EVALUATION OF ERROR PROPAGATION IN THE FIRST-ORDER GEODETIC NETWORK OF THE FCC TUNNEL USING TOPOGRAPHICAL TECHNIQUES

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Abstract

The Future Circular Collider (FCC-ee) is a next-generation electron-positron collider under design at CERN to advance particle physics beyond the Large Hadron Collider (LHC) era. This 91 km-long accelerator, located at a depth of about 200 m underground, raises significant challenges for the alignment of its components. Thousands of elements must be positioned within a few tens of micrometers precision relative to each other to ensure optimal machine performance. To achieve this, a first-order alignment network transferred from surface references must be established along the entire tunnel. This network should provide the basis for tracing, installation and absolute alignment of components prior to the relative alignment phase.

A dedicated simulation tool has been developed to model the FCC-ee tunnel, including shafts and bypasses. Then, different network configurations can be generated to simulate polar, gyroscopic, and leveling measurements. This paper presents the methodology used to build these simulations, and studies the resulting error propagation and expected precision for each measurement configuration.

INTRODUCTION

The Future Circular Collider (FCC-ee) is a 91 km-long electron–positron collider under development at CERN, which requires high-precision alignment to maintain the beam on a smooth trajectory, with expected tolerances around 150 μm for certain components to be aligned in arc sections [1]. To achieve these requirements, a First-Order Geodetic Network must be installed and measured along the entire tunnel to provide the reference for installation and absolute alignment of components, prior to the relative alignment phase. Based on LHC absolute alignment tolerances of approximately ±3 mm (1σ) [2] and considering that component positioning must not interfere with tunnel integration or exceed adjustment support limits, the FCC absolute alignment tolerances are expected to remain within ±5 mm (1σ), which is larger than for the LHC due to the size of the FCC. Given these tolerances, the 11.3 km between adjacent FCC shafts, which also corresponds to the spacing of network reference points transferred from the surface, makes error propagation along the tunnel a critical issue that needs to be studied. This paper presents a preanalysis-based approach to evaluate error propagation and assess whether the alignment tolerances can be achieved using polar, gyroscopic, and leveling measurements.

REALISTIC FCC GEOMETRY MODEL

Before simulations can be performed, a complete representation of the FCC alignment network must be generated. This requires a detailed geometric model of the entire accelerator infrastructure, serving as the basis for the definition of network points and measurements. This step already constitutes a major challenge due to the scale of the project and the complexity of the tunnel geometry, particularly in experimental and technical Long Straight Sections (LSS), as well as in shafts and associated bypasses. A dedicated Python software tool has been developed, to create a geometry as realistic as possible with respect to the expected final design of the machine infrastructure. It uses two different inputs: the integration design derived from CAD models and the optics design obtained from MAD-X files. From the integration data, two-dimensional cross sections of the tunnel are extracted. The longitudinal dimension of the model is introduced by assigning these cross sections to cumulative distance intervals. The resulting geometry is a linear tunnel. To account for the machine curvature, the current model is segmented into 1-m slices which are then successively positioned along the MAD-X reference trajectory. In parallel, shafts, bypasses, and other specific areas are loaded from the integration data using the same approach as for tunnel cross sections, with the two dimensions describing a top view rather than a transverse profile. These elements can then be inserted and positioned at their nominal locations by the software user.

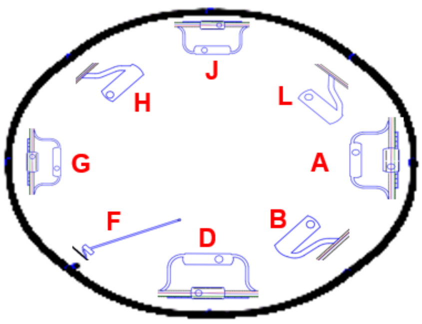

Figure 1: Generated FCC infrastructure

While developed and employed to model a finely detailed FCC geometry with the most up-to-date known information available (see Fig. 1), this software and its workflow could be applied to any other accelerator facilities where both tunnel data and a MAD-X beamline trajectory exist (usually available from the authors upon request).

FIRST-ORDER GEODETIC NETWORK

Once the FCC geometry is defined, the next step is the establishment of the First-Order Geodetic Network throughout the tunnel, corresponding to the definition of network points and observations. In practice, the network originates at the surface, based on the Primary Surface Geodetic Network and the geoid determination described in [3]. It is then transferred to the underground areas through the twelve access shafts distributed along the FCC [4]. For the simulations presented here, the First-Order Geodetic Network is defined directly in the underground tunnel, in the vicinity of the shaft locations. An a priori uncertainty of 5 mm is assumed on each reference point coordinate, resulting from the vertical transfer uncertainty, in accordance with the studies reported in [5]. The software allows the user to create points manually to link specific areas, such as shafts, to the main tunnel network. Points in the main tunnel network are then generated by placing them on a tunnel cross profile type and replicating this layout along the tunnel axis at user-specified intervals of x meters. Finally, the user can automatically define polar, leveling, and gyroscopic observation schemes between network points. Polar observations consist of a combination of horizontal direction, zenith angle, and slope distance observations. Gyroscopes provide absolute azimuth observations, which are a powerful means of transferring orientation over kilometer-scale distances in tunnels. The leveling model is implemented in a fully 3D framework [6]. Simulations can be widely tuned, from network configuration and density to the range, spacing, or a priori uncertainty of observations. All points and observations can be extracted from the software as input for the Logiciel Général de Compensation (LGC), a CERN in-house open-source compensation software able to run least-squares-based simulations [7]. These preanalyses yield 3D covariance matrices of the network points, from which point uncertainties can be extracted.

This workflow allows the generation of a wide range of simulation configurations. However, for clarity and relevance, this paper focuses only on a few realistic cases that provide an overview of error propagation and allow identification of the parameters with significant impact. Tab. 1 summarizes the assumed observation uncertainties for each measurement type at the 1σ level. Polar measurement standard deviations are based on laser trackers such as the Hexagon AT40x. The associated observation uncertainties, as well as those for levelling, are derived from empirical studies conducted at CERN [8] and CERN alignment team experience. Gyroscopic uncertainties are taken from [9], while those for the laser tracker inclinometer used for instrument verticalization come from [10]. Furthermore, it is important to note that, while the relative geometry of the network is realistic, its absolute position is entirely theoretical, derived from MAD-X survey files. Therefore, the simulations presented here consider only random errors modeled stochastically.

Table 1: Observation uncertainties for simulations

	Polar	Level	Gyro	Incl.
Distance / Height lect. (mm)	0.015 + 1 ppm	0.02	-	-
Two face angles / Azimuth (mgon)	0.2	-	0.8	0.3

No systematic errors are included yet, neither those arising from the geoid nor any other effects such as atmospheric refraction. The primary focus is to understand the propagation of random errors within such network geometries.

SIMULATIONS AND RESULTS

Since the simulation frame is purely theoretical, the covariance matrix provided by LGC has been transformed, using the 2-dimensional rotation matrix, to get longitudinal and radial uncertainties. The vertical component remains unchanged.

The first baseline simulation used polar measurements with 4-point profiles spaced every 20 m along the entire tunnel. Instruments were also placed every 20 m, shifted by 10 m so that each observed three consecutive profiles over a 50 m range, backward and forward. In all simulations, the links between the main tunnel network and the shaft networks are established using polar measurements only. The resulting network point uncertainties are shown in Fig. 2 as a function of the cumulative distance. This baseline simulation shows a similar error behavior along the FCC arcs. However, a pronounced error increase is observed around point F due to the 800 m long transfer between the access shaft and the FCC tunnel. Another increase appears downstream of point B, as the shaft B is located slightly upstream of the center of its LSS, leading to a larger distance between the reference points of shafts A and B. Finally, error propagation is 2 to 3 times smaller in the longitudinal direction than in the radial one, reflecting the impact of the laser tracker distance precision on the predominantly longitudinal geometry of the tunnel network. However, a small cross-direction error transfer in the middle of arcs is induced by the tunnel

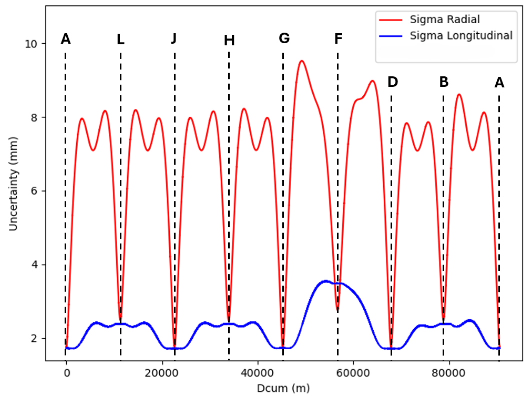

Figure 2: Network point coordinates uncertainty (1σ) as function of the tunnel longitudinal dimension, along the radial (red) and longitudinal (blue) axis

curvature. The uncertainty along the vertical axis, not shown here for scaling reasons, is addressed later in the paper.

To assess potential improvements of the network, the baseline simulation was repeated with modified parameters to evaluate their impact on the overall error propagation. The same configuration was thus simulated with point profiles and stations spaced every 10 m (case a), 8-point profiles (case b), and an increased measurement range of 90 m, corresponding to observations of five profiles per side (case c). The results shown in Tab. 2 indicate that the best uncertainties are achieved by increasing the range by a factor of 1.8, whereas the other scenarios rely on doubling the network density while still exhibiting slightly larger error propagation. Moreover, these alternative configurations require roughly twice as many tunnel points and instrument stations, along with a significantly higher number of measurements—exceeding one million in case a—despite providing worse performance. Hence, the most cost-effective parameter to increase seems to be the measurement range of the polar instrument. However, empirical studies reported in [8] show that, for laser tracker lines of sight longer than 55 m, the impact of systematic errors arising from atmospheric refraction on vertical angle measurements should be considered. Further investigations are therefore required to assess the impact of this effect and to explore possible mitigation strategies.

Table 2: Comparison of maximum radial uncertainty in different simulation cases

	Baseline	**a**	**b**	**c**
Max. error in regular arcs (mm)	8.2	6.0	6.5	5.2
Max. error near point F (mm)	9.5	6.9	7.5	5.9
Improvement (%)	/	27	21	37
Points	23k	46k	41k	23k
Stations	5k	9k	9k	5k
Measures	334k	1100k	662k	552k

Although the expected 5 mm tolerances are not achieved with the previous simulation scenarios in the radial direction, an essential measurement type for underground networks has so far been deliberately omitted: gyroscopic observations. Their contribution is therefore investigated by re-running the baseline simulation with the addition of gyroscope measurements. For simulation purposes, gyroscope observations were assigned to existing polar station points. In practice, gyroscopes are mounted on theodolites; however, rigid integration with a laser tracker is foreseeable. Numerous simulations were performed, varying from a single gyroscope station per arc to nearly fifty, each acquiring one backward and one forward observation. The measurement range was limited to 50 m in order to mitigate atmospheric refraction effects.

The result of these simulations has shown that approaching the 5 mm radial tolerances requires at least 50 additional gyroscopic observations per arc on top of the baseline scenario. Considering that a single azimuth observation requires approximately 8 to 10 minutes and must be repeated 2 to 3 times for control, this would correspond to more than 360 hours of pure measurement time. In addition, gyroscopes are fragile instrument and need to be often calibrated and controlled. This represents a substantial effort for only one component of the survey campaign. Gyroscopic observations therefore appear essential, yet insufficient on their own to rapidly establish a high-quality initial tunnel network.

The vertical component of the network was also investigated. In the baseline simulation, the obtained uncertainty never exceeds 0.8 mm. The assumption is that this submillimetric result comes from the mathematical model used in the simulations, which assumed perfectly verticalized instruments. For the same reasons, closed-loop leveling simulations show similar uncertainties, also remaining below 0.8 mm. To evaluate the impact of realistic verticalization imperfections, additional simulations including inclinometer measurements of instruments roll and pitch were performed. These simulations, which include a verticalization error of 0.3 mgon in two perpendicular directions, resulted in a peak uncertainty of around 1.7 mm in the arcs and demonstrate a well-determined vertical component compared to the other directions. In practice, laser tracker inclinometers are expected to achieve higher precision. The fact that they are equipped with inclinometers for verticalization establishes a direct link to gravity, which provides an absolute reference for the vertical direction. Nevertheless, systematic errors arising from vertical deflection and geoid model imperfections cannot be neglected and still need to be assessed.

CONCLUSION

A software tool has been developed to generate and tune realistic FCC network simulations. The simulation study highlights the key parameters affecting the first-order FCC-ee tunnel network. While the maximum uncertainty is mostly the same in different arc sections; distant shafts, such as at point F, can induce significant variations in error propagation, reaching up to 9.5 mm when the transfer tunnel is 800 m long. Absolute measurements, such as azimuths and inclinometer readings, prove to be powerful in constraining the network. Overall, the longitudinal and vertical components remain determined under the 5 mm tolerances expected; however, the radial direction is the main limitation to achieve the ±5 mm tolerance. Still, simulation results suggest that combining gyroscope observations with an increased laser tracker range and higher network density could reduce the radial error below the 5 mm tolerances targeted here.

Future work will focus on estimating dominant systematic effects, including geoid model imperfections and atmospheric refraction, to provide a more realistic error budget. Wire offset measurements could offer improvements for the radial component and merit dedicated simulation studies. In addition, the integration of network points and observation lines-of-sight in an already dense FCC-ee tunnel arc section layout will be essential to further constrain the network and ensure accurate absolute alignment.

REFERENCES

[1] H. Mainaud Durand, L. Watrelot, and B. Weyer, "Geodetic, survey and alignment challenges of the FCC-ee," *J. Instrum.*, vol. 19, no. 02, T02006, 2024.

[2] D. Martin, "Review of accelerator alignment," in *Proceedings of the FIG Congress, Apr. 2010*.

[3] B. Weyer and H. S. Konan, "Towards centimetric geoid over the FCC area: Application of the Stokes–Helmert method," in *Proceedings of the 16th International Workshop on Accelerator Alignment (IWAA), Ferney-Voltaire, France, Oct. 2022*, `https://cds.cern.ch/record/2849057`

[4] M. Benedikt, F. Zimmermann, et al., "Future Circular Collider feasibility study report, volume 3: Civil engineering, implementation and sustainability," CERN, Tech. Rep., 2025.

[5] A. Wieser and M. Varga, "Database of methodologies and instruments for position and orientation transfer into the FCC tunnel," Institute of Geodesy and Photogrammetry, ETH Zurich, Tech. Rep. FCC-Geodesy IGP-AA-2.3, 2025, FCC project internal report.

[6] J.-F. Fuchs, J.-F. Segers, and C. Vendeuvre, "Development of a new levelling process integrated into a 3D global calculation," in *Proceedings of the 17th International Workshop on Accelerator Alignment (IWAA), Menlo Park, USA, Oct. 2024*, `https://cds.cern.ch/record/2938905`

[7] G. Kautzmann, J. Gutekunst, et al., "LGC open-source: A strategy to share adjustment software and algorithmic development," in *Proceedings of the 17th International Workshop on Accelerator Alignment (IWAA), Menlo Park, USA, Oct. 2024*, `https://cds.cern.ch/record/2938907`

[8] G. Bourlon, "Évaluation de mesures combinées dans un arc du Large Hadron Collider," M.S. thesis, École Nationale des Sciences Géographiques (ENSG), 2025.

[9] DMT GmbH & Co. KG, *Gyromat 6000 technical manual*, Technical data and specifications, 2024.

[10] Leica Geosystems AG, *Nivel230 for absolute tracker user*, User Manual, Technical data and specifications, 2008.