Tropospheric Processing for NRT and Post-Processing GPS Applications at ASI

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Abstract
For several years, ASI has been involved in GPS data analysis of regional permanent network. One main activities is the computation of NRT tropospheric parameters. Zenith Total Delay estimates are delivered every hour to the European E-GVAP (EUMETNET GPS Water Vapour Programme) with the goal to use them for numerical weather prediction. At present on a routine basis a network of 120 permanent sites is processed in post-processing and half of them are analyzed in NRT.
Comparisons and validation will be provided together with an assessment of the ZTD uncertainties.

1 Introduction

Water vapor is a key element in the hydrological cycle and it is an important greenhouse gas in the atmosphere. The very inhomogeneous and highly variable distribution of the atmospheric water vapor makes it a crucial element in weather forecasting. Conventional observing systems such as radiosondes and microwave radiometer are insufficient for observing its high variability. The ground-based GPS provides on site continuous, high temporal resolution Zenith Total Delay (ZTD). It has a global coverage all over the continents but not over the oceans (Bevis et al. ,1992).
Therefore ground-based GPS receivers can be used as meteorological sensors. Techniques have been developed to acquire, process and distribute GPS derived atmospheric parameters which are useful for Numerical Weather Prediction (NWP) forecasts and climate applications. The atmospheric observable from ground-based GPS data is the ZTD, that is the additional propagation delay caused by dry air and water vapor in the atmosphere when the GPS signal propagates from the satellite to the receiver. It can be split into an hydrostatic part (ZHD), function of the surface pressure (Saastamoinen, 1972), and a wet component which depends on the water vapour content. ZHD can be easily computed using surface pressure measurements or pressure fields derived from NWP models and subtracted to the estimated ZTD to provide the Zenith Wet Delay (ZWD). This last is proportional to the Integrated Water Vapour (IWV). The non-dimensional constant of proportionality (Askne et al, 1987; Elgered et al., 1991) is a weak function of the weighted mean temperature of the atmospheric column and can be related to the surface temperature by a linear relationship (Bevis et al., 1994).
For NWP applications the goal is to produce ZTD estimates with a reasonable quality and in Near Real-Time (NRT) i.e. within 1h 45min from data acquisition.
Since 1999 in the framework of the MAGIC (Meteorological Applications of GPS Integrated Column Water Vapor Measurements in the Western Mediterranean) Project (Haase et al., 2001) at the Space Geodesy Center (CGS) of the Italian Space Agency (ASI) an operative and automatic system has been developed in order to deliver GPS tropospheric parameters on a daily basis with 2 week latency (Pacione et al., 2001). In June 2001 ASI joined the COST-716 Near Real-Time demonstration phase (COST-716, 2004) processing on hourly basis an European network of about 15 stations (Pacione and Vespe, 2003). In February 2003 under the umbrella of the TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) project the network grew up to 57 stations in June 2006. GPS data are processed at several institutions involved both in COST-716 and in TOUGH, to ensure consistent results independent of the software used and the applied strategy. Each analysis center is responsible for retrieving the GPS data, processing them and transferring the ZTD estimates to the project ftp site in NRT to make them available to the meteorological users. In processing the data, the centers include stations from a common reference

network to provide a means for cross-checking the quality of the ZTD estimates. Radiosonde observations are used as an important independent data set for validating GPS ZTD data. The quality of the radiosondes is high, but the temporal and spatial resolutions sometimes lead to problems. HIRLAM NWP analyses and forecasts are used as another source of independent data against which monitoring GPS ZTD and IWV. GPS ZTD and IWV data are continuously monitored, both to help to improve the product quality and to determine its error characteristics, which must be known when assimilating the data into NWP systems.

In this study we asses the accuracy of GPS derived atmospheric parameters delivered in Near-Real Time from an European ground-based network. A statistical method to assess the degree of reliability of the NRT ZTD and their real uncertainties is proposed and discussed in section 2. In section 3 after having briefly described the NRT ZTD delivering system, the results of an experiment of ZTD assimilation in the MM5 NWP model carried out nearby Matera Space Geodesy Center are shown. Finally the conclusions are drown in section 4.

2 Assessment of the uncertainties of NRT estimates

GPS data from 57 European stations are processed on hourly basis to provide ZTD to meteorological agencies. The ground-based GPS network covers the Central Mediterranean area with Italy as core region.

The GIPSY-OASIS II software (Webb et al., 1997) is used for data reduction with the standard technique of network adjustment. The IGS (Beutler et al., 1999) Ultra Rapid orbits are kept fixed but checked and “bad” satellites or stations are automatically excluded on the base of the analysis of post fit phase observation residuals, as suggested by Springer et al., (2000). Thus a noisy station is not analysed for the next 24 hours. A 24-hour sliding window approach for data handling is applied with a sampling rate of 5 minutes and a cut-off angle of 10^0. The ZWD is estimated every 5 minutes with a stochastic model (random walk) and a constraint of 20 mm/sqrt(h). The station coordinates are kept fixed to values provided by combining 1 month of daily post-processed (hereafter PP) solutions, whose repeatability is at the centimeter level or better and are updated every 30 days taking into account the tectonic movements of the area. A detailed description of the processing strategy is reported in Pacione (2005).

A post-processed solution is run on daily basis with the precise point positioning approach (Zumberge et al., 1997). The main goal of the PP solutions, whose features are reported in Pacione et al. (2001), is to provide both ZTD estimates useful for climate applications and site coordinates to fix in the NRT data processing. An accuracy check of the site coordinates is regularly performed considering their repeatability as an indicator of the ZTD quality. As a rule of thumb, 9 mm in the height component (i.e. 3 mm in ZTD as explained in Santerre, 1991) are needed to fulfill the requirement of getting IWV at a level of 0.5 kg/m^2 IWV (Bevis et al., 1994).

The ZTD internal consistency can be seen comparing NRT and PP ZTD estimates. For more details see (Pacione & Vespe 2008). In that paper It is shown an example of the daily variation in ZTD bias and standard deviation of the residual time series of PP minus NRT for 6 EUREF stations from January 2004 to June 2006. On daily basis the PP minus NRT ZTD station bias ranges from –4.9 mm to -1.9 mm and the related standard deviation is about 5 mm. Similar results have been obtained in the framework of the COST-716 Action comparing individual NRT solution with respect to a combined post-processed one (COST-176, 2004).

2.1 Comparison between individual NRT solutions

A time series of 39 EUREF stations 2-year long (January 2004 –December 2005) is used to compare NRT ZTD estimates coming from the following analysis centers involved in the European COST-716 Action and in the TOUGH project: ACRI-ST Mécanique Appliquée et Sciences de l’Envirinment (France), ASI Agenzia Spaziale Italiana (Italy) BKG Bundesamt für Kartographie und Geodäsie (Germany), GFZ GeoForschungsZentrum Potsdam (Germany), GOP Geodetic Observatory, Pecny (Czech Republic), IEEC Institut d'Estudis Espacials de Catalunya (Spain), LPT Federal Office of Topography (Swiss), NKG Nordic Geodetic Commission Norwegian Mapping Authority, (Norway), NKGS Nordic Geodetic Commission,(Sweden), SGN Institut Géographique National (France). We refer to the COST-716 (2004) final report for a description of all the processing techniques.

Pair wise comparison of individual NRT solutions show a good agreement over the whole period considering ASI solution as reference. The ZTD station bias is between ±6 mm that is about ±1 kg/m^2 IWV, in the computation gross error (i.e. values >30 mm) are rejected. The standard deviation is about 10 mm in the comparisons with respect to SGN lower (7-8 mm) in all the other comparisons. The obtained results can be considered an indication of the precision which can be now achieved by the GPS techniques.

2.2 Assessment of the uncertainties of NRT estimates

Comparing ZTD solutions coming from different analysis centers we realize that the ZTD estimates are very high correlated while there is a poor correlation between the related sigma. This means that the ZTD quality indicator obtained by the GPS processing could be not reliable. The formal standard deviation as computed from the inversion of the normal matrices is not a uniform quality indicator since different processing centers use different strategies to compute the ZTD standard deviation and have different detection levels to flag or reject bad data. We apply the method extensively applied by for galaxy redshifts catalogues (Tonry and Davis, 1979, Rood, 1982) to assess the degree of reliability and the real uncertainties of NRT ZTD. Let us describe in detail the approach.

If we have two different data sets x_i and y_i measurements of the same variable in time and space, we can assess the real uncertainties of that intrinsically less precise. Let us assume that y_i is more precise than x_i. Then we can define the non-dimensional data set z_i as

$$z_i = \frac{(x_i - y_i)}{\sqrt{\sigma_{x_i}^2 + \sigma_{y_i}^2}} \tag{1}$$

If x_i and y_i were unbiased and their internal error is not underestimated, z_i should behave according to a Gaussian distribution with mean μ=0 and variance σ_z^2=1. The error σ_μ on the mean should behave according to a Normal distribution

$$\sigma_\mu = \frac{\sigma_z}{\sqrt{n-1}} \tag{2}$$

where n is the number of measurements. If μ is significantly $\neq 0$ (i.e. out of 3 sigma range) it means that the x dataset is biased. On the other hand the variance behaves according to the χ^2 function with n-1 degree of freedom. We must check if the value σ_z^2=D_z=1 is within the variance interval, that is determined fixing the confidence probability at 90% level.

Thus we build another parameter as follow

$$V = \frac{\tilde{D}(n-1)}{D_{\exp}} \tag{3}$$

where $\boldsymbol{D_{exp}}$ is the variance of which we want to know the confidence interval and $\tilde{D}$ is the estimated variance of the "***z***" dataset. The parameter ***V*** in Eq. 3 behaves according the χ^2 distribution with n-1 degrees of freedom. It is well known that the χ^2 distribution is asymmetric. Thus the confidence interval at β level of probability (hereafter CI(β)), with β set in the present case to 0.9, is asymmetric around $\tilde{D}$ as well. In our case the CI(β) of "*V*" parameter is

$$X_1 \le V \le X_2 \tag{4}$$

were $\chi^2(X_1) = \frac{1-\beta}{2}$ and $\chi^2(X_2) = \frac{1+\beta}{2}$.

Thus merging Eq. 3 and Eq. 4 we get the CI(β) for the variance D

$$\frac{\tilde{D}(n-1))}{X_2} \le D \le \frac{\tilde{D}(n-1))}{X_1} \tag{5}$$

Thus if the nominal value of D_z =1 is out from the range set with Eq. 5 the variance is biased (underestimated/overestimated).

We apply this method considering as "x" dataset the 96 NRT ZTD time series coming from different TOUGH analysis centre and as "y" dataset the EUREF combined tropospheric solution (http://www.epncb.oma.be/_organisation/projects/trop_sp/ index.php). Plots of Figure 1 show the histograms of the "z" datasets defined in Eq. 1 compared to the Gaussian distribution (black lines) having the same μ and σ of the given series for the following analysis centers which have worked in the framework of TOUGH project: ACRI and SGN (France), ASI (Italy), BGK and GFZ (Germany), GOPE (Czech Rep.), IEEC (Spain), LPT (Swiss). We have applied for the analysis the optimistic 3-sigma criterion (Rood, 1982). The optimistic criterion is applied just when we do not want to underestimate the uncertainty and therefore no data must be rejected; as well as when we are confident that the final data are reliable. Both the reasons apply to our case because we want just the ZTD uncertainties be not underestimated; while along the processing chain outliers, namely stations coordinates, satellites orbits etc., have been filtered out. The χ^2 test applied between the histograms and the Gaussian distribution fails for most of the dataset. A mean scaled factor and scaled sigma (mm) are computed for each analysis centre and reported in Table 1.

Table 1 *scaled factor of the different AC*

	Scaled Factor	Scale Sigma (mm)
ACRI	0.9	8.3
ASI	2.4	5.6
BKG	2.7	3.2
GFZ	2.8	2.9
GOP	2.8	3.0
IEEC	1.4	7.7
LPT	3.5	3.9
SGN	5.8	3.6

It can be noticed that all Bernese and GIPSY solutions (BKG, GOP, LPT, SGN, ASI and IEEC) have underestimated their uncertainties and the statistical distribution is not exactly Gaussian; while ACRI solutions (GAMIT SW) have over-estimated uncertainties and their statistical distribution is rather Gaussian. Further on all the uncertainties seem to be correlated more to the analysis strategies (troposphere modelling and estimation process) than to the quality of the stations.

Indeed a measure of the quality of the station *i* is given by the non-dimensional quantity

$$\nu_i = \sum_{j=1}^{k} \frac{\sigma_{ij}}{\sigma_j} \tag{6}$$

where σ_{ij} is the mean value of the σ estimated by the AC_j for the station *i* and σ_j is the mean value of all the σ estimated by the AC_j.

The station *i* is considered 'good' or 'bad' if ν_i, as defined in Eq. 6, is significantly lower or greater than 1. The ν_i value is computed for the same station and AC previously considered and it is reported in *Fig. 2* where we observe that some stations perform better than the others. The understanding why some stations performs consistently better than others is an intriguing matter but out of the scope of the present paper. The performances of the stations indeed could depend on the quality of the equipment installed (receiver, antenna, internal/external clock) and on the site environment. It is worth mentioning that our approach could be very helpful in singling out stations which have problems and address the investigations needed to remove them.

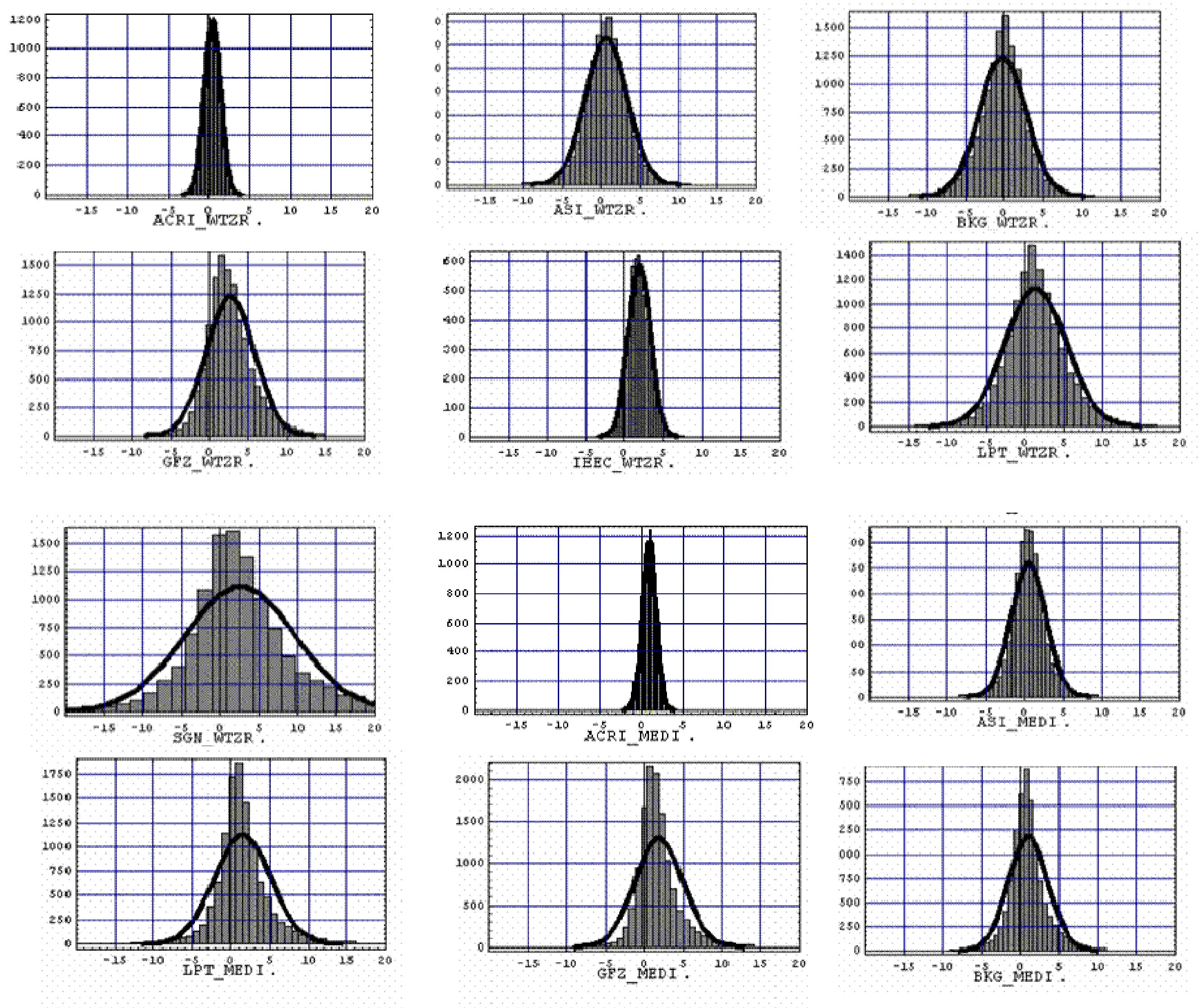

Figure 1. *The plots show the behaviour of the different LAC solutions. All the solutions but ACRI with GAMIT heavily underestimate the uncertainties up to a factor of ten.*

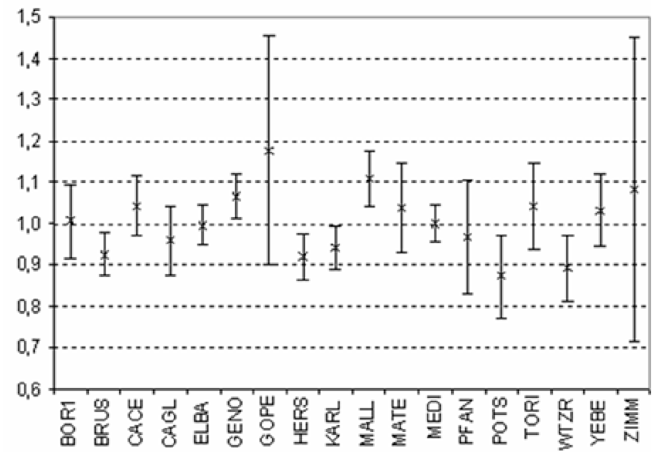

Figure 2 *it shows the value o the quality index as built in Eq. 6. For values significantly >1. In case of problems occurring in the ZTD solutions they are station dependent.*

3 An experiment of ZTD Assimilation on Regional scale

In 2001 AS established a regional GPS network of about 15 stations anchored to Matera ASI/CGS station. The GPS was mainly co-located with rain gauges distributed all over the area (they are the green dot in Fig 3)

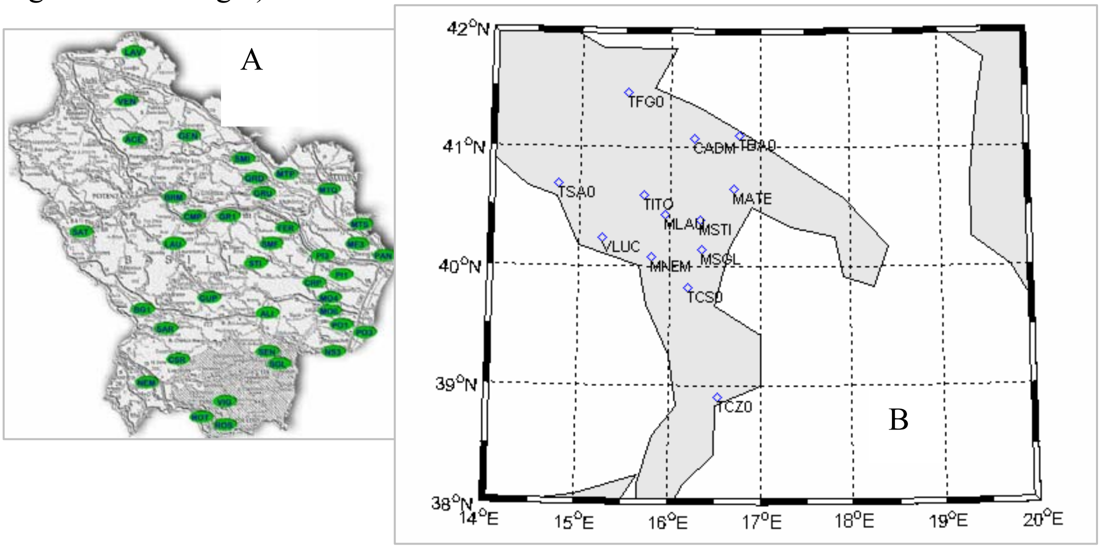

Figure 3*. The network of rain gauges used in our experiment (A quarter); while in B) is shown the GPS network used for the assimilation experiment*

Starting from 13 December 2003 all the available data form the stations are processed on routine basi sto deliver ZTD. The coordinates of the stations are estimated together with the ZTD. The heights of a station is indeed deemed a gauge of the quality of the solution. The rain gauges network on the other side provide the real trend of the precipitations in the region. So the Numerical Weather Prediction can be properly validated with real data.

The NWP are drawn with Pennsylvania State University / National Center for Atmospheric Research mesoscale model (known as MM5). It is a limited-area, nonhydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (Grell et al. 1994, Dudhia 1993) suitable just for the experiments we have planned to perform. The assimilation of the ZTD have been performed by applying a 3DVAR variational analysis not depending on time (Courtier et al. 1998). The geographical gridding is set up applying two nested domains in turn of 27 and 9 Km. Higher resolution domain is centered just on Basilicata region while the lower includes the south part of Italy .

Starting on October 20th 2003 2 experiments for each day have been performed: the CNTR experiments are delivered without ZTD; while EXP include them.

The experiments start from noon and a solution of NWP valid for next 36 hours is issued. For the CNTR experiment the initialization is performed using NCEP analysis currently available through internet; while for EXP it is performed by using just the ZTD in 3DVAR fashion. The evaluation of the results has been performed comparing the field of prediction with the real values of the daily rainfall given by the rain gauges. What we have computed has been the bias and rms of the 2 solutions against the real values

$$BIAS_i = \frac{MOD_i}{OBS_i} \quad \text{and} \quad RMS_i = \sqrt{\frac{\sum_i^N (OBS_i - MOD_i)^2}{N}} \tag{7}$$

Where i is the geographical point where a measurement of the rainfall is available; MOD stands for the model (in our case CNTR and EXP) ; while OBS is the real measurement.

We are going to show the results of an assimilation experiment In fig. 4

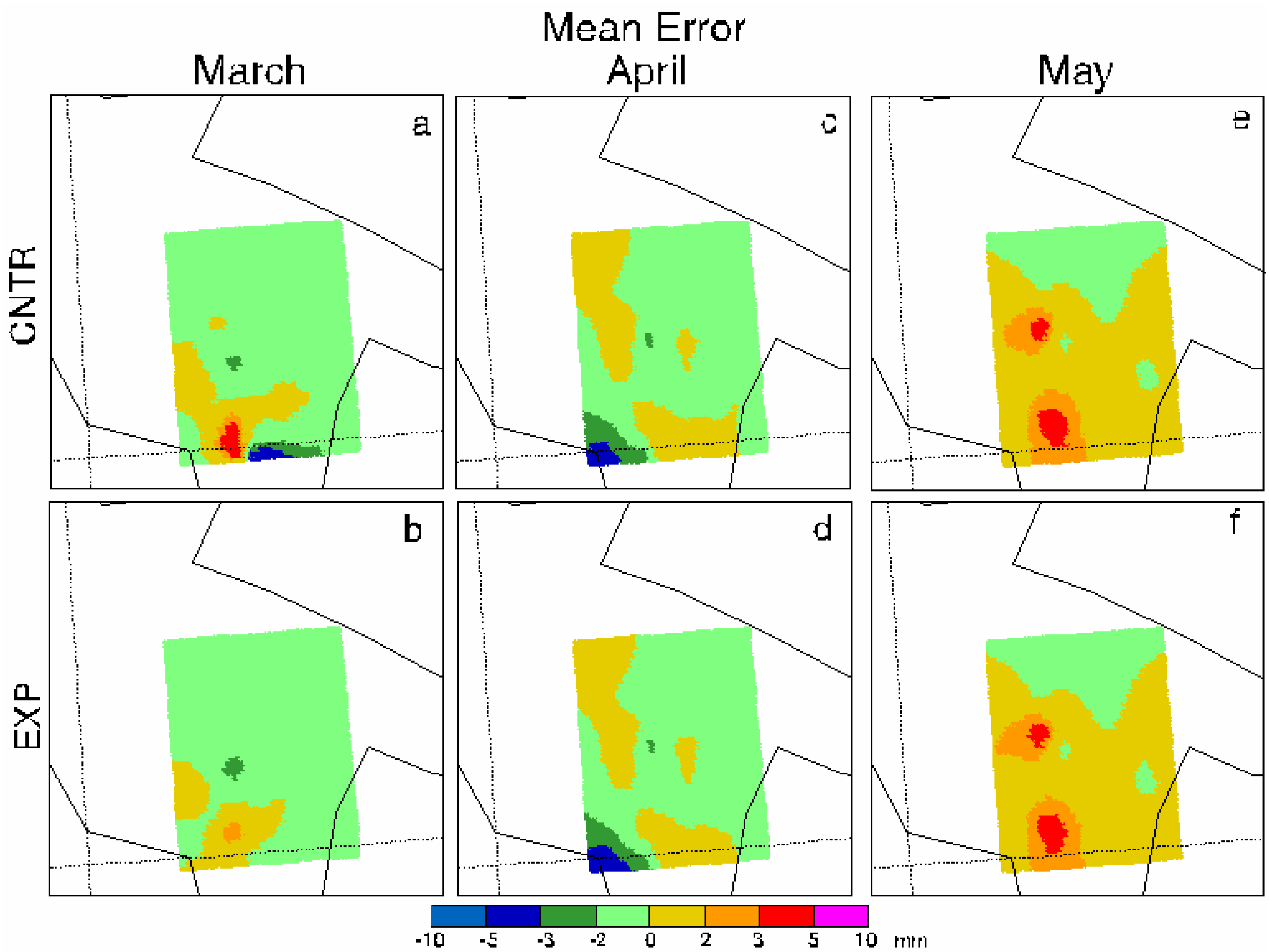

***Figure** 4. Figures a), c) and e) report the BIAS computed without ZTD assimilation (CNTR) for the months in turn of January, February and March 2004; while the portaits B,D ed F concern the same field of NWP but with ZTD assimilation*

3.1 The Results

In fig. 4 the behaviour of the BIAS parameter is shown averaging the residuals over one month. In winter monts the differences between CNTR and EXP are really negligible (they are the plots not shown in the present work). This is not for the Spring time where we expect an increase of the amount of water vapour content in the atmosphere and deemed GPS particularly effective to detect it. In March indeed we have an overall improvements of the field of numerical weather predictions by assimilating the ZTD provided by the GPS network. Particularly interesting is that the significant improvement have occurred in the south-west part of the area under investigation which is wetter, closer to the sea and with an uneven orography. Such evidence confirm that the impact of GPS ZTD in critical local area where the traditional forecasting is hardly to achieve, GPS can play a crucial role in improving the prediction.

4 Summary

Ground based GPS receiver is a useful tool for monitoring atmospheric parameters and for capturing their temporal variability. Data from European permanent sites are processed in Near Real Time mode and the estimated ZTD is validated against other GPS estimates delivered in the framework of the TOUGH project. The data set covers different climatic conditions varying from the Alpine to the Mediterranean ones. Comparisons between individual NRT solution show a good agreement with a delay bias of ±6 mm and a standard deviation of 7-8 mm. A new approach was proposed in order to assess the real uncertainties of the different GPS ZTD comparing them with EUREF solutions We realize that the uncertainties of the solutions came out from the involved analysis centers are underestimated and, therefore to be rescaled, of factors ranging from 1.4 to 5.8. Only the GAMIT solution (ACRI) have a re-scaling factor less than one (~0.9). Another remark is that closer to 1 is the re-scaling factor closer to a normal distribution the residuals are.

The experiment of assimilation performed in a region centered around Matera in South part of Italy has given promising results and the GPS data seem to have a not negligible impact. Anyway other experiments are worthwhile to be proposed to assess the real impact on NWP of ZTD observations. In particular the plan is to make denser the nested gridding. The NWP could be refined indeed by using a close mesh net of only 3 km.

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