Swiss Accelerator Research and Technology

CHART Scientific Report

FCC Geodesy

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1. Introduction / Original goals of this project

The FCC would cover an area around ten times larger than the current CERN site. It would extend over the Swiss/French border and span areas with vastly different topographical and geological features. The required alignment accuracies would be very high. Therefore, an evolution and extension of the geodetic reference systems and geodetic infrastructure currently available at the CERN site are needed. FCC Geodesy aimed at providing the knowledge required for optimally aligning this evolution and extension with the anticipated needs for the proposed FCC at CERN.

The first part of the project addressed the determination of a high-precision gravity field model for the new CERN site including the FCC region, which can replace the current geoid models dating back to 1985 and 2000. The geoid or quasi-geoid obtained from the new gravity field model should have a precision of 1 cm or better within the FCC region. The second part aimed at a concept for improvement of the geodetic reference frames and geodetic infrastructure, that are still based mostly on the LEP, which was inaugurated in 1989, and for the transfer of position and orientation into the FCC tunnel to a depth of around 300 to 400 m. The present report summarizes the research work and outcomes of the now completed project.

2. Realization

2.1 Gravity Field Modeling and preparatory work

The research on the gravity field comprised a study of applicable methodologies, required auxiliary datasets, and suitable instruments for the determination of a high-precision geoid model. The focus was placed on well-established instruments, such as the FG5 absolute gravimeter or the Burris relative gravity meter, but also instruments still in development were considered, if they have a high potential to surpass the performance level of the well-established instruments. A first gravity field model specially adapted to the FCC region was calculated using already available data. The model's accuracy and deficiencies in the area of the FCC tunnel were assessed in detail, using a high-accuracy validation profile measured specifically for this purpose from March 2021 to April 2022 between the current facilities of CERN and Annecy. Using a newly developed numerical simulation tool, critical auxiliary data and suitable configurations were analyzed, paving the way to the introduction of a suitably precise geoid model and a possible later transition to a dynamic model.

In parallel to the GNSS processing, several existing software packages for the calculation of consistent gravity field models for the whole FCC area were evaluated. Two software packages (GROOPS, TU Graz; QUAWIRK/HITCOL, swisstopo) were in principle suitable; due to better stability after an update of the operating system, GROOPS was finally used for the calculations. A closed-loop simulator was then developed in Python to study the performance of different gravity field determination scenarios. Finally, a comprehensive review of current and emerging techniques for gravity field determination, including quantum gravimeters and chronometric leveling, was conducted to guide the design of future measurement campaigns in the FCC region.

2.2 Reference Frames and Geodetic Infrastructure

The project part addressing the geodetic reference frames and the geodetic infrastructure started with an analysis of the needs and conditions to be accommodated by the frame and datum for the anticipated purposes during the entire life cycle of the FCC. Starting from there, concrete proposals for the coordinate reference systems as well as their implementation using a surface geodetic network were developed. The needs were analyzed also with the long-term perspective of dealing with temporal changes over the FCC's lifecycle through monitoring and kinematic modelling.

Starting with a collection and critical assessment of anticipated needs as well as a literature study, proposals were then developed how to transfer position, orientation and scale from the surface reference network down to the tunnel, as well as assuring high accuracy through testing and calibration of all involved geodetic equipment.

2.3 Knowledge transfer

Apart from scientific publications, the research and findings were reported directly to CERN through technical reports and oral presentations. They were extensively discussed within the FCC Geodesy Advisory Board, established by CERN. Where possible, CERN already started putting solutions in place that follow the results of the present study or were at least inspired by them.

3. Results / Conclusions / Deliverables

Gravity field modeling

A preliminary geoid and quasigeoid (FCC-G, FCC-QG) were calculated and tailored to the FCC region using previously existing gravity data from swisstopo (gravimetric atlas) and IGN (BRGM) as well as measurements from a new campaign (2022). Comparison of the FCC-QG to several national (e.g., CHQua04, RAF20) and global (e.g., EGM2008, XGM2019e) quasi-geoid models indicated best agreement with the hybrid models CHQua04 (Switzerland) and RAF20 (France) models. The standard deviations were 14 and 27 mm, respectively. The FCC-QG also agreed well ($\sigma \leq 9$ mm) with independent GNSS/leveling datasets from swisstopo and IGN.

Using RAF20 and CHQua04, the current precision of the FCC-QG solution along the FCC tunnel trajectory was estimated to be approximately 1.1 mm within a sliding window of 225 m. This implies that further improvement by a factor of 10 to 30 may be required to meet the target tolerance of 30 to 100 µm over a distance of 225 m.

The measurement campaigns for the 45 km long validation profile were conducted between March 2021 and April 2022 by personnel from CERN, ETH Zurich, swisstopo, and HEIG-VD. They comprised GNSS measurements (two 24-hour sessions per station), spirit leveling (8.8 km connection between existing Swiss and French leveling lines, near Perly/Saint-Julien-en-Genevois), astro-geodetic measurements of deflections of the vertical (DoV; stations roughly every 800 m), and gravimetry (at the GNSS stations and along the levelling lines).

Among a group of geoid and quasi-geoid models, the preliminary FCC-G and FCC-QG showed the best agreement to the validation profile; the standard deviations were between 0.7 cm (FCC-G vs. astro-geodetic geoid profile) and 1.7 cm (FCC-QG vs. astro-geodetic quasigeoid profile). However, also the other models did not fit much worse, and no single model performed best across all length scales.

Digital elevation models (DEMs) are essential for calculating topographic corrections to gravity observations. Their errors directly propagate into the final geoid heights. Within the present study, we found mean height differences of up to 11 m between eleven different DEMs covering the required region. However, local discrepancies in mountainous regions (foothills of the alps) reached several hundred meters due to shadowing effects and acquisition limitations. These differences mapped into geoid undulations biases of up to 3.5 cm (e.g., between the EuroDEM- and the TanDEM-X-based solution) and standard deviations of up to 6 mm (e.g., between the MERITand Viewfinder Panorama-based solution). Results of a trial to identify the existing DEM best suited for the present purpose by comparing to GNSS and levelling datasets were inconclusive. We conclude that the availability of a highly accurate DEM will be a limitation for the calculation of a CERN (quasi-)geoid and for the current validation approaches.

A closed-loop simulator was designed and implemented in GROOPS to enable experiments in a controlled environment. It generates a "true geoid" by combining the global geoid model XGM2019e (up to d/o 2159) with the digital elevation model FABDEM V1-2 under a standard constant density assumption of 2670 kg/m3, creates simulated observations therefrom, and computes an "estimated geoid" from these observations using the remove-compute-restore method. Within FCC Geodesy, we used the tool to study observation spacing and density assumptions by analyzing the differences between the initial and the estimated geoid.

According to Kaula's rule of thumb, achieving a 1 cm geoid precision requires a data spacing of approximately 1.5 km. Simulations with spacings varying from 0.5 km to 5 km confirmed that a 1 km spacing achieves millimeter-level consistency with the "true geoid", while a significantly larger spacing led to non-negligible biases. Observations denser than 1 km, i.e., slightly denser than according to Kaula's rule of thumb, are thus required to ensure sub-centimeter accuracy. The current density of gravity data is not sufficient; additional gravity campaigns will be needed in the region.

Density changes of only 60 kg/m^3 resulted in systematic offsets and variations up to several decimeters of the geoid. This exceeded the expected changes by more than an order of magnitude. The reasons could not be clarified; it seems likely that there is an issue in the variance component estimation used to weight the observations against the regularization term in the compute step. Further investigations are required to clarify and solve this.

We concluded the study with a systematic review of established and emerging terrestrial and airborne observation techniques relevant for geoid modeling. Ultimately, no single instrument is optimal for all purposes, and the choice depends on the required precision, environmental conditions, and the spatial scale of the study. The review will guide instrument selection for future gravity field measurement campaigns in the FCC region.

Implementation of Geodetic infrastructure

The concrete choice of coordinate reference systems (CRSs) and coordinate reference frames (CRFs) result as much in administrative and governance challenges as technical ones. Nevertheless, practical work with coordinates and achieving the required quality can be supported better by some choices than others, in particular with respect to need for special training of personnel, generation of new software tools, and combining geospatial data from CERN with data from other institutions. Based on these premises and a thorough study of the CRSs/CRFs in use at CERN, we proposed introducing a new solution rather than just adapting the existing ones.

Concretely, we developed a set of recommendations comprising (i) a static CERN Terrestrial Reference Frame (CTRF), coincident with an up-to-date realization of ETRS89 at a chosen reference epoch, for establishment of the geodetic surface network across the FCC area, for long-term monitoring and for connection to other reference frames; (ii) a projected reference frame (CPF) based on a conformal map projection and connected to the CTRF by conversion via a GRS80 ellipsoid as horizontal datum; (iii) a CERN Vertical Reference Frame (CVF) of gravity-based heights for the civil engineering works; and (iv) well-defined transformations for linking the existing CRSs to the new ones e.g., for connecting the FCC to existing CERN infrastructure. The 3D Cartesian coordinate systems (MAD) used by CERN for the planning and simulation of the accelerator physics/optics can then also be connected to the new systems by transformations.

We proceeded to develop a concept for the surface geodetic networks (SGN) and control baselines needed for the construction of the FCC tunnel. The SGN serves different purposes: it is the physical implementation of the coordinate reference systems (CTRF, CPF, CVF), it enables the civil-engineering and surveying works required for the construction of the tunnel, it provides providing the long-wavelength basis for the later alignment works, and it provides the reference for geokinematic monitoring of the FCC area. We argued for an early installation of a Primary SGN (P-SGN) which is later densified at specific locations using points of a Secondary SGN (S-SGN) and height benchmarks representing a Vertical SGN (V-SGN). Continuous and campaign-wise GNSS measurements can be used for the installation of the SGN and for the later geomonitoring.

Transfer of coordinates, orientation, and scale through the shafts will be necessary to establish the coordinate reference frame for the underground civil engineering construction of FCC. Each transfer must be accurate enough such that all breakthroughs between one-sided tunnel drivings in opposite directions are within the set tolerances. Using a literature review as well as numeric simulations, we studied the feasibility of a variety of existing and conceivable future solutions for each type of transfer aiming for concrete proposals and priorities.

We found that position and orientation transfer through the shafts will likely not be the main limitations of successful breakthroughs. There is no stringent need to develop new transfer solutions, and with few exceptions where we propose automation or small modifications, we primarily recommend solutions successfully applied already in recent large tunnel construction projects and relying on existing instruments and tools.

For coordinate transfer, we recommend mechanical and optical plumbing; for height transfer vertical EDM and geometric leveling using a calibrated long measurement tape; for orientation transfer gyro-thedolite measurements and measurements using an IMU platform plus autocollimation; and for scale transfer regular calibration of EDM instruments and meteo sensors, establishment of underground baselines, and atmosphere-compensating measurements of selected above- and underground baselines.

The analysis in this project cannot replace a thorough planning and geodetic pre-analyis of the underground geodetic network. This must be based on an assessment between geodetic expertise and civil engineering experts clarifying the admissible geodetic breakthrough errors in terms of the radius of the confidence intervals and associated confidence levels of the breakthrough points.

The research also indicated a significant gap in the literature regarding the atmospheric regime within shafts and tunnels during construction as well as associated limitations for and systematic effects on geodetic measurements. We see the FCC shafts as a unique opportunity for geodetic research and proposed to find ways to leverage this potential without impairing the construction process.

Finally, we developed a concept for calibration, checking, and testing (CCT) of geodetic instruments at CERN. The underlying research started again with a literature research. We also carried out a stakeholder survey among institutions carrying out CCT at a regular basis. We found that the CCT needs for the FCC will differ between the three phases construction, installation, and operation.

We anticipate the majority of geodetic CCT needs involving either direct activities from CERN or facilities at CERN to be encountered during the installation phase. We propose a mix of in-house activities and facilities as well as outsourcing to external service providers. The proposed in-house activities mostly relate to testing of total stations, levels, laser scanners and laser trackers, as well as calibration of leveling systems. For instruments whose mechanical and electronic components require regular maintenance by the manufacturer anyway, we propose to also have the calibration covered by the manufacturers through appropriate service contracts.

Surveying and alignment will need a high degree of automation during the operation phase of the FCC, possibly even earlier. The corresponding measurement systems and processes will likely be custom tailored and are so far unknown. CCT for these systems could thus not be included in the present study yet. We anticipate, however, that the developed proposals will be adaptable to fully automatic measurement systems for surveying and alignment, and can thus serve as a starting point for the later development of the related CCT concepts.

4. Publications and Outreach

- Benedikt M, Garayt B, Koch J, Mainaud Durand H, Marti U, Rothacher M, Ryf A, Soja B, Varga M, Weyer B, Wieser A, Willi D (2023) Ongoing and future geodetic studies for the CERN Future Circular Collider. Presentation at 21st Swiss Geoscience Meeting, Mendrisio, Switzerland, November 17-18, https://www.research-collection.ethz.ch/handle/20.500.11850/656372
- Edwards J, Roca F (2024) Comparing Geoid-Quasigeoid Separation Calculation Methods in the FCC Region at CERN. BSc thesis, ETH Zürich
- Fandré MJ (2022) Future Circular Collider at CERN: Gravity field modelling based on the information available on the geology in the region. MSc thesis, ETH Zürich
- Guillaume S (2022) Geodesy for science and society. Presentation at FCC Week, May 30 – June 3, Paris, https://indico.cern.ch/event/1064327/contributions/4888571/
- Koch J, Guillaume S, Soja B, Rothacher M (2024) Impact of a Detailed 3D Geological Model on

the Geoid Detmerination in the FCC Region at CERN. Poster presentation at AGU Fall Meeting 2024, Washington, DC, USA, December 9-13, https://agu.confex.com/agu/agu24/meetingapp.cgi/Paper/1674463, https://www.research-collection.ethz.ch/handle/20.500.11850/711699

- Koch J, Herrera Pinzón I, Varga M, Wieser A, Soja B, Rothacher M (2024) High-precision GNSS processing for the FCC at CERN. Presentation at AGU Fall Meeting 2024, Washington, DC, USA, December 9-13, https://agu.confex.com/agu/agu24/meetingapp.cgi/Paper/1672656, https://doi.org/10.3929/ethz-b-000711712

- Koch J, Marti U, Herrera Pinzón I, Willi D, Soja B, Rothacher M (2023) A high-precision profile for the validation of local high-resolution geoid models in the FCC region at CERN. Presentation at 28th IUGG General Assembly, Berlin, Germany, July 11-22, https://www.research-collection.ethz.ch/handle/20.500.11850/623598

- Koch J, Marti U, Herrera Pinzón I, Willi D, Soja B, Rothacher M (2024) Geoid Computation for the Future Circular Collider at CERN. International Association of Geodesy Symposia, Springer, Berlin, Heidelberg, https://doi.org/10.1007/1345_2024_275

- Koch J, Marti U, Rothacher M, Willi D (2022) High-precision Profile for Geoid Validation in the FCC Region at CERN. Poster presentation at GGHS 2022 Symposium, Austin, 12-14 September, https://www.csr.utexas.edu/gghs2022/gghs-2022-program/posters/, https://www.research-collection.ethz.ch/handle/20.500.11850/571609

- Koch J, Rothacher M, Marti U, Willi D (2022) Gravity field modeling. Presentation at FCC Week, May 30 – June 3, Paris, https://indico.cern.ch/event/1064327/contributions/4883205/

- Koch J, Soja B, Rothacher M (2025) Geoid Closed-Loop Simulator for the FCC at CERN, Poster, IAG General Assembly. https://doi.org/10.3929/ethz-c-000783643

- Koch J, Soja B, Rothacher M (2025) Impact of Different DEMs on High-Precision Geoid Modeling in the Region of CERN, International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2025_292

- Koch J, Soja B, Rothacher M (2024) Effect of the differences between available DEMs on high-precision geoid modelling in the region of CERN. Poster presentation at GGHS 2024 Symposium, Thessaloniki, 4-6 September, https://www.gghs2024.com/abstract-93/book-of-abstracts/, https://www.research-collection.ethz.ch/handle/20.500.11850/692848

- Koch J, Willi D, Marti U, Soja B, Rothacher M (2023) Geoid validation dataset from profile measurement campaigns for the FCC at CERN. Swiss National Report on the Geodetic Activities in the Years 2019 to 2023, Presented to the XXVIII General Assembly of the International Union of Geodesy and Geophysics in Berlin, Germany, July 2023, p- 56-59, ISBN 978-3-908440-55-0

- Mainaud Durand H (2022) Les défis liés à l'alignement d'accélérateurs. Presentation at Colloquium "Zukünftiger Teilchenbeschleuniger am CERN: Herausforderung für die Geodäsie", swisstopo, Wabern, 28.1.

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- Rothacher M, Koch J (2022) A new gravity field model for the FCC region. Presentation at Colloquium "Zukünftiger Teilchenbeschleuniger am CERN: Herausforderung für die

Geodäsie”, swisstopo, Wabern, 28.1.Soja B, Wieser A (2023) FCC Geodesy: Advances in high-precision gravity field determination, geodetic reference frames and geodetic infrastructure for the FCC region. Presentation at CHART Workshop 2023, Villigen, Switzerland, October 11, https://doi.org/10.3929/ethz-b-000637801

- Varga M (2022) Coordinate reference and networks. Presentation at FCC Week, May 30 – June 3, Paris, https://indico.cern.ch/event/1064327/contributions/4888555/
- Weyer B (2022) Handling Geodetic challenges at CERN. Presentation at FCC Week, May 30 – June 3, Paris, https://indico.cern.ch/event/1064327/contributions/4888561/
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- Wieser A, Varga M (2022) Geodetic Reference Challenges for a potential FCC. Presentation at Colloquium “Zukünftiger Teilchenbeschleuniger am CERN: Herausforderung für die Geodäsie”, swisstopo, Wabern, 28.1.
- Willi D (2022) La contribution de swisstopo à l’étude FCC. Presentation at Colloquium “Zukünftiger Teilchenbeschleuniger am CERN: Herausforderung für die Geodäsie”, swisstopo, Wabern, 28.1.
- Willi D, Koch J, Weyer B, Carrel J, Marti U (2022) Astrogeodätisches Profil am CERN. Cadastre (40), p. 16-18, https://www.cadastre.ch/de/services/revue.detail.publication.html/cadastre-internet/de/publications/revue/cadastre-40-2022-de.pdf.html

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