ANALYSIS AND EVALUATION OF THE CERN REFERENCE SYSTEMS

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Abstract

The work that will be presented has been driven mainly by the Future Circular Collider (FCC) study, a proposed next-generation particle collider with a circumference of 100 km and the aim of reaching collision energies of 100 TeV.

The new machine would be located in Swiss and French territories, and it would cover more than 10 times the area of the existing LHC facilities. For this reason, a better integration of the French and Swiss data is needed. The large dimensions of the future machine and the high alignment precision requirements make it necessary to review and analyse the reference and coordinate systems used at CERN, as well as to evaluate the extension of those to cover a much larger area. The current definitions of the CERN reference systems and the transformations between them have been analysed and tested. The proposed modifications and the future work that has to be done to prepare a conceptual design report for the FCC project by 2018 will be presented.

INTRODUCTION

Since the construction of the Proton Synchrotron (PS) in the 50's, CERN has used his own datum for both horizontal and vertical position. They have been evolving together with the new precision requirements of the new machines that have been built over the years.

The CERN Coordinate System (CCS) is used to define the relative position of all the accelerators and experiments at CERN. It has an associated horizontal geodetic datum, which is at the same time linked to the CERN Geodetic Reference Frame (CGRF). In turn, the CERN reference system is linked to different global systems and it makes possible to transform coordinates to the national reference systems (Figure 1).

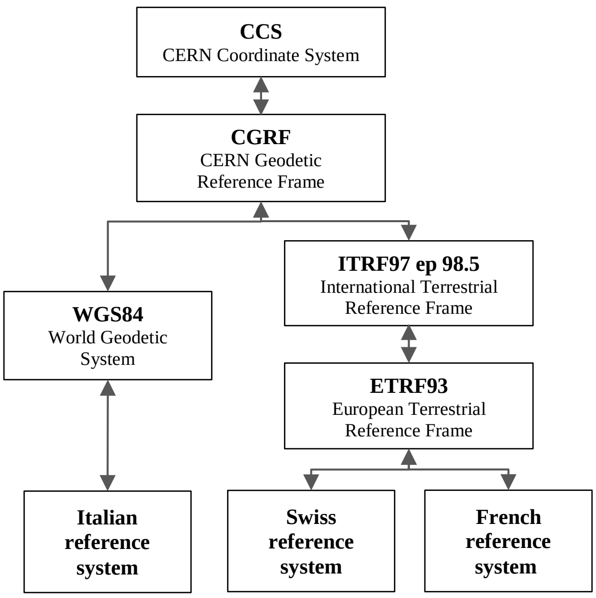

Figure 1: Transformation workflow between reference systems implemented in SurveyLib.

In the project called CERN Neutrinos to Gran Sasso (CNGS), it was needed to connect the CERN reference systems to the global systems in order to define the direction of the beam which was sent from CERN (Switzerland) to Gran Sasso (Italy). Back then, small misalignments between the global and CERN systems were already seen, but the effect of those small rotations was negligible.

The FCC will cover an area more than 10 times larger than the current installations (Figure 2), and the current reference systems would have to be extended. The differences caused by any misalignments would therefore become more significant across the new FCC site, and data from both France and Switzerland must be integrated.

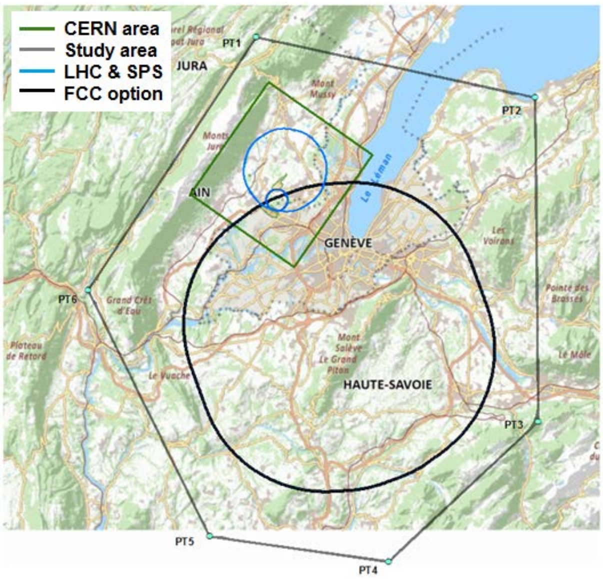

Figure 2: Extension of the study area and a potential FCC layout option.

The goal is to re-establish the position and orientation of the CGRF with respect to the ITRF97 in order to make them parallel. Therefore, it will avoid the introduction of any offset caused by the misalignment and it will ensure that the vertical deflection at P0 is truly zero. A new set of topocentric datum position parameters will be established and the CGRF will be re-defined. However, the coordinates of the points in CCS will not change. This is very important for CERN because nothing will change locally. Globally, the whole CCS will be located in another location, and orientation, with respect to the CGRF but won't change with respect to the ITRF97. In this way, the data sets of measurements that we already have, can still be used to calculate the relationship between CERN systems and the global ones.

DEFINITION OF THE PROBLEM

The misalignment between the ITRF97 epoch 98.5 and the CGRF not only can be seen in the transformation parameters used to transform points between both frames (Table 1), but also in recent studies of the deflections of the vertical [1]. According to the definition of the CERN reference system [2], the deflection of the vertical at P0, which is the principal point of the CCS located at the centre of the PS, should be zero (Table 2). Contrary to this statement, the transformed vertical deflections at P0 from both 1984 and 2010 measurement campaigns, from the Swiss system to the CERN system show values up to -19^{cc} in the north-south component and 10^{cc} in the West-East component. This means that the deflection of the vertical value at P0 is not actually zero.

Table 1: Transformation parameters between the ITRF97 and the CGRF from 2001.

Parameter	Value
Ω (x)	$-4.667865\ ^{cc}$
Ψ (y)	$18.251579\ ^{cc}$
K (z)	$9.910543\ ^{cc}$
T_x	76.3768280 m
T_y	131.9389844 m
T_z	-156.123
S	1

Table 1 shows the set of parameters used to transform coordinates from ITRF97 to CGRF. This set of parameters consist of three rotations around x-, y- and z- axes (Ω, Ψ and K respectively); three translations along the same axes (T_x, T_y and T_z) and a scale factor (S).

Table 2: Current CERN horizontal geodetic datum.

Parameter	Value
a	6378137.0 m
e^2	0.0066943800229
φ_0	$51.3692\ ^{g}$
λ_0	$6.72124\ ^{g}$
h_0	433.65921 m
α_0	$37.77864\ ^{g}$
ξ_0	$0.0\ ^{cc}$
η_0	$0.0\ ^{cc}$

On the other hand, Table 2 shows the values of the parameters used to defined the GRS80 reference ellipsoid: the semi-major axis (a) and the eccentricity (e^2); as well as the topocentric datum position parameters: geodetic latitude (φ_0), longitude (λ_0), ellipsoidal height (h_0), azimuth (α_0) and deflection of the vertical (ξ_0, η_0) at P0. These sets of parameters are used to define the link between the international and CERN global reference systems and to fix the position of the local reference system with respect to the global system.

Besides the disagreement found in the transformed deflection of the vertical values, differences between geoid models have been found when transforming heights from Swiss to CERN systems [3]. The most recent CERN geoid model, CG2000, was established using the deflection of the vertical data at grid points across the CERN site provided in the Swiss reference system. The geoid heights, also called undulation values, obtained through a transformation process are not the same as those given by the Swiss geoid model CHGEO85. Those geoid heights differences are best fit by a plane which has a shift (0.0251 m) and a tilt (0.343'') with respect to the CCS around an axis with an azimuth of 6.0423^{g}. The effect of the tilt is negligible at the farthest point from P0 within the area where the CG2000 is currently defined. In the case of a large extension of the current CERN area the effect of the tilt would become significant. In the FCC project, the area covered by the machine reach the pre-Alps. Here, the fact that the tilt exist makes that the geoid heights differ several tens of centimetres.

CALCULATION PROCESS

The following calculation process has been carried out in order to re-establish the CGRF with respect to the ITRF97. There are two main steps: First of all, the calculation of the new values of some of the topocentric datum position parameters. Secondly, the re-calculation of the transformation parameters between ITRF97 and CGRF. Finally, the process will be completed checking that the transformation chain is carried out correctly and the values of the parameters/variables, i.e. deflections of the vertical, are the ones expected when passing through the different reference systems.

Data sets

There are different data sets available in order to be able to reproduce the same steps as the ones followed at first place in order to calculate the transformation parameters:

- Deflections of the vertical at 8 astro-geodetic stations from two different measurements campaigns, the first one from 1984, and the second one from 2010.
- GPS and conventional surveying measurements at 4 pillars: coordinates of the pillars in ITRF97 epoch 98.5 and CERN XYH.
- Geoid models covering the CERN area: CG1985, CG2000 and CHGEO85. The last two geoid models are defined in a grid of points covering the current CERN area (Figure 3).

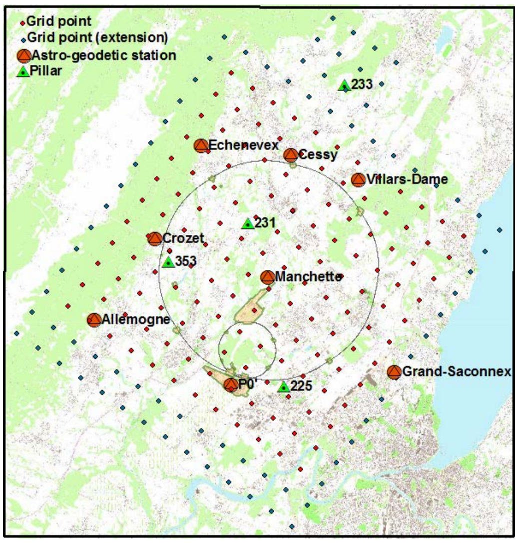

Figure 3: Different data sets across the CERN site.

Re-establishing the CGRF

It is clear that the deflection of the vertical angular values from the two measurement campaigns are directly correlated to the rotations coming from the transformation between ITRF97 and CGRF [4]. A rotation of the CGRF can be carried out in order to align both reference frames (Figure 4).

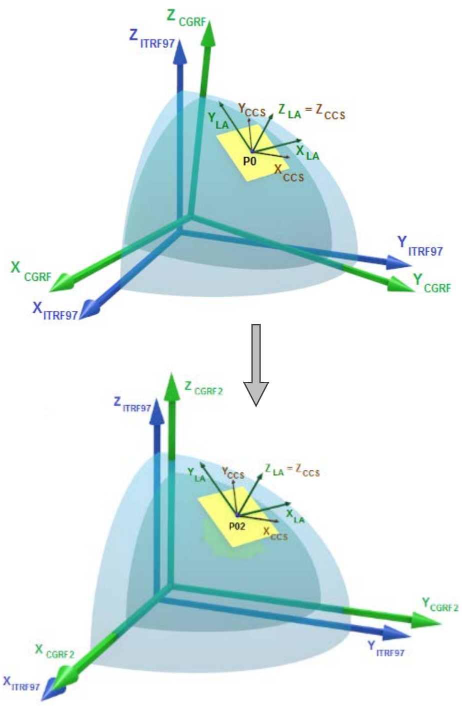

Figure 4: Re-establishing the CGRF.

Only the CGRF has been moved, meaning that the CCS reference system has been relocated in a different place with respect to the CGRF, but not with respect to the ITRF97. This means that some of the topocentric position parameters has been modified in order to re-define the link between CGRF and CCS systems (Table 3).

Table 3: Topocentric datum position parameters.

Parameter	Value
a	6378137.0 m
e^2	0.0066943800229
φ_0	51.36734 ^{g}
λ_0	6.722515 ^{g}
h_0	433.65921 m
α_0	37.779033 ^{g}
ξ_0	0.0 ^{cc}
η_0	0.0 ^{cc}

Transformation between ITRF97 and CGRF

Different sets of parameters must be used to compute the transformation between the CGRF and the ITRF97. They depend on the geoid models and the definition of the topocentric datum position parameters that are used in each case. Since the origin point has been changed, a new CGRF has effectively been defined (temporally identified as CGRF*). This may be further refined and the geocentric set of datum position parameters shown will be updated.

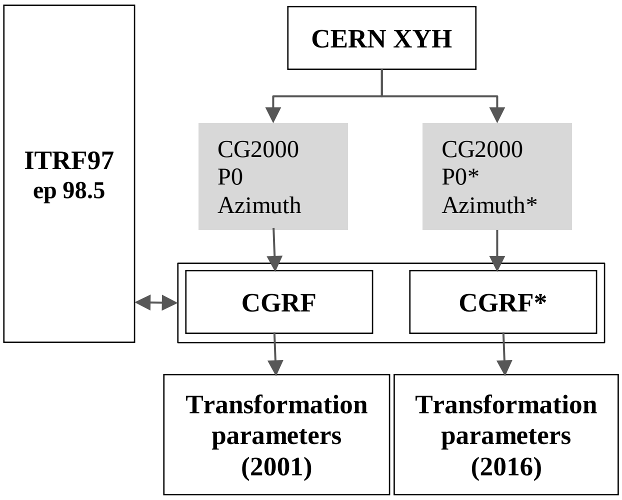

Figure 5: Workflow of the calculation process of the ITRF97-CGRF transformation parameters.

Figure 5 shows the process followed to compute the set of transformation parameters. The coordinates of four pillars in ITRF97 and CERN XY and orthometric height are the input. Firstly, the CERN XYZ coordinates have been transformed to the CGRF* using the new topocentric position parameters. Then, a 7-parameters Helmet transformation has been carried out using ChaBa, an adjustment software developed by the Survey Section at CERN. The resulting values can be seen in Table 4 [5].

Table 4: Re-calculated transformation parameters between the ITRF97 and the CGRF.

Parameter	Value
Ω (x)	-0.0169942 ^{cc}
Ψ (y)	0.0289072 ^{cc}
K (z)	0.0038244 ^{cc}
T_x	76.7267314 m
T_y	132.2499171 m
T_z	-155.6321962 m
S	1

NEXT STEPS

This has been one of the several studies that are needed to be done in the frame of the FCC project. The following points are the main questions that we should be able to answer in the CDR:

- Extension of the CG2000 geoid model. Our priority now is the study of the geoid model in the FCC area. A collaboration between IGN and Swisstopo in order to share their data of the area is already set up. This will allow us to work with both institutes and be sure about the additional data needed in the area.
- Extension of the surface network through the FCC area. Studies of the best configuration for the location of the new pillars must be performed, as well as to consider building permanent stations in the FCC area.
- Once the coordinates in the surface can be known in both international and CERN reference systems, those coordinates must be transfer from the surface to the tunnel. The shafts can be up to 400 m in depth, which is more than 4 times the current distance from the surface to the LHC tunnel. The same methodology used in the LHC must be tested in order to know if the transferred coordinates meet the precision requirements in the tunnel. Other methodologies will be studied.
- A proper underground network must be designed in order to get the required precision in the alignment of the machine. This is mainly related to the number of boreholes between shafts are needed and the kind of surveying measurements techniques performed in the in order to meet the precision requirements in the alignment of the machine.

In addition to these 4 main points, testing alignment instruments and measuring methodologies over longer distances must be done in order to ensure that it would be possible to meet the alignment precisions required in each machine case.

CONCLUSIONS

The re-stabilisation of the CGRF with respect to the ITRF97 epoch 98.5 has been successfully performed:

- The topocentric set of horizontal datum position parameters has been re-determined (Table 3).
- ITRF97 and CGRF are aligned (Table 4). It makes that the deflections of the vertical at P0, calculated directly in CGRF, are zero.
- The same process could be applied to adapt the CGRF to the new GNSS measurements for the FCC.
- There are still undulation differences between Swiss and CERN geoid models. Further studies might be carried out.

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REFERENCES

[1] N. Ibarrola, "Comparison between deflection of the vertical values" EDMS Document 1567014, CERN, Geneva, June 2015.

[2] M. Jones, "Geodetic definition (Datum Parameters) of the CERN Coordinate System" EDMS Document 107981, CERN, Geneva, February 2000.

[3] N. Ibarrola, "Comparison of geoid models covering the CERN site" EDMS Document 1566976, CERN, Geneva, May 2015.

[4] A. Wiart, "Parametres des transformations Helmert entre IRT97 et le systeme CERN CGRF" edms Document 323478, May 2001

[5] N. Ibarrola "Re-establishing the CERN Geodetic Reference Frame", EDMS Document 15681331, CERN, Geneva, November 2015.