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Advanced Magnetic Ranging and Gyroscopic Measurements for Complex Plug and Abandonment

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Abstract

This paper will discuss the implementation of advanced magnetic ranging technologies combined with simultaneous gyroscopic measurements, based on the series of case studies where the interception well was guided into the target well for complex plug and abandonment. The efficiency of the new procedure is reflected in total time savings while meeting all regulatory objectives. The advantages of this technique in comparison to the traditional methods will be explained, and the improvements in accuracy will be examined.

The new approach allows access to a complete suite of all modern magnetic ranging technologies, including access-dependent and independent active ranging, and passive ranging methods with gyroscopic attitude referencing. Active and passive ranging data is collected simultaneously with the tool motionless at stations but can also be collected on-the-fly with 3 ft/min logging speed, giving additional options for data collection. The technique also permits the collection of high-definition gyro surveys during the same run.

One of the key criteria of the new process is to treat every well as a single project. With the availability of all ranging and survey methods at the project location, the best solution for any scenario can be quickly found, tested, and executed while having the results confirmed using physically distinct data sources.

Based on the initial performance, the new methodology has resulted in a 50% time reduction compared to the client's initial expectations, significantly reducing the cost of the project. To date, every plug and abandonment in this project has been accomplished with a single wellbore with no sidetracks required.

Introduction

One third of all plug and abandonment operations in the continental United States are non-routine and 5% require re-entry (Greer, 2018). In cases where access to a problematic well is restricted, e.g., a wellhead is underwater, an obstruction in the well makes concentric re-entry costly or impossible, or there are safety risks associated with the presence of people at the target well location, drilling an interception well to provide means to plug the problem well may be the most economical and effective solution. The success of such operations highly depends on the accuracy of directional surveys of the target well and the interception well. Due to conventional wellbore survey uncertainty (Wolff, 1981; Williamson, 1999), the accuracy of relative guidance techniques, commonly called ranging ("ISCWSA: Well Intercept Sub-Committee eBook", 2017), becomes even more important.

In the present day, magnetic ranging is the most common type of relative guidance techniques. It can be active or passive, and access dependent or independent. In any scenario, a magnetic ranging system requires a magnetic field source and a magnetic field sensor. The source can be a target well casing with its remanent magnetization (passive ranging), or either an electromagnet or permanent magnet deployed in a target well or an interception well (active ranging). In many cases passive ranging is considered access independent, as it uses a casing itself as a source of magnetic field and does not require access to a target well. However, due to corrosion and degradation in harsh environments, steel casing will experience a weakening of its magnetic properties. Active ranging methods involve much stronger sources with known or well-modeled characteristics and therefore have much higher detection ranges and better accuracy. Although many active methods require access to the target well, some techniques allow for current injection through a formation to energize target casing, however, in this case, formation resistivity should be accounted for. The preferred approach is to have all ranging methods available at the rig location and be able to use all of them when needed. Even in cases where various methods give reliable results, combining data from multiple sources provides more detailed information, increasing confidence in the relative position measurements of a target well.

A processed magnetic ranging measurement typically consists of direction and distance to a target in the world "north-east-vertical" coordinate systems. The unoriented ranging direction and distance measurements must be transformed from the XYZ frame of the tool to the world frame as part of the data computation process. The transformation to the world frame consists of three passive rotations based on the ranging receiver's gravity highside toolface, inclination, and azimuth. When in close proximity to a magnetic field source, the measured magnetic azimuth may be inaccurate due to interference from the source. Therefore, the interpolated azimuth from a prior survey is typically used for ranging data computation. Frequently, the ranging receiver assembly is positioned near vertical, making use of the ranging receiver toolface and previously measured interpolated azimuth problematic. In this case, the ranging receiver assembly can be combined with a north-seeking gyro system for accurate orientation in space (Rassadkin, Ridgway, Moss, 2018).

In the following case histories, five wells were critically damaged due to a seismic shift that occurred in the formation, making the concentric re-entry for a typical plug and abandonment impossible. The owner of the wells had an objective to drill a series of interception wells to plug and abandon the corresponding target wells. The methodology included locating, following and intercepting the targets using ISCWSA Well-Interception Sub-Committee best practices coupled with industry-leading technologies.

Technology

Scientific Drilling offers a variety of access dependent and independent magnetic ranging methods, however, in this paper we describe methods which do not require the access into a target wellbore.

BlackShark – Active magnetic ranging based on the current injection through the formation. This is the primary ranging method that was used in the following case studies. The system is wireline-conveyed and consists of a source and a receiver in one assembly. It injects AC current into the formation, the current reaches the target well casing and the resulting magnetic field from the casing is being detected by the receiver. The main limitation of this method is related to the formation resistivity; however, the system can also collect passive ranging data that is not affected by this factor. The ranging measurements are collected while both motionless and on-the-fly. A north-seeking gyro sensor is integrated into the ranging system and is used for highly accurate real-time gyro surveying and an orientation of magnetic ranging measurements in the world coordinate frame, which is especially important when the tool is positioned vertically in a wellbore.

SynTrac – Active magnetic ranging based on a current injection from the surface (U.S. Patent No. 9,938,773B2, 2018). This method can be applied to the wellbores with electrically continuous casings with access from the surface. The system uses MWD sensors to measure the magnetic field from a target casing, as a result of the current applied to the casing at the surface and has a greater detection range than passive magnetic ranging. The main limitation for this method is the depth of the target well – the deeper the depth, the less current remaining on the casing making it more difficult to measure the resulting magnetic field.

MagTrac – Passive magnetic ranging. This method isolates the Earth's naturally occurring magnetic field from the target field measured through a series of raw MWD or wireline survey shots. The magnetic interference from a target wellbore is used to determine distance and direction to the target. The limitations are related to the condition of the target casing and its remanent magnetization as well as the accuracy of a local magnetic field model.

As described above, all methods have their limitations, but their combined use enables accurate results in almost every circumstance.

Common project details

During these projects, the active ranging data was collected using highly sensitive wireline-conveyed ranging receivers as well as the MWD-based receivers, where applicable, to reduce the number of wireline runs and save time.

Data collected while motionless, as well as on-the-fly were used in the analysis of active and passive magnetic ranging signals. The ranging data provides azimuth and highside directions to the target casing as well as a distance to target, which improves in accuracy with center-to-center distances between the wells of under 10ft, as reflected on the distance to target graphs .

The wireline-conveyed ranging receiver is integrated and aligned with a north-seeking gyro assembly, which improves the accuracy of the computed data. By using the gyro sensor for the simultaneous ranging orientation, wireline runs are reduced due to a higher quality of the ranging data obtained.

Using surface current injection to the target casing methodology and MWD-based ranging receiver enabled efficiency by a reduction in requirements of early wireline ranging runs, as the direction to the target was obtained while drilling a surface hole.

Passive magnetic ranging data is collected by both the MWD magnetic sensors, and the wireline-conveyed ranging assembly, and analyzed in real-time and post-job. In real-time, the data is used to produce a Continuous BTotal log, which shows constant magnetic field changes while drilling the interception well with the MWD sensors. Changes in the magnetic field from external interference, such as target well casing collars, damage, and other factors, are presented on a Continuous BTotal log. The log variation can indicate that the distance to the target well is decreasing which can be used to mitigate premature well intersection between the drilling well and the target well. Post analysis of the magnetic data collected by the wireline ranging tool was performed to further understand methods that could improve the efficiency of ranging runs on future projects.

Drilling Phases

The ISCWSA Well-Intercept Sub-Committee best practices and recommended phases for drilling on well interception projects are followed in the case studies described below. The planning and execution of all phases is done by collaborative efforts between Scientific Drilling and well interception and advanced survey management experts from PathControl. After the planning and approach the target phases conclude, magnetic ranging operations take place in the following drilling phases:

Locate phase. The objective of the locate phase is to perform the ranging measurements necessary to locate the target well relative to the offset well before the separation factor drops below one (SF<1), when the ellipsoids of uncertainty intersect. The detection of the target well likely leads to an updated interception well plan to comply with the ranging results.

Follow phase. The objective of this phase is to track the target well by monitoring its position relative to the interception well using the ranging methods. Adjustments to the well plan are being made based on the ranging results. At this stage, building the ranging data model should be based on consistent interpretation of all successive ranging runs on the one hand, and improved knowledge of the target well behavior on the other hand. This allows devising the most adequate plan forward that ensures not being too far away with the risk of losing the target, nor too close with the risk of premature interception.

Intercept phase. This is the final drilling stage. The interception angle depends on the selected communication option. During this phase a frequency of ranging runs increases with shorter drilling intervals to accurately close-in on the target well trajectory.

Interception Well #1 Case Study

The objective of drilling the Interception Well #1 was to plug and abandon the target well, which suffered casing damage at 515ft MD. The casing damage was confirmed by magnetic ranging data analysis. A variety of magnetic ranging methods, including access independent formation current injection active magnetic ranging as a primary method, were deployed to directionally drill the interception well and contact the target well at the specific depth of 1072 ft.

The data recorded during the ranging runs were consistent with the pre-job planning and modeling of the interception well. Due to shifts in the target well position relative to the interception well, the well plan was updated throughout the drilling course. The drop in the signal strength between 510ft and 636ft MD indicates a lack of electrical continuity due to a break in the casing (Figure 1). The continuous magnetic B-field (BTotal) plot based on the data, collected from the MWD sensors while drilling, also indicates a strong magnetic pole at 510ft which corresponds with a casing end (Figure 2). The distance to target results, based on the gradient magnetic field measurements from the wireline active ranging system, are consistent with the expectations: once the distance between the intercept and the target wells was under 6ft, the accuracy of the distance to target results improved (Figure 3). The well was drilled to 1078 ft where a soft touch and confirmation of physical contact with the target occurred.

The project execution followed the ISCWSA well interception best practices by drilling the well split into the following phases:

1. Locate. During drilling the section to 517ft, the drilling BHA MWD sensors were used to gather active ranging data, based on the surface current injection method, to calculate the direction to target well (Figure 4), which enabled the directional drilling team to improve the wellbore position relative to the target before running the wireline ranging log.

2. Follow. After the surface casing was set, the well continued to be drilled to a depth of 970ft MD with four ranging runs designated at depths calculated by potential deviation from the plan and wellbore uncertainty. The phase objectives were achieved with the drilling well twinning the target well. Gyro surveys were collected during the wireline active ranging runs to improve wellbore positional certainty in order to confidently drill longer intervals between wireline ranging runs.

3. Intercept. Ranging runs increase over shorter drilling intervals to improve confidence in target well location as the final approach to the soft touch occurs. Seven ranging runs were performed over this interval from 970ft to 1086ft. When drilling to 1096ft, circulation was lost and communication was established with the target well annulus. The final wireline ranging run #12 was performed to confirm target well location relative to the drilling well.

The interception objective was met at the intended measured depth and led to a successful abandonment of the target well by a cavity shot and cement squeeze. Drilling and ranging operations of this well took 10 days in total, 4 days ahead of the schedule.

Interception Well #2 Case Study

The objective of drilling the Interception Well #2 was to permanently plug and abandon the target well which suffered casing damage at 512ft MD. The casing damage was confirmed by ranging tool data analysis. The wireline-conveyed formation current injection active ranging tool was used as a primary ranging system to directionally drill the Interception Well #2 to be in contact of the target well at a measured depth of 942ft. The abandonment was accepted by the regulatory authority at the end of the operation.

The data recorded during the ranging runs were consistent with expected modeling and planning of the intercept well. Due to shifts in the target well relative to the drilling intercept well, the well plan was updated throughout the course of drilling the interception well. A drop in the signal strength between 520ft and 641ft MD indicates the break in the casing due to a lack of electrical continuity (Figure 5). The relative distance results based on the gradient magnetic field measurements showed consistent and reliable results in close proximity to the target well (Figure 6). The integrated gyro survey tool enabled highly accurate azimuth to target results in real-time during wireline ranging runs at a low inclination angle (Figure 7). The azimuth to target plot shows consistent results throughout the drilling of the well with overlap between runs which gives a high level of confidence in the ranging measurements. Passive Magnetic Ranging (PMR) was used to confirm the active ranging data results. The Continuous BTotal log provided real-time information while drilling and was used to track the distance to the target well by analyzing field strength variations (Figure 8). Due to the close proximity of the drilling well to the target well, casing collars can be seen on the Continuous BTotal plot as peaks and troughs in the field strength.

The project execution followed the ISCWSA well intercept best practices by drilling the well split into distinct phases:

1. Locate. The surface hole section was drilled to 525ft and then a wireline active ranging run #1 was completed to locate the target well. A well plan based on the shifts in the target well position with reference to the drilling well was created.

2. Follow. After the surface casing was set, the well continued to drill to a depth of 840ft MD with ranging runs taking place within this interval. Ranging runs #2 to #5 were performed in this phase.

3. Intercept. Ranging runs increase over shorter drilling intervals to improve confidence in the target well location as the final approach to the soft touch occurs. Ranging runs #6 to #10 were performed over this interval from 840ft to 942ft.

Milling operations commence with an adjustable conventional mud motor aligned in the direction of the target casing based on ranging results from the ranging run #10. A window was milled into the target well casing from 947.1ft MD to 950.5ft MD to allow tubing to be run into the target well. Tubing was run into the target well to a depth of 1193ft MD and cement plugs were set to plug and abandon the target well.

Drilling and ranging operations of this well took 8 days in total, 6 days ahead of the schedule.

Interception Well #3 Case Study

The objective of drilling the Interception Well #3 was to permanently plug and abandon the target well which suffered casing damage from 500ft to 650ft MD. The casing damage was confirmed by ranging tool data analysis (Figure 9, Figure 10). The wireline-conveyed formation current injection active ranging tool was used as a primary ranging system in order to directionally drill the well to contact the target well at a measured depth of 1040ft. The abandonment was accepted by the regulatory authority.

The project execution followed the ISCWSA well intercept best practices methodology by drilling the well split into distinct phases:

1. Locate. The surface hole section was drilled to 525ft and then a wireline active ranging run #1 was completed to locate the target well. A well plan based on the shifts in target well position with reference to the drilling well was created.

2. Follow. After the surface casing was set, the well continued to be drilled to a depth of 950ft MD with ranging runs taking place within this interval. Ranging runs #2 to #6 were performed in this phase.

3. Intercept. Ranging runs number increase over shorter drilling intervals to improve the confidence in the target well location as the final approach to the soft touch occurs. Ranging runs #7 to #10 were performed over this interval from 950ft to 1040ft.

Milling operations commenced with an adjustable conventional mud motor aligned in the direction of the target casing based on ranging results from the ranging run #10. A window was milled into the target well casing from 1039ft MD to 1045ft MD to allow tubing to be run into the target well. Tubing was run into the target well to a depth of 2160ft MD and cement plugs were set to plug and abandon the target well.

Drilling and ranging operations of this well took 6 days in total, 8 days ahead of the schedule.

Interception Well #4 Case Study

The objective of drilling the Interception Well #4 was to permanently plug and abandon the target well, which suffered casing damage from 554ft to 762ft MD. The surface section of the Interception Well #4 was drilled to 552ft where the wireline ranging shot was performed prior to 13-3/8in casing being set at 551.6ft. The well was then drilled to 896.5ft where a soft touch and confirmation of physical contact with the target well occurred.

Due to a proximity of a nearby frac salvage well that twinned the target well, an earlier intercept was chosen higher in the formation to avoid potential collision issues with the offset parasite well. The offset well also presented potential opportunities to apply different methods of current injection such as energizing the target well with the offset well return. This data showed the drop in the signal strength at 720 – 810ft MD (Figure 13) that was likely related to the conductivity of the formation and the connection between the electrode and the formation due to the well geometry. The results with a lower signal strength still were of high quality showing the correct azimuth and distance to the target.

Planning and modeling were performed before the spudding of the well to simulate the amount of current that would flow onto the offset well in comparison with the target well, which led to an optimized well plan that was executed through the project.

The directional services included conventional mud motors and GyroMWD. The project execution followed the ISCWSA well intercept best practices by drilling the well split into distinct phases:

1. Locate. The surface hole section was drilled to 552ft and then wireline active ranging run #1 was completed to locate the target well. A well plan based on the shifts in target well position with reference to the drilling well was created.

2. Follow. After the surface casing was set, the well continued to be drilled to a depth of 780ft MD with the wireline ranging runs taking place within this interval. The ranging runs #2 to #3 were performed in this phase. The interception well inclination during the Follow phase was below one degree and it was critical to hold it low to stay in close proximity to the target well.

3. Intercept. Ranging runs increase over shorter drilling intervals to improve the confidence of target well location as the final approach to the soft touch occurs. Ranging runs #4 to #8 were performed over this interval from 780ft to 896ft. Ranging run #5 was canceled due to encountering fill while trying to reach the bottom with the wireline assembly.

Due to the proximity of the frac salvage well, a contingency of using a solenoid-based active ranging method was considered, however, further progress showed that it was not required as the primary plan sufficiently located and tracked the target well with consistent results. Using different current injection methods and comparing the results provided confidence in the target well relative location and eliminated the need in the access to the offset well, which remained under production throughout the project.

Due to the low inclination angles in the intercept well, wireline active ranging system was integrated with a north-seeking gyro sensor, which eliminated potential issues with inconsistent ranging data caused by poor orientation measurements.

Milling operations utilized an adjustable conventional mud motor aligned in the direction of the target casing based on the results from the ranging run #8. A window was milled into the target well casing from 896.5ft to 904ft MD to allow tubing to be run into the target well. The initial milling attempt encountered difficulties getting a good ledge on the casing, however, a change in the motor bend angle then succeeded in milling the window. The tubing was run into the target well to a depth of 2462ft MD and cement plugs were set to plug and abandon the target well. Drilling and ranging operations of this well took 6 days in total, 8 days ahead of the schedule.

Interception Well #5 Case Study

The objective of drilling the Interception Well #5 was to permanently plug and abandon the target well which suffered casing damage at 516ft MD according to the workover report. The casing damage was confirmed by ranging tool data analysis and was estimated to be between 490-520ft.

The surface section was drilled to 550ft where ranging was performed prior to setting 13-3/8in casing at 550ft. The well was then drilled to 1132ft where a soft touch and confirmation of physical contact with the target well occurred.

The project execution followed the ISCWSA well intercept best practices by drilling the well split into distinct phases:

1. Locate. The surface hole section was drilled to 550ft while collecting surface current injection active ranging measurements with MWD system. At the end of the section, the wireline active ranging run #1 was completed to confirm the location of the target well. A well plan based on the shifts in target well position with reference to the drilling well was created.

2. Follow. After the surface casing was set, the well continued to drill to a depth of 1090ft MD with wireline ranging runs #2 to #5 taking place within this interval. Gyro surveys were performed during wireline active ranging runs to improve wellbore positional certainty to confidently drill longer intervals between ranging runs.

3. Intercept. Ranging runs increase over shorter drilling intervals to improve the confidence of target well location as the final approach to the soft touch occurs. Ranging runs #6 to #9 were performed over this interval from 1110ft to 1132ft.

Milling operations commenced after the soft touch at 1132ft MD. Contact with casing was estimated to be 1134ft MD. Milling proceeded with an adjustable conventional mud motor set at a 2.25-degree bend, aligned in the direction of the target casing based on ranging results from the ranging run #9. A window was milled into the target well casing from 1134ft MD to 1139.5ft MD to allow tubing to be run into the target well. Tubing was run into the target well to a depth of 1441ft MD and cement plugs were set to plug and abandon the target well. Drilling and ranging operations of this well took 6 days in total, 8 days ahead of the schedule.

The passive magnetic ranging (PMR) method was used to confirm the active ranging data results. The Continuous BTotal log provided real-time information while drilling and was used to confirm casing damage and track the distance to the target well by analyzing field strength variations (Figure 19).

While sufficient hole cleaning parameters were adhered to throughout the drilling process, there were several occasions where wiper trips were required to allow for a bottom hole deployment of the wireline-conveyed active ranging tool. It was recommended before each ranging run to perform a wiper trip to sufficiently clean out any fill that can accumulate on the bottom of the interception well during ranging activities.

Summary of the results

After the results from the first well of the project were analyzed, the forward plans were optimized to make it possible to drill longer intervals between wireline ranging runs without violating project objectives. Table 1 shows how project duration was decreased from well to well as a result of continuous process optimization.

The use of gyro-while-drilling technology for accurate directional control and the wireline active ranging system with integrated north-seeking gyro allowed a reduction in the number of wireline runs based on the improved quality of the ranging data and positional accuracy of the drilling well. Figure 20 reflects the consistency of the gyro-oriented ranging measurements in comparison to traditional ranging orientation technique (based on the magnetic survey data in this case). Typically, relief wells are drilled at more than 3deg inclination to be able to use wellbore highside as a reference for the target direction. However, the results described in these case studies proved that the new methodology enables navigation of vertical directional wells with precision and accuracy in order to successfully intercept another vertical well.

Conclusions

The following conclusions were developed from the material presented in this paper:

1. The recent progress in plug and abandonment techniques using eccentric methods permits significant operational time reduction and cost efficiency, making these methods more economical for the operators than in the past, and , in some situations, more optimal than traditional concentric methods.

2. The methods described in this paper allowed completion of a multi-well project with a 50% time reduction compared to the client’s expectations, reducing the cost of the operation while meeting all regulatory objectives. Every plug and abandonment in this project was accomplished with a single wellbore, with no sidetracks required.

3. These methods are suited for not only the wells presented in the case studies, but also in instances where surface well access is non-existent or not possible due to the health and safety reasons.

Nomenclature

AMR = *Active magnetic ranging*
BHA = *Bottomhole assembly*
ISCWSA = *Industry steering committee on wellbore survey accuracy*
MD = *Measured depth*

MWD = *Measurements while drilling*
PMR = *Passive magnetic ranging*
SF = *Separation Factor*

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Tables

Table 1. Project summary. The duration of late projects was decreased as a result of continuous process optimization

Interception Well #	Intercept Depth (ft)	# of Ranging Runs	Days Planned	Days Actual
1	1094	12	14	10
2	942	10	14	8
3	975	10	14	6
4	906	8	14	6
5	1132	8	14	6
		Total	70	36

Figures

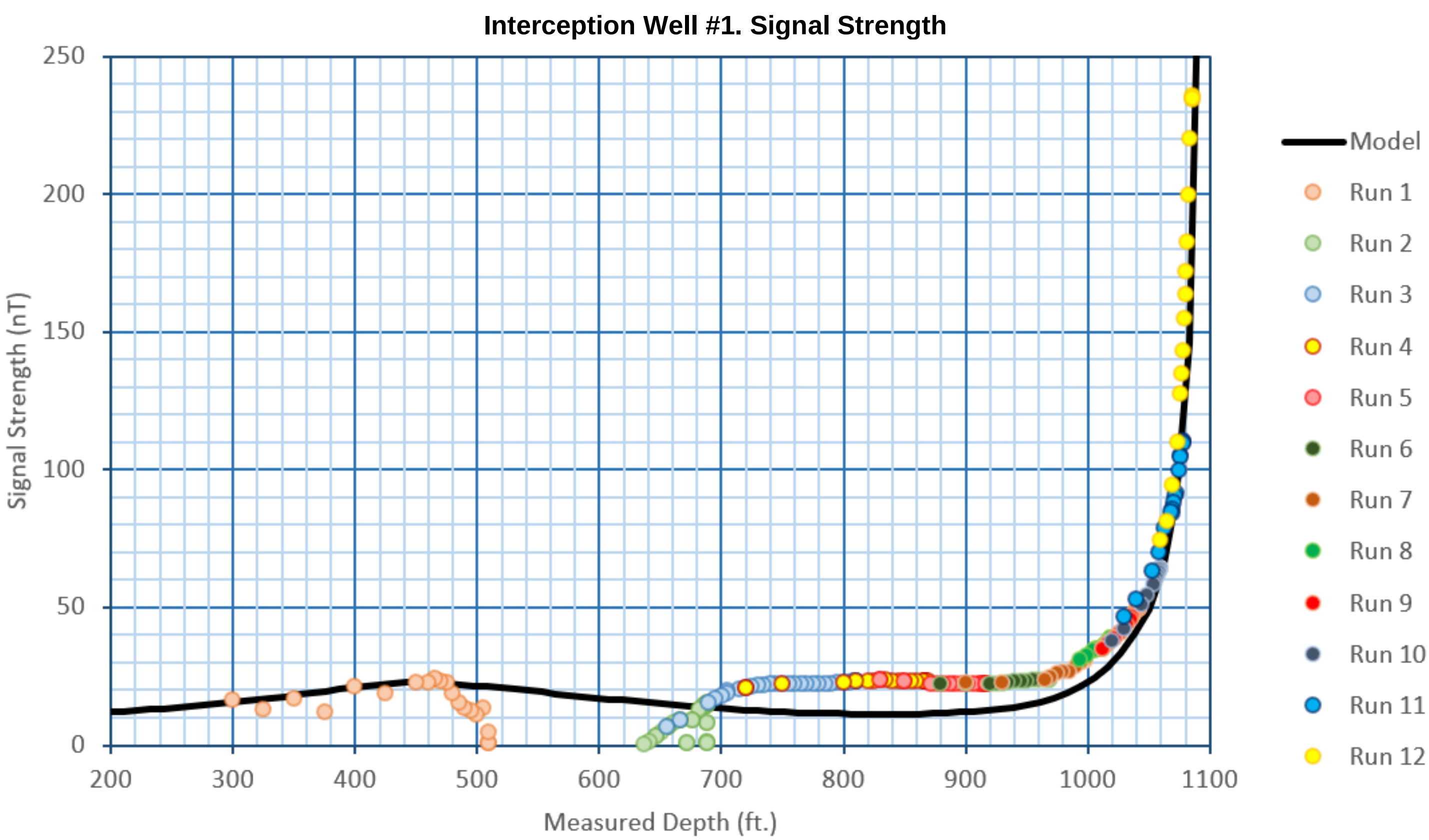

Figure 1. Interception Well #1. Primary wireline-conveyed formation current injection active magnetic ranging method. Signal strength

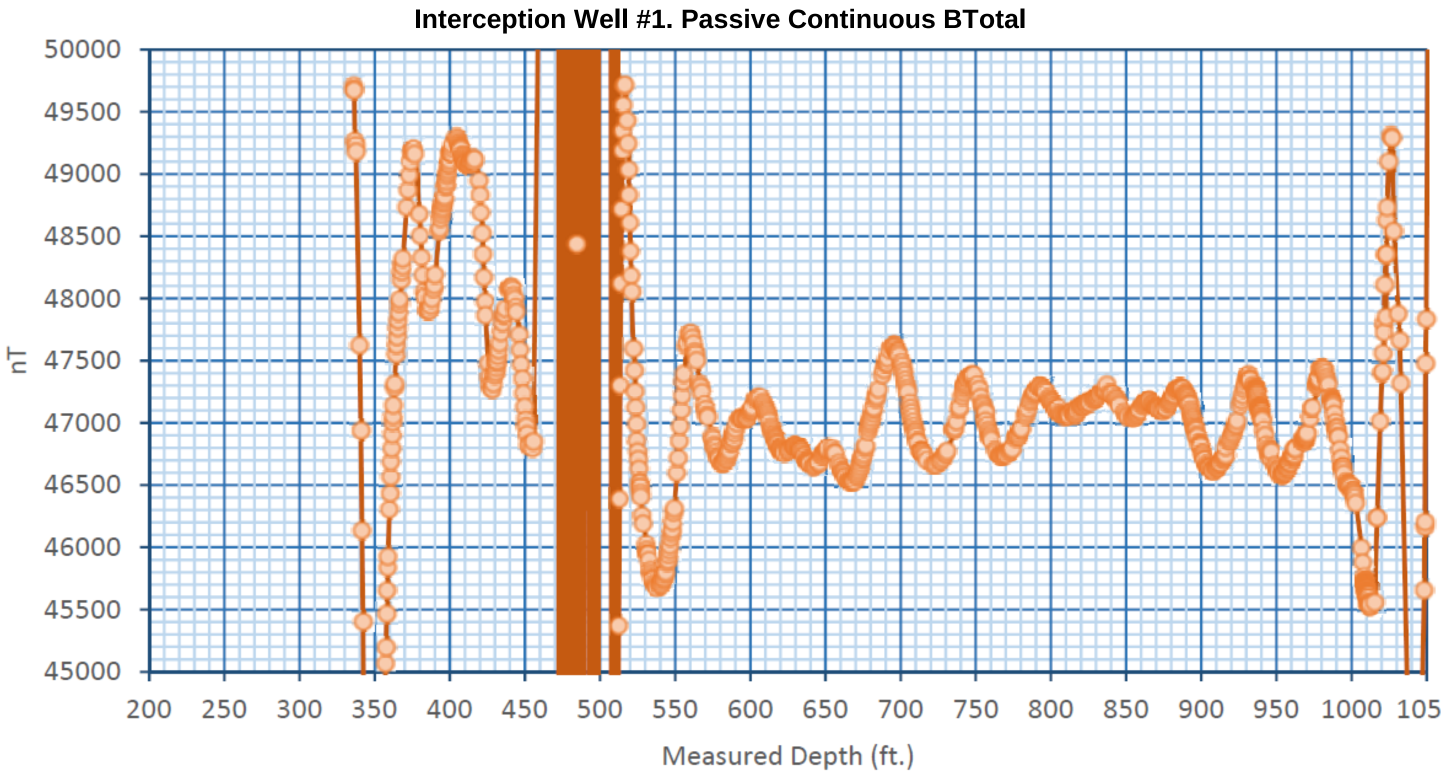

Figure 2. Interception Well #1. Passive magnetic ranging. Continuous BTotal

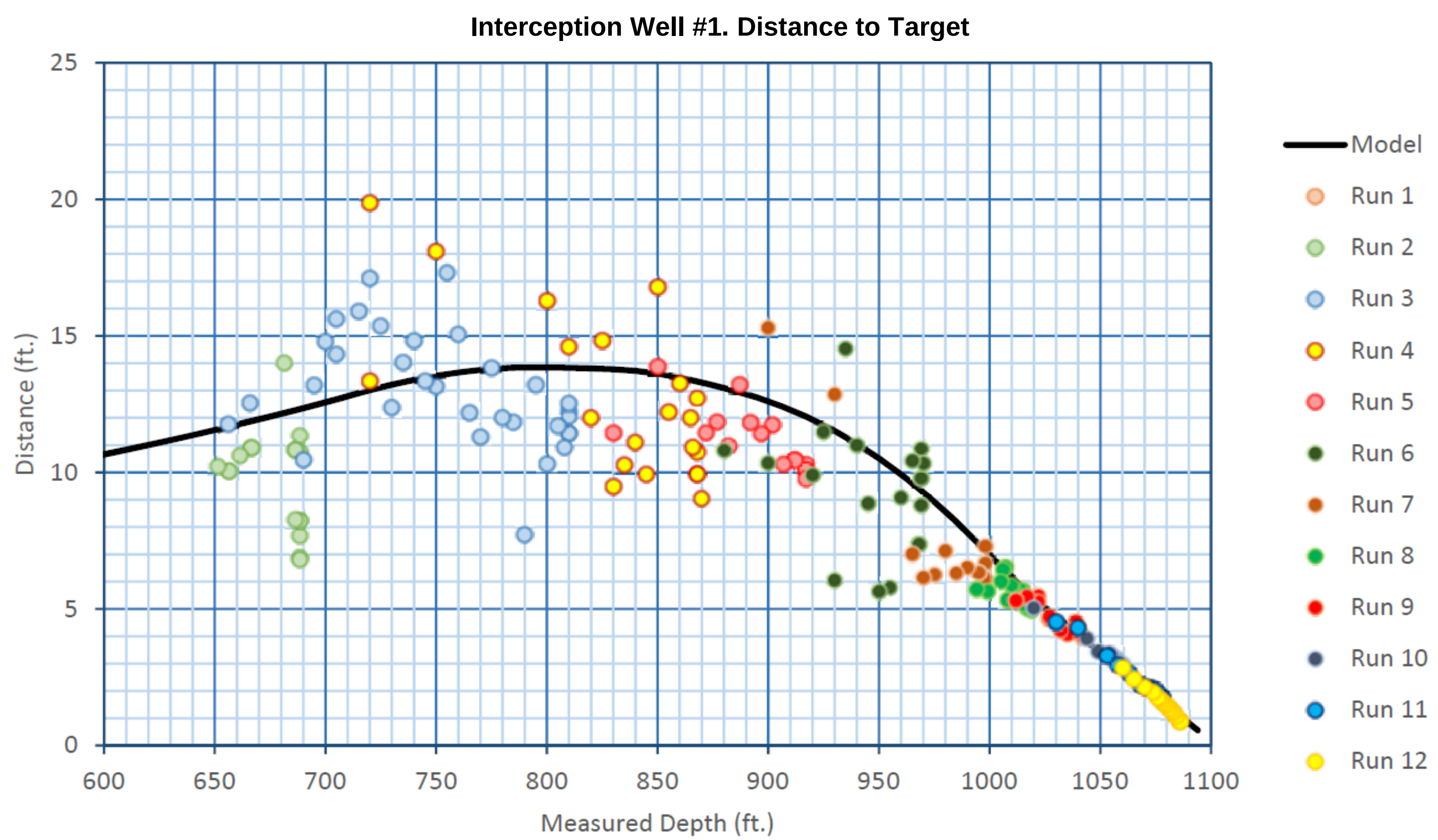

Figure 3. Interception Well #1. Primary wireline-conveyed active magnetic ranging method. Distance to target

Figure 4. Interception Well #1. Primary wireline and MWD-based (SynTrac) active magnetic ranging. Azimuth to target

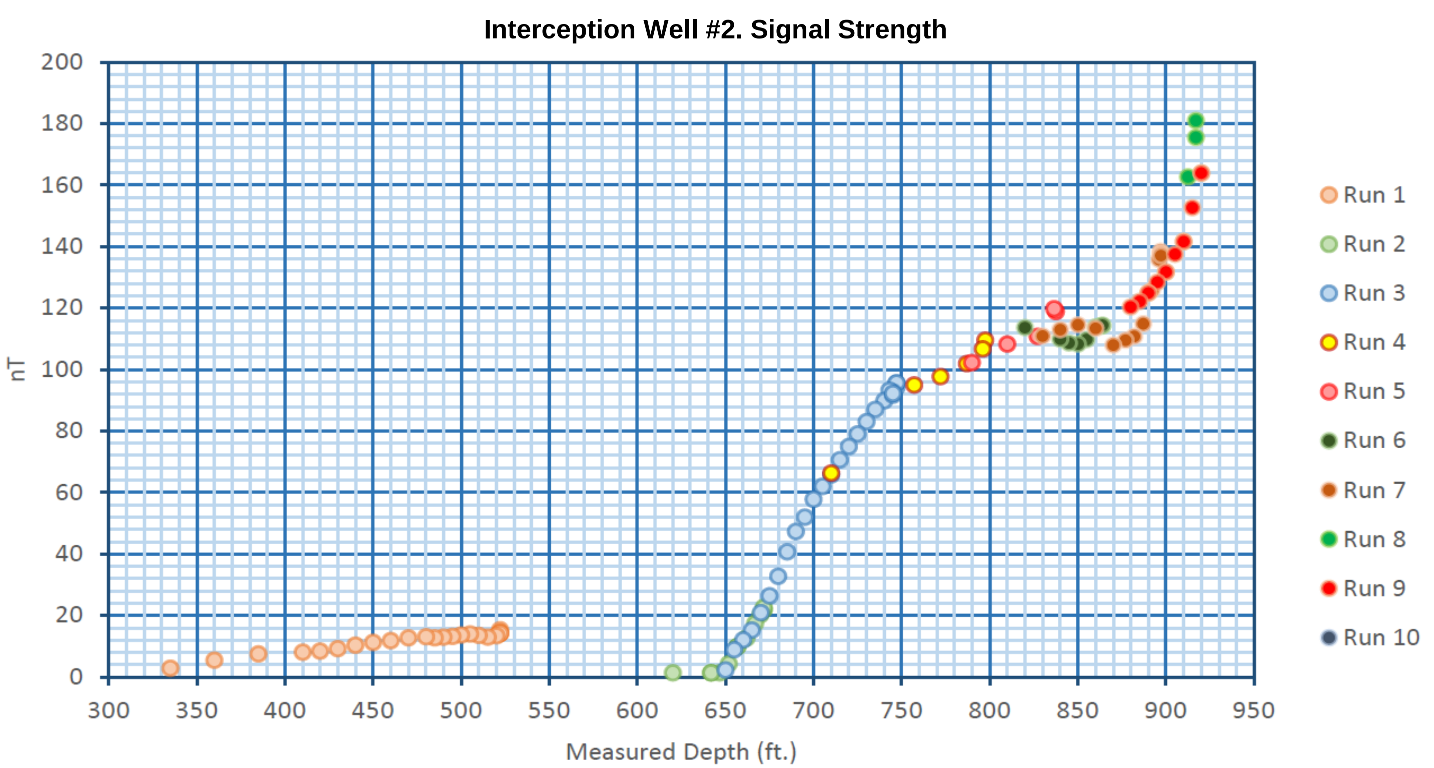

Figure 5. Interception Well #2. Primary wireline-conveyed formation current injection active magnetic ranging method. Signal strength

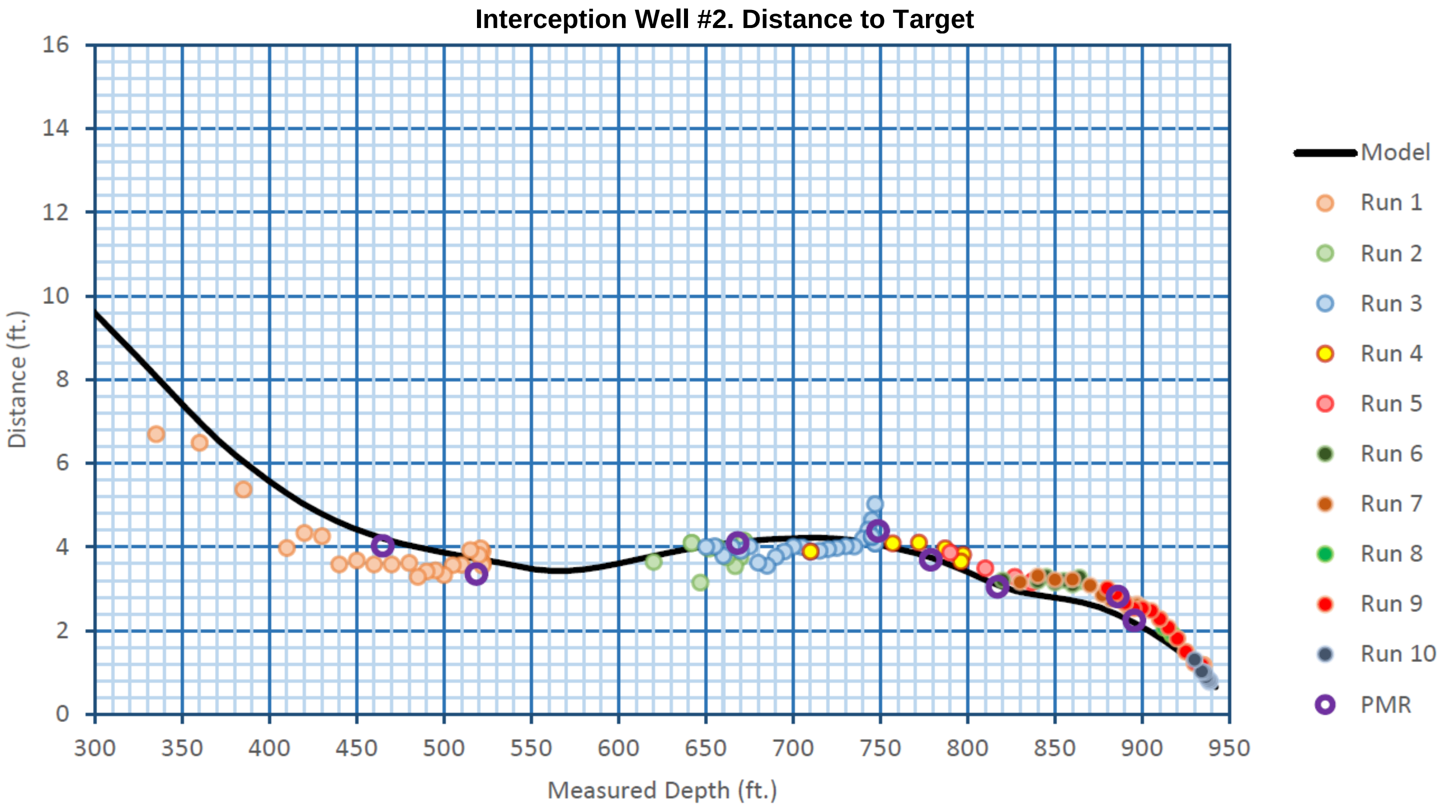

Figure 6. Interception Well #2. Primary wireline-conveyed active and passive (PMR) magnetic ranging methods. Distance to target

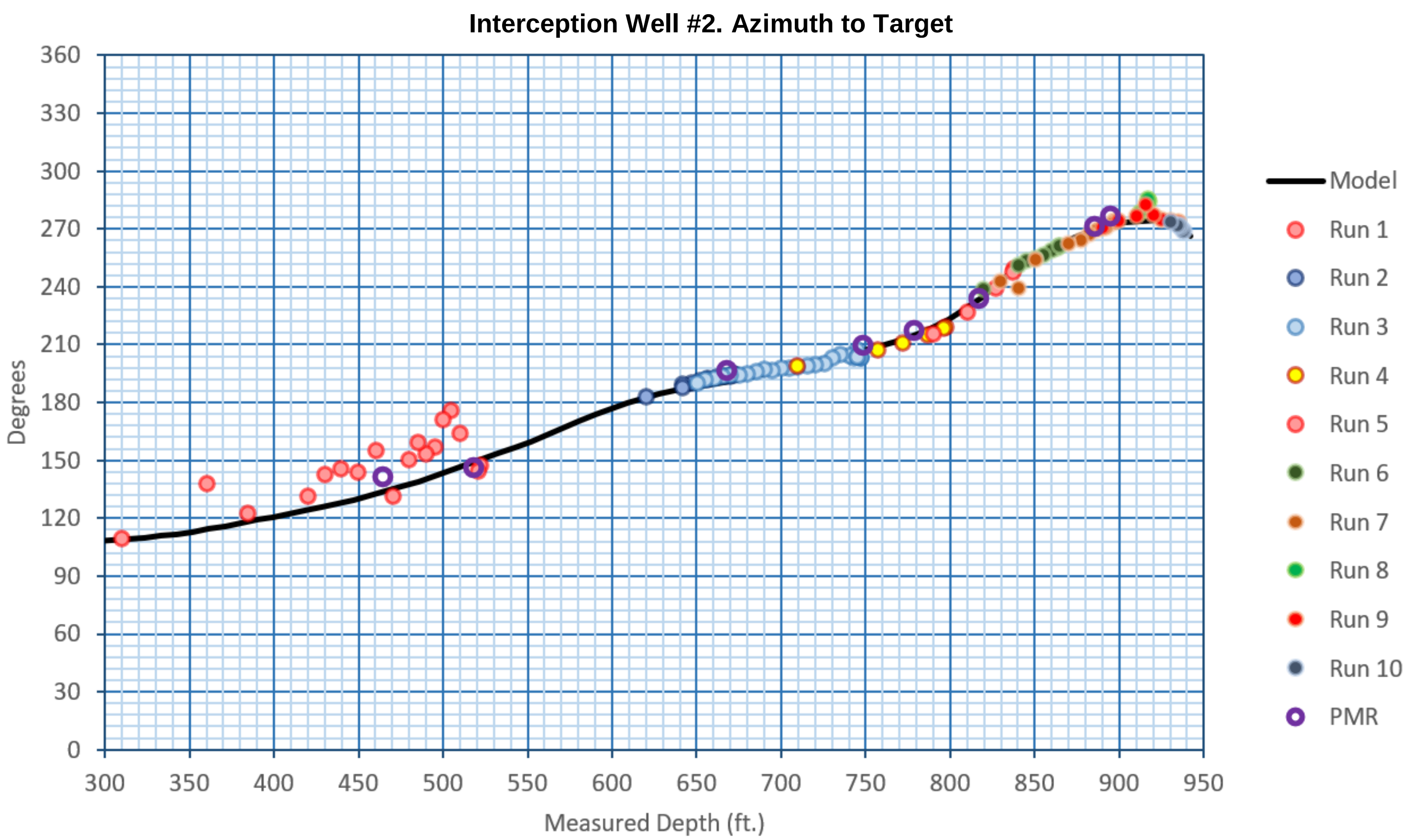

Figure 7. Interception Well #2. Primary wireline active and MWD-based passive (PMR) magnetic ranging. Azimuth to target

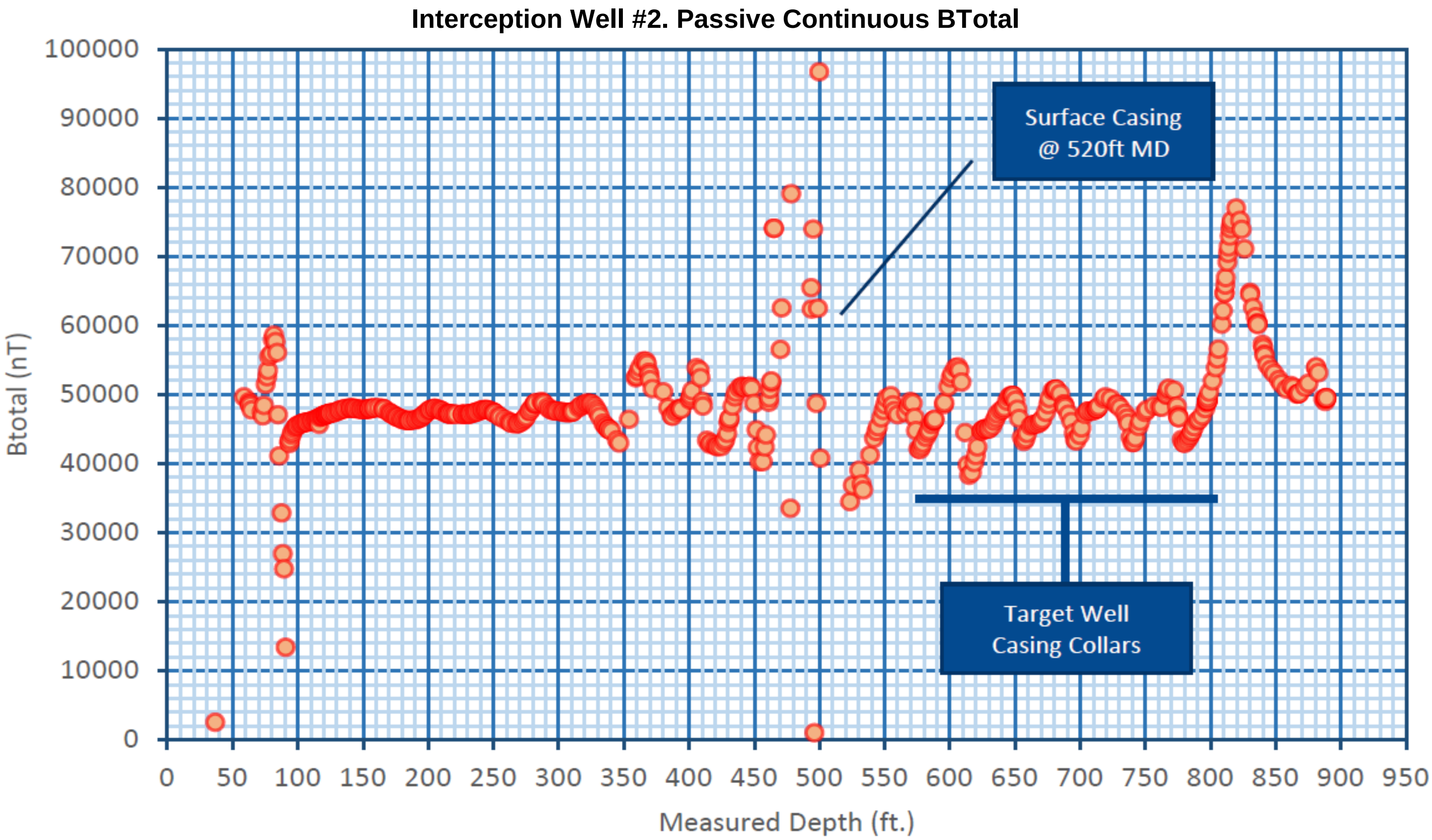

Figure 8. Interception Well #2. Passive Magnetic Ranging. Continuous BTotal

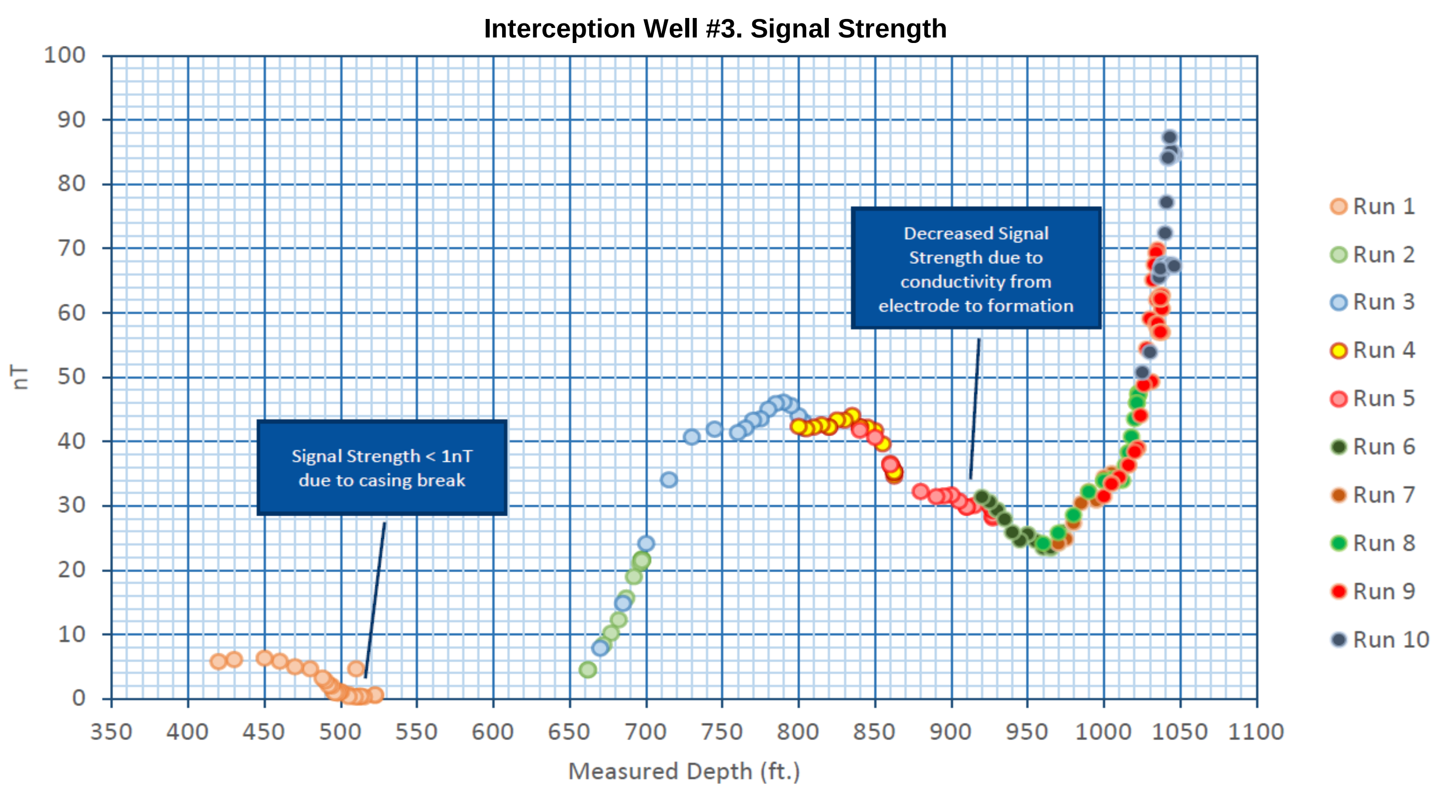

Figure 9. Interception Well #3. Primary wireline-conveyed formation current injection active magnetic ranging method. Signal strength

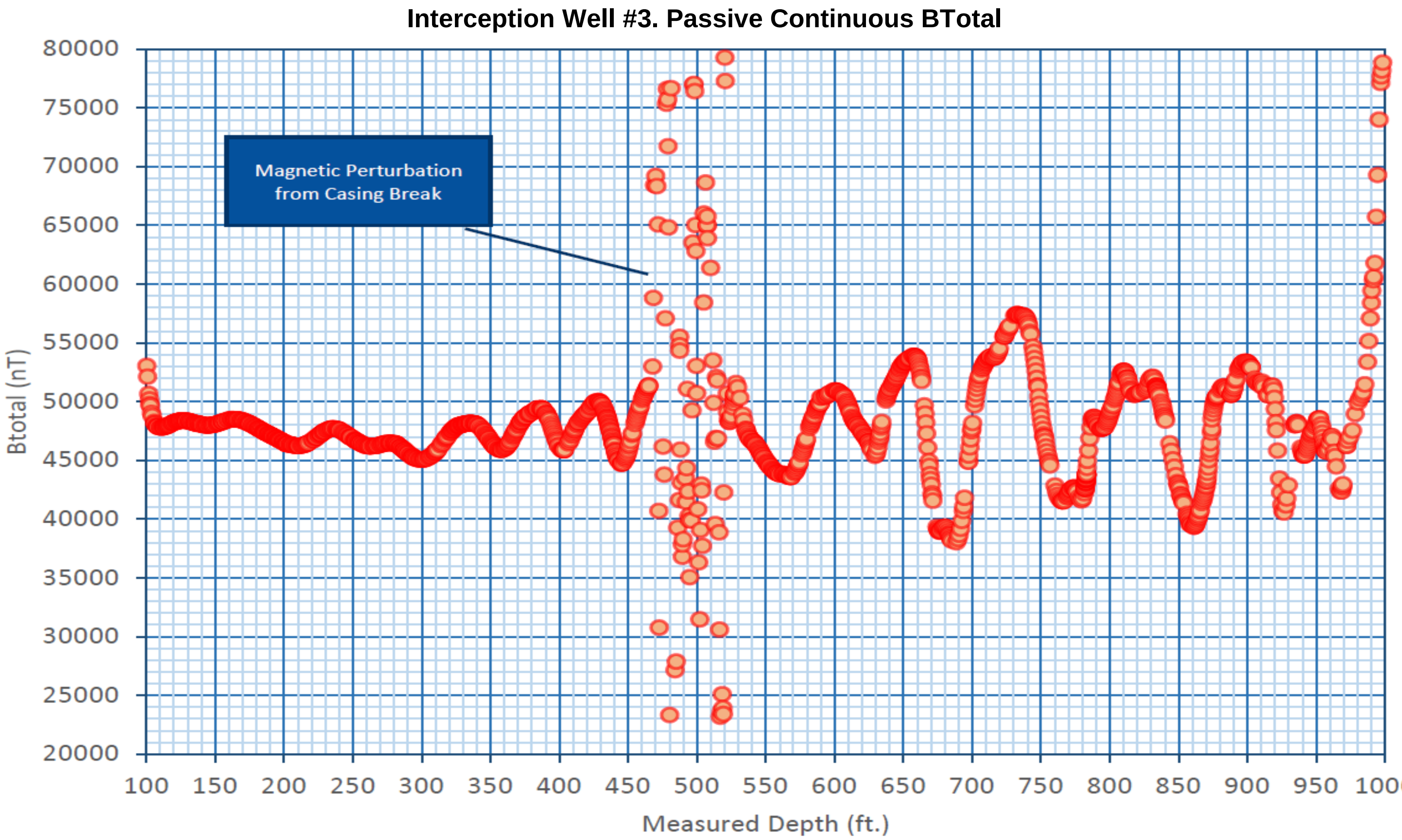

Figure 10. Interception Well #3. Passive Magnetic Ranging. Continuous BTotal

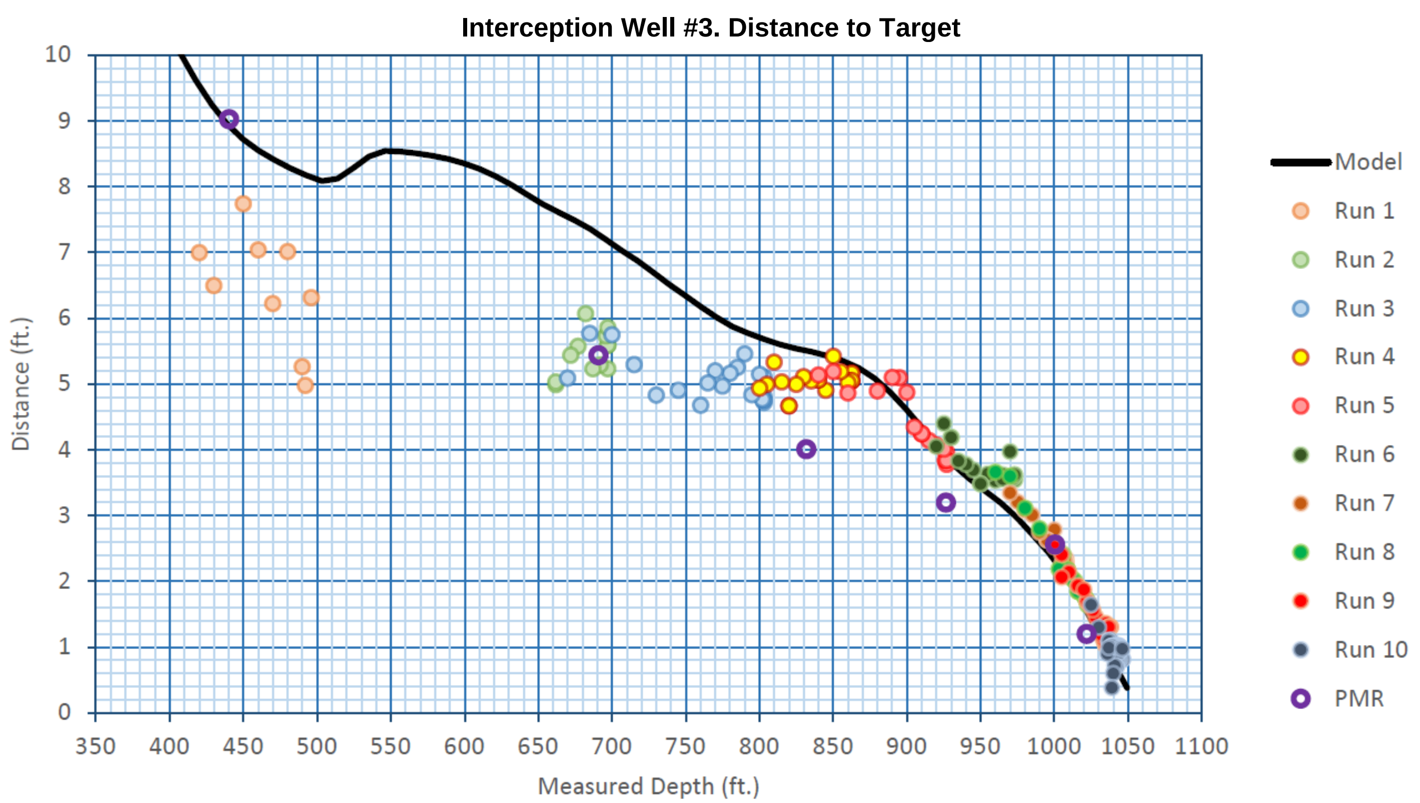

Figure 11. Interception Well #3. Primary wireline-conveyed active and passive (PMR) magnetic ranging methods. Distance to target

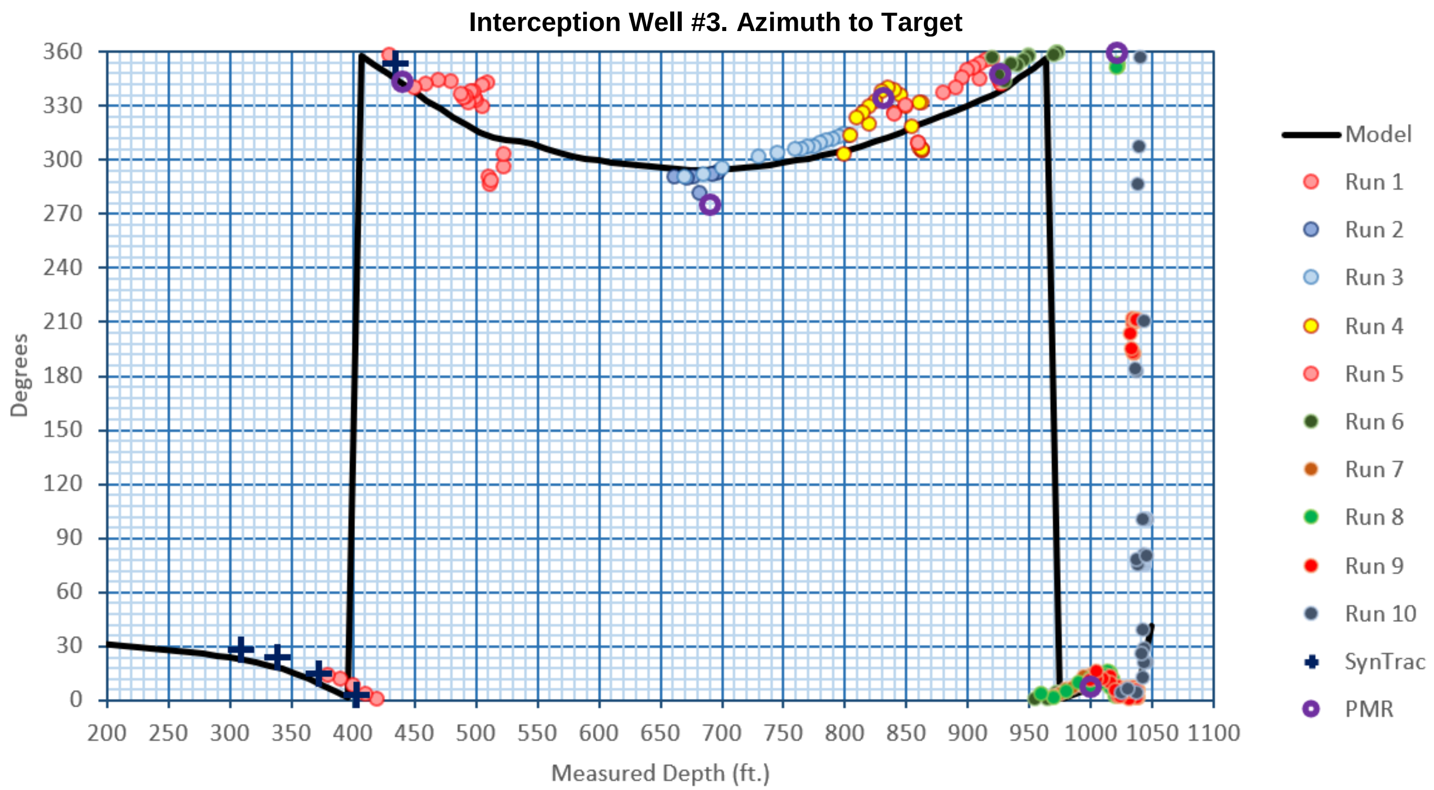

Figure 12. Interception Well #3. Primary wireline and MWD-based active (SynTrac) and passive (PMR) magnetic ranging. Azimuth to target

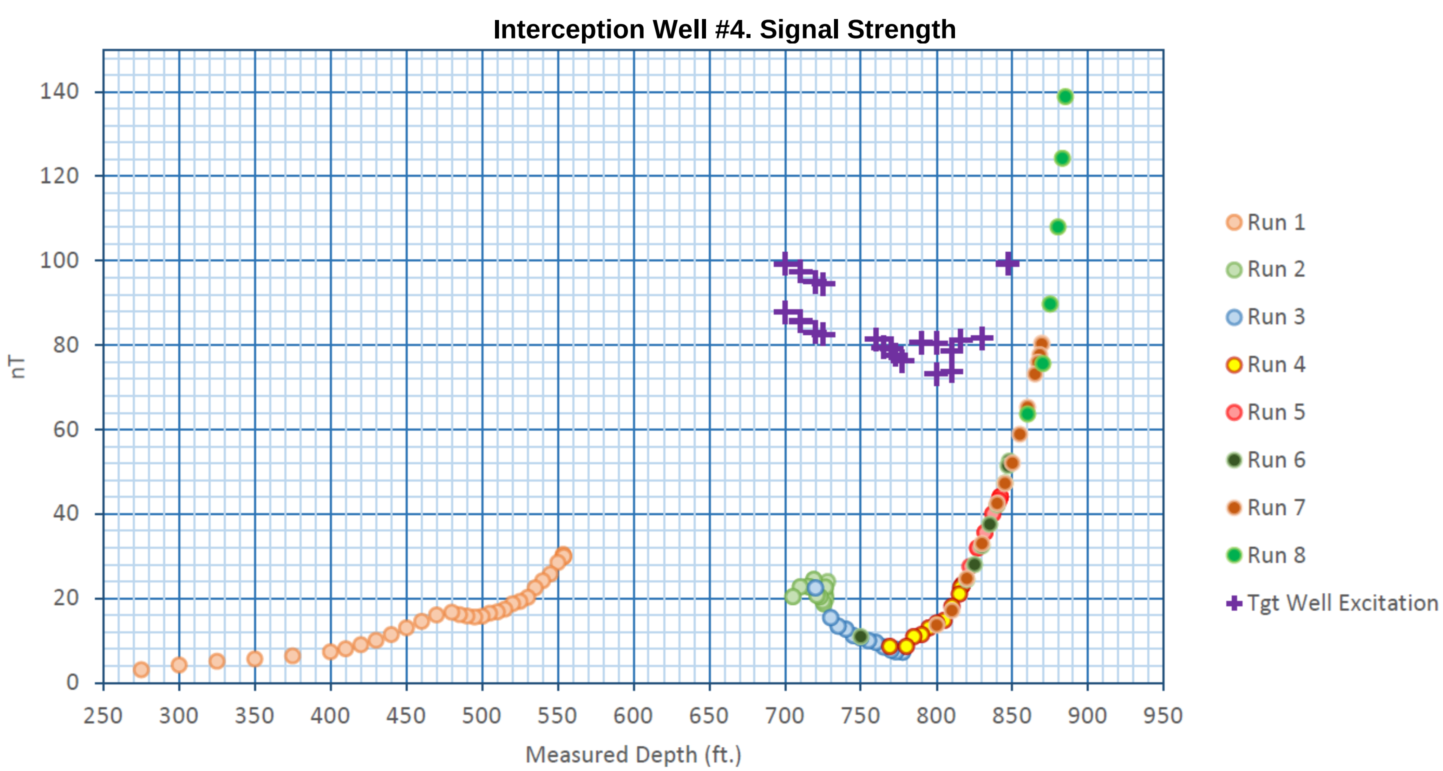

Figure 13. Interception Well #4. Primary wireline-conveyed active magnetic ranging method. Signal strength

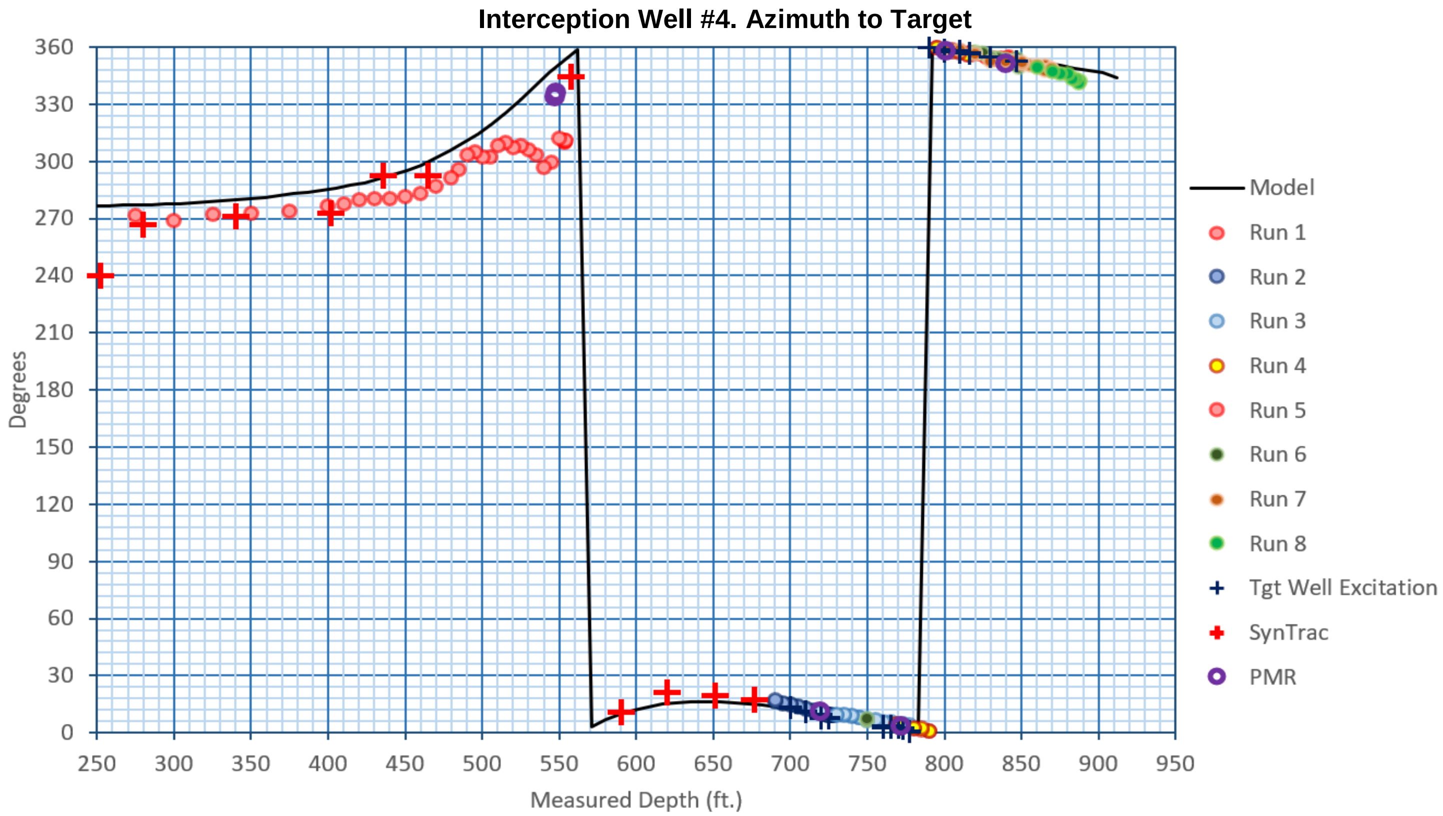

Figure 14. Interception Well #4. Primary wireline and MWD-based active (SynTrac) and passive (PMR) magnetic ranging. Azimuth to target

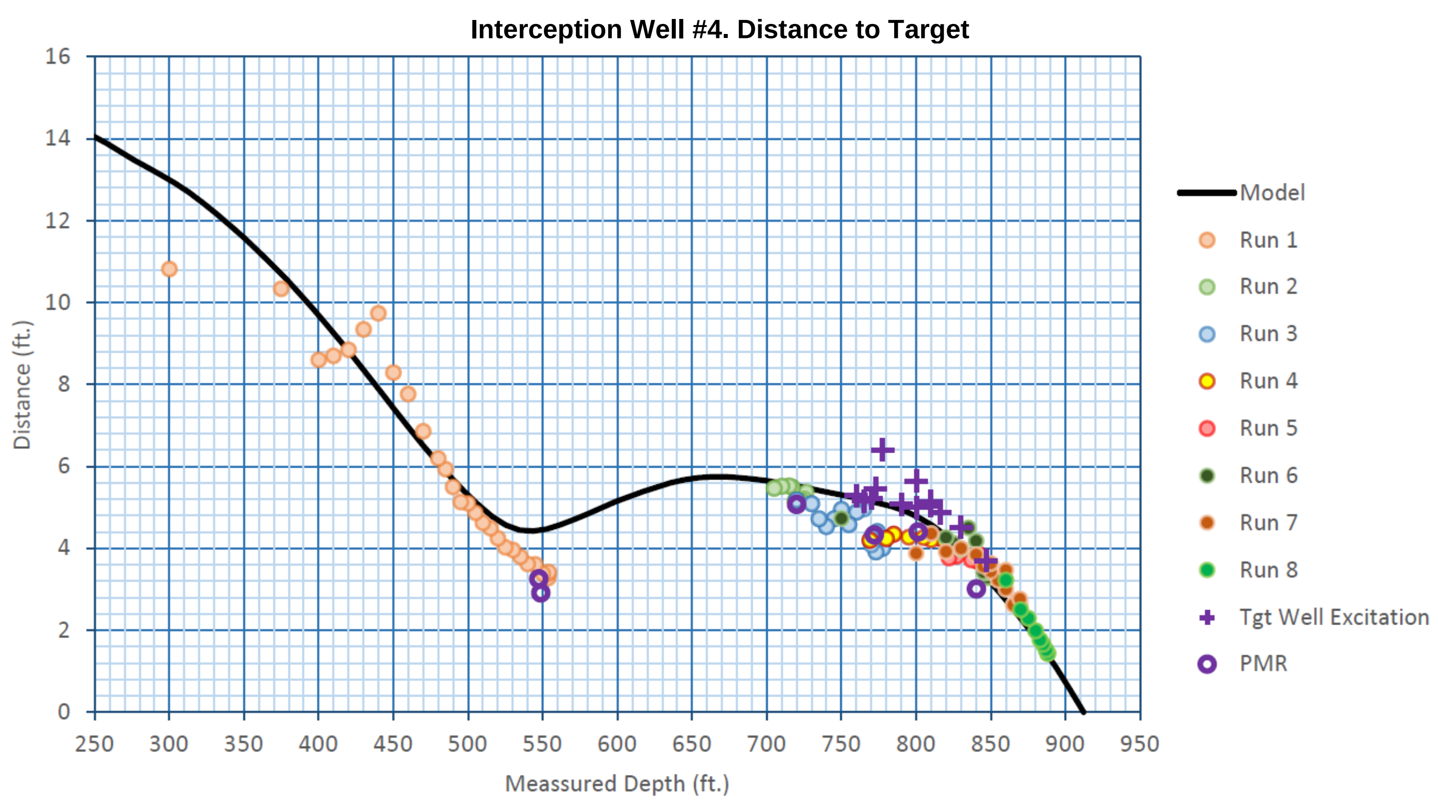

Figure 15. Interception Well #4. Primary wireline-conveyed active and passive (PMR) magnetic ranging methods. Distance to target

Figure 16. Interception Well #5. Primary wireline-conveyed formation current injection active magnetic ranging method. Signal strength

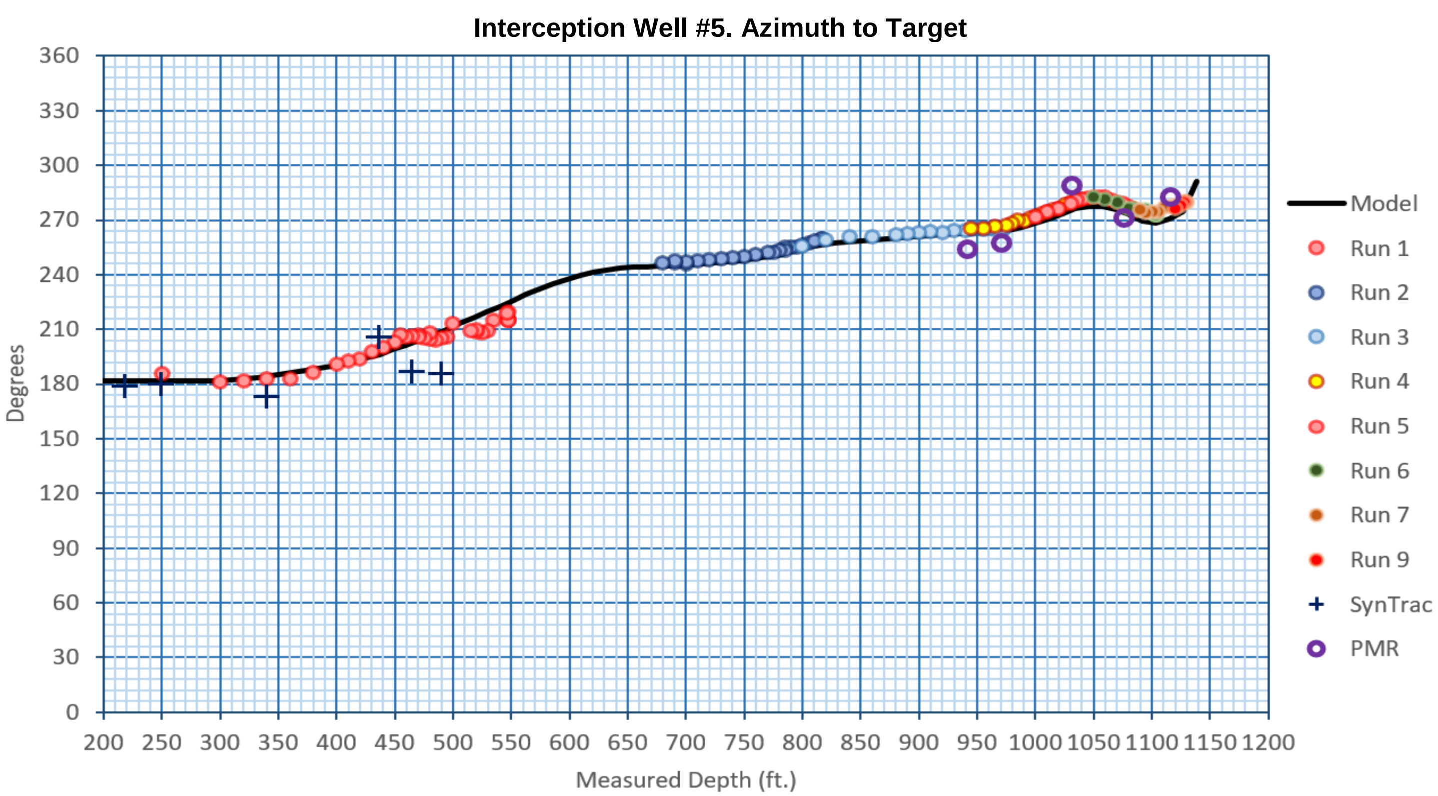

Figure 17. Interception Well #5. Primary wireline and MWD-based active (SynTrac) and passive (PMR) magnetic ranging. Azimuth to target

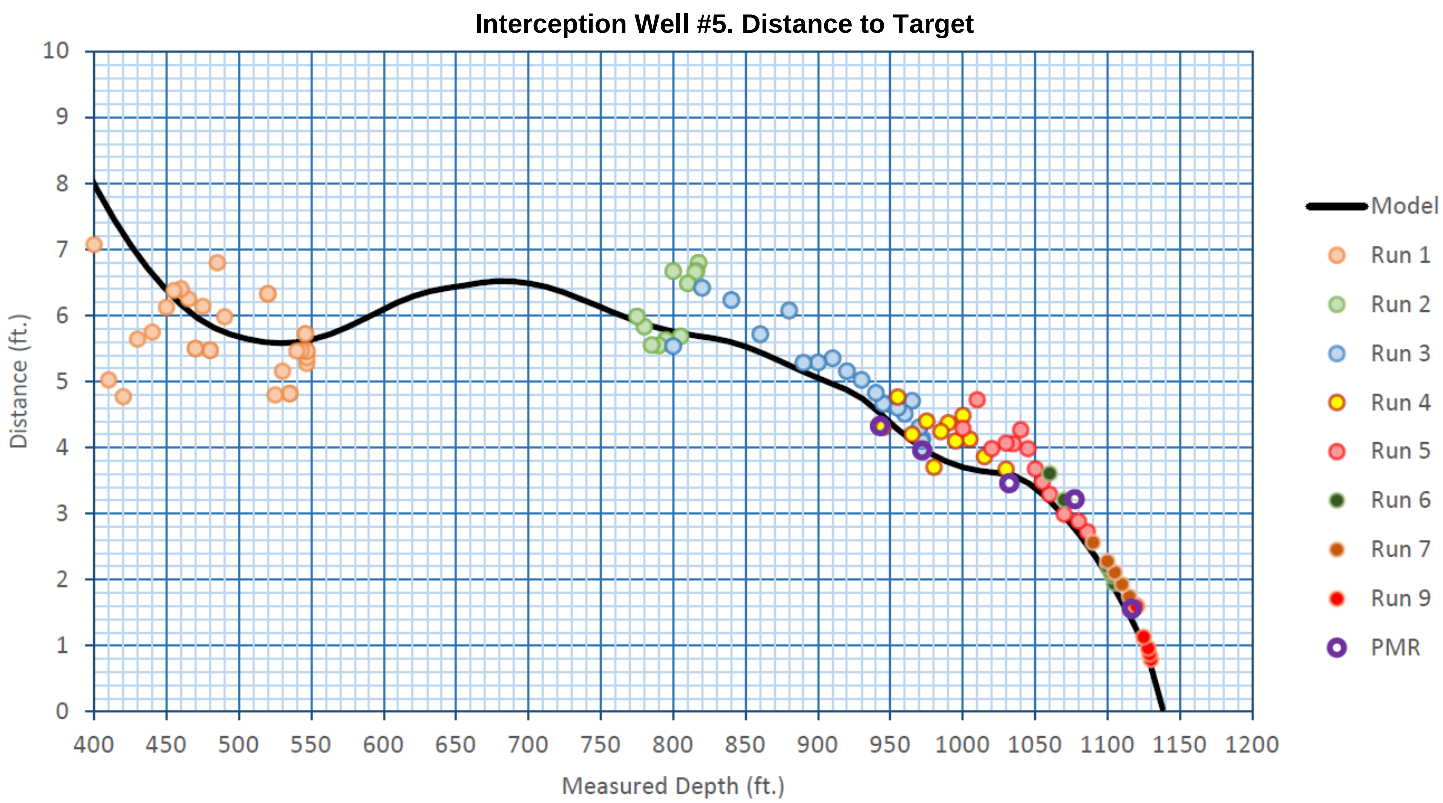

Figure 18. Interception Well #5. Primary wireline-conveyed active and passive (PMR) magnetic ranging methods. Distance to target

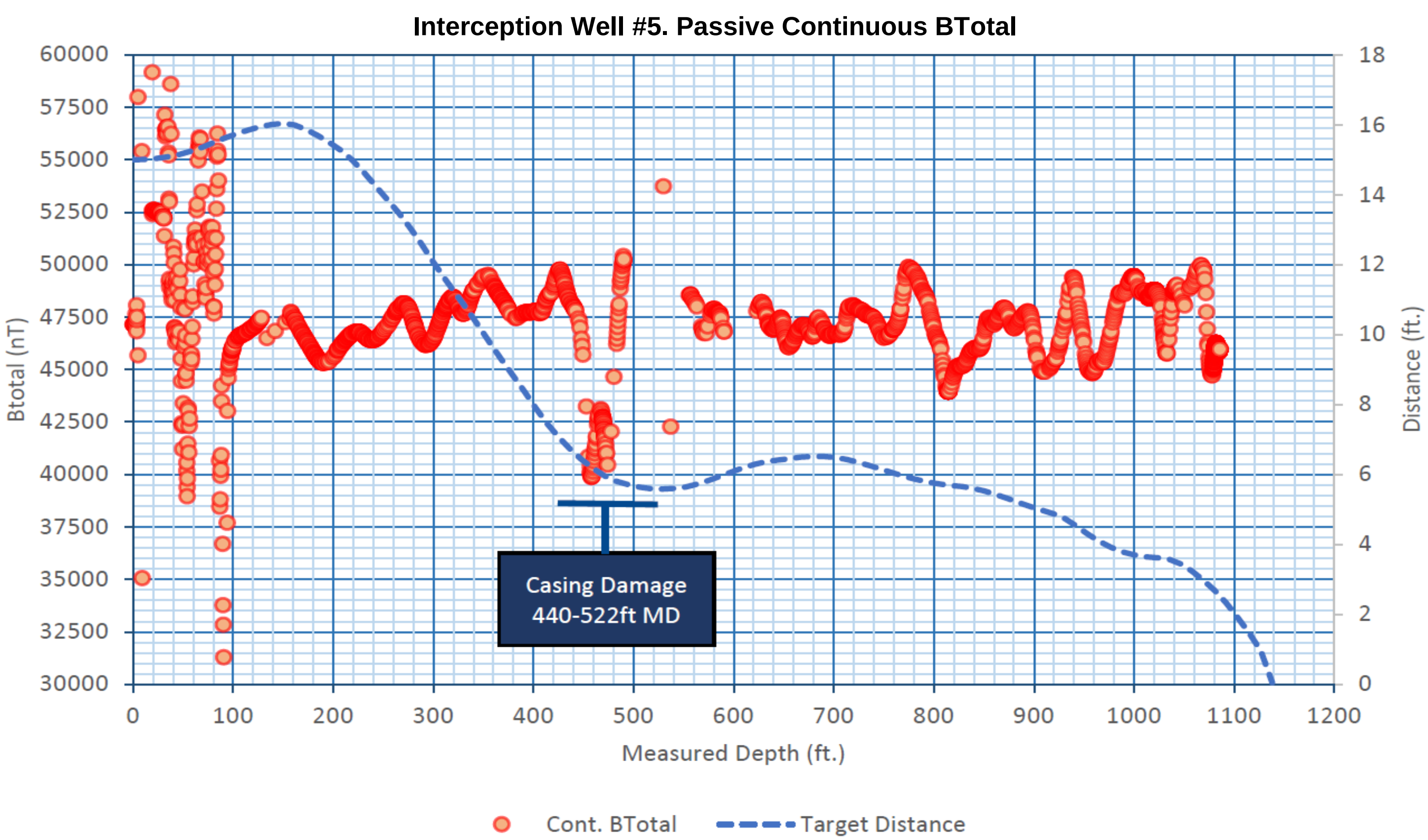

Figure 19. Interception Well #5. Passive Magnetic Ranging. Continuous BTotal

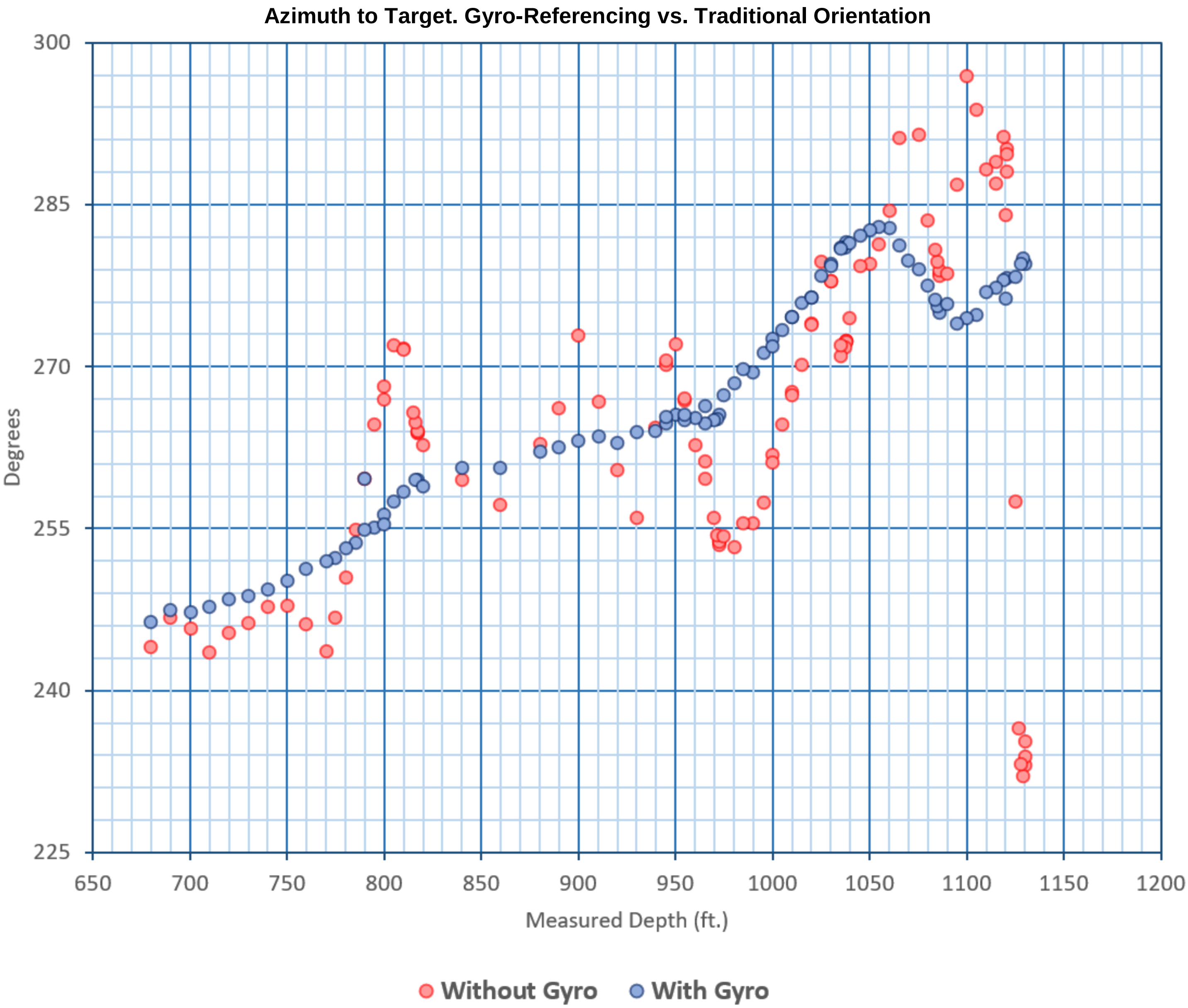

Figure 20. Azimuth to target: gyro-referenced ranging vs. traditional ranging orientation. Interception Well #5