DETERMINATION OF UPDATED VERTICAL GEODETIC REFERENCE SURFACES FOR THE CERN SITE

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Abstract

A new set of vertical geodetic reference surfaces have been determined covering the CERN site and baptised Cern Geoid 2000 (CG2000). These reference surfaces were established to provide an updated vertical reference surface for the CNGS Project. These surfaces provide the deviation of the vertical values at three different levels: mean sea level (Niv 0); in the plane of the LHC machine (Niv Machine) and at the ground surface.

The determination of the parameters defining these vertical reference surfaces is presented together with the method to be used to exploit them.

Mots-clés : Surface de Référence, Géodésique Verticale, Géoïde, CG2000

Key words : Vertical Geodetic Reference Surface, Geoid, CG2000
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1. INTRODUCTION

A new set of vertical geodetic reference surfaces have been determined covering the CERN site and baptised CERN Geoid 2000 (CG2000). These reference surfaces were established to provide an updated vertical reference surface for the CNGS (CERN Neutrinos to Gran Sasso) Project. These surfaces provide the deviation of the vertical values at three different levels: mean sea level (Niv 0); in the plane of the LHC machine (Niv Machine) and at the ground surface.

The Gran Sasso Laboratory consists of three underground experiment halls located next to the Gran Sasso tunnel under 1400 m of rock. During the LNGS design phase in 1979, these three underground caverns were oriented towards Geneva with possible future neutrino beams in mind. The CNGS Project [1] will now realise that planning and aims to investigate the 'oscillation' of neutrinos. A beam extracted from the CERN SPS accelerator will produce a beam consisting uniquely of muon-type neutrinos that will be directed underground to their destination, the Gran Sasso National Laboratory (LNGS) in Italy, 730 km from CERN.

![Fig. 1 Scale of the CNGS Project](image)

The goal for the maximum offset between the actual neutrino beam and the ideal beam position at the CNGS Detector has been fixed at 100 m [2]. The geodetic alignment process must therefore achieve an r.m.s. error in this offset of ±37 m, assuming the alignment is only affected by random errors. This corresponds to an angular error of ~10 arc seconds.

With modern surveying techniques (notably GPS) the error in the absolute positions of the origin and target of the beam line contributes little to the overall error budget. More important is our knowledge of the gravity vector at the origin; this defines the vertical reference surface (vertical datum or geoid) upon which the alignment of the beam line components is based.

Consultation with the national surveying bodies in France (IGN) and Switzerland (OFT) showed that the geoid model used for the LEP (Large Electron Positron Collider) would probably need to be updated for the alignment of the CNGS accelerator components.

Based upon the 1998 Swiss geoid model (CHGEO98) a new model of the geoid and technique for its exploitation has been implemented at CERN (CG2000). This new geoid model will be incorporated into our various computational algorithms.
2. DETERMINATION OF THE NEW GEOID MODEL

In the mid-1980s in the limited area of the CERN site, a precise study of the geoid was made for the benefit of the LEP Project [3]. This was done to take into account the effects of the Jura Mountains and was based upon a mass model of the area and accurate astro-geodetic measurements. It was shown that the maximum local distortion was ~14 cm over 10 km. The result of this study was a local geoid model detailing the undulations relative to the CERN horizontal reference datum, the GRS80 reference ellipsoid. This geoid model is a hyperbolic paraboloid tangent to the reference ellipsoid at the principal point, and is now referred to as CERN Geoid 1985 (CG1985).

Fig. 2 The CG1985 Geoid Model

2.1 Comparison of Geoid Models

These surfaces provide the deviation of the vertical values are three levels: mean sea level (Niv 0); in the plane of the LHC machine (Niv Machine) and at the ground surface. A collaboration, with the Laboratoire de Recherche en Géodésie (LAREG, Paris) and the Office Fédérale de Topographie (OFT), to review the different geoid models in Europe that covered the CERN site, revealed that there were some significant discrepancies between them [4]. Significant differences were also evident between the latest geoid model for Switzerland CHGEO98 and the previous model CHGEO78 (Fig. 3 and Fig. 4), and it was this latter geoid model that formed the basis for the local CERN geoid model of 1985.

Fig. 3 Geoid CHGEO98 in ETRF89 (RPN)  
Fig. 4 Geoid differences: GURTNER78 minus CHGEO98
After discussion it appeared that the geoid model CHGEO98 would be the most precise of those geoid models currently covering the local area. It is based upon a mass model, with each element covering an area 25 m by 25 m, in a grid that covers the whole of Switzerland and extends into all the surrounding countries. The model also takes account of a number of mass anomalies. It was therefore decided to use this model to derive a new local geoid model for the CERN site.

2.2 Transformation of CHGEO98 into the CERN reference system

The CG1985 was based upon a reference grid with each node at the corner of a square covering a total area 10 km by 10 km, aligned with the axes of the Swiss national reference system (nearly North & East), and with a step of 1 km between successive nodes of the grid. For the new model it was decided to adopt the same approach, but this time to orient the grid to follow the axes of the CERN Coordinate System (CCS).

The CCS is the reference frame used at CERN to describe the position and orientation of all the geodetically aligned elements, of all the accelerators. It is a 3-D Euclidean reference frame and was first established for the Proton Synchrotron (PS), the first CERN accelerator, in the late 1950s. The CCS is a modified local astronomical system [5]: the principal point is the pillar P0 at the centre of the PS; the Z-axis of this system is by definition coincident with the gravity vector at P0; the Y-axis of the system at P0 has an azimuth fixed by other geodetic pillars positioned around the PS, and runs nearly parallel to the Jura Mountains.

A reference grid 11 km by 11 km was initially decided upon (Fig. 5), but as the modelling technique was developed this was extended to provide a final squared reference grid 14 km by 15 km with a small extension (3 km by 3 km) to the North East to cover a geodetic pillar of the primary network. The X-, Y-coordinates of these grid points have an integer kilometre value in the CCS.

The coordinates of the grid points at each intersection node were determined in the plane of the Large Hadron Collider (LHC), the accelerator currently under construction in what was the LEP tunnel [6]. The coordinates were subsequently transformed into the ITRF97 reference frame and passed to the OFT who used the CHGEO98 geoid model to determine the deflection of the vertical values determined for each grid point at three different heights: for the actual point supplied in the plane of the LHC accelerator; for the corresponding point on the surface of the reference ellipsoid; and for the corresponding point at the surface.

A geodetic reference frame has also been implicitly defined at CERN (referred to as the CERN geodetic reference frame, or CGRF). A horizontal geodetic datum was established with a topocentric set of datum parameters for the LEP Project, using the GRS80 reference ellipsoid. The principal point was once again chosen to be the geodetic pillar P0, and the ellipsoid normal is defined to be coincident with the Z-axis of the CCS, and the local vertical. By definition the deflection of the vertical values at P0, with respect to the CERN horizontal geodetic datum, are therefore zero.

By means of interpolation, the deflection of the vertical values at P0 were calculated from the values at the grid nodes provided by the OFT. The computed values at P0 were then subtracted from the values provided for each reference grid node point to “normalise” them for the CERN horizontal geodetic datum. This left the possibility of a small translation error, but it was decided that this would have a minimal effect on beam the line to Gran Sasso.
These “normalised” deflection of the vertical values were used to determine the geoidal undulations across the CERN site. For each 1 km edge between adjacent reference grid node points the change in the deflection of the vertical values was used to calculate the change in the geoidal undulation between the two node points [7]. These changes in undulation were treated as height differences in a network of points in a local Euclidean reference frame (Fig. 7), and compensated together to yield geoid undulation values (Fig. 8) at each node of the reference grid. It was these compensated geoid undulation values that were then modelled.

2.3 Modelling of the Geoid

As has already been mentioned the geoid model CG1985 is a parabolic hyperboloid. This choice was made in part to take into account the computing limitations at the time it was established, and in part to make the calculation of geoid undulations as uncomplicated as possible.

A parametric model did not prove to be appropriate for the new geoid undulation data with too many parameters required to be able to closely follow the undulations [8].
decision was therefore taken to keep the full data set of geoid undulation values for each node of the reference grid and to interpolate values as required.

2.4 Interpolation Model

Different methods were examined [9] and the final method adopted was to employ a 16-point sub-grid, which lies about the point of interest and to perform the interpolation using Catmull-Rom splines [10].

If we consider the sub-grid of 16 points around the point of interest (fig. 9). The four points along line y1 (columns x1 to x4) are taken and a Catmull-Rom spline through the points determined and used to interpolate an undulation value at the X-coordinate of the point of interest. The same process is then applied for the lines y2, y3, and y4. The four values that are obtained are then used to define a Catmull-Rom spline in the opposite sense and that curve used to determine an undulation value at the Y-coordinate of the point of interest. This value is the geoid undulation at the point of interest.

Although seemingly a problem, any point lying directly on the line joining grid points will yield the same result independent of the 16-point sub-grid that is chosen (in fact the interpolated value may be determined with only one interpolation along the line). Furthermore the interpolated value is an average of the four values that may be determined with a parabolic interpolation method. The only disadvantage of this method was that the reference grid had to be extended in order to provide the same coverage of the CERN site.

3. TESTS OF THE GEOID MODEL

The derived geoid undulation values have been assessed by comparison with values provided by the OFT for all the reference grid points in a Swiss reference frame. Obviously after the transformations applied to the deflection of the vertical values we could not expect to find exactly the same values, however best fitting a plane to the differences between the geoid undulations showed negligible residuals.

The points on the geoid surface corresponding to the primary network points have also been transformed into the ITRF97 (ep. 1998.5) reference frame and, using the GRS80 reference ellipsoid, compared to values supplied by the OFT. Again a plane fitting approach was adopted and showed a vertical translation ~20 mm between CHGEO98 and CG2000, and a rotation difference ~1 dmgons.
4. APPLICATION OF THE NEW MODEL

The lattices for the different accelerators at CERN are nominally determined in a Euclidean reference frame with coordinates provided in a Cartesian coordinate system (typically using the software applications MAD or BEATCH). The Survey Group then determine the parameters and algorithms necessary to transform these lattice coordinates into the CERN Coordinate System, to fix the relative positions of the accelerators. The CERN XYH-coordinates of the lattice and derived points then become the measurable quantities that can be used and verified for all subsequent survey activities, even if 3D Cartesian coordinates were used to define the machine lattice positions.

Each accelerator is therefore permanently associated with those given Geodetic Horizontal and Vertical Reference Surfaces used at the time the accelerator lattice was first determined in the CCS. Extreme care is always necessary to apply those same reference surfaces whenever the lattice is changed. To simplify the day-to-day survey processes, the CERN-XYH coordinates, once determined for a given accelerator lattice, now provide the definitive survey reference coordinates.

The new geoid model should therefore become the vertical reference surface for all new accelerators at CERN. This will be the case for the CNGS, however, the fact that the LHC tunnel was constructed using the CG1985 geoid model imposes other constraints on the choice of geoid model for the LHC.

Comparisons of CG2000 with CG1985 showed significant differences around the LHC tunnel (Fig. 8). These differences are too large for the CG2000 model to be used for the determination of the heights of the LHC components that need to be aligned. The differences between the undulations presented by CG2000 and CG1985 along the CNGS tunnel (Fig. 9), at CERN are much smaller and the new geoid model will be used for the determination of the heights of the CNGS beam line components.

As part of the simplification process to be implemented in all day-to-day survey activities the new geoid model will be used in all geodetic compensation and other calculations where 3D Cartesian coordinates are required. The input data for such calculations will always be the XYH-coordinates of the points, and the latest geoid model will be used to determine the XYZ-coordinates when necessary. In this way the 3D coordinates of the points will always be
derived from the most recent and presumed best model available. This also facilitates the implementation of any future changes to the geoid models available for the CERN site.

For the points related to the CERN accelerator complexes, the geoid model corresponding to the plane of the LHC accelerator will be used. For points above ground e.g. points of the geodetic reference network, the geoid model at the ground surface will be the model used. The geoid model in each case will be used for the determination of the XYZ-coordinates from XYH-coordinates, and for the correct orientation of any Local Astronomical reference systems required.

5. CONCLUSIONS

For the installation and alignment of the CNGS beam line components, a new more precise geoid model over the CERN site has been determined, and will be used as the vertical geodetic datum. The new geoid model, CG2000, has also been integrated into a new programming library, SurveyLib, which will be used in the group’s software wherever this functionality is required.

SurveyLib, and in particular the new geoid model have been integrated into a new version of the general compensation program (LGC++) used extensively by the Survey Group. All calculations will therefore now use this new geoid model to convert the measured heights into Z-coordinates in the CCS.

With these tools in place, the Survey Group will be well prepared for the installation of the CNGS, the LHC, and to adapt the system to meet any future requirements.

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REFERENCES


