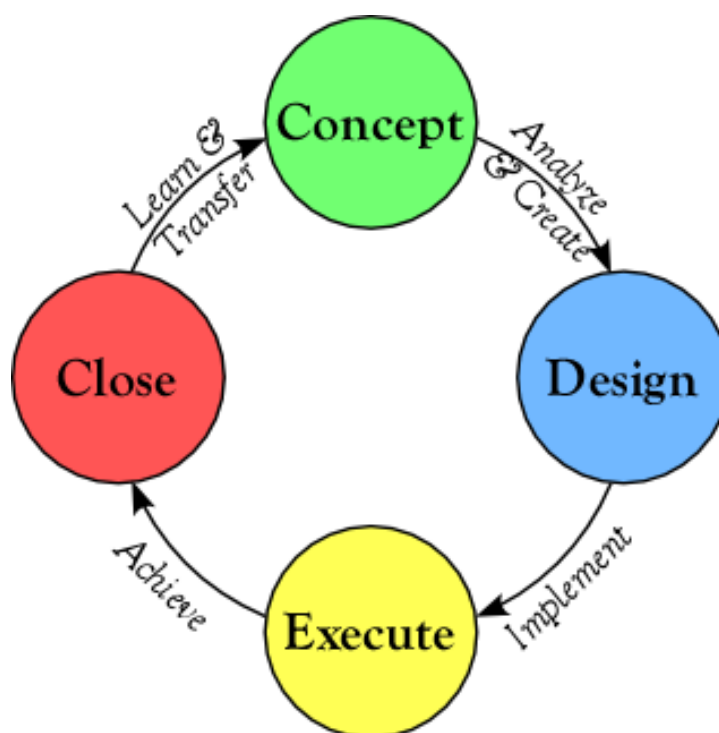


Figure 91—Well interception process cycle

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 one in which each new input, whether it is data or the findings from an investigation, must be analyzed and evaluated to ensure the plan continues to be one that creates success. Ultimately, a comprehensive and robust project plan is produced for the execution phase of the project ([Figure 92](#) and [Figure 93](#)).

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 objectives
- Define the intersection/kill points
- 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 locations
- 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 and intervention wells
- Define the kill/P&A/remedial equipment and kill/P&A/remedial procedures

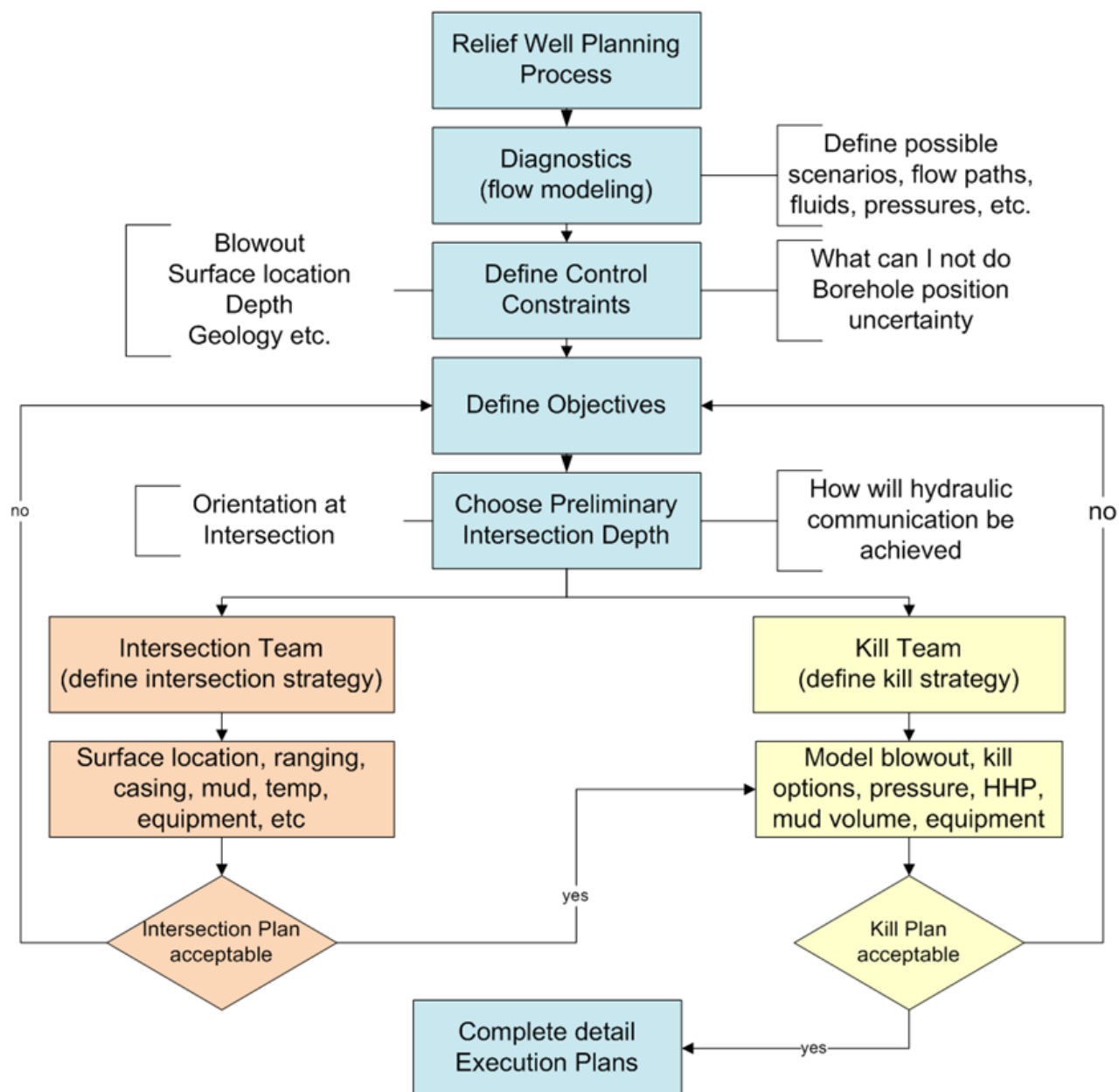


Figure 92—Summarized wellbore interception planning steps

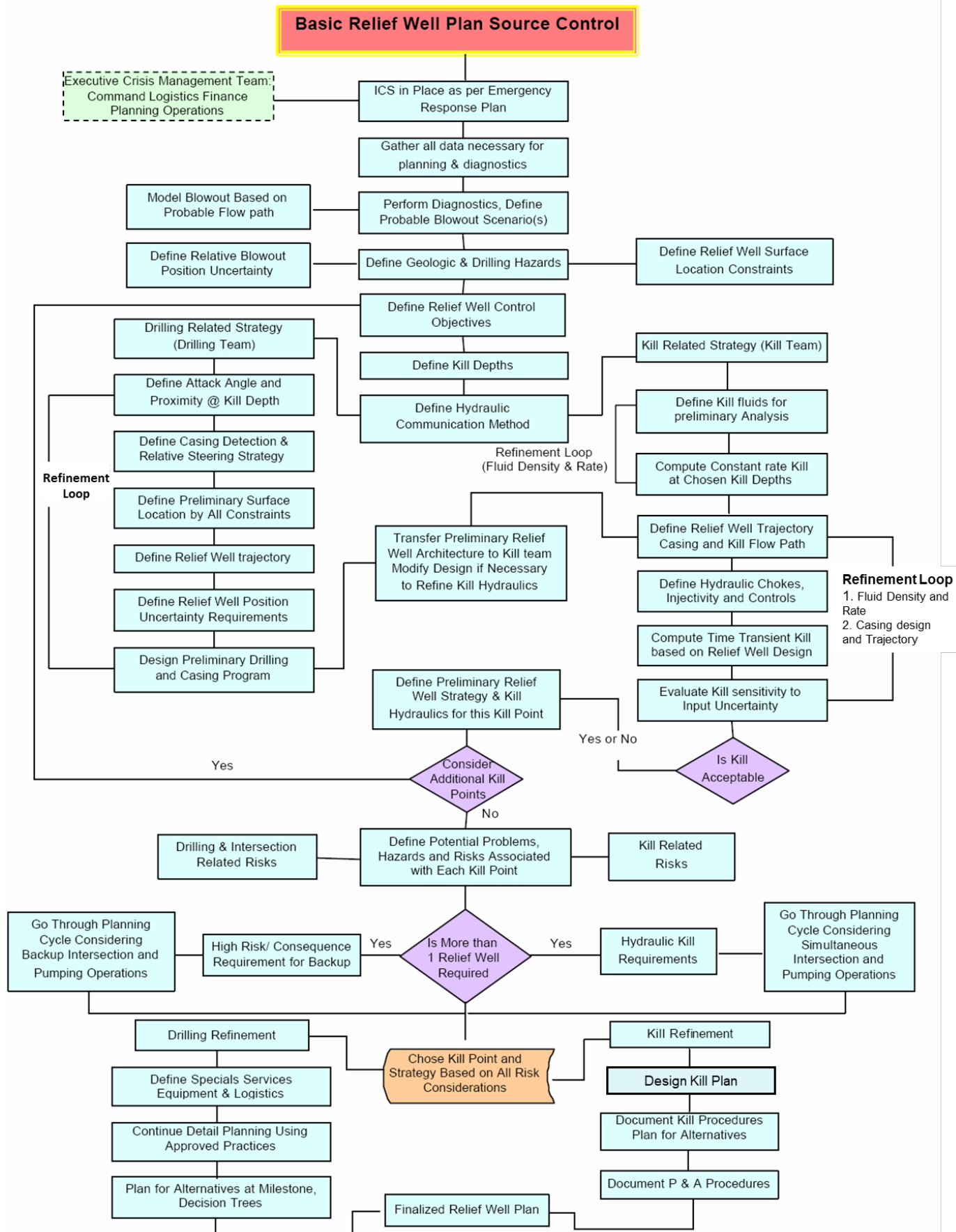


Figure 93—An example of detailed relief well planning process

8.4.3 Locating Phase

Locating the target well requires suitable ranging techniques. Positive detection requires deriving the relative position between the relief and target wells by measuring the distance and direction from the relief well to the target well. The Phase 3: Locate phase, as shown in [Figure 94](#), 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 EOUs and the expected ranging detection distance. In the worst-case scenario during which 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. Therefore, it is important to closely monitor the potential magnetic interferences by analysing the available raw data (near-bit direction and inclination packages, measurement-while-drilling), 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 will likely 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.).

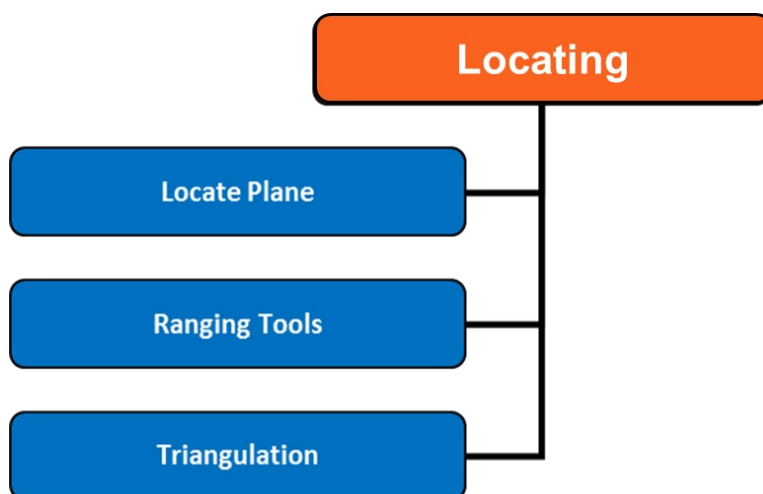


Figure 94—Locating, ranging technology selection for optimizing target wellbore detection

Phase 3, the Locating phase, defines the directional drilling parameters and an initial well trajectory, such as using magnetic ranging technology. This locates and “flies by” the target wellbore at a specified distance of +/- 300 m (+/-1,000-ft) MD above the intended intercept point, taking precautions to avoid an unintended collision.

[Figure 95](#) shows an example of key element tasks and responsibilities and [Figure 96](#) shows ranging decision flowchart in Phase 3, Locating phase.

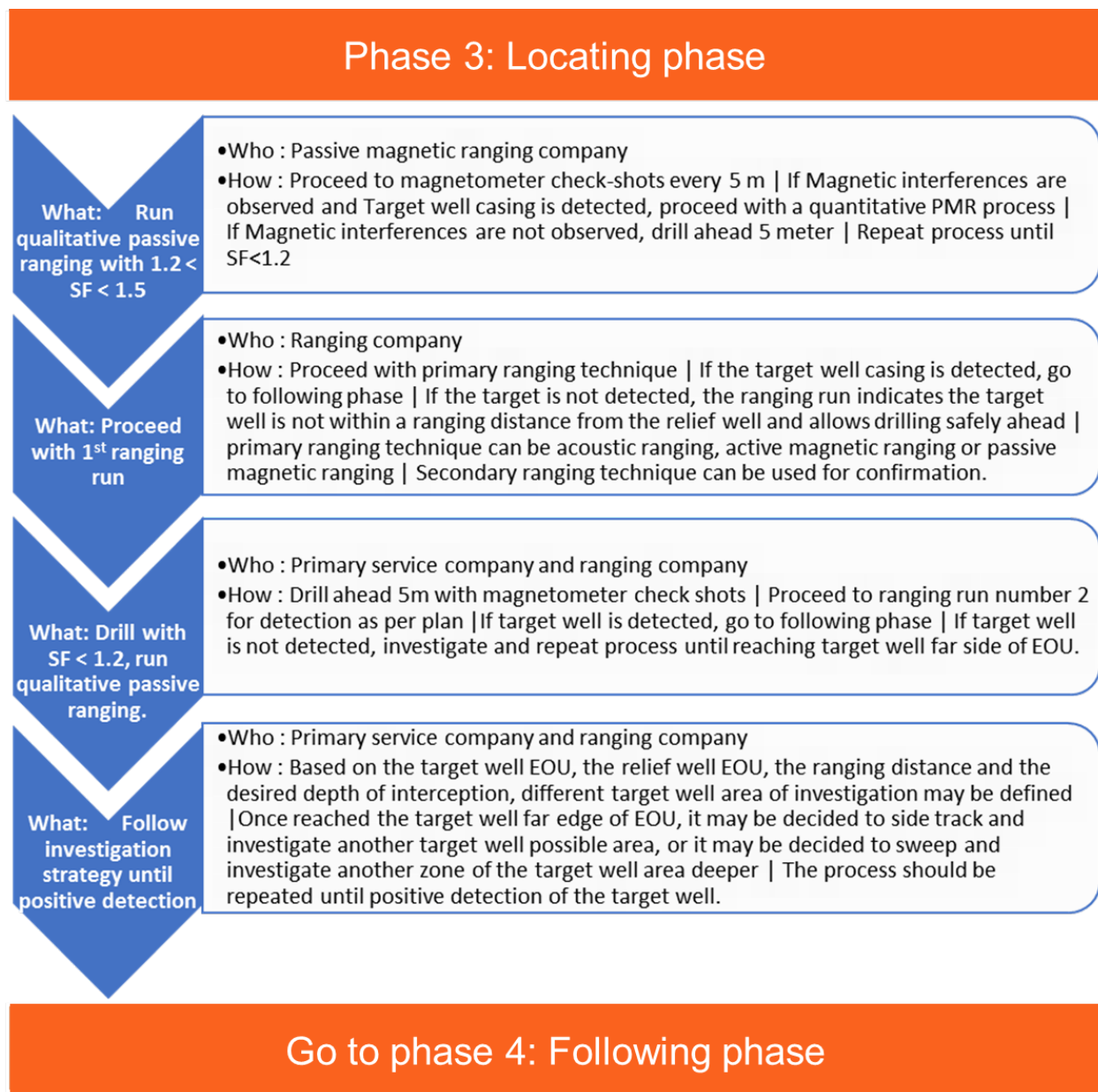


Figure 95—Phase 3: Locating phase key tasks and responsibilities

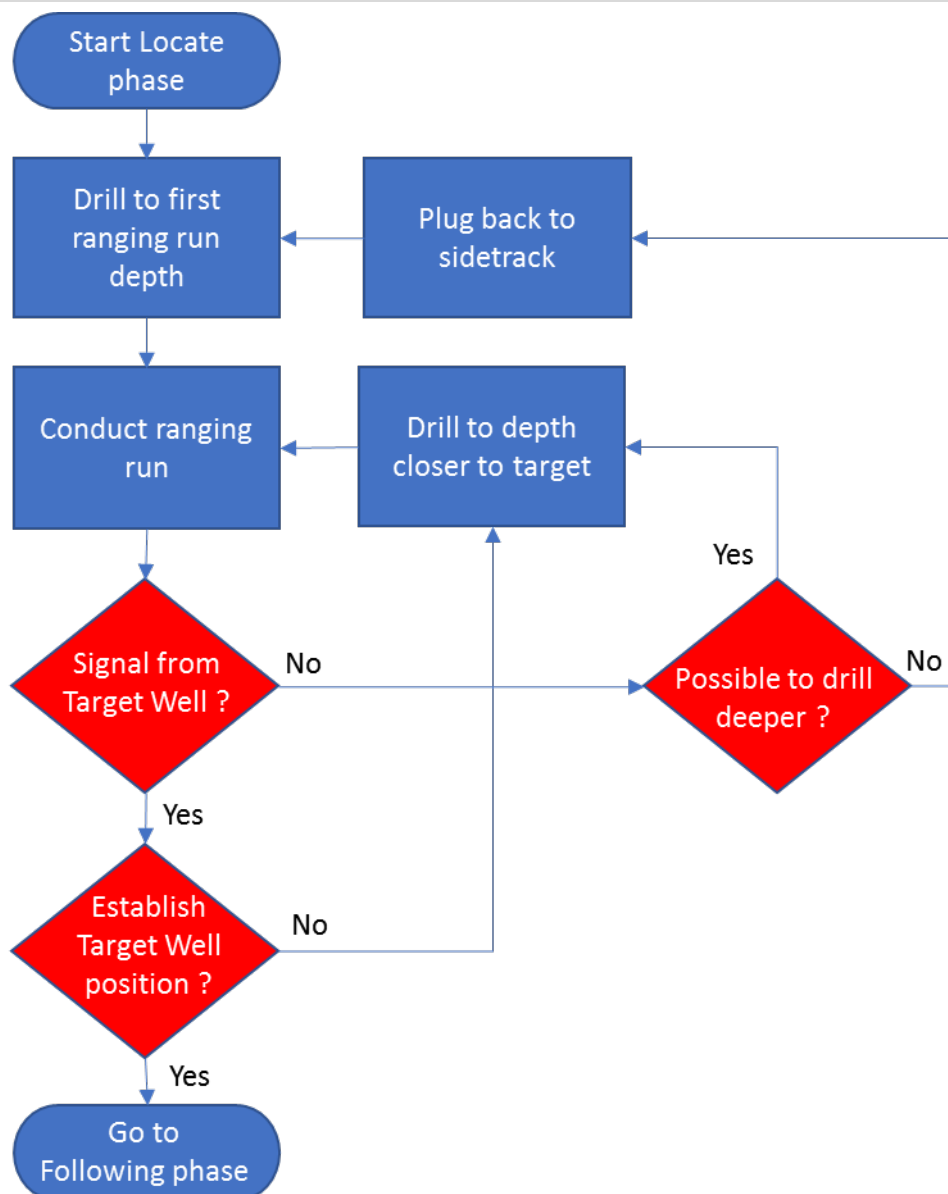


Figure 96—Locating phase ranging decision flow chart

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.
- Ellipses of Uncertainty of the target well and relief well.

Typically, the first ranging run will take place just as the entire EOU of the target well falls inside the modelled detection range. This can be safely done if the separation factor remains higher than 1.

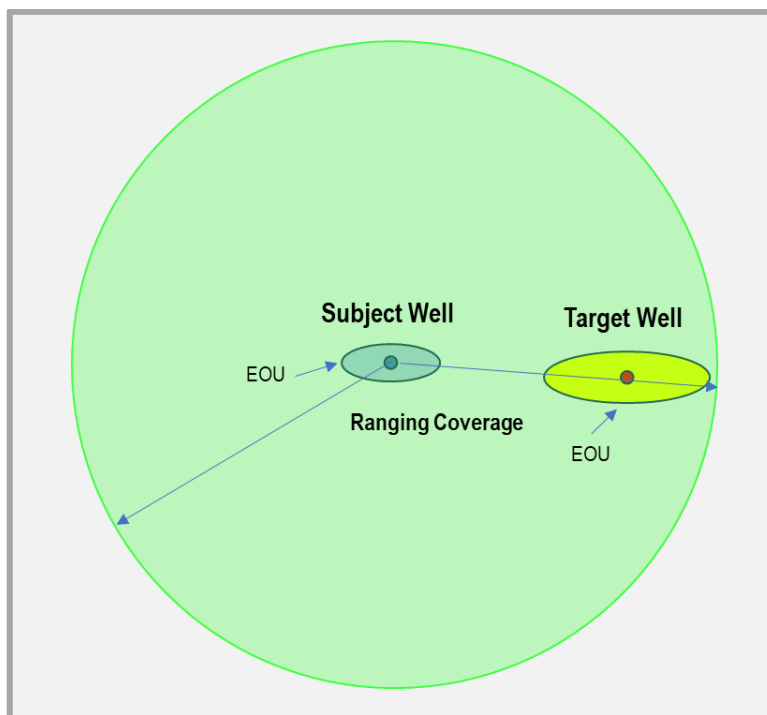


Figure 97—Ranging tool detection range

The first run may be used as an anti-collision run that could take place outside the expected detection range ([Figure 97](#)). Ranging at this point will determine if the target well falls within the drilling/relief wellbore EOUs, which could potentially cause an accidental interception. Completing this ranging run will allow drilling to continue without the risk of accidental collision. [Figure 98](#) illustrates an anti-collision run with the target well and relief well in the center of their ellipses and detection is less than the center-to-center (c-c) separation of the wells.

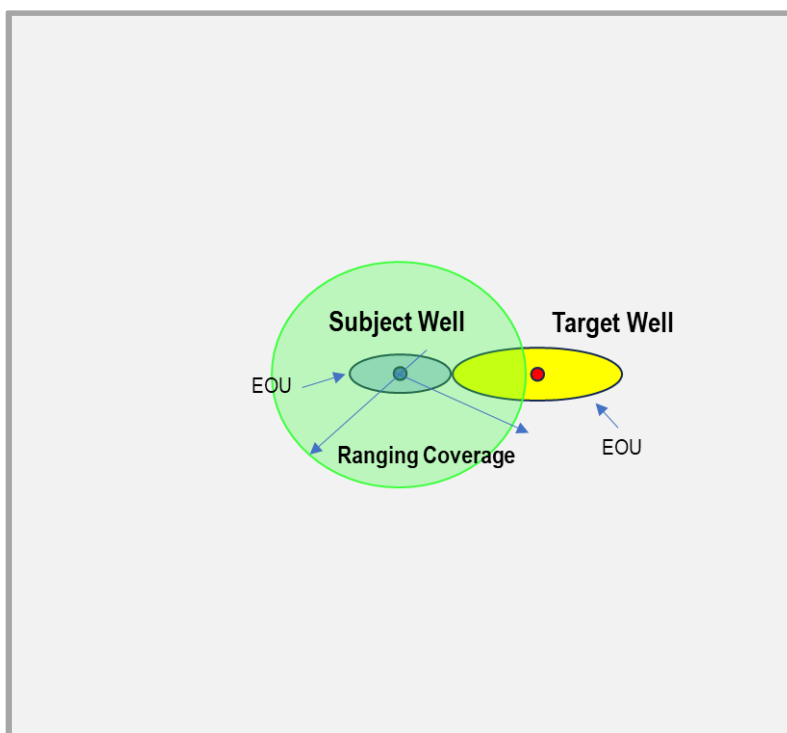


Figure 98—Anti-collision run

As shown in [Figure 99](#), once a ranging determination is complete, the results are reported in the ranging report as a direction and distance that have an associated uncertainty.

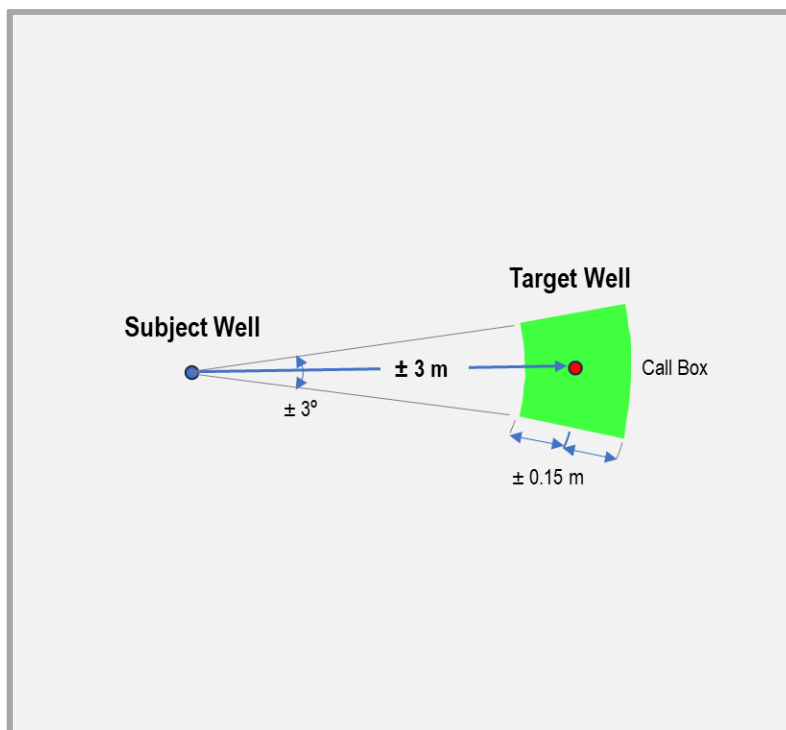


Figure 99—Ranging call with a direction of $270^\circ + 3^\circ$ and a distance of 3.0 meter + 0.15m

8.4.4 Following Phase

The objective of the Phase 4, Following phase ([Figure 100](#)) 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, which optimizes the ranging strategy.

However, the close proximity means that the relief well can suffer from the magnetic interference of the nearby casing, especially in cases when 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 BHA description, sliding or steering sheets, and drilling parameters.

In addition, given that the close proximity can raise some sensitivity risks that 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.

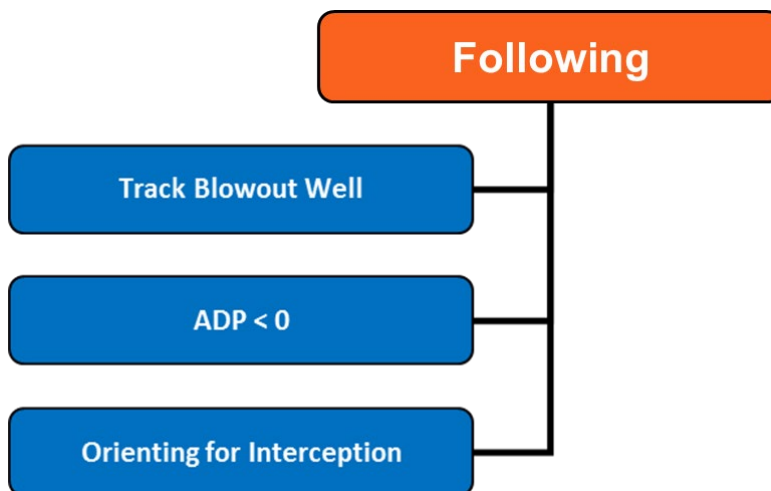
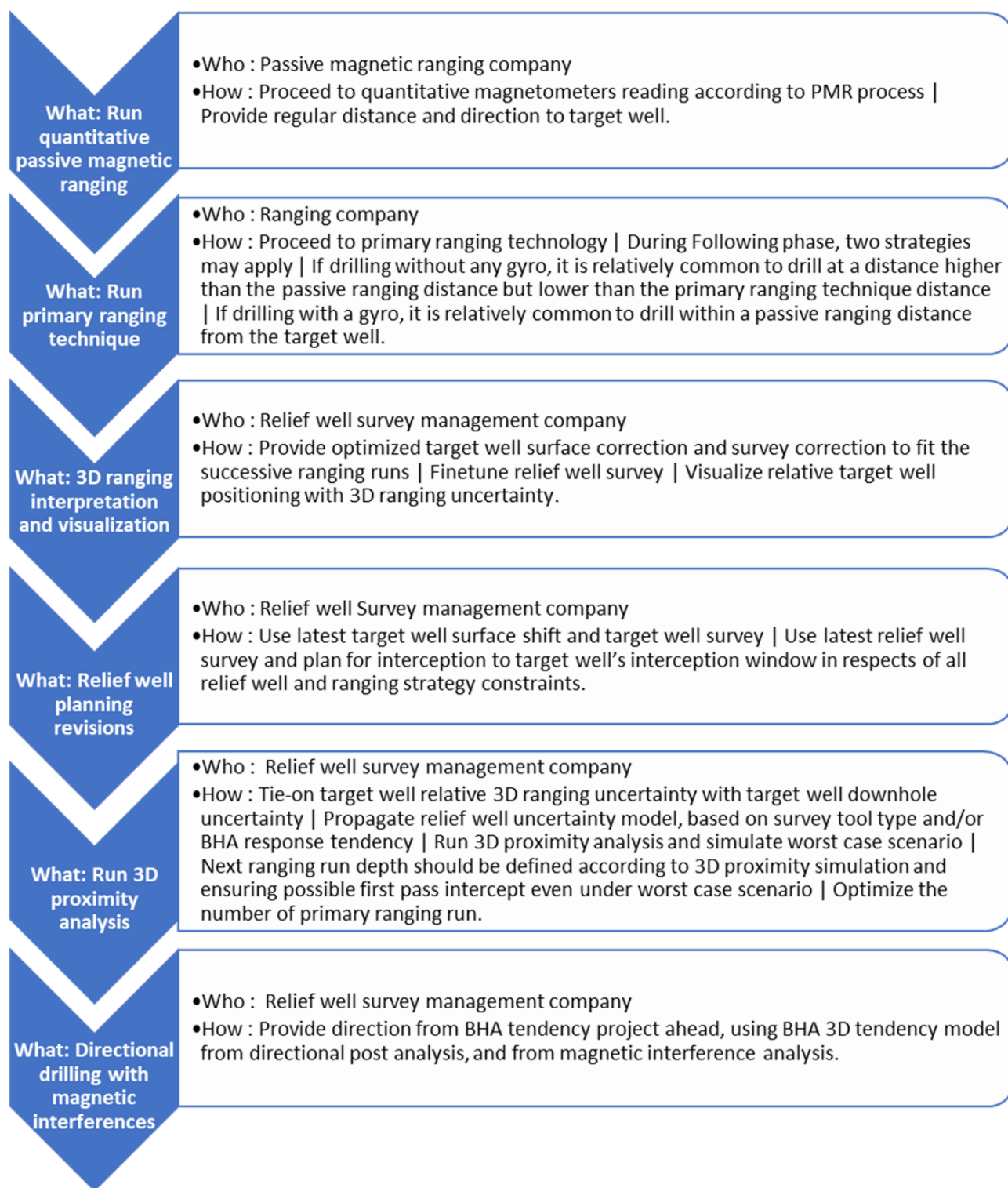


Figure 100—Following, ranging techniques selection & methodology for tracking to the required interception depth

During Phase 4, the Following phase, the well trajectory is designed so that 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 +/- 30-m (+/-100-ft) MD above it.

[Figure 101](#) shows an example of key element tasks and responsibilities and [Figure 102](#) shows ranging decision flowchart in Phase 4, Following phase.

Phase 4: Following phase



Go to phase 5: Intercepting phase

Figure 101—Phase 4: Following phase key tasks and responsibilities

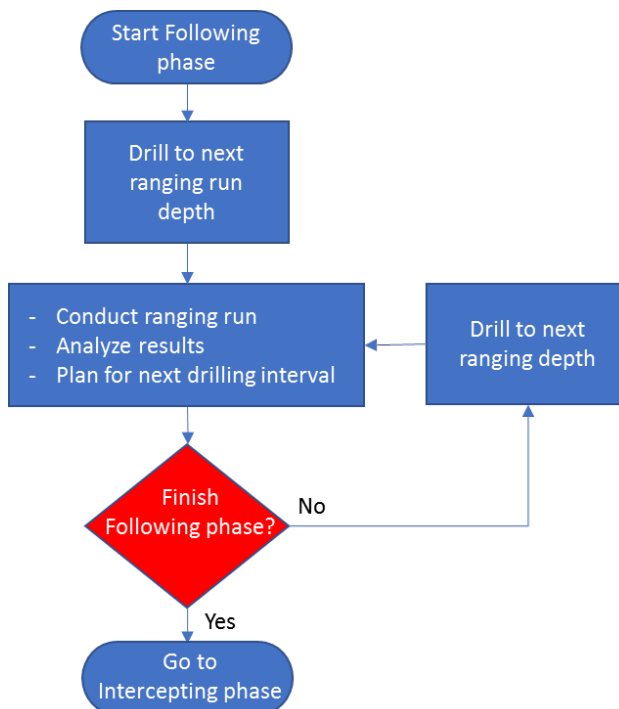


Figure 102—Following phase ranging decision flow chart

8.4.5 Intercepting Phase

As shown in [Figure 103](#), Phase 5, the Intercepting phase is the final objective in drilling a relief well, i.e., intercepting the target well. The interception angle depends on the communication option chosen—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.

The 3D reverse ranging engineering process allows modification of the target well surveys to correspond to the ranging calls to 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 ensuring a successful intercept on the first attempt.

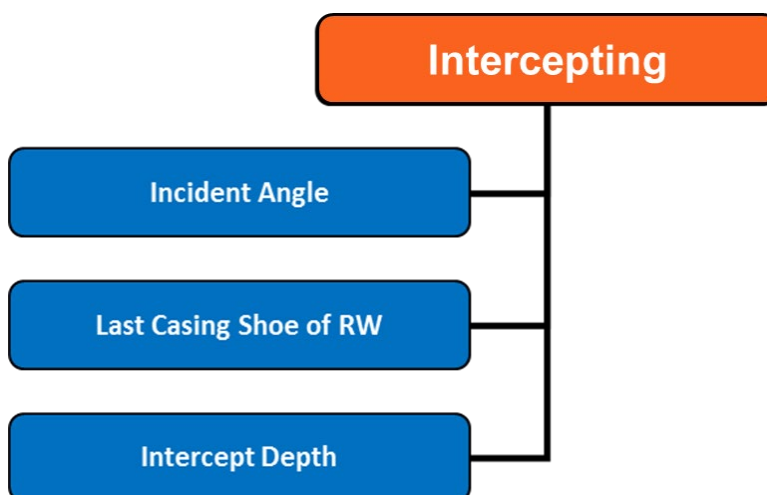


Figure 103—Intercepting, techniques and methodologies to allow positive interception

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

[Figure 104](#) shows an example of key element tasks and responsibilities and [Figure 105](#) shows ranging decision flowchart in Phase 5, Intercepting phase.

Phase 5: Intercepting phase



Go to phase 6: Killing operations

Figure 104—Phase 5: Intercepting phase key tasks and responsibilities.

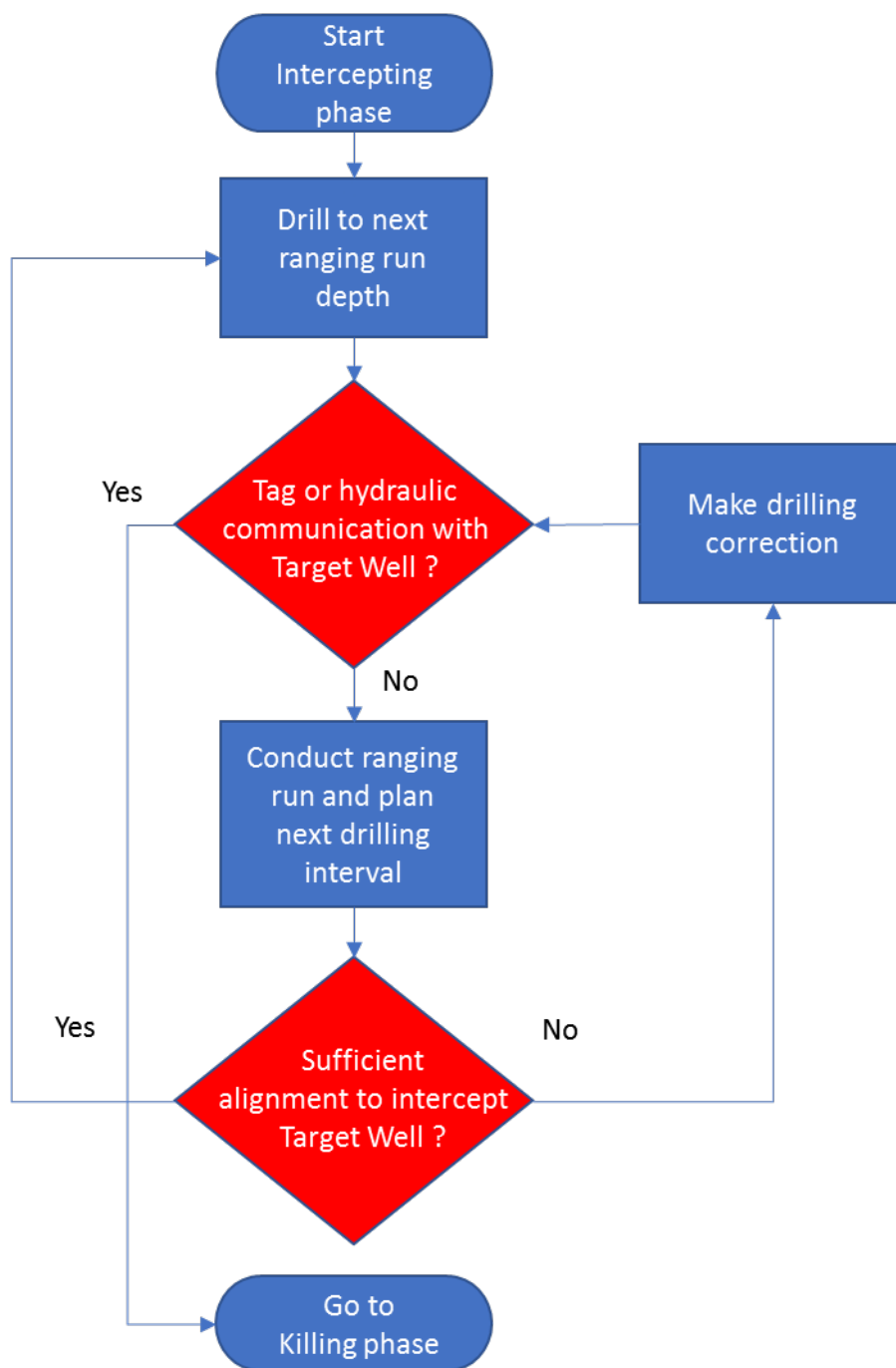


Figure 105—Intersecting phase ranging decision flow chart

As shown in [Figure 106](#), following the Locate phase using magnetic ranging technique, a “pass-by” (also known as a “fly-by”), 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.

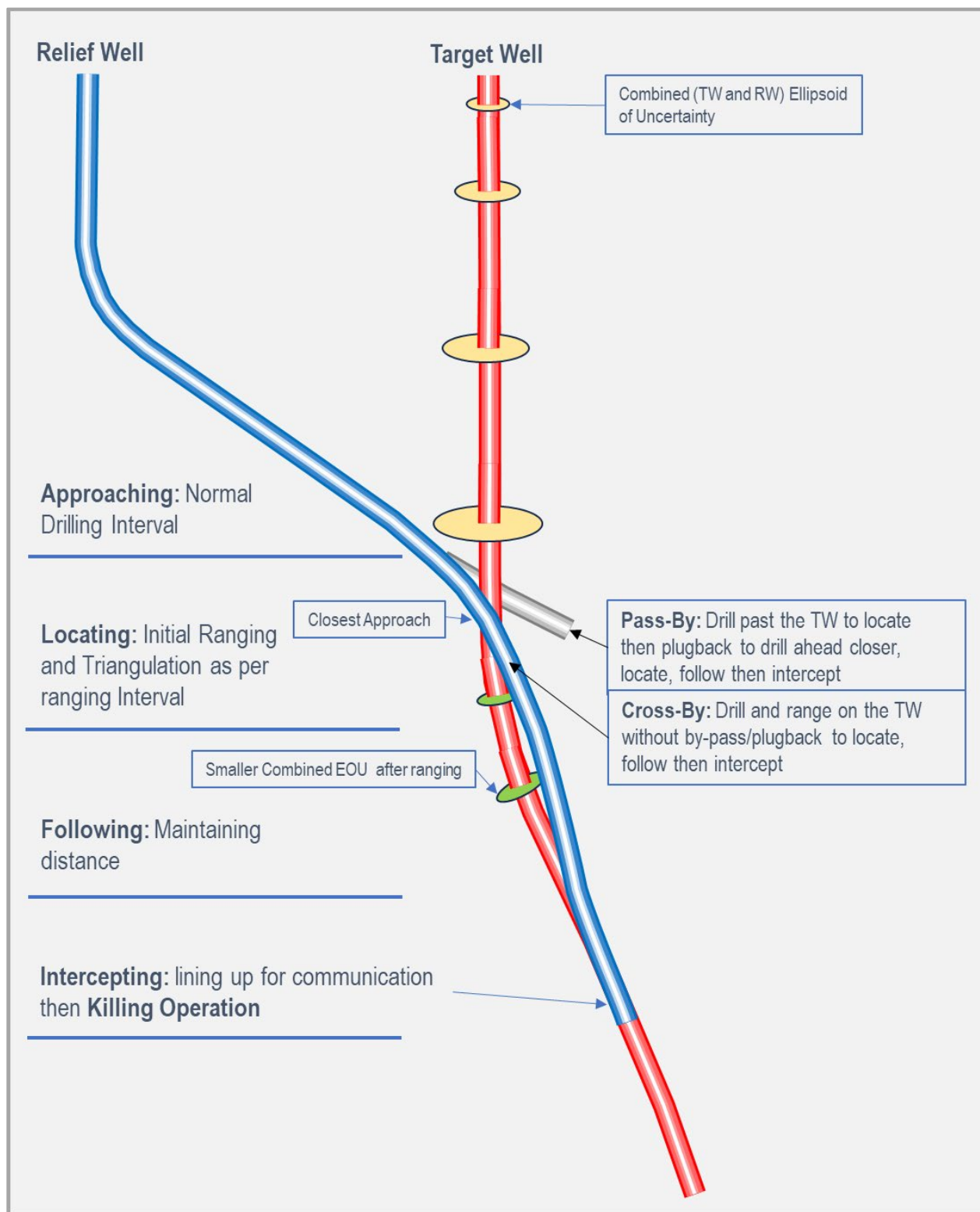


Figure 106—A diagram depicting a general breakdown of relief well elements

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). [Figure 107](#) shows the center-to-center distance plotted by measured depth target well as reference.

In well intercept strategies, planning for less complex 2D profiles is often preferred.

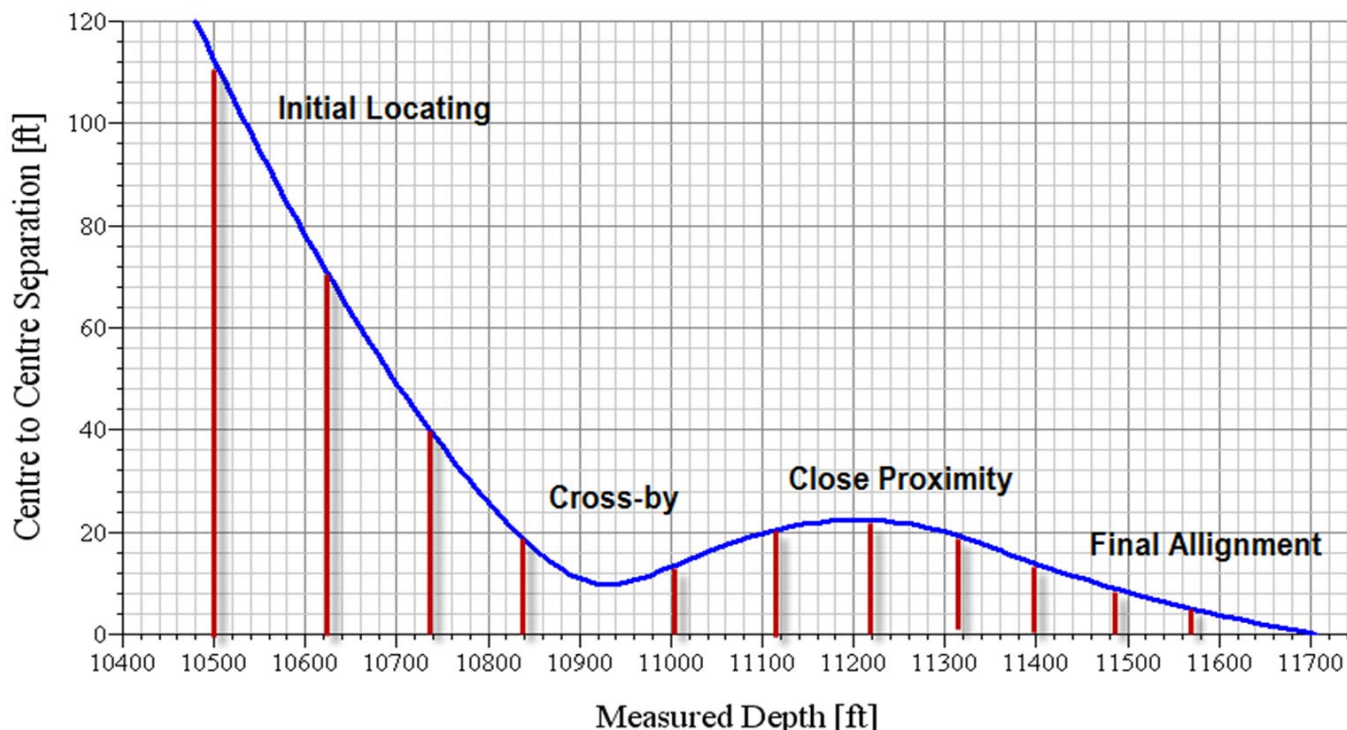


Figure 107—An example of relief well center-to-center distance to the target well plotted by measured depth

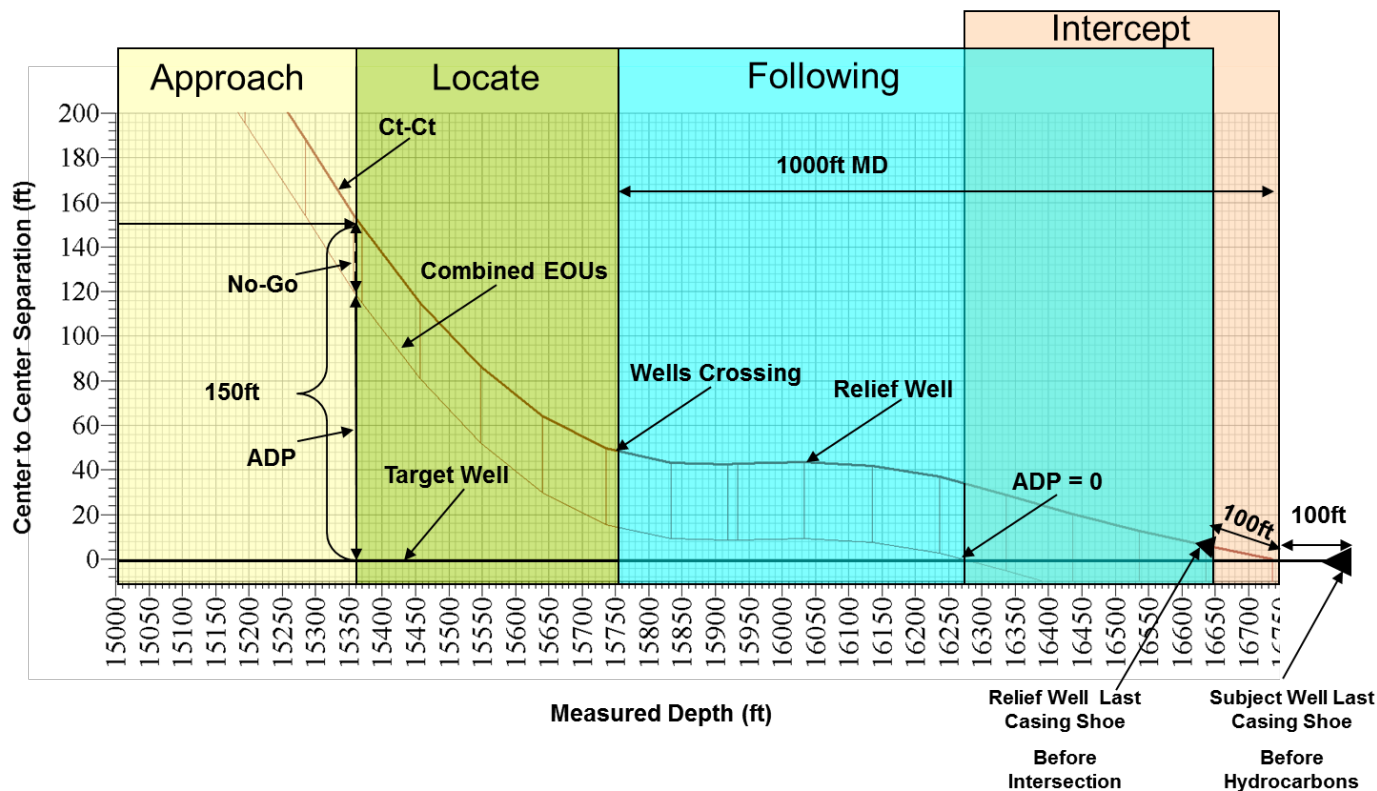


Figure 108—An example of GOM relief well ladder plot, center-to-center distance to the target relative to the relief well. Based on MWD+IFR+MS Surveys and BP Major Risk Criteria for the EOU calculation

Figure 108 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. Because current active magnetic ranging technology is not capable in the pure salt body, the plot shall also include markers indicating the top of salt (TOS) and base of salt (BOS).

For completeness, additional information from the data gathering while drilling can also be included in this plot. For example:

- TOS and BOS – to determine ranging interval
- Sail angle of the Relief Well <math>< 50^\circ</math> unless intercept point is shallow
- Pass-by angle at the Locate Point
- EOU at the last casing shoe prior to intersection
- Intersect Angle <math>< 5^\circ</math>

8.5 Relief Well Survey Management

Relief well Survey Management (SM) is a key component of a successful ranging and intersection plan. Every effort should be employed to increase survey accuracy to increase chances of a successful wellbore interception. SM services include ground shots to correct local declination errors and multi station analysis (MSA) to increase the accuracy of the surveys by the mitigation of instrument biases. Improving survey accuracy will reduce the EOU, which in turn will reduce the number of required ranging runs. For the locate phase of the relief well plan, SM will extend the depth to which drilling can continue before starting the first ranging run. SM may also include such services as IFR1 services, in which local crustal affects are taken into consideration and IFR2 services, or localized magnetic field variometer monitoring, to exclude diurnal “noise” from extended PMR operations.

8.5.1 Gyro Survey Requirements

There can be a combination of factors inherent to drilling a relief well that impact the survey and ranging accuracy of magnetic survey tools. First, the proximity to the target well casing causes interference on the magnetometer sensors (used for magnetic ranging), thus causing a degradation in absolute azimuth accuracy. Second, drilling at low inclination angles makes it challenging to derive a reliable high-side or gravity toolface since the non-axial accelerometers are perpendicular to the Earth’s horizontal plane. A solution to both issues is to use a gyroscopic survey sensor to detect the Earth’s rotation and produce a gyro toolface of the sensor’s orientation as well as the true north azimuth direction of the BHA (Figure 109).

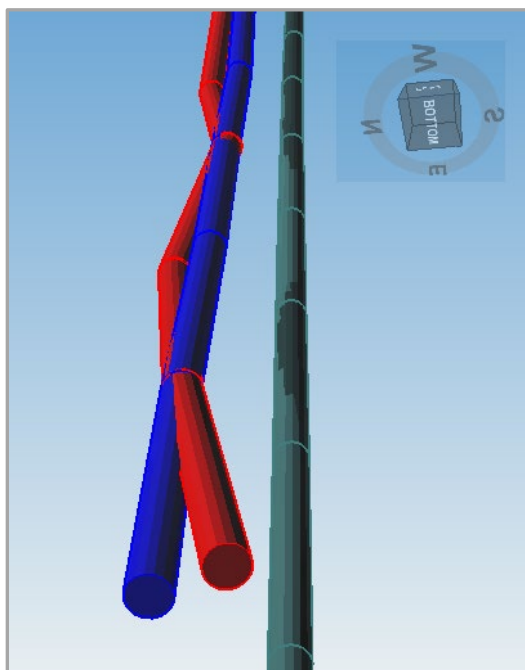


Figure 109—Ranged position of the drilling well (magnetic orientation – red, gyro orientation – blue) relative to the reference offset well (teal). Interference on the magnetic azimuth and high-side leads to unreliable ranging results.

To further explain the method of integrating gyroscopic data (Figure 110), Figure 109 presents a scenario where the Active Magnetic ranging tool is at 2° inclination and in proximity to the target wellbore. Magnetometers are unable to produce

an accurate azimuth direction because of the amount of magnetic interference from the target well. Ranging data at low inclinations is referenced by azimuth-to-target. However, the direction derived from the ranging shot is not accurate due to the inability to derive the correct magnetic toolface orientation of the sensor array, again due to interference from the target wellbore. Using a gyroscopic sensor module unaffected by magnetic interference fixed to a known orientation relative to the magnetic ranging sensors, it is possible to know the gyro toolface direction, thus enabling identification of an accurate azimuth-to-target.

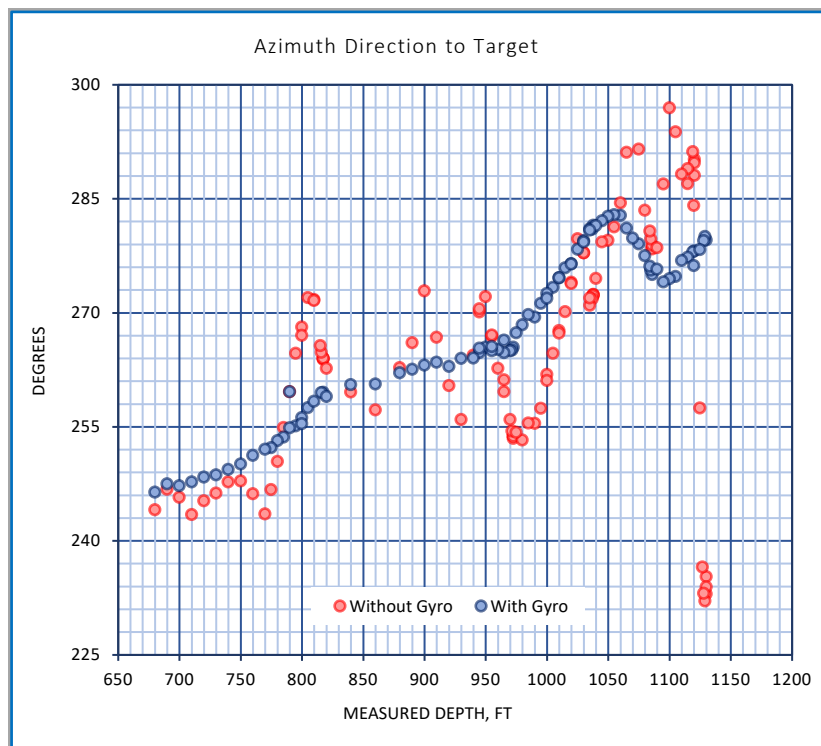


Figure 110—Azimuth direction to target ranging data including the gyro measurements and without gyro measurements at < 2 deg inclination

This problem commonly exists in relief wells since there can be a significant drilling interval that is near-vertical and parallel to the target well. Previous methods adjusted the trajectory of the relief wellbore while drilling to enable gravity tool faces to be derived. However, by combining technologies the issue is eliminated, producing a relief well with significantly less tortuosity. The ranging azimuth-to-target data will result in a smooth curve more readily fit to the target well position.

By using a gyro sensor while performing wireline ranging, it is also possible to attain a snapshot of the hole direction on bottom to be used in the decision-making process. However, this cannot be mistaken for a definitive survey because the ranging assembly is normally in open hole and is not centralized. Other methods of running drill pipe and gyro surveying also can result in a non-definitive survey due to changes in position of the drill pipe above the BHA and usually do not consider sag corrections. The definitive survey is commonly the sensor located in the drilling BHA, which can be combined with a definitive gyro survey run after casing has been set in the wellbore section to reduce the wellbore positional uncertainty.

The gyroscopic survey should be included as part of ranging options. The implementation method should be assessed during the planning phase with the option to either deploy while drilling, utilizing Gyro While Drilling (GWD), or after drilling by dropping the gyro tool inside the pipe on the top BHA or standalone OH wireline run to get closer to TD. For while drilling applications, the placement of the gyro measured point (GP) above or below the MWD in the BHA needs to be carefully considered as it will impact the ranging geometry based on distance to the bit (See [Section 7.2](#)).

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 stakeholder's requirements and limitations.

It should be noted that relief well planning and operations are composed of two teams: Intersection and Well Control (Figure 59). 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
 - Analyze 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 and 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 EOUs 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 accommodate 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.
 - Distribute 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 operations progress, 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. The ranging plan and the surface location selection are inter-related and dependant on each other using restrictions in one to limit choice in the other, and vice-versa. This study encompasses all relevant information, relief well trajectory options, interception depth/TVD options, 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, resistivity and acoustic properties
- 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 and additional, beneficial recommended services

8.7.2 Ranging Run 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 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 at rig-site that will be involved with the ranging runs
- Summary
 - Ranging call including the dimensions of the call box
 - Surface shift of the target well surveys required to place the well in the center of the call box
 - May contain a short summary of the ranging results in achieving the current run objective
- Analysis
 - An explanation of the ranging data quality
 - Outline of which surveys were used for the relief well and target well
- Technique
 - Overview of the wireline run Including any issues with reaching TD or depth tracking
- Recommendations
 - Length 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 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 to be performed within the next 6 hours, plan versus results, and the plan of actions. The report's 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 as well as the P&A of the Target Well (TW). The intersections 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: 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 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 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, 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

Hydraulic communication usually follows achieving the intersection, whether open hole, cased or within a proximity target boundary. 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 ultimately washing out of the formation between two wellbores with water or acid. Typically, direct open hole intersections are the simplest and quickest methods for gaining 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, 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 perforations ([Figure 111](#)).

In the past, specifically designed relief well perforating guns have been used 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) may be built to test the actual perforating results.

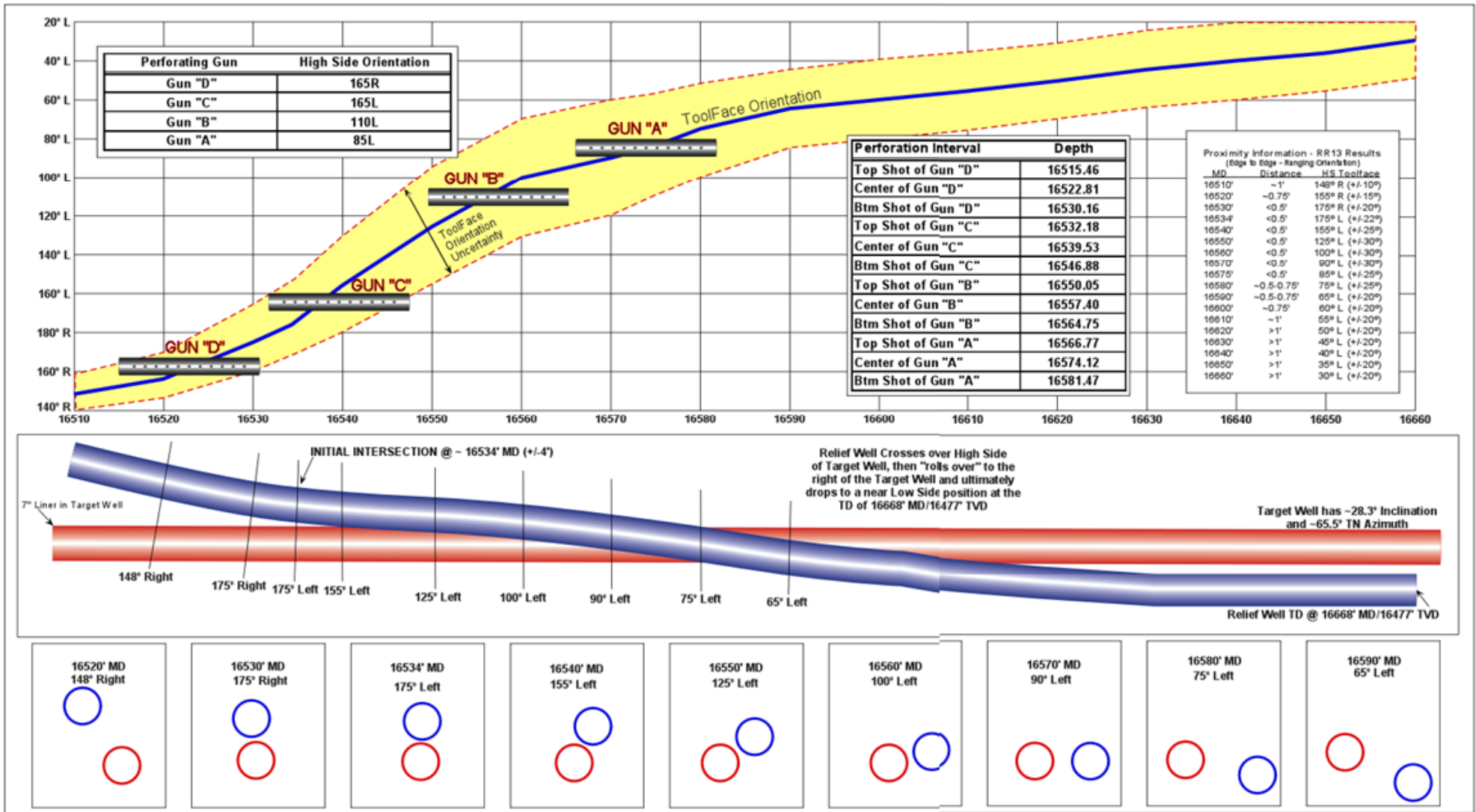


Figure 111—Example perforating method to establish hydraulic communication

9.2.3 Milling

Other methods for penetrating casing or other tubulars include milling with a mud motor or rotary bottom hole assembly, or by using a whipstock. Specially designed mills may be deployed to optimize tubular penetration and milling operation efficiencies.

Exact well alignment is imperative for any successful well-to-well (WTW) milling operations and precise incidence angle and centerline alignment are critical in preventing “rolling off” the TW tubular.

Project objectives may require a small hole of sufficient through-flow area (TFA) to allow well killing or plugging operations, or conditions may mandate that a “slot” be milled to allow casing re-entry to set or pull packers, plugs and other downhole assemblies. The presence of soft formations, centralizers, and high dogleg trajectories may further complicate these operations. To ensure WTW intersection in the face of these possible conditions and project objectives, accurate surveying and ranging techniques at the final alignment interval are essential.

Slot milling with a motor and mill have been performed successfully on previous projects ([Figure 112](#)). Whip-stock methods have been successfully used in WTW operations but may be hindered by such factors as whip-stock rotation, milling BHAs rolling off the whipstock, target-to-hole size ratios, high-strength casing grade, deep intersection points, and formation strength between the two wells ([Figure 113](#)).

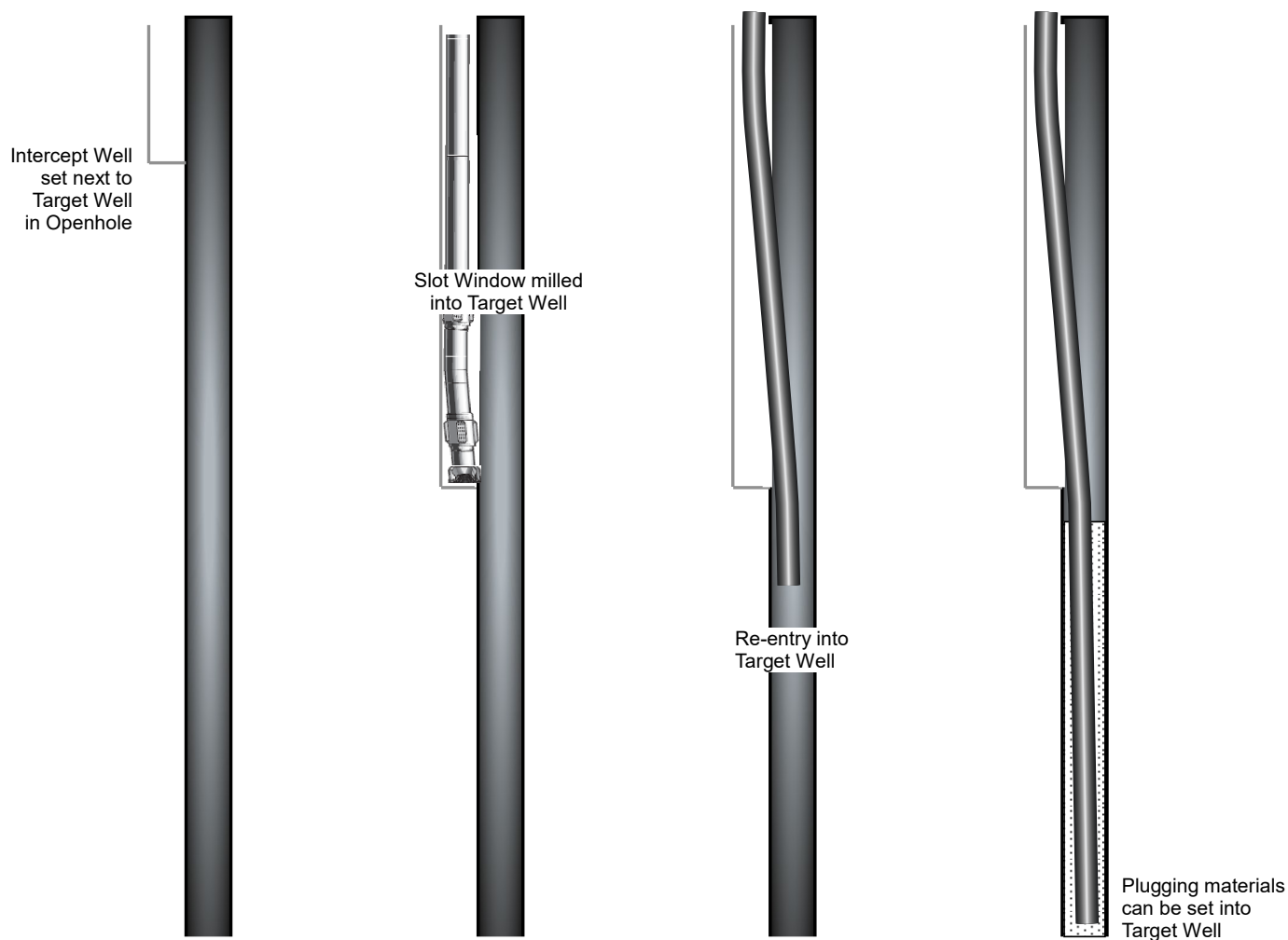


Figure 112—Slot milling method concept



Figure 113—Cased hole whipstock milling method concept

When planning milling operations at an intersection, operators must consider:

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

To achieve optimum milling performance, Concave Face Mills allow users to choose jet orientation, gauge lengths, and total length (Figure 114). Mill shoulder wear suggests that a ledge has been cut into the casing (Figure 115, left). Central wear and radial grooves on the mill face indicate horizontal displacement of the mill along the casing edge (Figure 115, right).



Figure 114—New Concave Face Mills. The orientation of the jets, the gauge lengths, and the total mill length are chosen based on targeted window length and actual incidence angle achieved at the point of contact. Then the milling parameters must be optimized to ensure effective milling performance. In most cases, multiple face mills are required when cutting through multiple concentric tubular strings.

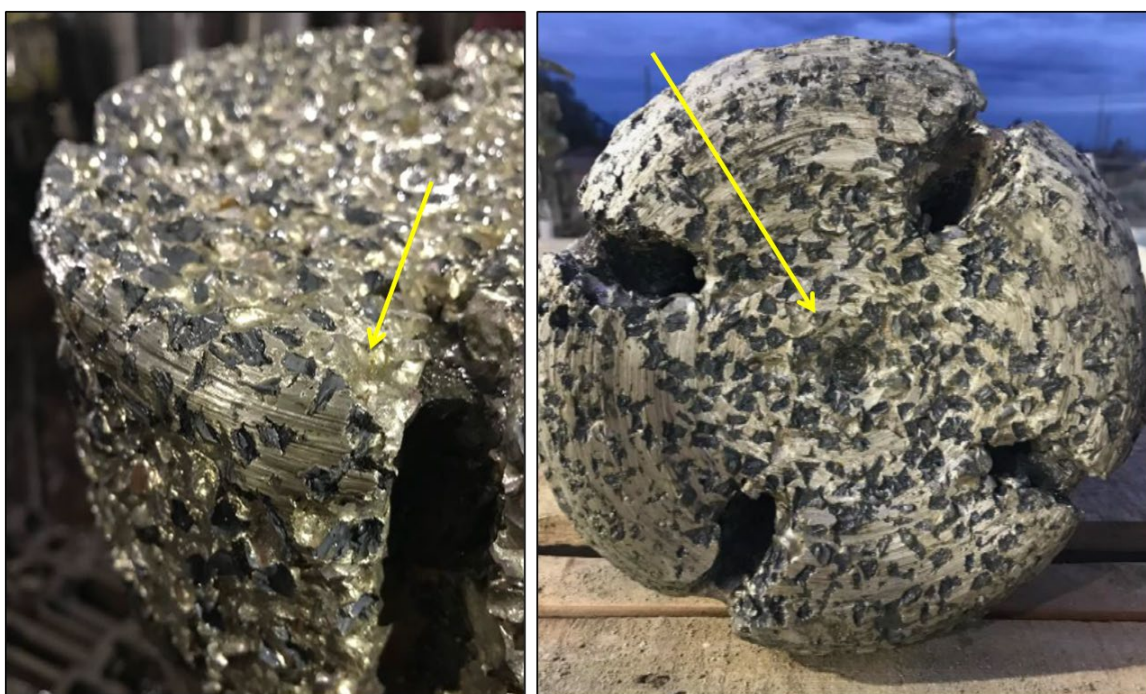


Figure 115—Shoulder wear on the mill shown along with surface milling data, suggest that a ledge has been cut into the casing (left). Central wear and radial grooves on the mill face indicate horizontal displacement of the mill along the casing edge (right).

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 be used to penetrate drill pipe or casing if the two wells are very close (usually <6-in 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 nozzles 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 and washed circumferentially.

Hydro-jetting is advantageous in the presence of a very limited intersection contact distance and the communication path must be made at a particular point because cutting nozzles are very close to the end of the tool string. This method has been considered as a secondary method in some situations where previous attempts were unsuccessful.

Also, in acid-soluble formations, acids can be pumped down hole to develop the final hydraulic channel through which to connect to the TW. And in the past, large volumes and high rates of water have been used to wash out a formation, 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 typically used in drilling and specialized tools. Specialized tools may include rotary steerable systems, steerable mud motors, and earlier style tools that may be more appropriate for the conditions.

Making the final intersection should be performed with tools that are not affected by the presence of magnetic tubulars, target well casing centralizers, or other adverse drilling environment conditions when drilling when uncertain about the 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 bottom hole location (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 and intervention well projects include:

- Enhanced well control equipment, such as larger diameter lines, additional BOP rams, drilling spools, RBOP.
- Large diameter, deep-penetrating perforation equipment
- Specialized plugging materials, such as GUNK, sodium silicate, polymer LCM
- High-pressure pumping equipment for hydro-jetting, fracturing, and well killing operations
- Specialized milling equipment, such as whipstocks

9.4 Killing Operations Phase

Following the successful intercepting phase, the first step of Phase 6, killing operation phase, shown in [Figure 71](#), is to successfully establish communication between the relief well and the target well by hydraulic communication, milling, or perforating. In this last 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.

[Figure 116](#) shows an example of key element tasks and responsibilities in Phase 6, Killing operation phase.



Figure 116—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 flow. The kill mud properties are defined at the planning phase based on killing simulations. Density, volume, flow rate, pressure, hole size and other fluid and pumping specifications are taken into consideration for a particular intersection point.

Modelling for these killing simulations can be complex with the goal being to establish pressure above the intersection point that is sufficient to counteract the pressure below the intersection point while maintaining the stability of the formation in both the relief well and the target well. The mechanism for achieving this is hydrostatic head, which is building a fluid column of the mud pressure that is higher than the reservoir fluid pressure. Some considerations for modelling in the planning phase of kill mud are shown in [Figure 117](#).

Formation stability from the end of the relief well casing to the target wellbore intersection needs to be accounted for by taking into consideration the formation pore pressure and fracture pressure. If kill mud properties exceed the fracture pressure of the formation the mud may not reach the target wellbore and be lost to the formation or cause another well control incident. With regards to pore pressure, kill mud needs to be able to support the relief wellbore's integrity and prevent collapse to prevent another well control incident.

Relief wellbore hole size and length are also taken into consideration, primarily to account for frictional pressure losses resulting from pumping at high flow rates. Increased relief well length and decreasing wellbore size will increase frictional pressure, which can result in exceeding fracture pressure. Typically, hole size of the relief wellbore is the same size or larger than the hole size at the intersection of the blowout wellbore.

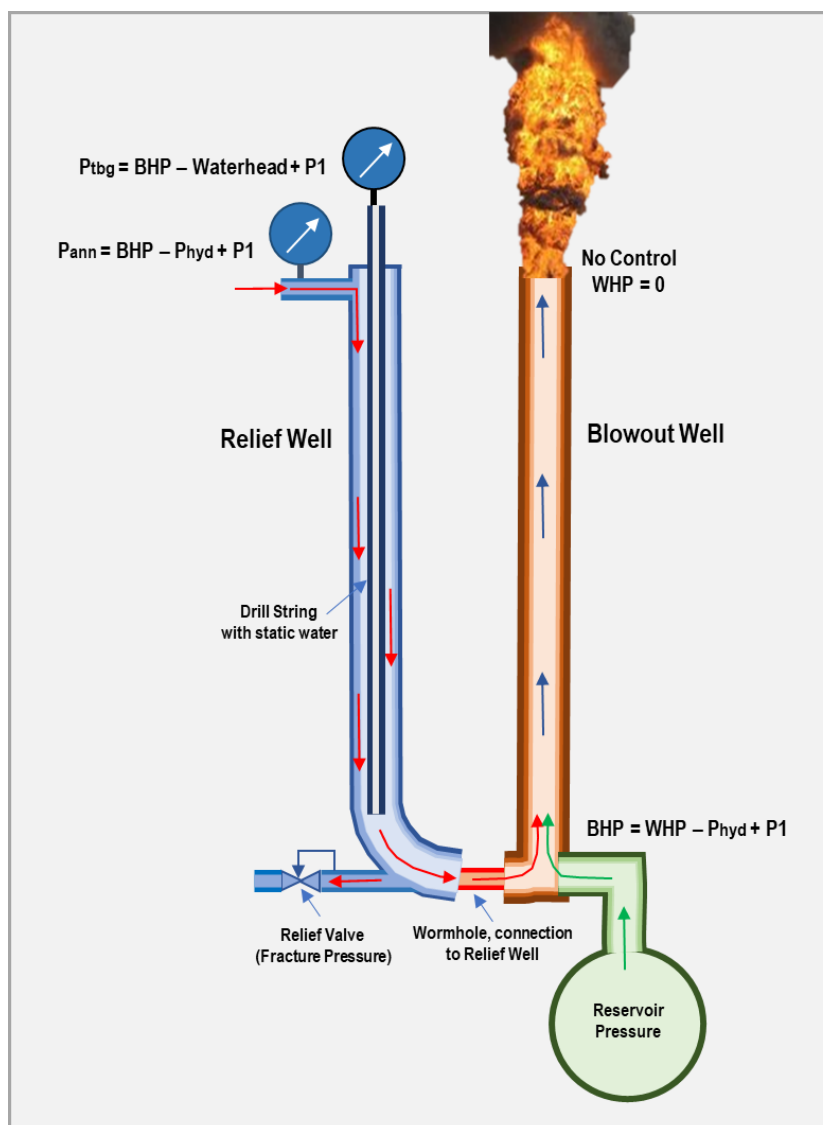


Figure 117—Illustration of the kill mud modelling in the planning phase

The number of reservoirs, reservoir fluid properties, mix of fluids, pressure and length and depth of the reservoirs are taken into consideration for modelling, as is the intersection location and angle of intersection; the higher the angle of the blowout wellbore the longer it takes to build sufficient hydrostatic head.

9.4.2 Stabilize Well

The objective of stabilizing the well process is to reduce 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 91, 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. In addition, in some cases bridge plugs may be required. Pressure tests are undertaken to ensure target well integrity.

An example of key element tasks and responsibilities in Phase 7 ([Figure 118](#)), Plug and abandon phase.

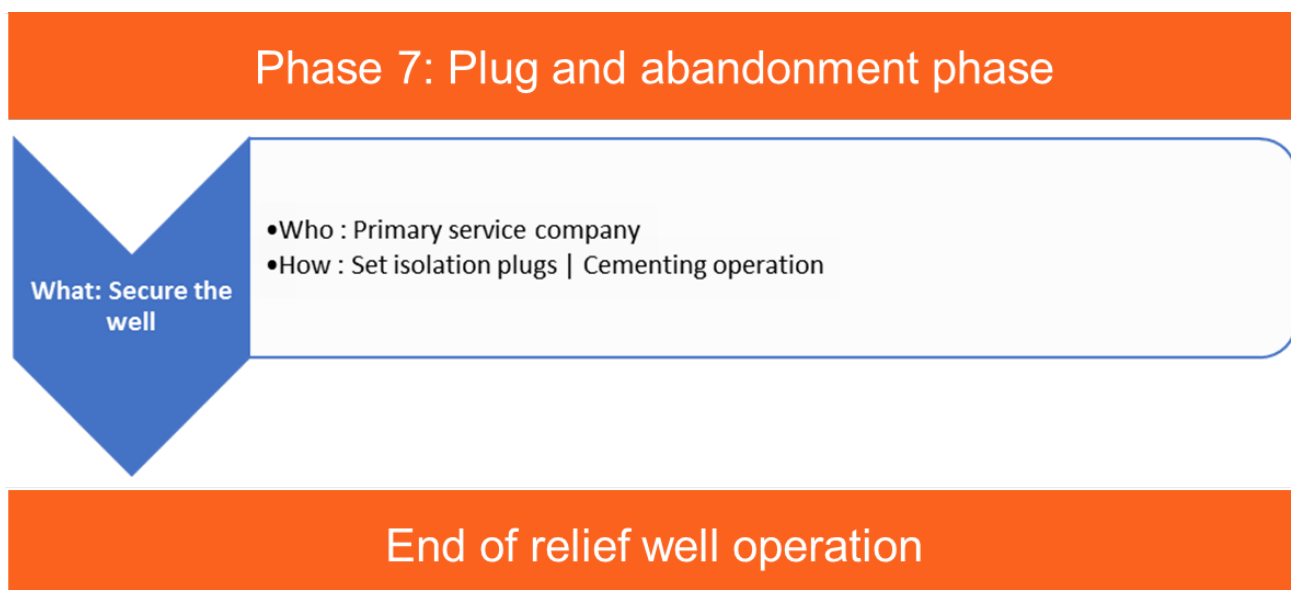


Figure 118—Phase 7: Plug and abandonment key tasks and responsibilities

9.6 Organization

With an average of only two or three relief wells completed per year, experience may be difficult to obtain. Whereas experience in blowout complexity is not necessary, intervention wells are drilled more routinely and more experienced personnel for this type of intersection are 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 that have 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 like 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 is responsible for all routine services for well construction design and delivery tasks. Typically, this branch is 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 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 includes gaining hydraulic communication between the relief and target well. 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 typically are led by this team include directional drilling, MWD, borehole and surface and subsea surveying, ranging, all related wireline, perforating, whipstocks, mills, and downhole tools.

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 119](#) shows an example of relief well team organization.

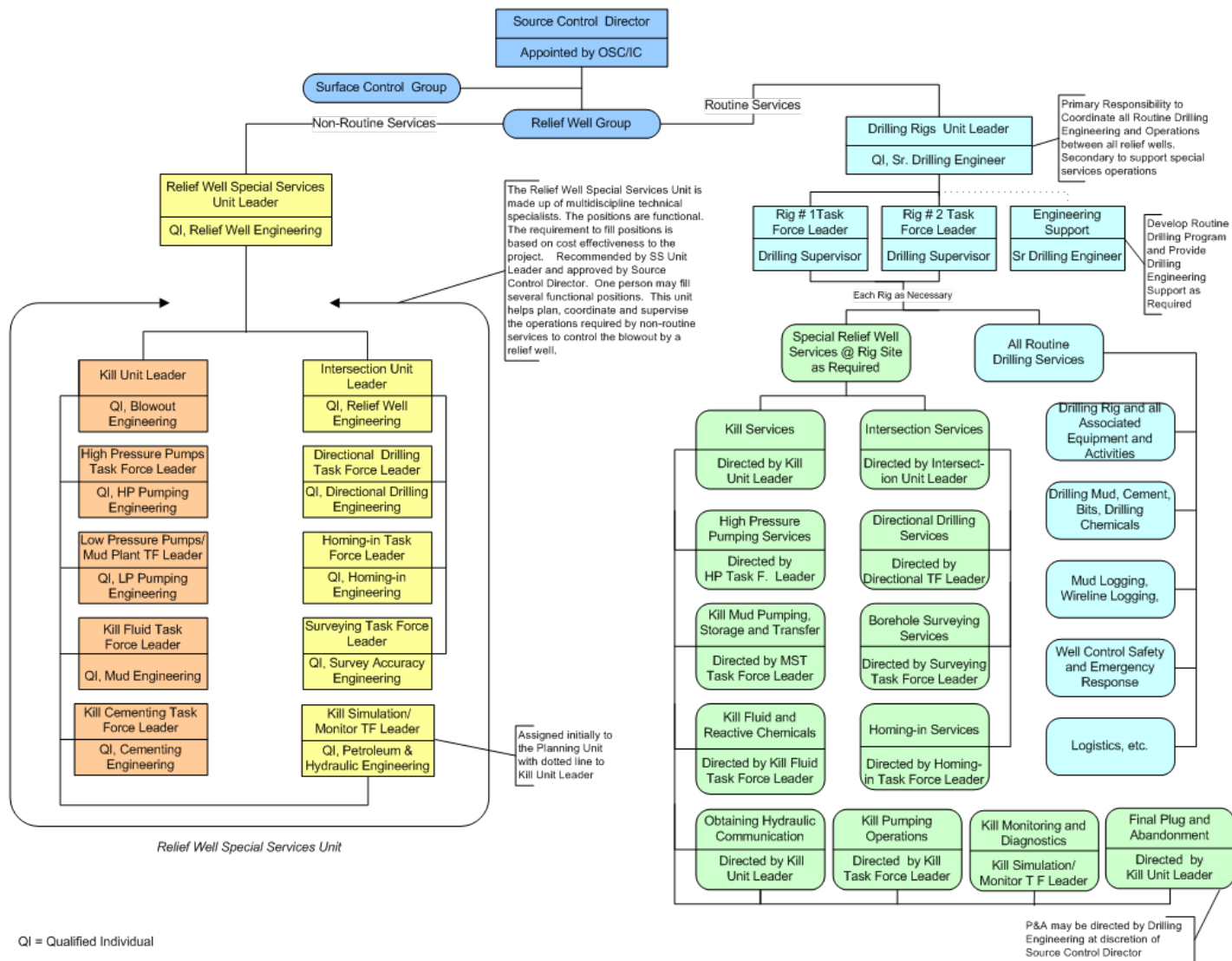


Figure 119—Example of relief well team organization

Appendix

A.1 Surface Intervention

Blowout control is often a two-pronged attack that involves surface intervention and relief well drilling operations simultaneously. Surface interventions are undertaken to create access to the wellhead for well kill and capping operations ([Figure 120](#)). This is usually the most expedient way to bring wells under control and to mitigate the safety, health, and environmental (HSE) impacts of an event. A relief well may be drilled to provide a conduit through which kill fluid can be placed in the blow out wellbore if surface capping operations are beyond acceptable risk, too lengthy, or deemed not likely to succeed.

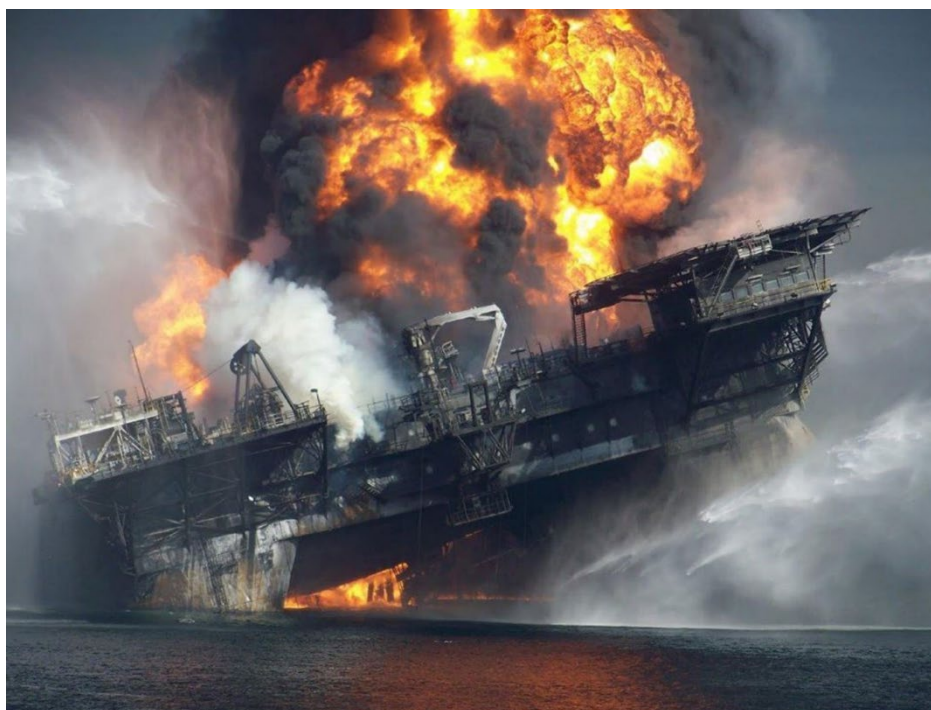


Figure 120—Deepwater Horizon blow out in Gulf of Mexico, April 20, 2010

In virtually all blowout events, surface blowout intervention is comprised of specific activities, including:

- Situation assessment
- Gaining wellhead access
- Installing new wellhead
- Capping and kill operations.

The situation assessment is performed to determine the nature of the flow and the most appropriate intervention method. For example, some blowouts can be killed by pumping operations without the need for capping the well.

Gaining safe access to the wellhead is essential to capping and kill operations and the primary activity of this part of the control effort typically involves debris removal ([Figure 121](#)). Debris removal includes cutting access-obstructing equipment and structures using mechanical shears, thermal lances, and rakes ([Figure 123](#)). After debris removal, high-pressure abrasive jet cutters and portable lathes can be used to remove damaged portions of casing and allow installation of a new wellhead ([Figure 122](#)).



Figure 121—Debris removal activities on the platform



Figure 122—Jet cutting operation to cut the wellhead. The position of the jet cutter below the lower-most leak (left) and the cross section of the cut afterward (right)



Figure 123—Rakes (right), are metal devices that may be attached to the end of the Athey Wagon to grab the debris and drag it away from the wellhead and surrounding area.

It is usually necessary to install or repair the wellhead when a well is on fire but is also required when wellhead failure is the underlying cause of the blowout. A new wellhead or wellhead components may be installed while the well is still flowing and is required to provide pressure containment for capping or killing the well ([Figure 125](#)).

Typically, before capping a well and after surface access is achieved, well control companies attempt to sting and kill a well unless it is known for certain that the sting will fail. Cap and kill operations can include a wide variety of options whose complexity ranges from relatively basic installation of a capping stack and shut-in of a well, to designing and rigging intricate high-flow rate diverting systems and killing the well via coiled tubing or snubbing operations.



Figure 124—Unrestricted and vertical flow of the gas after cutting the wellhead

These basic steps are valid for both land and offshore operations. In shallow waters, these surface intervention operations may also be conducted when the wellhead can be accessed from a fixed platform or jackup rig. In deepwater, capping operations are extremely complex but may still be possible, as proven by contractors at the Gulf of Mexico 2010 Macondo blowout ([Figure 120](#)).

Accessibility to the blowout well is key to determining whether capping and kill operations will be successful. If it is possible for well control specialists to physically touch the wellhead, the chances for a successful surface intervention are extremely high (>95%). As a result, relief wells are planned and implemented on only a small percentage of well control events.

If, for mechanical or safety reasons, access to the wellhead is impossible or even questionable, a relief well intervention should be implemented as soon as possible. A relief well becomes a major component of the control effort in certain situations, including:

- Offshore environments, in which drilling a relief well is the primary operation because safe access to the well is extremely complex and therefore time-consuming, especially for jackup and platform fires and subsea wells.
- Offshore or land wells that have cratered and lost wellhead accessibility, making it impossible to cap the well; the relief well intervention must be engineered so that the cratered well and the flow from it does not negatively impact the relief well operations.
- Pad drilling, which uses numerous directional and high-angle wells drilled from a relatively small location, or pad, which presents special challenges to surface intervention during blowouts. Wellheads on pads may be separated by as little as 10 feet, which provides certain economic and environmental advantages by greatly reducing location size but creates numerous surface intervention problems during well control events.
 - Because the wellheads on pads are close to each other, fire in one wellhead can result in collateral damage during which heat from one well damages adjacent wells and allows the fire to spread to multiple wells on the pad and extinguishing multiple fires becomes far more complex and time-consuming. In this case, a relief well, or multiple relief wells, may have to be planned and implemented owing to the complexity and resulting extended time required to deal with multiple well fires.
 - Wellhead proximity also creates difficulties placing flow control equipment in place ([Figure 125](#)).
 - Because pad wells are used predominantly for hydraulically fractured wells (US Land), kill fluid may be lost to the induced fractures, further complicating efforts to stop flow.



Figure 125—Cross-fire from failed wellheads intensified the operation complexity

- Wells with parted or damaged casing may require operators to drill a relief well to control the blowout. It is not uncommon for uncontrolled flow from a well to result in significant wellbore damage during drilling, completion, workover and production operations. This damage may prevent the implementation of a kill solution and require a relief well as the final well control operation.

A.1.1 Simultaneous Operations (SIMOPS)

When surface intervention and relief wells are implemented simultaneously, a high degree of coordination between the two operations is essential.

Operators often have emergency response plans that serve as a guide for handling blowout incidents and describe organizational needs for effective surface and relief well intervention. To bring the event to a successful conclusion, the well control team must make numerous decisions regarding the relief well and the capping and control operations. The control effort is influenced in many ways by decision-making in numerous areas that include:

- Location
- Surveying
- Pollution
- Timing
- Intercept
- Kill operations
- Post well-kill securing

A.1.2 Location

The relief well location must be chosen with the intent to ensure that the relief well and the capping operation have minimal impact on each other. Choosing the relief well location involves numerous factors. In land, mountainous or swamp environments, a location may have to be built. This can require extensive construction operations, such as dirt work or dredging. Additionally, access to each site in these scenarios may be limited to a single road or waterway, which makes decisions involving the movement of equipment and personnel a daily activity for the SIMOPS organization.

For offshore, the relief well location must be chosen so that it is not negatively impacted by the flow at the platform or an oil and gas boil on the sea surface.

Environmental factors will need to be considered in land and offshore situations. Historical weather data becomes important for creating offshore and onshore exclusion zones that must be considered for the relief well rig.

Surface operations can influence downwind hazards. For example, if the capping operation includes diverting the well, the burn pit location is important and the horizontal flow has a different impact on the environment than does the flow from a vertical well. This situation can be exaggerated if the flow will not burn.

A.1.3 Well Reference Position

Surveying of the relief and the blowout well surface location is vital to the success of the relief well directional drilling operation. For land operations, surveying the blowout well may require capping operations to be temporarily halted.

Offshore, moving the relief well rig onto location may also require suspending capping efforts. Placing surveying crews on the platform will require well control specialists that can ensure that the surveying activity is conducted safely. This also applies to land blowouts.

In deepwater, using ROVs to survey wellheads at the seafloor may take considerable time. This activity is very important and the SIMOPS team will need to adjust the schedule for all operations to expedite this phase of the control effort.

A.1.4 Pollution

Pollution control is important on land, inland and offshore blowouts and is a major SIMOPS activity. Moving equipment and working personnel inside containment areas offshore must be coordinated so that the timeline for capping and the relief well is not significantly impacted.

For land locations, containment ponds for oil and produced water may have to be quite large and it is imperative that they are in place before work on the blowout or relief well location is started. Drainage from the blowout site must be designed so that access to the relief well is not impacted. Water runoff from firefighting at the blowout must be included in pollution control efforts.

A.1.5 Timing

The goal of capping and relief well operations is to bring the blowout under control as quickly as reasonably possible. The SIMOPS team must coordinate activities at both sites using this goal as the guiding principle. Operator and well control personnel should discuss the likelihood of success in daily SIMOPS meetings.

The relief well is often suspended when it becomes evident that the capping and or kill operation will be successful. Conversely, if success of direct intervention at the blowout becomes less likely, the relief well may become the focus of the control effort. In these cases, it is important that the capping team is given ample time to configure the blowout well for a relief well kill if possible.

A.1.6 Intercept

When the relief well becomes the avenue for ultimate control of the blowout, the SIMOPS team must determine the required blowout site actions to prepare for the relief well intercept and kill. Before the intercept is made, the SIMOPS team may:

- place the well on divert.
- secure the site.
- perform fire suppression operations.
- expand pollution containment systems.
- suspend nearby production operations.
- protect nearby wells and infrastructure.

These activities may take considerable effort and time to complete. The SIMOPS team should anticipate a need for expediency to prevent the intercept being delayed. Once the intercept is made, the relief well and the blowout well are hydraulically connected. At that point, because of the u-tube effect from the relief well into the blowout well, delaying the kill operation is usually no longer possible.

A.1.7 Kill Operations

Because killing a blowout from a relief well usually requires detailed engineering, advanced software is often used to model the reservoir, flow path, fluid flow characteristics and kill operations. The time invested in pre-kill engineering, drills and readiness is highly beneficial when the actual well kill is done.

At the blowout well and at the relief well locations, it is safest to conduct kill operations during daylight hours. Observations of the reaction at the blowout site should be outlined and coordinated by the SIMOPS team.

Well control operations in the relief well must be carefully monitored and the potential for a kick must not be discounted. Because records reveal that relief wells have also experienced blowouts, all personnel should be on high alert once intercept into the blowout well is made.

Although observing surface conditions is necessary to determine the effectiveness of the kill attempt, operations at the blowout site are usually limited when the relief well kill is underway.

A.1.8 Post Kill Well Securing

After the blowout has been killed, the next operation is to secure the blowout well. Relief well intervention for a blowout presents the unusual situation in which two wells are hydraulically connected. This u-tube situation presents advantages and disadvantages in terms of well control because:

- circulation within the relief well can be limited or impossible.
- any work inside either wellbore influences both wells simultaneously.
- loss fluid zones in the blowout well influence the relief well.
- bridging in the blowout well influences the relief well.

Surface operations on the blowout well should be suspended until it has been properly secured and verified as such. The most common action employed to secure the blowout well is to circulate a cement plug into it from the relief well. Other means to decouple the wells hydraulically also exist and should be considered by the intervention team.

Blowout recovery operations, such as wellbore repair or plugging on the blowout well, can be extensive. Further operations on the relief well at this time depend on the strategy devised by the operator or required by the local regulatory agency. These may include:

- converting the relief well into a producer.
- converting the relief well into a monitoring well.
- maintaining the relief well for further kill operations.
- sidetracking the relief well to place additional barriers in the blowout well.
- suspending the relief well for further operations.
- plugging the relief well.

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 as drilled wellbore may deviate from the subject well plan.
Angle of Incidence	The relative angle between two wells, expressed in degrees ($^{\circ}$), which defines the total angular difference in the well trajectory vectors. Can be expressed as a two or three-dimensional difference(s) and having either converging or diverging vectors. Typically used to describe the angle present between the RW and the TW during ranging operations and when attempting to make the final intersection.
Approach	Refer to Approach Phase
Approach phase	A drilling stage where the trajectory objective is to get closer to the target well until reaching the desired detection range.
Attack Angle	See Angle of Incidence
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	During the planning phase, a pass-by will be planned, however if the target well is located in an optimal position it may be possible to drill the relief well into the follow phase with a trajectory that avoids a sidetrack and still achieves a definitive target position during the locate phase. Changes in aspect direction to target can still be performed in order to triangulate the target well position with a drop in 3D incidence angle to drill parallel to the target well (see Figure 81).
ct-to-ct	Refer to ct-ct
ct-ct	Center to Center distance, is the measured distance between the center 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 target 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 distance that is dependent on the relative position of the two wellbores, formation properties and geological structure.

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 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
Ellipse of Uncertainty (EOU)	The area produced by projecting an ellipsoid of uncertainty onto a defined plane.
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/fish by re-entering the subject well.
Follow	Refer to hand railing, twinning or following phase
Following phase	A drilling stage after locate phase where the trajectory objective to follow the target well to ensure positive detection at all times until reaching the desired intercept depth
Formation Hot Spot	A geological formation. A magnetic anomaly resulting from a variation in the rock type from that of the surrounding formations.
Ghost Wells	Cased or open hole wellbores that are missing from the survey database used for anti-collision analysis.
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	A ranging technique to "follow" an existing well. Commonly used in operations such as SAGD where only first well, producer has an absolute positional survey, and the additional offset well position is calculated relative to the existing well.
Hazard and Risk Control (HARC)	A standard risk assessment process to identify hazards, assessing associated risk and defining required control measures, ie. preventive and mitigation actions to be taken to keep the risk level at ALARP (As Low As Reasonably Practical) at all time.
Homing in	The iterative process of deploying ranging techniques to establish a relative position between the subject well and target well, with each successive iteration, reducing the relative uncertainty between wellbore positions. The homing in process continues until the goal has been achieved.
Homing in Point	The initial point in the target well where to range to. It is the target point to establish a relative position to the subject well at shallower depth.

Injector Well	See SAGD description.
Injector	See SAGD description.
Intercept Depth	See Intercept Point
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 target wellbore where the relief well intersects in order to create hydraulic communication between the wells.
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.
Kill Depth	Refer to Kill Point
Kill Point	A point at which desired hydraulic communication is established between the target well and relief well.
Killing Operation	Operation to bring the target well under control. To balance the hydrostatic pressure of the subject well with slightly higher than the target well to stop the flow.
Killing phase	The operation after intercepting phase with the main objective to create hydraulic communication in order to perform killing operations. The target well will be brought under control and stabilized prior plug and abandonment operations
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
Lateral Distance (LD)	The horizontal distance between two wells to define the positional difference between well centers 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 a point source consisting of a pair of poles. An example is a casing joint joining a south and north pole at one point.
Magnetic Guidance	An induced magnetic field that is utilized in a ranging operation in order to correlate locations between wellbores for their relative position to each other.
Magnetic Guidance – WISC Lexicon	A ranging technique that utilize an induce magnetic field in the target well to correlate its relative locations/separation to the subject well.

Magnetic Hot Spot	A magnetic anomaly located on the bottom hole assembly or casing string that exhibits a higher level of residual magnetism.
Magnetic Monopole	A single North or South magnetic pole. Does not actually exist in nature but can be a useful in constructive mathematics
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.
Mapping Run	A mapping run is performed across a longer ranging interval to collect a greater amount of ranging data in order to better model the relative position of the target well. The mapping run provides higher target well relative position definition across the ranging interval, which then allows a higher precision position in the next approach to refine the subject well trajectory for the following and intercepting phase. Synthetic surveys for the target well can be derived after a mapping run by taking into account relative changes in the target well trajectory. These synthetic surveys will optimize the approach to take in subsequent phases.
Measured Bearing	Toolface angle defining the measured direction to the target well, as determined by ranging data.
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.
Minimum Pass-by Distance	Minimum ct-to-ct distance during a pass-by operation performed to locate the target well by triangulation. The desired distance for an optimum ranging operation as well as to prevent unintentional collision.
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 Pass-by and Direct Intercept definition.

Object Well	Offset Well
Observation Well	A (typically) vertical well used to measure parameters relative to other nearby wells in a field.
Offset Well from CA Lexicon – to modify	An existing or planned well that is to be evaluated for risk of collision with the subject well
Oriented Intercept	An S-shaped two dimensional or three dimensional well that is designed to locate and intercept the blowout well at two distinct points. This design requires a pass-by for triangulation to confirm the position of the blowing well and to reduce the positional uncertainty.
Parallel Track	An S-shaped two-dimensional or three-dimensional well design which tracks the blowout well once located which can be perforate and establish communication with the blowout well. In this design a pass-by to triangulate the position of the blowing well is not performed, if the confidence in the survey position of the well is considered to be high.
Pass-By	The Pass-By is defined when the relief wellbore is planned and drilled during the locate phase in a trajectory past the target wellbore in order to achieve a high change in aspect direction to target, which when combined with ranging methods, will allow a very high confidence to be achieved in the positional certainty of the target well. It is common to sidetrack after the pass-by due to the trajectory being sub optimal for drilling deeper in the follow phase due to high 3D incidence angles. The trajectory is optimized to cross the ellipse of uncertainty in order to apply the detection range of the ranging system most effectively to locate the target well. For target wells with increased uncertainty, it might be required to drill multiple pass by sidetracks in order to cover large elliptical error surfaces and definitively locate the target well (see Figure 81).
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.
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.
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 Well	A well that is producing hydrocarbon either naturally or utilizing artificial lifting mechanism.
Producer	Producer Well
Ranging Phase	The section of the subject well where ranging operations are to be performed

Ranging Uncertainty	Relative position uncertainty described in terms of a distance and direction/bearing uncertainties.
Reference Depth	The reference depth could be presented either in TVD or MD or both as required and stated clearly in documentation. For example, for well planning the horizontal target well, the reference depth should be in MD and vertical or slanted target well should be in TVD.
Reference Well Analysis (RefWA)	Reference well Analysis (RefWA) is the well that used as a reference for the analysis that depend on the specific drilling objective, it can be either the target well (TW) or the subject well (SW). The objective could be the following: <ul style="list-style-type: none"> - Collision avoidance: SW is selected as RefWA - Relief well operations; Planning Phase: TW is selected as RefWA where the RW trajectory options are presented and visualized. During drilling execution: SW is selected as RefWA where the relative position of the TW is plotted against it. - Twinning well: TW is selected as RefWA
Reference Well Translation	Interpretation of the target wellbore position through the iteration process using the multiple ranging results.
Relative Position	Offset well position described as a distance and bearing to the point of closest approach.
Relative Positional Uncertainty	The uncertainty associated with the distance and bearing.
Relief Well	This refers to the well drilled to intercept the target well for the purpose of restoring well control.
Remnant Magnetism	This refers to the residual magnetization of steel components after degaussing.
Reverse Survey	Adjustment of the survey of the target well so that it is consistent with the range and bearing of the latest ranging measurement.
Rotating Magnets	Radially-oriented permanent magnets located in a sub that rotates with the BHA.
Rotation Shots	This is the acquisition of at least 4 magnetic surveys in at least 3 different quadrants at the same measured depth (+/-1 m). It is often employed to ensure an MWD tool does not have toolface-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. Wells are typically instrumented by a large number of sensors, some permanent and others transitory, let alone temporary
Simple Intercept	A two-dimensional J-shape well, designed to intercept the target well at a specific TVD that would not require any pass-by to locate. 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
Subject Well	The well of interest, existing or planned that would be or being drilled as part of the drilling execution operations
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 locate or range to for either intercepting or twinning.
Track Phase	The following phase of a drilling operation after the locating phase to track the target well until prior to intersection. Also see Following Phase.
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.
Twinning Well – New	This refers to the subject well that would be or being drilled to twin the target well or offset well for the purpose of maintaining a certain offset distance. Twinning well is similar to “parallel” well drilling.
Collision Avoidance	Well Avoidance

Well Avoidance	Observing anti-collision rules for the purpose of maintaining an accepted safe distance between wells.
Well Reference Point	A point on the ground level or at the mud line which defines the initial starting point of the well. It defines the X-Y surface coordinates of the well which the surveys are tied into. It is a permanent, recoverable, fixed point in the well.
Wellbore Geometry	The geometrical description of the wellbore in 3-dimensional space as defined by a measure of inclination with respect to the vertical plane and a measure of azimuth (direction) with respect to a specific north reference. Wellbore geometry at each survey point is used to interpolate the wellbore trajectory using minimum curvature.
Worst Case Discharge (WCD)	The maximum flow rate of produced fluid during an uncontrolled wellbore flow event—that is, the average daily flow rate on the day that the highest rate occurs, under worst-case conditions (a blowout). It is a single value for the expected flow rate calculated under worst-case wellbore conditions using known or expected formation properties. In assessing WCD, “worst case” pertains to the loss of pressure containment in the well with a wellbore configuration terminating at surface; and no equipment present in the well (BHA, drill string, testing assembly, wireline etc.). Formation properties if unknown should be selected as best technical estimates for the WCD calculation.

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Submissions for Assessment

The authors of this publication, WISC team is 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 for assessment for inclusion in the next revision should email to publisher:

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WELL INTERCEPT SUB-COMMITTEE eBOOK R4

Wellbore Ranging Technologies, Intercept, Applications and Good Practices