GEODETIC ACTIVITIES AT CERN FOR CURRENT AND FUTURE PROJECTS

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Abstract

A number for geodetic activities are in progress to provide the necessary infrastructure for the High Luminosity LHC (HL-LHC) project. The results from these activities will also provide the opportunity to investigate and resolve known anomalies identified in the CERN geodetic reference systems, and related parameters, which would benefit this and future projects.

A new high precision GNSS measurement of 15 pillars of the surface geodetic reference network has been integrated into the network, and the Gyromat-2000 and Mekometer ME5000 have been put back into service. Work to control and establish reference azimuths for the HL-LHC, at two points around the LHC ring for the new civil engineering works, are in progress, and our long distance geodetic baseline has also been re-measured with the Mekometer ME5000, for the use of the civil engineering teams. These activities, together with the ongoing and planned future work, are presented.

INTRODUCTION

The HL-LHC project is now in the construction phase, with the site Engineers and Constructors both now on site at LHC Point1 and LHC Point5. The ground breaking for the shafts down to the new technical gallery, that will need to run parallel to the existing LHC tunnel, was in the summer of 2018. The majority of the geodetic infrastructure and instrumentation necessary for this project needed to be re-determined, or put back into service, since it had not been used for close to 20 years for either the CNGS project, or the dismantling of the LEP accelerator and the installation of the new LHC accelerator.

Although the primary goal for this work has been the HL-LHC project, it is useful and timely to: provide input for the update of some parameters of the CERN reference systems; allow us to examine more closely, and help resolve, some anomalous results identified in the last 20 to 30 years; refresh our understanding of the infrastructure and organisation required for new tunnelling projects; and thereby provide information pertinent to future projects being studied at CERN such as CLIC, the FCC, and the HE-LHC.

GEODETIC SURFACE REFERENCE NETWORK

The CERN Geodetic Surface Reference Network currently consists of approximately 40 geodetic pillars across the whole of the CERN site, and a permanent GNSS reference station on the CERN Prévessin site, which has been integrated into the French Réseau GNSS Permanent (RGP) since 2011. The majority of the pillars are on the CERN Meyrin and Prévessin sites and typically date back to the installation of the PS and SPS machines. Geodetic pillars can also be found on the roofs of the access shaft buildings around the SPS, and the rest are more generally spread across the whole site and were constructed for the LEP/LHC tunnel construction. For the LEP construction and installation there were also pillars on each of the access shaft sites, but most of these no longer exist. Some pillars were also added for the construction of the CNGS tunnel, and the two LHC transfer lines (TI2 and TI8), but these were largely temporary too.

For the HL-LHC project it was decided that no new pillars needed to be added, and 15 pillars across the CERN site were selected to be re-measured to provide reference points for the civil engineering works (see Fig. 1). Some baselines previously used for the control of gyro-theodolites were deliberately included in the list too.

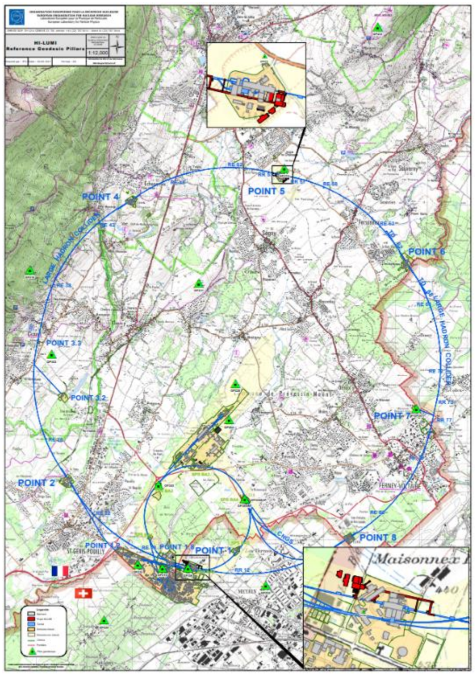

Figure 1. Location of 15 geodetic pillars measured by GNSS for the HL-LHC project

The measurement by GNSS of these pillars was carried out by IGN (France) in October 2017. Two sets of measurements were made, each for a period of 48 hours, using recently calibrated antennas. In each set of measurements all 15 points were measured. Between the two campaigns the antennas were moved between pillars. Although all fifteen points were measured, it was noted that two of them were masked either by the Jura Mountains or nearby trees, and that this reduced the precision of the estimated coordinates. Various calculation options and checks were made, the final calculations being in the ITRF14 (IGS14) reference frame (epoch 2017.74), and the other 13 pillar locations were all asserted to have been determined within the specified 2 mm precision in planimetry, and 5 mm in altimetry, for the results.

For the moment, a preliminary calculation has been undertaken to update the coordinates of these pillars in the CERN Coordinate System (CCS). The link between the CERN reference systems and global geodetic reference systems is through a transformation to the ITRF97 (ep 98.5) reference system. The GNSS results in this system were also provided by the IGN. It was decided that given the precision of these coordinates, the new measured values would become the new reference values. They were therefore adapted onto the existing coordinates of the pillars in the CERN Geodetic Reference Frame (CGRF). Some of the points were known to have moved, and others had not been measured in more than 30 years. The shift in the coordinates of some of the pillars was up to 150 mm, and in the end only 12 points were used in the calculation, with an average 3D shift of 8.8 mm in the coordinates and a maximum shift of 14 mm for one of the points. The scale factor for the transformation was fixed equal to one.

The results from this calculation were transformed back into the CCS, and the orthometric height of the points was also determined. These values were then documented and provided to the civil engineering teams as reference coordinates for the geodetic pillars.

For the transformation of the original point coordinates from the CERN Project System to the CGRF, the revised transformation parameters determined by Nerea Ibarrola [1] were used. The rotation parameters, determined in the transformation above, were seen to all be less than 0.1 mgon, which confirms that they give a consistent realignment of the CGRF with the ITRF system.

The next steps will be to: refine the transformation parameters between the ITRF97 and CGRF systems; determine the same transformation parameters for ITRF14; study the use cases for transformations into the international reference systems; and decide which transformations need to be maintained.

AZIMUTH OF THE HL-LHC TECHNICAL GALLERIES

Another important parameter necessary for the excavation of the HL-LHC new technical galleries, see Fig. 2, was their azimuth. During the excavation of these galleries a direct link to the LHC tunnel will not be available. This access will be achieved at a point close to the access shaft in 2020, and only at the other end after the excavation is completed.

To assure the radiation safety of the people working in the technical gallery when the LHC is running, the path from the gallery to the LHC tunnel necessarily includes several twists and turns, and very short lines-of-sight. This is not ideal for transferring an orientation from the LHC to the new gallery, and given the diameter of the access shafts it was decided that one or more gyro-theodolite azimuth determinations would be required to assure the construction remained with the specifications for the offset with respect to the LHC.

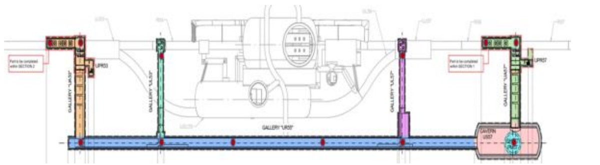

Figure 2. Plan of the new HL-LHC galleries at LHC Point 5

The CERN Gyromat 2000 gyro-theodolite was purchased for the dismantling of the LEP machine, the installation of the new tunnel network for the LHC, and the transfer of the LEP orientation to the LHC beamline elements. It was used intensively between 1997 and 2005, and had seen little service since then. Although it was proposed to be used for the LINAC 4 tunnel, it was found that the instrument was no longer in working order, and an inspection by DMT determined that the batteries need to be changed. Finally for LINAC 4 an outside company was brought in to determine azimuths in the main tunnel.

The azimuth measurements on the LEP machine [2], and for the LHC [3], had shown systematic discrepancies between the theoretical values around the accelerator ring and the measured values. A gyro-theodolite was also used to control the civil engineering works of the LEP/LHC tunnel, with no documented problems of this type. No explanation for this anomaly has ever been determined, and pragmatically only the relative orientation along the tunnel was applied. Assigning an azimuth for the new civil engineering works is therefore a delicate matter.

Ideally, the anomaly in the theoretical and real azimuths in the LHC tunnel should be investigated and clarified for the HL-LHC and future projects. With this in mind, and also taking into account the problems of shifting LHC work schedules for outside contractors, the decision was taken to finally repair the batteries in the CERN Gyromat 2000. Unfortunately, at this time DMT informed us that it was no longer just a question of replacing the batteries, but using a new battery type, which conformed to new European standards, and making additional changes in the electrical system. Fortunately, upon inspection of the CERN instrument, it was found that the electronics were still in good working order, and the decision to repair the instrument was taken. A TDA 5005 acquired for the LHC installation was installed on the Gyromat 2000 at the same time.

With limited time available, a pragmatic approach was adopted again for the HL-LHC project. With no explanation of the differences between the theoretical and the real values of the azimuths measured for the LHC, it was decided to re-measure azimuths in the Long Straight Sections (LSS) of the LHC at Point 1 and Point 5. During this measurement campaign azimuths would also be measured at the CERN Geodetic Base, with the potential to be transferred later to a control baseline more readily accessible to the civil engineering contractors. The azimuth of the CERN control baseline and the measured azimuth for the LHC machine would then be provided to the contractors, such that the relative azimuth difference would be applied for the civil engineering works by their own specialists.

Figure 3. Gyromat 2000 stationed on a underground network reference point in the LHC tunnel

Unfortunately, the CERN Gyromat 2000 (Fig. 3) was tilted beyond the handling specifications during transport back to CERN from DMT. More than 30 North determinations, showed a larger than expected dispersion of the measurements, a large shift in the average value, and groupings of north determinations with different average values. Under these circumstances DMT asserted that the instrument should be returned to them and re-controlled and calibrated. However, there was no longer sufficient time to guarantee that the instrument would be back in time for the measurement window in the LHC year-end technical stop. It was decided that the instrument would be used as is, since, even with the degraded precision, it would still be sufficient for the HL-LHC project.

Figure 4. Overhead view of the layout of the principal pillars along the Long Distance Control Baseline

The measurements in the tunnel were carried out as planned in February 2018. Frequent controls in the LHC tunnel, and at the Geodetic Base, were included in the measurement campaign and no changes were observed in the calibration constant. Measurements from three network points on either side of each interaction point were made, corresponding as close as possible to previous measurements made in 2004 and 2005. Some changes were made in the field due to access restrictions. At each station 5 North determinations were made, and azimuths to 3 or 4 reference points were measured. The dispersion of the calculated azimuths for a given instrument station was typically ~2.0 mgon. At the same time, Total Station measurements were undertaken to link the reference network points to the tunnel beamline elements. These measurements are now being processed, together with the survey control and alignment measurements in the LSS, and the measurements from the permanent position monitoring and alignment system around the LowBeta magnets -linking both sides of the cavern.

The results from this will provide an azimuth value for the LHC machine in the LSS at Point 1 and Point 5, and a corresponding azimuth value at our control baseline at the Geodetic Base.

LONG DISTANCE CONTROL BASELINE

For previous civil engineering tunnelling projects at CERN we have also provided access to our long distance control baseline (Figures 4 and 5), of 13 pillars spaced out along a straight line over 1.5 km. Although not necessarily essential for new technical galleries of ~300 m, and with changes in technology leading to the initial determination of pillars on the civil engineering sites being carried out by GNSS, we decided to make the baseline available if requested.

This work had been done using the CERN Mekometer in the past, which has a nominal precision of 0.2 mm + 2 ppm. To carry out the work using the same instrument involved putting the original CERN Mekometer back into service after 7 or 8 years of storage. The Mekometer was controlled on the CERN calibration bench at 5m distances between ~20 and 50 m. These values were used to determine a new calibration constant for the instrument.

Figure 5. Mekometer ME5000 stationed on a pillar of the Long Distance Control Baseline

Two sets of measurements on the external baseline were carried out in October and November 2017. Large temperature differences were noted during the day of the October measurements, and differences between the two sets of results were up to 5 mm at 1000 m. A further set of measurements were carried out in January 2018, and more care was taken with the protection of the instrument from the sun.

The January 2018 results were much more coherent, and these were used as the basis for the determination of the distances along the control baseline. Only 12 of the 13 pillars were measured, the first pillar of the baseline no longer being accessible, and in the end only the distances between the 11 remaining pillars on the Prévessin Site were provided to the civil engineering teams.

As part of an ETHZ Geodetic Project Course hosted at CERN, the modulation frequency of both CERN Mekometers (a second instrument was acquired a number of years ago from PSI, Switzerland) were controlled against a precision time source. It was found that the original instrument had a significant offset in the modulation frequency (larger than the other instruments tested), and a correction ~0.4 ppm was applied to the measurements.

The SURVEY database has now been modified to include this scale error in the Mekometer parameters, and to also apply it in the pre-processing step when new measurements are inserted. The measurements were processed in the latest version of LGC, using the nominal precision values, resulting in a determination of all the distances between the 2nd and 13th pillars, see Table 1. The σ_0 value from the final calculation was 1.15 (not significantly different to 1.0), the mean residual was 0.04 mm and the standard deviation of the residuals was 0.24 mm.

Table 1. Distances along the Long Distances Control Baseline

Pillar	Distance from PBASE.2. (m)
PBASE.2.	0.000
PBASE.3.	49.992
PBASE.4.	100.005
PBASE.5.	150.002
PBASE.6.	199.997
PBASE.7.	250.002
PBASE.8.	299.997
PBASE.9.	350.011
PBASE.10.	400.013
PBASE.11.	450.012
PBASE.12.	500.006

CERN REFERENCE SYSTEMS

Documents describing the CERN reference systems, their relationships and the transformations required to pass between them are typically included in the call for tender for projects such as HL-LHC. For this project the necessary documents were provide to the CERN Civil Engineering team, but it was noted that the principal document [4] that had been used in the past was now forty years old, and was written when the largest accelerator at CERN was the SPS.

Subsequent documents on the CERN reference systems did not seek to replace this original document, providing complementary information, and descriptions. Analysis of the GNSS measurements made on the CERN site for the CNGS, LHC, and HL-LHC projects have shown that the defining parameters of the CCS should be refined, and the decision was taken to create a new revision of the documentation of the CERN reference systems. It was similarly decided to create separate documents for different end users (Internal Use and Civil Engineering/Integration).

The limited resources available has meant that this work is still to be started, and the necessary studies required will need some time to complete.

GEODETIC PROJECT COURSE

The ETHZ Geodetic Project Course has already been mentioned in the context of long distance control baseline. This course took place in September 2017 over a period of nearly 3 weeks. Four supervisors from the ETHZ, Institute of Geodesy and Photogrammetry, Mathematical and Physical Geodesy group, and 13 students, came to CERN for a course involving practical geodetic exercises. Many of the practical exercises included work that would be of potential interest to the CERN survey team. These were separated into four different projects: High-Precision Determination of the CERN Surface Network; Gravity and Geoid Determination; Transfer of position in a Vertical Shaft; and Determination of high-precision heights.

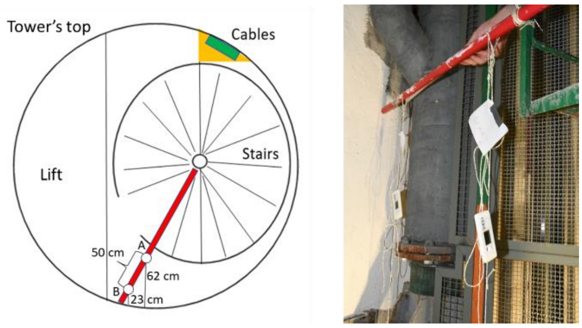

Figure 6. Deployment of Smart Gadget Temperature Sensors

The first project included GNSS measurements of the same 15 points measured for the HL-LHC Project, and long distance measurements of up 6 km. Simultaneous zenith distance measurements were made from each end of the long baselines measured, and these were used to correct for the vertical refraction effects on the distance measurements. The next project included gravimeter measurements between absolute gravimeter points at CERN, in France and Switzerland as well as the start of an astro-geodetic levelling profile to Annecy, an area covered by the proposed FCC project. The third project looked at position transfer techniques in a vertical shaft, with an evaluation of refraction effects. The final project investigated high precision height differences, using, amongst other techniques, the QDaedalus package and, once again, reciprocal zenith distance measurements to determine the refraction coefficient. A comparison of different height determination methods for alignment (HLS, laser tracker, geodetic levelling and QDaedalus) was included in this project.

The last subject appeared to confirm that refraction was a very good explanation of the anomalies that we have seen in the geodetic levelling in the LHC, and in other accelerators at CERN.

CONCLUSION

All of the work that is required for the HL-LHC civil engineering project is completed or underway. Two old instruments have been put back into service to achieve this, with a few hiccups along the way.

The data and results from this work will be further analysed in the coming months and years to refine our definitions of the CERN reference systems, and the processing of our observations. They will also provide essential input into future accelerator projects.

Some directions for future research and development have also been identified and will also be critical in meeting the requirements of future projects.

ACKNOWLEDGMENT

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