



COMBINATION OF LEVELLING, WIRE OFFSET, AND LASER TRACKER MEASUREMENTS IN A 3 KM LHC ARC: KEY FINDINGS AND FUTURE STRATEGIES

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BACKGROUND & MOTIVATION

CERN's ~60 km accelerator beam line must be smoothed (initial measurement and relative displacement) during Long Shutdown 3 (LS3, 2026–2030), demanding survey procedures that combine the accuracy required for accelerator alignment with the efficiency needed to meet the schedule. The historical LHC workflow starts with roll angle adjustment, then smooths vertical position (levelling) and radial position (ecartometry) independently.

However, laser trackers have yet to replace levelling and ecartometry at the scale of a several-kilometre LHC arc. To address this, CERN surveyed the full LHC Arc 2-3 during the 2025 technical stop, combining traditional levelling and ecartometry with 3D laser-tracker measurements and an Ecartometry Measurement by Automatic Photogrammetric Survey (EMAPS), producing a unique benchmark dataset to guide LS3/LS4 survey strategy.

A LARGE-SCALE MEASUREMENT DATASET

2.8 km

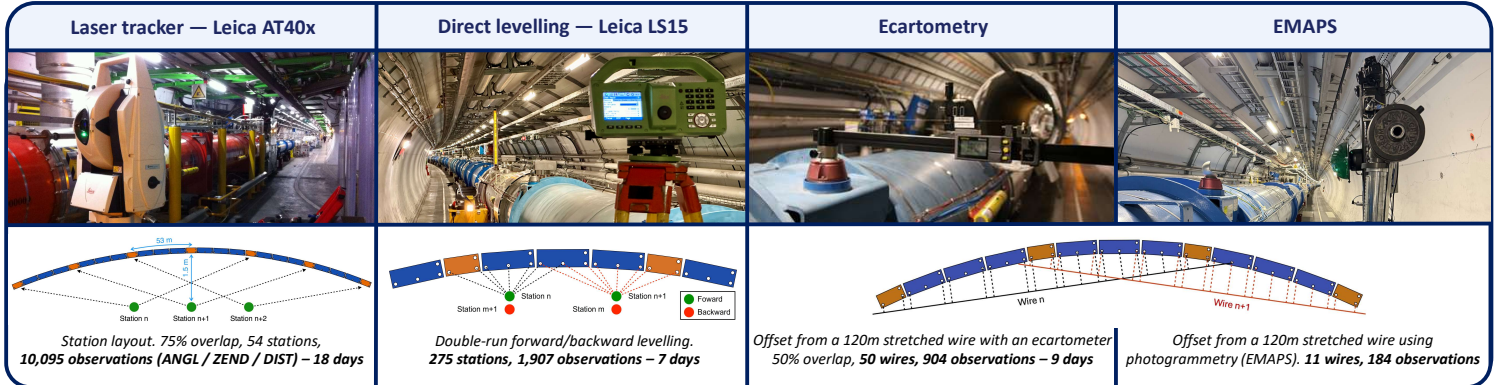
LHC arc surveyed (Arc 2-3)

~1.5 month

Campaign duration

4

Measurement techniques



PRECISION OF EACH TECHNIQUE

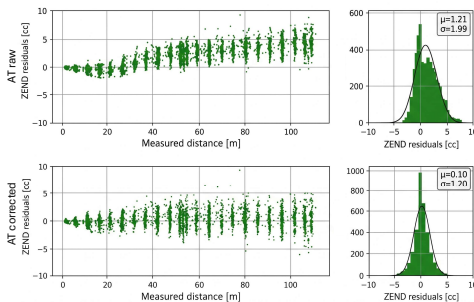
Each technique was analysed independently through a free-network least-squares adjustment. Residual RMS values are corrected using each observation internal-reliability coefficient, giving a realistic representative precision. These values are used in a combined least-squares adjustment integrating all available measurements.

Measurement methods	Precision
Levelling	15 μm
Traditional ecartometry	38 μm
Photogrammetric train	24 μm
AT horizontal angle	0.11 mgon
AT vertical angle	0.15 mgon
AT distance	32 μm

Laser tracker:

atmospheric refraction on vertical angles (ZEND)

Vertical angles corrected using a linear model of atmospheric refraction. After correction, the residual on the vertical angle (RMS ZEND) falls from 0.24 to 0.12 mgon.



COMBINED ADJUSTMENT

The combined adjustment shows good overall consistency between the measurement techniques. The residual means is close to zero for all observation types. Laser tracker and levelling exhibit only minor degradation, confirming their compatibility with the combined calculation. Ecartometry shows a stronger degradation, likely reflecting limitations of the stretched-wire geometry, residual systematic effects, and small variations between measurement sessions.

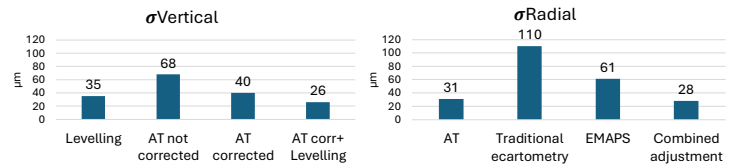
Measurement methods	Precision
Levelling	17 μm
Traditional ecartometry	61 μm
Photogrammetric train	34 μm
AT horizontal angle	0.12 mgon
AT vertical angle	0.17 mgon
AT distance	32 μm

CONCLUSION

Even current measurement precisions already meet LHC alignment tolerances, the results of this study suggest that the greatest potential gains lie in the development and qualification of an optimized process based on 3D laser-tracker measurements for LS3 and LS4. Key priorities include automatically accounting for atmospheric refraction and

PERFORMANCE COMPARISON APPLIED TO LHC

LHC alignment tolerance is expressed as a relative requirement over a 200 m sliding window. Relative precisions below are evaluated over 214 m (five quadrupoles) by using covariance propagation for the vertical dimension and Monte-Carlo simulation for the radial dimension.



WORKFLOW OPTIMISATION FOR LS3 / LS4

Time analysis

AT measurements require longer station occupation times due to the extensive observation sequences. However, laser trackers provide a complete 3D solution from a single measurement campaign. In contrast, the historical workflow requires separate levelling and ecartometry campaigns followed by independent processing stages. This capability partially compensates for the longer acquisition time and offers opportunities for future simplification of the alignment process.

Methods	σ_V [μm]	σ_R [μm]	Nb meas.
Levelling	35	-	8
AT corr*	40	31	62
AT raw	68	31	62
AT shorter*	73	91	27
AT reduced*	81	53	32
Ecartometry	-	110	18
EMAPS	-	61	18

*vertical angles corrected from atmospheric refraction

Optimization of laser tracker geometry

Although reducing the number of observations inevitably degrades the achievable precision, the study shows that a substantial margin remains with respect to the LHC alignment requirement of 200 μm . Therefore, future campaigns could investigate optimized acquisition strategies balancing observation density and operational efficiency.