CERN-LNGS distance computation for the OPERA Project

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The goal

- To compute the **distance** traveled by neutrinos between CERN and LNGS with accuracy of **few decimeters**

with the aim

- To check if neutrinos **fulfil or not** the Lorentz invariance with an unprecedented accuracy

The methodology 1/3

To estimate the positions of **suited benchmarks** at CERN and within the OPERA hall at LNGS in the **same reference frame (ETRF2000)**

The positions of the neutrino beam **starting point at CERN** and of the **ending point at OPERA detector** with respect to these benchmarks were already known both at CERN and at LNGS from previous surveys, with an accuracy better than **one millimeter**

The methodology 2/3

The most **efficient, reliable and accurate geodetic technique** to estimate positions in a common reference frame (considering the distance between CERN and LNGS, approx. 730 Km) is based on the **Global Positioning System** (GPS)

Since the suited benchmarks at CERN and LNGS are located **underground**, **they can not be directly surveyed by GPS**

Ancillary outdoors benchmarks should have been surveyed by GPS and their positions estimated within the **common reference frame ETRF2000** (the latest realization of the European reference system)

The methodology 3/3

Therefore 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 starting point at CERN and of the ending point at the OPERA detector in the common reference frame ETRF2000 and to compute their **3D distance** (Phythagoras theorem)

Remark 1

GPS scale vs. Scale realization within ITRF and ETRF 1/3

The computation of the distance traveled by neutrinos beam is based on the **GPS distance scale**

The GPS distance scale is

- based on the **speed of light**
- **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**), linked to ITRF2008 by a transformation to account for and remove the **geodynamics** of the **European region**

Remark 1

GPS scale vs. Scale realization within ITRF and ETRF 2/3

The **cross-check** between the different techniques is **allowed** since

- 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**

Remark 1

GPS scale vs. Scale realization within ITRF and ETRF 3/3

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
- 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})

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

Remark 2

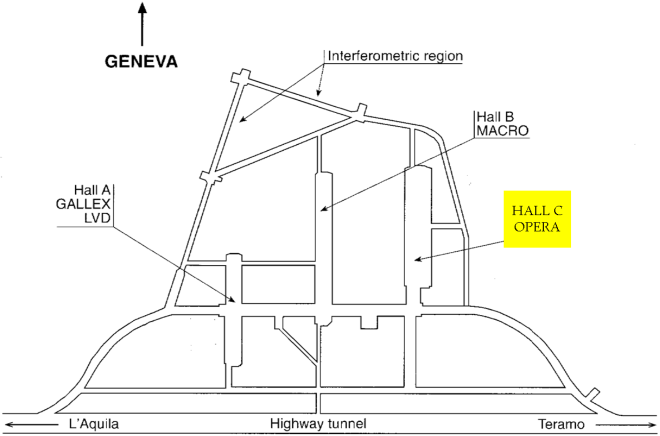
The already available geodetic information and

the role of the Area di Geodesia e Geomatica-Univ. di Roma "La Sapienza"

Actually at CERN the positions of the **suited benchmarks** were already **available** in an **old** global reference frame (ITRF97) with an accuracy of **few centimeters**

On the LNGS side, 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** through the Gran Sasso highways tunnel (**10.5 Km length**) towards the LNGS OPERA hall

The OPERA hall at LNGS



LNGS new geodetic network

A **mixed** GPS - terrestrial survey was mandatory due to the **underground location** of the OPERA hall

in order to **link**

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

The constraints

The survey design was driven by the

accuracy requirements

few decimeters

reliability requirements

strong and fast (on-the-field) internal measurements check

logistic constraints

- no traffic stop
- right lane (Teramo-l'Aquila direction) available for traversing only
- faster-better (only few days available, due to right lane occupation daily high cost)

The GPS benchmarks 1/3

Two benchmarks close to **each entrance** of the highway Gran Sasso tunnel were **realized** with steel nails settled on already existing **concrete basements** and duly located in order

- to be **outside from highway lanes** (long GPS measurements sessions for their link to ETRF2000)
- to be **mutually visible** (traverse **link and orientation**) from the very entrances of the tunnel (materialization of additional benchmarks on the tunnel wall to strenght the inside-outside link)
- to be (eventually) **visible from inside** of the tunnel close to the two entrances (same as before)

The GPS benchmarks 2/3

4 GPS receivers - antennas

- 2 TPS EGGD - TPSPGA1
- 2 Leica GX1230 GG - LEIAS10, LEIAX1230GG

2 days (Sept. 23-24, 2010), 2 sessions 7 hours long (1 second sampling interval)

GPS observations **processing** with Bernese software v 5.0 including observations from 3 **EPN stations** (UNPG-Perugia, UNTR-Terni, M0SE-Roma) **constrained** at their ETRF2000 coordinates with (East, North, Up = 2mm, 2mm, 4mm) precision

The GPS benchmarks 3/3

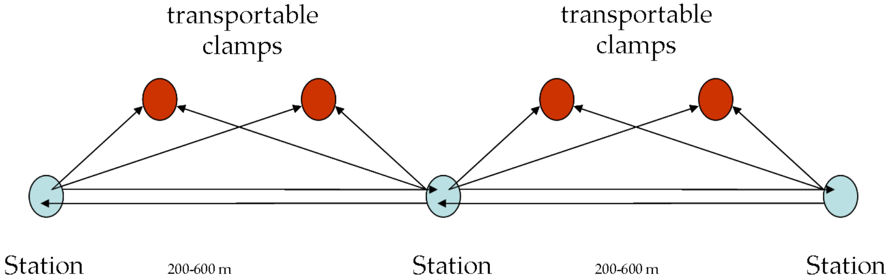
ETRF2000 positions of the four GPS benchmarks

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 traverse along the tunnel 1/4

An **enhanced traverse design** was adopted in order to

- comply with the **logistic constraints** (4 days available: July 13-16, 2010)
- fulfil the **reliability requirements**



The traverse along the tunnel 2/4

Leica TS30 motorized total station

4 repetitions (double sighting) each station

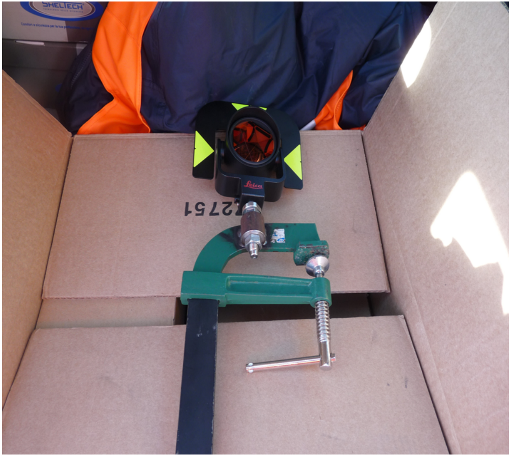
Terrestrial observations **processing** with scientific software CALGE (developed at Politecnico di Milano) **3D network adjustment** in a **local cartesian coordinate system**

obstervation posterior re-weighting analysis

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

The traverse along the tunnel 3/4

Two *ad-hoc* **prism** transportable supports (clamps) were realized



The traverse along the tunnel 3/4

Two *ad-hoc* **prism** transportable supports (clamps) were realized

The traverse along the tunnel 4/4

Several benchmarks (prism supports) were **materialized** on the tunnel and LNGS walls for eventual **survey checks** (also with gyro-theodolites) and possible **future additional surveys**

Mixed GPS - terrestrial survey adjustment 1/4

Definition of the **local cartesian coordinate system** (LCCS)

- **origin** - GPS1
- **cartesian axes** - ellipsoidal East, North, Up

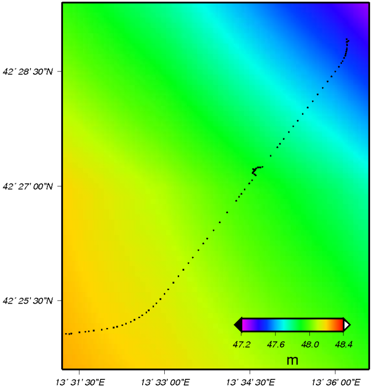
Preliminary minimal constraints adjustment

- outliers detection
- observation re-weighting analysis

Final traverse adjustment **constrained** on the four GPS benchmarks with **proper precision**, accounting for the **geoidal undulation to link ellipsoidal height to orthometric height differences**

Transformation of the LCCS **positions** and **covariance matrices** of the existing benchmarks in the OPERA hall into ETRF2000

Mixed GPS - terrestrial survey adjustment 2/4



Geoidal undulation (The black spots are the traverse stations along the tunnel)

Mixed GPS - terrestrial survey adjustment 3/4

LCCS constrained adjustment featutures

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

Mixed GPS - terrestrial survey adjustment 4/4

ETRF2000 positions and precision of the OPERA detector

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

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

The first distance computation 1/2

On **February 2011** a meeting was held at CERN to **join** all the geodetic information

The positions of the CERN benchmarks and the starting point (**T-40-S-CERN**), available in the old ITRF97, were **transformed** into ETRF2000 following the international conventions
http://www.epncb.oma.be/_dataproducts/coord_trans/

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

The first distance computation 2/2

For additional convenience, the starting point at CERN and the ending point at OPERA detector were also transformed into the so called **OPERA system**

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

The resulting distance was : 730534.610 m

New GPS measurements for additional checks 1/3

- **New GPS measurements** for additional checks were carried out in June 2011
- The goal was to **check** the inner **consistency** of the geodetic reference frame realized by the **outdoors benchmarks** both at CERN and Gran Sasso
  - 2 (out of 4) benchmarks were surveyed at Gran Sasso
  - 3 benchmarks were surveyed at CERN (thanks to Dominique Missiaen, Mark Jones and the geodesy group)
- **Positions** of all the mentioned benchmarks were **directly estimated in ETRF2000**, avoiding the transformation from ITRF97 to ETRF2000 for the CERN benchmarks (necessary for the first CERN-LNGS distance computation, due to the original different reference frames used at CERN and Gran Sasso)

New GPS measurements for additional controls 2/3

- **No additional** terrestrial underground surveys were necessary
- The **reliability** of the terrestrial surveys, linked both at CERN and Gran Sasso at the mentioned benchmarks, have been already **guaranteed** by **strong geodetic network designs**
- The **precision** of the terrestrial surveys has been already assessed at the level of
  - **2 cm** at CERN
  - **20 cm** at Gran Sasso

New GPS measurements for additional controls 3/3

- The **relative positions** of the 2 sets of outdoors benchmarks at CERN and Gran Sasso was **confirmed** at the level of **3 cm**

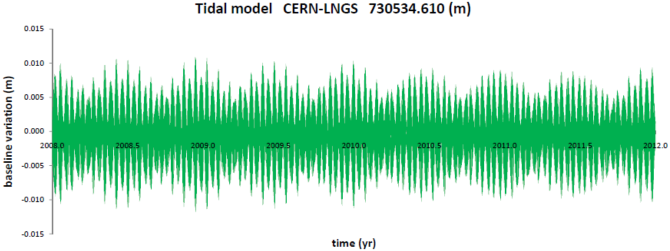
- The already computed CERN-LNGS distance was **confirmed**, with the same standard deviation, at the level of **20 cm**

Additional effects (1) on the CERN-LNGS distance: solid Earth tides

Geodetic observables and parameters estimated from them are affected by the so called "**solid Earth tide**"

Therefore, the observed site positions are affected **(continuosly changed)** by solid Earth tides

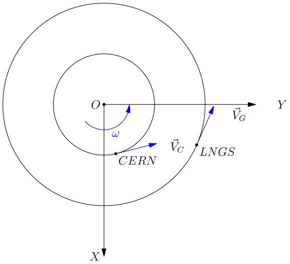
Correspondingly, it seemed reasonable to evaluate the **impact** of the solid Earth tides on the baseline CERN-LNGS during the CNGS neutrino experiment



Additional effects (2) on the CERN-LNGS distance: the Sagnac effect

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 traveled** by neutrinos

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



The Sagnac effect on the CERN-LNGS distance 2/2

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 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 be taken into account

Thank you very much for your kind attention !