Densification of IGS/EPN by local permanent networks: sensitivity of results with respect to the adjustment choices

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Abstract

Local GNSS permanent networks materialize the global reference frame through their estimation and distribution of coordinates and velocities. These estimates are provided by the classical network adjustment process, including several nearby reference IGS/EPN permanent stations as fiducial constraints. GNSS data modelling is still a topic of research as the final results can be very sensitive to the processing choices: during the last years, IERS conventions as well as IGS and EPN guidelines have been periodically updated in order to reflect the state of the art. This work aims to evaluate the sensitivity of the adjustment results with respect to the processing choices. To perform the tests, two local permanent networks, characterized by different geometries and geographic locations are used; the first network is in Lombardia, a region in the northern pre-alpine Italy; the second is in Puglia, in the southern Mediterranean Italy. Respectively, 12 and 6 months of data are analysed. Different processing choices are applied and the relevant results are compared: firstly different constraining weights for the fiducial stations are tested, secondly the estimation of ZTD's alone is compared with the estimation including horizontal gradients, and finally the ocean loading effects are analyzed.

In the adjustment of a local network the normal practice is the inclusion and constraining of some IGS stations; we have studied the adoption of a national zero order network as a link between the global and the local networks. The new zero order network of Istituto Geografico Militare (IGM, the Italian Cartographic Institute) is used for an experimental test; in this case, only one month of data is available and is analysed. At the end the differences between IGS05 and ITRF2005 coordinates are analysed.

1. Introduction

In '80 and '90, zero order networks of GPS stations were established in almost all the European countries, designed to disseminate the datum with an accuracy of some cm for cartographic purposes. In case they have not been periodically resurveyed, neither displacements in time nor velocities have been estimated, as a consequence they are defined as static networks, which materialize static reference frames. For example, the Italian static network is IGM95 (Surace, 1997). To fully exploit new GPS/GNSS techniques, permanent networks have been set up in many European countries during the last twenty years, with the aim to provide positioning services to users. Besides distributing RINEX files and estimated coordinates of the stations, typically they provide network products for real time surveys (see for example, Wübbena et al., 2001; Xiaoming et al., 2003).

To guarantee maximum reliability and accuracy, a positioning service should monitor its stations coordinates by a continuous adjustment in the global IGS network, by constraining IGS coordinates, ephemerides, EOP's and by adopting the IERS Conventions (Mc Carthy et al., 2003), the IGS (Ferland et al. 2002, Kouba, 2003, http://igscb.jpl.nasa.gov/) and EPN (EPN, 2002, http://www.epncb.oma.be/) data processing guidelines. In this way, at its spatial scale, a positioning service materializes and distributes the current IGS realization (Beutler et al., 1999; Ray et al., 2004) of ITRS, at present IGS05 (Gendt, 2006, Ferland, 2006). Several topics relevant to the distribution of reference frames by positioning services have been discussed in Benciolini et al. (2008) where the use of IGS05 weekly solutions to constrain IGS stations in the adjustment of local networks is suggested. Indeed the low update rate of the long term ITRF solution (Altamimi et al., 2007) poses a technical problem in the forward propagation of coordinates and velocities for IGS permanent stations, that often (in average each 20 months) experience hardware changes. At last, note that most of the users need to be connected to the national cartographic reference frame so that, to be effective for cartographic and cadastral applications, the positioning services should also estimate and distribute the transformation between IGS05 and the national cartographic reference frame.

GNSS positioning services are in full development in Italy as presented at the EUREF 2007 symposium (Biagi et al., in press), but the situation is rapidly evolving. For administrative reasons public positioning services are designed, created and managed at a local scale, corresponding to Italian Regions (Fig. 1): to give a more precise idea, Italy has an extension of 301388 km^2 and includes 20 regions, whose extensions range within 3262 km^2 (Val D'Aosta) and 25708 km^2 (Sicilia). At the present, about 10 local positioning services are officially operating and distributing data to the user community while 6 others are under development. Moreover, a private firm (Leica Geosystems Italia, http://www.leica-geosystems.com/it/) manages a permanent network (ItalPos, http://www.italpos.it) composed of about 100 stations over the nation and distributing both RINEX files for post-processing and RTCM streams for real time.

To guarantee the distribution of consistent reference frames at the national scale, all the local positioning services should be adjusted and continuously monitored in a common zero order permanent network; moreover, the transformation between the global and the national cartographic reference frames should be estimated and continuously monitored. Clearly, the IGS network represents the zero order permanent network at the global scale but, on the other hand, zero order permanent networks at the national scale provide a densification of IGS network that could be better designed and suited for national needs and purposes. In addition to that, national zero order permanent networks can also monitor both the coordinates distributed by local sub-networks and the transformation between the global and cartographic national reference frames. Finally, national zero order permanent networks can be coupled by national geodetic authorities that could certify coordinates and products distributed by all the local positioning services. A test for an Italian zero order permanent network was already presented and discussed at EUREF 2007. During the last year the Italian geodetic and cartographic national agency (Istituto Geografico Militare, http://www.igmi.org) has defined a new, official, zero order network, called Rete Dinamica Nazionale (RDN, National Dynamic Network, Fig. 1), aimed to update the adjustment of IGM95. RDN is composed of about 100 stations selected from the already existing permanent stations in Italy; all of them are permanently running, but at present not all are freely publishing the data and none automatically transfers the data to IGM.

The first test of the paper is a comparison of the results and the quality indexes provided by different processing choices in the adjustment of local networks: in particular different constraining strategies for IGS fiducial stations are analysed, then the estimation of ZTD's alone is compared with the estimation including horizontal gradients, and at the end ocean loading effects are analyzed. The second test is to verify if the adjustment of local networks benefits from a zero order national network, in this case the RDN. The last comparison concerns the differences between IGS05 and ITRF2005 at the Italian scale. The data set and the general analysis methodology are described in Sect. 2. The comparisons and their motivations are discussed in Sect. 3 and 4, and conclusions are given in Sect. 5.

2. Test data set and results analysis

To achieve general results, morphology and geographical features of Italy were taken into account in the choice of the case studies: significant differential movements of about 1 cm/y exist between Northern and Southern Italian regions (Jimenez et al., 2006), moreover Italy presents mountains as

well as planes and coasts and finally the shapes of Italian regions, and related local networks, are very heterogeneous. Lombardia and Puglia networks provide a representative sample: Lombardia is a pre-alpine and alpine region in the North, whereas Puglia, in the South, has mainly planes and costal areas; Lombardia is almost squared, while Puglia is very elongated. Lombardia network (http://www.gpslombardia.it, Fig. 2) services an area of 23861 km^2 and is composed of 17 stations, with a mean distance of about 50 km; one year of data has been used for the test, from March 18th 2007 (GPS Week 1419) to March 15th 2008 (GPS Week 1470). Puglia network (http://gps.sit.puglia.it, Fig. 2) services an area of 19365 km^2 and is composed of 12 stations, with a mean distance of about 60 km; in this case six months of data are available, from September 30th 2007 (GPS Week 1447) to March 15th 2008 (GPS Week 1470).
RDN is composed of 102 stations almost homogeneously distributed over the peninsula and most of them belongs to previously established networks: all the Italian IGS and EPN stations, many stations of ASI (http://geodaf.mt.asi.it) and INGV (http://ring.gm.ingv.it) networks and stations of local positioning services (where already operating) have been included. At the present, available RDN data set spans from December 23rd 2007 (GPSW1459) to January 19th 2008 (GPSW1462).

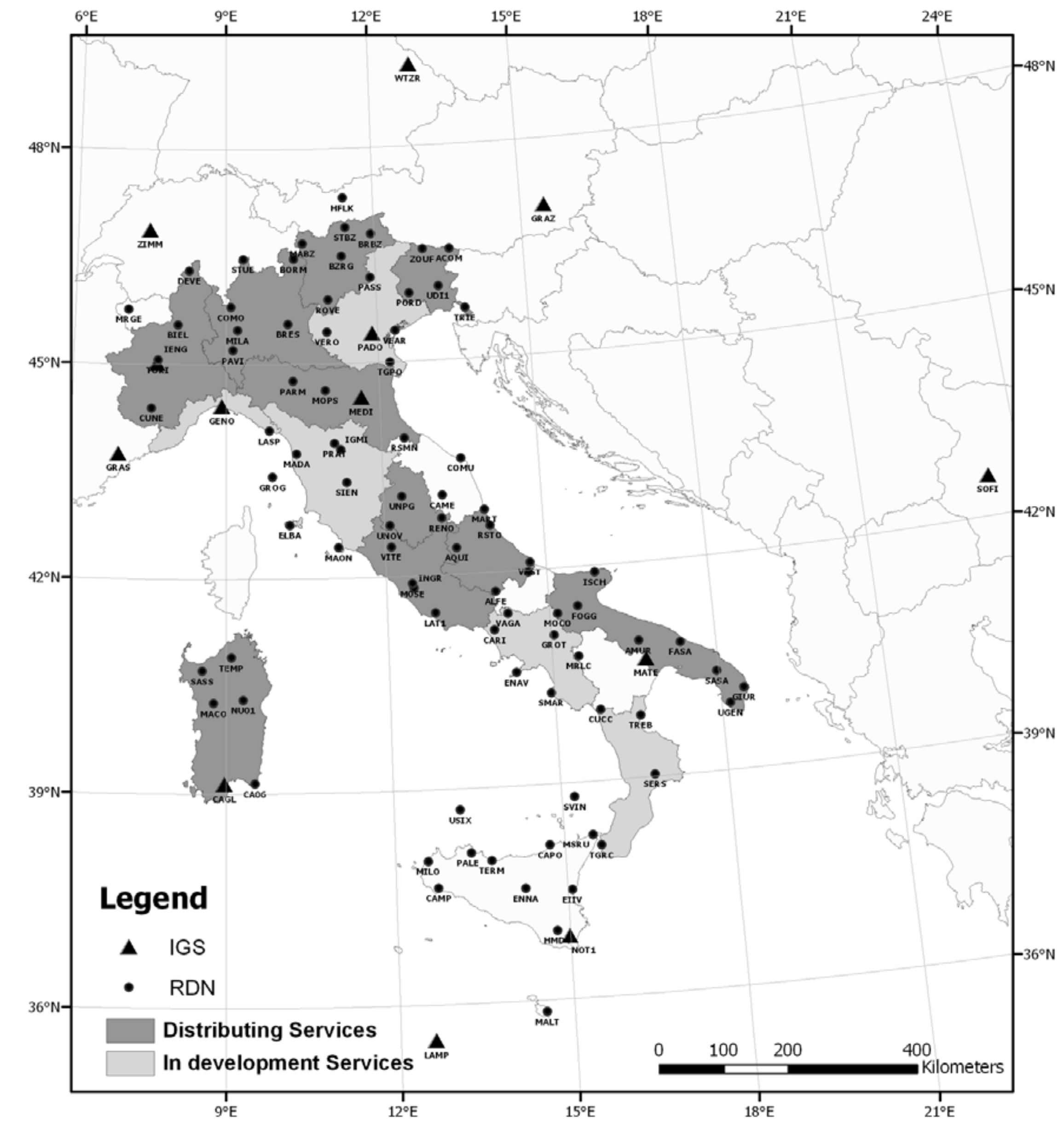

Figure 1. Italian regions and local positioning services. IGS permanent stations and RDN network.

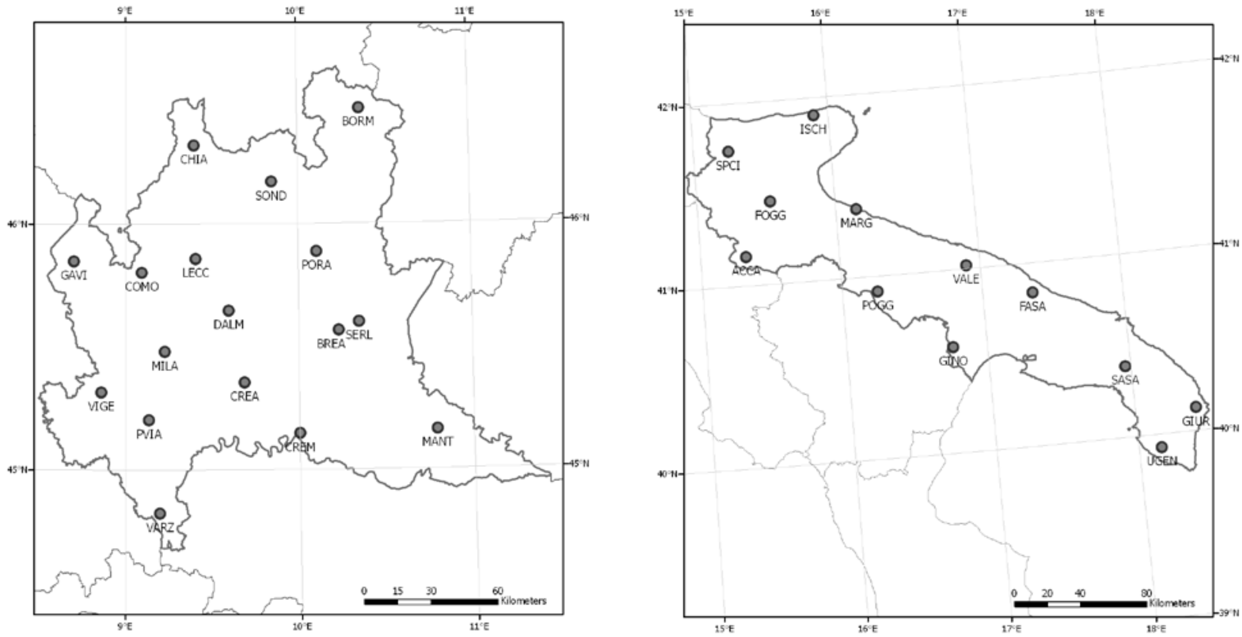

Figure 2. Test networks: Lombardia (left) and Puglia (right) positioning services.

The data have been processed by daily sessions, organized in weekly campaigns, with the Bernese 5.0 Software (BSW5.0, Dach et al., 2007). All the comparisons are based on a common set of processing choices. The daily sessions have been adjusted by constraining the coordinates of a set of fiducial IGS stations, that have been chosen according to the following requirements: well distributed, characterized by good data quality and present in almost all the weekly IGS solutions of the test year. CAGL, MATE, WTZR, GRASS, MEDI, ZIMM, GRAZ, PADO (8 stations) have been chosen in Lombardia adjustment, CAGL, NOT1, MATE, SOFI, MEDI (5 stations) have been used in Puglia adjustment and all of them in RDN adjustment. DUBR and ORID have not been included because of their large data gaps but, on the contrary, despite several data gaps MEDI and NOT1 have been included because of their importance in the Italian framework. To compute the IGS coordinates at the central epoch of each week, the approach proposed in Benciolini et al. (2008) has been applied: a robust interpolation of the previous 52 weekly IGS solutions has been computed and all the propagated IGS coordinates have been constrained in the adjustment. In this paper an over-constrained approach is used, while IGS and EPN guidelines suggest a minimum constraints approach. The minimum constraints approach is correct in the estimation of sub-network solutions that are redirected to a final, joined adjustment as in the case of IGS and EPN LAC's, on the other hand, we are adjusting a local network to estimate a local densification of the global reference frame and in this case the over-constrained solution seems appropriate in order to exploit all the information provided by IGS. The final IGS products (EOP, EPH and PCV) have been used and the BSW5.0 guidelines have been applied in the data processing (Rothacher et al., 1998, Rothacher, 2002, Dach et al., 2007).

Note that the lengths of internal baselines (e.g. connecting stations of the local networks) range from 20 Km to 70 Km, whereas the baselines connecting the local networks to IGS are typically longer than 100 Km, with two baselines of about 600 Km.

To model Lombardia time series of daily coordinates, the sum of a linear term plus a periodic signal, with an assigned period of one year, has been adopted:

$$x(t) = x_0 + v_x \cdot t + \alpha_x \cos(\omega t) + \beta_x \sin(\omega t) \qquad (1)$$

where x is either East, North or Up, t is the day, x_0 is the t_0 coordinate, v_x is the linear velocity, α_x, β_x are the amplitudes of periodic cosine and sine and conventionally $\omega = 2\pi / 365$; the power of the periodic signal can be computed by the $P_x = \sqrt{\alpha_x^2 + \beta_x^2}$.
In Puglia network analysis, only the linear regression has been used to model the time series, whereas in all the comparisons involving RDN (one month) just a constant coordinate model has been adopted. For each processing option, the model parameters have been estimated by least squares for each station i and each component x, and station daily residuals $r_{i,x}(t_j)$ have been computed with respect to the model. Station standard deviations, daily standard deviations and a global standard deviation have been derived from residuals:

station std.dev.: $$\sigma_{i,x} = \sqrt{1/N(S_i) \sum_{j=1..N(S_i)} r_{i,x}^2(t_j)} \quad (2)$$

daily std.dev.: $$\sigma_x(t_j) = \sqrt{1/N(t_j) \sum_{i=1...N(t_j)} r_{i,x}^2(t_j)} \quad (3)$$

global std.dev.: $$\sigma_x = \sqrt{1/N \sum_j \sum_i r_{i,x}^2(t_j)}, \quad (4)$$

where $N(S_i)$ is the number of days involving station i, $N(t_j)$ is the number of stations in day j, and
$N = \sum_j N(t_j) = \sum_i N(S_i)$
Note that the estimation of velocities and annual signals powers has not geophysical meaning because of the short duration of the data set, however it is useful to correctly model the deterministic component of the time series and to obtain almost uncorrelated final daily residuals.

3. Processing options comparisons

Fiducial coordinates modelling: hard constraints versus soft constraints. In an over-constrained adjustment, different weighting strategies of the constrained coordinates can produce different results: among all the possible choices, two cases have been analysed. A quasi deterministic constraining is the classical approach and consists in attributing very small standard deviations to the constraints, for example values of 0.1 mm both in plane and in height. These accuracies are not realistic but it is sometimes reported that this approach guarantees the best repeatability. A more conservative approach consists in attributing realistic accuracies to the constraints, for example 2 mm horizontally and 4 mm in height. In the following comparisons, the first approach will be called *Hard constraints*, the second one *Soft constraints*: note that our Soft approach is different from the so called Loose constraints, in which accuracies of about 10 cm are applied to the "constrained" coordinates.
Troposphere modelling: no gradient versus gradient estimation. The estimation of Zenith Tropospheric Delays significantly improves coordinate repeatability of permanent networks at each spatial scale: in BSW5.0 ZTD's are modelled as a stepwise function, whose estimation is suggested at one hour intervals. In the adjustment of regional networks also the troposphere horizontal gradients must be estimated: in BSW5.0 the estimation of two directional derivatives for each station, each day is suggested. We investigated the effects of troposphere gradients on the estimates of local network; for this reason the results provided by a *No gradient estimation* approach have been compared with those provided by a *Yes gradient estimation* approach.
Ocean loading modelling: no ocean loading versus ocean loading modelling. We investigated the actual effect of ocean loading on local networks estimates; for this reason a comparison has been performed between an adjustment involving ocean loading modelling and one without. Particularly in the *Yes ocean loading* adjustment the GOT00.2 model (Ray, 2005) has been applied

and all the stations coefficients have been downloaded from the Onsala Space Observatory website (http://www.oso.chalmers.se). The updated IERS Conventions propose a different model, FES2004, but as we will show later it is not necessary to repeat the tests with this new model.
The second and the third test seem technical but, in a more methodological perspective, analyse the reference frame sensitivity with respect to the processing choices. In principle, the correct modelling of atmospheric and tidal phenomena allows obtaining less noisy coordinate time series. However, as we were unsure about the opportunity of estimating troposphere gradients for local networks, where the shortest baselines are of about 20-40 km, this had to be tested. Moreover, we wanted to investigate if, at the local scale, a simplified processing is equivalent to the rigorous one. This analysis is also useful to understand if local networks can be adjusted by using commercial software that typically implement simplified processing options.

3.1. Reference solution: Soft constraints, Yes gradient, Yes ocean loading

A reference solution has been obtained by following IGS and EPN guidelines in the data modelling (*Yes gradient*, *Yes OC*) and by applying realistic accuracies to the constrained coordinates (*Soft constraints*) and it provides satisfactory results, for both the networks. Daily initial ambiguities (Fig. 3) and fixing percentages (Fig. 4) are typically normal, but some exceptions exist related to baselines involving MEDI and MATE stations, which show anomalous peaks. Despite that, daily BSW5.0 RMS's (Fig. 5) and coordinates standard deviations (Fig. 6, Tab. 1) are completely satisfactory; just some mediocre result appears in the final Up time series, but no real outlier so that all the data and the results have been retained for the following comparisons. As already stated, the estimates of velocities and annual signals powers are not significant: the horizontal velocities (Tab. 2) are consistent with the known Italian geodynamics, the bias in vertical velocities of Puglia stations is probably due to the availability of just a semi period of the annual cycle, BREA shows a significant horizontal annual signal probably due to a thermal cycle of the building, and the greater height signals are typical to alpine or pre-alpine stations. Note that during summer Lombardia network statistics (Figs. 4 and 5) are slightly worse, which is probably due to the residual ionospheric effect (Brunner and Gu, 1991).

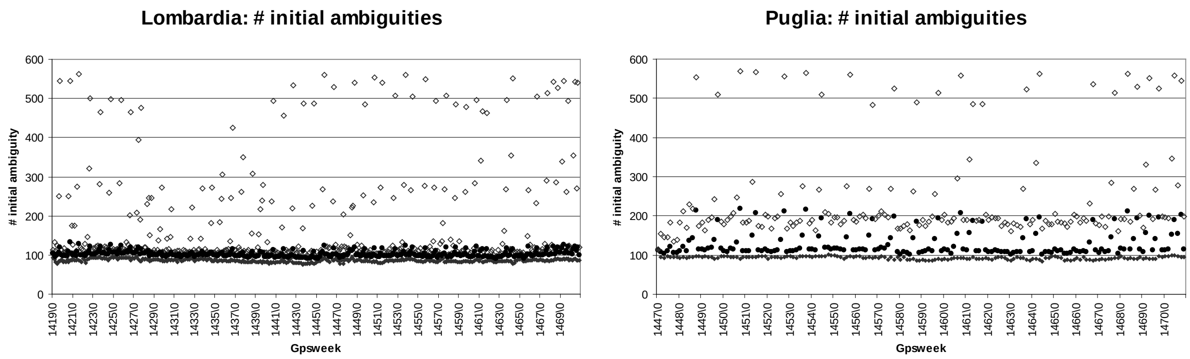

Figure 3. Reference solution. Statistics of initial ambiguities (single baselines).
Filled grey and black squares: daily minima and means; empty grey diamonds: daily maxima.
The maxima are typically relevant to baselines involving MATE station.

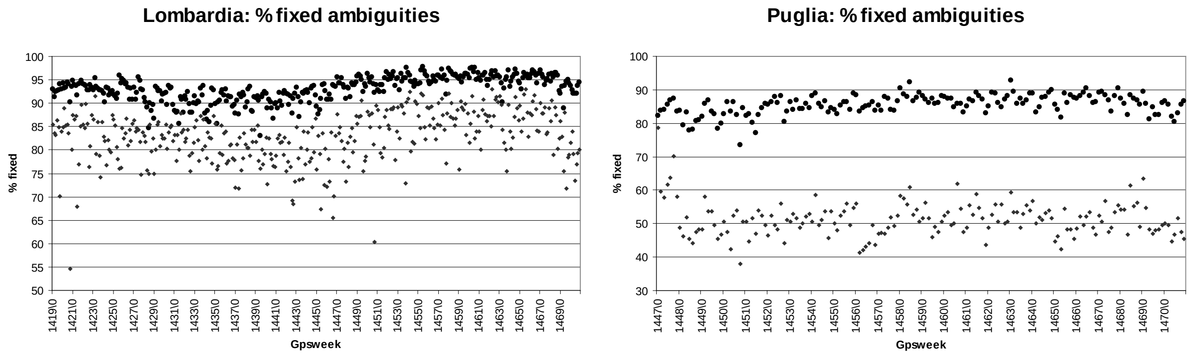

Figure 4. Reference solution. Statistics of percentages of fixed initial ambiguities. For Lombardia network: smaller percentages during summer (about from GPSW 1425 to GPSW 1445)
Black series: daily means; empty grey diamonds: daily maxima.
The minima are typically relevant to baselines involving MATE station.

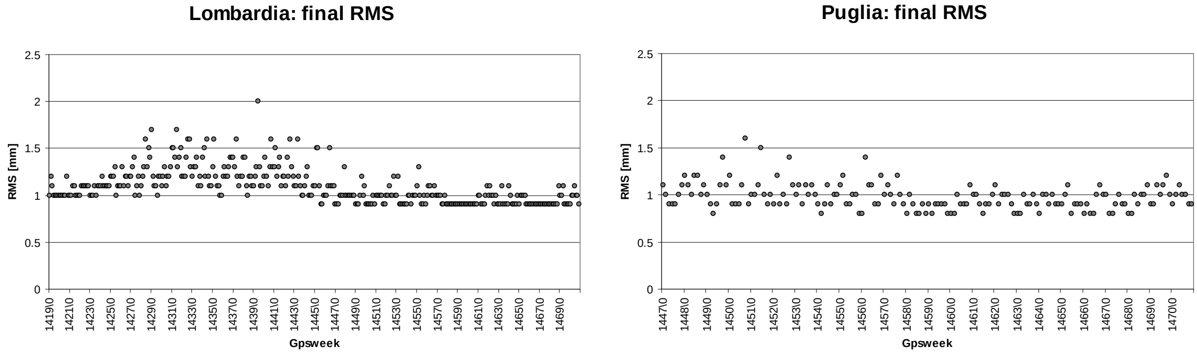

Figure 5. Reference solution: daily final BSW5.0 multibase RMS's.
For Lombardia network: higher RMS's during summer (about from GPSW 1425 to GPSW 1445).

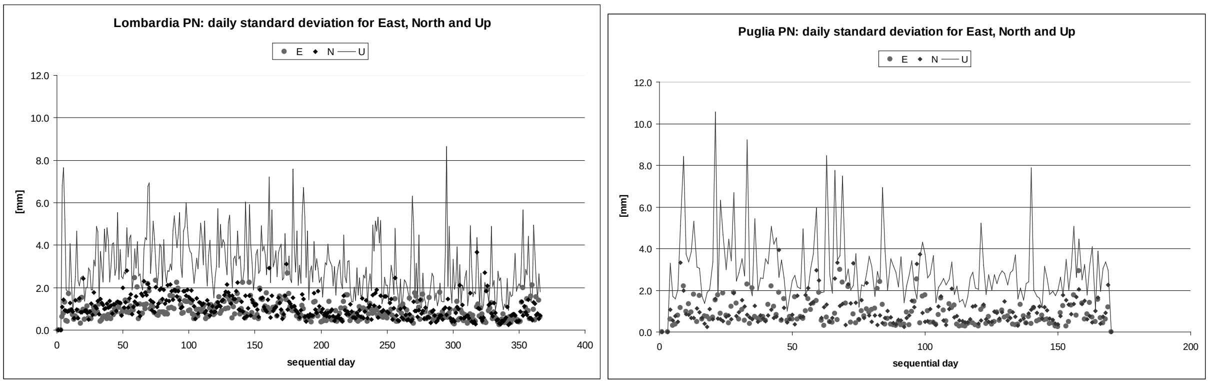

Figure 6. Reference solution: daily standard deviations.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	1.0	1.2	3.4	1.2	1.3	3.6
σ_{Max}	1.5	1.8	4.9	1.4	1.6	4.3
σ_{Min}	0.8	0.8	2.7	1.0	1.2	3.0
r_{Max}	9.9	9.4	21.3	5.7	7.3	18.5

Table 1. Statistics of the reference solution (*Soft constraints*, *Yes gradient*, *Yes ocean loading*). $\boldsymbol{\sigma_G}$: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

Lombardia network												
	East				*North*				*Height*			
	V	σ_V	*P*	σ_P	*V*	σ_V	*P*	σ_P	*V*	σ_V	*P*	σ_P
BORM	17.9	0.5	1.6	0.2	17.0	0.5	0.4	0.2	-7.4	1.4	4.3	0.5
BREA	19.4	0.3	0.6	0.1	19.4	0.4	4.6	0.2	-0.2	0.8	0.9	0.2
COMO	20.8	0.3	1.4	0.1	17.2	0.3	0.9	0.1	-0.9	0.9	2.0	0.4
CREA	20.0	0.2	0.5	0.1	17.3	0.2	0.0	0.1	-4.3	0.8	1.5	0.2
CREM	20.1	0.2	0.7	0.1	17.7	0.2	0.6	0.1	-4.2	0.8	0.7	0.3
DALM	19.5	0.3	2.0	0.1	17.1	0.3	1.0	0.1	-2.9	0.8	0.8	0.2
GAVI	18.9	0.4	0.5	0.1	16.7	0.4	1.7	0.2	-2.2	0.9	0.8	0.4
LECC	18.5	0.3	1.4	0.1	16.9	0.4	1.1	0.2	-1.9	1.1	0.5	0.4
MANT	20.2	0.3	0.1	0.1	17.7	0.3	1.2	0.1	-4.5	0.9	1.1	0.3

MILA	19.6	0.3	1.2	0.1	18.0	0.3	1.3	0.1	-6.3	0.9	1.0	0.3
PORA	18.9	0.3	0.6	0.2	18.0	0.4	0.6	0.2	-2.3	1.2	1.3	0.5
PVIA	20.1	0.3	1.9	0.1	17.7	0.3	1.2	0.1	-4.5	0.8	1.6	0.2
SOND	18.3	0.3	0.6	0.1	18.0	0.5	0.6	0.2	-3.8	1.4	4.0	0.6
VARZ	19.7	0.3	1.6	0.1	17.1	0.4	0.7	0.1	-1.0	1.1	2.6	0.3
VIGE	20.4	0.3	0.9	0.1	17.1	0.3	0.3	0.1	-3.0	0.9	1.0	0.2

Puglia network						
	VEast	σ_{VEast}	*VNorth*	σ_{VNorth}	*VHeight*	$\sigma_{VHeight}$
ACCA	22.5	0.8	21.4	0.9	-16.5	2.3
FASA	25.9	0.8	19.1	0.8	-11.4	2.0
FOGG	26.3	0.6	17.7	0.7	-13.4	2.4
GINO	24.9	0.6	20.4	0.7	-14.3	2.0
GIUR	27.3	0.7	19.0	0.7	-10.5	1.9
ISCH	26.7	0.6	19.8	0.8	-5.2	2.6
MARG	25.0	0.6	20.2	0.7	-9.5	2.1
POGG	22.6	0.7	16.9	0.7	-0.4	2.2
SASA	25.6	0.7	20.8	0.7	-9.7	1.7
SPCI	22.0	0.7	17.4	0.8	-12.9	2.3
UGEN	27.8	0.7	20.2	0.7	-8.9	2.0
VALE	26.9	0.6	22.6	0.7	-7.1	1.8

Table 2. Estimated velocities (V), annual signal power (P) (only for Lombardia) and related standard deviations (σ). Velocities in mm/y, powers in mm. Note that the numerical values are reported for completeness, but are not significant from a geophysical point of view, being estimated from one year (Lombardia) or six month (Puglia) of data.

3.2. Fiducial coordinates modelling: Hard versus Soft Constraints comparison

For IGS stations, the differences between a priori and daily estimated coordinates are always smaller in the Hard solution. In particular the mean differences (over all the days, all the IGS stations) are negligible in both the solutions, but the Soft standard deviations are of 2 mm horizontally and 4 mm in height, while the Hard are smaller than 1 mm in all the components. However, the statistics of the adjusted stations (Tab. 3) are almost equal between the two solutions: contrary to popular belief, harder constraints don't improve significantly estimated time series. Horizontal model parameters (Tab. 4) are substantially equal, except for a small but clear bias of 1 mm and 1 mm/y in North coordinate and velocity; larger differences of about 2 mm exist in height.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	1.0	1.1	3.1	1.0	1.1	3.5
σ_{Max}	1.5	1.8	4.9	1.2	1.5	4.2
σ_{Min}	0.7	0.8	2.5	0.9	0.9	2.9
r_{Max}	9.9	9.1	21.9	5.3	7.5	19.6

Table 3. Statistics of Hard constraints solution (Yes gradient, Yes ocean loading). $\boldsymbol{\sigma_G}$: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

Lombardia Permanent Network: Hard versus Soft constraints									
	Coordinates differences			Velocities differences			Periodic signal differences		
	ΔEast	*ΔNorth*	*ΔUp*	*ΔVEast*	*ΔVNorth*	*ΔVUp*	*ΔPEast*	*ΔPNorth*	*ΔPUp*
Mean	0.3	-1.5	1.3	-0.5	1.1	0.1	0.0	0.1	-0.2
Med	0.3	-1.5	1.4	-0.5	1.1	0.0	0.1	0.2	-0.1
σ	0.1	0.1	0.4	0.1	0.1	0.3	0.1	0.2	0.1

Max	0.5	-1.2	1.7	-0.4	1.2	0.9	0.2	0.3	0.1
Min	0.1	-1.6	-0.1	-0.7	1.0	-0.2	-0.2	-0.3	-0.6

Table 4. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates and Power differences in mm, velocities in mm/y.

Puglia Permanent Network: Hard versus Soft constraints						
	Coordinates differences			Velocities differences		
	ΔEast	*ΔNorth*	*ΔUp*	*ΔVEast*	*ΔVNorth*	*ΔVUp*
Mean	-0.7	-1.0	-1.9	0.5	1.0	2.0
Med	-0.7	-0.8	-1.8	0.6	0.9	1.9
σ	0.2	0.2	0.6	0.2	0.2	0.6
Max	-0.5	-0.7	-1.1	0.8	1.4	2.9
Min	-0.9	-1.4	-2.8	0.3	0.7	1.2

Table 5. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates differences in mm, velocities in mm/y.

3.3. Troposphere modelling: No Gradient versus Yes gradient comparison

For both the networks, the estimation of troposphere gradients significantly improves horizontal statistics (Tab. 6), in Lombardia the final estimates (Tab. 7) are practically equal with the exception of North coordinates, for Puglia network (Tab. 8) the vertical velocities increase in magnitude and this is probably an emphasizing of the annual signal already existing in the reference solution (Guenter Stangl, personal communication).

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	1.5	1.6	3.3	1.6	1.7	3.4
σ_{Max}	1.7	1.9	4.5	1.9	2.0	4.0
σ_{Min}	1.3	1.4	2.7	1.4	1.4	2.8
r_{Max}	9.5	10.9	19.4	7.6	9.7	18.1

Table 6. Statistics of No Gradient solution (Soft constraints, Yes ocean loading). $\boldsymbol{\sigma_G}$: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

Lombardia network: No gradient versus Yes gradient estimation									
	Coordinates differences			Velocities differences			Periodic signal differences		
	ΔEast	*ΔNorth*	*Δ Up*	*ΔVEast*	*ΔVNorth*	*ΔV Up*	*ΔPEast*	*ΔPNorth*	*ΔP Up*
Mean	0.0	1.1	0.5	0.0	0.0	-0.9	-0.1	0.2	-0.1
Med	-0.1	1.0	0.4	0.0	-0.2	-0.5	0.0	0.2	-0.2
σ	0.5	0.7	0.3	0.3	0.6	0.8	0.2	0.4	0.7
Min	-0.8	-0.5	-0.1	-0.5	-0.8	-2.7	-0.5	-0.6	-1.4
Max	0.8	2.4	1.2	0.3	1.2	0.0	0.3	0.9	1.4

Table 7. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates and Power differences in mm, velocities in mm/y.

Puglia network: No gradient versus Yes gradient estimation						
	Coordinates differences			Velocities differences		
	ΔEast	*ΔNorth*	*Δ Up*	*ΔVEast*	*ΔVNorth*	*ΔVUp*
Mean	0.9	0.5	-3.1	-0.7	-0.5	5.1

Med	1.1	0.3	-2.8	-0.7	-0.3	4.7
σ	0.6	1.0	1.1	0.8	0.9	1.2
Min	-0.2	-1.3	-5.3	-2.0	-3.2	3.5
Max	1.7	3.3	-1.6	1.0	0.3	7.5

Table 8. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates and Power differences in mm, velocities in mm/y.

3.4. Ocean loading: No ocean loading versus Yes ocean loading modelling comparison

Except for numerical noise, no differences exist between *Yes OC* and *No OC* approaches (Tabs. 9, 10, 11) both for Lombardia and Puglia networks: considering these results, a comparative test with the newer FES2004 model is not useful.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	1.0	1.2	3.4	1.2	1.3	3.6
σ_{Max}	1.5	1.8	4.9	1.4	1.6	4.2
σ_{Min}	0.8	0.8	2.7	1.0	1.2	2.9
r_{Max}	9.9	9.3	21.1	5.7	7.3	17.6

Table 9. Statistics of No ocean loading solution (Soft constraints, Yes gradient). σ_G: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

Lombardia Network: No Ocean Loading versus Yes Ocean loading estimation									
	Coordinates differences			Velocities differences			Periodic signal differences		
	ΔEast	*ΔNorth*	*ΔUp*	*ΔVEast*	*ΔVNorth*	*ΔVUp*	*ΔPEast*	*ΔPNorth*	*ΔPUp*
Mean	0.0	0.0	-0.1	0.0	0.0	0.2	0.0	0.0	0.0
Med	0.0	0.0	-0.1	0.0	0.0	0.2	0.0	0.0	0.0
σ	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Min	-0.1	-0.1	-0.1	-0.1	0.0	0.1	0.0	-0.1	-0.1
Max	0.1	0.1	0.0	0.1	0.1	0.2	0.0	0.1	0.1

Table 10. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates and Power differences in mm, velocities in mm/y.

Puglia Network: No Ocean Loading versus Yes Ocean loading estimation						
	Coordinates differences			Velocities differences		
	ΔEast	*ΔNorth*	*Δup*	*ΔVEast*	*ΔVNorth*	*ΔVUp*
Mean	0.1	-0.1	-0.2	0.0	0.0	0.1
Med	0.1	-0.1	-0.2	0.0	0.0	0.1
σ	0.1	0.1	0.1	0.1	0.1	0.1
Min	0.0	-0.2	-0.3	-0.2	-0.1	0.0
Max	0.2	0.0	0.0	0.1	0.1	0.3

Table 11. Comparisons of model parameters. Station coordinates, velocities and power of the periodic signals: mean, median, greatest and smallest difference in East, North and Up components. Coordinates and Power differences in mm, velocities in mm/y.

4. Adjustment strategies comparisons: RDN and reference frame influences

At first, RDN daily sessions have been adjusted in IGS and the daily solutions have been used to estimate the coordinates of all RDN stations in IGS05 at the mean epoch of the month. Afterwards, Lombardia and Puglia networks have been independently adjusted in RDN. The results provided by the two step process have been compared with those provided by the direct adjustment (on the same

month) of the local networks in IGS. In the following, the first adjustment will be called *RDN adjustment* and the second *IGS adjustment*. The results provided by the adjustment of RDN in IGS, here not discussed, are quite satisfactory and are discussed in a more detailed technical report (Biagi et al., 2008). In RDN adjustments of Lombardia and Puglia, only RDN stations in a radius of 200 Km have been included and constrained.
Finally, to investigate the differences between IGS05 and ITRF2005 in our regions, RDN has been adjusted once again by constraining the IGS stations at their propagated ITRF2005 coordinates; then Lombardia and Puglia have been adjusted in RDN-ITRF2005 and the results have been compared with the RDN-IGS05 adjustment. In all the processing the Soft constraints, Yes gradient, Yes ocean loading approach has been applied

4.1. RDN influence: RDN versus IGS adjustments

Horizontal differences (Tab. 14) between RDN and IGS adjustments are typically smaller than 1 mm, with just one exception for Puglia network where height differences are greater but not really significant. However, the use of RDN as a link between global and local networks improves significantly the daily statistics (Tab. 13), particularly for Puglia network. In other words, the final estimates are not sensitive to the choice of the constraining stations (provided that the constrained coordinates are consistent) while the reduction of the baselines lengths and the increase of the number of constraints improve the final accuracies. This is mainly clear for Puglia, whose position with respect to IGS network (Fig. 1) is not optimal.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	0.8	0.9	3.1	1.2	1.2	2.6
σ_{Max}	1.1	1.3	5.4	1.3	1.6	3.1
σ_{Min}	0.6	0.5	2.0	0.9	1.1	2.1
r_{Max}	2.7	3.2	17.0	4.1	4.6	9.9

Table 12. Statistics of the direct adjustment (one month of data) of the local networks in IGS. $\boldsymbol{\sigma_G}$: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	0.5	0.7	2.6	0.5	0.6	2.0
σ_{Max}	0.9	1.2	5.1	1.0	1.3	2.9
σ_{Min}	0.3	0.4	1.3	0.4	0.2	1.2
r_{Max}	2.7	2.6	16.6	3.5	4.1	11.0

Table 13. Statistics of the adjustment of the local networks in RDN. σ_G: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

Coordinates differences: direct IGS versus RDN adjustments						
	Lombardia network			Puglia network		
	ΔEast	*ΔNorth*	*ΔUp*	*ΔEast*	*ΔNorth*	*ΔUp*
Mean	-0.6	-0.4	-0.8	-0.7	0.3	1.0
Med	-0.6	-0.4	-0.8	-0.7	0.3	1.0
σ	0.1	0.1	0.7	0.2	0.2	0.9
Min	-0.7	-0.5	-1.8	-1.1	0.1	-0.6
Max	-0.5	-0.3	0.4	-0.5	0.6	2.1

Table 14. Comparisons of final coordinates for Lombardia and Puglia PN's: mean, median, greatest and smallest difference in East, North and Up components. All values in mm.

4.2. Reference frame: ITRF05 versus IGS05 comparison

The differences (Tab. 15) between IGS05 and ITRF2005 coordinates for IGS stations are smaller than 5 mm in the plane and 1 cm in height: MEDI and PADO show the greatest values. The differences of the adjusted coordinates are almost equal for all the stations and, in plane, reflect the mean differences in the constrained coordinates. The statistics of RDN-ITRF2005 adjustment (Tab. 17) are similar to the statistics of RDN-IGS05 adjustment.

	East	*North*	*Up*
Mean	1.4	0.6	0.3
σ	2.2	1.2	4.9
Min	-1.9	-1.0	-7.7
Max	5.0	2.7	9.0

Table 15. Comparisons of apriori coordinates for IGS stations: ITRF2005-IGS05: mean, standard deviation, smallest and greatest difference in East, North and Up components. All values in mm.

Coordinates differences: ITRF05 versus IGS05 adjustments						
	Lombardia network			Puglia network		
	ΔEast	*ΔNorth*	*ΔUp*	*ΔEast*	*ΔNorth*	*ΔUp*
Mean	1.6	0.7	-0.3	1.8	0.5	-0.6
Med	1.6	0.7	-0.3	1.8	0.5	-0.6
σ	0	0.0	0.0	0.0	0.0	0.0
Min	1.6	0.7	-0.3	1.7	0.4	-0.6
Max	1.6	0.7	-0.2	1.8	0.6	-0.5

Table 16. Comparisons of final coordinates for Lombardia and Puglia networks: mean, median, greatest and smallest difference in East, North and Up components. All values in mm.

	Lombardia network			Puglia network		
	East	*North*	*Up*	*East*	*North*	*Up*
σ_G	0.6	0.7	2.6	0.5	0.6	2.0
σ_{Max}	0.9	1.2	5.1	1.0	1.3	2.9
σ_{Min}	0.4	0.4	1.4	0.4	0.2	1.2
r_{Max}	2.7	2.7	16.7	3.3	4.0	11.1

Table 17. Statistics of adjustment in ITRF2005. σ_G: global standard deviation; σ_{Max}: greatest station standard deviation; σ_{Min}: smallest station standard deviation; r_{Max}: greatest daily residual. Values in mm.

5. Conclusions

An experiment has been performed on two local permanent networks, located in Lombardia and Puglia Italian Regions. Firstly the differences in the results provided by different processing choices have been analysed. Secondly the adoption of a national zero order network as a link between the global and the local networks has been investigated. For this purpose the new IGM network, called RDN, has been used. Finally, the differences between IGS05 and ITRF2005 have been studied. The results show that on a local scale the ocean loading effects are negligible, while the estimation of troposphere gradients improves the horizontal repeatability. From a practical point of view, the international guidelines for regional networks should be applied also on the local scale. The increase of the constraints weights in an over-constrained adjustment improved the repeatability of the constrained stations, but the repeatability of the other stations didn’t change and the differences in the final results are not significant. The adjustment of local networks using the RDN as a link to the IGS network improved the repeatability with respect to the adjustment using only IGS. This is due both to the increase of constrained stations and to the shorter baselines. As in the previous test the differences in the final results are not significant and the coordinates estimates don't change with respect to the adjustment using only IGS. In particular, at the time of writing this paper, one month of RDN data is available and was used, but the adjustment of RDN should after a startup period switch to a continuous and automated process in order to really provide a permanent and dynamic monitoring of the reference frame at the national scale. Finally, at the Italian scale, differences up to 5 mm in plane and 10 mm in height exist between the propagated, long term, ITRF2005 solution and the weekly IGS05 solutions: these differences partly propagate in the results of the adjustment of local networks.

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References

Altamimi Z., Collilieux X., Legrand J., Garayt B., Boucher C., *ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters*, Journal of Geophysical Research, VOL. 112, 2007

Benciolini B., Biagi L., Crespi M., Manzino A., Roggero M., *Reference frames for GNSS positioning services: some problems and proposals*, Journal of Applied Geodesy, N. 2, 2008.

Beutler G., Rothacher M., Schaer S., Springer T.A., Kouba J., Neilan R.E., *The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences*, Adv. Space Res. Vol. 23, No. 4, 1999

Biagi L., Caldera S., Mazzoni A., *Rete Dinamica Nazionale: risultati di inquadramento ottenuti dal gruppo G3*, technical report, on line, geomatica.polimi.it, 2008

Biagi L., Caldera S., Crespi M., Manzino A., Mazzoni A., Roggero M., Sansò F., *A zero order network of permanent stations for the positioning services in Italy: some hypotheses and tests,* EUREF2007 Workshop Proceedings, in press

Boucher C., Altamimi Z., Memo, *Specifications for reference frame fixing in the analysis of a EUREF GPS campaign*, http://lareg.ensg.ign.fr/EUREF/, 2007

Brunner F. K., Gu M., *An improved model for the dual frequency inospheric correction of GPS observations*, Manuscripta Geodaetica 16(3), 1991

Dach R., Hugentobler U., Fridez P., Meindl M., *Bernese GPS Software Version 5.0*, Astronomical Institute, University of Berne, 2007

Dermanis A., *The ITRF beyond the linear model. Choices and challenges*, VI Hotine Marussi Symposium on Mathematical Geodesy, Wuhan, China, May 2006, IAG Symposia, Vol. 132, Springer-Verlag, Berlin, 2008

EPN, *Guidelines for EPN analysis centres*. On-line on the website http://www.epncb.oma.be/, 2002

Ferland R., Gendt. G., Schone T., *IGS Reference Frame Maintenance*, IGS Workshop 2004, AIUB, Berne, 2004

Ferland R., IGSMail 5447, http://igscb.jpl.nasa.gov/mail/igsmail/, 2006

Ferland R., Altamimi Z., Bruyninx C., Craymer M., Habrich H., Kouba J., *Regional Networks Densification, IGS*, Towards Real Time Network, Data and Analysis Centre 2002 Workshop, Ottawa, on line http://igscb.jpl.nasa.gov/, 2002

Gendt G., IGSMail 5438, http://igscb.jpl.nasa.gov/mail/igsmail/, 2006

Jimenez-Munt I., Sabadini R., Gardi A., Bianco G., *Active deformation in the Mediterranean from Gibraltar to Anatolia inferred from numerical modeling and geodetica and seismological data*. J. Geophys. Res Vol 108, 2006

Kouba J. , A guide to using International GPS Service (IGS) products, on-line on the ftp site

ftp://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGSProducts.pdf, 2003
McCarthy D. D., Petit G. eds., *IERS Conventions*, IERS Technical Note No. 32, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, 2004
Ray J., Dong D., Altamimi Z., *IGS Reference Frame: Status and Future Improvements*, Proceedings of IGS: Celebrating a decade of the International GPS Service, Berne, March 1-5, 2004, AIUB, Berne, 2004
Ray J., 2005, *IGSMail* n° 5167
Rothacher M., Springer T. A., Schaer S., Beutler G., *Processing strategies for regional GPS networks*, Advanced Positioning References Frames, IAG Symposia Volume 118, Springer-Verlag, 1998
Rothacher M., *Estimation of Station Heights with GPS, Vertical Reference Systems*, IAG Symposia Volume 124, Springer-Verlag, 2002
Surace L., *La nuova rete geodetica nazionale IGM95: risultati e prospettive di utilizzazione*, Bollettino di Geodesia e Scienze affini, Anno LVI, N° 3, 1997
Wübbena G., Bagge A., Schmitz M., *Network−Based Techniques for RTK Applications*, presented at the GPS Symposium, GPS JIN 2001, Tokyo, Japan, http://www.geopp.de/download/, 2001
Xiaoming C., Herbert L., Vollath U., *New Tools for Network RTK Integrity Monitoring*, ION GNSS 2003