Estimating the Baseline between CERN Target and LNGS Reference Points

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Abstract: This work is part of the European Organization for Nuclear Research (CERN) Neutrinos to Gran Sasso (CNGS) Project, aimed at estimating the velocity of neutrino beams directed from CERN in Geneva toward the Gran Sasso National Laboratory (LNGS) in Assergi, Italy. In particular, the distance has to be estimated between the Large Volume Detector, Icarus, and Borexino reference points, located inside LNGS, and the CERN laboratory target. All the points at LNGS and CERN are placed in underground laboratories. Traditional surveying methods must then be applied for connecting the reference points to benchmarks established outside the underground laboratories in the open field. In this way, the two local LNGS and CERN geodetic networks can be connected by the Global Navigation Satellite System (GNSS) technique. The CERN target was already estimated with respect to a local GNSS network in the International Terrestrial Reference Frame 97. To estimate the position of LNGS points, a new local GNSS network has been materialized. This network integrates with an underground topographic network that connects the reference points in the laboratories. The distance between CERN and LNGS is approximately 730 km, and the required accuracy is better than 0.1 m. Therefore, GNSS processing and underground surveys must be performed according to high-precision standards. This paper describes the performed operations and the obtained results. **DOI: 10.1061/(ASCE)SU.1943-5428.0000173.**

Author keywords: GNSS permanent network; Geodetic survey; Network adjustment.

Introduction

This work is part of the European Organization for Nuclear Research (CERN) Neutrinos to Gran Sasso (CNGS) Project (Alvarez Sanchez et al. 2012; Antonello et al. 2012), which is aimed at observing, for the first time and in a direct way, neutrino oscillations. In particular, in the CERN laboratory, a beam of muon neutrinos is generated by collision of protons accelerated toward a graphite target (named the target point or TT41_T_40S). The generated beam is directed to the Gran Sasso National Laboratory (LNGS), where neutrinos are observed by the instruments of the experiments, named Large Volume Detector (LVD) (Agafonova et al. 2012), Icarus, and Borexino. Therefore, the distances from the CERN graphite target to the LVD, Icarus, and Borexino reference points have to be estimated. The LNGS and CERN laboratories are approximately 730 km apart, and the distances between the points must be estimated with at least decimeter accuracy, which in time units is equal to approximately 0.3 ns. Global Navigation Satellite System (GNSS) techniques can achieve these accuracies. It is obvious that the network must be designed properly, the sessions must last long enough, and the data must be processed according to scientific standards. In fact, the GNSS processing of baselines, and the adjustment of local and regional networks, has been the subject of much research in recent decades, and many scientific papers have proven that accuracies better than 1 cm at the regional scale can be reached (Rothacher et al. 1998; Adam et al. 1999; Mao et al. 1999; Becker et al. 2001; Barzaghi et al. 2004; Williams et al. 2004; Ray et al. 2008; Amiri-Simkooei 2009; Dach et al. 2009).

Because the reference points at CERN and LNGS are in underground laboratories, the GNSS survey must be integrated with traditional geodetic methods. The processing and integration of GNSS networks at the local and regional scales is a standard task. The same applies to the combined adjustment of GNSS and traditional geodetic networks, which have been presented in many papers (Barbarella and Gandolfi 2003; Carosio and Reis 1996). However, the required final accuracy and the different spatial scales of the involved networks require proper methodological refinements that must be accounted for to solve possible technical criticalities. Previous surveys were carried out at LNGS (Colosimo et al. 2011), but the required accuracy was approximately 1 m, i.e., 1 order of magnitude greater than the one required in this case. To reach the target, the authors carefully revised the whole surveying procedure and the design of the networks.

The reference point at CERN, the graphite target, was surveyed by CERN geodetic staff (CERN Survey Section, personal communication, 2012). Its coordinates were estimated in a local network that includes GNSS benchmarks and one GNSS permanent station (PS) in International Terrestrial Reference Frame 97 (ITRF97) at epoch 1998.5.

In this paper, the design, survey, and adjustment of a geodetic network at LNGS is described. On the basis of this network, the distances between the CERN target and the reference points located on the LVD, Icarus, and Borexino experiments were estimated. Therefore, the neutrino velocity was computed from the travel time of the beam, which was observed in the experiments at LNGS

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(Alvarez Sanchez et al 2012; Antonello et al. 2012; Agafonova et al. 2012).

The entrance of LNGS is at the sixth kilometer of L'Aquila-Teramo highway tunnel (under the Gran Sasso massif), which has a total length of approximately 11 km and is oriented from southwest to northeast. To estimate the distances between the LNGS points and the CERN targets, the following three operations were needed:

- The LNGS underground points were connected by a geodetic three-dimensional traverse to benchmarks outside the highway tunnel;
- The benchmarks were surveyed, using GNSS techniques, in a local network in the LNGS area; and
- The local GNSS network was adjusted in a regional GNSS network that also includes CERN points.

Therefore, a regional network was established to link the local GNSS networks at CERN and LNGS. It included PSs that belong to the Global International GNSS Service (IGS) Network (igscb.jpl.nasa.gov) (Dow et al. 2009; Kouba 2003), the EUREF Permanent Network (EPN) (Bruyninx et al. 2012; EPN Central Bureau 2015), and the national Italian Positioning Service (ItalPoS) Network, which is operated by Leica Geosystems Italia (Cornegliano Laudense, Italy; ItalPoS 2013). The network was adjusted and aligned with accuracies of a few millimeters to International Terrestrial Reference Frame 2008 (ITRF2008) at epoch 2012.3 (Altamimi et al. 2011). This process is explained in the "Regional Network" section.

Three stations of the regional network were close to the Gran Sasso tunnel. They provided the reference for a local GNSS network, which consisted of six benchmarks, three close to the southwest entrance of the tunnel and three close to the northeast entrance. The benchmark points of this network were monumented by forced centering pillars; 24-h Global Position Satellite (GPS) sessions were surveyed for 3 consecutive days. The local network adjustment is described in the "Local Network at LNGS" section.

Starting from the GPS benchmarks close to the northeast tunnel entrance, a high-precision, geodetic three-dimensional traverse was surveyed to connect the reference points inside LNGS. This traverse was then continued out of the tunnel and connected to the GPS points at the southwest entrance. In this way, the three-dimensional traverse was adjusted by constraining the GPS benchmarks of the local network. Finally, inside LNGS, benchmark points were established to estimate the target points of Borexino, Icarus, and LVD. The "Underground Network," "Data Preprocessing," and "Network Adjustment" sections discusses the underground network survey and adjustment.

Proper transformations were also considered for getting the point coordinates in a unique reference frame, because the CERN point coordinates were in the ITRF97 frame, whereas those surveyed during the LNGS campaign were given, as already mentioned, in ITRF2008. The transformation is discussed in the "Transformation of CERN Coordinates to ITRF2008" section.

GNSS Networks

Regional Network

Strictly speaking, only one baseline is needed to connect CERN and LNGS. However, a regional network of PSs was designed, because a regional network with relatively short baselines provides more accurate and reliable results than a single long baseline does. At first, all IGS PSs within a distance of 700 km were included to align the regional network to the global reference frame (RF). The remaining PSs were chosen to ensure a spatial homogeneous distribution. The network (Fig. 1) included 31 PSs, of which 13 are IGS PSs, 13 are EPN PSs, 3 are ItalPoS PSs, and 2 PSs are close to the laboratories, the CERN PS [named CNGC] and the LNGS PS (named HPTF).

Note that the regional network was composed entirely of PSs that distributed the data through their control centers. The network adjustment was based on 14 daily sessions that corresponded to GPS Weeks 1684 and 1685. The adjustment was performed using *Bernese GPS 5.0* GPS software (Dach et al. 2007) by adopting the procedures discussed by Biagi et al. (2007) and Biagi and Caldera (2011). In particular, the network was aligned to ITRF2008 (April 22, 2012, epoch 2012.3) in the following way:

- The a priori coordinates of the IGS PSs were linearly interpolated by the 52 weekly IGS solutions before the campaign;
- The network was adjusted by imposing a no-net-translation condition with respect to the barycenter of the a priori IGS PS coordinates; and
- The final IGS products, earth orientation parameters (EOPs), ephemerides (EPHs), and phase center variation (PCV), were adopted without further estimation.

The daily sessions were processed according to the following scheme:

1. Acquisition of EOPs, EPHs, and final PCV from IGS;
2. Interpolation of the orbits;
3. Single-station processing of ionospheric free codes, for clock estimation;
4. Definition of the baseline graph by adopting a minimum distance criterion;
5. Identification and estimation of cycle slips;
6. First estimation of the baselines by float ionospheric-free solution (L3);
7. Resolution of the ambiguities using the quasi-ionospheric-free algorithm; and
8. Final multibase network estimations by ionospheric-free ambiguities-resolved observations, estimating one hourly zenithal tropospheric delay and one daily horizontal gradient for each station.

All the quality indicators provided by *Bernese GPS 5.0* output reports denoted good data quality. The statistics of the coordinates' time series were satisfactory, with a root-mean-square (RMS) value typically smaller than 5 mm horizontally and 6 mm high (Table 1). Only two daily height residuals of TERA exceeded 1 cm.

The final coordinates of the stations in ITRF2008 were estimated by combining the 2 weeks of daily solutions using RegNet libraries (Biagi and Caldera 2011).

Local Network at LNGS

Three PSs of the regional network were included in the local LNGS network (Fig. 2): AQUI (EPN), TERA (ItalPoS), and HPTF (the PS of LNGS). Moreover, the local network consisted of the following six benchmarks:

- Three at the Teramo northwest side entrance of the highway tunnel (CER1, CER2, and TERO); and
- Three at the L'Aquila southwest side entrance (ASS1, ASS2, and ASSE).

The six benchmarks of the local network were materialized using forced centering pillars (Fig. 3). They were surveyed continuously from 1600 hrs, April 16, 2012, Day of Year (DOY) 107, GPS Week 1,684, to 2400 hrs, April 19, 2012, DOY 110, with dual-frequency geodetic GPS receivers. To process the data, four sessions were considered: a first session, 8 h long (DOY 107), and three sessions, 24 h long each (DOY 108, 109, and 110).

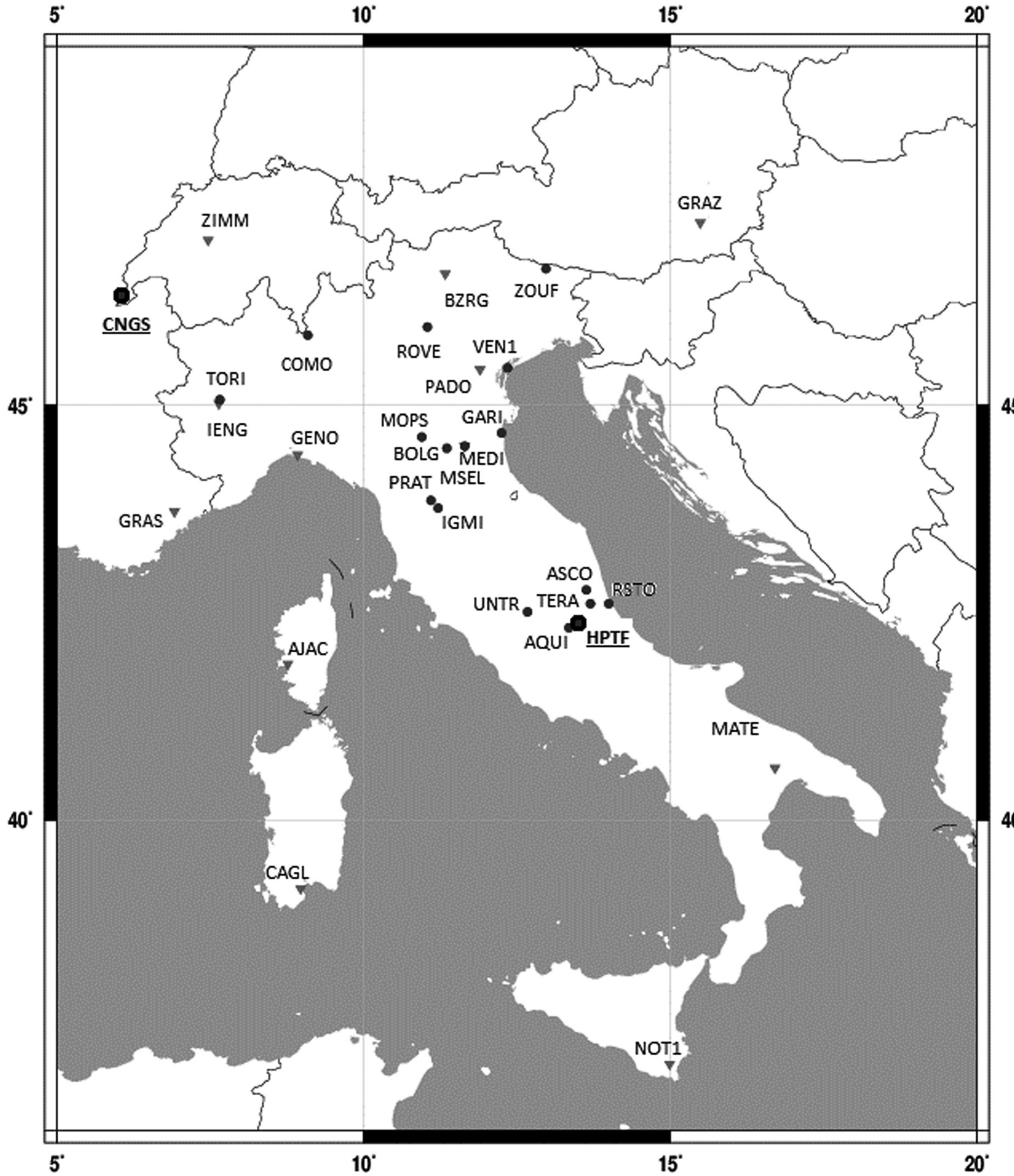

Fig. 1. Regional GNSS network; triangles represent IGS PSs (Note: the network also includes the WTZR PS in Germany, which is outside the figure's boundaries; dots are other PSs; and CNGS and HPTF are marked by black circles with the underlined PS name)

Table 1. Regional Network: Statistics in a Local (East, North, Up) Coordinate System

Statistic	East (mm)	North (mm)	Up (mm)
Mean σ	1.4	1.1	3.1
Maximum σ	4.7	2.0	5.8
Minimum σ	0.4	0.6	1.6
ΔMax	6.7	3.8	18.0

Note: Shown are statistics of the 14 daily coordinates in a local Cartesian coordinate system; σ = standard deviation; ΔMax = maximum discrepancy between daily solutions.

The barycenter of AQUI, HPTF, and TERA was fixed at its estimate provided by the adjustment of the regional network.

In the processing of the GPS data, all the approaches that were described by Dach et al. (2007) were tested. The best results were obtained by adopting the same procedures used to adjust the regional network, with only one difference: because of the local spatial scale of this network, zenith total delays were estimated on a 2-h basis, and no horizontal gradients were estimated.

The final network baseline graph was obtained by comparing different configurations and different criteria, implemented either automatically in *Bernese GPS 5.0* (MIN_DIST and OBS_MAX) or manually. The best results were provided by the graph shown in Fig. 2 and are satisfactory. Their statistics are presented in Table 2.

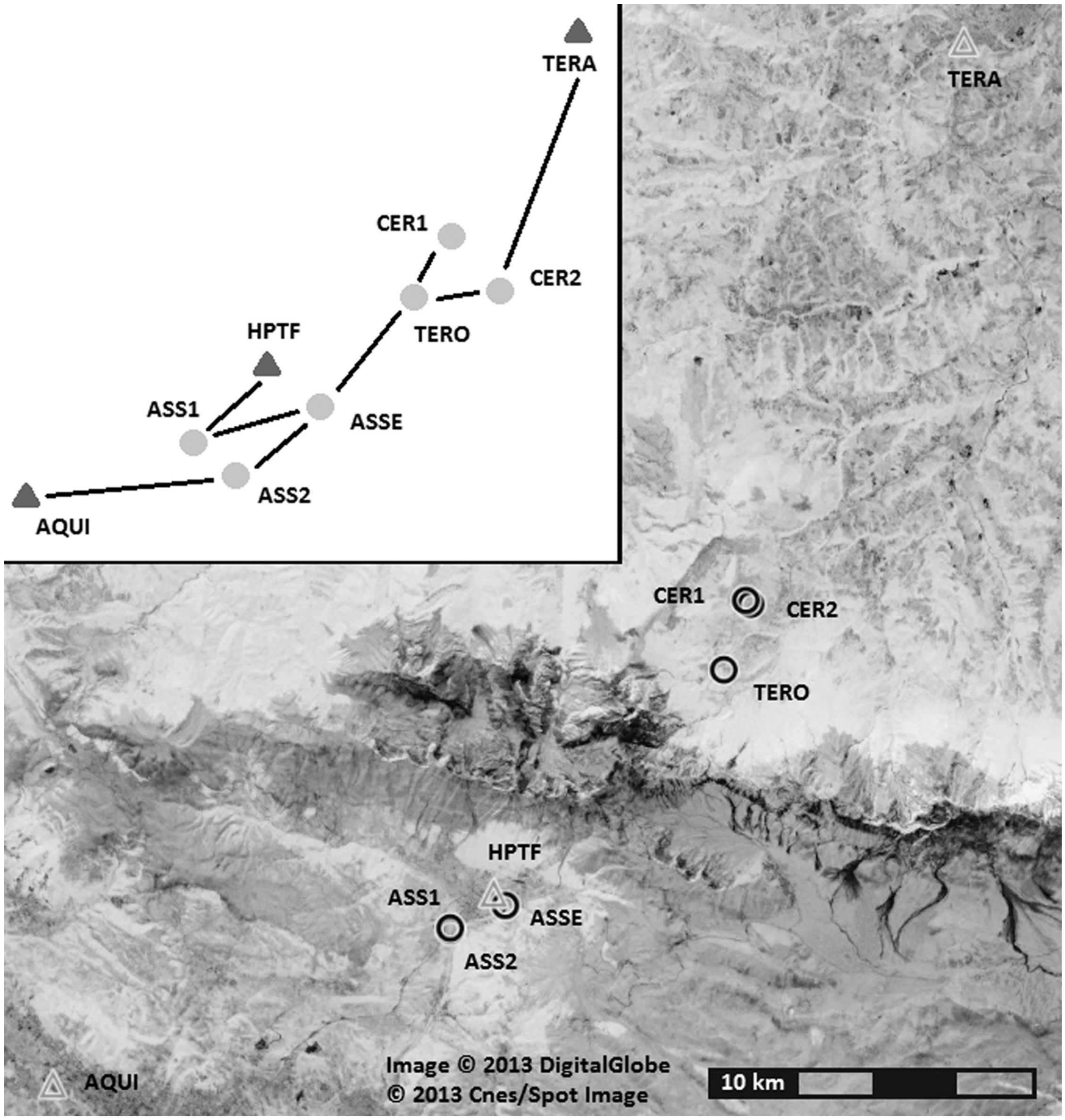

Fig. 2. Local GNSS network near LNGS [Note: triangles and circles represent PSs of the regional network and local forced centering pillars, respectively; baseline graph adopted for *Bernese GPS 5.0* processing is shown in the upper left corner (Image © 2013 DigitalGlobe, © 2013 Cnes/Spot Image)]

Another cross check was performed by comparing the estimates of AQUI, HPTF, and TERA obtained from the regional and local adjustments; the agreement was good (Table 3). In particular, the AQUI differences were less than 1 mm in all the components, whereas TERA and HPTF height differences were approximately 4 mm.

Underground Network

To estimate the coordinates of LVD, Icarus, and Borexino reference points in the LNGS laboratories, a high-precision geodetic network has been designed and materialized.

The first branch of this network (Fig. 4) runs along the Gran Sasso highway tunnel (the A24 highway). It is approximately 11 km long and consists of 53 benchmarks, which are materialized close to the tunnel axis to minimize possible effects caused by the lateral refraction. The starting and final benchmarks are ASSE and TERO, respectively, at the southwest and northeast entrances. ASS1 and ASS2 are the orientation points for ASSE, and CER1 and CER2 are the orientation points for TERO. As described before, they all belong to the local GNSS network. The sectional lengths of the traverse are between 50 and 300 m.

Inside the LNGS laboratories, a closed traverse that connects two benchmarks (2100 and 2300) of the tunnel network was designed (Fig. 5). This traverse consists of 10 benchmarks that have been materialized with topographic nails fixed to the concrete floor with a two-component resin. The traverse closure was obtained through a link along the service tunnel inside LNGS that is parallel to the highway tunnel.

Three benchmarks of this LNGS network (17000, 16000, and 15000) are located at the entrances of Rooms A–C (Fig. 5). These are the starting points that were used to survey the reference points in the LVD, Icarus, and Borexino experiments.

The whole network was surveyed with a Leica (Heerbrugg, Switzerland) TM30 theodolite with an angular accuracy of ±0:15

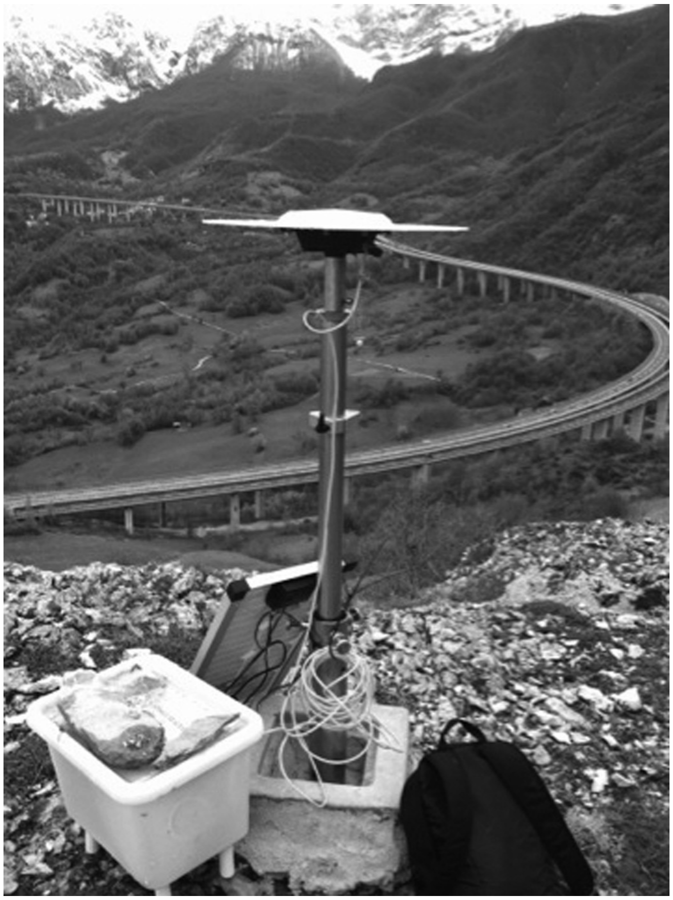

Fig. 3. Forced centering pillar used in the local GPS network survey (image by Livio Pinto)

Table 2. Local GNSS Network: Statistics in a Local (East, North, Up) Coordinate System

PS	σ_{east} (mm)	σ_{north} (mm)	σ_{up} (mm)	σ_{ME} (mm)	σ_{MN} (mm)	σ_{MU} (mm)
ASS1	0.8	0.1	4.1	0.9	0.1	5.0
ASS2	0.4	0.6	3.6	0.5	1.1	4.7
ASSE	0.5	1.0	5.2	0.9	1.6	7.1
CER1	1.8	2.1	5.7	2.4	2.2	8.5
CER2	1.3	1.7	4.7	1.4	2.2	6.8
TERO	1.0	0.7	1.8	1.0	1.0	2.1

Note: Shown are accuracies (σ) and maximum session residuals (ΔM) with respect to the final coordinates (E = east; N = north; U = up). PS = permanent station.

Table 3. Common Stations to Regional and Local GNSS Networks: East, North, and Up Differences between Regional and Local Adjustments

PS	Δeast (mm)	Δnorth (mm)	Δup (mm)
AQUI	0.4	0.2	0.2
TERA	−0.2	−0.7	−4.2
HPTF	−0.3	0.4	3.9

Note: PS = permanent station.

mgon and a distance accuracy of 0.6 mm + 1 ppm. It is a motorized theodolite equipped with an automatic target-recognition (ATR) system for automatic prism collimation. When equipped with prisms, the electronic distance measurements (EDMs) have a range of 3,000 m (Leica Geosystems 2016). Angular and distance observations were carried out in a conjugate mode. The instrumental height on the benchmark points was measured with an accuracy of approximately 2 mm.

Furthermore, in each network point, temperature, pressure, and humidity were recorded using an Oregon Scientific meteo sensor (Tualatin, Oregon). The field corrections (for atmosphere, earth curvature, and deflection of the vertical) were applied as described in the next section.

On the tunnel network points, the measurements were obtained by collimating prisms mounted on tripods that were placed vertically on the benchmarks. To minimize interference with vehicular traffic, the network was surveyed during the nights between May 21 and 25, 2012. This tunnel network was surveyed as a double-traverse (i.e., from each station point, the two backward and two forward points were measured, thus increasing redundancy with respect to a simple traverse design). Each measurement was made in conjugated positions using the ATR system for automatic prism collimation. At the start and end of each day, four common benchmark points were surveyed to link the two subsequent measuring sessions.

Also, at the end of each measuring session, the angular observations of the triangles were checked for misclosure (the misclosure tolerance was set to 3.6 mgon). If a check failed, measurements were repeated. Furthermore, at the starting and ending points of the tunnel, observations of the orientation benchmarks were repeated five times, in conjugated positions, and their means were computed and used in the network adjustment.

After the survey of the tunnel traverse, the survey inside LNGS started (May 21, 2012). Following the same observing scheme adopted in the tunnel, the traverse in Fig. 5 was surveyed, and then, as stated before, three benchmarks were used as starting points for estimating the LVD, Icarus, and Borexino reference points. In Room A, the coordinates of 12 points (numbered from 17051 to 17062) were surveyed from benchmark 17000. They are materialized with markers on the southwest uprights of LVD. In Room B, four points (16051, 16053, 16055, and 16057) placed on the cylinder heads IL4, IL10, IR4, and IR10 of the Icarus experiment were surveyed from Benchmark 16000. For both experiments, these surveyed points enabled the estimation of the reference points to be used in data analysis for neutrino speed estimation. These reference point coordinates were computed on the basis of the surveyed points and the three-dimensional layouts of the Icarus and LVD experiments.

Points in the Borexino experiment could not be surveyed directly from 15000 due to the Borexino experiment position inside Room C. One more traverse was then established and surveyed around the Borexino experiment in Room C, from which 13 points were observed on the beams that hold the instrument case. As for the other two experiments, the Borexino reference point was estimated using these surveyed points and the experiment layouts.

Data Preprocessing

Before adjusting the observations and estimating the coordinates, the measurements were corrected for known environmental biases.

In particular, EDMs were corrected for atmospheric refraction using the following formula (see Leica Geosystems 2011):

$$\Delta D_1 = 286.34 - \left[\frac{0.29525 \cdot P}{(1 + \alpha \cdot T)} - \frac{4.126 \cdot 10^{-4} \cdot h}{(1 + \alpha \cdot T)} \cdot 10^{x}\right]$$

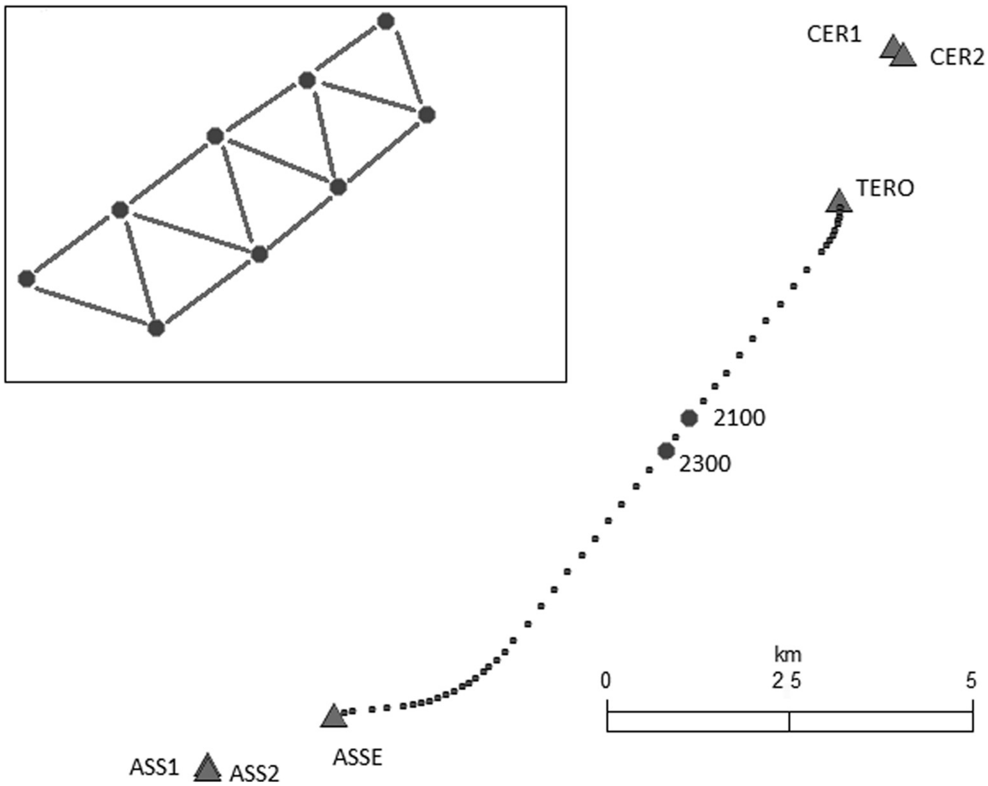

Fig. 4. Highway network points (Note: connection to the local GNSS network and network points inside the LNGS are labeled); (upper left) survey scheme

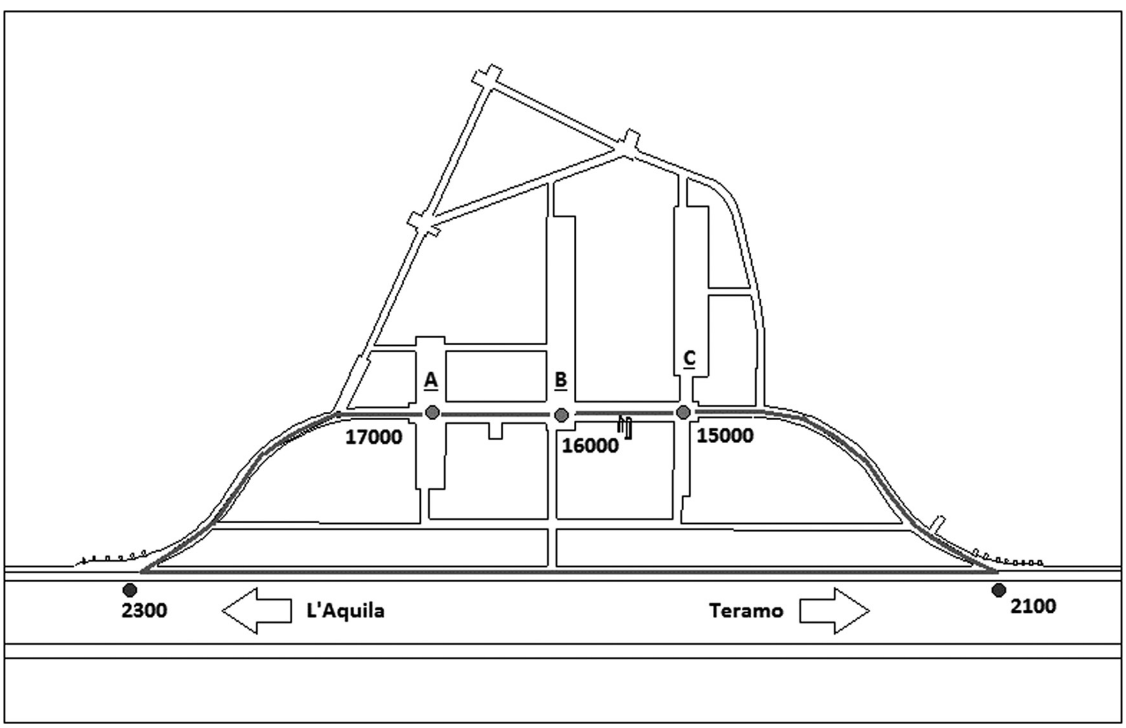

Fig. 5. Details of the LNGS network [Note: closed line passing for points 2100 and 2300 is the closed traverse; points 2300 and 2100 are the connection to the primary highway network; and 17000, 16000, and 15000 are the connections points to Rooms A (LVD), B (Icarus), and C (Borexino)]

where ΔD_1 is atmospheric refraction effect in parts per million; P is pressure in millibars; T is temperature in °C; h is percentage humidity; $\alpha = 1/273.15$; and $x = 0.7857 + 7.5 \cdot T/(237.3 + T)$.

By applying this formula, distance corrections that ranged between 27.4 and 34.5 ppm were obtained, which implies up to 1-cm meteorological correction for the longest section.

The adjustment of the underground network was performed in a local three-dimensional Cartesian frame. This frame has an origin in TERO (the X, Y, and Z axes along the TERO parallel, meridian, and vertical, respectively). The coordinate transformation between this local system and the Cartesian geocentric coordinates of a point P in ITRF2008 is given by the following:

$$\mathbf{x}_{\mathrm{loc}}(P_i) = \mathbf{R}_0[\mathbf{x}_{\mathrm{ITRF08}}(P_i) - \mathbf{x}_0] \tag{1}$$

where $\mathbf{x}_{\mathrm{ITRF08}}(P_i)$ and $\mathbf{x}_{\mathrm{loc}}(P_i)$ are, respectively, the ITRF2008 geocentric and the local Cartesian coordinates of Point P; $\mathbf{x}_0$ are the coordinates of the local origin (TERO) in ITRF2008; and $\mathbf{R}_0$ is a rotation around the local origin:

$$\mathbf{R}_0 = \begin{bmatrix} -\sin\lambda_0 & \cos\lambda_0 & 0 \\ -\sin\varphi_0\cos\lambda_0 & -\sin\varphi_0\sin\lambda_0 & \cos\varphi_0 \\ \cos\varphi_0\cos\lambda_0 & \cos\varphi_0\sin\lambda_0 & \sin\varphi_0 \end{bmatrix} \tag{2}$$

The φ_0 and λ_0 values in Eq. (2) were estimated using the GPS coordinates and the deflection of the vertical of the TERO point (the deflection of the vertical was computed by collocation using the Italian gravity database; Barzaghi et al. 2007).

To reduce the observations to the local three-dimensional frame, the zenithal and azimuthal angles were corrected for the Earth's curvature, the deflection of the vertical, and the atmospheric refraction. These corrections were computed on the basis of the approximate coordinates of the points.

The correction formula for the zenithal angle contains two terms. The first formula is for atmospheric refraction, and the second is for the curvature of the local sphere and the deflection of the vertical (Brovelli and Sansò 1989).

$$TC_\zeta = \left[\frac{kD\mathrm{sen}\zeta}{2R}\right] + \left\{\frac{(x_B - x_A)}{D\mathrm{sen}\zeta}\left[(\eta_A - \eta_B) + \frac{x_A}{R + z_A}\right] + \frac{(y_B - y_A)}{D\mathrm{sen}\zeta}\left[(\xi_A - \xi_B) + \frac{y_A}{R + z_A}\right]\right\}$$

where k is the refraction coefficient; D is the approximate distance; ζ is the zenithal angle; x_A, y_A, z_A, x_B, y_B, and z_B are the approximate coordinates of the extreme of zenithal angle observation; R is the radius of the local sphere; and η_A, η_B, ξ_A, and ξ_B are the meridian and parallel components of the deflection of the vertical at the extreme points of the zenith direction observation.

The effect of the deflection of the vertical in the azimuth observation is similar to that of an error of verticality and can be computed by the following formula (Brovelli and Sansò 1989):

$$TC_\alpha = \frac{(z_B - z_A)}{D^2_{\mathrm{horizontal}}}\left[\frac{x_B - x_A}{R + z_A}\tilde{y}_A + (\xi_A - \xi_B)(x_B - x_A) - \frac{y_B - y_A}{R + z_A}\tilde{x}_A - (\eta_A - \eta_B)(y_B - y_A)\right]$$

The deflections of the vertical were computed using the ITALGEO05 geoid model (Barzaghi et al. 2007). A plot of the deflection of the vertical in the network points is given in Fig. 6 and is basically related to the shape and position of the Gran Sasso massif.

At the Teramo northeast tunnel entrance, the deflection of the vertical is maximum in modulus (approximately 11 mgon) and is in the northeast direction. The maximum values of the derived corrections were 10.7 and 0.2 mgon, respectively, for the zenithal and azimuthal angles; these values are very small because of the almost horizontal visuals.

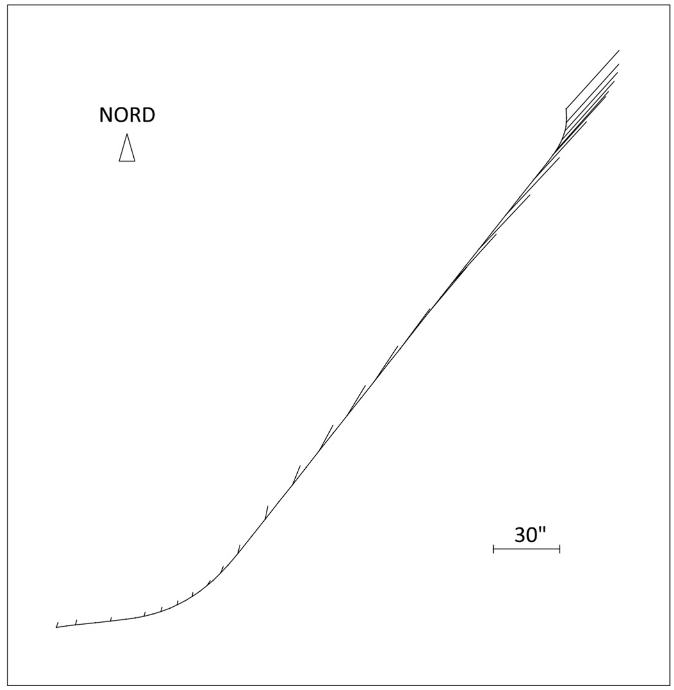

Fig. 6. Deflection of the vertical along the tunnel geodetic network

In computing the atmospheric effect, a constant average value of 0.14 was adopted for the refraction coefficient because it was sufficiently accurate for the whole three-dimensional traverse. The effect of refraction was generally quite small; it reached a value of 0.02 mgon only for the observations at the orientation points in TERO and ASSE. Finally, the effect of the Earth's curvature was evaluated in spherical approximation; its maximum was on the points of the traverse opposite to the origin of the reference system (TERO), namely the southwest orientation points, at which the correction was approximately 2 mgon.

Network Adjustment

CALGE software, developed at Politecnico di Milano (Forlani 1990), was used for the least-squares (LS) adjustment of the underground network.

The LS system consisted of 1,172 linearized equations, 38 of which were pseudo-observations to constrain repeated measurements on the same benchmarks. The system contained 575 unknowns (492 coordinates and 83 orientations). TERO and ASSE were constrained to their three-dimensional coordinates in the local system; furthermore, ASS2 horizontal coordinates (local x and y) were constrained. Thus, a total of eight constrain equations were imposed.

The following accuracies were assigned to the different observation types.

- Azimuthal directions = 0.5 mgon;
- Zenithal directions = 1.0 mgon; and
- Distances = 1 mm + 1 ppm.

As stated earlier, to tie the survey between 2 consecutive days, observations from the last station point were remeasured at the beginning of the subsequent campaign days. In adjusting the network,

Table 4. Underground Network: Statistics of Estimated Standard Deviations

164 Points	East	North	Up
Mean σ (mm)	10.5	15.7	6.93
Maximum σ (mm)	19.4	47.8	34.44

Table 5. Detail Points of LVD, Icarus, and Borexino: Estimated Standard Deviations in ITRF2008

Reference site	Number of points	Mean X σ (mm)	Mean Y σ (mm)	Mean Z σ (mm)
LVD	12	6.7	20.9	10.7
Icarus	4	7.0	21.0	10.8
Borexino	13	8.5	21.0	11.1

a constraint of 2 mm in horizontal coordinates and 1 mm in vertical coordinates was set for these common network points.

The network adjustment provided the coordinates of all the points of the underground network and of those on LVD, Icarus, and Borexino. Table 4 shows the statistics of the adjusted coordinates in the local three-dimensional frame.

The east, north, and up coordinates in the local reference system were then transformed to ITRF2008 (2012.3) using the inverse of Eq. (1). By applying covariance propagation, the covariance matrix of the transformed coordinates was also computed.

$$\mathbf{C}_{P_i,\mathrm{ITRF2008}} = \mathbf{R}_0^t \mathbf{C}_{P_i,\mathrm{loc}} \mathbf{R}_0$$

where $C_{p_i,\mathrm{loc}}$ is the covariance matrix of the points in the local three-dimensional system. The accuracies of the points on the LVD, Icarus, and Borexino experiment, as derived from the least-squares adjustment, are shown in Table 5. As one can see, they fully match the initial requirements.

Transformation of CERN Coordinates to ITRF2008

The distances from LNGS points to the CERN target point must, in the end, be computed. As previously stated, CERN target coordinates were computed in ITRF97 (epoch 1998.5) by the CERN geodetic team. At present, no direct connection can be estimated from the CERN target and the CERN PS. Therefore, to compute the distances properly, the coordinates of the CERN target must be transformed to ITRF2008 (epoch 2012.3), which was done according to the following scheme:

1. Helmert transformation from ITRF97 to ITRF2008 at 1998.5 epoch was applied; and
2. Time propagation in ITRF2008 from epoch 1998.5 to epoch 2012.3 was computed.

In Step 1, the International Earth Rotation and Reference Systems Service official transformation formulas were applied (Boucher and Altamimi 2011). In the latter step, the velocity of the CERN target point was not available, because the CERN PS is not included in the IGS and/or the EPN frames. Consequently, the ITRF velocity of Zimmerwald (ZIMM) was used. Because the ZIMM IGS PS is approximately 130 km away from CERN, its geodynamic motion should be similar to the one of CERN PS and the target points. This is indeed an approximation, but the error induced in the coordinate estimate can be checked.

To verify the transformation precision, the available ETRF93 (epoch 1993.0) CERN PS coordinates (CERN Survey Section, personal communication, 2012) were transformed to ITRF2008 (2012.3) by applying the procedure detailed earlier. They were then compared with the ITRF2008 (2012.3) coordinates estimated in the regional network adjustment. The differences are approximately 1 mm in X, 8 mm in Y, and 25 mm in Z. In the case of these CERN GPS PS coordinates, the time propagation refers to a longer time span (19.3 years) than in the propagation related to the target point (13.8 years). Therefore, it can be concluded that the application of ZIMM velocity is appropriate and should not introduce errors that exceed 30 mm.

The coordinates of the CERN target point in ITRF2008 RF epoch 2012.3, computed according to the discussed transformation procedure, are as follows:

1. $X = 4{,}394{,}368.952$ m;
2. $Y = 467{,}748.181$ m; and
3. $Z = 4{,}584{,}236.410$ m.

Table 6. Computed Distances and Their Standard Deviations

Reference point to CERN target	Distance (m)
LVD (mean point on Line IL10)	730543.426 ± 0.046
Icarus (mean point of Line 10, top floor of the detector)	$730{,}488.225 \pm 0.046$
Borexino (center of the Borexino sphere)	$730{,}472.082 \pm 0.046$

Conclusions

The distances between the reference points of LVD, Icarus, and Borexino in LNGS laboratories and the target point of CERN can be computed as the lengths of the ITRF2008 tridimensional bases (the Sagnac effect was accounted for by the team in charge of the time measurements). Moreover, the accuracies of the derived distances were computed by covariance propagation. For the target, an accuracy of 30 mm is assigned to all the coordinates (CERN Survey Section, personal communication, 2012), which, by error propagation, was conservatively increased to 40 mm to account for reference frame transformation errors. On the basis of the discussion given in this paper, the following estimated distances (and their standard deviations) between the LNGS reference points and the CERN target were obtained [results for other network points are discussed in a technical report by Barzaghi et al. (2013)].

Thus, as shown in Table 6, the precision in the distances is well below the required benchmark value of 1 dm.

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