

EVALUATION OF ORIENTATION TO GRAVITY (OTG) PROCEDURE OF AT500 LEICA LASER TRACKER AND COMPARATIVE ASSESSMENT WITH AT403 LEICA LASER TRACKER

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Abstract

This study compares the vertical measurement accuracy of two Leica laser trackers: the AT500, which uses Orientation to Gravity (OTG), and the AT403, which provides continuous dual-axis compensation. Laboratory tests using a network of ten stations with a maximum baseline of 18 m showed that OTG correction produces vertical angle uncertainties of up to 0.4 arcsec, making single-instrument vertical positioning 25–50% less precise than continuous compensation. Long-term monitoring over 10.5 hours revealed high-frequency fluctuations of 0.8 arcsec peak-to-peak for the AT500. Network simulations based on a 560 m particle accelerator alignment showed that combining OTG measurements with traditional leveling produces vertical positioning errors about 30% larger than continuously compensated systems with leveling, while omitting gravity correction entirely increases errors by 135%. OTG procedures therefore provide acceptable vertical accuracy for large-scale applications when combined with leveling, but measurement networks must account for the resulting uneven precision distribution, especially for points far from leveling lines. The dual-OTG protocol, which brackets measurements with initial and final gravity determinations, reduces the vertical angle uncertainty from 0.4 arcsec to 0.2 arcsec (a 50% reduction) compared to single-OTG measurement.

INTRODUCTION

Surveying networks have traditionally combined polar measurements (horizontal directions, vertical angles, and slope distances) with leveling to achieve accurate three-dimensional positioning. Both modern total stations and laser trackers deliver angular precisions on the order of 1 arcsec, a benchmark in surveying and metrology. In surveying networks, gravity-based measurements are particularly valuable because they strengthen the determination of vertical components that would otherwise be poorly constrained by polar measurements alone [1].

In precision networks, gravity can enter the measurement process in two complementary ways. First, precise leveling provides the link to gravity by transferring height differences between points along local level surfaces, yielding a robust vertical datum for the entire network [2]. Second, a laser tracker establishes its own local vertical reference at each instrument setup. The instrument measures the direction of the local gravity vector (the plumb line)

using bubble levels and/or dual-axis tilt sensors (compensators). Together, leveling constrains heights across the network, while leveled polar stations stabilize the orientation of angle measurements at each station [3]. Vertical precision in polar networks degrades with distance due to angular uncertainty propagation and atmospheric refraction effects, which can introduce arcsecond-level systematic errors [4, 5]. Gravity-based leveling provides robust vertical datums but requires appropriate Earth curvature corrections for large networks [6].

Gravity compensation in total stations and laser trackers

Classical total stations incorporate gravity-based leveling and compensation systems. After coarse leveling with a bubble level, a dual-axis compensator measures small instrument tilts within a limited range and corrects the reported horizontal and vertical angles accordingly. The magnitude of these corrections depends on the tilt direction relative to the sight line: tilts along the line of sight primarily affect vertical angles. The compensator achieves final leveling accuracy 0.5 – 1.0 arcsec, comparable to the instrument's nominal angular accuracy, making this correction essential for maintaining specified performance. In modern instruments, this is typically implemented with electronic tilt sensing and firmware correction, enabling stable angular performance despite minor dynamic inclinations during setup [7].

Laser trackers, in contrast, are optimized for high-rate coordinate acquisition and flexible mounting in industrial environments, including sideways or inverted configurations. Unlike total stations, most trackers include inclination sensors primarily for monitoring and setup verification rather than for continuous real-time compensation. Integrating continuous gravity compensation into high-rate tracking systems is challenging because the compensation mechanism's response time can degrade dynamic tracking performance. Moreover, gravity-dependent compensators typically fail to operate when the instrument is tilted significantly from vertical, conflicting directly with the flexible mounting capability that is a key advantage of laser trackers [8].

The Leica AT40X tracker series became the dominant platform in particle accelerator alignment and large-scale industrial metrology. This series represented a hybrid approach by combining laser tracker metrology with contin-

uous gravity compensation based on a dual-axis fluid inclination sensor similar to those in total stations. The instrument had to be leveled within a specified range for the compensator to operate [9]. Newer platforms like the Leica AT500 have shifted toward an initialization only workflow, commonly referred to as Orientation to Gravity (OTG). In this approach, the tracker's inclinometer is used at the start of a measurement session to establish a gravity aligned reference frame. However, subsequent base motion or settlement is not automatically compensated and typically requires re-initialization of OTG [10]. Removing the total station-like compensator allows for faster measurements and operation upside down, but it calls into question the vertical accuracy of the laser tracker.

Research gap and objectives

This paper investigates the vertical measurement performance of the Leica AT500 tracker operating with an OTG workflow and compares it with the earlier Leica AT403 architecture that featured continuous gravity compensation. We quantify the differences in vertical accuracy when using initialization only gravity alignment instead of real time compensation. Performance is assessed experimentally in a controlled 18 m network and through numerical simulation of a 560 m configuration, using precise leveling as the reference standard.

A controlled, application-focused comparison of this type is not currently available in the peer-reviewed literature, despite its practical importance for high precision industrial metrology. Even large state-of-the-art studies do not discuss this important topic [8]. This gap is particularly important in particle accelerator alignment, where the AT40X hybrid capabilities became widely adopted because of the scale of these facilities [11]. With the AT40X series now being discontinued, the transition to OTG based platforms like the AT500 is becoming unavoidable. While other manufacturers such as API and FARO offer laser trackers with similar leveling approaches, none, to our knowledge, replicate the unique combination of laser tracker metrology with continuous gravity compensation that the AT40X provided.

METHODOLOGY

All short-distance experiments were conducted in a controlled underground laboratory providing optimal measurement conditions: temperature stability within $\pm 0.5^\circ\text{C}$, negligible air turbulence, and isolation from mechanical vibrations. The experimental program employed two laser tracker systems representing distinct gravity-referencing architectures: the Leica AT403 with continuous dual-axis compensator, and the Leica AT500 operating with OTG initialization workflow. Prior to measurements, each instrument was leveled according to manufacturer specifications, the AT403 using a precision tribrach with bubble level, and the AT500 using its dedicated leveling base.

OTG repeatability and long-term stability

To characterize the stability and repeatability of the OTG procedure over extended periods, the AT500 was installed in the underground laboratory and programmed to execute consecutive OTG measurements at regular intervals over a 10.5-hour period. Each OTG determination lasted 38 seconds and measured the inclination in four quadrants of the horizontal plane, yielding two angular parameters referenced to the local gravity vector in the tracker's internal system: R_{long} (rotation in the longitudinal plane) and R_{trans} (rotation in the transverse plane). This dataset enabled quantification of both short-term repeatability and potential long-term drift in the gravity initialization procedure. Two independent series were acquired in different places of the underground laboratory.

Short-distance test

The primary experiment consisted of measuring a stable three-dimensional network of ten Spherically Mounted Retroreflectors (SMRs) mounted on laboratory walls and two fixed supports. The control points were positioned to form an approximately uniform angular distribution around a central instrument location. Measurements were acquired from ten independent stations, each station representing a similar nominal instrument position but with successive 36° increments in horizontal orientation (yaw angle).

For each AT500 station, a standardized measurement sequence was executed. First, the instrument was manually leveled using the integrated inclinometer display. An initial OTG procedure (OTG_{initial}) was performed to record R_{long} and R_{trans} , followed by activation of continuous inclinometer logging with time-stamping. All network points were then measured from the station. Upon completion, continuous logging was deactivated and a final OTG procedure (OTG_{final}) was performed to record updated rotation parameters.

This protocol provided three categories of gravity-reference data per station: two discrete OTG determinations bracketing the measurement session and a continuous time series of inclination readings during active measurements. Continuous monitoring was suspended during tracker repositioning to prevent motion-induced transients from corrupting the data.

An exploratory analysis investigated whether continuous inclinometer data could improve upon the two-point OTG approach. The continuous measurements exhibited systematic offset and scale differences relative to OTG values. Linear scaling was applied to force agreement with OTG_{initial} and OTG_{final} at the session boundaries, but this approach yielded no accuracy improvement and is therefore not presented in this study.

The AT403 measurement protocol followed conventional compensated total station practice: after manual leveling via tribrach, the dual-axis compensator operated continuously throughout the measurement session, applying real-time corrections to all angular observations. No additional gravity-referencing procedures were required.

The ten-station network was analyzed using in-house least-squares adjustment software as a free network (no datum constraints on coordinates) [12]. Two fundamental adjustment scenarios were implemented for both instruments: the fixed-rotation scenario, in which station inclination R_{long} and R_{trans} were constrained to zero, treating each setup as perfectly leveled, and the free-rotation scenario, in which station orientations were estimated as additional parameters in the adjustment, allowing empirical determination of residual instrument tilt.

For the AT403, raw observations incorporated real-time compensator corrections applied by the instrument firmware and therefore represented gravity-compensated measurements throughout the analysis. For the AT500, two post-processing correction variants were evaluated: the initial OTG only approach, in which all observations within a station were corrected using $\text{OTG}_{\text{initial}}$ parameters and the mean OTG approach, applying station-wide correction based on the arithmetic mean of $\text{OTG}_{\text{initial}}$ and $\text{OTG}_{\text{final}}$.

Long-distance simulation

To assess the practical significance of OTG uncertainty in large-scale precision networks, numerical simulations were conducted using an example of a 560 m network section at the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory. The simulated network encompassed the Undulator Hall, Front End Enclosure (FEE), and Near and Far Experimental Halls, representing typical operational alignment conditions in a modern X-ray free-electron laser facility. The coordinate system in which the results are presented is the LCLS geodetic system [13], where the Z -axis follows the beam direction, the Y -axis is vertical, and the X -axis is in the radial direction.

Three adjustment scenarios were formulated to isolate the impact of gravity-referencing methodology and supplementary leveling constraints (Table 1). The baseline scenario replicated the conditions of the actual 2025 LCLS network adjustment, which employed AT403 instrumentation with continuous dual-axis compensation. This baseline scenario adopted a vertical a priori angle uncertainty of $\sigma_v = 0.8 \text{ arcsec}$ (derived from empirical a posteriori statistics of 2025 LCLS adjustment), station rotations fixed at $R_{\text{long}} = R_{\text{trans}} = 0$, and direct geometric leveling over the full network length to constrain vertical components.

Table 1: Long-distance simulation scenarios

Scenario	OTG applied	Station rotation	σ_v (arcsec)
Baseline (AT403)	N/A	Fixed	0.8
AT500	No	Free	0.8
AT500	Yes	Fixed	1.2

The degraded vertical angle uncertainty of $\sigma_v = 1.2 \text{ arcsec}$ in OTG-based scenarios was chosen as a conservative estimate that combines the nominal instrument precision of 0.8 arcsec with the empirically determined OTG uncertainty of approximately 0.4 arcsec (derived from

short-distance experiments). This value represents a worst-case assumption where instrument precision and gravity-referencing errors add linearly ($0.8 + 0.4 = 1.2 \text{ arcsec}$), rather than in quadrature as would be appropriate for independent random errors. This conservative formulation ensures that the simulation captures potential systematic relation between instrumental and OTG-induced errors.

RESULTS

The results of the repeatability and long-term stability of the OTG are presented in Figure 1. The figure shows the readings for inclinations R_{long} and R_{trans} from a 10.5-hour measurement series. The x-axis represents time in hours and the y-axis represents inclination in arcseconds. This dataset represents one of two tests performed to assess the stability of OTG measurements and identify potential systematic patterns.

Depending on the series and direction, the general drift was more or less prominent, ranging from semi-stable long-term behavior in Figure 1 to approximately 1 arcsec over 10.5 hours in the most extreme case. At the beginning of each series, heating of the instrument caused larger drift over approximately 30 minutes of measurement, even when the tracker had been acclimatized in the area for several hours.

While the long-term drift is relatively slow compared to the duration of average single-station measurements in real-world network adjustments, there are short-term sinusoidal fluctuations in the readouts. After removing the initial heating drift and long-term drift, the maximum data range of the fluctuations for both sessions is approximately 0.8 arcsec . The acquisition from one of the two sessions is presented in Figure 1.

Short-distance test

The short-distance network was independently measured eight times on different dates, four times using the AT403 and four times using the AT500. The results using inclination-corrected data are presented in Table 2. The network was adjusted twice: once with fixed station rotations (pitch and roll) and once completely free. The results show obvious degradation of the a posteriori precision of adjusted observations when constraining station rotations (pitch and roll), which is predominantly visible in the vertical angles.

Table 2 presents this degradation for the AT403 and AT500 trackers. In the case of the AT500 two variants are presented, one using only a single initial OTG procedure to correct the observations and another the correction based on the average of the dual OTG measurements acquired at the beginning and at the end of each station occupation.

The differences between the variants are marginal for horizontal angles and distances. The largest discrepancies are visible for vertical angles, where the vertically fixed version of adjustment yielded on average 0.4 arcsec worse results than the free version for AT500 with a single OTG and 0.2 arcsec for double OTG. The equivalent difference

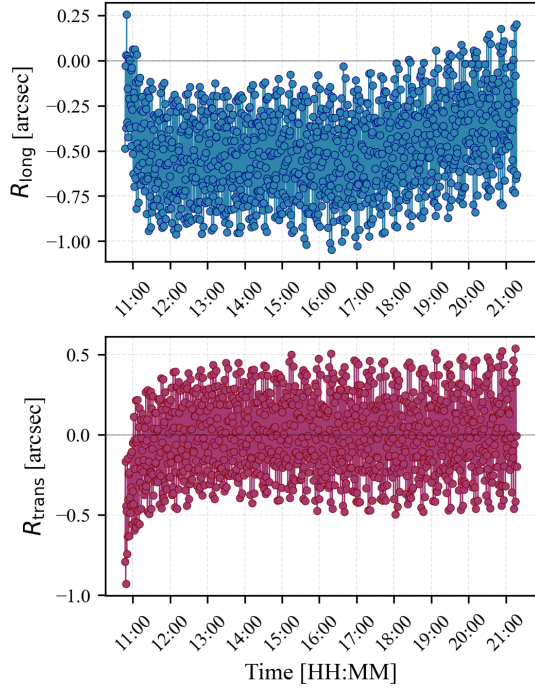


Figure 1: OTG stability measurements showing longitudinal and transverse rotations over a 10.5-hour period.

Table 2: A posteriori precision of adjusted observations for different OTG correction strategies. Values represent standard deviations of unit weight for horizontal angles, vertical angles, and distances.

Session	Horizontal Angle (arcsec)	Vertical Angle (arcsec)	Distance (μm)
<i>AT403 measurement</i>			
S1	0.0	0.0	0.0
S2	0.0	0.0	0.2
S3	0.0	0.0	0.0
S4	0.0	0.1	0.0
<i>AT500 measurement – single OTG</i>			
S5	0.0	0.4	0.3
S6	0.0	0.3	0.7
S7	0.0	0.6	0.7
S8	0.0	0.4	1.2
<i>AT500 measurement – dual OTG</i>			
S5	0.0	0.0	0.2
S6	0.0	0.1	0.3
S7	0.0	0.4	0.5
S8	0.0	0.4	1.0

for AT403 was not larger than 0.1 arcsec for all measurement sessions.

Long-Distance simulation

Figure 2 presents the a posteriori standard deviation in the vertical direction based on network adjustment simulations. The y -axis shows the standard deviation of the vertical position of the points for three adjustment simu-

lation variants, whereas the x -axis represents the longitudinal position along the tunnel corresponding to the global Z -coordinate of the points. The lowest standard deviations are observed for the simulation variant with leveled stations and direct leveling, using an a priori vertical angle standard deviation of 0.8 arcsec (depicted as blue circles), which mimics measurements with the Leica AT40X series. Simulation using OTG is less precise because the a priori vertical angle standard deviation was increased to 1.2 arcsec; however, OTG still helps maintain relatively low standard deviations, as shown by the green triangles. The orange squares illustrate the effect of measuring the network without leveling the stations while still employing direct leveling between points on the floor; this results in significantly degraded vertical accuracy compared to the aforementioned simulation variants.

The average standard deviation of the vertical coordinate Y of the AT403 simulated network is 27 μm , which compares to a small decrease in average accuracy to the level of 35 μm when using AT500 with OTG. OTG provides similar results for the vertical accuracy of the network as the continuous dual-axis compensator in AT403, while not using OTG at all and adjusting the network with all station rotations free but with an a priori precision of vertical angles of 0.8 arcsec yields an average standard deviation of 63 μm , approximately two times worse than AT403.

DISCUSSION

OTG stability monitoring revealed a consistent 30-minute thermal stabilization period following the start of consecutive OTG procedures, observed across two independent test sessions regardless of prior acclimatization. More significantly for practical operations, high-frequency fluctuations with around 0.8 arcsec peak-to-peak amplitude were observed in both R_{long} and R_{trans} components across both sessions. Long-term drift over 10.5 hours was within 1 arcsec but it usually represents a secondary concern given typical station occupation times of minutes rather than hours.

Short-Distance test

The controlled network experiment demonstrates that OTG-based gravity referencing introduces measurable degradation in vertical positioning accuracy compared to continuous compensation. While the AT403 measurements maintain expected vertical precision with fixed station rotations, the AT500 configuration exhibits vertical uncertainty increases of approximately 50% when applying a single OTG correction and 25% when employing the dual-OTG averaging approach. These empirical results must be incorporated into network design and uncertainty budgeting for metrology applications requiring sub-millimeter vertical accuracy.

The dual-OTG protocol, applying corrections based on the arithmetic mean of initial and final gravity determinations, consistently outperformed single-OTG correction. Comparison of $\text{OTG}_{\text{initial}}$ and $\text{OTG}_{\text{final}}$ parameters revealed

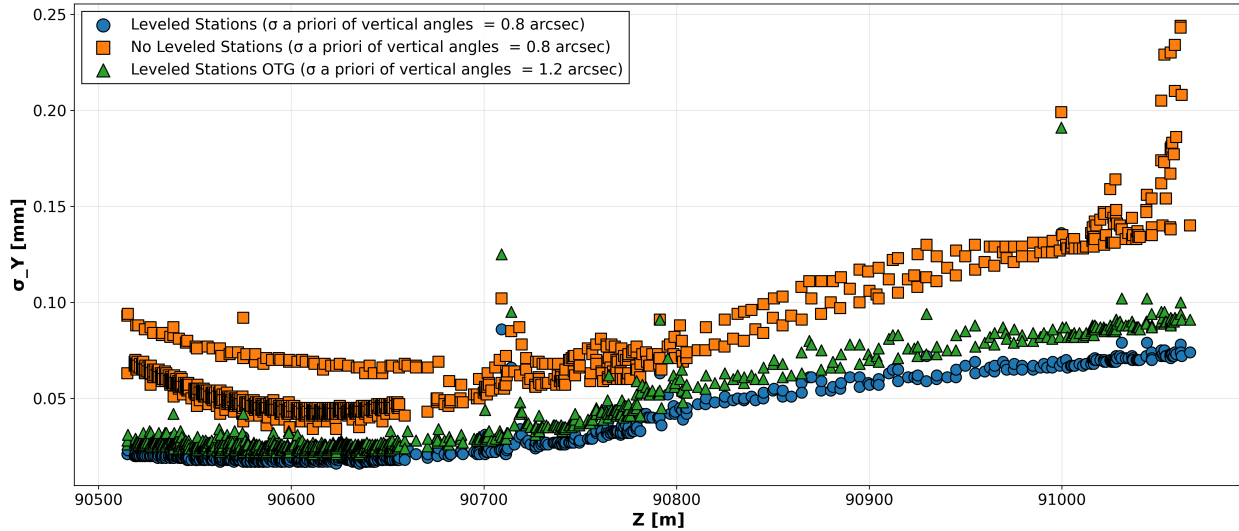


Figure 2: A posteriori standard deviations of vertical positions along the tunnel for three simulation variants: leveled stations (OTG) with direct leveling ($\sigma_v = 0.8$ arcsec, blue circles), non-leveled stations (no OTG) with direct leveling ($\sigma_v = 0.8$ arcsec, orange squares) and OTG-leveled stations with direct leveling ($\sigma_v = 1.2$ arcsec, green triangles). The x-axis represents the longitudinal position along the tunnel.

measurable station settlement or base deformation occurring during measurement sessions, with typical changes in the range of $0.2 - 0.5$ arcsec. Averaging these bracketing measurements partially compensates for linear drift within the session, effectively reducing the systematic component of OTG error.

The continuous inclination data stream available from the AT500 did not provide useful correction information. Both absolute offsets and temporal variation patterns in the continuous data diverged significantly from the discrete OTG determinations, preventing effective integration of these datasets. Attempted post-processing schemes, including linear interpolation between initial and final OTG values with observation time-stamping, did not yield large improvements over simple arithmetic averaging. This negative result suggests fundamental differences in sensor operation mode or data processing between the OTG measurement protocol and continuous logging, requiring further investigation of the instrument's firmware implementation.

Despite these limitations, the dual-OTG protocol offers an operational advantage analogous to classical drift checking in total station networks. Comparing initial and final gravity determinations provides quality control information about station stability, enabling detection of significant base settlement or instrument displacement during measurement sessions. Substantial divergence between bracketing OTG measurements may warrant station remeasurement, similar to the criterion applied when repeated measurements of initial control points exceed acceptable thresholds.

Large-Scale simulation

The numerical simulations extend the controlled experimental results to operational configurations characteristic of particle accelerator alignment networks. Two fundamental operational strategies emerge for AT500 deployment in large-scale networks. The first approach applies OTG correction to maintain gravity reference for polar measurements, accepting the associated vertical accuracy degradation relative to continuous compensation. The second approach forgoes OTG entirely, prioritizing rapid data acquisition without gravity initialization. Both strategies still require supplementary precise leveling to achieve vertical accuracy specifications comparable to historical AT403 networks, as polar measurements alone provide insufficient vertical constraint in elongated network geometries regardless of gravity-referencing methodology.

Application of OTG correction with constrained station rotations results in vertical positioning standard deviations approximately 30% larger than the AT403 baseline scenario. While this represents measurable performance degradation, the vertical accuracy remains within acceptable tolerances for most accelerator alignment applications when combined with direct leveling constraints. In contrast, the free-rotation scenario without OTG application produces vertical uncertainties 135% larger than baseline, clearly demonstrating that gravity referencing, even with the limitations of OTG initialization, provides substantial improvement over purely geometric polar measurements.

Detailed examination of the adjusted coordinate uncertainties reveals systematic spatial patterns in vertical accuracy degradation. Several individual points in the OTG-constrained scenario exhibit anomalously large vertical standard deviations, particularly for long sightlines

with limited geometric redundancy. These isolated points may achieve lower individual accuracy than corresponding points in the free-rotation scenario, despite the latter's overall poorer network performance. This observation highlights the importance of network design and measurement geometry in mitigating systematic error sources.

The free-rotation scenario exhibits characteristic vertical accuracy patterns related to the network's geometric configuration. Points positioned on lateral tunnel walls receive systematically larger vertical uncertainties than points located along the central leveling traverse. This behavior reflects the network's elongated geometry: with station rotations unconstrained and the leveling traverse approximately linear along the tunnel axis, rotation about the longitudinal Z -axis remains poorly determined. Consequently, points distant from the leveling control line, particularly those in lateral positions, inherit larger vertical uncertainties through weakened geometric constraint. This effect becomes pronounced at the extremities of the network, particularly near the 9100 m global longitudinal coordinate, where laser tracker stations are spaced farther from the leveling traverse and geometric control degrades rapidly.

These simulation results provide quantitative guidance for operational decision-making in transitioning from compensated to OTG-based instrumentation. The 30% vertical accuracy penalty associated with OTG methodology represents an acceptable trade-off for applications where sub-millimeter vertical precision remains achievable through combined polar-leveling networks. However, the spatial heterogeneity in point accuracy demands careful attention to network geometry and measurement planning, particularly for control points located away from primary leveling constraints.

CONCLUSIONS

This study provides the first comprehensive evaluation of OTG initialization workflows in laser tracker metrology, quantifying the vertical accuracy implications of transitioning from continuous gravity compensation (Leica AT403) to initialization-only referencing (Leica AT500).

OTG procedures introduce measurable but manageable vertical accuracy degradation. Short-distance experiments quantified this effect at approximately $0.2 - 0.4$ arcsec beyond nominal instrument precision. Long-term stability monitoring revealed a 30-minute thermal stabilization period and high-frequency fluctuations reaching 0.8 arcsec peak-to-peak.

Large-scale network simulations demonstrated that OTG-based measurements combined with supplementary leveling achieve vertical positioning within 30% of continuously compensated baselines for 560 m particle accelerator configurations. This performance remains acceptable for most operational specifications. However, measurements without gravity referencing produced 135% larger vertical uncertainties, establishing that gravity initialization provides essential constraint despite discrete rather than continuous compensation.

Operational best practices for AT500 deployment include a dual-OTG protocol, mandatory thermal stabilization, and strategic network design. As these findings are based on a single instrument of each type, broader validation across multiple units is recommended. The dual-OTG protocol brackets each measurement session with initial and final gravity determinations. This provides improved accuracy through averaging and enables quality control monitoring of station stability. Following instrument initialization, a mandatory 30-minute thermal stabilization period must be observed. Network design should account for spatial heterogeneity in vertical precision, particularly for points distant from leveling traverses. The dual-OTG approach reduces vertical angle uncertainty from 0.4 arcsec to 0.2 arcsec compared to single OTG initialization. Additionally, it enables detection of base settlement during measurement sessions.

With Leica discontinuing the AT40X series and no current manufacturer offering equivalent combined capabilities, these results provide essential guidance for the particle accelerator alignment community's transition to OTG-based platforms. The 30% vertical accuracy penalty is acceptable for most applications when combined with established leveling practices.

Future research should investigate the periodic fluctuation mechanism, explore interpolating OTG correction using observation timestamp, and confirm simulations using experiments.

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