Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Accelerating Closed-Loop Geothermal Well Construction: Cost and Time Reductions via While-Drilling Active Magnetic Ranging Technology

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Keywords: Geothermal Well Construction, Active Magnetic Ranging, AMR, Closed-loop Geothermal System, Wellbore Surveying, Relative Wellbore Placement, Drilling Cost Reduction, Operational Time Savings

ABSTRACT

Closed-loop geothermal systems demand precise lateral well connections to ensure efficient heat exchange and system integrity. Traditional wireline-conveyed Active Magnetic Ranging (AMR) surveys provide high accuracy but significantly increase operational time and cost due to repeated pump-and-reposition cycles and wireline handling. In this study, we present a novel While-Drilling AMR solution developed jointly with drilling and engineering teams and compare its performance against wireline AMR during parallel and intersection drilling of lateral well pairs. Both AMR systems were deployed across a closed-loop geothermal construction campaign, where laterals were drilled to target depth and consistently achieved sub-meter convergence, enabling safe and reliable lateral tie-ins. Data acquisition and processing workflows were optimized for real-time operation, eliminating the delays associated with wireline deployment. The While-Drilling AMR solution reduced operational time by approximately four days per lateral pair and lowered drilling costs by roughly €500,000 per pair. Workflow simplification enabled AMR surveys to be completed in less than 30% of the time required for wireline AMR operations. The While-Drilling AMR's accuracy met or exceeded wireline benchmarks, achieving positional uncertainty below 2% at 65-meter wellbore separation. These results demonstrate that integrating While-Drilling AMR into closed-loop geothermal well construction shortens project schedules, reduces capital expenditure, and supports accelerated learning curves in drilling operations - advancing scalable, cost-effective deployment of closed-loop geothermal systems worldwide.

1 INTRODUCTION

Geothermal energy offers a reliable, zero-emission heat and power source, but its scalability remains constrained by the technical complexity and cost of constructing deep, risk-managed wells (Al-Jubori, 2021). Closed-loop geothermal systems, such as the Eavor-Loop, rely entirely on engineered subsurface pathways rather than natural permeability, making accurate wellbore placement fundamental to system performance (Falcone, 2024).

In these systems, paired lateral wellbores must be drilled in parallel and guided to converge within sub-meter tolerances across several kilometers of horizontal displacement. Any deviation from the planned trajectory can reduce thermal efficiency, compromise hydraulic continuity, or jeopardize the ability to complete lateral tie-ins (Holmes, 2021).

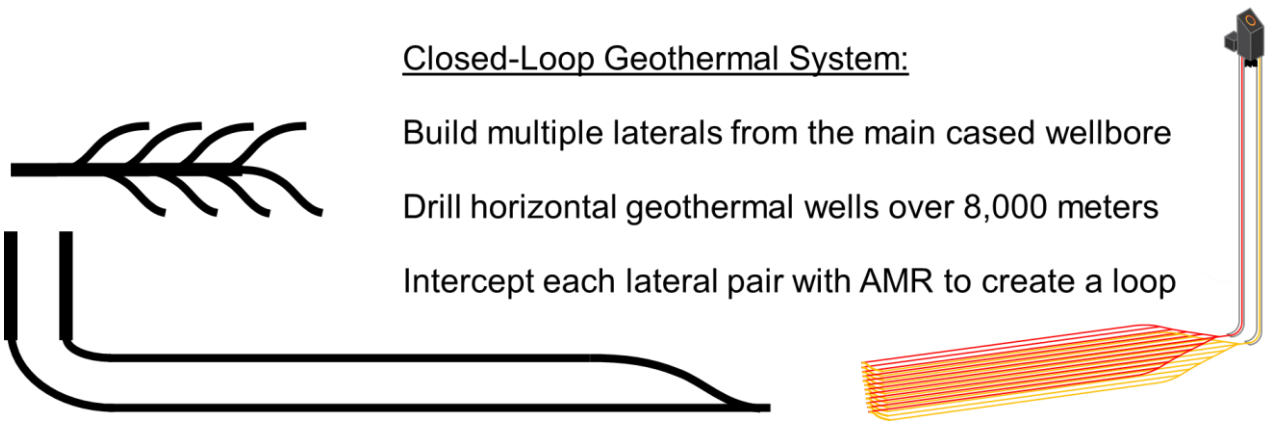


Figure 1. Eavor-Loop schematics with multi-lateral wellbores forming a closed-loop geothermal system

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Active Magnetic Ranging (AMR) provides the relative positioning required for complex subsurface geometries by measuring the magnetic field induced between a source and target well. Wireline-conveyed AMR remains the industry standard for high-accuracy ranging but substantially increases operational time due to repeated pump-and-reposition cycles and wireline handling (Husby, 2024).

To address these limitations, a While-Drilling AMR solution was developed to integrate continuous, real-time ranging directly into the drilling workflow. This approach maintains wireline-grade accuracy while removing the operational bottlenecks associated with wireline conveyance, enabling more efficient well construction and improving the reliability of lateral intersections in closed-loop geothermal systems.

2 PROBLEM STATEMENT

Closed-loop geothermal construction requires precise relative wellbore positioning to ensure reliable lateral tie-ins and long-term system performance. This level of precision is required to maintain thermal uniformity, enable efficient fluid circulation, and preserve the mechanical integrity of lateral connections at total depth. As the two laterals advance in parallel, the risk of positional divergence increases due to accumulated survey uncertainty, magnetic interference, and limitations in conventional absolute positioning workflows (ISCWSA, 2021). These tolerances must be maintained over horizontal displacements often exceeding 3,000 m, where even small survey biases can compound into large positional deviations.

Standard directional surveys, including magnetic and inertial systems, provide absolute wellbore position but do not offer the relative accuracy required to maintain sub-meter separation between paired laterals (Rassadkin, 2023). Compounding these uncertainties are magnetic disturbances from steel casing and downhole tool components, as well as temperature-driven sensor drift at extended depths. In east–west laterals, unfavorable Earth magnetic field geometry further degrades azimuthal control, accelerating error accumulation. These effects can result in lateral trajectories diverging from the target path or converging prematurely, jeopardizing thermal performance, hydraulic continuity, intersection geometry, and increasing the risk of collision. Although gyroscopic surveys improve absolute accuracy, they do not provide real-time relative tracking and are therefore insufficient as the primary ranging method in CLGS applications.

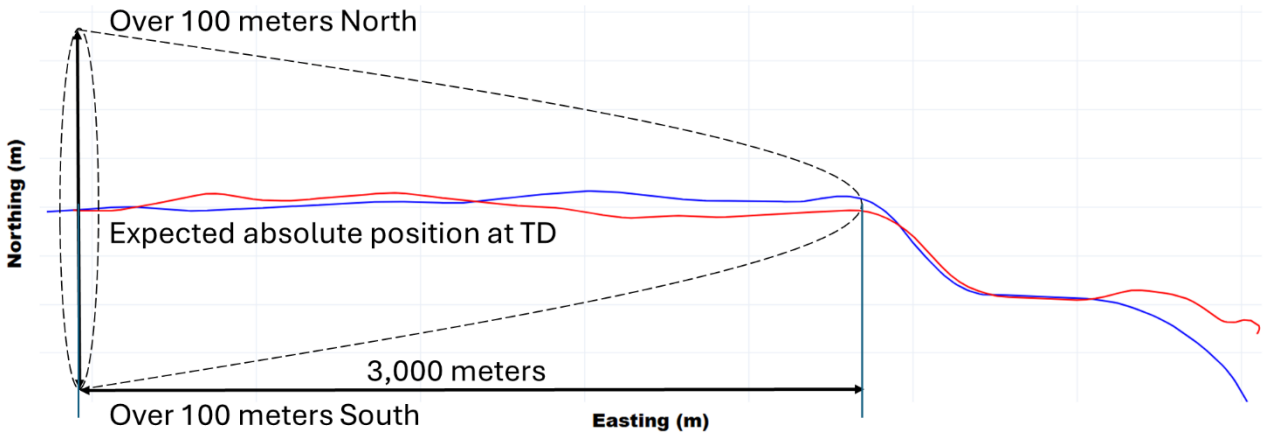


Figure 2. Accumulated positional errors exceeding 100 meters over the 3,000 m horizontal section.

Active Magnetic Ranging (AMR) is required to provide the high-accuracy relative positioning needed to drill paired laterals within sub-meter tolerances across multi-kilometer horizontal sections. Wireline-conveyed AMR has traditionally served as the industry benchmark for these operations due to its reliable, high-resolution ranging measurements. However, wireline AMR pump-and-reposition cycles typically consume several hours per run and must be repeated frequently as laterals approach planned tie-in depth. In parallel well construction, coordinating wireline operations between both laterals further compounds additional operational time.

Beyond time and cost penalties, repeated wireline conveyance introduces mechanical and operational risks – including cable sticking, tool damage, and exposure to open-hole conditions in high-angle or extended-reach wells. These limitations make wireline AMR a significant bottleneck in large-scale closed-loop geothermal development, despite its accuracy.

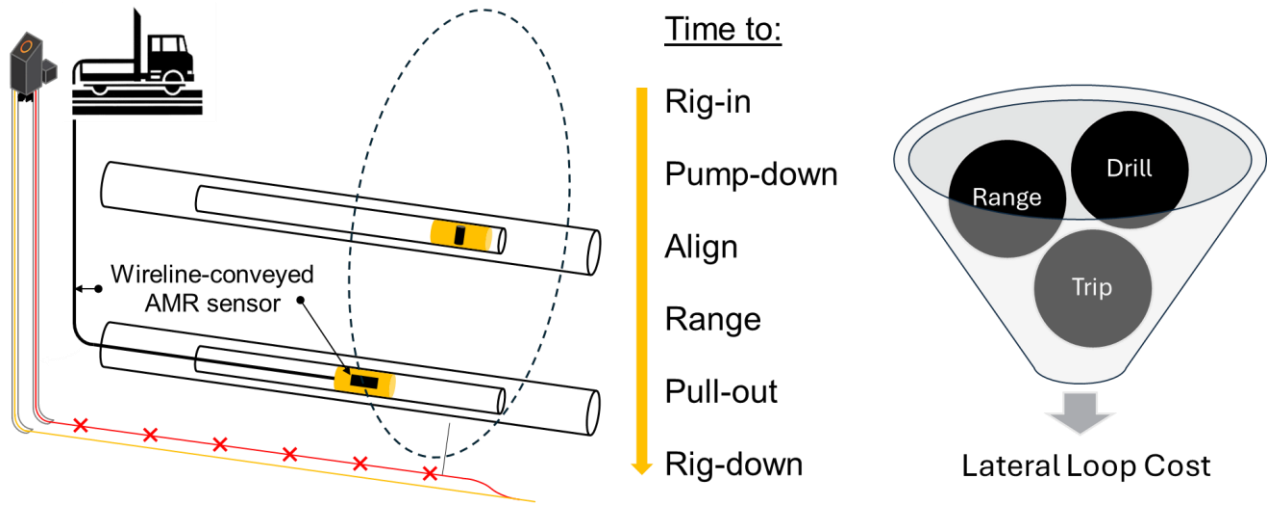


Figure 3. Time and cost impact of WL AMR operations with two rigs drilling simultaneously in CLGS.

The challenge addressed in this study is therefore to maintain wireline-grade ranging accuracy while minimizing operational delays and mechanical risk.

3 WHILE-DRILLING AMR DEVELOPMENT, RESULTS, AND TECHNOLOGY QUALIFICATION

A While-Drilling AMR system was developed to enable continuous relative positioning without interrupting drilling progress. To achieve this, magnetic ranging capability was integrated directly into the Bottom-Hole Assembly (BHA), enabling real-time measurement of induced magnetic fields while drilling ahead.

Initial development efforts focused on validating magnetic signal strength, optimizing transmitter–receiver spacing, and ensuring noise immunity at stand-off distances typical of closed-loop geothermal drilling (~60–70 m). Laboratory testing and controlled downhole experiments established baseline performance for sensor stability, thermal endurance, magnetometer calibration, and downhole data acquisition fidelity.

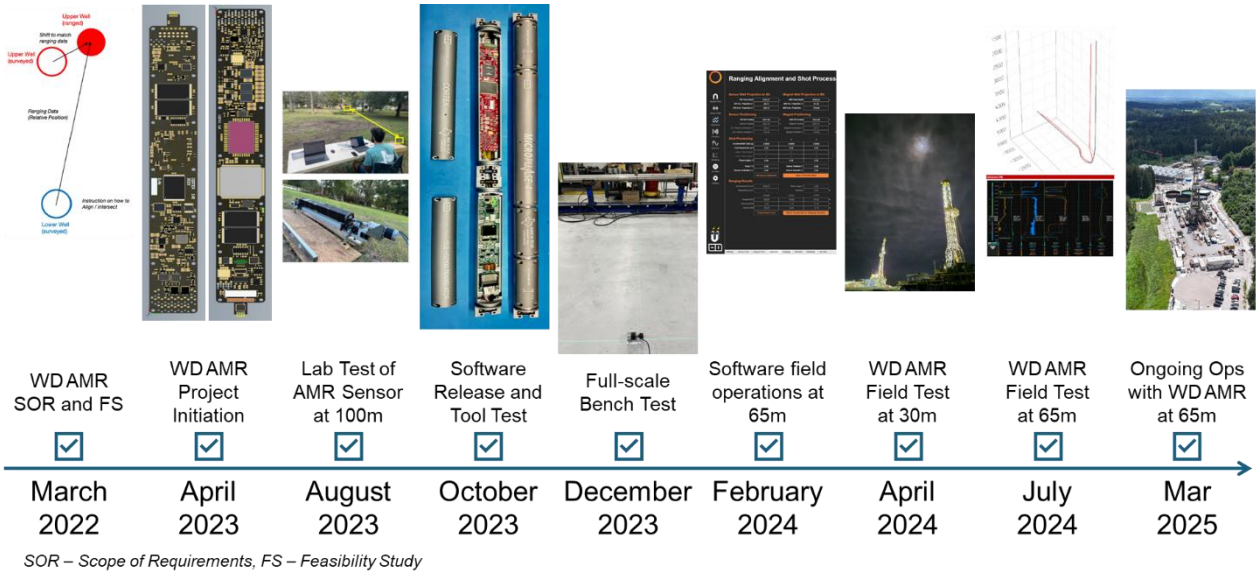


Figure 4. The technology development timeline of while-drilling active magnetic ranging solution.

Following these technical validations, the system was deployed in field operations in a “shadow-mode” configuration, operating in parallel with wireline AMR to benchmark measurement accuracy and ranging consistency.

The field trials also enabled iterative refinement of the system’s downhole calibration procedures, real-time signal filtering, and surface processing workflows. Improvements were made to account for toolface-dependent magnetic distortion, persistent downhole temperature gradients, and interference from BHA components.

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Enhancements to surface processing algorithms allowed ranging vectors to be computed and delivered to the directional driller in real time, significantly reducing operational latency.

Together, these development and qualification phases established the technical foundation for deploying the While-Drilling AMR system as a field-ready alternative to wireline AMR.

4 PERFORMANCE ANALYSIS OF WHILE-DRILLING AMR IN CLGS

4.1 Transition and Field Benchmarking in Lateral Pair 4

The While-Drilling AMR system was introduced during the drilling of Lateral Pair 4 to benchmark its performance against conventional wireline-conveyed AMR (WL-AMR). Both laterals were advanced in parallel from approximately 5,000 m MD to 8,000 m MD, with WL-AMR being a primary ranging method to establish a high-accuracy baseline before integrating the while-drilling system.

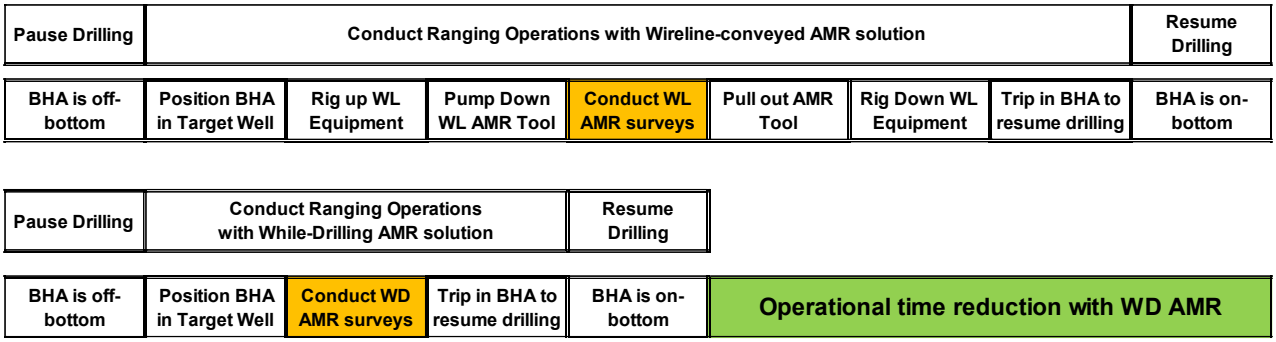


Figure 5. Simplified operational timeline in CLGS comparing WL AMR and WD (While-Drilling) AMR operations.

Figure 5 compares the operational workflows of WL-AMR and While-Drilling AMR.

Wireline AMR workflow requires:

- Positioning BHA in both the Target and Intercept Wells
- Rigging up wireline equipment
- Running in hole and pumping down the AMR tool
- Stabilizing and acquiring AMR data
- Retrieving the tool and processing results at surface
- Rigging down wireline equipment
- Repositioning BHA to resume drilling

This sequence must be repeated for every ranging run, resulting in multi-day delays.

While-Drilling AMR workflow requires only:

- Positioning BHA in both the Target and Intercept Wells
- Collecting and processing ranging measurements in real time
- Repositioning BHA to resume drilling

Both wells can continue drilling immediately after measurement acquisition. This simplified process reduces logistical complexity, eliminates rig-time exposure related to wireline handling, and enables higher-frequency ranging without operational penalty.

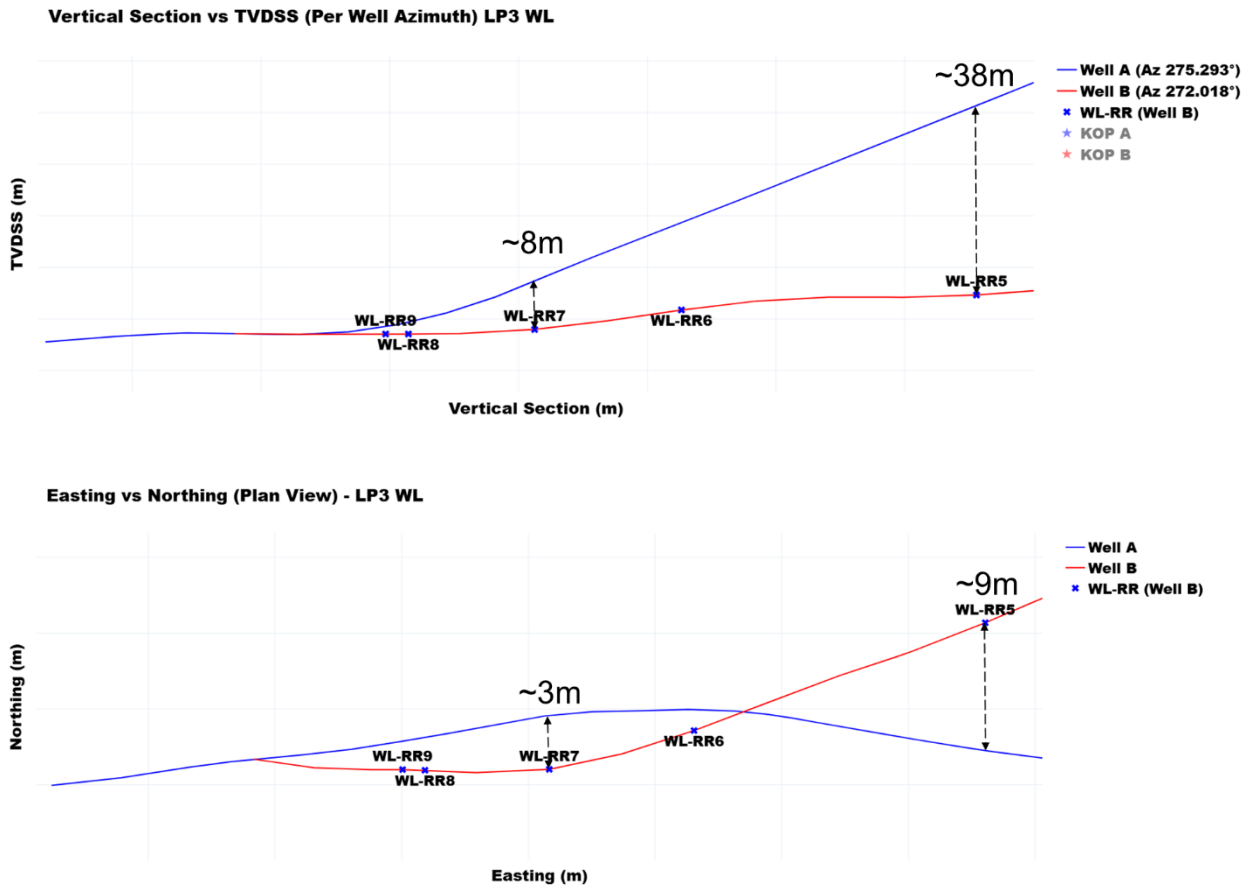


Figure 6. Vertical Section and Map View of Lateral Pair (LP) 3 interception phase, ranged with Wireline AMR.

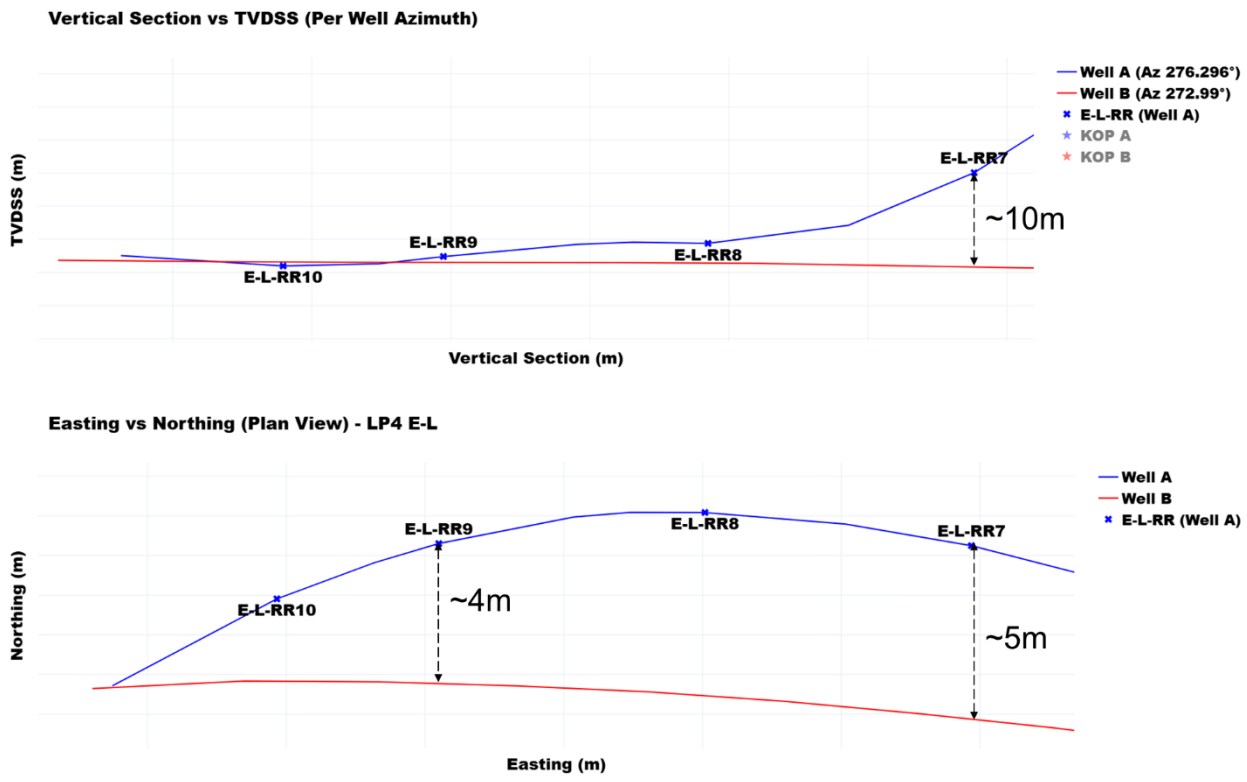


Figure 7. Vertical Section and Map View of Lateral Pair 4 interception phase, ranged with WD AMR (E-L RR).

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Figures 6 and 7 illustrate the ranging results from WL-AMR (Lateral Pair 3) and While-Drilling AMR (Lateral Pair 4), respectively. WL-AMR required multiple ranging runs at decreasing separations to guide the wells into final convergence. The While-Drilling AMR system required similar number of ranging runs to achieve equivalent intersection confidence. This enhanced spatial resolution contributed to the reliable first-attempt intersection in Lateral Pair 4, confirming the WD AMR system's suitability for CLGS geometries.

4.2 Operational and Economic Performance in Laterals 5 and 6

After successful qualification in Lateral Pair 4, the While-Drilling AMR system was used as the primary ranging method in Laterals 5 and 6. The system operated continuously throughout both the parallel drilling and intersection phases, transmitting real-time magnetic field data to surface, where automated algorithms computed the relative offset and ranging vector.

Compared to historical WL-AMR operations, the While-Drilling AMR system delivered:

- Time savings of ~4 days per lateral pair
- Cost savings of ~€500,000 per pair, driven by elimination of wireline equipment handling
- Higher survey density and improved convergence control
- Fewer corrective runs, due to continuous feedback

During the parallel phase of Laterals 5 and 6, three while-drilling surveys were collected at ~60–65 m stand-off. During the intersection phase, six surveys tracked convergence from ~60 m to ~5 m, providing precise guidance (Figures 8 and 9).

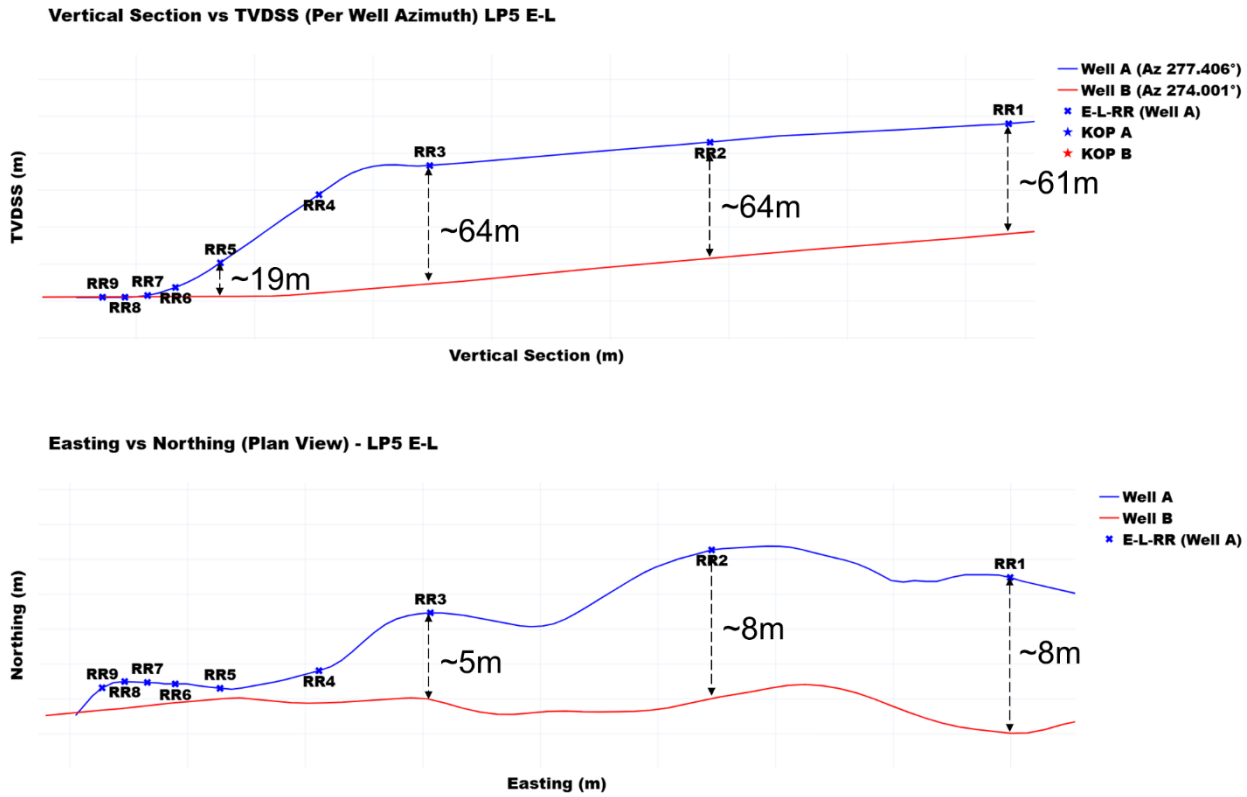


Figure 8. Vertical Section and Map View of Lateral Pair 5, in parallel drilling and interception phase, ranged with while-drilling AMR (E-L RR).

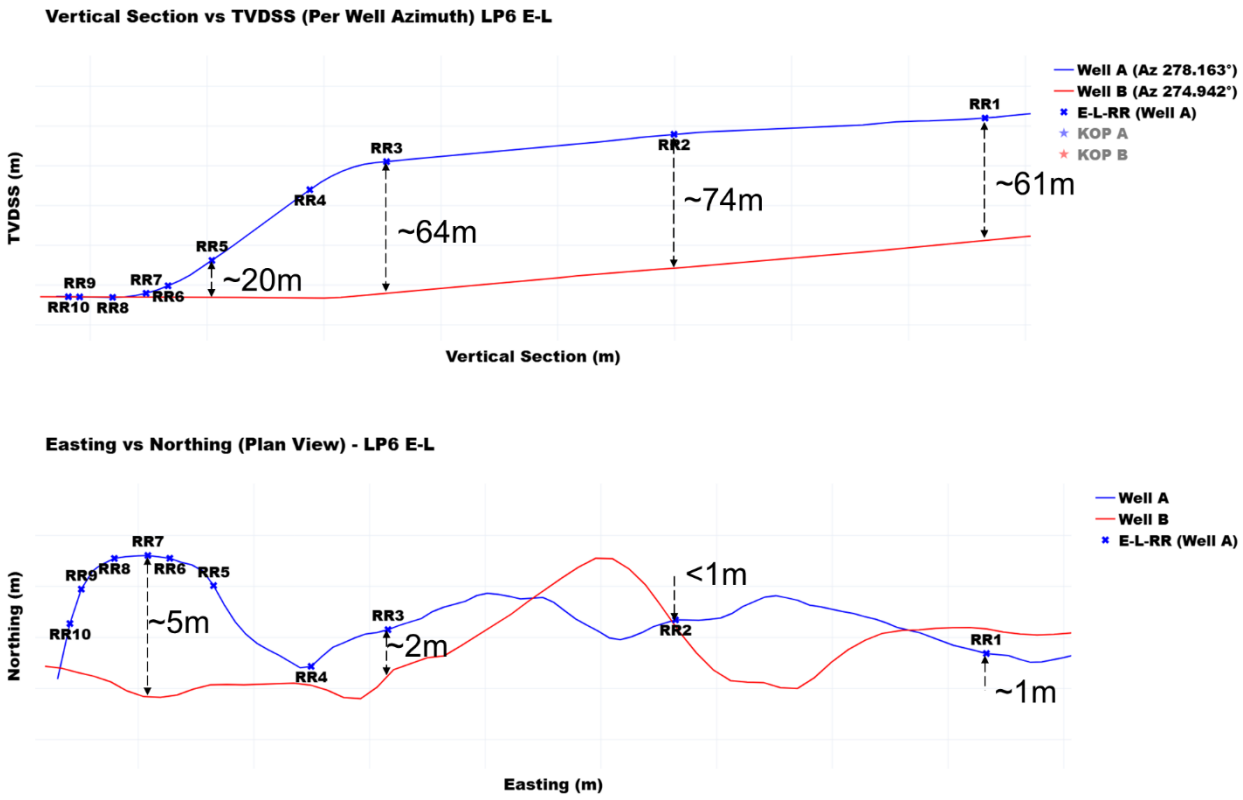


Figure 9. Vertical Section and Map View of Lateral Pair 6, in parallel drilling and interception phase, ranged with while-drilling AMR.

For Lateral Pair 6, most of the parallel drilling was performed within the same vertical plane, as illustrated in Figure 9 by while-drilling ranging runs RR1–RR4, during which the relative vertical separation remained below 2 m while the lateral spacing was maintained at approximately 60–70 m. As the wells approached the final tie-in point, azimuthal steering was used to approach the reference well from the northern side (RR5–RR10), while maintaining both wellbores within approximately the same horizontal plane. During the final interval, the intercept wellbore was drilled using fixed depth control with variable azimuth control to accurately intersect the target wellbore.

4.3 Comparative Results and Lessons Learned

A comparative assessment of wireline AMR and While-Drilling AMR was completed across six lateral pairs. Table 1 summarizes the operational metrics, demonstrating consistent improvements in operational uptime when using the while-drilling approach. The transition to real-time ranging reduced total AMR-related operational time from 131 hours to 38 hours per lateral pair. Across three lateral pairs, the cumulative schedule compression totaled 11 operational days, resulting in cost savings exceeding €1.5 million.

Transitioning from wireline to While-Drilling AMR eliminated risks and failures, associated with wireline conveyance:

- Cable sticking in high-angle or ERD sections and inability to convey due to pump off events
- Mechanical tool damage and failures, repetitive issues with swab cups on a wireline tool string
- Well-control exposure during open-hole wireline deployment
- Surface/rig-floor handling hazards

Field deployment of the While-Drilling AMR system also yielded several operational and technical insights. High-frequency calibration of downhole magnetometers was required to manage toolface-dependent magnetic distortion, particularly in long horizontal sections. Real-time communication between drilling and ranging personnel proved essential for effective steering during the final convergence phase. Continuous bottom-hole exposure validated the thermal stability and signal integrity of the integrated magnetometer sensors. These lessons enabled immediate refinement of field procedures, processing workflows, and operational practices for

subsequent lateral pairs, demonstrating the adaptability of the while-drilling system under active drilling conditions.

Table 1. Performance analysis of WL vs non-WL AMR in Loop 1 of CLGS.

Parameter	Wireline AMR	While-Drilling AMR	Improvement
Ranging Accuracy	< 2%	< 2%	–
AMR Operational Time per Lateral pair	131 hours per pair	38 hours per pair	70 % reduction

The combined results confirm that the While-Drilling AMR system delivers wireline-grade accuracy with substantially improved operational efficiency and reduced complexity. By eliminating wireline conveyance, the system enhances measurement density, minimizes ranging operational time, and improves the reliability of lateral tie-ins in closed-loop geothermal well construction.

5 FUTURE IMPROVEMENT AND OTHER WELL CONSTRUCTION APPLICATIONS

The successful field deployment of the While-Drilling Active Magnetic Ranging (AMR) system has demonstrated the viability of continuous, real-time ranging for precise wellbore placement in closed-loop geothermal systems (CLGS). Building on this foundation, future development will focus on increasing downhole intelligence, enhancing telemetry bandwidth, and advancing autonomous subsurface navigation capabilities to further expand the operational envelope of WD AMR.

5.1 Downhole data processing and smart telemetry

Current WD-AMR operations transmit raw magnetic field data to the surface for processing and interpretation. Next-generation systems will integrate downhole computational modules capable of filtering, interpreting, and compressing magnetometer data in real time. By transmitting only high-value, preprocessed ranging vectors through mud-pulse telemetry, these systems will reduce bandwidth requirements and provide faster positional updates to the directional driller.

5.2 Dual-BHA communication and autonomous relative positioning

A more advanced configuration will enable two active BHAs drilling in parallel to share relative position information directly through downhole telemetry. Each assembly would locally process magnetic field data, exchange relative offsets, and autonomously adjust its steering commands to maintain the required spacing or convergence trajectory. This BHA-to-BHA communication loop would enable near-autonomous wellpair alignment over long lateral sections exceeding 3,000 m.

5.3 Wired drill pipe and coiled tubing integration

Integrating WD AMR with wired drill pipe or wired coiled tubing would further improve data bandwidth and latency. High-speed telemetry would support the full transmission of magnetic field vectors, temperature-compensated data, and real-time trajectory updates, enabling advanced drilling automation and greater ranging accuracy at extended depths.

5.4 Downhole data fusion and PMR integration

Combining WD AMR with Passive Magnetic Ranging (PMR), gyroscopic measurements, accelerometers, and electromagnetic sensors will enable multi-sensor fusion workflows that enhance spatial accuracy and robustness in magnetically complex formations. A hybrid AMR–PMR system could provide continuous relative positioning even when active transmission is limited, broadening the operational envelope of closed-loop geothermal drilling.

5.5 Broader Applications Beyond Geothermal

While-Drilling AMR has the potential to transform subsurface construction and resource development across multiple industries:

- Unconventional oil and gas batch drilling: improving well spacing and collision avoidance in high-density pads.
- Steam-Assisted Gravity Drainage (SAGD): enhancing horizontal wellpair alignment to optimize steam chamber growth and recovery.
- Deep mineral exploration and mining: enabling precise directional guidance toward ore bodies or geophysical targets.
- Selective solution mining: allowing real-time well alignment to optimize dissolution patterns and reduce subsurface risks.
- Civil and tunneling engineering: supporting accurate intersection and alignment control for tunnels, pipelines, and deep urban infrastructure.
- Deep subsurface sensing and communication networks: enabling magnetically linked channels for long-range autonomous telemetry.
- Hybrid and emerging geothermal architectures: including open/closed-loop hybrids, Enhanced Geothermal Systems (EGS), and supercritical geothermal concepts.

6 CONCLUSIONS

Closed-loop geothermal systems require sub-meter relative wellbore placement to ensure hydraulic integrity, thermal efficiency, and reliable lateral tie-ins across multi-kilometer horizontal sections. Conventional wireline-conveyed AMR has historically provided the accuracy necessary to achieve first-attempt intersections, but its reliance on pump-and-reposition cycles, rig-time exposure, and conveyance risk imposes significant operational inefficiencies in parallel well construction.

The introduction of a While-Drilling AMR system addressed these limitations by delivering continuous, BHA-integrated ranging without interrupting drilling progress. Field deployment demonstrated wireline-grade accuracy with sub-meter convergence and <2% positional uncertainty at ~65 m stand-off. In shadow-mode and subsequent primary applications, the system achieved 100% first-attempt intersections, validating its effectiveness for complex closed-loop geometries. Across the full drilling program, the while-drilling approach reduced AMR-related operational time by approximately four days per lateral pair, corresponding to direct rig-cost savings of roughly €500,000 per pair.

Operational risk was also reduced. Eliminating wireline conveyance removed failure modes such as cable sticking, mechanical tool damage, and open-hole exposure during wireline deployment. The BHA-integrated design simplified logistics and improved reliability, particularly in high-angle and extended-reach drilling environments.

The campaign underscored key practices necessary for repeatable performance: frequent downhole magnetometer calibration to mitigate toolface-dependent distortion, real-time communication between drilling and ranging teams, and rapid refinement of processing workflows based on field data. These components were critical to consistent intersection success and the observed schedule and cost improvements.

Looking forward, integrating downhole data processing, dual-BHA communication, high-bandwidth telemetry, and multi-sensor fusion will expand the operational envelope of While-Drilling AMR. As these enhancements mature, the system will evolve into a comprehensive subsurface navigation platform, enabling continuous spatial awareness and predictive trajectory control.

In sum, the While-Drilling AMR adoption shortens project schedules, lowers capital cost, and reduces execution risk, supporting scalable deployment of closed-loop geothermal systems.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the investors, sponsors, and strategic partners who enabled the development and deployment of the While-Drilling Active Magnetic Ranging (AMR) system. We extend our appreciation to the industry experts, research laboratories, and technical advisors whose insights were essential during the concept development, modeling, and experimental validation phases.

We also thank the field operations personnel, drilling supervisors, directional drilling crews, and engineering teams whose commitment and expertise ensured the successful qualification and field trials of the technology. Their collaboration across disciplines – from systems engineering to real-time operations – was central to demonstrating the performance, reliability, and operational value of the While-Drilling AMR system.

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