Scientific Report of the CHART Project "FCC Geodesy"

Intermediate report 2021 – 2022
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1. Introduction

This report summarizes the goals of the CHART project "FCC Geodesy", the activities, progress and achievements during the first two years. FCC Geodesy aims at establishing a solid geodetic foundation for the planning, construction, alignment and operation of the proposed FCC at CERN. The FCC is around ten times larger than the current CERN site, spanning over the Swiss and French borders and areas with different topographical and geological features. Therefore, an evolution and extension of the geodetic reference systems and geodetic infrastructure currently available at the CERN site is needed.

The "FCC Geodesy" project consists of two main parts. The first part has the goal to determine 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 second part aims at the improvement of the geodetic reference frames and geodetic infrastructure, that are still based mostly on the LEP, which was inaugurated in 1989, and the transfer of position and orientation into the FCC tunnel to a depth of around 300 to 400 m.

The analysis on the gravity field comprises a study of relevant methodologies, auxiliary datasets and suitable and innovative instruments available for the determination of a high-precision geoid model. The focus is placed on the one hand on well-established instruments, such as the FG5 absolute gravimeter or the Burris relative gravity meter, on the other hand instruments still in development with a high potential to surpass the current level of precision and accuracy are highlighted. A first gravity field model will then be calculated using all available data in the region. Especially the model's accuracy and deficiencies in the area of the FCC tunnel will be assessed in detail, using the high-accuracy validation profile measured during this project. Based on this preliminary gravity field and the review of different sets of alignment requirements, the impact of additional measurements at locations of insufficient data availability will be studied but also the effect on the model, if specific measurements are not feasible. The final task is the development of a detailed conceptual design to establish a dynamic gravity field model based on simulations and test measurements.

The project part covering the geodetic reference frames and the geodetic infrastructure starts from 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. The existing reference frames and datums of CERN, Switzerland and France are studied to see whether and how they can be incorporated into the new geodetic network or new systems need to be established. A conceptual design study is included to propose reference points and control baselines which will support maintenance of the geodetic infrastructure and precise long-term geodetic monitoring, e.g., to determine land subsidence or geodynamic movements, as well as coordinate transfer to the access shafts of the FCC tunnel.

An overview of available and promising potential future solutions for the transfer of position and orientation from the surface reference network down to the tunnel is being developed. Due to the meticulous requirements for the alignment in the tunnel, in this concept, innovative methodologies and novel instrumentation must be considered and their development must be anticipated. In the end, all sensors and mathematical observation models used in the position and orientation determination or re-positioning system for the alignment activities in the FCC tunnel will need to be rigorously checked for systematic effects induced by (insufficient) calibration, refraction, environmental effects and, possibly, the gravity field. The error budget and the impact on the alignment is assessed and calibration and qualification methods are established to guarantee the requirements of alignment in the different phases of the facility's construction and operation.

2. Gravity Field Modeling and preparatory work

Julia Koch started her work in September 2021 with a review on the instrumentation available for the measurement of observables of the Earth's gravity field. The list contains instruments, which are widely used and based on well-established measurement principles, but also instruments still under development, e.g., chronometric levelling systems based on atomic clocks, free-fall cold atom gravimeters based on atomic interferometry, and the High-Precision Interferometric Deflectometer at CERN, which measures the relative deflections of the vertical. The content of this report is complete and is currently under revision to be submitted to CERN. The content of this work package and report is planned to be published in 2023.

During this project special focus is given to the High-Precision Interferometric Deflectometer, a prototype of which has been developed and realized at CERN. It measures the variation of the deflection of the vertical with respect to a straight line, realized by a laser source, corner cube reflectors and tiltmeters. Over the course of this project, the deflectometer was reassembled and refined. Currently, test measurements are conducted in order to assess whether this instrument is suitable to enable establishing a precise gravity field model in the FCC tunnel.

Two Lippmann tiltmeters have been sent back to the manufacturer in early 2022 for calibration, after having identified that both had a reading error. At reception, different tests of qualification were performed, including cross-comparison with the Agilent interferometer, stability measurements over 3 days and repeatability measurements. The two first tests were successful, but not the last one. Both tiltmeters and interferometer are repeatable when performing a static measurement, but not when the cart (on which the tiltmeters and corner cube reflectors are installed, see Fig. 1) is displaced. The measurements are not repeatable at the same points along the tube as expected (see charts below). Repeatability tests in different conditions were undertaken, showing that cable vibrations are the main source of noise in the system. We concluded that we are at the limit of the resolution of the deflectometer devices to establish a precise relative gravity field model. The moving mechanism will have to be changed to reduce the vibrations. A stable environment with constant temperature will be required, combined with fast measurements (maximum 1h).

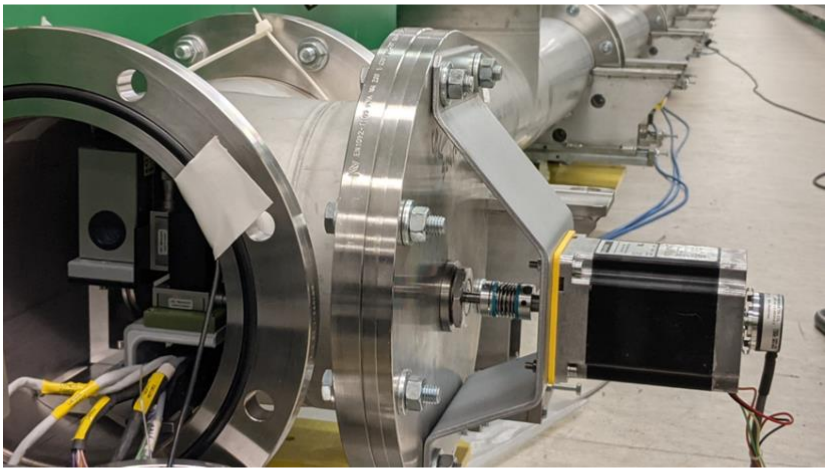
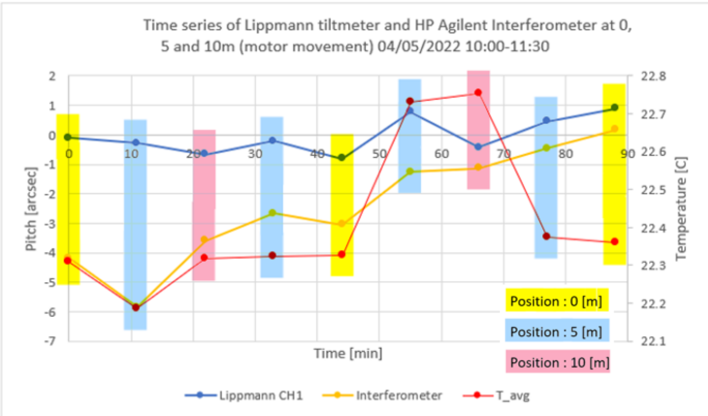


Figure 1: Deflectometer test assembly



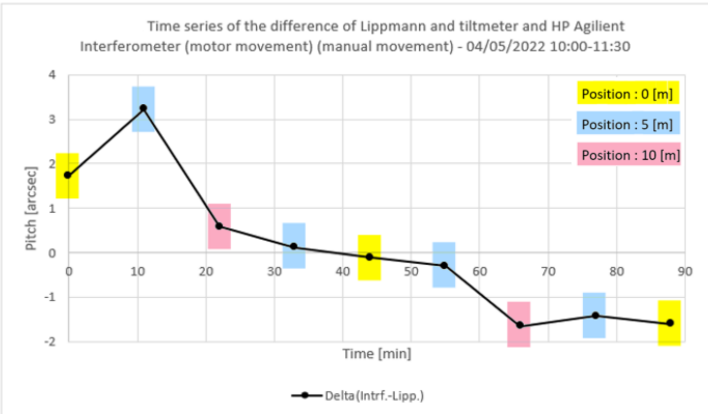


Figure 2: Results of tiltmeter tests (see text for explanation)

From March 2021 until April 2022 several measurement campaigns were conducted in the region of the FCC, with a special focus on the densification of measurements along the validation profile. This measuring profile transits from the Northern part of the FCC at the current facilities of CERN to the French city Annecy, which is located at the Southern end of the FCC area. This profile was chosen such that the different topographical and geological features of the region are included, and it follows the street network, which makes it accessible for bulkier instruments in the future. In these campaigns 36 GNSS-Levelling points were established and measured, 55 gravity measurement points were observed, and 61 deflections of the vertical measurements were taken (see Figure 3). We recently processed the data of the measurement campaigns. These solutions will be crucial in the coming years to evaluate the accuracy of the existing and improved geoid models as well as newly developed transportable instruments in a realistic setting. The processing and evaluation of the measurements for the deflections of the vertical, relative gravity, and geodetic levelling is currently being finalized. The reports are already submitted to CERN and will need only minor revision, if the final GNSS solutions deviate drastically from the preliminary results, which were shared with the project partners in May 2022. The GNSS measurements are currently in the final stage of validation before submission. The planned timeline for the GNSS processing was considerably prolonged due to unforeseeable problems in the final GNSS solution.

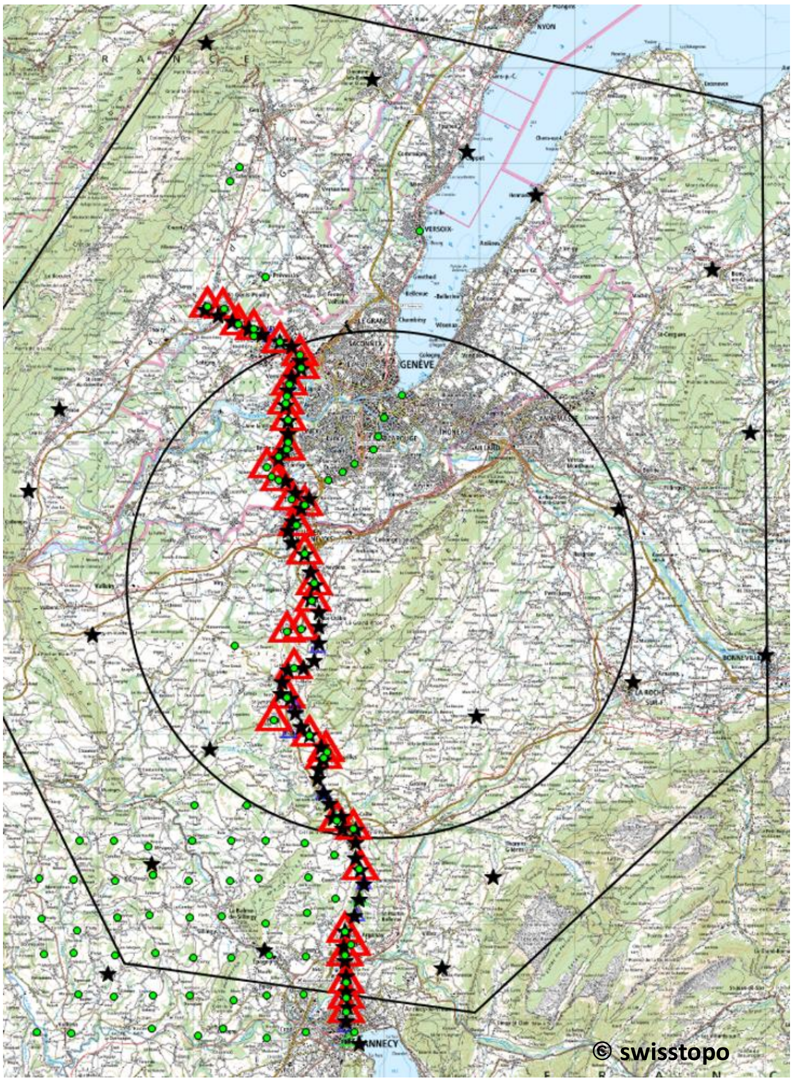


Figure 3: Location of the measurements along the profile. The black circle designs the approximate location of the FCC and the black polygon shows the wider area of interest of the project. Red triangles: GNSS-levelling points, green dots: relative gravimetry, black stars: DoV stations

In parallel to the GNSS processing, Julia Koch evaluated several existing software packages for the calculation of consistent gravity field models for the whole FCC area. Considering that a lot of zenith camera measurements are available in the area and two zenith cameras are maintained by our project group, which can be used if more measurements are needed, two software packages are chosen, which are able to also process deflections of the vertical data. The first software package is groops, developed at TU Graz, and the other one comprises QUAWIRK and HITCOL from Urs Marti at swisstopo. The software of swisstopo needs several partial updates, which are currently developed.

3. Reference Frames and Geodetic Infrastructure

Work in the improvement of the Geodetic Reference Frames and the Geodetic Infrastructure (i.e., work unit IGP-AA-2 of the project) began in February 2021 with the start of the newly hired postdoc Matej Varga. The work unit consists of five work packages (WP), two of which have been completed during the first year, two are close to completion, and one is to be started in February 2023.

Within work package 1 "Proposition of Coordinate Reference Systems (CRS) for FCC we compiled an overview about CRSs currently or previously used by CERN and analyzed whether they are usable also for planning, constructing, maintenance and operation of the FCC. We concluded that it is recommendable to create an own 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 as well as between local geospatial data from CERN and geospatial data from other entities anywhere in the world, or geospatial data available in an international or regional reference frame. Additionally, mostly for planning and carrying out the construction works, we proposed a CERN projected reference frame (CPF) and a (gravity-based) CERN Vertical Frame (CVF). Finally, we proposed transformations to link existing and new CRSs.

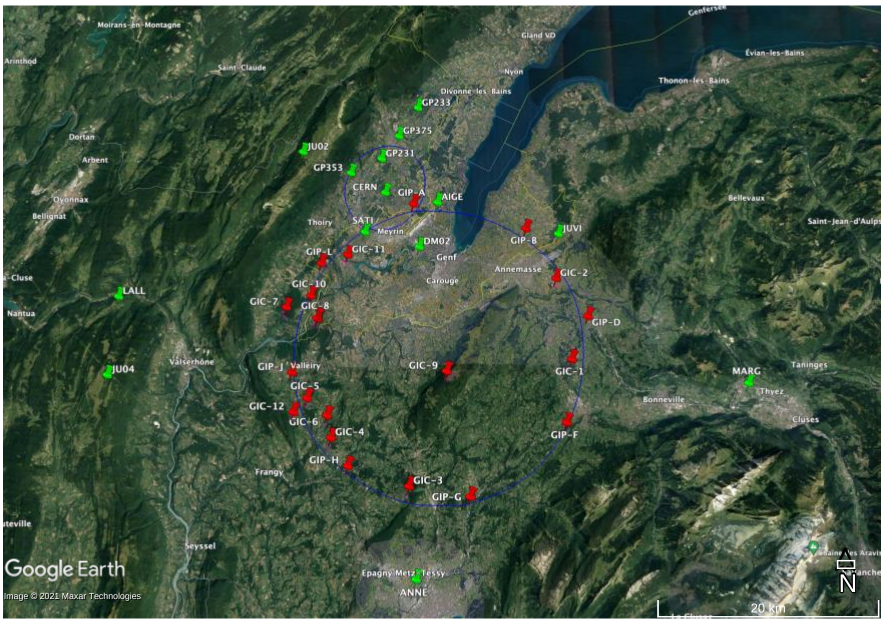


Figure 4: Conceptual proposal of P-SGN comprising points to be newly established (red) and existing points (green).

Work package 2 was devoted to the "conceptual design for the establishment of a surface geodetic reference network including control baselines". This surface geodetic network (SGN) will serve various purposes such as the realization of the coordinate reference systems, supporting civil engineering and surveying, providing a reference for alignment, and monitoring the FCC area. In a first step we collected the use cases and needs for the SGN based on literature, meetings with stakeholders within CERN, and own experience. Starting from there, we developed and proposed a concept comprising a primary SGN with densification using secondary SGN points and height benchmarks. We determined advisable geometric configurations based on accuracy simulations, taking into account technical and non-technical criteria for the location of the SGN points, see Fig. 4.

Within work package 3, we have investigated methodologies and instruments for position and orientation transfer into the FCC tunnel. This research has been conducted in 2022 and a report summarizing the findings is in the final stages of preparation for submission. Therein we discuss the characteristics of various absolute and relative (coordinate-based and angle-based) azimuth and position transfer methods, including gyro-theodolite, mechanical, optical and laser plumbing, 3D geodetic network, IMU, polarized light, image correlation, and TPS-based angle measurements. Numerical simulations were performed for some methods to quantify and compare the expected uncertainties.

We also started investigating the connection of the geodetic underground monitoring system to the civil engineering one. The main objective of this work package 4 is to find an efficient combination between different monitoring systems of the FCC, primarily civil engineering and geodetic, using new and original methods. The goal is to maximize automation and utilize complementary information from various sensors.

4. Astrogeodetic Validation Profile

The precise knowledge of the geometry of the gravity field is crucial for the work related to the FCC, as well as for the pre-alignment of the various parts of the particle accelerator once the construction is achieved. The equipotential surface at sea level of the Earth gravity field is called geoid. In geodesy, the determination of the geometry of the geoid is referred to as geoid modelling or geoid determination.

One key issue in geoid determination is the validation of geoid models by comparing the results to a ground truth data set. The determination of an astro-geodetic geoid- profile is an excellent way to do so. In order to obtain a sufficient accuracy at all wavelengths (and especially at short wavelengths), a dense sampling is needed.

The established astro-geodetic profile, already mentiones above, is about 50 km in length, covers the whole FCC project area and runs from Meyrin to Annecy (see Figure 3). It comprises the following measurement types:

- deflections of the vertical measurements (DoV) with a spacing of 800 m,
- levelling and relative gravity measurements along the profile (available official Swiss and French leveling results are integrated where possible), and
- GNSS measurements to create GNSS-levelling height-benchmarks.

4.1 Astrogeodetic observations

The DoV measurements must be undertaken at night and under clear sky conditions, as stars must be visible. The measurements were conducted with the zenith camera CODIAC developed at ETH Zurich and now in use at swisstopo. The campaign started in March 2021 and lasted until September 2021. Despite very bad weather conditions, all 61 measurement points were obtained in 15 nights. The final surface DoV are shown in Figure 5; the average spacing between the stations is 791 m.

The DoV processing was carried out in the software AURIGA, which uses the sky images acquired with

CODIAC and the inclinometer measurements. The GNSS measurements obtained on board of CODIAC are only used to provide a precise time stamp for all observations. For the final computation of the DoVs, the geodetic positions were acquired using RTK-GNSS measurements relying on the swipos positioning service.

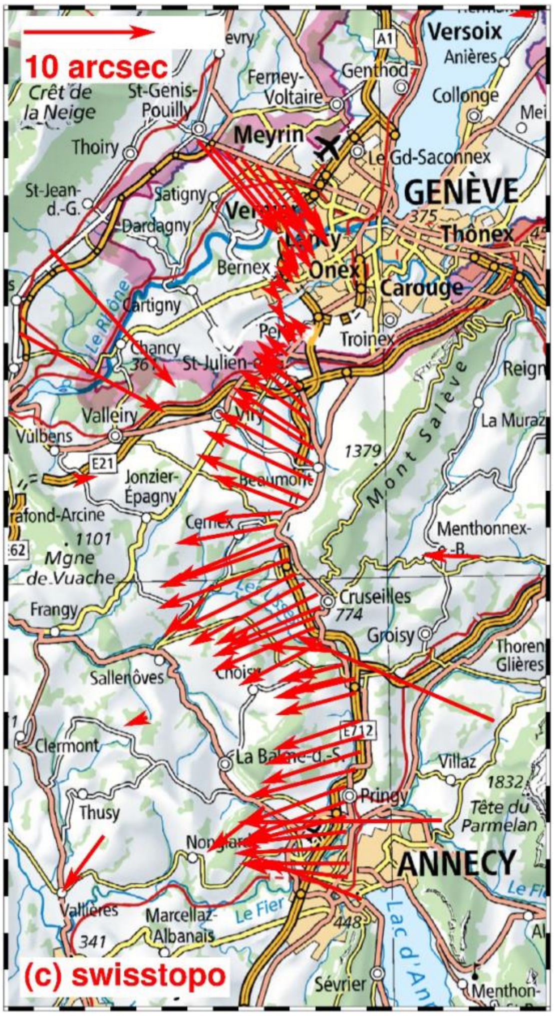


Figure 5: Final (not yet reduced) surface DoV along the astro-geodetic profile between Meyrin and Annecy. The magnitude of the DoV is around 10 arcsec. Some DoV were measured outside of the profile to enhance the geoid determination in the following project steps.

The results show a very good internal consistency of the DoV. The preliminary geoid profile solutions computed from the DoV are shown in Figure 6. As soon as the final set of GNSS-levelling data is available, the astronomic profile will be validated and combined with the other datasets. At this point, no additional measurements seem to be necessary.

The geoid profile solutions shown in Figure 6 are obtained by least-squares collocation with correlation lengths between 1250 m and 2500 m, which showed in a pre-study to lead to the most plausible, thus best, results. It must be noted, that DoV is only a relative validation tool, since only the slope can be determined but no absolute values on the points. Therefore, all solutions are fixed to zero on the first observation station. The negative slope in the first part of the profile is very well modelled by the French and Swiss model (RAF20 and CHGeo04 respectively), but the two global models (EGM2008 and XGM2019e) show some deficiencies, especially the EGM2008 model. In the other parts of the profile, all models agree generally well, but the global models clearly show limitations in their spatial resolution. For instance, between kilometer 10 and 20 and between 30 and 40, where all reference models lack high frequency signals compared to the geoid profile solutions.

The difference between GNSS levelling and the various geoid solutions from DoV show only very small differences to each other. The differences to the GNSS leveling are within +4.5 cm and -2 cm for all models and no clear trend is determined.

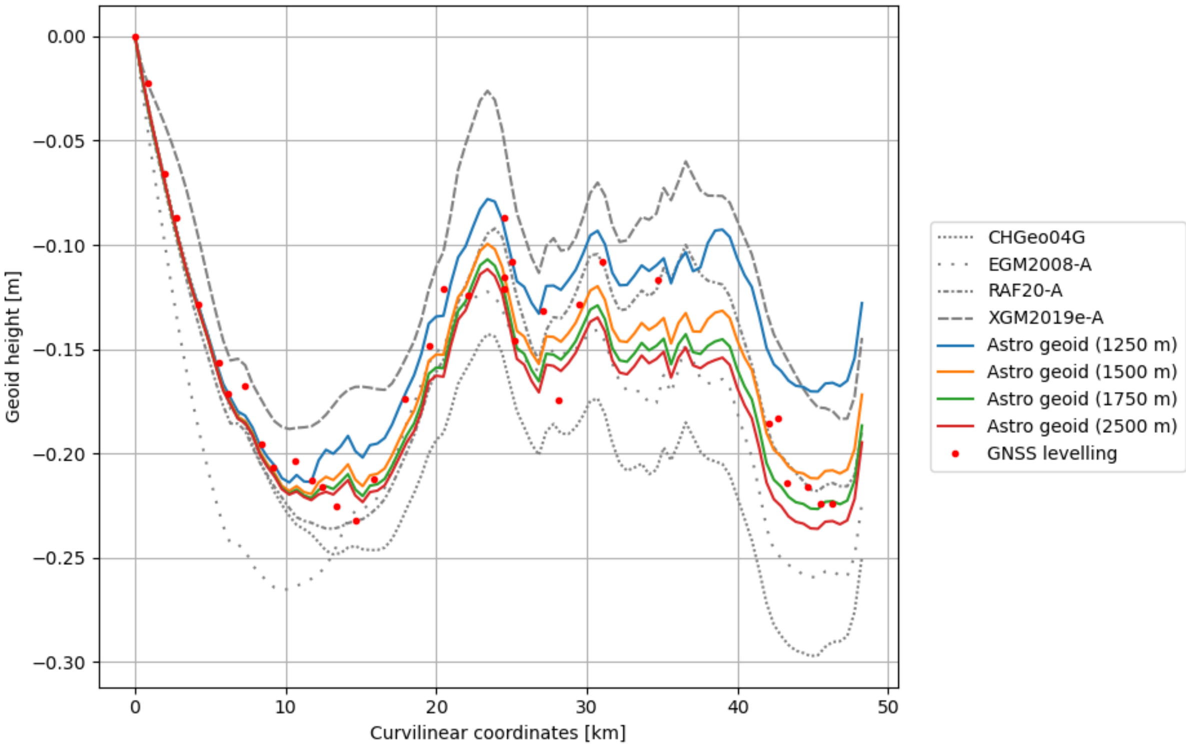


Figure 6: Geoid profiles obtained with least-squares collocation compared with Swiss (ChGeo04), French (RAF20) and global geoid models (EGM2008 and XGM2019e) and with the preliminary GNSS-Levelling solution. All models are offset to equal on the first value of the profile.

4.2 Leveling Observations

For the validation of geoid solutions with GNSS-Levelling, measurements of GNSS, geodetic levelling and gravimetry must be available on the same locations. Since it was not possible to re-measure the whole levelling line, we had to rely on existing levelling data and only short paths between the GNSS-levelling station and the height benchmark were newly measured. Additionally in May 2021, a levelling campaign was launched by swisstopo experts and coordinated by CERN, to connect the French and Swiss vertical networks on both sides of the boundary, from Saint-Julien-en- Genevois to Bernex. The purpose of these measurements was to remove a potential unexpected referencing bias between the systems, since each materialized network is separately maintained by its own national institute, i.e., IGN in France and swisstopo in Switzerland.

By fixing the height of the starting point in Bernex to its official value in the Swiss Height System, the differences to the heights of height benchmarks along the line until Lully can be calculated. All differences were below 1 mm, with the exception on a bridge in Lully, which showed differences of 1.1 cm and 1.8 cm. Even the very old benchmarks in Certoux and Perly showed minor differences of +/- 3 mm.

Comparing the heights in Bernex with the published French heights showed an offset of 32.03 cm between the Swiss and French height system. In St. Julien, the mean difference is 31.2 cm. Since the points in Bernex are only connected to the French levelling network by GNSS-levelling, for future studies the offset determined for the comparison in St. Julien should be used as reference.

In April 2022, gravity measurements along the whole profile were performed by swisstopo using the Scintrex CG-6 (#248). The absolute station in the CERN area at Prévessin and its gravity value from the Swiss National Gravity Network (LSN) was used as reference. All measurements are without any problems, only some vibrations near the principal roads occurred sometimes, which did not influence the results significantly. The adjustment of the data was done using swisstopo's program GRAVNET, which is used for the adjustment of the national gravity network of Switzerland too.

Using the gravity measurements and the levelled heights, normal heights are determined, and height anomalies can be calculated by comparing the results of the GNSS campaign with normal heights. Figure 7 shows the results using the preliminary GNSS coordinates on the GNSS levelling benchmarks. Both sets of GNSS coordinates result in a similar course along the profile. Furthermore, it is visible that the solution fits rather well to the slope of the Swiss quasigeoid CHGeo2004 until approx. kilometer 32 but deviates then significantly from the solution derived from GNSS levelling. This was to be expected, since the Swiss quasigeoid is fitted to the area of Switzerland and the full Southern part of the profile is on French side.

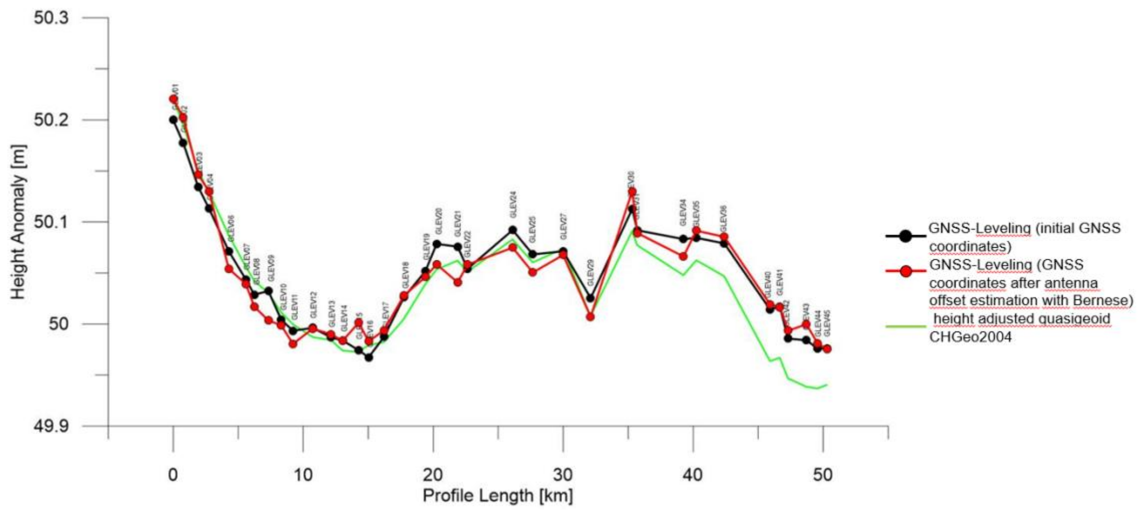


Figure 7: Observed height anomalies using the initial GNSS coordinates and the preliminary GNSS coordinates compared to the height adjusted quasigeoid CHGeo2004.

4.3 GNSS Observations

In October and December 2021, two GNSS measurement campaigns were carried out along the geodetic profile crossing the FCC area (see Figure 2). The measurements were conducted by personnel from CERN, ETH Zurich, and HEIG-Vaud. A total of 36 survey markers, located in the vicinity of the existing levelling benchmarks that are part of the Swiss and French levelling network were observed. Each point was observed during two independent sessions of 24 hours, with two different antenna setups, different antenna heights and different antenna and receiver types and manufacturers. At the end of the survey, the data were sent to ETH Zurich for processing. ETH Zurich computed the 3D coordinates of the survey markers with the scientific Bernese GNSS software developed by the Astronomical Institute of the University of Bern. The goal was to compute as accurately as possible the ellipsoidal height of each levelling benchmark in order to locally derive the geoid-ellipsoid separation, i.e., the difference between the ellipsoidal height and the orthometric height, which are used in section 4.2 for the derivation of the GNSS-levelling solution.

The initial results were available in January 2022 (see Figure 9, IGS). Since on all stations two 24h-sessions were conducted, it is possible to compare the derived coordinates to validate the quality of the coordinates by their repeatability. As it is visible in the plot, the mean RMSE of the residuals of the coordinates in the Up component is 17.6 mm. This means that the coordinates deviate by around 35 mm, since this is the deviation from a weighted average coordinate for each point. These discrepancies are too significant to use this set of coordinates as ground truth for the validation of the accuracy of geoid solutions in the further progress of this project.

Therefore, the following months were used to determine the source of the high deviations and the most probable cause was found in the IGS antenna phase center offset and variation pattern for the Trimble R8 RTK-GNSS antenna. An antenna calibration was conducted on the rooftop of ETH Zurich using a robot of KUKA robotics, which is programmed for GNSS antenna calibrations and an in-house analysis software. The antenna pattern and offsets of the original (IGS) and new calibration (ETHCal) can be seen in Figure 8. A clear difference between the results is visible, especially for the linear combination L3, which was used in the GNSS processing chain to minimize the influence of the ionosphere on the coordinates. Using the ETHCal calibration lowered the average RMSE of the residuals to 8.8 mm, however, the repeatability in the North component was worse, therefore an additional antenna offset estimation in the Bernese Software was necessary (see solution ETHCal offset in Figure 9). Currently the last validation calculations are in progress and the report with the final coordinates is planned to be submitted in February 2023.

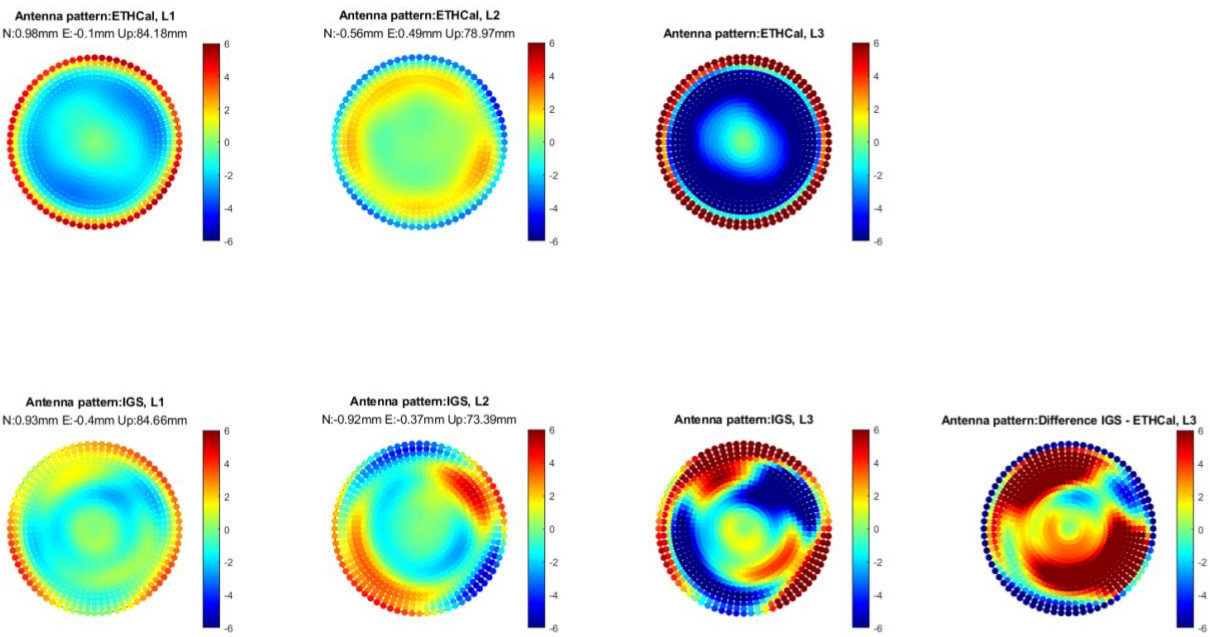


Figure 8: Phase center offsets and variation patterns from an antenna calibration on the rooftop of ETH (ETHCal, top row) and the original values provided by IGS (IGS, bottom row), the plot on the lower right shows the difference between IGS and ETHCal in the antenna pattern effective for the linear combination L3.

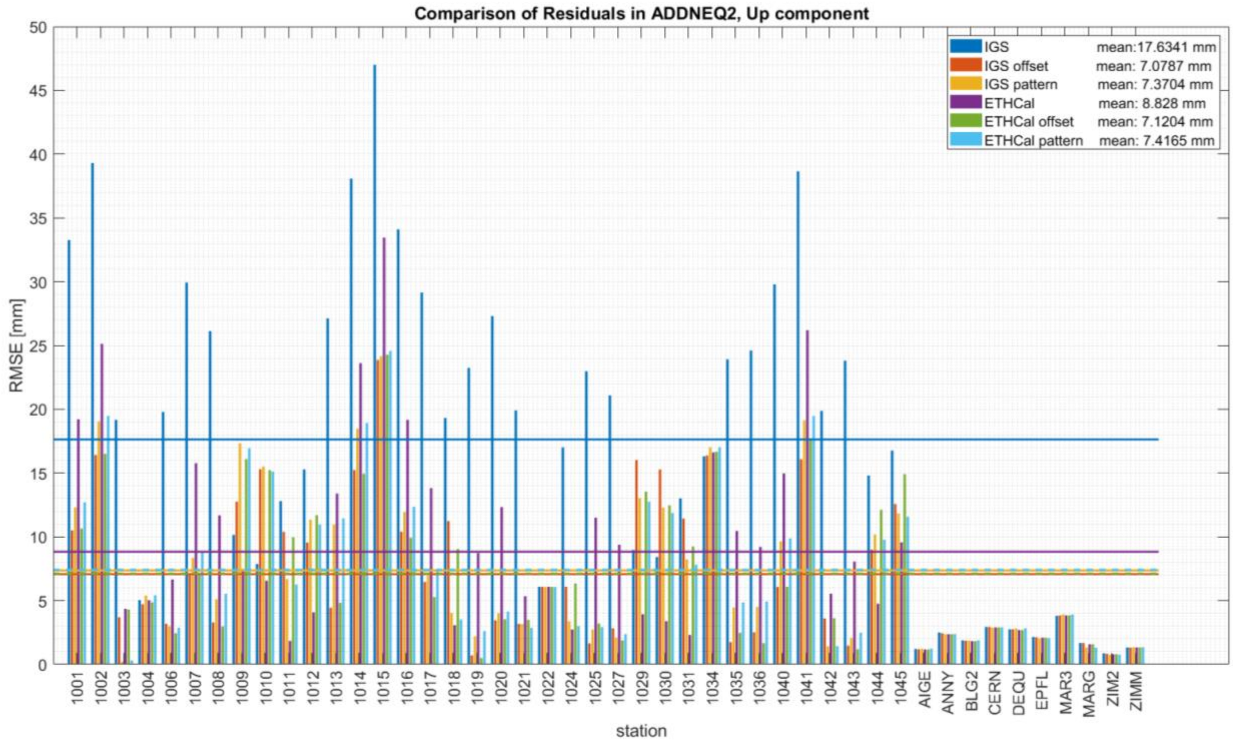


Figure 9: RMSE of the residuals on the weighted average Up-component of the coordinates using the offset and pattern provided by ISG and ETHCal and the estimation of a correction phase center offset or pattern in the GNSS Bernese software using the IGS or ETHCal solution as a priori information

5. Conclusions

In the first two years of the project, the review of present and future instrumentation for the determination of a high-precision geoid model was performed, as well as the measurement and most of the data processing of the astrogeodetic validation profile. Additionally, the high-precision interferometric deflectometer available from an earlier project at CERN, has been reassembled and tested to prepare for further experiments. At present, all these parts of the study are being finalized. Based on an in-depth analysis of the future requirements of CERN regarding coordinate reference systems for the planning, construction, and design of the FCC has been carried out and the way to realize the proposed CERN Reference Systems (CRSs) with the installation of a new or extended geodetic surface network and, at a later stage, the installation of a network of subsurface geodetic benchmarks, was addressed.

The achievements and insights obtained so far have been shared with CERN in the form of technical reports, and with the FCC community at large through presentations at the FCC week. Additionally, results have been published and further publications are under preparation. A tangible and important outcome which will likely have significant impact beyond FCC is the validation profile. The data from the campaign, enabled through the present CHAR project, will enable validation of the high-precision geoid models to be computed for the FCC region as well as for the evaluation of the deflectometer. Also other new instruments, that have become available just recently (e.g. a quantum gravimeter) or will be produced commercially in the near future, will be tested along this unique profile.

6. Publications and outreach

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, 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/

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.

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.

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/

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