Determination of the CNGS global geodesy

Gabriele Colosimo
Mattia Crespi
Augusto Mazzoni

Area di Geodesia e Geomatica
Dipartimento di
Ingegneria Civile Edile e Ambientale
Università di Roma La Sapienza

Federica Riguzzi

Istituto Nazionale di Geofisica e Vulcanologia

Mark Jones
Dominique Missiaen

Survey Team
CERN

OPERA public note 132 v3

April 14, 2012

Contents

List of Figures

List of Tables

1 Overview

This paper describes the activities carried out in order to estimate the distance traveled by the neutrinos beam between CERN and LNGS with an accuracy better than 1 meter. In particular, the distance between two fundamental points has been estimated: the start point at CERN (defined as T-40-S-CERN) and the OPERA detector point (defined as A1-9999). The measurements campaings, at CERN and at LNGS, were performed using both terrestrial and Global Positioning System (GPS) based geodetic techniques. The positions of the two fundamental points were estimated in a common reference frame through the processing of the collected observations. The resulting distance (730534.610 m) was estimated with an accuracy at the level of 20 cm, remarkably better than the stated limit.

2 The methodology

The positions of the start point and the detector point were already known from previous surveys, both at CERN and at LNGS, with respect to benchmarks, with an accuracy better than one millimeter.
Therefore, it was necessary to estimate the positions of these benchmarks at CERN and at LNGS (within the OPERA hall) in a common reference frame.
In this context, the most efficient, reliable and accurate geodetic technique to estimate positions in a common reference frame (also considering the distance between CERN and LNGS, approximately equal to 730 Km) is based on Global Positioning System (GPS). Nevertheless, since the benchmarks at CERN and LNGS are located underground, they cannot be directly surveyed by GPS. This is the reason why much more complex geodetic surveys had to be designed and carried out.
Ancillary outdoors benchmarks were surveyed by GPS and their positions were estimated within the common reference frame ETRF2000 (the latest realization of the European reference system), hence proper geodetic surveys based on terrestrial techniques were carried out at CERN and LNGS in order to link the underground benchmarks to the ancillary ones. Finally, it was possible to estimate the positions of the start point and the OPERA detector point in the common reference frame ETRF2000 and compute their 3D distance.
Actually, at CERN, the positions of the benchmarks were already available in an old global reference frame (ITRF97) with an accuracy of 2 cm. On the contrary, at LNGS, it was necessary to design a completely new geodetic network as regards both the outdoors ancillary benchmarks suited for GPS surveys and the underground link to connect the LNGS OPERA hall through the Gran Sasso highways tunnel. (Figure 1).

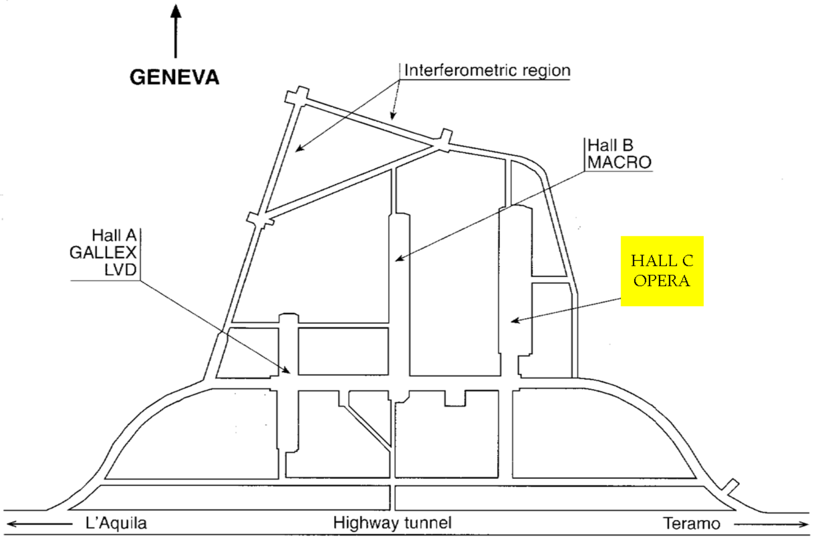

Figure 1: The OPERA hall at LNGS

3 The LNGS new geodetic network

Summarizing, it was mandatory to design and carry out a mixed GPS - terrestrial survey, in order to link the new suited outdoors ancillary GPS benchmarks to the already existing suited benchmarks located in the OPERA hall with a high precision traverse along the highway Gran Sasso tunnel (10.5 Km length).

3.1 The constraints

The survey design was driven by the accuracy, reliability and logistic constraints.
In this last respect, it was not possible to stop the traffic through the tunnel during the underground geodetic surveys; therefore, only the right lane (on the Teramo-L'Aquila direction) was available for five days, due to the lane occupation high daily cost. In this context, strong and fast (on-the-field) internal measurement checks was designed, in order to achieve in a reliable way the requested accuracy in a short time.

3.2 The GPS benchmarks

Two benchmarks close to each entrance of the highway Gran Sasso tunnel were realized with steel nails settled on already existing concrete basements. They were duly located to be surveyed by GPS (outside from highway lines) and to be mutually visible from the very entrance of the tunnel, in order to link and orientate the traverse. Additional benchmarks on the the tunnel wall were realized to strength the inside-outside link.
Four GPS geodetic class receivers - antennas were utilized in the GPS benchmarks surveys. Two sessions 7 hours long (at the sampling rate of 1 second) were carried out on 2 days (Sept. 23-24, 2010).
The collected observations were processed together with observations from 3 permanent stations of the European Permanent Network (UNPG - Perugia, UNTR - Terni, M0SE - ROMA) using the scientific software Bernese v. 5.0 [2] in a differential approach. In particular, the permanent stations coordinates were constrained to their known positions in ETRF2000 (with East, North, Up = 2mm, 2mm, 4mm 1-sigma precision).
The four GPS benchmarks estimated coordinates in ETRF2000 are showed in Table 1

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

Table 1: The GPS benchmarks estimated coordinates in ETRF2000

3.3 The traverse along the Gran Sasso motorway tunnel

An enhanced traverse design was adopted in order to comply with the mentioned logistic constraints (only Teramo-L'Aquila right lane available for five days: July 13-17, 2010) and fulfil the reliability (fast and strong checks during the surveys) and accuracy requirements. The traverse was surveyed from one entrance to the other (passing through the LNGS underground laboratories, including OPERA hall) following a set enhanced pattern (Figure 2) using also two transportable clamps for electronic distance meter (EDM) prism (Figure 3).

In addition, several benchmarks (EDM prism support Figure 4) were materialized on the tunnel and LNGS laboratory walls for eventual survey checks (also with gyro-theodolites, not used in this survey) and possible future additional surveys.

A Leica TS30 motorized total station was used for the traverse survey. Four repetition for each station were performed in double sighting.
The terrestrial observations were processed with the scientific software CALGE (developed at Politecnico di Milano, Italy). A 3D adjustment in a local cartesian coordinate system (LCCS) with origin in one of the GPS benchmarks (GPS1) was carried out, accounting for the geoid undulation which changes regularly but remarkably (about 80 cm) along the tunnel (Figure 5).

A preliminary minimal constraints adjustment was performed in order to detect and remove outliers and to re-weight the observations, estimating their actual 1-sigma precisions (Table 2).

The final adjustment (Table 3) was carried out constraining the four GPS benchmarks with proper precision accounting for the geoid undulation.

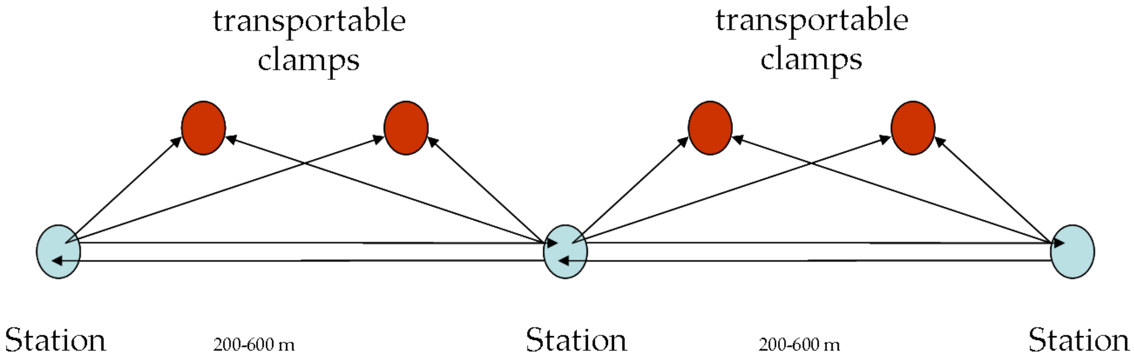

Figure 2: The traverse surveying pattern

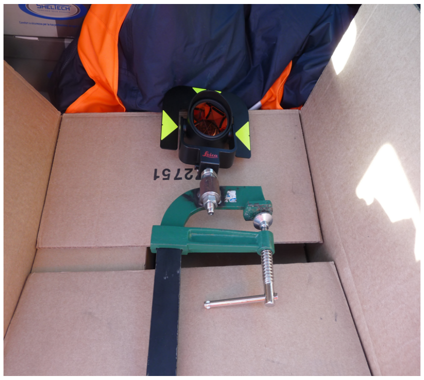

Figure 3: The transportable clamp with prism

Figure 4: Example of additional benchmark materialized on the tunnel wall

OBSERVATION	**POSTERIOR ESTIMATED PRECISION**
HORIZONTAL	5 cc
ZENITH ANGLE	12 cc
DISTANCE	0.6 mm

Table 2: Observations posterior re-weighting analysis results

It has to be underlined that, prior to the final adjustment, the relative positions between the pairs of GPS benchmarks at the opposite entrances of the Gran Sasso tunnel were independently available both from the traverse

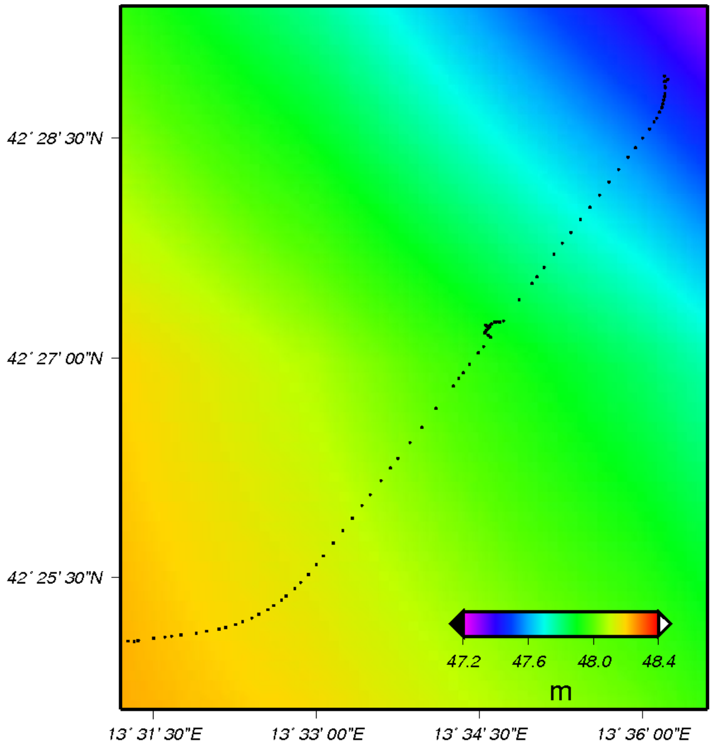

Figure 5: Geoid undulation (The black spots are the traverse stations along the tunnel)

adjustment and from the GPS survey: they were compared and found well consistent, at the level of 4 cm.
Finally, the positions and the covariance matrices of the existing benchmarks in the OPERA hall were trasformed from the LCCS into ETRF2000.

HORIZONTAL DIRECTIONS	254
DISTANCES	254
ZENITH ANGLES	254
STATIONS	53
TOTAL POINTS	127
EQUATIONS	780
UNKNOWN PARAMETERS	432
REDUNDANCY	348

Table 3: Main features of the final traverse adjustment

The final results of the adjustment and the transformation for the OPERA detector point are shown in Table 4

4 The first computation of the CERN-LNGS distance

On February 2011 a meeting was held at CERN to join all the geodetic information, that is the results of the geodetic survey at LNGS with those ones already available at CERN.
The positions of the CERN benchmarks and the neutrinos beam start point (T-40-S-CERN), available in the old ITRF97, were transformed into ETRF2000, following the international conventions implemented into the on line converter [3].
The resulting ETRF2000 positions of the two fundamental points of the neutrinos beam (the start point at CERN and the OPERA detector point at LNGS) are shown in Table 5.

Id	**X (m)**	**Y (m)**	**Z (m)**
A1-9999	4582167.465	1106521.805	4283602.714

	Covariance Matrix			**St. Dev.**
	(mm^2)			**(mm)**
Component	**X**	**Y**	**Z**	
X	14037	-8170	-12670	118
Y	-8170	5565	7293	75
Z	-12760	7293	11732	108

Table 4: ETRF2000 positions and precision of the OPERA detector point

Id	**X (m)**	**Y (m)**	**Z (m)**
T-40-S-CERN	4394369.327	467747.795	4584236.112
A1-9999	4582167.465	1106521.805	4283602.714

Table 5: ETRF2000 positions of the neutrinos beam start point at CERN and the OPERA detector point at LNGS

For additional convenience, the two fundamental points of the neutrinos beam were also transformed into the so called OPERA system (Table 6).

Id	**x (m)**	**y (m)**	**z (m)**
T-40-S-CERN	3177.974	729297.439	-42378.794
A1-9999	0.000	0.000	0.000

Table 6: OPERA system positions of the neutrinos beam start point at CERN and the OPERA detector point at LNGS

The resulting distance was **730534.610 m**; considering both the accuracy of the already available benchmarks at CERN (included T-40-S-CERN), at the level of 2 cm, and that one of the determined OPERA detector point at LNGS, at the level of about 20 cm, the overall accuracy of the distance is about 20 cm.

5 New GPS measurements for additional checks

New GPS measurements for additional checks were carried out during the month of June 2011. The goal was to check the inner consistency of the geodetic reference frame realized by the outdoors benchmarks both at CERN and LNGS. To this aim, two (out of the four GPS benchmarks) were surveyed again at Gran Sasso and three GPS benchmarks were surveyed at CERN.
Therefore, the positions of all the newly surveyed benchmarks were estimated directly in ETRF2000, avoiding the transformation from ITRF97 to ETRF2000 for the CERN benchmarks used in the first CERN-LNGS distance computation.

6 The final assessment of the CERN-LNGS distance

The additional GPS measurements confirmed the relative positions of the two sets of benchmarks at CERN and LNGS with a precision at the level of 3 cm. No additional terrestrial undergroung surveys were necessary since the reliability of the terrestrial surveys, linked both at CERN and LNGS to the GPS benchmarks have been already guarateed by strong geodetic networks design. As mentioned, the precision of the terrestrial surveys had been already assessed at the level of 2 cm at CERN and 20 cm at LNGS.

Finally, the already computed CERN-LNGS distance of **730534.610 m** was confirmed with the same accuracy, at the level of 20 cm.

7 Additional remarks

In this section some additional remarks are presented in order to clarify some of the questions arised by the scientific community after the pre-publication of [1].

7.1 GPS scale vs. Scale realization within ITRF and ETRF

The computation of the distance is based on the GPS distance scale. The GPS distance scale, based on the speed of light, is cross-checked with the distance scales of other space geodesy techniques (Very Long Base Interferometry - VLBI and Satellite Laser Ranging - SLR), which realize the scale of the International Terrestrial Reference Frame (currently ITRF2008) and the European Terrestrial Reference Frame (currently ETRF2000).
Also, the distance scales of VLBI and SLR are based on the speed of light, but each technique uses electromagnetic signals at proper frequencies:

- GPS - L-Band signals (two frequencies, L1 and L2)
- VLBI - Signals from Quasars
- SLR - optical and near-infrared signals

Each technique has to comply with the atmospheric refraction problem with a proper refraction model. In particular, GPS signals are very sensitive to the ionospheric refraction which may induce a scale factor up to some part per million (10^{-6}) if neglected. The ionospheric refraction is commonly (state-of-art methodology) accounted of and removed by a proper combination (ionospheric-free) of L1 and L2 signals. Overall, the inter-techniques (inner) scale consistency of the ITRF2008 (then of ETRF2000) is at the level of 1 part per billion (10^{-9}) [4]

7.2 Earth tides effect on the CERN-LNGS distance

Some geodetic observables and related parameters are affected by so called “solid Earth tide”. The gravity (which is directly accessible to observation) and the related potential in the vicinity of the Earth are a combination of gravity field of the Earth and of the tidal effects due to external bodies (the Moon, the Sun, and the planets), the (external) tidal potential contains both time independent (permanent) and time dependent (periodic) parts.

Similarly, the observed site positions are affected by displacements driven by solid Earth tides; these displacements also include permanent and time dependent parts.

The amplitude of the displacements due to solid Earth tides often reach +/- 20 cm, and can exceed 30 cm, so that they must be taken into account into the routinary processing of space geodesy observations. Appropriate models have been developed to this aim within IAU (International Astronomical Union) and IAG (International Association of Geodesy) [6]. Therefore, the effect of the solid Earth tides was duly considered during the GPS data processing, in order to estimate the positions of the GPS benchmarks both at CERN and at LNGS free from this effect.

Correspondingly, it is reasonable to evaluate the impact of the solid Earth tides on the baseline CERN-LNGS during the CNGS neutrino experiment, since, of course, also the distance between the beam start point at CERN and the OPERA detector point at LNGS varied for the tidal effects.

To this purpose, we modeled the coordinate variations of CERN and LNGS by the software SOLID [5], which implements the International Earth Rotation and Reference Systems Service (IERS) conventions [6].

The software has been modified to directly retrieve the tidal variations on the geocentric Cartesian coordinates (X, Y, Z) of CERN and LNGS, at a sampling rate of 2 hours for a time span of 4 years. Subsequently, we computed the correspondent tidal variations of the baseline with respect to the “tide free” baseline. The Figure 6 shows that the tidal variations of the baseline are within -/+ 1.9 cm, so that they are even negligible with respect the distance accuracy.

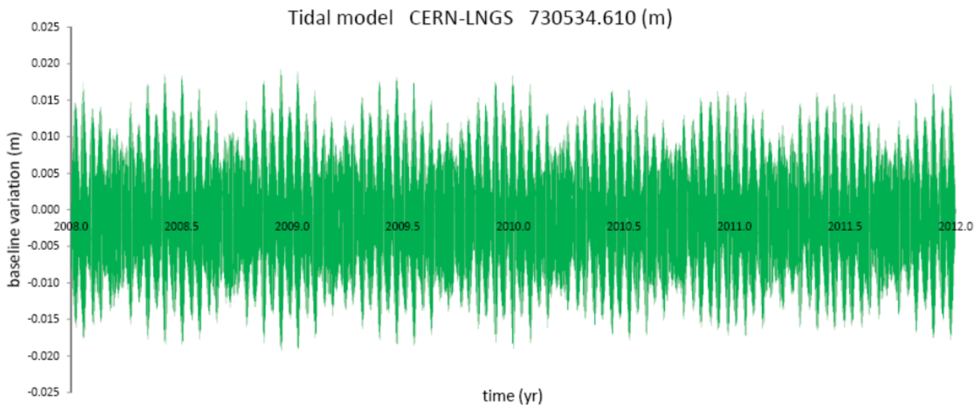

Figure 6: Tidal variations of the baseline CERN-LNGS

7.3 The Sagnac effect on the CERN-LNGS distance

The Earth rotation effect (so called Sagnac effect), that is the displacement of the OPERA detector point at LNGS during the neutrino Time Of Flight (TOF) due to the Earth rotation, must be considered, in order to compute the distance really travelled by neutrinos, and then to correctly evaluate the neutinos velocity.

At first, it is quite important to underline that neutrinos move, with respect to the Earth, from N-W (CERN) to S-E (LNGS) and the Earth rotates towards E, therefore Earth rotation causes an increase of the distance with respect to the already computed geometric distance in ETRF2000.

To compute the Sagnac effect, the following hypotheses were introduced:

- the angular velocity of the Earth is considered constant during the neutrinos TOF
- the reference system with origin in Earth barycenter, but not rotating with the Earth, is considered quasi-inertial
- special relativity rules for the velocities composition are hold [7][8] in this quasi-inertial reference system

Under these hypotheses, the calculation yields an increase distance of 66 cm, corresponding to a TOF of 2.2 ns; therefore, the Sagnac effect is certainly significant with respect the distance accuracy and has to taken into account.

7.4 Geodynamic effects

Space geodetic measurements provide information on the temporal deformations of the Earth's crust induced by various sources such as solid tides, Earth's rotation, polar motion and plate motion. Consequently, in the measure of long inter-distances between observing sites on the Earth's surface, as the case under investigation, the first (the periodical effects) are modeled and removed; the last, appearing as continental drift or instantaneous offsets due to earthquakes, must be taken into account. The Italian peninsula is a rather interesting natural laboratory for geophysical investigations. Its geodynamic evolution is driven by the interactions of the African and Eurasian plates and the whole area is subjected to slow crustal deformations. In particular, the Italian peninsula has a relative motion with respect to Eurasia of about 5 mm/yr [9][10] (Figure 7), with slow-varying patterns according to the main tectonic features. Along the whole Apennine chain a clear NNE-NE trending velocity marks a belt of extension along which seismic activity takes place.

The laboratory of CERN (Ginevra) is located on the stable part of the Eurasian plate, whereas the Laboratori Nazionali del Gran Sasso (L'Aquila) are located on the Apennine chain. On April 6, 2009, 01:32:39 GMT, the area of L'Aquila was struck by a Mw 6.3 earthquake that killed 309 people, causing severe destruction and ground cracks in a wide area around the epicenter. The maximum horizontal and vertical coseismic surface displacements detected by local GPS stations was 10.4±0.5 cm and 15.6±1.6 cm [11]. Then, the earthquake affected the area of the Laboratori Nazionali del Gran Sasso, this is well evident in the time series of the GPS working within the OPERA framework (LNGS). Due to the earthquake, LNGS experienced a 3D step of about 8.7±0.4 cm (the red line in the Figure 7 marks the epoch of event).

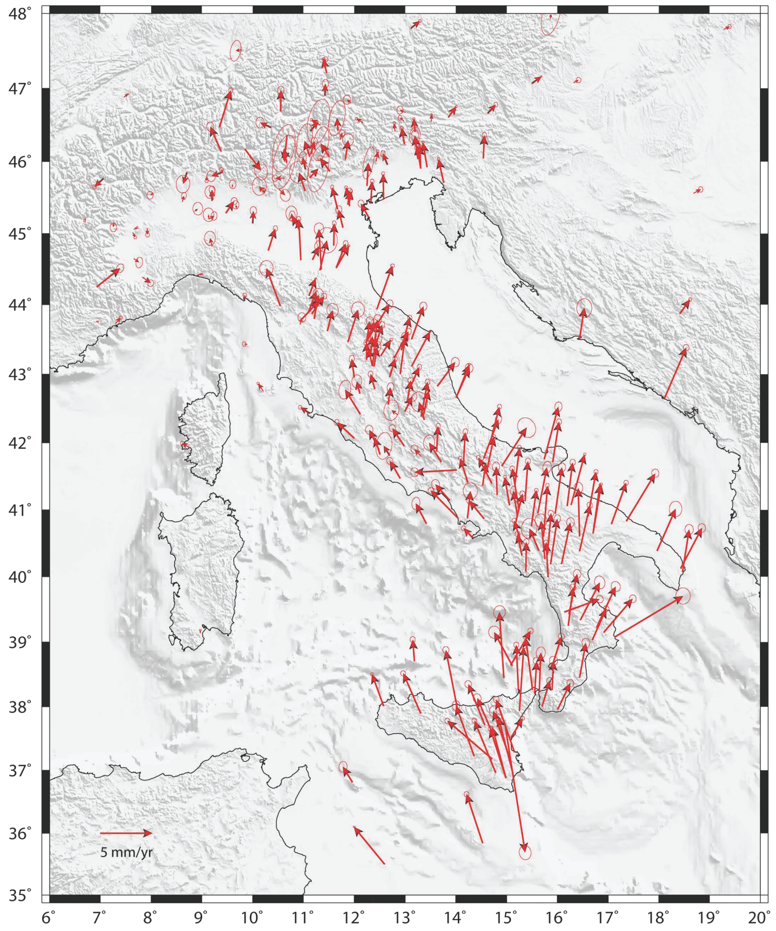

Figure 7: Present day kinematics of Italy

Taking into account that the GPS stations located at CERN (first CER1, after CERN) are located on the stable part of Eurasia, far from L'Aquila, we can confidently assume that they were not affected directly by the earthquake occurrence (Figures 9,10, Table 7).

The time series of the GPS baseline CERN-LNGS starts on DOY 160, 2009; its mean length is 730658.42m with values oscillating within about 1 cm. Unfortunately, since the GPS at CERN started to work just the day after the L'Aquila earthquake, a direct analysis of the earthquake effects on the GPS baseline CERN-LNGS cannot be done. To roughly evaluate if the earthquake occurrence affected in some way the length of the baseline, we have considered a similar baseline tracked from Zimmerwald (ZIMM) to LNGS, since ZIMM is the GPS permanent station nearest to CERN (Figure 11). The analysis shows that, even if each Cartesian component of the baseline is clearly affected by the seismic event of L'Aquila, the baseline does not, at least within the uncertainty (Figures 12,13).

GPS permanent station	**X (m)**	**Y (m)**	**Z (m)**
CER1	4393400.661±0.001	466460.949±0.001	4585421.842±0.001
CERN	4393400.503±0.001	466460.964±0.001	4585421.852±0.001
LNGS	4585754.924±0.001	1102187.603±0.001	4280932.955±0.001

Table 7: CER1, CERN and LNGS estimated coordinates in ITRF2005 at reference epoch 2009 DOY 152

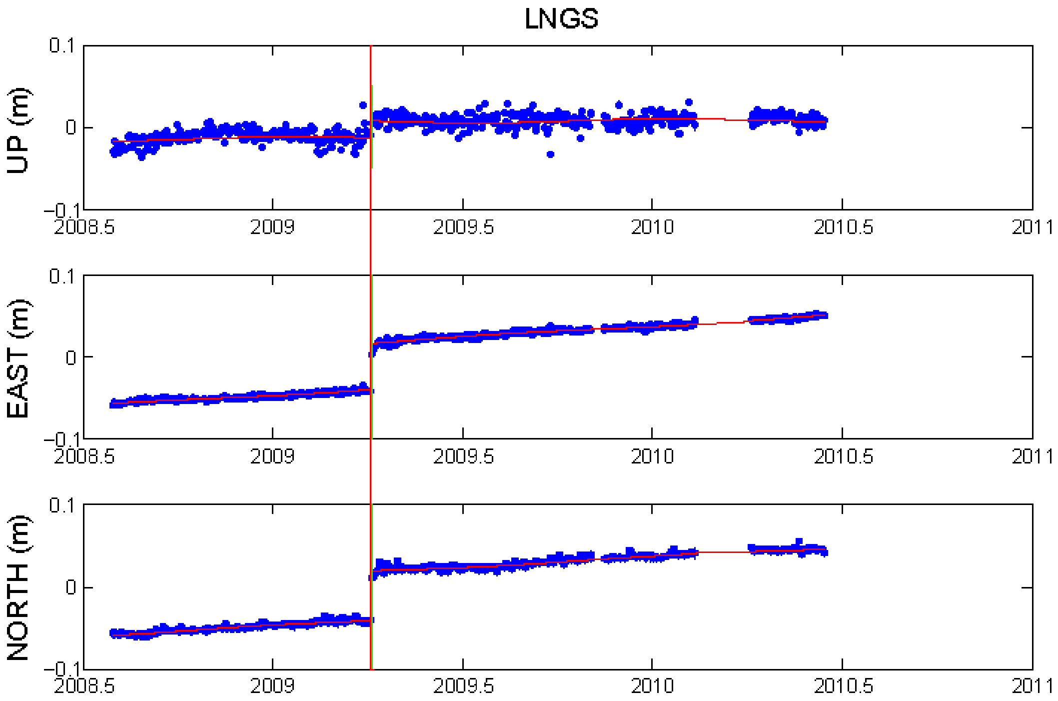

Figure 8: Time series of the LNGS GPS permanent station (red line corresponds to the April 6, 2009 earthquake)

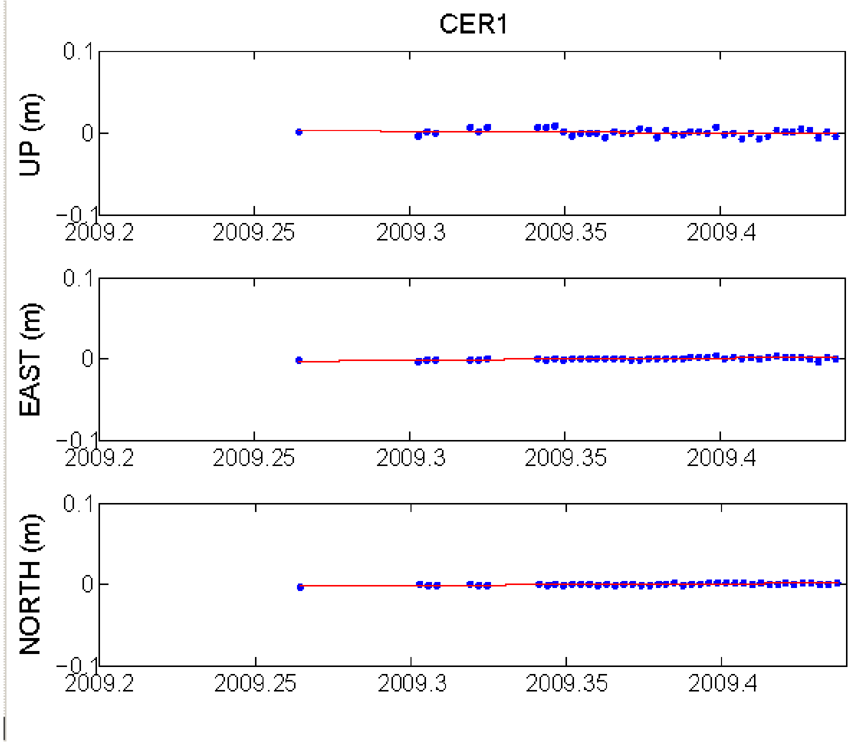

Figure 9: Time series of the CER1 GPS permanent station

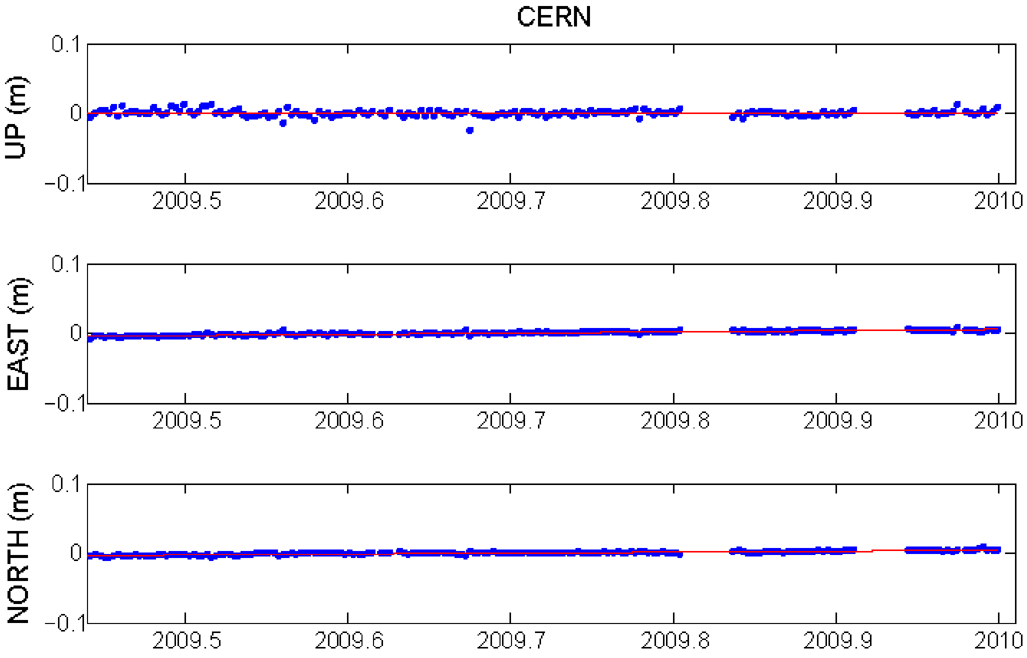

Figure 10: Time series of the CERN GPS permanent station

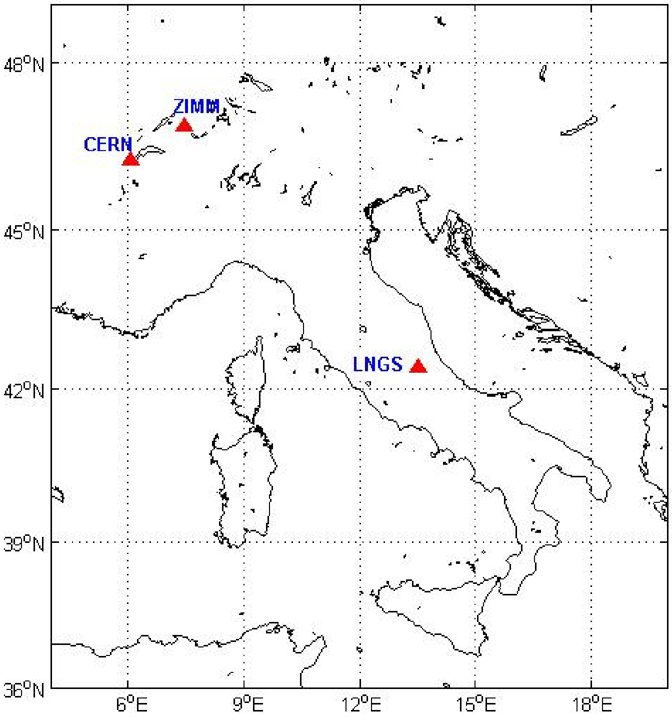

Figure 11: ZIMM, CERN and LNGS permanent stations

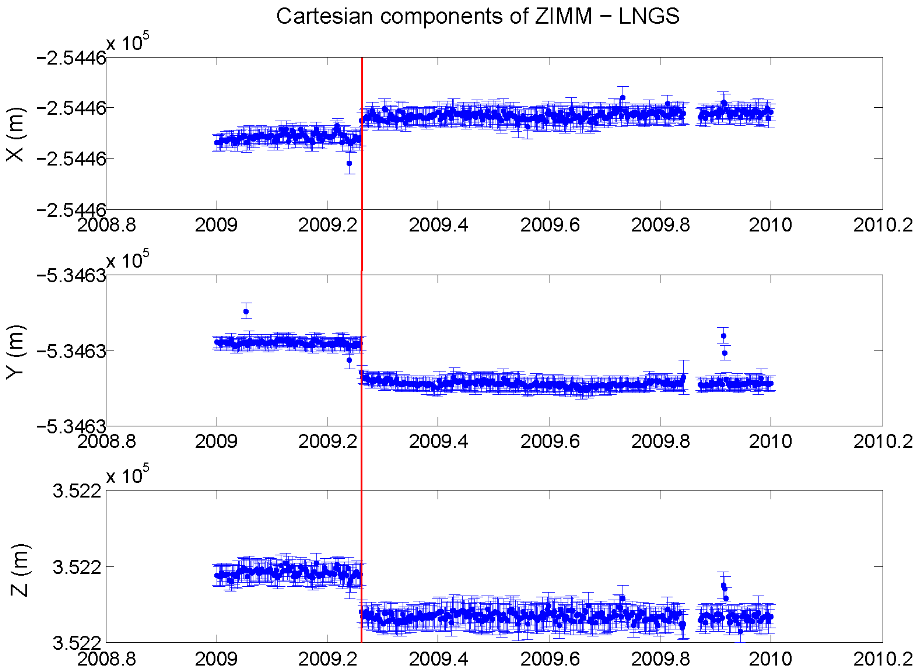

Figure 12: Time series of the cartesian components of the ZIMM-LNGS GPS baseline (red line corresponds to the April 6, 2009 earthquake)

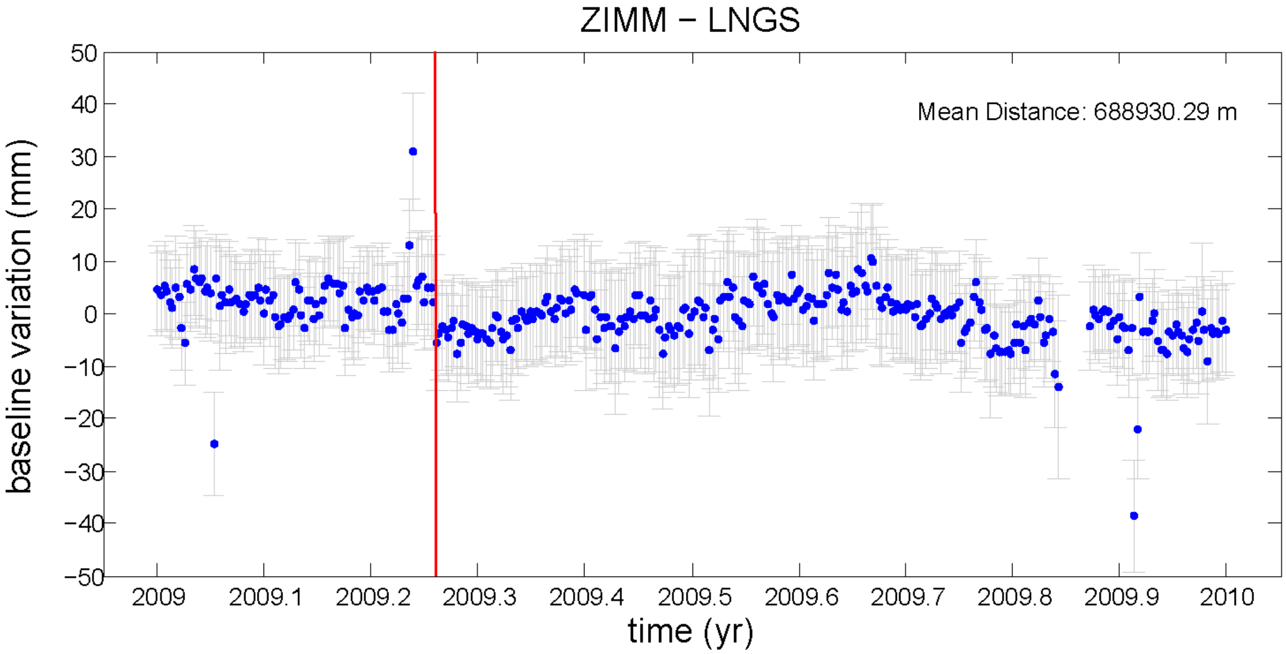

Figure 13: Time series of the length of the ZIMM-LNGS GPS baseline (red line corresponds to the April 6, 2009 earthquake)

8 Acknowledgements

This work would not have been possible without the support and the valuable cooperation of several people; the Authors thank very much and are sincerely indebted to

- Eng. Francesco Mongiardini and his staff at Strada dei Parchi SpA for the logistic and safety support during the surveys along and outside the Gran Sasso motorway tunnel
- Eng. Antonio Giampaoli and his staff at LNGS for the logistic and safety support during the surveys inside the underground Gran Sasso Laboratories
- Representative of Leica Geosystems SpA Mr. Celano and the CEO of Leica Geosystems SpA Eng. Marco Nardini for supplying the high precision total station TS30, the clamps and other instruments used during the surveys
- Dr. Chiara Porporato and Dr. Giulia Brunetti for the helpful and very nice support during the surveys
- Dr. Roberto Devoti and Dr. Grazia Pietrantonio at Istituto Nazionale di Geofisica e Vulcanologia for the valuable support in computing the geodynamical effect

9 Bibliography

References

[1] T. Adam, N. Agafonova, A. Aleksandrov et al, *Measurement of the Neutrino Velocity with the OPERA Detector in the CNGS Beam*, hep-ex/1109.4897

[2] Beutler, G. et al, *Bernese GPS Software* In: Dach R., Hugentobler U., Fridez P., Meindl M. (Eds), Astronomical Institute, University of Bern. 2007 `http://www.bernese.unibe.ch/`

[3] `http://www.epncb.oma.be/_dataproducts/coord_trans/`

[4] Z. Altamimi, X. Collilieux, L.Metivier, *ITRF2008: an improved solution of the international terrestrial reference frame.* J. of Geodesy, DOI 10.1007/s00190-011-0444-4, 2011

[5] Milbert D., Solid Earth Tide, software solid.f, `http://home.comcast.net/~dmilbert/softs/solid.htm`

[6] IERS Technical Note No. 32, 2003 `http://www.iers.org/nn_10970/IERS/EN/Publications/TechnicalNotes`

[7] E. Persico, *Fisica matematica* Zanichelli, 1946

[8] W. Rindler *Essential Relativity (2nd ed.)* Springer, 1977

[9] R. Devoti, G. Pietrantonio, A. R. Pisani, F. Riguzzi, E. Serpelloni, *Present day kinematics of Italy.* J. of the Virtual Explorer, vol. 36, 2, ISSN: 1441-8142, 2010

[10] R. Devoti, A. Esposito, G. Pietrantonio, A. R. Pisani, F. Riguzzi, E. Serpelloni, *Evidence of large scale deformation patterns from GPS data in the Italian subduction boundary.* Earth Planet. Sci. Lett., vol. 311, p. 230-241, ISSN: 0012-821X, doi: 10.1016/j.epsl.2011.09.034. 2011

[11] M. Anzidei, E. Boschi, V. Cannelli, R. Devoti, A. Esposito, A. Galvani, D. Melini, G. Pietrantonio, A. R. Pisani, F. Riguzzi, V. Sepe, E. Serpelloni, *Coseismic deformation of the destructive April 6, 2009 L'Aquila earthquake (central Italy) from GPS data.* Geophys. Res. Lett., vol. 36, ISSN: 0094-8276, doi: 10.1029/2009GL039145. 2009.