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True or false GPS-derived deformations?

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Abstract
In this paper we focus on the question whether GPS networks born with cartographic aims can be safely used in crustal deformation control. We carried out a test on a network of five vertices located in the Rome district, comparing two data sets, the first coming from the adjustment of the survey carried out in 1994 in the frame of the IGM95 project, the second coming from the surveys carried out in 1996 and 1999 by the DITS of the «La Sapienza» University of Rome. Our analysis shows how the detection of crustal deformation becomes extremely critical in absence of significant seismicity or when deformation events are limited. In other words, it is possible to find false deformations due to residual systematic effects affecting the coordinate estimates.

Key words *deformation analysis – GPS networks – IGM95 – Rome area*

1. Introduction

Recently, some papers reported crustal deformation detection after the occurrence of moderate seismic events by the comparison of two Cartesian coordinate sets of GPS networks estimated in different ways and with different aims (Anzidei *et al.*, 1999, 2000; Hunstad *et al.*, 1999). In such cases, coordinates were estimated before (sometimes a few years) the occurrence of seismic events in occasion of GPS surveys mainly devoted to cartographic purposes (like the IGM95 network, see later on) and after the events themselves.

Other authors (*e.g.*, Bianconi *et al.*, 1999; Bonci *et al.*, 2000) considered it useful to investigate crustal deformations just on the basis of this kind of networks, established with other aims, even in absence of significant deformation episodes (for instance earthquakes with appreciable magnitude or landslides).

Careful tests showed that local GPS networks (baseline ranging from few to 20 km) are able to correctly identify horizontal and vertical displacements respectively at level of 5 and 10 mm. Nevertheless, this holds only for networks suitably designed for deformation control and under optimal survey and processing conditions (Betti *et al.*, 1999).

On the contrary, in the above mentioned cases, GPS-derived coordinates may be affected by three main sources of systematic errors: 1) observation strategy errors: the networks are not properly designed and surveyed for crustal deformation monitoring (many sites need tripods, observing sessions could be too short); 2) processing errors: observations were processed with different analysis procedures (*e.g.*, the use of broadcast rather than precise ephemerides; different or not at all troposphere delay estimation, crucial in height determina-

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tion), and 3) reference frame inconsistency: coordinates are referred to different reference frames, since satellite ephemerides are computed on yearly updated ITRFYY.

The first two sources may deceptively affect the deformation analysis, the last may be taken into account performing a Helmert 7-parameter transformation, once the parameters (translation, rotations and scale) are estimated on a subset of sites that by assumption did not undergo deformations.

In this paper we show how the analysis and the detection of crustal deformations become extremely critical in the absence of significant guarantees of observation and processing strategies. In other words, it is possible to highlight false deformations of the network due, in our opinion, to residual systematic effects affecting in different ways the two coordinate estimates. This fact may appear statistically significant, at least in some sites of the control network, even if the precision of the coordinates is rather low.

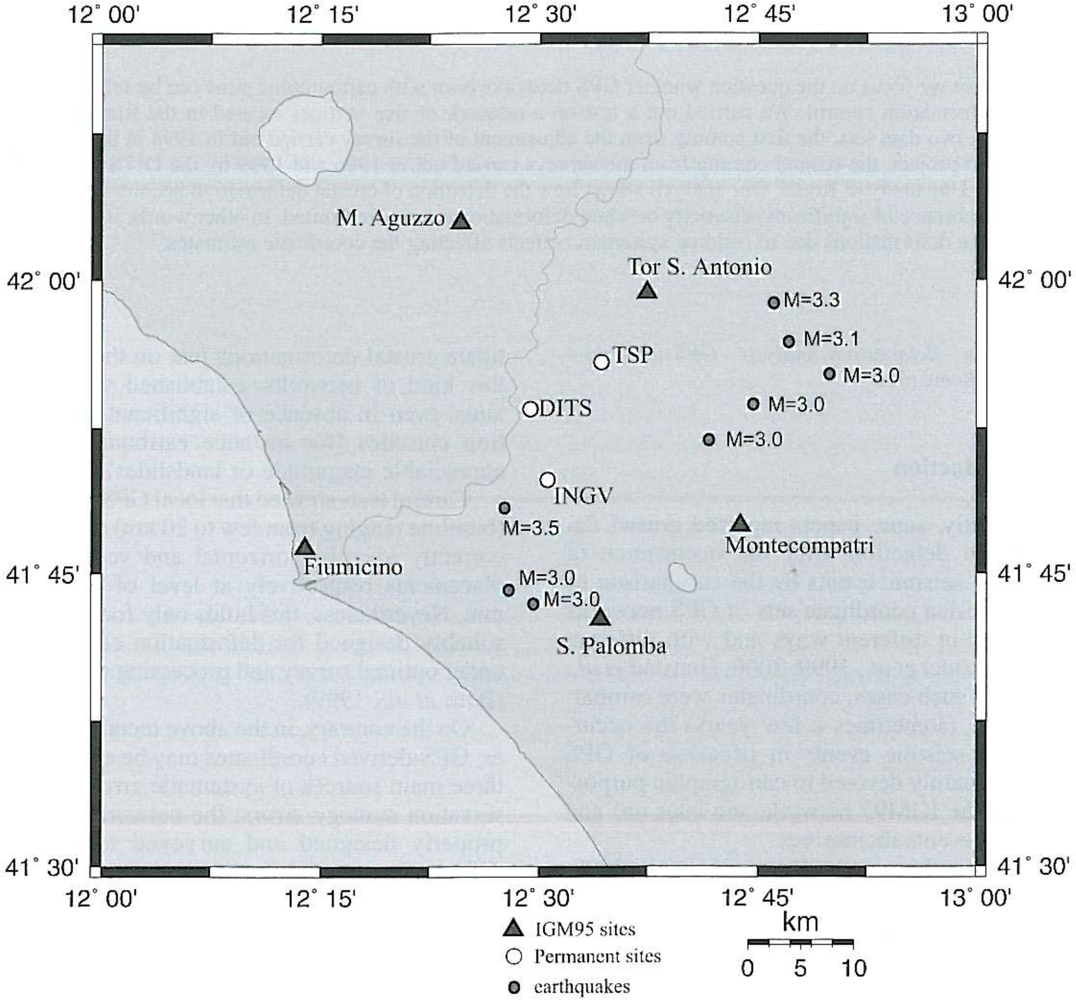

Fig. 1. GPS sites and seismicity from 1994 to 1999.

In this respect, we show the results obtained after a test carried out on a network of 5 vertices located in the Rome district, more or less along a circle covering an area of about 900 km^2 around downtown Rome.

From a geophysical point of view, this area may be considered quiet enough, with a low seismicity level and without noticeable environmental geological phenomena (landslides, subsidence, active faulting and so on). About seismicity, from 1994 up to date, only 8 events were recorded by the national seismometric network with magnitudes ranging from 3.0 and 3.5 (ING Seismological Bulletin) (fig. 1), but they were not enough strong to produce topographic deformations of the Earth surface (Wells and Coppersmith, 1994).

For the test, we considered two coordinate sets: the first coming from the adjustment of the survey carried out in 1994 in the frame of the IGM95 project by the Istituto Geografico Militare Italiano (IGMI); the second coming from the surveys carried out in 1996 and 1999 by the Dipartimento di Idraulica Trasporti e Strade (DITS) of the «La Sapienza» Rome University.

2. The IGM95 GPS network

In 1992 the IGMI developed IGM95, the most important recent geodetic project in Italy (Surace, 1993, 1997; Pierozzi and Surace, 2000), by establishing the first GPS network at national scale, with the aim of:

– Materializing a national geometric reference for GPS measurements, mainly devoted to cartographic purposes.

– Determining the relations between the existing national geodetic systems (Roma40 and

Table I. DITS-IGM95 common sites: Cartesian coordinates.

Site	ETRF89 (IGM95)			ITRF97 (epoch 1999.345)		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
M. Aguzzo	4631678.926	1019502.229	4250973.670	4631678.648	1019502.479	4250973.736
S. Palomba	4654451.422	1038091.659	4221518.234	4654451.092	1038091.896	4221518.331
Fiumicino	4655784.959	1009304.564	4226851.687	4655784.624	1009304.824	4226851.734
Tor S. Antonio	4632987.777	1037573.578	4244973.002	4632987.464	1037573.783	4244973.064
Montecompatri	4645932.507	1049441.944	4228663.119	4645932.264	1049442.133	4228663.246

Table II. DITS-IGM95 common sites: geodetic coordinates.

Site	ETRF89 (IGM95)			ITRF97 (epoch 1999.345)		
	ϕ (d p s)	λ (d p s)	h (m)	ϕ (d p s)	λ (d p s)	h (m)
M. Aguzzo	42 03 45.689	12 24 49.341	294.93	42 03 45.6953	12 24 49.3542	294.813
S. Palomba	41 42 26.841	12 34 22.851	175.57	41 42 26.8492	12 34 22.8641	175.432
Fiumicino	41 46 21.139	12 13 53.764	84.74	41 46 21.1460	12 13 53.7781	84.568
Tor S. Antonio	41 59 28.508	12 37 23.869	136.45	41 59 28.5152	12 37 23.8807	136.298
Montecompatri	41 47 25.346	12 43 42.905	586.29	41 47 25.3533	12 43 42.9153	586.229

Table III. Precision at 95% level.

Site	DITS network			IGM95 network		
	S_{max} (cm)	S_{min} (cm)	$CI\ h$ (cm)	S_{max} (cm)	S_{min} (cm)	$CI\ h$ (cm)
M. Aguzzo	1.1	0.9	2.1	2.0	1.7	1.8
S. Palomba	1.2	0.9	2.1	2.7	2.4	3.1
Fiumicino	1.3	1.1	2.6	3.4	2.9	2.7
Tor S. Antonio	1.1	0.7	1.8	3.2	2.9	3.1
Montecompatri	1.1	0.8	2.0	4.6	3.9	4.5

IGM83; Pierozzi and Surace, 2000) and the EUREF network, composed by about 100 reference GPS sites with sub-decimetre accuracy all over Europe (Gurtner *et al.*, 1992).

– Contributing to the national geoid definition.

After 4 years of hard work, 1236 points uniformly distributed, located at easily accessible sites at a mean distance of about 20 km, were established and GPS-observed at least twice, using 11 Trimble double frequency 4000SSE receivers. About 66% of these points are located in coincidence, or directly connected, to vertices of the classical triangulation network, while about 34% of them are connected to the fundamental levelling network.

The network adjustment was divided into 2 blocks, the Italian Peninsula plus Sicily (block 1) and Sardinia (block 2), framing each adjustment into the ETRF89 reference system, defined by the European GPS permanent stations at epoch 1989.0 (Gurtner, 1993). The mean relative precision achieved for the block 1 is 0.9 cm for the horizontal and 1.8 cm for the vertical components at 1σ level (Surace, 1997).

In this paper we focus our attention on 5 IGM95 sites located in the Rome area: Monte Aguzzo (IGM95 code: 143902), Pomezia S. Palomba (150903), Fiumicino (149901), Tor Sant'Antonio (150904) and Montecompatri (150905). These sites were surveyed in 1994 and their coordinates (tables I and II) come from the IGM95 block 1 adjustment. The mean relative precision achieved for the 5 sites are reported in table III in terms of horizontal error ellipsis semiaxes and height confidence interval at 95% level (Pierozzi, 2000).

3. The DITS GPS network

In 1996 the DITS established a new GPS network in the Rome district with the aim to densify the IGM95 network in the Rome area. The necessity of this densification derived from the absence of trigonometric vertices and levelling benchmarks in this area, as most of them established by IGMI more than 100 years ago disappeared because of bad maintenance or damage.

The DITS network (fig. 2) was composed of 18 main sites located at a mean distance of about 10 km and 21 auxiliary vertices; it was designed to reach a precision in the coordinate estimation suitable for the main topographic and cartographic purposes; the network was connected to the IGM95 GPS network, by including the five IGM95 sites already mentioned (Monte Aguzzo, Pomezia S. Palomba, Fiumicino, Tor Sant'Antonio, Montecompatri) and to the fundamental national levelling network (Crespi *et al.*, 2000).

The mean relative precision at 1σ level at the 18 main sites is 0.5 cm (horizontal) and 1 cm (vertical), about twice better than the IGM95 network.

At the end of 1999, the DITS network was observed again using 2 Trimble Total Stations

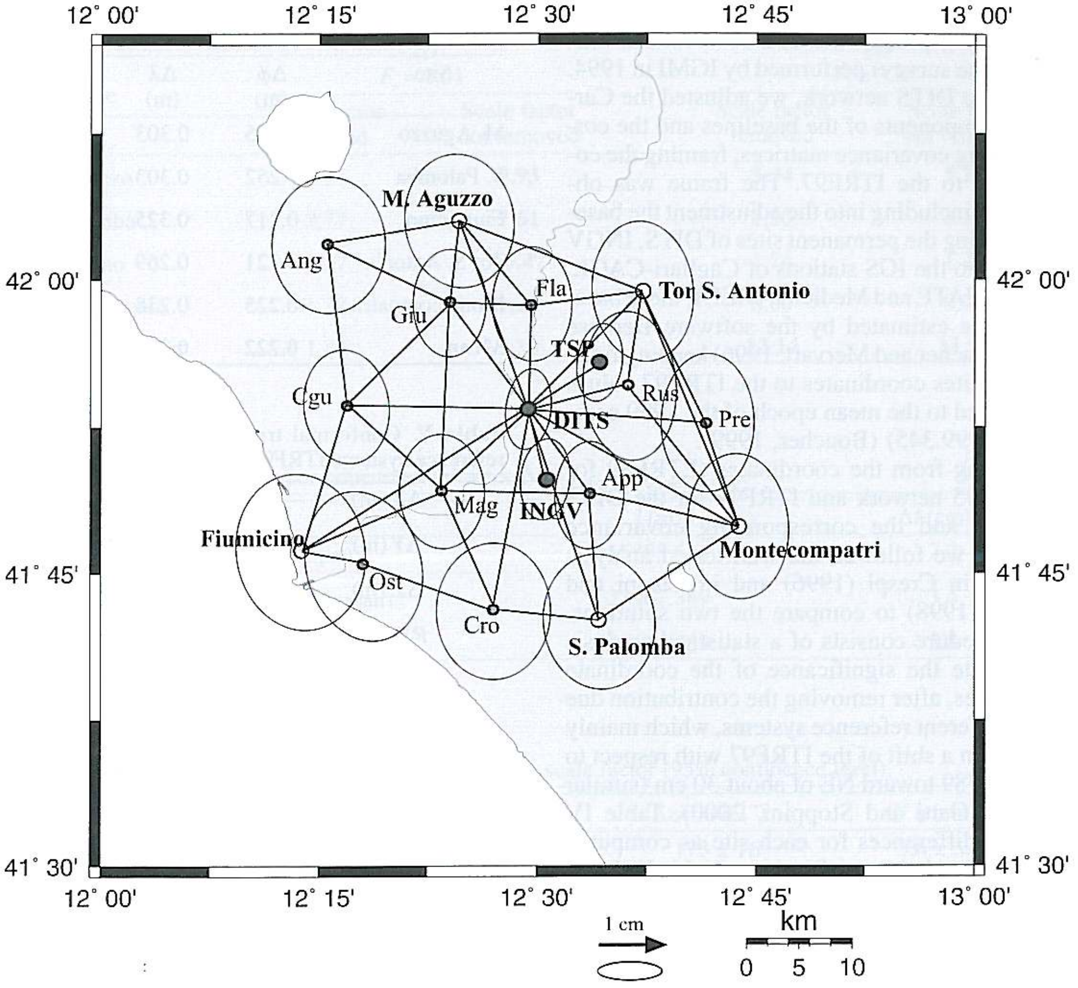

Fig. 2. DITS GPS network (error ellipsis at 95% confidence level).

4800, 1 Trimble 4000SSI, 1 Trimble Total Station 4700 and 1 Ashtech Z-12. During the survey, the stations of INGV (Istituto Nazionale di Geofisica e Vulcanologia) and DITS (University) worked permanently and GPS observations coming from the Rome Telespazio (TSP) permanent station were included in the processing. The two surveys were at first compared in order to highlight possible deformations; since no significant coordinate changes were detected, they were adjusted together.

Tables I, II and III show the adjusted coordinates of the 5 sites shared with the IGM95 network and their precision, in terms of horizontal error ellipsis semiaxes and height confidence interval at 95% confidence level.

4. Analysis

In this paper we consider the Cartesian coordinates ETRF89 (table I) with their covariance matrix coming from the adjustment of the block 1, without re-process the GPS observations concerning the surveys performed by IGMI in 1994.

For the DITS network, we adjusted the Cartesian components of the baselines and the corresponding covariance matrices, framing the coordinates to the ITRF97. The frame was obtained by including into the adjustment the baselines linking the permanent sites of DITS, INGV and TSP to the IGS stations of Cagliari-CAGL, Matera-MATE and Medicina-MEDI; these baselines were estimated by the software Bernese 4.0 (Rothacher and Mervart, 1996) keeping fixed the IGS sites coordinates to the ITRF97 values propagated to the mean epoch of the 1999 campaign (1999.345) (Boucher, 1999).

Starting from the coordinates (ETRF89 for the IGM95 network and ITRF97 for the DITS network) and the corresponding covariance matrices, we followed the well-tested analysis reported in Crespi (1996) and in Crespi and Riguzzi (1998) to compare the two solutions. The procedure consists of a statistical analysis to evaluate the significance of the coordinate differences, after removing the contribution due to the different reference systems, which mainly consists in a shift of the ITRF97 with respect to the ETRF89 toward NE of about 30 cm (similar value in Gatti and Stoppini, 2000). Table IV lists the differences for each site as computed from the geodetic coordinates and table V shows the estimates of the conformal transformation 7 parameters (3 translations, 3 rotations and 1 scale factor) between the reference systems: the translations and scale reach significant values, while the rotations are negligible.

Table IV. DITS-IGM95 common sites: differences between ITRF97 and ETRF89.

Site	$\Delta\phi$ (m)	$\Delta\lambda$ (m)	Δh (m)
M. Aguzzo	0.195	0.303	– 0.117
S. Palomba	0.252	0.303	– 0.138
Fiumicino	0.217	0.325	– 0.171
Tor S. Antonio	0.221	0.269	– 0.152
Montecompatri	0.225	0.238	– 0.061
Mean	**0.222**	**0.288**	**– 0.128**

Table V. Conformal transformation between the reference systems ITRF97-ETRF89.

ΔX (m)	**– 0.300 ± 0.011**
ΔY (m)	**+ 0.228 ± 0.006**
ΔZ (m)	**+ 0.080 ± 0.010**
RX (rad)	$0.94 \cdot 10^{-6} \pm 0.69 \cdot 10^{-6}$
RY (rad)	$0.68 \cdot 10^{-6} \pm 0.75 \cdot 10^{-6}$
RZ (rad)	$-0.68 \cdot 10^{-6} \pm 0.76 \cdot 10^{-6}$
Scale factor	$\mathbf{1\text{-}0.14 \cdot 10^{-5} \pm 0.40 \cdot 10^{-6}}$

Table VI contains the results of the 2D and 1D deformation analysis performed at the significance level $\alpha = 5\%$: only the sites having an experimental F value greater than F_t (threshold value) show significant coordinate differences between the two network solutions. The deformation analysis was performed in two different cases: after removing the scale factor and without removing it. Concerning the 2D analysis, in the first case all the sites do not exhibit significant coordinate differences, while in the second case the sites M. Aguzzo, S. Palomba and Fiumicino show significant F values. Concerning the 1D analysis, in both cases M. Aguzzo and Montecompatri exhibit significant height differences. The remarkable scale factor (1.4 ppm) is therefore able to absorb the horizontal deformation but does not affect the vertical one; this effect results in a contraction of the ITRF97 network with respect to the IGM95 one (table VII).

The horizontal displacement vectors and their precision were computed on the local tangent plane at 95% confidence level, taking into account the results of the significance analysis; *i.e.* they were computed with respect to the centroid of the sites that did not show significant coordinate differences (S. Palomba, Fiumicino and Tor S. Antonio).

In order to stress the effect due to scale factor, we reported in tables VIII and IX the residual displacements obtained without removing the scale factor and after removing it, both at 95% confidence level. Moreover, the 2D displacement

Table VI. Deformation analysis ($\alpha = 5\%$).

Site	2D $F_t = 3.01$		1D $F_t = 3.85$	
	Scale factor removed	Scale factor not removed	Scale factor removed	Scale factor not removed
M. Aguzzo	0.21	**9.93**	**5.34**	**5.24**
S. Palomba	2.77	**7.61**	1.20	1.18
Fiumicino	1.37	**10.47**	1.24	1.25
Tor S. Antonio	1.32	1.20	0.00	0.00
Montecompatri	1.84	1.19	**12.14**	**11.95**

Table VII. Baseline contractions due to scale factor $\Delta l = l_{ITRF97} - l_{IGM95}$.

Baseline	l (m)	Δl (cm)
S. Palomba-Montecompatri	15888.616	− 2.2
Tor S. Antonio-Montecompatri	23967.389	− 3.4
M. Aguzzo-S. Palomba	41614.559	− 5.8

Table VIII. Residual displacements without removing scale factor (95% confidence level).

	2D vector (cm)	Azimuth (°)	*CI h* (cm)
M. Aguzzo	3.6 ± 1.1	173 ± 16	3.6 ± 3.1
S. Palomba	2.3 ± 1.0	8 ± 22	1.6 ± 2.9
Fiumicino	3.1 ± 1.0	117 ± 20	− 1.7 ± 2.9
Tor S. Antonio	3.2 ± 1.0	− 106 ± 19	0.0 ± 2.8
Montecompatri	6.3 ± 1.7	− 94 ± 19	9.2 ± 5.1

Table IX. Residual displacements after removing scale factor (95% confidence level).

	2D vector (cm)	Azimuth (°)	*CI h* (cm)
M. Aguzzo	0.3 ± 1.1	− 63 ± 201	3.7 ± 3.1
S. Palomba	1.5 ± 0.9	71 ± 37	1.6 ± 2.9
Fiumicino	2.2 ± 1.1	− 178 ± 25	− 1.7 ± 2.9
Tor S. Antonio	2.2 ± 1.0	− 39 ± 26	0.1 ± 2.8
Montecompatri	5.0 ± 1.8	− 64 ± 23	9.2 ± 5.1

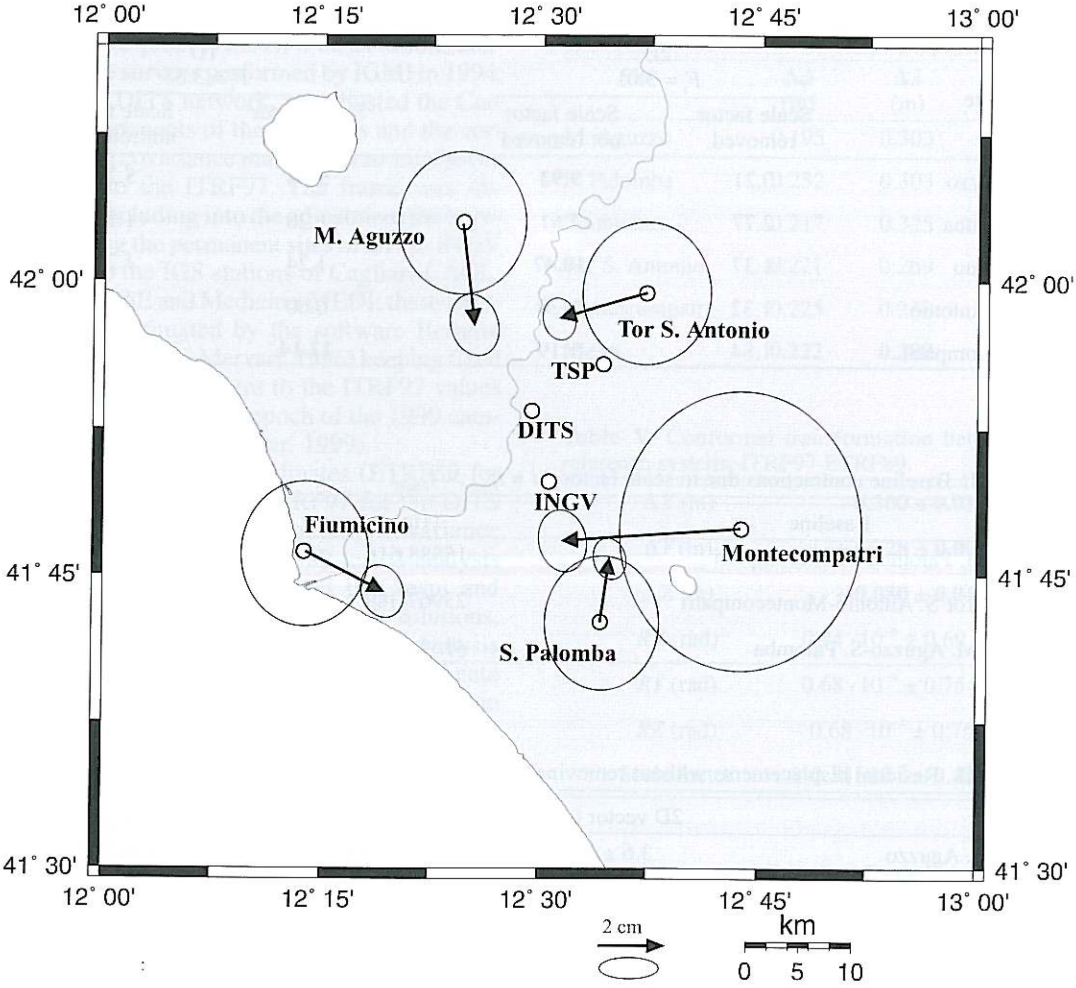

Fig. 3. Horizontal displacements without removing the scale factor (error ellipsis at 95% confidence level).

vectors in the two cases and the corresponding error ellipses are shown in figs. 3 and 4.

Excluding any geophysical process capable of producing such a contraction across the Rome area, we think that the scale factor shows a strong bias due to the analysis itself. In particular, since both the networks were processed in almost ionosphere free condition (using the L3 linear combination) for baselines longer than 5 km, it seems that only erroneous satellite orbits could produce a remarkable network horizontal scaling. As widely reported in GPS literature, the relative precision of the orbits directly reflects into the baseline relative precision (Bauersima's rule of thumb)

$$\frac{|\Delta b|}{|b|} \approx \frac{|\Delta r|}{|r|}$$

where $|b|$ is the baseline length, $|\Delta b|$ is the

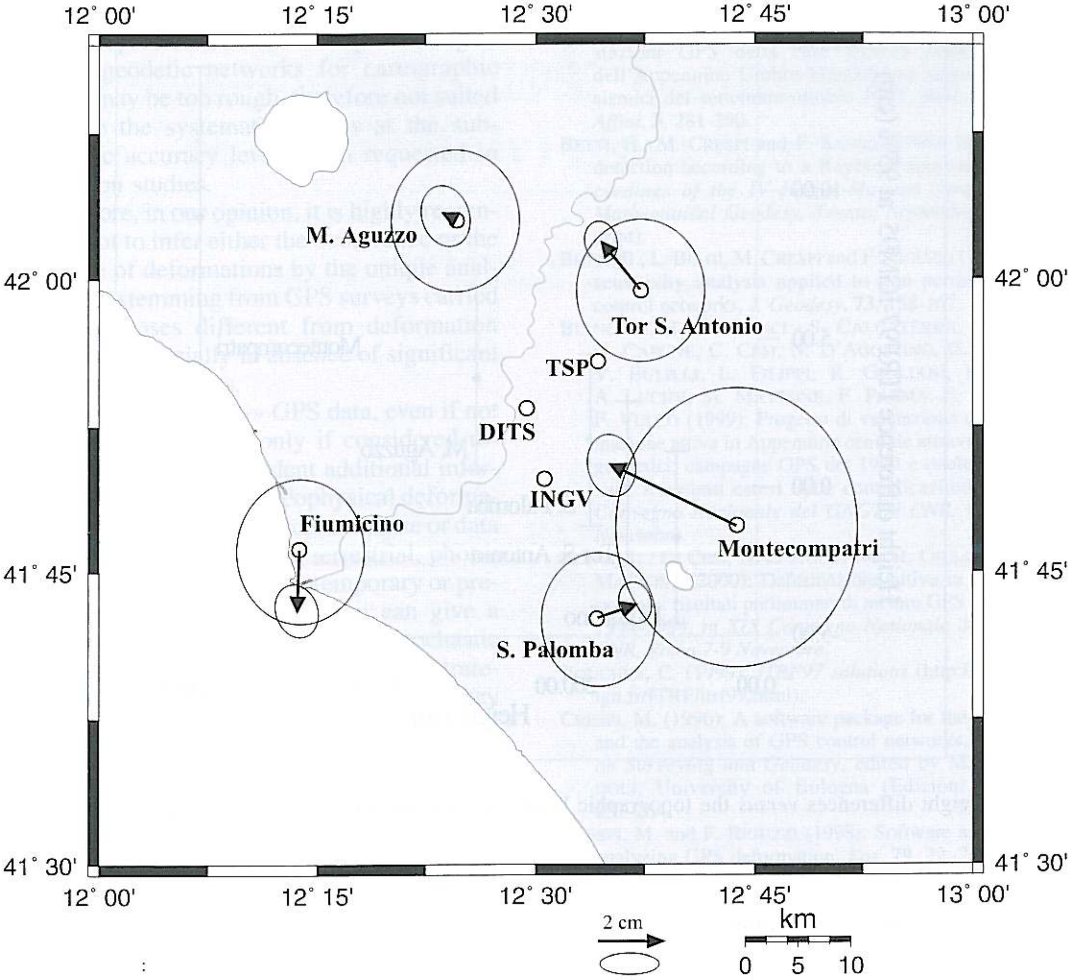

Fig. 4. Horizontal displacements after removing also the scale factor (error ellipsis at 95% confidence level).

error on the baseline, $|r|$ is the distance of the satellite from the geocenter and $|\Delta r|$ is the orbit error. In our case both the analysis were made with the broadcast orbits, but the broadcast orbits in 1994 were remarkably worse than in 1999, so that an error $|\Delta r|$ of 20 m can be assumed as realistic, causing a relative baseline error of 1.0 ppm.

Now, focusing on the height differences, they result independent from the scale factor removal (tables VIII and IX) but exhibit a strong correlation with the site heights: the height differences increase about linearly with the site heights, as shown in fig. 5. This fact reveals the presence of systematic effects due to incorrect troposphere delay modelling (no troposphere delay estimation with respect to the standard model were performed in the baseline processing for both the networks).

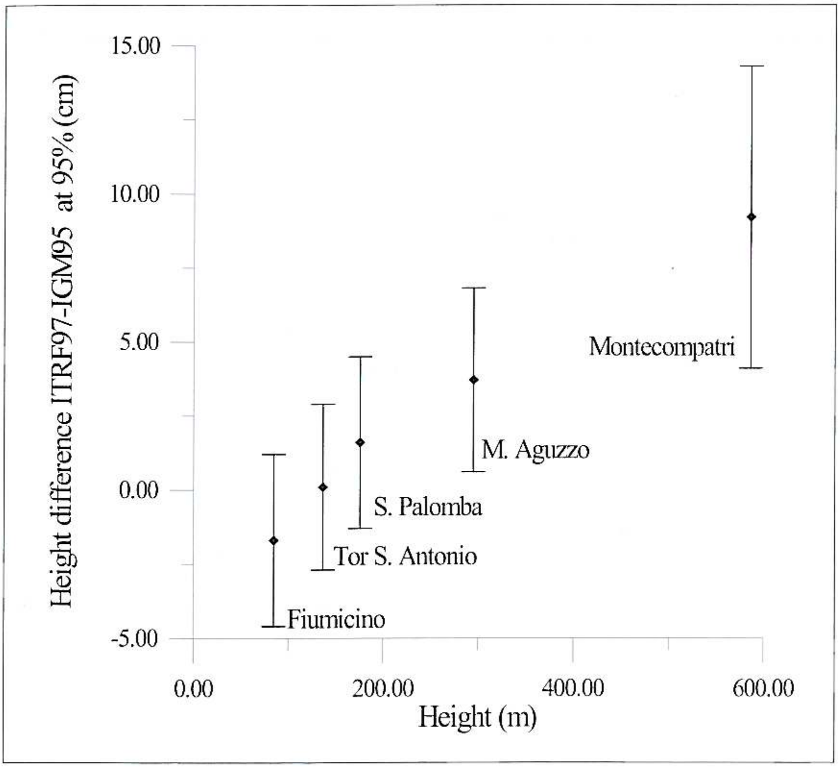

Fig. 5. Height differences *versus* the topographic height of each site (confidence interval at 95% confidence level).

5. Discussion and conclusions

In this paper we focused on the question whether GPS networks born with cartographic aims can be safely used in crustal deformation control, even in absence of large sporadic or episodic deformation signals.

In other words, we performed a «zero» test to establish whether the contribution of some residual systematic errors, some of them intrinsically related to the GPS, observation strategies and data processing, prevails on the random noise normally accounted by the error ellipsoids, by producing unreliable deformation patterns of the network.

The test was performed on a network of 5 sites located in the Rome district, over an area with a radius of about 30 km. Two GPS surveys were carried out, in 1994 by IGMI and in 1996-1999 by DITS (Rome University «La Sapienza»); this is a time span in which no slow deformation episodes or significant seismic events occurred.

The deformation analysis showed that:

– Remarkable scale factor probably due to orbit errors may lead to wrong conclusions about horizontal deformations.

– Unmodeled troposphere delays may cause false vertical displacements.

We conclude that the shown displacements do not represent real deformations, but they are exclusively due to residual modeling errors, which may be not crucial for GPS networks established for cartographic purposes but are critical in deformation monitoring, because they escape a simple statistical significance analysis.

In other words, the functional and stochastic models adopted in the GPS data processing to establish geodetic networks for cartographic purposes may be too rough, therefore not suited to remove the systematic effects at the sub-centimetric accuracy level, often requested in deformation studies.

Therefore, in our opinion, it is highly recommended not to infer either the occurrence or the magnitude of deformations by the unique analysis of data stemming from GPS surveys carried out for purposes different from deformation monitoring, especially in absence of significant deformation processes.

These «low accuracy» GPS data, even if not optimal, may be useful only if considered together with other independent additional information, like geological or geophysical deformation models, geomorphological evidence or data from other surveys (geodetic terrestrial, photogrammetric or SAR), both contemporary or previous. The additional information can give a significant contribution as *a priori* stochastic model in a Bayesian deformation testing strategy proposed in (Betti *et al.*, 1998), even if they are not strictly related to the sites monitored by GPS but generally to the area covered by the GPS network.

Finally, a remarkable improvement in deformation detection reliability is likely to be supplied by the availability of coordinate time series rather than couple of coordinate estimates and future work will be driven also in this investigations.

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