

# THE DISTANCE FROM CERN TO LNGS

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## Abstract

The calculation of the distance from CERN to Gran Sasso involves the combination of three independent sets of measurements: the calculation of the distance between pillars included in the geodetic reference network at CERN and the Lab Nazionale Gran Sasso (LNGS); and the transfer on each site of coordinates, from the geodetic surface network, underground into the tunnel or experiment hall installations.

The transfer of coordinates, from the surface, underground at the two sites was not done as part of the CNGS Project. Initial survey concerns for the project were directed towards the orientation of the beamline from CERN to LNGS to within  $\sim 100$  m. Gyro-theodolite measurements underground were planned at CERN so a transfer would effectively only translate the target point. Given the precision estimated for previous transfers, it was decided not to undertake expensive and time-consuming measurements campaigns for a negligible gain in accuracy. Therefore only GPS measurements at the two sites were carried out.

The Opera results which raised questions about the speed at which neutrinos travelled, increased interest in the calculated distance between the two installations. In spite of the estimated distance precision, two measurement campaigns to establish the link between the surface network and the underground networks were undertaken, together with further GPS measurements. Details of these campaigns, with comparisons to the initial values, and revised estimates of the distance will be given.

## INTRODUCTION

The determination of the distance between CERN and the LNGS laboratory in Italy for the CNGS experiment is obviously not possible using direct geodetic measurements, since both the accelerator at CERN and the experiments at LNGS are underground. (The neutrinos themselves take the direct route! Figure 1).

In fact there have been three parts to the overall distance measurement calculation: a network of measurements to link the benchmarks on the surface at CERN and the geodetic reference points on the SPS and CNGS accelerator elements in the tunnel; an equivalent network of measurements to transfer the coordinates between the surface benchmarks and reference points in the experiment hall at LNGS; and GNSS measurements between benchmarks on the CERN site and at the LNGS Site. These three components then need to be brought together with appropriate transformations into a common reference frame, thereby rendering the calculation of the

distance and the direction the neutrinos needed to follow extremely simple.

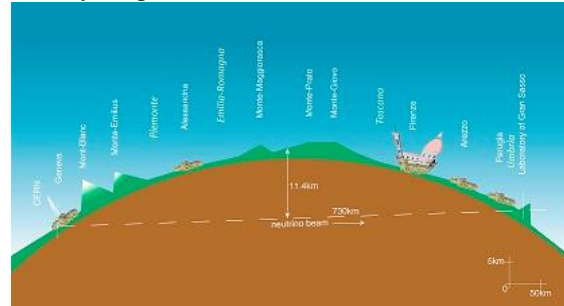


Figure 1 : Schematic profile of the neutrino path

## INITIAL DETERMINATION OF PARAMETERS

The initial parameters for the beamline between the two sites were being established in the late 1990s [1]. In fact parameters were determined 20 years before, and the experimental halls at LNGS were aligned to point at the CERN site!

In collaboration with the Sapienza Università di Roma simultaneous GPS measurements on both the CERN and the LNGS sites were carried out, and a direct link between them was established for the first time. The size of the densest part of the neutrino beam arriving in Gran Sasso was determined to be a cone of  $\sim 100$  m diameter, which corresponded to a required angular precision in the direction of the neutrino beam  $\sim 15$  arc seconds ( $3\sigma$ ). The planimetric precision specified for the GPS campaign on the CERN site was  $\pm 5$  mm, and as a consequence the error in the relative positions of the two sites was considered far less critical than setting the orientation of the beamline. Such changes in the distance would have negligible effect.

Partly for this reason no direct transfer at CERN from surface into the CNGS tunnel was made. For both the SPS tunnel and the LEP tunnel (now the LHC tunnel) the positions of points at the surface had been accurately transferred underground. The SPS is the source of the CNGS beamline, and a connection to the LHC tunnel was also possible to provide control of the alignment. In addition gyro-theodolite measurements were carried out along all the beamlines.

However, it remained vitally important to determine the orientation of the CERN site, and model as accurately as possible the geoid across the site.

The Federal Office of Topography (OFT) integrated a second smaller GPS campaign of CERN geodetic pillars, carried out a few months after the first, into the

calculation of the Swiss Geodetic Network. The planimetric precision of the second campaign was estimated to be just ~3 mm (~6.5 mm in height), and an accurate determination of the transformation between the CERN reference frame and ITRF97 (ep.1998.5) was established. This gave a global position and orientation for the CERN site.

A precise model of the geoid at CERN had been made in the 1980s for the LEP project (CERN Geoid 1985, CG1985). For the CNGS project a collaboration with the Laboratoire de Recherche en Géodésie (LAREG, Paris) and the OFT, led to a review of the geoid models in Europe that covered the area around Geneva. Significant differences were noted, including difference between the latest geoid model for Switzerland CHGEO98 and the previous model CHGEO78. The latter was the basis for CG1985, and it was decided to use CHGEO98 as the basis for a new local geoid model, CG2000. For further details see [1].

The third part of the puzzle, namely the position of the detectors on the LNGS site still needed to be resolved. The only access that would allow a precise survey to be carried out was a road tunnel passing through the mountain in which the underground experiment halls had been excavated. The GPS measurements had been carried out at each end of the tunnel, and the intention had been to traverse between the two. However, in the end, the cost and difficulty of closing the road down for the time required for such a traverse meant that the idea was abandoned.

Instead, the original survey data for the civil engineering, and the design plans for the tunnel and laboratory, were used to determine the coordinates of a few reference points in the experiment halls (the detectors were only installed later). The benchmarks where the GPS measurements were made provided the link between the underground and the surface data. The coordinates of the LNGS reference points were then transformed into the ROMA40 reference frame, from there into the ITRF97 reference frame, and then finally into the CERN Coordinate System (CCS).

This gave both the neutrino source (CERN Target) and the Experiment Hall (LNGS) position in the same reference frame, so the orientation of the CNGS beamline could be determined with sufficient accuracy. The new geoid model also ensured that the vertical reference surface used for the alignment was as accurate as possible too.

Although at the time it was not really part of the alignment problem, the distance between the two sites was calculated to be 730520.3 m with an estimated precision ~1 m.

We now know that neutrinos arrive, and are detected, in Gran Sasso in the expected numbers, so the beamline alignment can be considered to have been successful.

## REDETERMINATION OF THE CERN LNGS DISTANCE

Interest in the distance travelled by the neutrinos between CERN and LNGS was driven by the need to synchronise the timing between the proton bunches used to create the neutrinos, and the neutrinos identified in the OPERA experiment. This synchronisation provides additional proof that the observed neutrinos were created at CERN, and were not merely neutrinos coming from outer space in the same direction. It was also realised that, if the timing system were sufficiently precise, the speed of the neutrinos could be determined, and the timing team pushed the system to provide not just the micro-second synchronisation originally requested but nano-second synchronisation.

The anomalies seen in the synchronisation, equivalent to 15-20 m in the distance, inevitably led to requests to confirm the distance estimated between the two laboratories, and to determine the distance to the reference point of the OPERA experiment.

It was clear that the biggest uncertainty lay in the difference of position between the underground network points at LNGS, and the OPERA reference point. The decision was therefore taken to close part of the road tunnel through the mountain to enable a new determination of the position of the underground experiment hall and the OPERA detectors to be made.

In July 2010 one lane of the road in the tunnel was closed for 5 days and a traverse from one end of the tunnel to the other was carried out using a Leica TS30 total station. The instrument stations were 200-600 m apart and observations between stations and to intermediate targets were integrated into the network design. The traverse included the underground laboratory OPERA experiment hall, and was connected to four benchmarks on the surface, two at each end of the tunnel.

A couple of months later, in September 2010, the benchmarks at each end of the tunnel were measured by GNSS using geodetic class receivers and antennas. The GNSS measurements were processed in the ETRF2000 reference frame, together with 3 stations from the European Permanent Network (EPN). The calculated coordinates of the four measured benchmarks can be seen in Table 1.

Table 1 : The GPS benchmarks estimated coordinates in ETRF2000

Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

The underground traverse was calculated in a local coordinate system, taking into account the geoid undulations which changed by 0.80 m between the two

ends of the tunnel. These results and those of the GNSS measurements were then all brought together in ETRF2000. The differences between the coordinates estimated from the GNSS measurements and those from the traverse were ~40 mm, and the accuracy of the OPERA reference point was estimated to be about 200 mm. This relatively high value was assumed, due to the lack of gyro-theodolite measurements that would otherwise help to control any systematic errors in the total station horizontal angle measurements.

The beamline reference points for the CNGS accelerator, including the target at CERN and the elements used for the timing, were transformed into the ITRF97 reference frame and from there into the ETRF2000 reference frame as well. The precision of these points was estimated to be ~20 mm.

The complete set of point coordinates were then transformed into the OPERA reference system, and the coordinate of the CERN target and the origin of the local system (the principal reference point for the experiment), used to calculate the distance. The coordinates of the CERN Target and the OPERA experiment reference point are given in Table 2.

Table 2 : ETRF2000 positions of the CERN Target and the OPERA experiment reference point

Id.		X (m)	Y (m)	Z (m)
CERN	Target	4394369.327	467747.795	4584236.112
(T.40)				
OPERA	Ref.	4582167.465	1106521.805	4283602.714
Pt. (A1-9999)				

The calculated distance was determined to be 730534.610 m, with an overall accuracy ~200 mm. When compared to the original estimate, the difference of 14.3 m appears to correspond very well with the anomaly seen in the synchronisation. It has however been verified that this difference comes from the difference in the position of the OPERA experiment reference used in 2001 when compared to the point used in 2010 to within 200 mm. Further details of this work may be found in [2].

## ADDITIONAL DISTANCE CONTROLS

In February 2011 a meeting was held at CERN to discuss the estimates of the distance between the two sites, to explore possible sources of error, and to identify possible additional controls that could be made.

The estimated precision in the distance was already high when compared to necessary error of 15-20 m needed to solve the synchronisation anomaly. In the end 4 possibilities were identified: an independent re-calculation of the GNSS and network measurements; additional simultaneous GNSS measurements of benchmarks on the two sites to eliminate any possibility of gross errors in the major component of the distance determination; the addition of gyro-theodolite measurements to the traverse through the road tunnel to

the underground LNGS laboratory to reduce the possibility of systematic errors caused by refraction influencing the distance; and a new transfer of points coordinates, at CERN, from the surface to the CNGS tunnel and elements along the beamline to confirm the position of the beamline and provide an estimate of the precision.

These possibilities were considered to be in order of both increasing difficulty and cost, and the biggest decrease in the uncertainty of the distance was expected to come from the gyro-theodolite measurements in Italy.

## GNSS Measurements

The first step taken was to plan a simultaneous (or nearly simultaneous) measurement of benchmarks and geodetic pillars by GNSS.

Unfortunately the only weekend where this was possible in Italy, where the effect on the road traffic would be minimised, was a bank holiday weekend, and it was not possible to measure points at CERN during the same period.

Although the Geodetic Reference Network of pillars on the surface around the CERN site have existed for many years, until the 1990s it had primarily been measured using traditional triangulation and trilateration techniques. The instrumentation was not always traditional though, and a Terrameter (a two colour EDM providing a precision of 0.1 ppm) was used to establish the network as it was extended for the LEP construction.

The initial GPS campaigns for the LHC/CNGS were carried out and processed by outside companies, and it was not until 2009 that the CERN survey team acquired a GPS system for a research project (a permanent station system and a rover).

In June 2011, two of the original four benchmarks at LNGS were re-measured, and during the following week three of the CERN geodetic pillars were also measured. The permanent station on the CERN site was able to provide a link between all the measurements of the campaign.

These measurements confirmed the previous estimate of the distance to within 30 mm, and the overall distance measurement was confirmed at the same 200 mm level of accuracy.

## Re-Calculation of the GNSS measurements

In order to carry out an independent re-processing of the 2010 and 2011 GNSS measurements for CNGS project a collaboration was set up with the Ecole Supérieure des Géomètres et Topographes. CERN also acquired a licence for the Bernese GPS software in order to be able to better control and analyse the GNSS measurements themselves.

The processing of the GNSS data from both 2010 and 2011 was carried out using Bernese in the ITRF2008 reference system and combined together to provide a single set of point coordinate results. Twelve other permanent stations from the EPN were included in the calculations. The resulting coordinates were subsequently

transformed using Bernese into ETRS89, see Table 3. The differences between the results from different epochs were generally of the order of a few tens of millimetres. One of the benchmark points in Italy showed a movement of several centimetres between the 2010 and 2011 measurements, and one of the geodetic pillars at CERN indicated a larger than expected standard error in the vertical component.

Table 3 : ETRS89 positions of CERN pillars and LNGS benchmarks

Id.	X (m)	Y (m)	Z (m)
CERN	4393400.816	466460.629	4585421.600
P225	4395209.690	467745.772	4583513.219
P306	4395156.089	466102.189	4583756.791
P314	4394058.169	467176.174	4584698.980
GPS1	4579518.831	1108193.525	4285874.160
GPS2	4579537.662	1108238.871	4285843.994
GPS3	4585824.414	1102829.287	4280651.211
GPS4	4585839.714	1102751.487	4280651.181

The point coordinates were best fit onto the actual CCS coordinates of the three geodetic pillars on the CERN site, using a 6-parameters Helmert transformation. The residuals for each point were very small, ~2 mm. The other ETRS89 points were transformed into the CCS at the same time. A similar approach was taken to best fit the LNGS GPS benchmarks calculated in the ETRF2000 system onto the benchmark's coordinates in the CCS. Here the residuals from the Helmert transformation were larger, in the range of 60 – 100 mm. It must be noted that these residuals are much larger than expected.

With the second transformation the coordinates for the current OPERA reference point were determined in the CCS. When considering the distance between the two sites, it is clear that this method of transforming the points into the same reference frame is not the most reliable (since small angular errors become significant), however the distance was calculated to be 730534.535 m, just 75 mm less than the value calculated in [2] and well within the estimated 200 mm accuracy. For the purposes of this control this was considered sufficient.

### Vertical Descent

After some deliberation of the different possibilities it was decided that a connection between the geodetic pillars on the surface and some elements at the start of the CNGS beamline, including the beam current transformer used by the timing team (Figure 2), would be possible.

The idea of an independent survey team carrying out this connection was discussed, but due to the restricted access to the underground areas this was put to one side.

A test of some vertical descent techniques had been carried out at CERN in 2010 by a student from ESGT. This was done, as part of the CLIC research project, down

a 65 m shaft giving access to the LHC. It was the first time such a transfer had been carried out since the construction of the LEP/LHC tunnel, and was something of a re-learning process, since many of the staff from that period had already retired. Although many different techniques had been assessed for the transfer, the test had been carried out using plumb bobs suspended from special plates and forced centring systems, with the weight suspended in a small oil bath, see Figure 3.

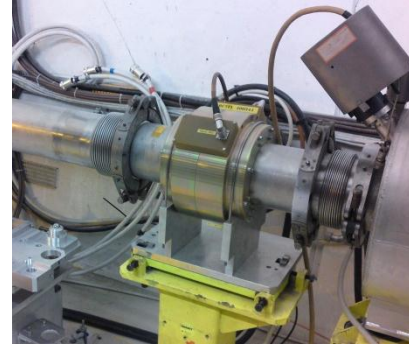


Figure 2 : Primary Beam Current Transformer of the CERN CNGS timing system

At the surface Taylor Hobson balls could be used as targets on the same forced centring points, and underground total station measurements (essentially horizontal directions) were made. Total station measurements from the bottom of the shaft to targets on the forced centring plate at the surface were also tried. The near vertical total station measurements generated a number of problems, and of the two methods the plumb bobs were assessed to have been the most accurate.



Figure 3 : Adapted Taylor Hobson sphere and forced centring plate above the ECA4 shaft

The shaft to be used to gain access to the tunnels of the CNGS beamline dropped down some 50-60 m into one of the old SPS experiment halls. The plumb bob system was again chosen as the principal transfer method, and a zenith optical plummet placed on an xy-translation plate underground provided a second method to assess the differences between these two possibilities. The optical plummet observed targets on the forced centring plate,

and the translation stage was used to bring the instrument and target in line.

After some time spent organising and preparing for the intervention, a number of reference points were installed in the hall at the bottom of the shaft (ECA4), and during a technical stop in April 2012 a traverse was made between the experiment hall and the start of the CNGS beamline. A number of elements were then measured along the beamline, including the principal beam current transformer used by the timing team. It should be noted that this transformer was not equipped with targets so some improvisation was necessary!

Shortly afterwards three geodetic pillars close to the site were measured by GNSS. These were then measured by total station and a small network established to connect these pillars to points installed around the access shaft. Three forced centring plates were installed around the perimeter of the access shaft and targets measured on each plate, prior to their use to make the vertical descent.

Plumb bobs, see Figure 4, were installed on each plate, and the wires observed by a total station, at two different instrument stations in the experiment hall. The reference points that had been added in the hall were also measured. The optical plummet was then installed and aligned with the target at the surface; the instrument replaced by a target and further total station measurements made to connect the plummet location to the reference points.



Figure 4 : Plumb bob suspended from the top of the ECA4 shaft

All the measurements (except the GNSS measurements) were then combined into a calculation using the CERN survey team's general compensation program (LGC), and computed in 3D in the CERN Coordinate System. Although an observation model for the offset to a vertical line exists in LGC it was found that adding fictitious total station observations to constrain the vertical alignment of the surface and underground points provided a more reliable result. The three plumb bobs were used for the transfer and the optical plummet location used as a control. With the difference between the vertical and underground plumb bob points held to  $\sim 0.1$  mm, the difference with respect to the plummet point was  $\sim 0.8$  mm.

Taking independently calculated coordinates for the underground points and the surface points involved in the vertical descent, and performing a best fit using a 6-parameter Helmert transformation gave another indication of the quality of this transfer. For the points of the plumb

bob transfer the range of the residuals was  $0.2 - 0.4$  mm, for the points of the optical plummet transfer the range was  $0.2 - 0.8$  mm. The plumb bob transfer was clearly more accurate. Interestingly introducing a scale factor into the transformation reduced the maximum of the range in both cases by  $\sim 0.2$  mm. Understanding why this might requires further investigation.

As a whole, relative to the surface geodetic pillars, the positions of the elements of the CNGS beamline were found to be within 16 mm of their theoretical planimetric position, although an angle  $\sim 14$  mgrad was evident between the theoretical and determined positions of the beamline elements. The standard error of the estimated coordinates was also of a similar magnitude,  $\sim 12$  mm, and this appears to be directly linked to the relative angular uncertainty between the points established for the transfer from the surface to the underground hall.

Adding an azimuth observation, derived from the original gyro-theodolite observations carried out in the tunnel during the installation of the machine, achieved the desired results of leaving the calculated position of the beamline elements more or less parallel to the theoretical positions, but offset by  $\sim 15$  mm on the opposite side of the beamline to the calculation without the azimuth observation. A side effect of this calculation was to increase the range of the residuals between the points at the surface and those underground to  $0.4 - 1.0$  mm for the plumb bob transfer. Here too there does remain a question regarding the transfer of the orientation from the surface, and some further investigation is necessary to understand this better.

This measurement campaign nonetheless appears to confirm the location of the CNGS beamline elements within the previous overall precision estimate, for this part of the distance determination, of 20 mm.

### *Gyro-Theodolite Measurements*

Despite the greatest potential increase in the estimated precision of the distance measurement coming from a gyro-theodolite traverse through the road tunnel in Gran Sasso, it was unfortunately decided that the cost of such a measurement campaign was too great. The uncertainty in the transfer of the coordinates from the surface into the underground LNGS experiment halls therefore continues to dominate the uncertainty in the overall measurement.

## **OTHER DISTANCE DETERMINATIONS**

With all the interest provoked by the preliminary OPERA results, other experiment collaborations on the LNGS site have also been working to repeat the work of OPERA in order to see if the astonishing results could be repeated. The CERN survey team have provided these collaborations with the same ITRF97 coordinates for the CNGS beamline elements, as input data for their work.

As a group it is understood that these experiments have established a collaboration with Milan University, and have completed a gyro-theodolite traverse through the

Gran Sasso road tunnel. Unfortunately we have not yet seen the results from this measurement campaign.

## **CONCLUSION**

The steps undertaken to determine the distance between the CNGS target at CERN and the OPERA experiment at LNGS have been presented, together with the estimated error in the distance of ~200 mm.

A number of different controls have been carried out to minimise the risk of measurement or computational errors, and these have all shown that the estimated error in the distance is reliable.

This error estimate could be further reduced by including a gyro-theodolite traverse along the LNGS access tunnel, and such a traverse has now been organised by other LNGS experiments.

Combining all the recent measurements would therefore give the best estimate of the distance between the two sites and the precision of that distance. However there is absolutely no evidence of an error in the distance ~15 m, and additional controls of the timing system appear to have identified a fault that would account for the anomaly.

The experience gained here regarding the transfer underground of coordinates determined for points on the surface, has again shown that the transfer by means of a plumb bob is the best method. Some questions still remain to be answered, especially regarding the transfer of the orientation before this technique can be considered to be fully re-mastered.

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