

CHART Scientific Report (Final Report for Phase 2)

Determination of a high-precision gravity field model for the FCC region and improvement of the Geodetic Reference Frames and the Geodetic Infrastructure (FCC Geodesy studies)

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1. Introduction / Original goals of this project

The area enclosed by CERN facilities in case the FCC is built, will be more than ten times larger than the currently enclosed area (about 1000 vs. 70 km²). It will extend well beyond the border between France and Switzerland, spanning areas with different national coordinate reference systems, different topographical and geological features, and potentially relevant geokinematic processes. Assessing the geokinematics, planning, constructing, aligning and operating the FCC would not be possible with the coordinate reference systems currently in use by Switzerland, France, or at CERN, nor with the available gravity field models covering the area. The "FCC Geodesy study" aims at providing the scientific basis for implementing geodetic reference systems and infrastructure of sufficient quality to enable the FCC.

The study consists of two main parts: the first one has the goal to determine a high-precision gravity field model for the extended CERN site, including the FCC region, which is more accurate, possibly

dynamic, and can replace the currently used geoid models which date back to 1985 and 2000. The goal of the second part is to improve the geodetic reference frames and geodetic infrastructure, that are still based mostly on the LEP, inaugurated in 1989. Challenges to be addressed include the choice of appropriate coordinate reference systems, their physical implementation through materialized points and coordinates, the transfer of position, orientation and scale into the FCC tunnel to a depth of around 300 m, the connection of the geodetic networks and the civil engineering monitoring, and the rigorous quality assurance of all geodetic instruments used during the life-cycle of the FCC.

2. Realisation

The research regarding the two parts above is primarily carried out by ETH Zürich. Julia Azumi Koch, a doctoral student, works on the gravity field model and all related aspects. She is supervised by Profs. Rothacher and Soja. Matej Varga, a postdoc researcher worked, together with Prof. Wieser, on the geodetic reference frames and infrastructure.

The research is supported by Swisstopo, who contributes software tools and ample expertise regarding gravity field modelling as well as supports field work with instruments and personnel. Also Prof. Sébastien Guillaume supports fieldwork and data processing related to the gravity field with expertise and personnel. CERN staff assures that the experiences, constraints and requirements regarding past and future geodetic work at CERN are available to the ETH research staff. CERN also helped with personnel during the field work. Finally, the FCC study leader has installed an “FCC Geodesy Advisory Board” which, among other activities, cares for a broader discussion of the research methods and results from the FCC Geodesy study. This board also helps to bridge the gap between the research results and their implementation by CERN. It provides input assuring that the research results are communicated in the appropriate form to be taken into account for the FCC feasibility study and to have early impact at CERN.

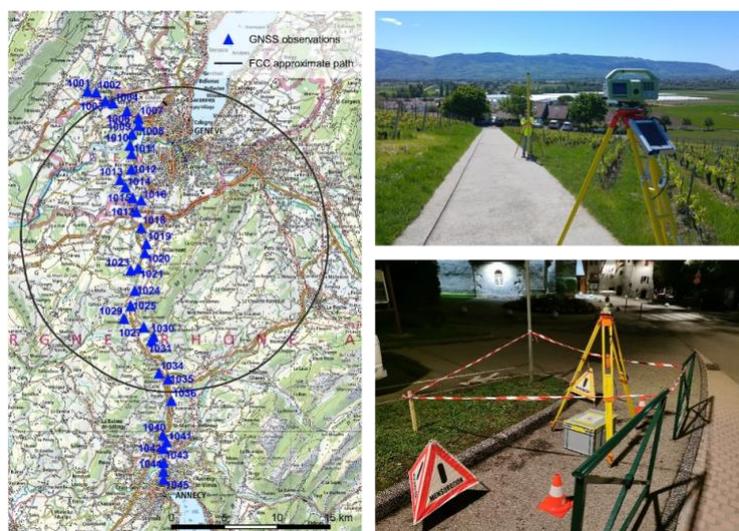


Fig. 1: GNSS stations along the validation profile (left, background map by swisstopo), precision levelling near Bernex (right, top), example of a GNSS station (right, bottom).

The research regarding the above questions is based on literature studies, theoretical derivations and numerical simulations. Additionally, extensive field work has been designed and carried out for the

gravity field study. This field work comprised spatially dense measurements along a chosen “validation profile” with the goal to provide highly accurate ground truth data for exposing limitations or deficiencies of existing gravity field models in the FCC area and enabling critical assessment of the quality of the newly derived models. This profile extends from Meyrin to Annecy over a length of about 40 km (see Fig. 1). It comprised

- measurements of deflections of the vertical (DoV) approximately every 800 m,
- geometric levelling (height measurements between national height benchmarks and the stations of the profile),
- relative gravity measurements, and
- GNSS measurements (i.e., coordinate measurements) approximately every 1 km.

Most of the measurements were carried out between March and December 2021, except the gravity measurements, which Swisstopo performed in April 2022. For the low-level data processing standard geodetic software was used. For the estimation of gravity field models from the available data and prior models, only scientific software and proprietary software is available. GROOPS from TU Graz and QUAWIRK/HITCOL from Swisstopo were tested. Both need adaptations by the PhD student for processing all the available data within this project.

3. Results / Conclusions / Deliverables

The literature study resulted in a list of instruments and sensing principles for data which can contribute to the estimation of the gravity field. We assessed the solutions regarding the anticipated need for a highly accurate gravity field model with very fine spatial resolution. During the construction, installation and operation phases of the FCC, instruments currently under development may become applicable, e.g., chronometric levelling systems based on atomic clocks, or free-fall cold atom gravimeters based on atomic interferometry. However, the time by which the required accuracy will be practically achievable using them under field conditions cannot yet be predicted. So, the experimental part of the research and the development of an actual gravity field model within this project were based on established measurement principles and terrestrial instruments already widely used.

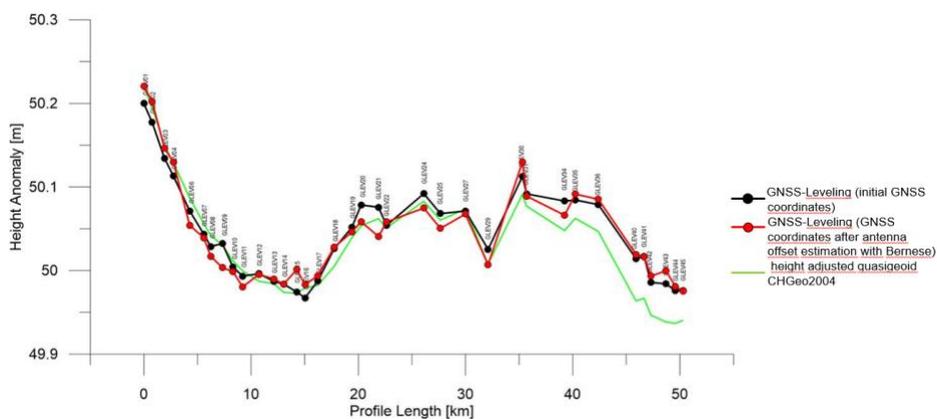


Fig. 2: Observed height anomalies using the initial GNSS coordinates and the preliminary GNSS coordinates compared to the height-adjusted quasigeoid CHGeo2004.

Using the gravity measurements and the levelled heights from the profile, normal heights were determined, and height anomalies calculated using the data from the GNSS campaign. Fig. 2 shows the results obtained from the preliminary GNSS coordinates of the GNSS levelling benchmarks. Both sets of

GNSS coordinates result in a similar pattern along the profile. Furthermore, we can see that the solutions match the slope of the Swiss quasigeoid CHGeo2004 well until approximately kilometer 32 but then deviate significantly. The Swiss quasigeoid is optimized for the area of Switzerland, and the part of the profile beyond about kilometer 15 is located on the French side (see Fig. 1).

Fig. 3 shows the calculated height anomalies in the region of CERN and the differences to GNSS levelling points provided by swisstopo and IGN. The spatial variability of these anomalies within the region of interest (RoI), which is the area that includes all current and planned facilities of CERN, is below 1 m. This corresponds to what may be expected from the topography. Outside the ROI, larger variability is found (more than 4.5 m within the area shown in the figure), but still in agreement with what may be expected based on the topography. Comparing the calculated solutions to GNSS levelling points in the full region, the standard deviation (STD) of the differences is approximately 30 mm. However, within the RoI it is only 7 and 9 mm for the datasets of Switzerland (swisstopo) and France (IGN), respectively. As expected, the strongest deviations are found at locations close to the border of the full region, where the deviations reach values up to 14 cm. The deviations are also higher in regions with distinctive topographic features, such as the Jura mountain range in the North of the FCC, as well as the Prealps in the South to Southeast direction. This first comparison is promising and lets us conclude that the final solution for the 1-cm (quasi)geoid, which will be mainly used in the construction phase, is in close reach.

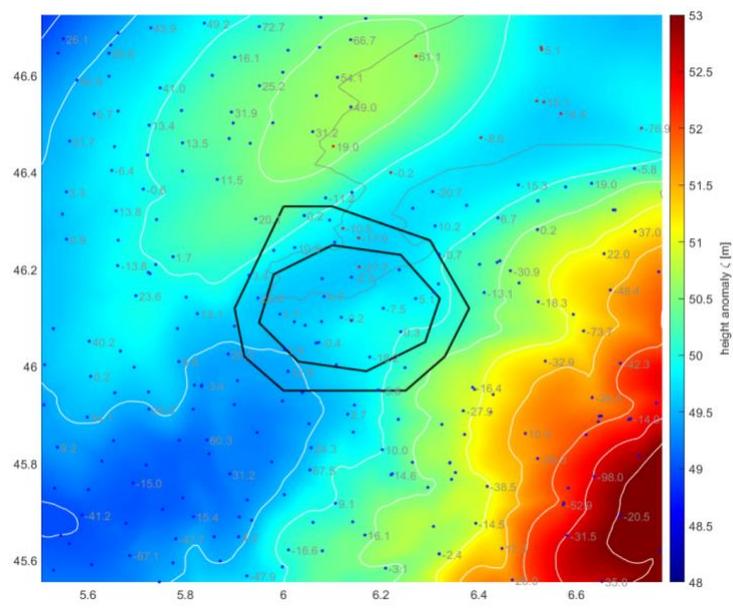


Fig. 3: Preliminary quasigeoid calculated for an extended region around the FCC, based on the hybrid global geoid GOCO06EGM08 and gravity measurements calculated with the GROOPS software. The region of interest (RoI) and the approximate location of the FCC tunnel are shown as black polygons. The locations of GNSS levelling points provided by swisstopo and IGN, are indicated by red and blue dots, respectively. For a selection of locations, the deviation (in mm) between the height anomaly derived in GROOPS and the GNSS levelling datasets are reported in grey.

The high-precision gravity field model will be needed in particular for the (pre-)alignment of the machine parts. From a practical perspective, the model will need to represent the deviations of equipotential surfaces from geometrically simple and unambiguous reference lines or surfaces like straight lines or an ellipsoidal surface. The main source of uncertainty, and thus of potential errors, is the transfer of the gravity measurements from the topographic surface to the level of the FCC tunnel, which is affected by unknown density variations of the rock/material along the respective plumbline. The uncertainties can theoretically be reduced by measuring the gravity field (variations) directly in the tunnel. In an earlier collaboration between CERN and ETH Zürich an instrument (Differential Geodetic Interferometric

Deflectometer) has been developed specifically for this purpose. Unfortunately, experimental research carried out within the present study indicated that the repeatability of the measurements with this instrument is not good enough and the instabilities of the moving cart within the instrument, causing the poor repeatability, can likely not be mitigated even with a redesign. Future research will need to look into alternatives, possibly avoiding the need for moving parts.

The work related to the reference frames and geodetic infrastructure started with a literature research, a detailed analysis of the coordinate systems and reference frames used by CERN so far, and a prediction of the future needs related to planning, construction, installation and operation of the FCC. From this analysis we concluded that it is best to create a specific and proprietary static CERN Terrestrial Reference Frame (CTRF) as a backbone of all future CERN infrastructure and as a central hub for transformation between legacy data and future data. For planning and carrying out the construction works with distinction between horizontal and vertical situation, we proposed a CERN projected reference frame (CPF) and a (gravity-based) CERN Vertical Frame (CVF) uniquely linked to the CTRF. We also proposed transformations to link the existing and new reference frames.

We developed the concept of a multi-purpose surface geodetic network (SGN) as a backbone for implementing the above reference frames, for all civil engineering and surveying works as well as for monitoring the FCC area. We determined advisable geometric configurations based on numerical simulations taking into account technical (e.g., accuracy) and non-technical (e.g., accessibility) criteria for the location of the SGN points. This resulted in a conceptual proposal of a geometric configuration (Fig. 4) that has in the meantime already been picked up by CERN and is currently being implemented.

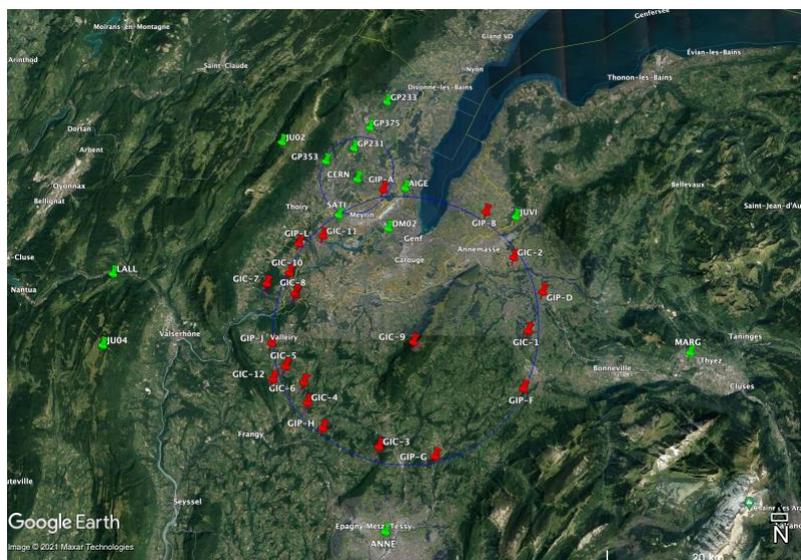


Fig. 4: Conceptual proposal of primary SGN comprising points to be newly established (red) and existing points (green).

The coordinates, orientation, and scale realized above ground by the SGN points and points derived therefrom, need to be transferred into the tunnel during the construction. Since the tunnel can only be reached through the narrow vertical shafts with depths on the order of 300 m and diameters on the order of less than 20 m, and the required accuracies will be very high, this transfer will be particularly demanding. We analyzed the characteristics and potential of various absolute and relative methods, including gyro-theodolite, mechanical, optical and laser plumbing, 3D geodetic network, IMU, polarized light, image correlation, and TPS-based angle measurements. Using numerical simulations we identified

a combination of plumbing, gyro-theodolites, and careful calibration of EDM as the most likely only solution which will be available at the time of tunnel construction.

Once the construction is completed and the installations start, the geodetic underground measurements and civil engineering monitoring will need to be connected, allowing for measurements with a high degree of automation. A preliminary study of available information about the FCC area revealed the presence of potentially significant surface and subsurface displacements exceeding 1 mm/yr. We concluded that continuous and interdisciplinary geomonitoring of the area should start well before the FCC tunnel construction and proposed to initiate a dedicated study.

Finally, we addressed the importance of calibration, checking, and testing (CCT) of geodetic instruments. We developed a concrete concept of how to establish CCT-based quality assurance throughout the life cycle of FCC. Based on a questionnaire sent to several institutions and stakeholders, we collected information on best practices, required facilities, references, and reviewed the related literature. We analyzed CCT procedures at other accelerator laboratories, academic institutions, and metrology organizations worldwide, as well as the services offered by instrument manufacturers. Based on all this, we worked out a hybrid approach mixing in-house activities, (new) CERN facilities, and outsourcing to external service providers. This balances reaction times, flexibility, required facilities, needs for training and maintenance of experience as well as the quantitative needs which will drastically change between the construction, installation and operation phases. CERN is currently analyzing the results of these investigations and proposals for subsequent adoption into practice as needed.

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, <https://www.research-collection.ethz.ch/handle/20.500.11850/656372>
- 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
- Edwards J, Roca F (2024) Comparing Geoid-Quasigeoid Separation Calculation Methods in the FCC Region at CERN. BSc 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, 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, 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 (2023) Geoid computation for the Future Circular Collider at CERN. Together Again for Geodesy: 28th General Assembly of the IUGG, Berlin, Germany, July 11-20 (in print)
- 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, Paris, <https://indico.cern.ch/event/1064327/contributions/4883205/>
 - 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.
 - Mainaud Durand H, Watrelot L, Weyer B (2024). Geodetic, survey and alignment challenges of the FCC-ee. Journal of Instrumentation, 19(02), T02006
 - 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, 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/>
 - Weyer B (2023) Geodesy and survey update. Presentation at FCC Week 2023, June 5 – June 9, London, <https://indico.cern.ch/event/1202105/contributions/5385361/>
 - Weyer B (2024) Geodesy update. Presentation at FCC Week 2024, June 10 – June 14, San Francisco, <https://indico.cern.ch/event/1298458/contributions/5976112/>
 - 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-manual.admin.ch/de/fachzeitschrift-cadastre>

This final report is only a very brief summary of all activities. More detailed scientific reports are published at <https://chart.ch/reports/>