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THE DISTANCE FROM CERN TO LNGS

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Abstract

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Until the Opera results raised questions about the speed at which neutrinos travelled, the main alignment concern for the CNGS beamline had been an orientation problem -to ensure that the beamline arrived to within ~100 m of its target at LNGS. GPS measurements at the two sites, and the use of gyro-theodolite measurements in the tunnel at CERN, ensured that the absolute alignment of the beamline was established to the required accuracy.

New determinations of the links between the surface and the tunnel were not considered necessary until interest grew in the distance between the sites, at which point additional measurement campaigns were organised in order to further reduce the uncertainty in the distance. Details of all these campaigns and the distance estimates will be given.

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INTRODUCTION

Direct geodetic measurements between the accelerator at CERN and the experiments at LNGS are not physically possible. The results from three sets of measurements need to be brought together into a common reference frame, in order to allow the distance to be calculated. (The neutrinos themselves take the direct route! Figure 1).

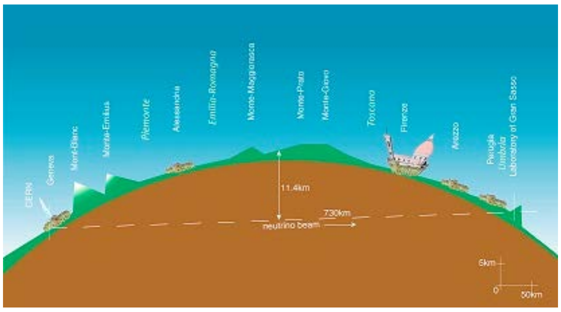

Figure 1 : Schematic profile of the neutrino path

These measurement campaigns provide: a link between the benchmarks on the surface at CERN and the geodetic reference points on the CNGS accelerator elements underground; an equivalent link between the surface benchmarks and reference points in the experiment hall at LNGS; and GPS positions of benchmarks on the CERN site and the LNGS Site in the same reference frame.

INITIAL PARAMETER DETERMINATION

The initial parameters for the beamline between the two sites were being established in the late 1990s [1]. The size of the densest part of the neutrino beam arriving in Gran Sasso was determined to be a cone of ~100 m diameter, 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 -the required angular precision in the direction of the neutrino beam being ~15 arc seconds (3s).

In part for this reason, no new 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, and the alignment in the CNGS tunnel was attached to both these machines. In addition gyro-theodolite measurements were carried out along all the beamlines to provide an absolute reference for the direction.

A GPS measurement campaign of pillars in the surface geodetic reference network at CERN, enabled the global location of the CERN site to be precisely determined. Unfortunately a measurement campaign to completely resolve the third part of the puzzle, namely the position of the detectors on the LNGS site was not possible.

GPS measurements were carried out at each end of the tunnel, however dedicated access to the road tunnel, and the experiment halls, was not possible. 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 GPS measurements did enable the coordinates of the LNGS reference points to be transformed into the CERN Coordinate System (CCS) and the distance between the two sites was calculated to be 730520.3 m with an estimated precision ~1 m.

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 arrival of the neutrinos identified in the OPERA experiment. The anomalies seen in the synchronisation, equivalent to 15-20 m in the distance, inevitably led to requests to confirm 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.

This measurement campaign was carried out in July 2010 during a 5 day period. A couple of months later, in September 2010, the benchmarks at each end of the tunnel were measured by GPS using geodetic class receivers and antennas. By bringing these two measurement campaigns together, it was possible to estimate the accuracy of the position of the OPERA reference point. A relatively high value for the accuracy was asserted (~200 mm), due to the lack of gyro-theodolite measurements that would otherwise have 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 (estimated precision ~20 mm), were 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 1.

Table **1** : Coordinates of the CERN Target and the OPERA experiment reference point

Id.	X (m)	Y (m)	Z (m)
CERN Target (T.40)	3177.974	729297.439	-42378.794
OPERA Ref. Pt. (A1-9999)	0.000	0.000	0.000

The calculated distance was determined to be 730534.610 m, with an overall accuracy estimate ~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 a change in the position of the OPERA experiment reference point 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

Following the measurement campaigns in 2010 the estimated precision in the distance was already high when compared to an error of 15-20 m needed to solve the synchronisation anomaly. Following a number of discussions, 4 possible additional controls of the distance were identified: an independent re-calculation of the GPS and network measurements; additional simultaneous GPS measurements of benchmarks on the two sites to eliminate any possibility of gross errors in the major component of the distance determination; a new transfer of points coordinates, from the surface to elements along the CNGS beamline at CERN, to confirm the position of the beamline timing elements and provide an estimate of the precision; and 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.

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.

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

An independent re-processing of the 2010 and 2011 GPS measurements for the CNGS project was undertaken in collaboration with the Ecole Supérieure des Géomètres et Topographes.

The GPS data processing was carried out using the Bernese [3] software in the ITRF2008 reference system and combined together to provide a single set of point coordinate results. Twelve other stations from the European Permanent Network (EPN) were included in the calculations. The differences between the results from different epochs were generally of the order of a few tens of millimetres.

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. This provided the coordinates for the all points in the CCS. A similar approach was taken to best fit the LNGS GPS benchmarks onto the benchmark's coordinates in the CCS. Here the residuals from the Helmert transformation were larger than expected, in the range of 60 – 100 mm.

After the second transformation, the coordinates for the current OPERA reference point were also available 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 from the coordinates in Table 1, and well within the estimated 200 mm accuracy.

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.

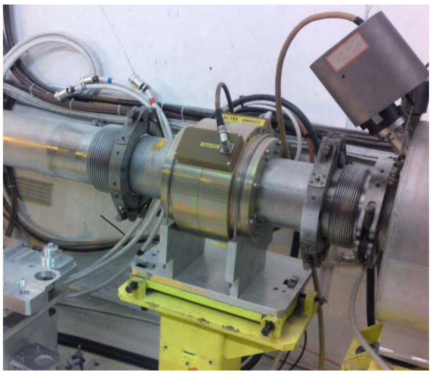

Figure 2 : Primary Beam Current Transformer of the CERN CNGS timing system

The access shaft (ECA4) was used to gain access to the tunnels of the CNGS beamline. This shaft dropped down some 50-60 m into one of the old SPS experiment halls. A plumb bob system was chosen as the principal planimetric coordinate transfer method, and a zenith optical plummet provided a second control method.

In April 2012 survey measurements established a link between reference points in the experiment hall (ECX4), at the bottom of the shaft, and the start of the CNGS beamline. Shortly afterwards three geodetic pillars close to the site were measured by GPS, and a small survey network established, and measured, to connect these pillars to points installed around the access shaft. Plumb bobs were installed on forced centring plates, Figure 3, and the wires were observed by a total station, at two different instrument stations in the experiment hall.

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

The survey measurements were then combined into a 3D calculation using the CERN survey team's general compensation program (LGC). When the differences between the vertical and underground plumb bob points were held to ~0.1 mm, the difference with respect to the plummet point was found to be ~0.8 mm.

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. An angle ~14 mgrad was evident between the theoretical and determined positions of the beamline elements. Adding an azimuth observation, derived from the original gyro-theodolite observations carried out during the installation of the machine, resolved this orientation problem, with no significant effect on the magnitude of the difference between the theoretical and measured beamline element positions.

Without the gyro-theodolite observation, the standard error of the estimated coordinates was ~12 mm, and this was shown to be directly linked to the relative angular uncertainty between the points established for the transfer from the surface to the underground hall.

This measurement campaign appears to confirm the location of the CNGS beamline elements, at least 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 this part of the distance determination therefore continues to dominate the uncertainty in the overall measurement.

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 updated estimated error in the distance of ~200 mm. A more detailed account of this work is given in [4].

A number of different controls have been carried out to minimise the risk of measurement or computational errors, and confirmed the estimated error in the distance.

The uncertainty in the distance could be further reduced by including a gyro-theodolite traverse along the LNGS access tunnel. It is understood that another LNGS experiment has apparently made such measurements, although these were not available for this work.

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