GPS coordinate estimates by *a priori* tropospheric delays from NWP using ultra-rapid orbits

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Abstract
High accuracy GPS positioning estimates using scientific GPS software through three different processing strategies were compared. The two Italian baselines in a time period of 5 months during 2004 made a calculus data set. For high accuracy GPS differential positioning the use of global tropospheric delay models can be replaced by the implementation of other techniques. The GPS coordinate can be repeated when the tropospheric delay is calculated in Near-Real Time (NRT) from a Numerical Weather Prediction (NWP) model. For the NRT approach IGS ultra-rapid orbits instead of precise orbits were used. Concerning coordinate repeatability, the NWP-based strategy with tropospheric error adjustment appeared more accurate (at the submillimetric level) than a standard GPS strategy. Furthermore, several hundreds km long baselines demonstrated the standard deviation at the level of millimeters (from 4.2 to 7.6 mm). Practically, the NWP-based strategy offers the advantage of tropospheric delay estimations closer to realistic meteorological values. The application of a more accurate meteorology leads to satisfactory coordinate estimations, and *vice versa* well-defined GPS estimations of coordinates may serve as the additional meteorological parameters source.

Key words *GPS coordinates – zenith tropospheric delay – numerical weather prediction – ultra-rapid orbits – Bernese GPS software*

1. Introduction

When GPS satellite signals are transmitted through the atmosphere they are affected by the media. In the neutral atmosphere refraction is a function of the meteorological conditions such as pressure, temperature and humidity along the signal path, and this effect is referred to in GPS terminology as the tropospheric delay.

In the GPS positioning process this effect represents an important error source introducing primarily biased station heights and scale biases of estimated baseline length (Beutler *et al.*, 1988).

Usually, GPS software employs global tropospheric models (based on a standard atmosphere) to handle this effect. Instead global, other meteorologically based tropospheric delay models can be implemented, applying observational data sources. The tropospheric delay calculated from a Numerical Weather Predictions (NWP) analysis and/or forecast was already tested, (*e.g.*, Cucurull *et al.*, 2002; Jensen *et al.*, 2002; Fazlagić, 2003). In Cucurull *et al.* (2002) MM5 model forecasts are applied in GIPSY software precise point positioning to estimate the hourly improvement of geodetic vertical coordinate in 24-h reference solutions. In Jensen *et al.* (2002) NWP zenith delays are used within a GPS static positioning processing to correct

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the tropospheric delay estimation, where 15 of the total 26 baselines showed an improvement in the position accuracy with respect to a global model.

Following the GPS coordinate analysis suggested by Fazlagić (2003), coordinates of two Italian sites (Genoa and Venice), for the time period of 5 months using three different processing strategies are examined.

Ways of tropospheric delay handling may determine different approaches. The three strategies for the coordinate estimates applied in this work were:

– [MET] Meteorological strategy: by introduction of Zenith Tropospheric Delay (ZTD) *a priori* calculated from meteorological data-analysis and forecasts by a NWP model, without any further tropospheric delay error adjustment;

– [STD] Standard strategy: by ZTD *a priori* obtained by the global Saastamoinen model (Saastamoinen, 1972) followed by the tropospheric delay error adjustment;

– [MIX] Mixed strategy: by introduction of ZTD *a priori* calculated from meteorological data, like in the MET strategy, but with afterward tropospheric error adjustment, as in the STD strategy.

Also (Kleijer, 2004) discussed the differences between the approach based on ZTD «tropospheric-fixed» model, and other «tropospheric float model» techniques.

Differential positioning with GPS Bernese Software 4.2 (Hugentobler *et al.*, 2001) is applied in this work, taking a GPS observation window of 12 h at first, and then using a shorter observation window of 6 h. In this paper only results obtained with the 6-h window are shown: the wider 12-h window results do not offer significant differences.

The two independent baselines, for Venice and Genoa GPS sites, are created by the introduction of the third (fixed) GPS site, the IGS (International GPS Service) station of Medicina.

It is well known that in high accuracy positioning the prevailing source of error is originated by satellite orbits so the introduction of precise ephemeredes is suggested. Since a Near Real Time (NRT) approach is important for meteorology purposes, IGS ultra-rapid orbits (Springer and Hugentobler, 2001) are introduced instead of IGS Final orbits. In 2004 IGS ultra-rapid orbits were available twice daily offering a good accuracy (about 25 cm was indicated in http://igscb.jpl.nasa.gov).

2. Data sources and baselines definition

The GPS sites Venice (VENE) and Genoa (GENO) were selected (both with long time stable record, located in the same tectonic plate in Northern Italy and belonging to EPN – European Reference Frame Permanent Network).

Looking for a reference spot the station of Medicina (MEDI-IGS station, located in Northern Italy) appeared convenient. Thus two independent baselines were formed: Venice-Medicina (VE-ME) and Genoa-Medicina (GE-ME).

Figure 1 shows the map featuring the three GPS stations. The baseline lengths are 115351.7578 m for Venice-Medicina and (almost twice longer) 217154.4860 m for Genoa-Medicina respectively.

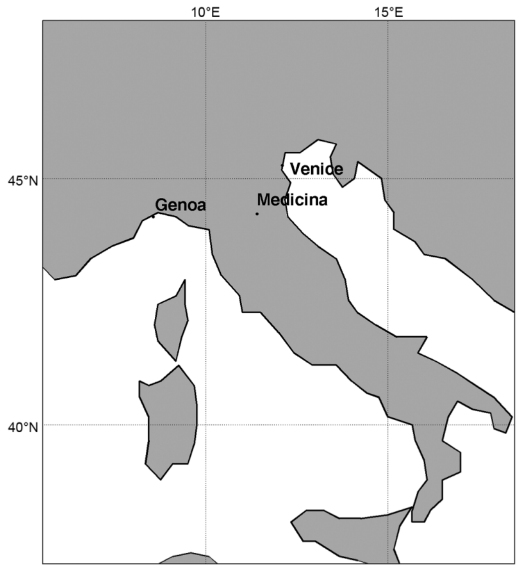

Fig. 1. The geographical map showing the GPS sites used in this work.

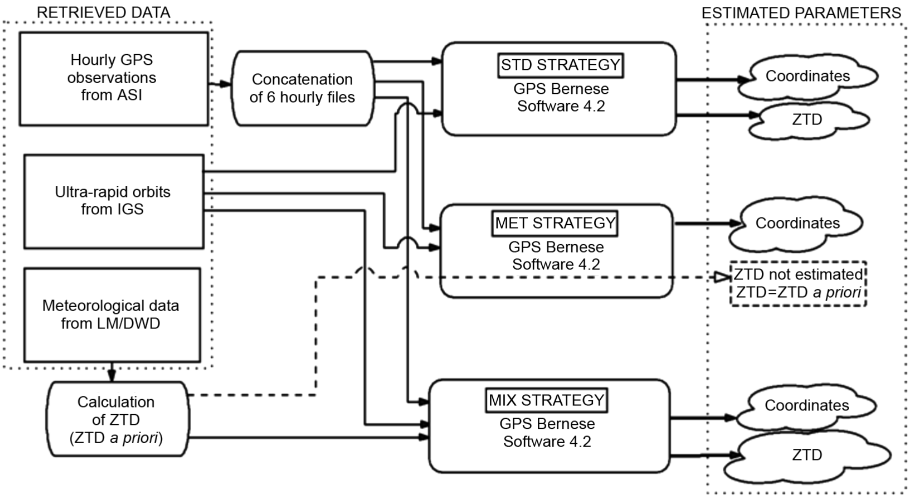

Fig. 2. Coordinate estimation block diagram for all strategies.

The Bernese processing was set up to: elevation cut-off at 15°; *Quasi*-Ionosphere-Free (QIF) algorithm in baseline mode as ambiguity resolution strategy; ionosphere-free linear combination to mitigate ionosphere dispersion; no ocean loading (its effect for the test sites and for the limited testing period was evaluated to be of the submillimeter order); tropospheric model (when used): Saastamoinen; automatic processing with the Bernese Processing Engine (BPE).

The following two datasets were retrieved:

– GPS hourly observations (for all three stations), from Agenzia Spaziale Italiana (ASI), appropriately merged to obtain a 6 h (and 12 h) window observation session (ftp://geodaf.mt.asi.it).

– The most recent GPS ultra-rapid orbits available (and Earth Rotation Parameter files) from IGS data center (ftp://igs.ifag.de).

Also, for the two meteorologically based strategies (MET and MIX) the Deutscher Wetterdienst (DWD) Local Model (LM) (DWD, 2003) analysis and forecasts interpolated over the selected sites data were retrieved. DWD data were available twice daily, where each data set is referred to 00 UTC analysis or 12 UTC analysis plus forecasts up to 48 h. DWD data refer both to the surface level and to upper air levels.

The testing period lasted five months: from January 03, 2004 to May 31, 2004, four 06-h session data windows were processed so coordinate estimates became available four times a day (00-06, 06-12, 12-18, 18-24).

Figure 2 presents a synthetic flow chart with input and output data for all three strategies.

3. Tropospheric delay modeling

In high accuracy differential positioning based on the carrier phase observable, as in the GPS Bernese Software, the slant tropospheric delay ρ_k^i between a GPS receiver k and a GPS satellite i is estimated as

$$\rho_k^i(t) = \mathrm{ZTD}_{\mathrm{apr},k} f_{\mathrm{apr}}(z_k^i) + \mathrm{ZTD}_k(t) f(z_k^i) \quad (3.1)$$

where $\mathrm{ZTD}_{\mathrm{apr},\,k}$ is the Zenith Tropospheric Delay according to the *a priori* model (or other data source) specified; $\mathrm{ZTD}_k(t)$ is the (time dependent) zenith tropospheric parameter for station k, which corrects the previous term; z_k^i is the zenith distance; f_{apr} is the mapping function of the *a priori* model; $f(z_k^i)$ is the mapping function used for the parameter estimation.

For NWP-based strategies (MET and MIX), $ZTD_{apr,\,k}$ were calculated from DWD/LM, using ZTD expressed by means of a sum of different contributions (Thayer, 1974). The largest atmospheric delay results from hydrostatic constituents (Zenith Hydrostatic Delay - ZHD). ZHD (in meters) is calculated as (Davis *et al.*, 1985)

$$\mathrm{ZHD} = 0.0022768 p_s \cdot f(\varphi, h) \tag{3.2}$$

where p_s, is the surface air pressure (in hPa) and f is a function depending by the geographical latitude ϕ and ellipsoidical height h. The sites selected for this work present $f(\phi, h)$ values close to one. The second largest contributor to tropospheric delay is water vapor, which corresponds to Zenith Non Hydrostatic Delay (ZNHD), given in meters, as reported in Vedel *et al.* (2001)

$$\mathrm{ZNHD} = 10^{-6} \int_0^{p_{\mathrm{site}}} \frac{R_d}{g_\varepsilon} q \left[(k_2 - k_1 \varepsilon) + \frac{k_3}{T} \right] dp \tag{3.3}$$

where q is specific humidity (kg/kg), T is the temperature (K), p is the upper-air pressure (in hPa), R_d is the dry air specific constant (R_d=287.05 $\mathrm{Jkg^{-1}K^{-1}}$); g is gravity acceleration (fixed constant to 9.81 $\mathrm{ms^{-2}}$); ε is the ratio between the dry air and water vapor molar mass; k_1, k_2, k_3 are coefficients (Bevis *et al.*, 1994) (k_1=77.6 K/hPa, k_2=70.4 K/hPa, k_3=3.739·10^5 $\mathrm{K^2}$/hPa).

On the other hand, the DWD data set provides all meteorological parameters necessary to calculate the tropospheric delay contribution.

Very low contributions to the atmospheric refractivity are due to nongaseous atmospheric constituents, hydrometeors and other particulates (Solheim *et al.*, 1999). The delay due to hydrometeors (ZHMT), can be expressed in (meters) as

$$\mathrm{ZHMT} = 1.4510^{-3} \cdot \int_{\mathrm{site}}^{\mathrm{TOA}} CW \cdot \rho_{\mathrm{air}}\, dz \tag{3.4}$$

where CW is the cloud water content (kg/kg) in the atmosphere and ρ_{air} is the air density. The cloud water content available from DWD data permitted us also to consider even this usually neglected contribution.

Table I. ZTD *a priori* sources and different estimation approaches.

Strategy	$ZTD_{apr,\,k}$ source	$ZTD_k(t)$
MET	NWP (DWD/LM)	Non estimated
STD	Saastamoinen Model	Estimated
MIX	NWP (DWD/LM)	Estimated

In STD strategy, $ZTD_{apr,\,k}$ is calculated by Bernese using the Saastamoinen equation

$$\mathrm{ZTD}_{\mathrm{apr},\,k} = 0.002277 \left[p_s + \left(\frac{1255}{T_s} + 0.05 \right) \cdot e_s \right] \tag{3.5}$$

where p_s, T_s and e_s are the surface air pressure (in hPa), the surface air temperature (in K) and the surface partial water vapor pressure (in hPa) respectively. In Bernese p_s, T_s and e_s are set to constant values.

Table I, referring to eq. (3.1) presents a review of $ZTD_{apr,k}$ sources and $ZTD_k(t)$ approaches for all three strategies.

Mapping function $f(z_k^i)$ in eq. (3.1), when used, was always the zenith angle cosine.

4. Results on coordinate repeatability impact

For the total sum of 608 sessions obtainable to estimate (4 coordinate sets for 152 days), just the number of coordinates estimates as given in table II, were suitable for processing, due to poor availability of data (observations, orbits or meteorological data lack).

Estimated global Cartesian coordinates (X, Y, Z) for Genoa and Venice, together to the local coordinates: Up (U), North (N) and East (E); with respect to the corresponding estimated coordinates mean values are discussed.

Table III shows the Cartesian coordinates (X, Y, Z) mean biases between different strategies for Genoa and Venice. It can easily be seen that the biases corresponding to MIX-STD comparison are minimal with respect the two other comparisons involving MET strategy.

Also the data accuracy, represented in table IV by means of Cartesian global coordinates standard deviations (σ_X, σ_Y, σ_Z) and local coordinates standard deviations (σ_{Up}, σ_{North}, σ_{East}), indicates an equivalence between the MIX and STD strategies with respect to the repeatability.

Table II. Number of coordinate estimates for each strategy and for each site.

Strategy	Sites	No. of coordinate estimates
MET	Genoa	554
	Venice	552
STD	Genoa	577
	Venice	578
MIX	Genoa	554
	Venice	552

Table III. Cartesian coordinates mean biases for Genoa and Venice and for all strategies.

Bias (mm)	Genoa	Venice
$\Delta\overline{X}_{MET-STD}$	16.2	2.5
$\Delta\overline{X}_{MET-MIX}$	16.3	2.1
$\Delta\overline{X}_{MIX-STD}$	0.1	0.4
$\Delta\overline{Y}_{MET-STD}$	1.2	0.9
$\Delta\overline{Y}_{MET-MIX}$	2.2	0.9
$\Delta\overline{Y}_{MIX-STD}$	1.0	0.0
$\Delta\overline{Z}_{MET-STD}$	14.3	2.8
$\Delta\overline{Z}_{MET-MIX}$	14.6	0.9
$\Delta\overline{Z}_{MIX-STD}$	0.3	0.0

Table V. Mean baseline lengths and standard deviation values for all strategies.

Baseline/Strategy	$\overline{L}_{ME-site}$ (m)	$\sigma_{L_{ME-site}}$ (mm)
ME-GE/MET	217154.4754	9.6
ME-GE/STD	217154.4772	8.6
ME-GE/MIX	217154.4762	7.6
ME-VE/MET	115351.7705	5.8
ME-VE/STD	115351.7703	4.8
ME-VE/MIX	115351.7700	4.2

Moreover, the dependence of tropospheric delay error modeling on the variations of the vertical local coordinate component (Up) appears confirmed; vertical components in MET strategy show the largest dispersion: 31-35 mm.

In conclusion, the MIX and STD strategy was equivalent with respect to coordinate repeatability. The MET strategy shows that avoiding tropospheric error delays estimation is not sufficiently correct.

Table V shows baseline length mean values ($\overline{L}_{ME-site}$) and their standard deviations ($\sigma_{L_{ME-site}}$). The repeatability of baseline lengths with respect to the reference station of Medicina for all three strategies shows a good agreement, varying only from a submillimetric to a millimetric level. The standard deviations of the baseline lengths, with almost doubled values for Genoa with respect to Venice, are consistent with the baseline length differences.

The standard deviation values showed the convenience of MIX strategy, achieving results very close to the STD strategy, again with differences at the submillimetric level.

Table IV. Cartesian global coordinates and local coordinates standard deviations for Genoa and Venice and for all strategies.

Site/Strategy	σ_X (mm)	σ_Y (mm)	σ_Z (mm)	σ_{Up} (mm)	σ_{North} (mm)	σ_{East} (mm)
Genoa/MET	26.2	10.9	23.3	35.0	5.2	9.7
Genoa/STD	8.5	9.0	8.2	11.4	4.2	8.6
Genoa/MIX	8.6	8.2	8.3	11.5	4.1	7.7
Venice/MET	22.9	10.9	21.1	31.2	4.9	9.5
Venice/STD	8.5	7.0	7.7	10.7	4.9	6.4
Venice/MIX	8.0	6.9	7.4	10.3	4.2	6.4

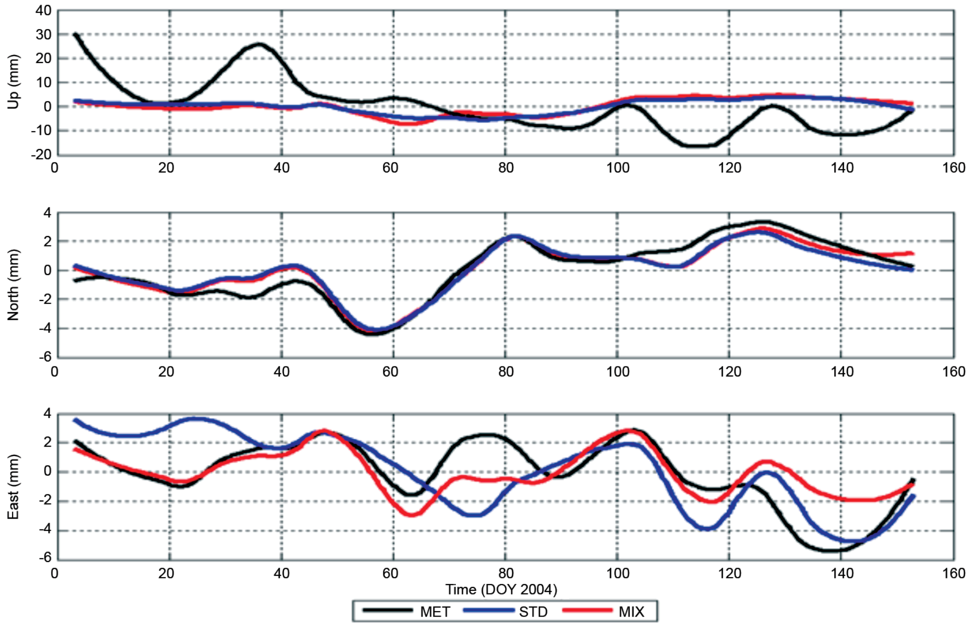

Fig. 3. Smoothing curves of estimated local coordinates for Genoa for all strategies.

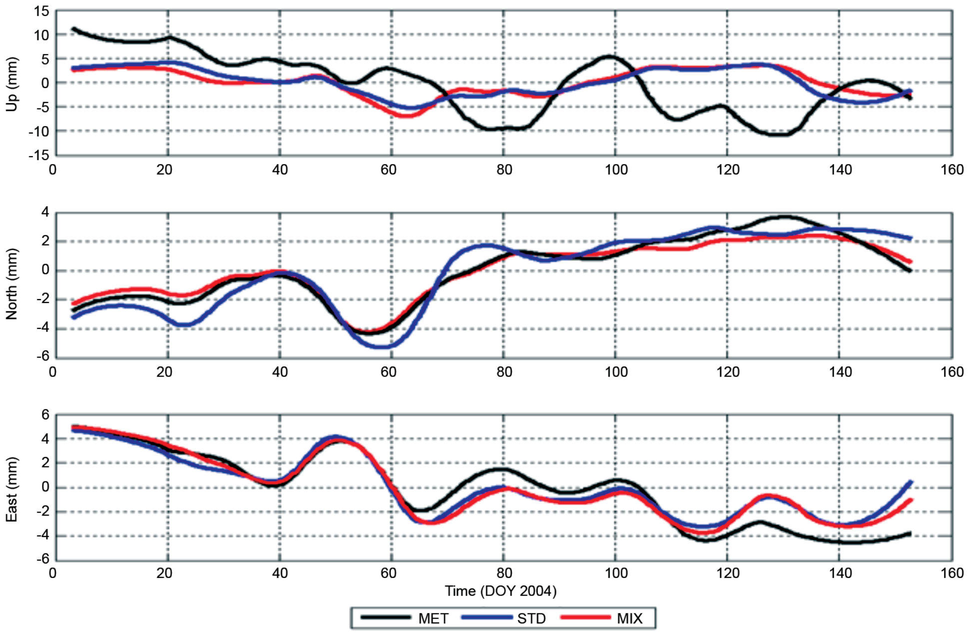

Fig. 4. Smoothing curves of estimated local coordinates for Venice for all strategies.

Figures 3 and 4 show the smoothing curves (quadratic fit) of local coordinates (U, N, E) time series for all three strategies. (The MIX strategy curve is in red color, the STD strategy is in blue and the curve of the MET strategy is in the black color). Generally, all three MIX and the STD curves follow an analogous pattern, while the MET strategy Up curve shows expected meteorological variability dependence (cm range against mm range for N and E components).

Table VI. Mean ZTD differences and standard deviation values, 6-h averaged.

ZTD bias and standard deviation	Genoa	Venice
$\Delta\overline{ZTD}_{STD-MET}$	13.4	−7.6
$\sigma_{\Delta ZTD_{STD-MET}}$	39.5	34.4
$\Delta\overline{ZTD}_{STD-MIX}$	21.9	−9.3
$\sigma_{\Delta ZTD_{STD-MIX}}$	38.0	33.2
$\Delta\overline{ZTD}_{MET-MIX}$	8.6	−1.7
$\sigma_{\Delta ZTD_{MET-MIX}}$	13.7	11.8

Moreover, it is necessary to confirm that the reciprocal position of the three sites were considered time stationary. However, from the EUREF improved time series (http://epncb.oma.be) the kinematical displacements of the local coordinates of three sites appear about 0-3 mm/yr.

5. ZTD comparison

As explained in the introduction, tropospheric errors adjustment is part of STD and MIX strategies, while in MET strategy tropospheric delays are fixed.

Table VI shows ZTD mean differences (biases) and standard deviations, averaged for a 6-h estimation window. It can be seen that both ZTD biases and their standard deviations are minimal between two meteorologically based strategies (MET, MIX), but larger when the comparison is made to the STD strategy. That confirms that avoiding of the introduction of measured or modeled meteorological parameters (as in STD strategy) cannot provide an adequate ZTD estimation. Furthermore, comparing the standard deviations for both testing sites

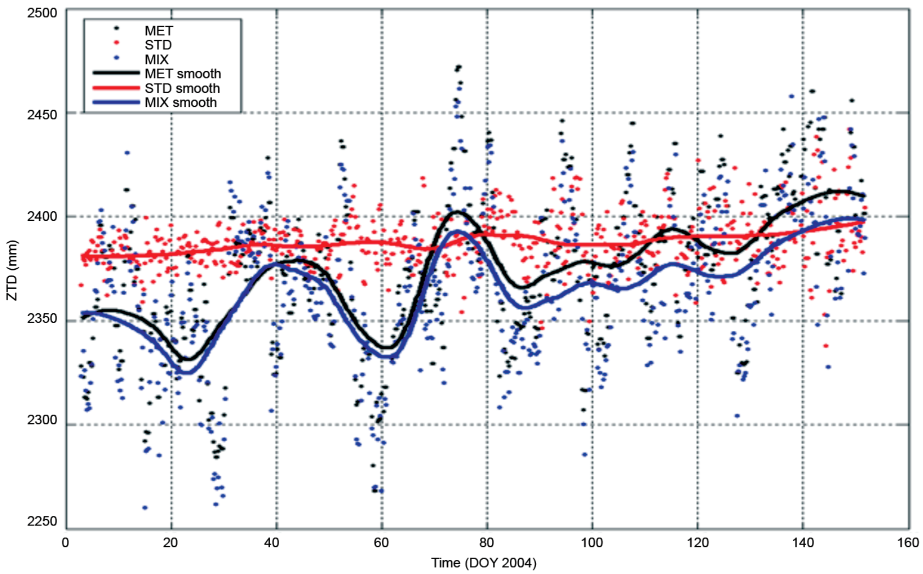

Fig. 5. ZTD_{MET}, ZTD_{STD} and ZTD_{MIX} with smoothing curves for Genoa site.

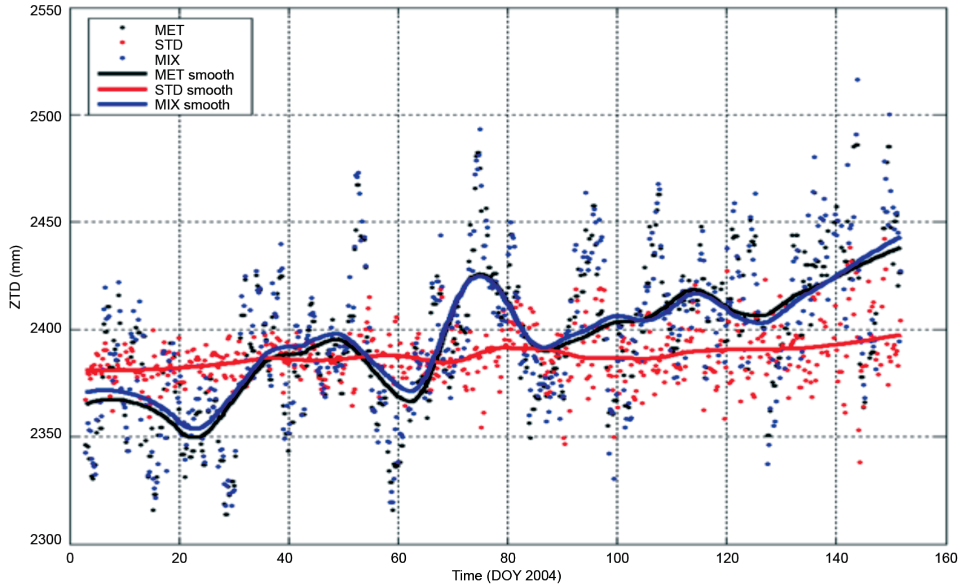

Fig. 6. ZTD_{MET}, ZTD_{STD} and ZTD_{MIX} with smoothing curves for Venice site.

Genoa and Venice very small differences are verified. Figures 5 and 6 show ZTD 6-h averaged with smoothing curves.

From figs. 5 and 6 it can be noted that the two strategies MET and MIX proceed simultaneously, while the STD strategy moves rather linearly. Yet the coordinates obtained by either MIX or STD strategy are practically equal, leading to the assumption that NWP models applied in the MIX strategy gave a sufficient contribution.

6. Conclusions

In order to discuss the possible application of Numerical Weather Prediction (NWP) meteorological parameters in GPS elaboration, and *vice versa* accurate GPS elaboration as further information on meteorological fields, the three strategies for the GPS coordinate estimates are implemented. The so called MET and MIX strategies were based on the introduction of Zenith Tropospheric Delays (ZTD) calculated from NWP meteorological data while the STD strategy assumed the most used GPS elaboration mode based on ZTD obtained by a global model. STD and MIX strategies performed the estimation of both coordinates and tropospheric errors; while MET strategy produced only the coordinate estimation. For that purpose, two baselines formed by GPS sites of Venice, Genoa and Medicina, belonging to EPN in Northern Italy were tested.

Biases of global Cartesian coordinates values between various strategies and their standard deviations show that two strategies based on ZTD corrections (MIX and the STD) produce more adequate and similar results with respect to the third strategy (MET) based on the «errorless *a priori*» ZTD. The difference between MIX and STD strategy is generally at the submillimetric level, while for the MET strategy the difference with respect to other two strategies varies from millimetric to centimetric level. Also the standard variations values for three local coordinates confirm that both STD strategy and MIX strategy again gave comparable values. The dependence of tropospheric delay error modeling on the vertical local coordinate (Up) appears confirmed; the vertical components in MET strategy show the largest dispersion.

On the other hand, ZTD and their standard deviations are minimal between two meteorologically based strategies (MET, MIX), but much larger when the comparison is made between the STD strategy and the other two. Yet the coordinates obtained by either MIX or STD strategy are practically equal, leading to the assumption that NWP models applied in the MIX strategy gave a sufficient contribution.

We can conclude that reciprocally an accurate meteorology leads to a more precise coordinate estimation, and *vice versa* the well-defined GPS estimation of the coordinates may serve to take the place of lacking information on meteorological parameters.

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