GEODETIC PARAMETERISATION
OF THE
CNGS PROJECT

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1. ABSTRACT

The CNGS (CERN Neutrinos to Gran Sasso) project 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.

For the CNGS project it is evident that our knowledge of the relative position of the two Laboratories, indeed the relative position of the neutrino target at CERN and the detector at Gran Sasso, is essential. Up until the CNGS Project the position of the CERN accelerators on a global scale has not been critical. Two GPS campaigns carried out in 1998, have now resolved this question to a high degree of accuracy, and a GPS survey campaign at Gran Sasso has provided us with the relative position.

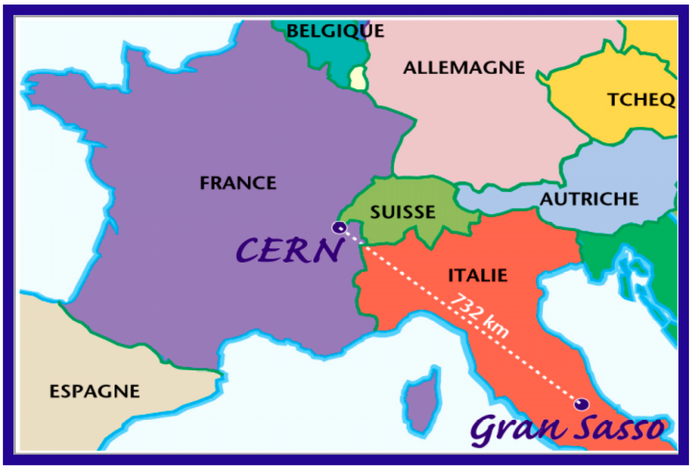

Fig. 1 Scale of the CNGS Project

The parameters for the civil engineering work that started in September 2000 are all based upon the information from these two GPS campaigns. However, consultation with the national surveying bodies in France (IGN) and Switzerland (OFT) showed that the geoid model used for the LEP 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). The parameters establishing the position of the CERN Laboratory together with those of the CNGS beam line have now been refined again. This new geoid model is currently being incorporated into our various algorithms.

2. BACKGROUND

The CNGS project [1] will produce a beam of muon-type neutrinos and direct it underground to their destination, the Gran Sasso National Laboratory (LNGS) in Italy, 730 km from CERN. Once the absolute positions of the origin (CERN Target) and target (CNGS Detector) have been determined in a common reference frame the geometric parameters (azimuth and slope) of the vector between the two may be determined.

The Gran Sasso Laboratories consists of three underground experiment halls located next to the Gran Sasso Tunnel under 1400 m of rock (Fig. 2). During the LNGS design phase in 1979, these three underground caverns were oriented towards Geneva with possible future neutrino beams in mind.

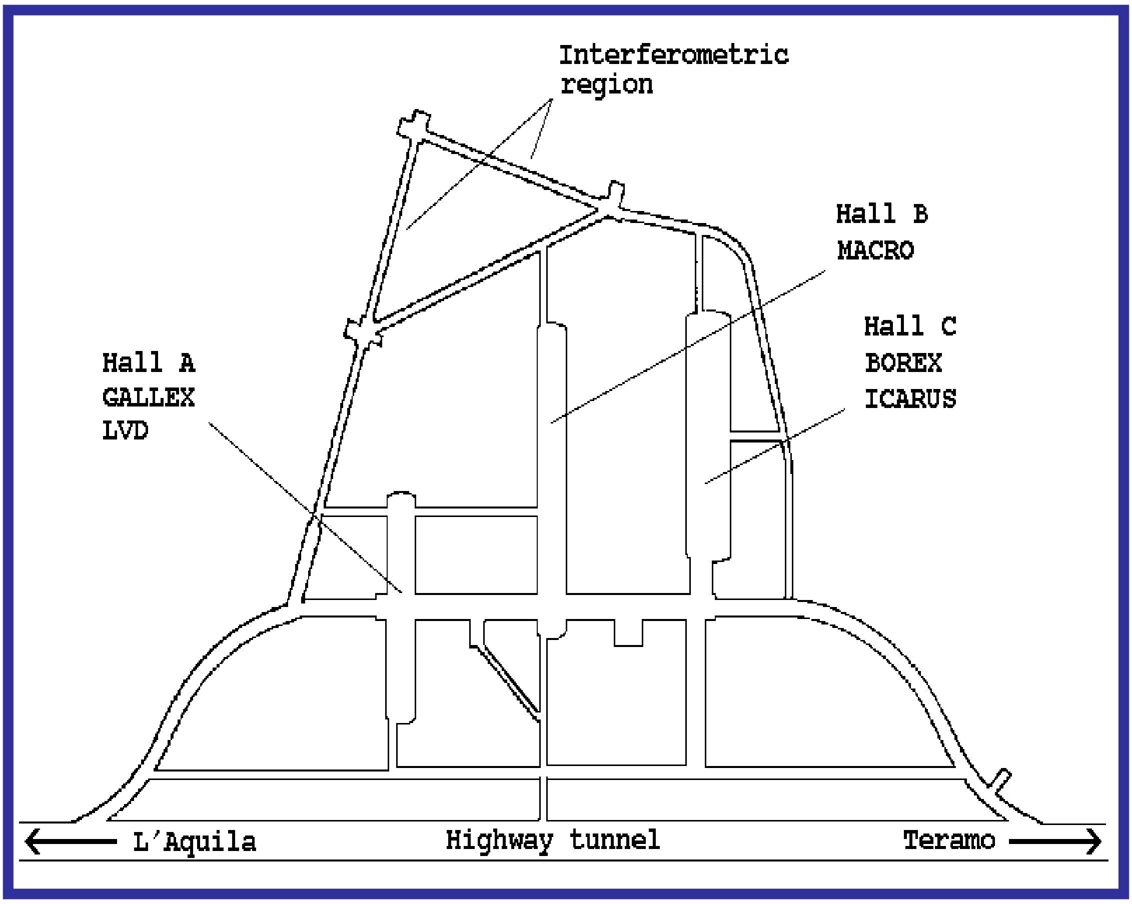

Fig. 2 Layout of the LNGS underground facilities

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. 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 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.

The calculations, for the determination of the CNGS beam line, have been refined a number of times. For each successive refinement either the relative position of the CERN target and the Gran Sasso detector was better determined, the precision of the algorithm to determine the beam line parameters improved, or the model of the geoid changed.

The preliminary data for the calculations were either coarse geodetic coordinates (latitude and longitude) interpolated from cartographic maps or, more precisely, issued from transformations between national and global systems. These ellipsoidal data were transformed into isometric coordinates on a sphere, in order to solve the `position' triangle by the means of spherical trigonometry.

Using more precise coordinates for the Gran Sasso detector (determined during a survey of the site in December 1989 [2]), the geodetic parameters for the beam line were refined and verified in calculations based upon the geodesic on the ellipsoid using Bessel’s and Sodano’s formulae. Subsequent optimizations of the determination of the geodetic parameters of the CNGS beam line were carried out in 3-dimensions as detailed below.

3. DETERMINATION OF THE GLOBAL POSITION OF CERN AND LNGS

In order to determine the absolute and relative position of the CERN target and the CNGS detector, three GPS campaigns were carried out. It was determined that the precision in the relative position between the two points in question was required to a precision of a few metres.

3.1 Secondary Network Measurement at CERN

In March 1998 a GPS campaign to measure 19 points across the CERN site (Fig 3) was commissioned. (One of these points was a reference point of the French geodetic network.) This campaign was primarily intended to update the positions of a number of geodetic pillars in the CERN surface network and to add a number of new geodetic pillars necessary to provide control for the civil engineering works of the LHC Project. Two of the new pillars also serve as control for the CNGS civil engineering.

This campaign was the first major re-determination of the CERN geodetic surface network since the network was measured using the Terrameter in the period leading up to the construction of the LEP tunnel. It was also the first concerted use of GPS on the CERN site since trials were carried out with an early GPS system in 1972. The specified planimetric precision for the GPS campaign was ±5 mm, the precision in height was to be good enough to assure the planimetric accuracy. The entire network of points was measured on two successive days in order to provide additional control of the measurements.

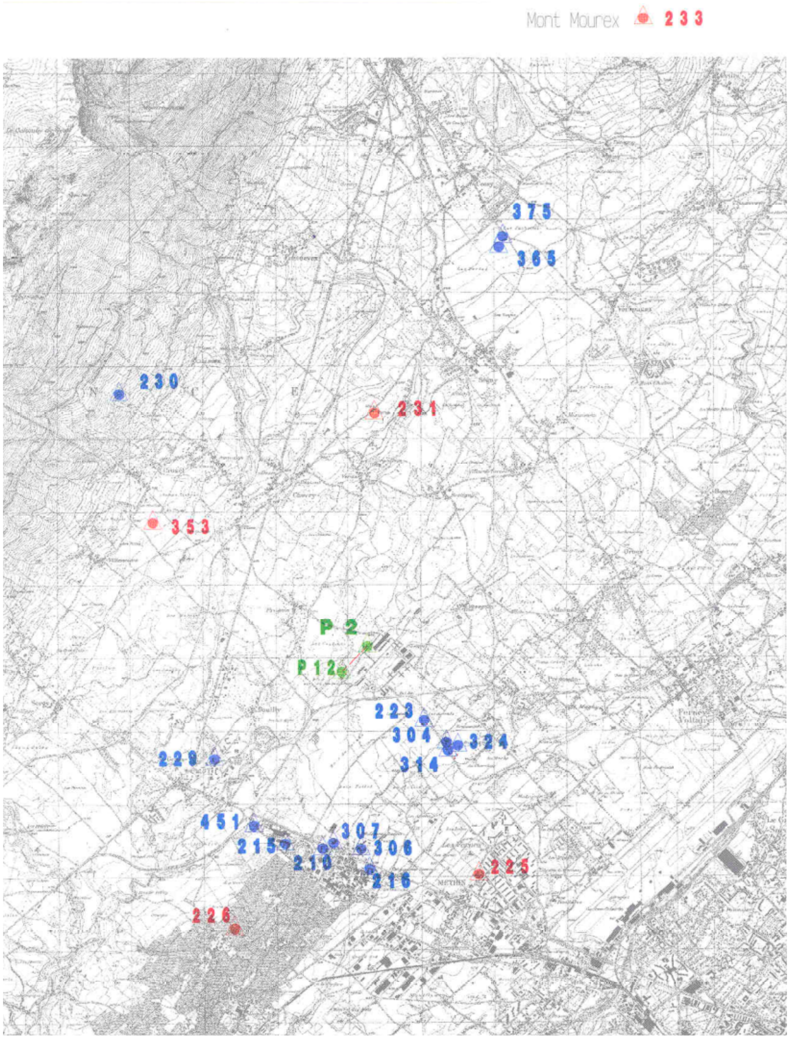

Fig. 3 CERN geodetic pillars measured by GPS

3.2 Network Measurements at Gran Sasso Laboratory

At the same time as the CERN GPS campaign, two points, one at each end of the Gran Sasso Tunnel, were measured, again by GPS. This campaign was undertaken in collaboration with the Facoltà di Ingegneria at the Università di Roma "La Sapienza".

It was intended to carry out a local survey linking these two GPS control points, at the same tying in the location of the CNGS detector. This survey has not been possible since the tunnel providing access to the detector hall is also used by road traffic. Permission to close the tunnel during the period of the survey could not be obtained. Instead the determination of the geodetic parameters has had to rely upon a site survey of the LNGS carried out in 1989 [2]. The GPS measurements have nonetheless been used to control the transformation of the site survey coordinates into the WGS84 reference system.

3.3 Primary Network Measurement at CERN

In August 1998 a second GPS campaign on the CERN site was commissioned. This second campaign involved the measurement of 5 geodetic pillars of the surface network. These five points were all included in the initial campaign in March, and are now referred to as the primary network points. The remaining 13 CERN geodetic pillars of the March campaign are now referred to as the secondary network points.

This second campaign of measurements was timed to coincide with a complete re-measurement of the Swiss geodetic network by GPS. Exactly the same GPS receivers as those employed by the Swiss Office Fédéral de Topographie (OFT, Bern) were used, in order to eliminate antenna offset errors. The measurement data obtained by CERN was processed independently and also as part of the final calculation of the Swiss geodetic network. For this campaign all 5 points were measured at the same time, continuously, for a period of 12 hours. The final calculation by the OFT [3] has indicated a planimetric precision of ~3 mm at 1 sigma for all these points and a height precision of ~6.5 mm.

3.4 First 3-D calculation of the Geodetic Parameters

Following the first of the GPS campaigns described above, the geodetic parameters of the beam line were determined in 3-dimensions for the first time.

The reference frame used at CERN to describe the position and orientation of all the geodetically aligned elements, of all the accelerators, is a 3-D Euclidean reference frame referred to as the CERN Coordinate System (CCS). The CCS was first established for the Proton Synchrotron (PS), the first CERN accelerator, in the late 1950s. The CCS is a modified local astronomical system [4]: 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; and the Y-axis of the system at P0 has an azimuth fixed by other geodetic pillars positioned around the PS.

A geodetic reference frame has also been implicitly defined at CERN (referred to as the CERN geodetic reference frame, or CGRF), although until the CNGS project it was not often used explicitly. 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 coincident with the Z-axis of the CCS.

Using the coordinates last determined for the geodetic reference surface network in 1986, and the coordinates for the same points as determined by GPS, a Helmert transformation program established a new set of coordinates for the surface network pillars. The adaptation between the two

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systems also provided the parameters of the transformation between the WGS84 reference system and the CGRF, the geocentric datum parameters of the CERN horizontal geodetic datum.

Mattia Crespi, working at the Facoltà di Ingegneria at the Università di Roma "La Sapienza", determined and provided the transformation parameters between the Italian geodetic reference frame (Gauss Boaga) and the WGS84. Using these parameters, the coordinates of the CNGS detector were transformed into the WGS84 reference system, and from that system into the CGRF and finally the CERN Coordinate System.

3.5 First update of the 3-D geodetic parameter calculation

Following completion of the Swiss geodetic network measurements and the calculation of the coordinates of the complete network, the positions of the primary network points were provided, as agreed, in the ITRF97 (ep. 1998.5) reference frame.

The same Helmert transformation program as before determined a new set of coordinates for the primary network points in the CGRF and hence the CCS. The precision of the coordinates resulting from the August 1998 GPS measurements and an analysis of the Helmert transformation results implied that one of the primary network pillars had moved between 1986 and 1998. Reluctantly this point was removed from the transformation calculation. As before the adaptation also provided the parameters of the transformation between the ITRF97 (ep. 1998.5) reference frame and the CGRF.

The secondary network positions were adapted onto the positions of the primary network points. Analysis of the results revealed a near perfect match between the relative positions of the primary network points determined from the March GPS campaign, and those determined from the August GPS campaign.

Again the Università di Roma "La Sapienza" provided coordinates for the CNGS detector in the ITRF97 (ep. 1998.5) reference frame, and these were transformed into the CCS to enable a refined set of geodetic parameters to be determined.

4. RE-EVALUATION OF THE VERTICAL DATUM

The determination of the global position of CERN and LNGS enabled us to refine the geodetic parameters of the CNGS beam line, however the alignment of the beam line components at CERN will depend upon the vertical reference surface for the levelling measurements, i.e. the equipotential surface of the Earth's gravity field at mean sea level, the geoid.

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 [5]. 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 P0, and is now referred to as CERN Geoid 1985 (CG1985).

4.1 Comparison of Geoid Models

Although concerns about the orientation and precision of the CG1985 were largely answered when the GPS campaigns of 1998 enabled the geocentric set of datum position parameters of the CERN horizontal geodetic datum to be established, there remained some questions. A collaboration, with the Laboratoire de Recherche en Géodésie (LAREG, Paris) and the OFT, to review the different geoid models in Europe that covered the CERN site, revealed that there were some significant discrepancies between them [6]. Significant differences were also evident between the latest geoid model for Switzerland CHGEO98 and the previous model CHGEO78 (Fig. 5 and Fig. 6), and it was this latter geoid model that formed the basis for the CERN geoid model of 1985.

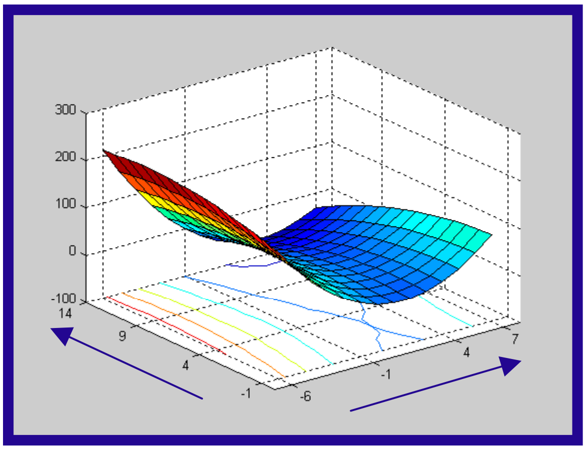

Fig. 4 The CG1985 Geoid Model

After discussion it appeared likely that the geoid model CHGEO98 was likely to be the most precise of all those 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.

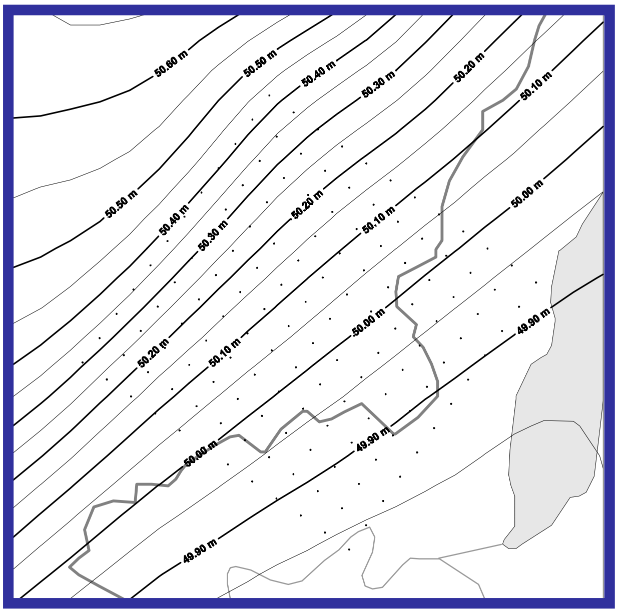

Fig. 5 Geoid CHGEO98 in ETRF89 (RPN)

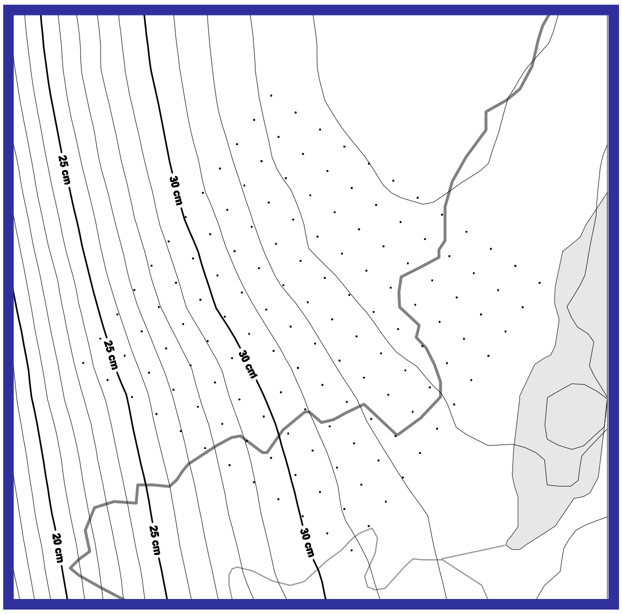

Fig. 6 Geoid differences: GURTNER78 minus CHGEO98

4.2 Transformation of CHGEO98 into the CERN reference system

The geoid model of 1985 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, 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 (the Y-axis of the CCS has an azimuth ~37 gons), in this way the grid would run 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 coordinates of the grid points at each intersection node were transformed into the reference frame used by the CHGEO98 geoid model and the deflection of the vertical values determined at each.

By means of interpolation, the deflection of the vertical values at P0 were calculated. By definition of the CERN reference frames, the deflection of the vertical values at P0 are zero. The computed values at P0 were therefore subtracted from the values provided for each reference grid node point to "normalise" them for the CERN site. This left the possibility of a small translation error, but 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 [7]. 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 (Fig. 7). These changes in undulation were treated as height differences in a network of points in a local Euclidean reference frame, 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.

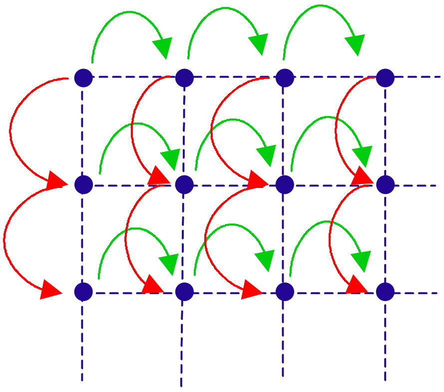

Fig. 7 Determination of differences in Geoidal undulation

4.3 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.

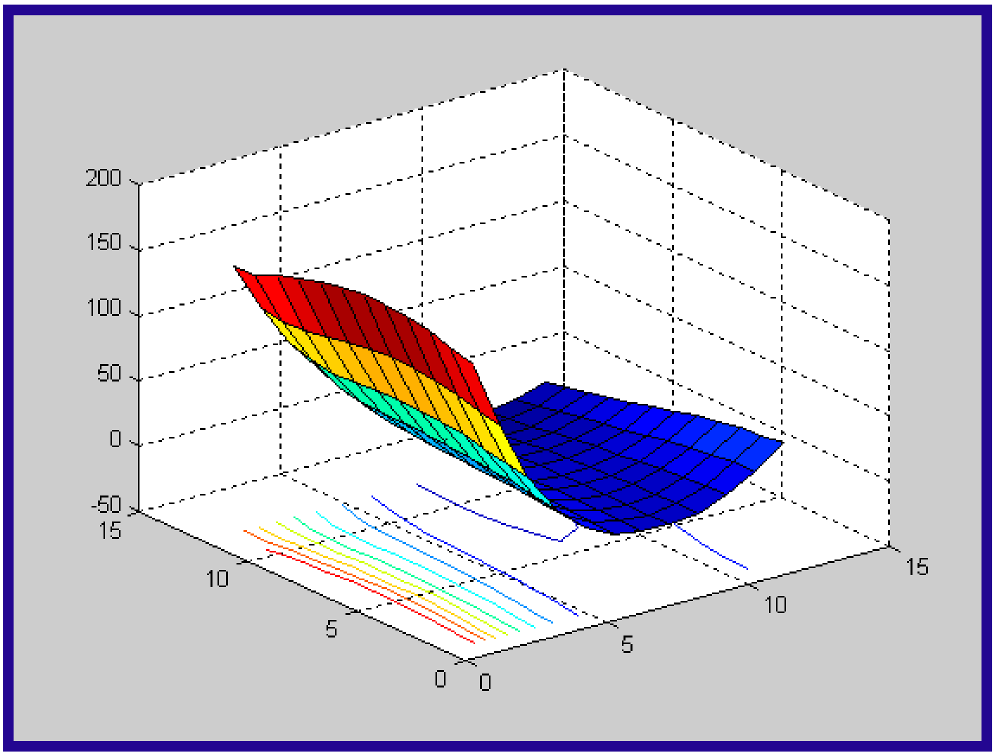

Fig. 8 Undulations of the CERN Geoid 2000 (CG2000)

Although present computational limitations are almost negligible in comparison to 17 years ago, it was decide to try the same approach to keep the model as simple as possible.

4.3.1 Parameteric Models

Building upon the experience gained when the geoid around CERN was first modelled, the first model fitted to the new data was another hyperbolic paraboloid. A least squares approach was again adopted, but the results returned residuals of up to ±40 mm.

Visually analysing a 3D plot of the residuals identified several additional terms that could be added to the model, in order to better fit the geoidal undulations. In total 8 additional terms were added, giving a final surface with some 6th order terms. The residuals resulting from the least squares fit were somewhat reduced (~±20 mm), but it was felt that they were still not good enough in light of the estimated precision of the OFT model from which the geoid undulations were derived. An attempt was also made to introduce a weighting scheme to favour the modelling around the LHC tunnel, but in the end it was also decided that the model was becoming too complex.

The obvious alternative was to keep the full data set of geoid undulation values for each node of the reference grid and to interpolate values as required.

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4.3.2 *Interpolation Models*

Building upon previous experience of one of the authors with geoid models used in the USA (a grid of undulation values was stored and a bi-quadratic interpolation method employed), this same methodology was first assessed.

This interpolation method requires that a 9-point sub-grid, which lies about the point of interest, be identified. If we consider Fig. 9 the first three points along line y1 (columns x1, x2, and x3) are used to define a quadratic curve, and the Newton-Gregory method 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 and y3. The three values that are obtained are then used to define a quadratic curve in the opposite sense and the Newton-Gregory method 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.

The main disadvantage of this method is that in the majority of cases, for any given point, there are 4 different sub-grids of nine points that can be used. To further complicate the situation each of these sub-grids will give a different undulation value for the point of interest. Some tests showed a spread of values between the four solutions ~ 1 mm.

A solution is to use a 16-point sub-grid, which lies about the point of interest. Although the process adopted follows a similar pattern, this time four lines are used parallel to the X-axis and the four derived values combined in the other sense. It is clearly necessary to use a different interpolation method, and we used Catmull-Rom splines [8].

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 the average of the four values that may be determined with the parabolic interpolation method. The only disadvantage was that the reference grid had to be extended in order to provide the same coverage of the CERN site.

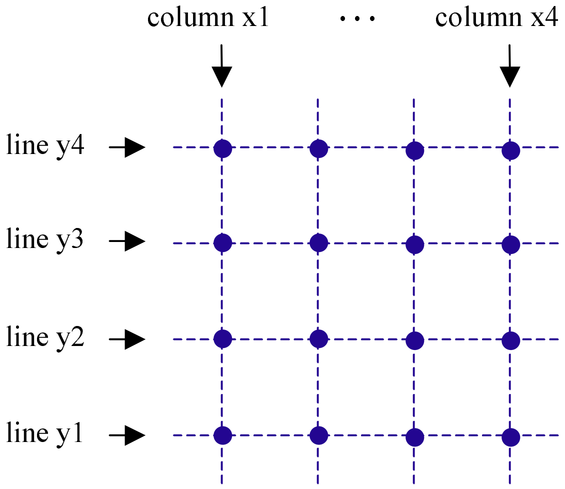

Fig. 9 Reference grid for interpolations

It is this interpolation model that was finally chosen and implemented. This geoid model is now referred to as CG2000. Details of the modelling process may be found in [9].

4.4 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.

Comparisons of CG2000 with CG1985 showed significant differences around the LHC tunnel (Fig. 10). 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. 11), 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. The new geoid will also be used in all geodetic compensation calculations.

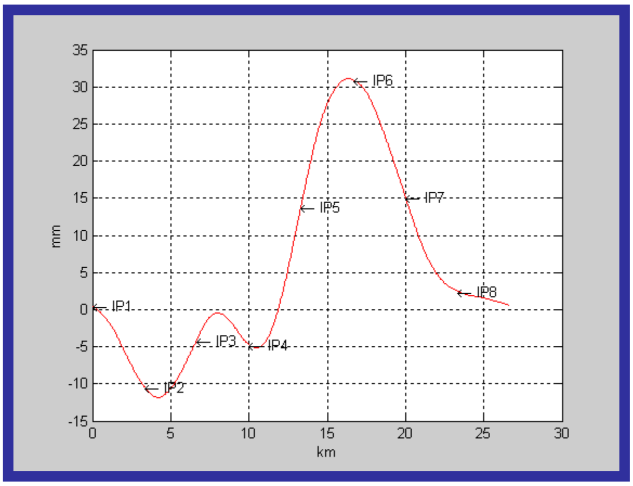

Fig. 10 Difference between CG2000 and CG1985 along the LHC tunnel

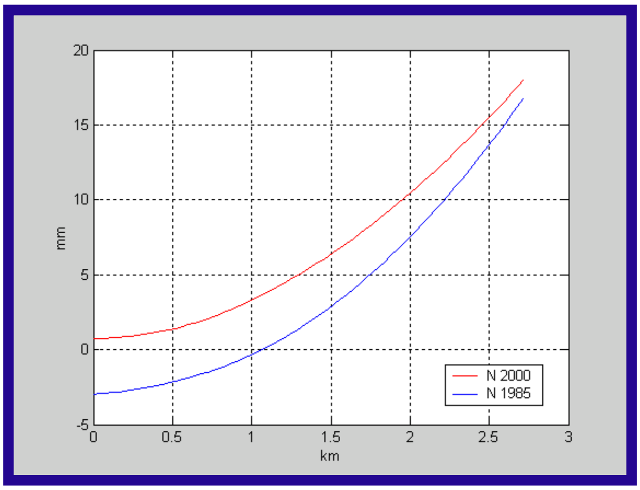

Fig. 11 CG2000 and CG1985 undulations along the CNGS tunnel

4.5 Final update of the 3-D geodetic parameter calculation

As a final refinement of the determination of the geodetic parameters of the CNGS beam line, the new geoid model CG2000 has been used in the conversion of the heights of the primary network points into Z-coordinates in the CERN Coordinate System. This has in turn permitted a refinement

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of the transformation parameters between the ITRF97 (ep. 1985) reference frame and the CGRF, and thereby a new determination of the coordinates of the LNGS detector in the CCS.

The new geodetic parameters for the bearing and slope of the beam line each altered by less than one arc second and a recalculation of the lattice of the CNGS beam line showed that movements were minimal, and that no further design iterations were necessary.

5. CONCLUSIONS

Within the available budget and personnel constraints the Survey Group have undertaken the steps necessary to identify and eliminate as many sources of error as possible in the determination of the geodetic parameters of the CNGS beam line.

The absolute and relative positions of the CERN target (the origin of the beam) and the LNGS detector (the target) have been determined to a high level of precision by GPS. The calculation of the direction in which the beam has to be sent, has been done directly in the CERN Coordinate System, a 3-dimensional system. As such they are calculated directly in the system in which they are used.

Two programs have been developed in order to permit the transformation of point coordinates between the CERN reference frames and projections, and to permit the transformations between the CERN reference frames and other geodetic or geocentric reference frames. The transformation algorithms are currently being integrated into a new programming library, SurveyLib, which will be used in all the group's software wherever this functionality is required.

For the installation and alignment of the 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 SurveyLib.

SurveyLib, and in particular the new geoid model are being integrated into a new version of the general compensation program (LGC++) used extensively by the Survey Group. Once implemented all calculations will used 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.

6. ACKNOWLEDGEMENTS

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