Annual Report 2021 of the CHART Project "FCC Geodesy"

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1. Introduction

This is the annual report 2021 of the CHART Project "FCC Geodesy". It gives a summary of the goals and achievements of the project during the year 2021. This project aims at establishing a solid geodetic fundament 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 m.

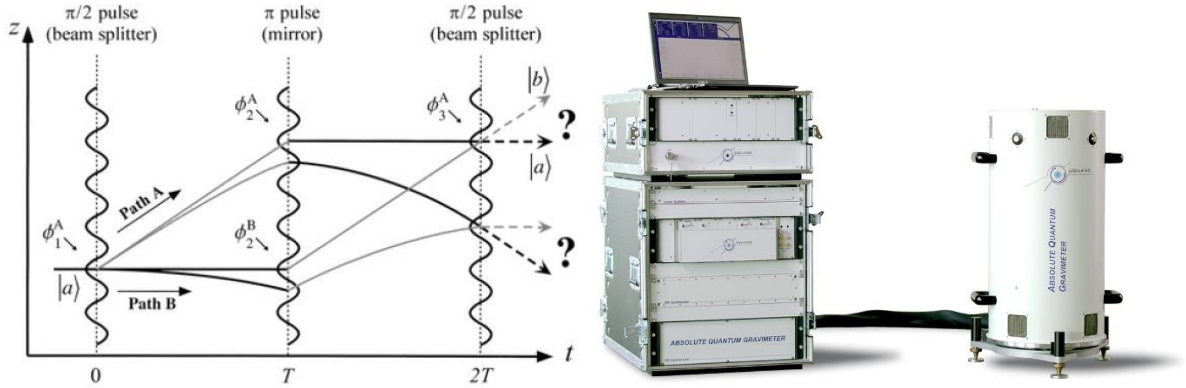
The analysis on the gravity field begins with a study on relevant methodologies, auxiliary datasets and suitable and innovative instruments available for the determination of a high-precision geoid model. The focus is placed on the one hand on well-established instruments, such as the FG5 absolute gravimeter 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. In the next step, a first gravity field model will 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 profiles 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 first determines the needs and conditions to be accommodated by the frame and datum for the anticipated purposes during the entire life cycle of the FCC. Then, the existing reference frames and datums of CERN, Switzerland and France are studied to see how they can be incorporated into the new geodetic network and where reference points and control baselines must be established in order to enable precise long-term geodetic monitoring, e.g., to determine land subsidence or geodynamic movements and the access shafts to the FCC tunnel.

In a next step, a concept will be developed to enable the transfer of position and orientation from the surface reference network down to the tunnel. Due to the meticulous requirements for the alignment in the tunnel, in this concept, innovative methodologies and novel instrumentation must be considered and developed. 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 are rigorously checked for systematic effects induced by refraction, air currents and, possibly, the gravity field. The error budget and the impact on the alignment is assessed and calibration and qualification methods are established to guaranty the requirements of alignment in the different phases of the facility's construction and operation.

2. Work on Gravity Field Modeling

The PhD student started her work on September 1st, 2021, with a review of the instrumentation available for the determination of the new gravity field model (first work package). Besides a summary of instruments already widely used and established such as the FG5 by Micro-g LaCoste and the Burris Gravity Meter by ZLS Corporation, the measurement principle and current and expected accuracies of instruments still under development are studied too, as the FCC construction will only start around 2030. One of these instruments at the edge of commercial production is the quantum gravimeter based on free falling atoms.



[Peters et al., 2001] [μQUANS]

Figure 1: Left: Principle of Mach-Zehnder atom interferometry with splitting, deflecting and splitting of the atom cloud along the free fall path, using a π/2, π and π/2 pulse, respectively, leading to a measured phase difference, caused by the influence of the gravitational acceleration g. Right: Full instrumental setup of the first commercial "Absolute Quantum Gravimeter" (QAG) by μQUANS.

A free-fall cold atom gravimeter exploits the principle of atomic interferometry. In an ultra-high vacuum environment, ^{87}Rubidium atoms are pumped into a magneto-optical trap (MOT), where the atoms are cooled down to temperatures of some micro-Kelvin in order to minimize the thermal movement of the atoms. After the atomic cloud is released from the MOT, it is subject to a sequence of three Raman laser beams arranged to realize a Mach-Zehnder atom interferometer. At the first laser beam, a $\pi/2$ pulse is used, which splits the atom cloud into two groups by changing their hyperfine ground state. One group follows the straight path, the other group receives a photon momentum kick resulting in an increased transverse velocity component. Therefore, these atoms rise in height (Path A and Path B in Figure 1 (left)). With the subsequent π pulse both sub-clouds are deflected and superimpose at the final $\pi/2$ pulse. This last pulse puts the atoms into the same hyperfine ground state. Now the relative population of the atoms in the same ground state are measured by fluorescence detection. The gravity acceleration g bends the paths of the atomic clouds (see Figure 1 (left)) and leads to an accumulated phase difference $\Delta\varphi$, which can be derived from the interferometer contrast using the fluorescence detection.

Currently the most stable instruments are the falling corner-cube absolute gravimeters, which have a total uncertainty of $2.0\ \mu Gal$ and are therefore used for the determination of the gravity datum. However, because they use macroscopic test masses, they need massive concrete pillars to reduce the effect of floor recoil. Additionally, the moving mechanical parts in the instruments need regular maintenance. Therefore, they are not suited for continuous gravity measurements over month or even years. Atomic free fall gravimeters overcome both demerits and provide absolute gravity measurements, which is also an advantage over relative gravimeters. The current sensitivity is at the μGal-level and with the development of atomic gravimeters by industrial companies like μQUANS (see Figure 1 (right)), an increasing developmental speed can be expected in the next few years.

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 is reassembled, refined and it is assessed whether this instrument is suitable to establish the precise gravity field model in the tunnel.

Since the start of the project, all components of the Deflectometer were recommissioned from the previous project with some changes such as connectors and USB-to-serial converter to meet compatibility with Windows 10. Two tiltmeters were added to check the accuracy of the Lippmann tiltmeters and an additional one to measure the cross-axis tilt. One step motor was added to the assembly, so the instrument can be displaced inside its vacuum pipe remotely now. The first results from December 2021 taken at three points (0m -> 5m -> 10m) were not consistent. The vacuum was not established in the tube yet. The deflectometer cart, however, after coming back to the initial position at 0m and leveling the platform to zero, did not give the same result as in the beginning of the measurement, as we would have expected. After checking the correlation of the Lippmann tiltmeters with Sherborn tiltmeters, we found that the Lippmann tiltmeters need to be calibrated to meet the required precision. There are two Lippmann tiltmeters and the measurement of both output a reading error every few iterations and the offset between both tiltmeters is increasing proportionally to the measured angle. To resume the measurements, we have to send back the Lippmann tiltmeters to the manufacturer for calibration.

In the beginning of October 2021, a GNSS measurement campaign was conducted along the planned measuring 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 (see Figure 2). 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. It is planned that along this profile, gravity values are determined using different means, e.g., GNSS/Levelling, zenith cameras, relative and absolute gravimeters. This profile will be crucial in the future to evaluate the accuracy of improved geoid models as well as newly developed transportable instruments in a realistic setting.

During the campaign, 38 points were measured with GNSS along the profile (see Figure 2), where each point was occupied twice with a 24h measurement session. The processing of the collected GNSS data has already started using RTKLIB, the Bernese GNSS software and GNSS data from surrounding reference stations. Since the Up component of the GNSS point coordinates is the most crucial quantity for the evaluation of a geoid model, but is, at the same time, the most imprecise component, every step and setting in the GNSS processing chain must be carefully verified and optimized. About 80% of the processing has been performed by now and is expected to be finalized in the next weeks with a final target of reaching a precision of 2-3 mm in the Up component of the measured points.

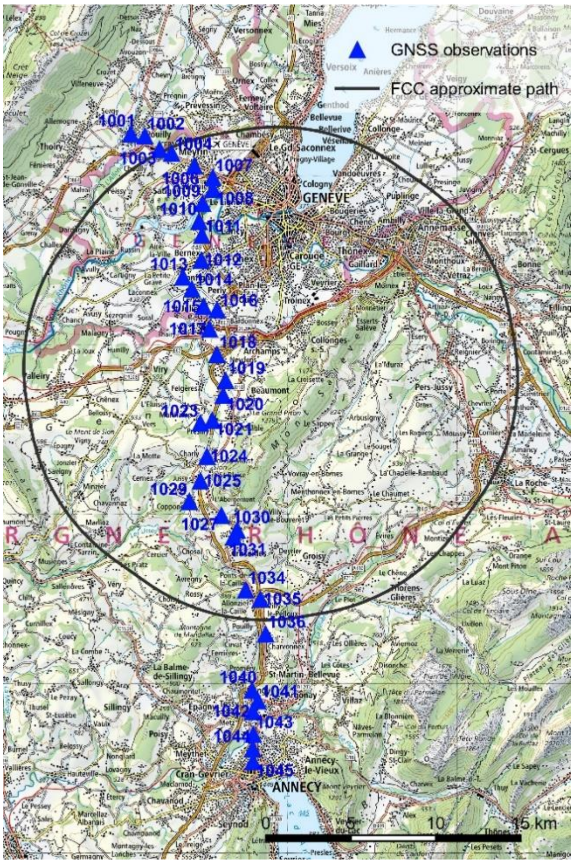


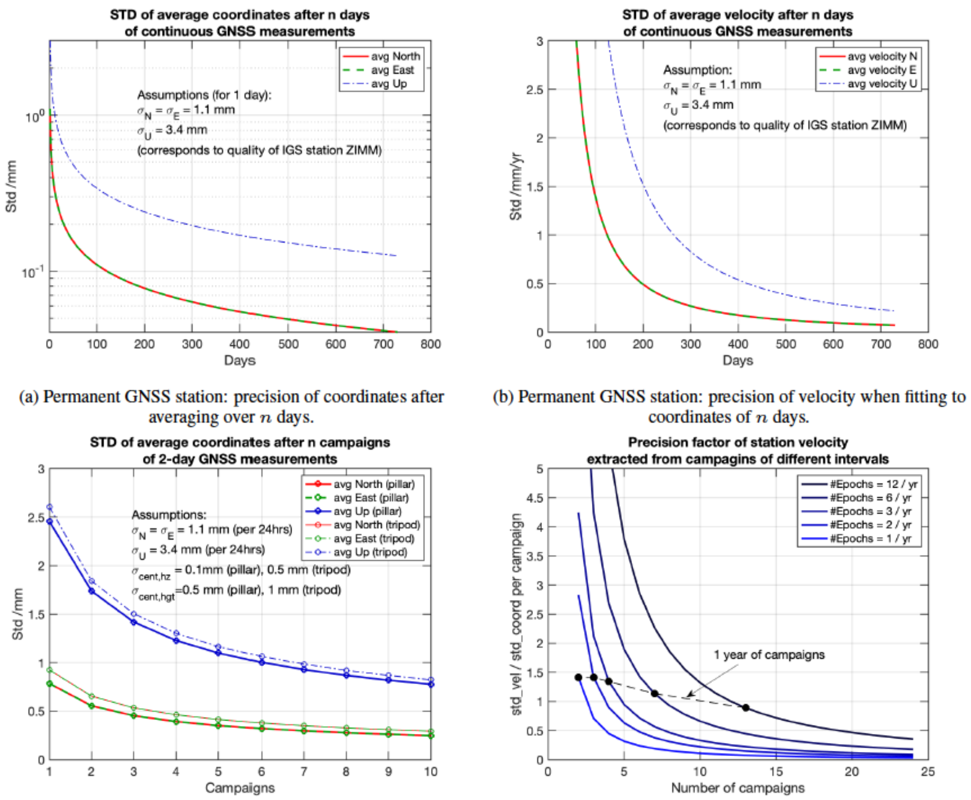
Figure 2: GNSS observations carried out along the geodetic profile crossing the FCC area.

3. Work on Reference Frames and Geodetic Infrastructure

We have carried out an in-depth analysis of the future requirements of CERN regarding coordinate reference systems for the planning, construction, and design of the FCC. At this step we have carried out numerical simulations, studied reports about similar projects, and conducted interviews with potential stakeholders within CERN. Based on this we have developed a proposal of new coordinate reference systems (CRS) for CERN, which are (i) closely related to an existing European coordinate reference system (ETRS89) and (ii) using the same datum for 3D Cartesian coordinates and horizontal coordinates. We found that the basis of the new CRS should be a static terrestrial reference frame (CTRF) corresponding to an official ETRF, i.e., a realization of ETRS89, at a chosen reference epoch and paired with CERN’s own kinematic model (CKM) that describes the small but possibly non-negligible differential displacements of points within the CERN area resulting from geodynamics and local processes. For supporting the construction works in an optimal manner, horizontal North and East coordinates obtained from the CTRF by Transverse Mercator projection of the GRS80 ellipsoid centered at the origin of the CTRF and paired with orthometric heights related to CERN’s own highly accurate geoid model should be used. The corresponding two frames, CPF (projected) and CVF (vertical) will facilitate construction works, alignment and possibly other activities benefiting from an explicit distinction between horizontal and vertical components. The perfectly Euclidean, Cartesian coordinate systems (MAD) used for physics simulations and planning of the accelerators or colliders will be related to these systems by transformation. This also holds for CERN’s legacy coordinate reference systems, in particular the various versions of the CERN Coordinate System (CCS).

The realization of the proposed CRSs requires the installation of a new or extended geodetic surface network and, at a later stage, the installation of a network of subsurface geodetic benchmarks. We have addressed this in the second work package of this project. Again, based on a literature study and numerical simulations, we have developed a concept consisting of a primary surface geodetic network (P-SGN) and a secondary surface geodetic network (S-SGN). The points of the P-SGN ideally comprise 10 to 15 existing nearby continuously operating GNSS reference stations (CORS), eight geodetic pillars near the eight anticipated access shafts of the FCC tunnel, and a few additional pillars or well-founded ground level points for long-term, GNSS-based geomonitoring. The main purposes of this P-SGN are the establishment of the CTRF, the quantification of the geokinematics of the larger CERN area, and - at a later time - the connection of the individual tunnel access sites as a main tunnel network.

The P-SGN is thus also necessary for determining the parameters of the transformations between the existing and new CERN coordinate reference frames and external coordinate frames like the Swiss and French national frames, the European ETRF and the international ITRF which will be needed during the feasibility study and the construction of the FCC. The points of the S-SGN are used to densify the P-SGN in areas, where this is needed for monitoring the geokinematics or for construction, in particular for construction of the FCC tunnel. The densification for geomonitoring purposes is needed already well before the construction starts; the densification related to the construction works will be needed shortly before the construction starts or during the construction. This also comprises installation of azimuth control baselines near each access. The above points may have to be extended by a vertical surface geodetic network (V-SGN) comprising height benchmarks in the vicinity of the FCC tunnel, in particular for tunnel construction.



(a) Permanent GNSS station: precision of coordinates after averaging over n days.

(b) Permanent GNSS station: precision of velocity when fitting to coordinates of n days.

(c) GNSS campaigns: precision of average coordinates from n campaigns.

(d) GNSS campaigns: ratio between standard deviation of coordinates per campaign and standard deviation of average velocity from n campaigns.

Figure 3: Impact of observation period (permanent GNSS stations) and number/temporal spacing of campaigns on the precision of coordinates and velocities. Assessment is based on empirical standard deviations of EUREF coordinates of station ZIMM.

This early analysis of the coordinate reference situation has shown that there may be locally differential surface displacements of up to about 1 mm/yr vertically and horizontally. In order to understand the geokinematics of the area well when the construction starts such that (i) the CTRF can be based on P-SGN points mutually sufficiently stable, and (ii) the geokinematic deformations possibly impairing alignment are known and to a large degree modeled by a kinematic model (CKM), a comprehensive surface geomonitoring concept needs to be worked out and implemented. This will likely comprise the evaluation of the CORS, which are part of the P-SGN, quasi-permanent GNSS measurements of further P-SGN and possibly S-SGN points, local terrestrial measurements within small subnetworks of the S-SGN, local high-precision geometric levelling networks, and InSAR analyses. Simulation-based assessments of the required duration of monitoring observations for detecting the above displacement rates (see Figure 3) may be a starting point for the development and implementation of such a monitoring concept in the future.

4. GNSS Leveling Campaign

The precise knowledge of the geometry of the gravity field is crucial for the construction work related to the FCC, as well as for the 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. In order to assess the accuracy of geoid models a ground truth is needed. 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 wavelength), a dense sampling is needed.

The foreseen astro-geodetic profile is 50 km in length, covers the whole FCC project area and runs from Meyrin to Annecy (see Figure 2). It comprises the following measurement types:

- Deviation of the vertical measurement (DoV) with a spacing of 800 m,
- Levelling measurements along the profile (available official Swiss and French leveling results are integrated where possible)
- GNSS measurements on selected height-benchmarks.

4.1 Astro-geodetic Observations

The DoV measurements must be undertaken at night and under clear sky conditions, as stars must be visible. The measurements started on March 29, 2021. The last station was acquired on September 6, 2021. Despite very bad weather conditions, all 60 stations could be acquired in 2021. The surface DoV are shown in Figure 4.

The first results show a very good internal consistency of the DoV. The preliminary geoid profile computed from the DoV is shown in Figure 5. As soon as the levelling and the GNSS 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.

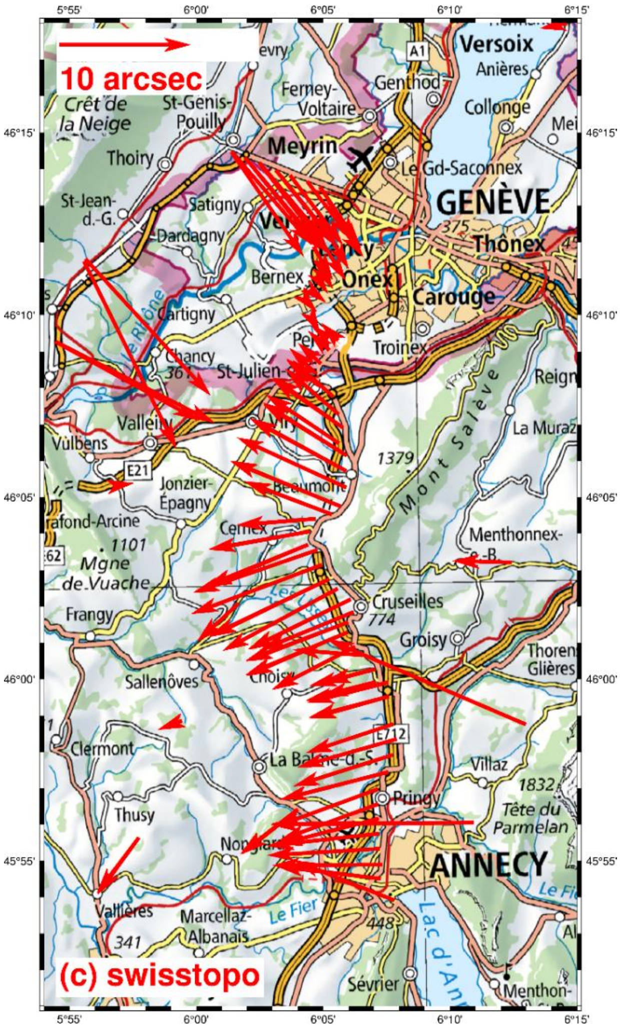


Figure 4: Surface DoV on the surface along the astro-geodetic profile between Meyrin and Annecy.

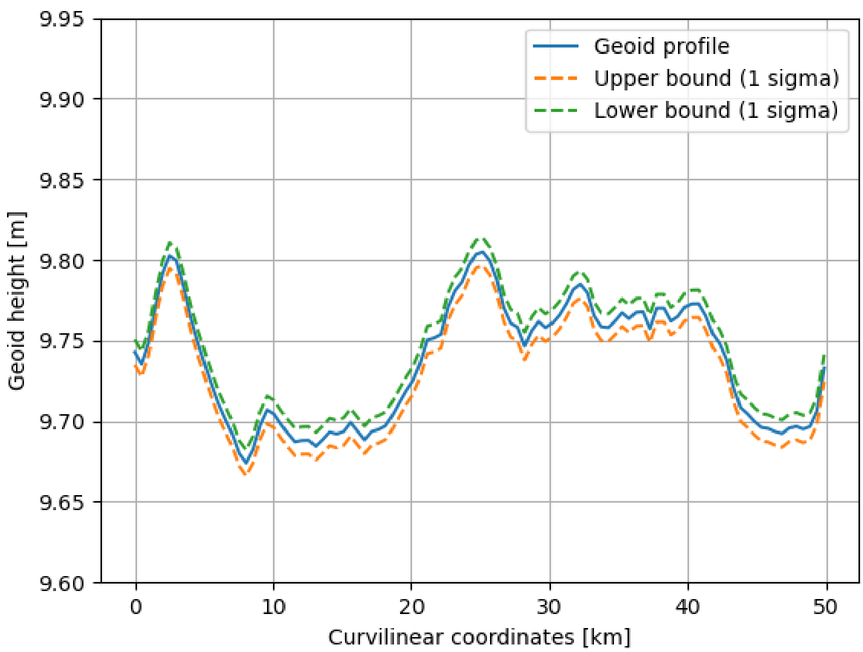


Figure 5 Surface DoV on the surface along the astro-geodetic profile between Meyrin and Annecy.

4.2 Leveling Observations

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 (FR) to Bernex (SW) (see Figure 6).

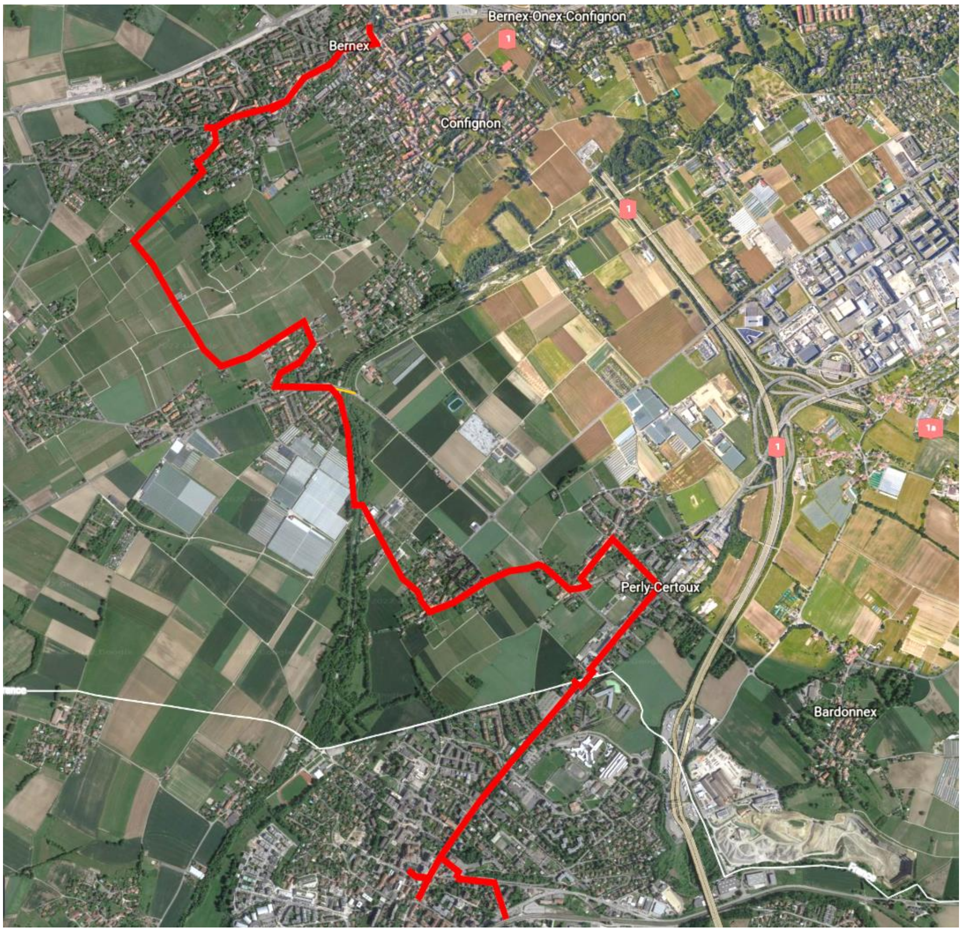


Figure 6: Map showing the levelling path (in red) – Credit GoogleEarth

The purpose of these measurements was to remove a potential unexpected referencing bias between the systems. Indeed, each materialized network is separately maintained by its own national institute, i.e., IGN in France and swisstopo in Switzerland. The benchmarks used to access the reference frame are part of the third order network.

Over a 9 km length traverse, the path crossed urban and rural areas, including a high slope section (about 14%) in the Bernex's vineyards (see Figure 7).

Several days before the beginning of the campaign, a training session was held at CERN to teach the swisstopo acquisition software (LNAUS) to the CERN operators. This was also an opportunity for swisstopo to provide the instrumentation, namely a Leica DNA03 and a ZEISS-TRIMBLE DiNi03. The auxiliary points, so called "reversal traverse points", were jointly staked out by swisstopo and CERN during the recognition steps just before the observation campaign. These points were wisely chosen within the length and vertical drop tolerances fixed by swisstopo, considering the stability, durability and accessibility of these markers. The measurements were performed between the 25th and the 28th of May by 8 CERN operators, rotating on teams with 2-3 persons. The team leaders were kept all along the measurements to ensure the technical continuity.

The usual performance level used for the Swiss federal levelling campaigns was applied during this week. This frame notably gave us the tolerances to respect between forward and backward traverses, the maximum sighting distance offset, the station closure, but also the collimation check frequency. The forward and backward traverses were made at the same time and in opposite directions, using different setups (Leica/Trimble), so that both determinations were independent. The measurement strategy consisted in a simple run levelling path (forward/backward) with an RVVR sequence, allowing to check the instrument stability during the whole station occupation.

During the measurement campaign, the preprocessed observations were shared daily with swisstopo experts who performed the calculation using the LNAUS software. In average, only 23% of the allocated closure tolerance was reached. More than 2000 measures were stored (from about 500 stations) during the campaign. The goals were achieved thanks to the very professional collaboration between swisstopo and CERN services. This measurement campaign was the object of several articles on the CERN side: Millimetric precision for a Future Circular Collider | CERN (home.cern), Surveyors eye up a future collider – CERN Courier

Figure 7: View of the sloping Bernex's vineyards, the PDA acquisition device is connected to a Trimble DiNi03.

4.3 GNSS Observations

Between the 3rd and the 10th of October and between the 6th and the 8th of December 2021, GNSS observations were carried out along the geodetic profile crossing the FCC area (see Figure 2). 13 persons from CERN (Geodetic Metrology group), ETH Zurich (Institute of Geodesy and Photogrammetry) and HEIG-Vaud (Institute of Territorial Engineering) took part in the measurements. 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 started to compute the 3D coordinates of the survey markers with the scientific Bernese GNSS software developed by the Astronomical Institute of the University of Bern (AIUB). The goal is to compute as accurately as possible the ellipsoidal height of each levelling benchmark in order to locally derive the geoid-ellipsoid separation (difference between the ellipsoidal height and the orthometric height). These observations will help assessing the accuracy of the geoid model that is under development.

5. Conclusions

In the first year of the project, the review of present and future instrumentation for the determination of a high-precision geoid model was performed. At present this study is finalized by looking at the benefit to be expected from the use of auxiliary data like digital elevation models and geological information in the gravity field modeling. In addition, an in-depth analysis of the future requirements of CERN regarding coordinate reference systems for the planning, construction, and design of the FCC was 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.

A very important achievement in 2021 was also the conducted measurement campaigns collecting different and complementary measurements (GNSS, leveling, deflections of the vertical) along a profile covering the essential parts of the planned FCC. After processing all this data, the campaign data will be an extremely valuable dataset to validate the high-precision geoid models to be computed for the FCC region as well as for the evaluation of the deflectometer that is presently developed at CERN in the framework of this project. Also 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.