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Survey Management and Azimuthal Accuracy in Closed-Loop Geothermal Laterals

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1 ABSTRACT

Closed-loop geothermal systems require drilling laterals in parallel at a defined separation and maintaining their relative spacing within a tight tolerance over several kilometers of measured depth (MD). In east–west drilling environments, magnetic survey quality degrades significantly due to unfavorable geomagnetic field geometry, axial magnetic interference, and drift in standard Measurement-While-Drilling (MWD) azimuth. Across the first lateral pairs in this program, MWD-only surveys exhibited azimuth deviations of up to 3°, resulting in more than 200 m of unintended lateral divergence. Multi-Station Analysis (MSA) reduced high-frequency noise but did not resolve the underlying systematic azimuth bias.

To improve directional accuracy, a hybrid survey strategy was implemented using drop-in gyroscopic sensors, Gyro-While-Drilling (GWD) tools, controlled curve-calibration techniques using in-hole reference geometry, and calibrated MWD azimuth modeling. In later wells, GWD delivered high-accuracy north-referenced surveys but exhibited temperature limitations and reliability constraints. The controlled curve-calibration methodology, tested using 20° turn sections, substantially improved magnetic field geometry and enabled robust MSA performance. By integrating MWD, GWD, and Active Magnetic Ranging (AMR) measurements, a corrected MWD azimuth model achieved approximately ±1° accuracy along the lateral sections.

AMR measurements at each lateral pair intersection provided independent ground-truth validation of relative spacing and confirmed the effectiveness of the corrected survey management workflow. The resulting process minimized azimuth drift, improved directional repeatability across multiple laterals, and reduced reliance on continuous gyro deployment. This paper presents the survey quality challenges encountered, the correction models developed, and the recommended surveying workflow for closed-loop geothermal drilling campaigns.

2 INTRODUCTION

Closed-loop geothermal systems require drilling paired laterals in parallel at a defined stand-off distance and maintaining that spacing with minimal variation over several kilometers of measured depth (MD). This geometric precision is essential for hydraulic performance, thermal efficiency, and safe execution of lateral tie-ins. Achieving such accuracy is particularly challenging in east–west drilling environments, where low geomagnetic dip angles, limited cross-axial magnetic field strength, and strong axial interference from the drillstring degrade the quality of magnetic measurements. Under these conditions, Measurement-While-Drilling (MWD) azimuth may appear stable at surface while deviating significantly from true wellbore direction (ISCWSA, 2017).

The drilling program described in this paper demonstrated these challenges in practice. Both wells began from casing shoes near 5,000 m MD within the same vertical plane, with the A well positioned 65 m above the B well. As illustrated in Figure 1, the plan was to introduce a small azimuthal turn, bring both laterals onto a 270° tangent, maintain a 65 m separation for ~2,200 m, and then steer the A well downward over the final 500 m to intersect the B well at approximately 8,000 m measured depth (MD).

Despite the apparent simplicity of this well geometry, significant survey uncertainty emerged early. Pre-job modeling assumed MWD azimuth bias would remain within 1° (ISCWSA, 2021), enabling the wells to remain within planned separation limits. Instead, within the first 800 m from the casing shoe the two laterals diverged sharply while MWD surveys continued to report a nominal 270° azimuth. Contingency AMR measurements revealed a separation exceeding 120 m, and subsequent drop-gyro checks confirmed that both wells were drifting in opposite azimuthal directions.

Corrective steering relied on gyro anchoring and AMR-based relative positioning to return the wells toward the planned separation. The lateral tie-in was ultimately achieved on the first attempt, but only after significant operational overhead, including multiple gyro runs, BHA-level modifications, and extensive survey processing time. Subsequent wells depended heavily on gyros for absolute positioning and AMR for tie-in validation, exposing the cost and time risks associated with gyro-centric survey strategies.

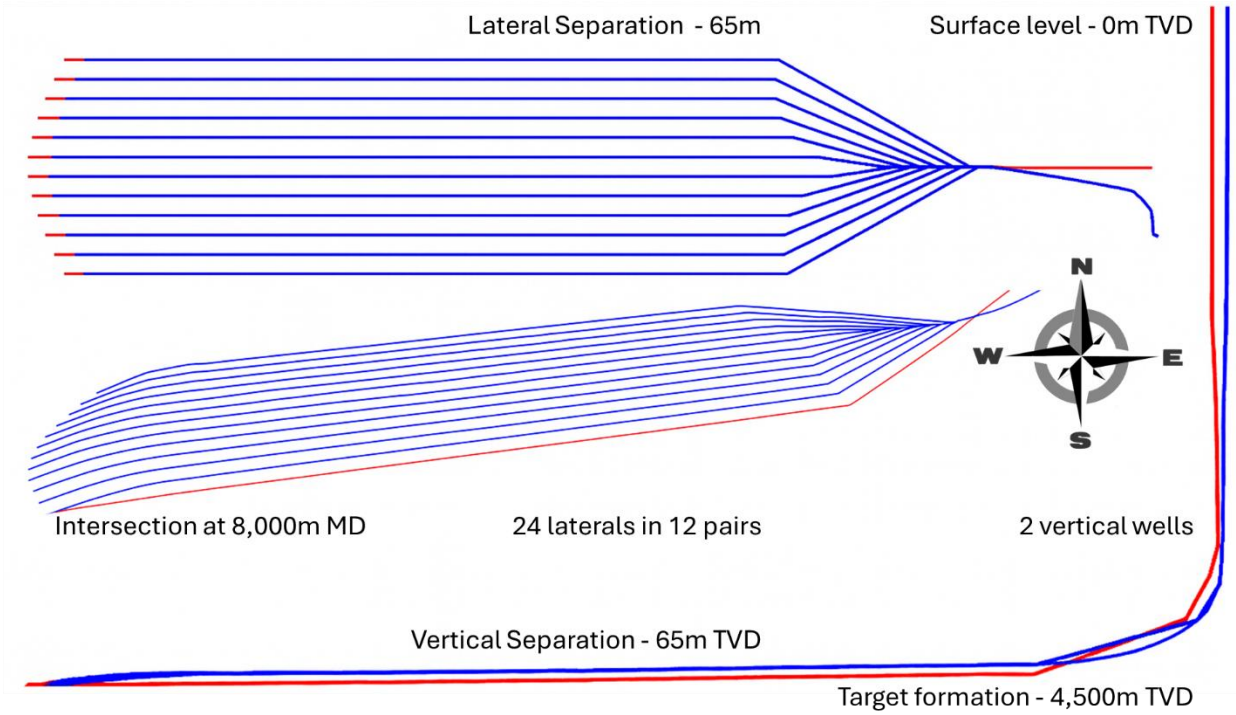


Figure 1. Planned geometry of the Closed-Loop Geothermal Wells in the East-West direction.

These lessons motivated the development of a more sustainable survey management methodology that reduces dependence on continuous gyro deployment while maintaining the accuracy required for closed-loop geothermal construction. The methodology along with the operational learning gained through its evolution are detailed in the following sections.

3 PROBLEM STATEMENT

Directional control in closed-loop geothermal laterals requires maintaining sub-degree azimuth accuracy over extended tangent sections. Prior to operations, it was assumed that MWD azimuth drift in east–west laterals would remain within 1° (Figure 2). This was expected to maintain planned well spacing and keep AMR transmitter–receiver distances within the operational limit of 150 m. Field performance from the start of drilling campaign contradicted this assumption. In the first lateral pair, MWD-only surveys exhibited azimuth deviations approaching 3°, causing the wells to diverge by more than 120 m within the first 800 m, instead of expected 1° bias, resulting in much narrower divergence of two wells within the same drilled section. Because MWD reported a stable 270° azimuth, the divergence remained undetected until AMR and drop-gyro measurements were acquired.

This experience highlighted a key challenge: in low-dip geomagnetic environments, MWD can produce a stable but incorrect azimuth, and MSA cannot resolve the underlying systematic bias without improved field geometry or independent reference measurements (ISCWSA, 2018). Without external validation, lateral separation can drift far beyond acceptable limits before any error becomes visible to the drilling team.

A temporary response using frequent gyro surveys, AMR measurements, and reactive steering proved effective but introduced significant operational cost and nonproductive time. Such an approach is not sustainable for multi-well development. The challenge addressed in this paper is therefore twofold: (1) to correct MWD azimuth bias in magnetically unfavorable drilling environments, and (2) to deliver that accuracy with reduced operational burden while maintaining safe, reliable wellbore intersections.

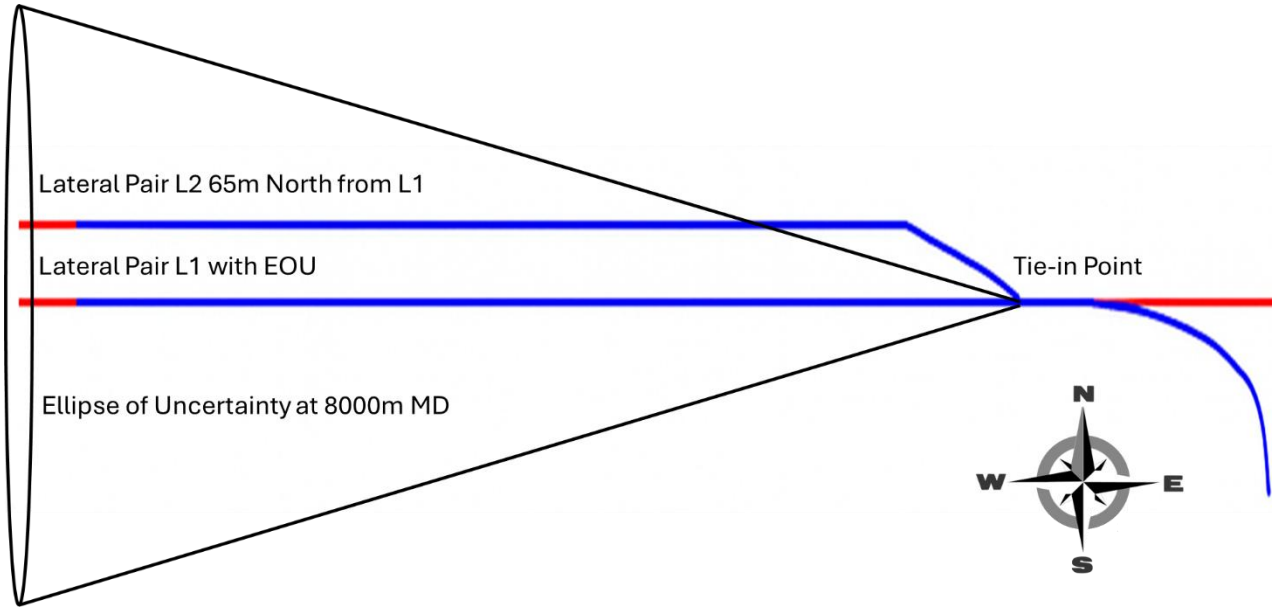


Figure 2. Expected Ellipse of Uncertainty (EOU) at TD for a lateral pair, due to Magnetic field geometry in east–west drilling environments, with MWD azimuth highly susceptible to systematic bias.

4 SURVEY METHODS AND TECHNOLOGIES

4.1 MWD Azimuth, MSA Performance, and Initial Limitations

MWD surveys served as the primary continuous directional measurement while drilling, but their performance in east–west laterals was limited by the magnetic field geometry. Low dip angles provided minimal cross-axial magnetic field strength, the BHA introduced strong axial magnetic interference, and high temperatures contributed to magnetometer drift (Bulychenkov, 2023).

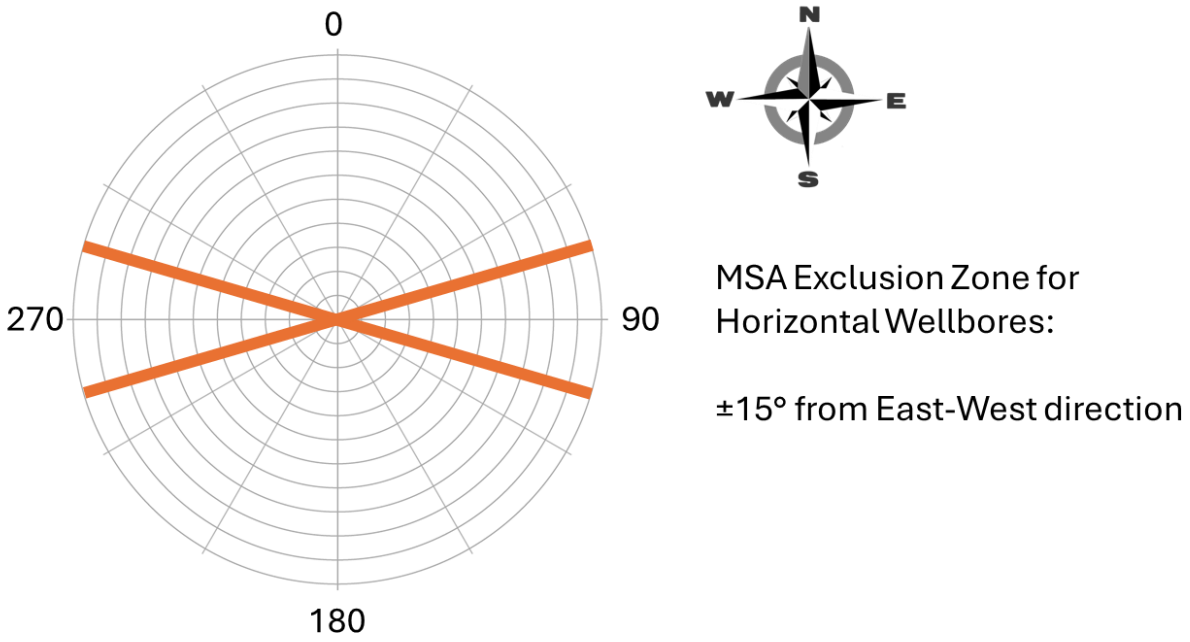


Figure 3. MWD azimuth error behavior in East–West laterals.

Under these conditions, MWD azimuth tended to be smooth but systematically biased. MSA reduced axial noise but could not resolve this bias when the magnetic geometry lacked sufficient toolface diversity (Figure 3). After

the initial divergence event, it became clear that MWD azimuth required external referencing for reliable directional control.

4.2 Gyroscopic Surveying and Selective GWD Deployment

Gyroscopic surveys were therefore introduced to anchor the trajectory to true north (Torkildsen, 2008). Drop-gyro surveys established high-accuracy references early in the lateral and during divergence recovery, confirming both absolute azimuth and AMR-derived relative spacing. GWD tools extended this capability during drilling by supplying continuous gyro-quality azimuth, improving directional confidence in long tangents. However, downhole dysfunctions, stabilization delays, and configuration limitations meant that GWD could not be deployed continuously, reinforcing the need for a hybrid survey methodology.

4.3 Controlled Curve-Calibration and Integration with AMR

To reduce reliance on gyros, a controlled curve-calibration method was incorporated into the well plan. A ~20° intentional turn early in the lateral exposed the BHA to diverse toolface orientations and significantly improved magnetic geometry for MSA. Wells with this calibration feature exhibited markedly reduced MWD azimuth bias, allowing the corrected MWD model to remain stable for long tangent drilling.

Active Magnetic Ranging (AMR) provided the direct measurement of relative spacing between the two laterals. Early AMR measurements revealed the initial divergence not visible in absolute MWD surveys, while later AMR surveys validated the corrected trajectory and confirmed tie-in geometry with sub-meter accuracy. Combined with gyro anchoring and the controlled calibration curve, AMR measurements enabled the construction of a calibrated MWD azimuth model that maintained ±1° accuracy across long tangent intervals.

Table 1. Survey Method Performance Summary

Survey Method	Strengths	Limitations	Typical Role
MWD (raw)	Continuous, low cost	Systematic azimuth bias in E–W laterals	Base survey stream
MWD + MSA	Removes axial noise	Cannot fix bias without good magnetic geometry	Smoother azimuth trend
Drop Gyro	High-accuracy absolute azimuth; drift-free	Requires tripping/pulling; time intensive	Anchor points, validation
GWD	Continuous gyro-quality azimuth	Reliability issues in HT or high VSS environment; stabilization delays; costly	Selective deployment in early curves and tangents
AMR	Direct relative spacing; sub-meter accuracy	Limited range; operational prep	Parallel drilling & tie-in validation

5 FIELD RESULTS AND ANALYSIS

5.1 Divergence in Early Wells and Corrective Steering

The performance of the initial lateral pair provided the clearest evidence of the limitations of relying on MWD-only survey data in east–west drilling environments. Both wells were initiated from casing shoes at approximately 5,000 m MD, separated vertically by about 65 m, and planned to follow a shared 270° tangent. After the initial azimuthal turns, for the following 500m MD in parallel tangent drilling MWD azimuth readings in both wells appeared stable, reporting consistent values close to 270° with minimal noise or toolface variability. Based solely on MWD data, both wells appeared to be tracking the planned trajectory and placed in the same vertical plane.

However, divergence was already underway at this stage (Figure 4). Within approximately 800 m MD from the corresponding casing shoes, the two laterals had begun drifting in opposite azimuthal directions, despite MWD surveys continuing to indicate perfectly aligned trajectories within the same vertical plane. This behavior is

characteristic of east–west drilling in low magnetic dip environments, where the Earth's magnetic field provides very limited cross-axial strength. Under these conditions, even small amounts of axial magnetic interference within the BHA – such as that introduced by pipe joints, collars, or stabilizers – can generate systematic azimuth bias that Multi-Station Analysis (MSA) cannot fully remove.

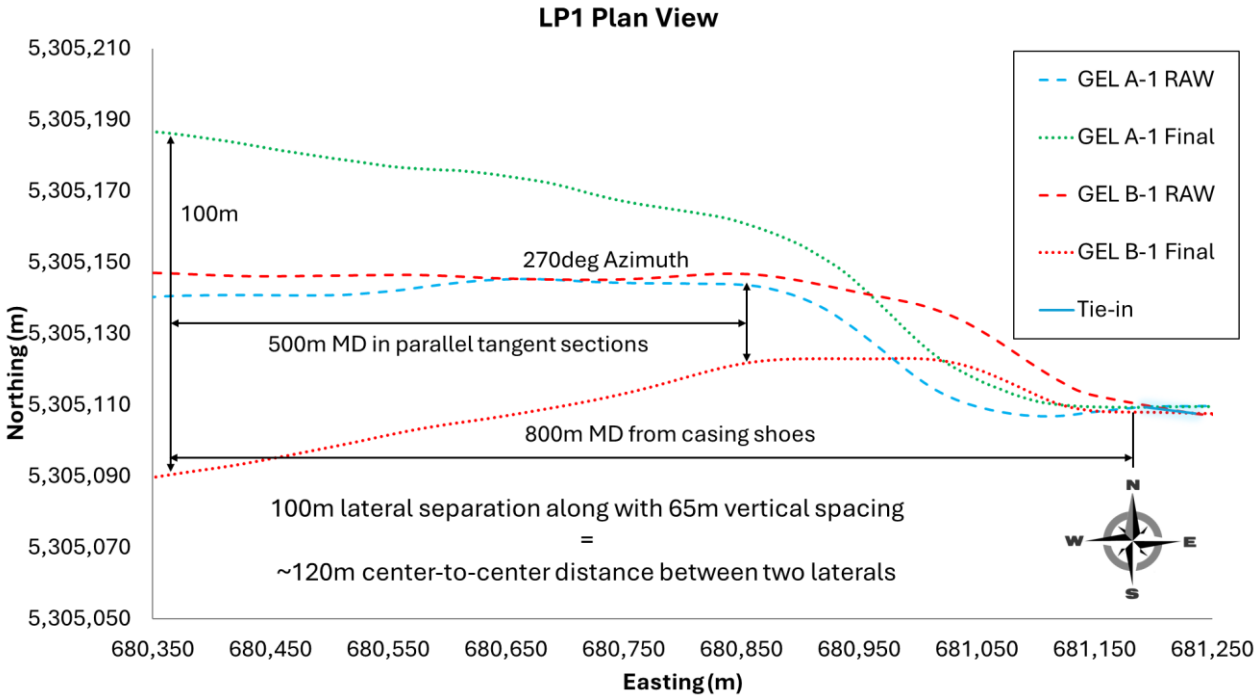


Figure 4. Expected (dashed) versus actual (dotted) relative wellbore positions based on MWD-only surveys in Lateral Pair 1. MWD reported consistent 270° azimuth (dashed), AMR and gyro measurements revealed early divergence (dotted) exceeding 120 m in actual distance between two laterals over the first 800m MD.

The first confirmation of divergence came from contingency Active Magnetic Ranging (AMR) measurements. AMR was initially deployed as a precautionary measure to verify relative lateral spacing during early drilling; however, the results within the first 800 m MD indicated a separation exceeding 120 m. This was well outside the expected 65 ± 10 m range and approached the upper limit of reliable AMR transmitter–receiver distance. The magnitude of this discrepancy prompted additional validation using drop-gyro surveys.

Drop-gyro measurements confirmed that the MWD-based azimuth in both wells was biased by approximately 2.5–3.5°, and importantly, the bias occurred in opposite directions. Rather than one well deviating while the other remained on course, both wells were drifting away from the planned shared azimuth. This opposite-direction azimuth drift, when combined with the long tangent section, resulted in a rapid amplification of center-to-center spacing error.

Correcting the divergence introduced several operational challenges. The corrective steering had to be executed while maintaining safe separation between the wells, avoiding over-correction and potential collision risk. In addition, each steering decision required careful interpretation of both AMR and gyro data, which increased decision latency and contributed to additional operational delays.

Despite these challenges, coordinated steering adjustments successfully guided the A well southward and the B well northward in azimuth until the spacing trend was reversed (Figure 5). Gyroscopic surveys were used to control the absolute placement of the B well, which served as the reference trajectory. Continuous AMR surveys then confirmed a progressive reduction in relative separation, reflecting an improved understanding of the spatial relationship between the two wells. This feedback enabled corrective steering adjustments in both wells, allowing them to approach each other and remain within the same vertical plane prior to the final intersection. Once the A well was safely positioned above the B well, downward steering of the A well was initiated, and a first-attempt intersection was successfully achieved at the total depth of the B well.

Although technically successful, the corrective process added several days of surveying time to the overall project schedule, along with additional costs associated with increased gyro deployment and more frequent AMR surveys required to control relative spacing during parallel drilling and intersection operations. The

experience from the first lateral pair clearly revealed the operational vulnerability and economic inefficiency of relying on MWD-only survey data in east–west closed-loop geothermal drilling.

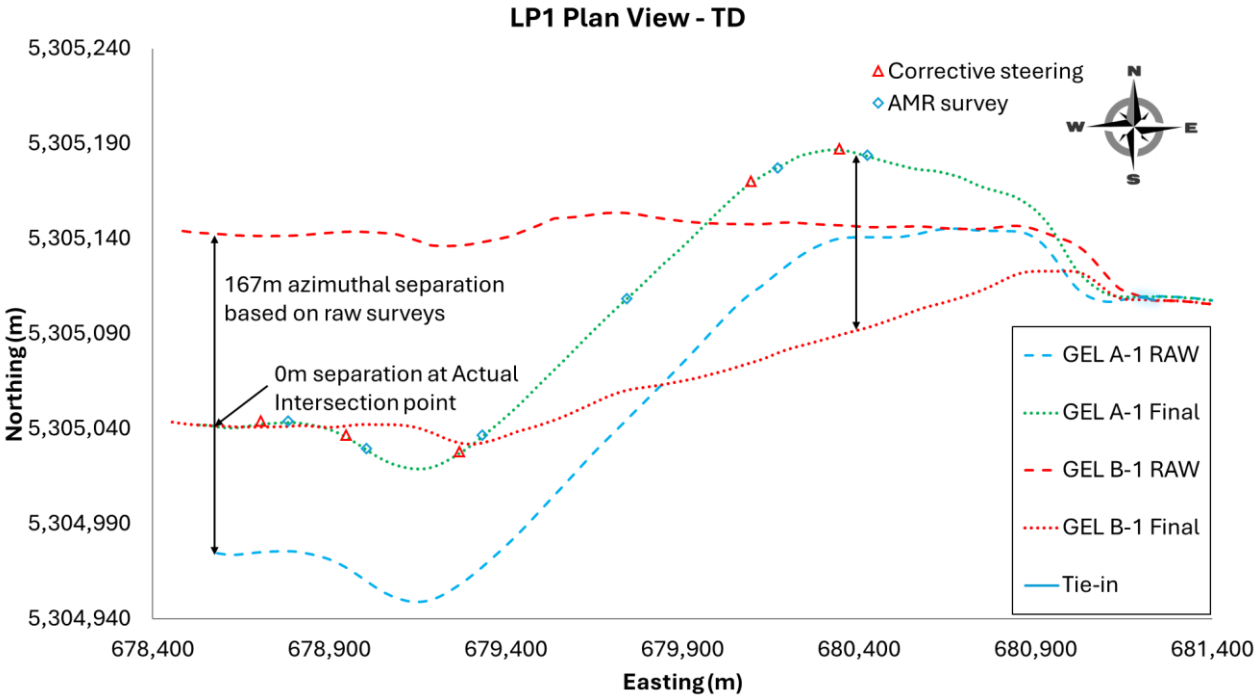


Figure 5. Sequence of survey measurements during the lateral pair 1. AMR first revealed unexpected divergence, and drop-gyro surveys confirmed true azimuth error, requiring a series of corrective steering actions and additional surveys to achieve the final intersection.

5.2 Performance of GWD and Impact of Curve Calibration

Following the early divergence event, Gyro-While-Drilling (GWD) tools were introduced to establish continuous gyro-based azimuth while drilling subsequent lateral pairs. Initially, GWD significantly improved directional control, maintaining azimuth within approximately ±1° even in extended tangent sections. This allowed much earlier identification of drift than in the initial wells and provided higher confidence in wellbore placement.

However, field deployment revealed several important limitations of GWD under the demanding downhole conditions present in deep CLGS laterals:

- GWD sensors repeatedly approached or exceeded their operating thresholds. In several cases, tools required extended cooldown periods or shut down mid-run, leading to gaps in azimuth data precisely when continuous measurements were needed most.
- After each survey or trip connection, the GWD system required stabilization time to align its internal sensors. In high-angle horizontals with low sliding intervals, stabilization took longer than expected, reducing effective survey density.
- Additional time was required for surface processing of gyro sequences, tool configuration, and repeated BHA connections, slowing down drilling progress relative to MWD-only operations.
- Not all GWD tools were compatible with the BHA and hole conditions encountered during multi-run tool combinations used in the CLGS design. In some cases, this required compromises in BHA design or steering strategy.

Because of these limitations, GWD could not be relied upon as the primary continuous survey solution. Instead, it was deployed selectively – typically at the start of the lateral, after BHA changes, during magnetic field transitions, and approaching the tie-in interval. This reduced gyro usage without sacrificing directional awareness.

The introduction of controlled curve calibration proved to be a pivotal improvement. Based on magnetometer analysis, an intentional 20° azimuthal deviation from 270° HZ wellbore azimuth was incorporated near the beginning of each lateral to generate a diverse magnetic signal (Figure 6). This improved the ability of MSA to correct axial interference and provided a more stable reference frame for the MWD azimuth.

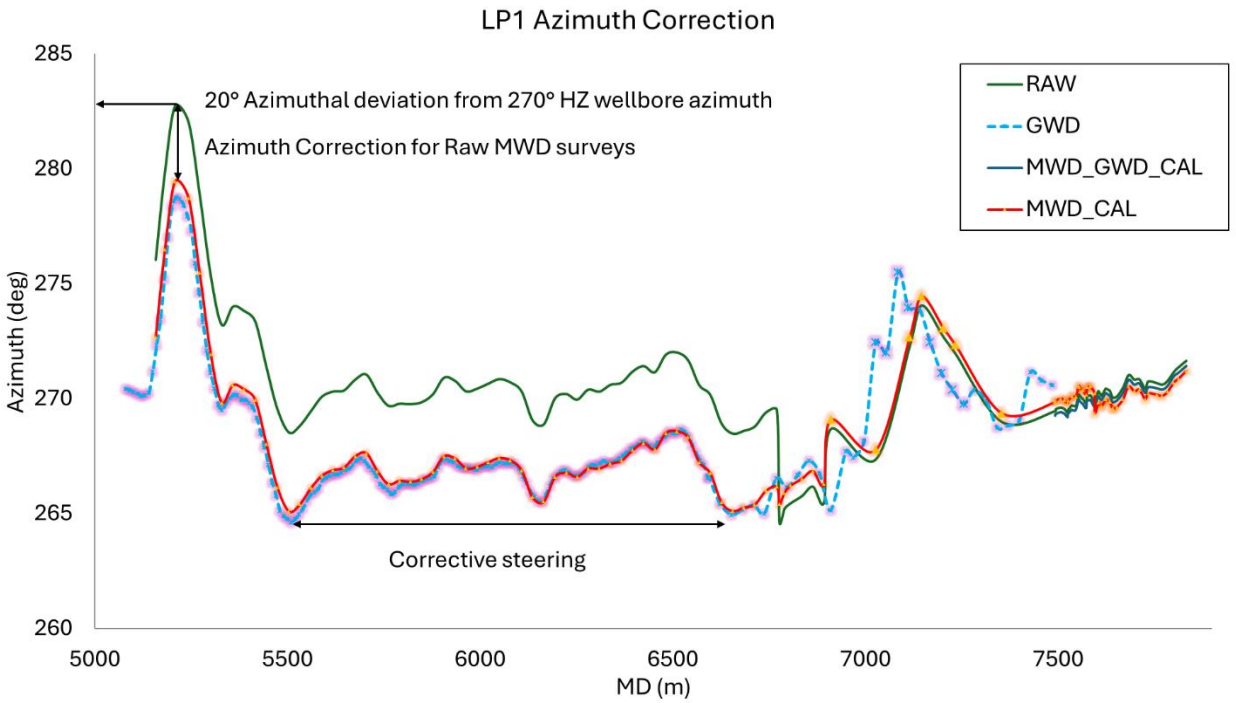


Figure 6. Controlled curve-calibration geometry and effect on MSA performance.

Field data demonstrated that:

- MWD azimuth bias dropped sharply immediately after the calibration curve.
- The corrected azimuth remained stable across 2,000–2,500 m of tangent section.
- Steering adjustments became smaller and less frequent.
- GWD requirements decreased significantly after the curve.

In addition to azimuth correction, inclination measurements were corrected to maintain accurate vertical positioning and support successful intersection of the two laterals at total depth (Figure 7).

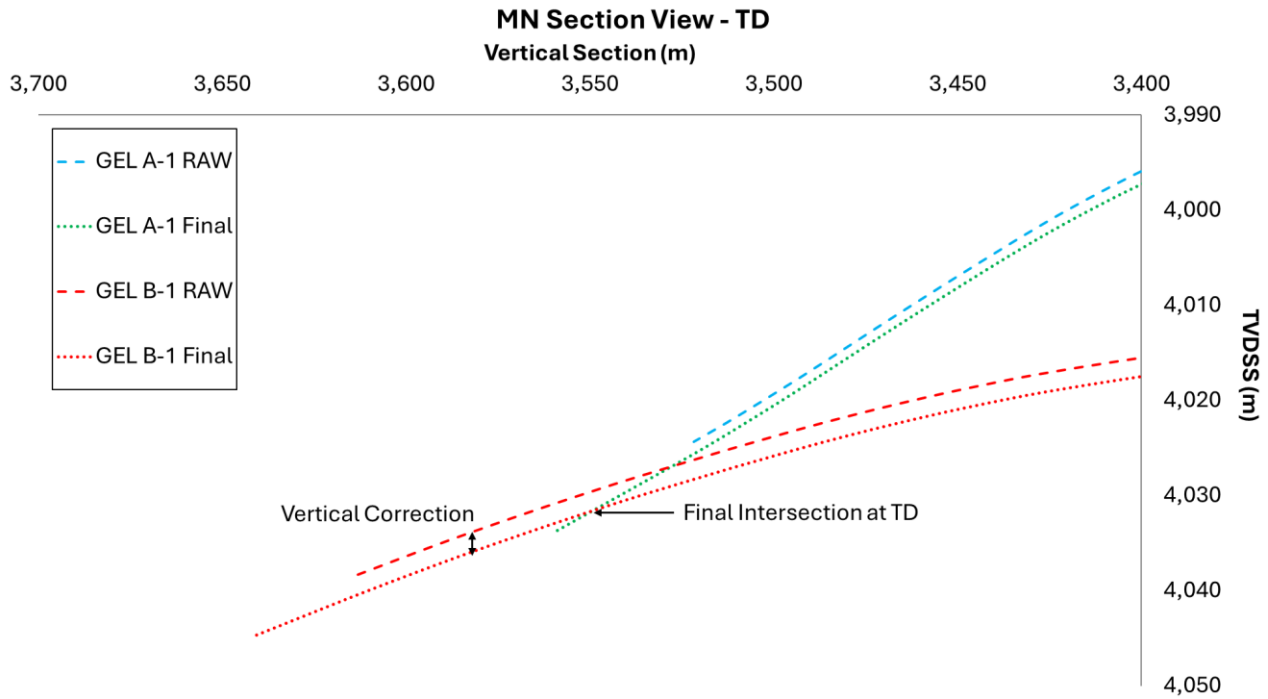


Figure 7. Final intersection in TVDSS, with a vertical correction applied to MWD surveys.

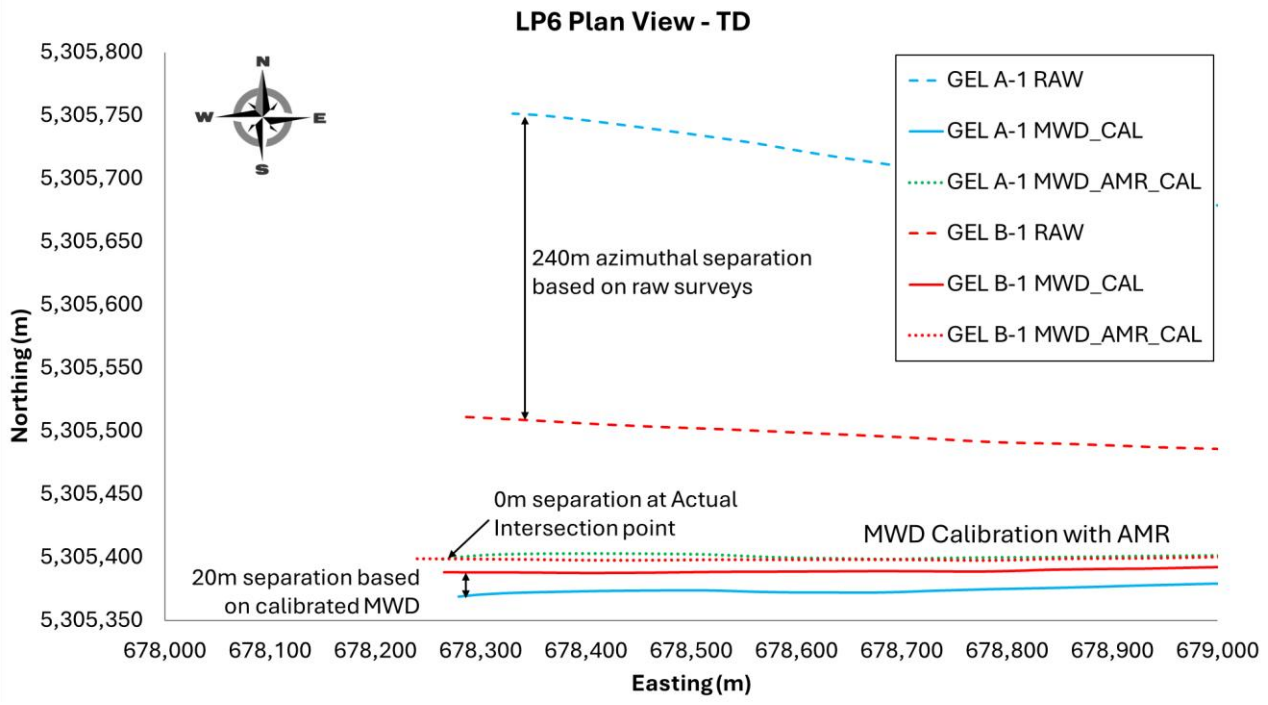
5.3 Calibrated MWD Model Performance and AMR Validation

Across laterals 3–6, integration of gyro anchoring, controlled curve calibration, MSA-refined MWD surveys, and periodic AMR checks resulted in a calibrated MWD model that consistently maintained azimuth within approximately ±1°. Several key observations emerged:

- Unlike the first lateral pair, where azimuth bias accumulated exponentially, later wells showed minimal divergence based on the MWD surveys corrected with the calibrated model (Table 2). Even when minor drift occurred, the calibrated model accurately predicted the direction and magnitude of drift, enabling timely correction while drilling both wellbores in the lateral pair.
- With MWD azimuth stabilizing after the controlled curve, steering corrections became smaller, and fewer slide sequences were required. This reduction in tortuosity produced smoother wellbores, lower friction factors, and improved rate of penetration (ROP) consistency.
- AMR measurements were easier to execute and interpret because lateral spacing stayed within predictable bands. AMR data, when compared to the calibrated MWD model, showed alignment within <1 m of uncertainty. In all laterals where the calibrated model was applied, AMR measurements during the tie-in phase indicated convergence within <1 m of the expected intersection point. This reduced risk during the final convergence and eliminated the need for last-minute steering corrections.

Table 2. Comparison of Azimuthal Separation between two wellbores for each lateral pair at total depth. MWD surveys calibrated with GWD and AMR allowed the intersection of two wells from the 1st attempt.

Comparison of Azimuthal Separation at Total Depth						
Center-to-Center Distance between GEL A-1 and GEL B-1 for each lateral pair	**LP 1**	**LP 2**	**LP 3**	**LP 4**	**LP 5**	**LP 6**
MWD surveys without calibration	**167.0 m**	**29.0 m**	**59.0 m**	**92.0 m**	**11.0 m**	**240.0 m**
MWD surveys calibrated with GWD	**29.0 m**	**0.1 m**	**5.0 m**	**4.0 m**	**6.0 m**	**20.0 m**
MWD surveys calibrated with GWD and AMR	**0.1 m**	**0.0 m**	**0.1 m**	**0.2 m**	**0.2 m**	**0.1 m**



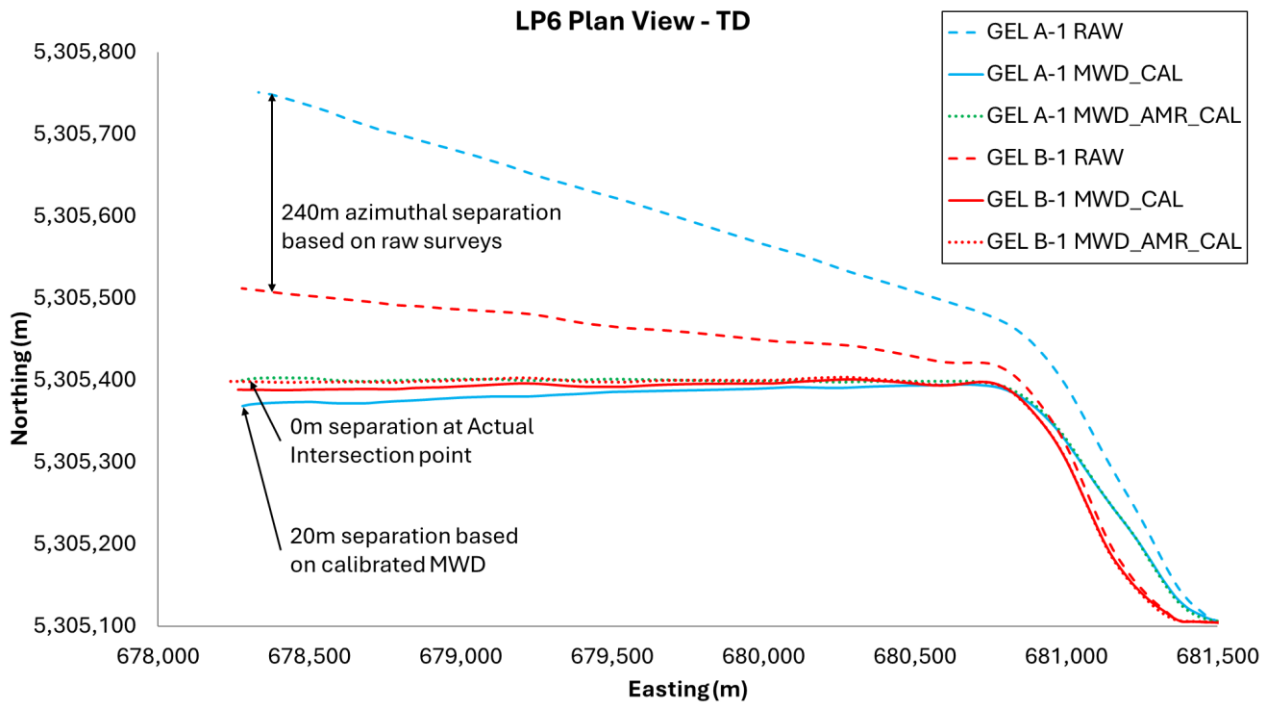


Figure 8. Calibrated MWD model performance and AMR validation in Lateral Pair 6 at Total Depth.

For Lateral Pair 6, the two wells initially began drifting apart due to significant errors in the raw MWD readings. As shown in Figure 8, application of the calibrated survey model enabled proactive correction of the MWD surveys, allowing both wells to be drilled in parallel within the same vertical section with minimal corrective steering over the full length of the laterals. As a result, the wells were successfully intersected on the first attempt at total depth.

Collectively, these results demonstrate that the calibrated MWD approach – anchored by gyro reference points, strengthened by controlled curve geometry, and validated by AMR measurements – provides a robust and repeatable method for maintaining directional accuracy in challenging east–west geothermal laterals.

6 FINAL SURVEY MANAGEMENT WORKFLOW

The recommended workflow for future closed-loop geothermal wells drilled in east–west or west–east orientations integrates calibrated MWD surveys, selective gyro anchoring, controlled calibration-curve geometry, and AMR validation into a unified system for directional control. Planning begins with an evaluation of local magnetic conditions and the incorporation of an early calibration curve into the planned well trajectory to optimize Multi-Station Analysis (MSA) performance. During drilling, MWD provides continuous directional measurements that are interpreted through a calibrated survey model refined using data from earlier wells.

Gyros can be deployed at strategically selected intervals – typically near the start of the lateral, following the calibration curve, and when drift indicators exceed expected tolerances. This targeted deployment significantly reduces the operational burden associated with continuous gyro usage while maintaining confidence in absolute wellbore orientation. As drilling progresses, the calibrated model provides stable steering guidance, minimizing the need for corrective turns and resulting in smoother wellbores with reduced tortuosity. Active Magnetic Ranging (AMR) plays a focused role during the parallel-drilling phase and serves as the primary validation tool during the tie-in phase, confirming relative wellbore spacing with high accuracy.

Each well contributes new continuous MWD and AMR data, along with selective gyro data, that are used to iteratively refine the calibrated survey model. This continuous feedback loop enhances predictive capability and supports increasingly efficient, repeatable construction of closed-loop geothermal laterals.

7 CONCLUSIONS

This study demonstrates that maintaining the directional accuracy required for east–west closed-loop geothermal laterals cannot be achieved through Multi-Station Analysis (MSA) corrections of MWD data alone. Field results from the initial lateral pair showed that, in magnetically unfavorable environments, MWD can provide a smooth but systematically biased azimuth, leading to rapid and undetected wellbore divergence.

While Gyro-While-Drilling (GWD) tools offer high-accuracy azimuth measurements, continuous reliance on GWD is operationally complex and economically impractical for multi-well development.

To address these limitations, a hybrid survey management workflow was developed that integrates calibrated MWD surveys, selective gyro anchoring, controlled calibration-curve geometry, and Active Magnetic Ranging (AMR) validation. Application of this methodology across subsequent lateral pairs produced a calibrated MWD survey model capable of maintaining azimuth accuracy within approximately ±1° over long tangent sections. The approach improved directional reliability, enabled predictable lateral convergence, and reduced survey-related operational time.

The results further indicate that, as additional field data are incorporated into predictive azimuth-bias models, future drilling campaigns can increasingly rely on the calibrated MWD model while reducing the frequency of absolute gyro surveys and AMR checks during parallel drilling. This evolution will minimize corrective steering, reduce wellbore tortuosity, and support smoother, more efficient well construction.

GWD remains an important contingency tool within the workflow and can be deployed selectively when discrepancies arise between the calibrated model, MWD measurements, and AMR observations. Additional calibration opportunities, such as intentional doglegs or inclination variations, may further enhance model robustness; however, these options require careful evaluation due to their potential impact on drilling cost, torque and drag, operational efficiency, and reservoir exposure.

Overall, the integrated survey strategy developed in this campaign provides a scalable, efficient, and repeatable foundation for constructing east–west closed-loop geothermal lateral systems. By combining continuous MWD measurements with targeted absolute and relative referencing, the workflow enables reliable directional control while reducing operational complexity and cost, supporting the broader deployment of closed-loop geothermal technology.

8 ACKNOWLEDGEMENTS

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