# **Combination of GPS Near Real-Time tropospheric parameters**

B. PACE<sup>1</sup>, R. PACIONE<sup>1</sup>, F. VESPE<sup>2</sup>

<sup>1</sup> e-GEOS, Centro di Geodesia Spaziale, 75100 Matera Italy

<sup>2</sup> Agenzia Spaziale Italiana, Centro di Geodesia Spaziale, 75100 Matera Italy

# Presented at EUREF Symposium 2009 Florence, 27-30.05.2009 VOLUME LXIX – BOLLETTINO DI GEODESIA E SCIENZE AFFINI – N. 1, 2010

#### Abstract

Within E-GVAP (The EUMETNET GPS Water Vapour Programme, http://egvap.dmi.dk) several GPS sites are processed by different analysis centres using different networks, different processing softwares and different processing settings. In this paper we describe a method for combining Near Real-Time (NRT) tropospheric solutions. The method provides, along with a combined NRT Zenith Total Delay (ZTD) estimates and its standard deviations, site and analysis centre specific biases and weights. It is applied routinely to the data stream set-up in E-GVAP but it could also be used to combine atmospheric parameters retrieved from various geodetic techniques as GPS and VLBI. The NRT combined tropospheric product is validated against radiosonde observations and EUREF Post-Processing combined solutions. The mean ZTD bias of the NRT combined product with respect to radiosonde observations suggests that GPS is, beside significant seasonal variations, 'too dry', while the mean std ranges from 5 to 14 mm. The EUREF Post-Processing combined solutions are even dryer (1-4 mm ZTD) when comparing to the NRT combined ZTDs.

### **1** Introduction

The EUMETNET GPS Water Vapour Programme (E-GVAP) has been set-up in April 2005 as an inter-European project tasked for taking GPS meteorology in Europe to an operational status and delivering high quality GPS ZTD observations to the meteorological community. Within the project, 13 European national met offices are in collaboration with geodetic institutes and GPS network providers.

Currently, 11 E-GVAP Analysis Centers (ACs) are processing RINEX GPS data covering all Europe and sending NRT ZTD products every hour to a common ftp-server at the UK Met Office: ASI (Agenzia Spaziale Italiana, Italy), BKG (Bundesamt für Kartographie und Geodäsie, Germany), GFZ (GeoForschungsZentrum Potsdam, Germany), GOP (Geodetic Observatory, Pecny, Czech Republic), IGE (National Geographic Institute Spain), KNMI (Royal Netherlands Meteorological Institute, Netherlands), LPT (Federal Office of Topography, Switzerland), METO (Met Office, UK), NGAA (Nordic Geodetic Commission Sweden), ROB (Royal Observatory of Belgium, Belgium) and SGN (Institut Géographique National, France). The number of operational GPS sites used in E-GVAP is about 1000, among which about 200 are analyzed at least by 2 ACs and about 150 are analyzed at least by 3 ACs. Based on a recommendation from the E-GVAP expert team on data processing, a set of Super Sites is processed by all ACs (Figure 1). The Super Sites have been selected on the base of the following criteria: RINEX data should be available at least in 15 minutes after the full hour, the site should be geodetically stable and with high installation standards and the collocation with meteorological equipment (radiosonde and/or water vapor radiometer) is required for validation. The Super Site network should cover Europe, coastal sites need to be included for monitoring of ocean tide loading effects. All ACs must include in their processing Super Site data in order to make comparisons between processing centre solutions and validation against independent meteorological observations.

**Formattato:** Tipo di carattere: 10 pt, Non Corsivo, Inglese (U.S.A.)

**Formattato:** Tipo di carattere: 10 pt, Non Corsivo, Inglese (U.S.A.)

Eliminato: Figure 1

We present a method for combining NRT tropospheric solutions. This study is motivated by the need of having an internally consistent Zenith Total Delay (ZTD) product on the basis of several individual troposphere solutions obtained from parallel Near Real-Time processing.

The combination of NRT ZTD solutions is a good tool for detecting problems in data processing and providing a reliable quality indicator for each contributing solution, which is an essential step when using observations in an operational application, such as numerical weather prediction.



Figure 1: E-GVAP Super-Sites geographical location. In June 2009, an other Super Site has been added: Guimar (IZAN, Spain)

In section 2, the combination strategy is described while in section 3 the performance of the method is tested on a 15-month (July 2008 - September 2009) dataset with respect to radiosonde observations and on a 14-month (July 2008 - August 2009) dataset having the EUREF Post-Processing combined solutions as reference. A summary is given in section 4.

# 2 NRT ZTD Combination Strategy

We consider the time series of GPS ZTD estimates obtained by different analysis centers for the same GPS site. Ideally the time series within each batch should have the same length and sampling interval but in practice they do not necessarily have the same structure (see <u>Table 1</u>). So there is the need to specify a set of equidistant time tags at which to perform the time series combination. For some time series it may first be necessary to interpolate linearly the ZTD estimates to the new sampling interval. For a single site, ZTD is modeled as:

$$y_n^k = Y_n + b^k + e_n^k \qquad n = 1, \dots, N \quad \text{epochs} \tag{1}$$
$$k = 1, \dots, K \quad \text{ACs}$$

where  $Y_n$  is the 'true' ZTD at epoch  $t_n$ ,  $b^k$  is the analysis center bias and  $e^k_n$  is the residual between  $Y_n$  and  $y_{n}^{k}$ . If we collect all such equations for all the epoch we get the linear function model which can be solved in a generalized least square sense by adding the following constrain equation:

$$\sum_{k} b^{k} = 0 \tag{2}.$$

Eliminato: Table 1 Formattato: Tipo di carattere: 10 pt, Non Corsivo Commento [PR1]: Verificare

Eliminato: 14 Eliminato: 13



AC	# samples	@
ASI	4	00-15-30-45
BKG	1	30
GFZ	4	07,30-22,30-37,30-52,30
GOP	2	00-59
IGE	5	00-15-30-45-59
KNMI	5	00-14-29-44-59
LPT	2	00-59
LPTR	11	02-07-12-17-22-27
		-32-37-42-47-52
METO	5	00-15-30-45-59
NGAA	4	00-15-30-45
ROB	5	00-15-30-45-59
SGN	5	00-15-30-45-59

Table 1: E-GVAP AC ZTD samples (column 2) and epoch (column 3) for each hourly batch.

In collocated sites, the method can be used to combine atmospheric parameters retrieved from various space-geodetic techniques as GPS and VLBI. In this case the bias will be the sum of site/analysis centre bias and technique bias.

The first step in the combination process is reading and checking the input files in COST-format [4], whose name identifies the solution epoch and the delivering AC. At this stage, gross errors (i.e. ZTD estimates with sigma larger than 30 mm) are detected and removed. Data or processing problems are identified and e-mails are sent to the ACs. The combination starts if there are at least 3 different solutions available for a single site. Then, a first combination is performed to compute proper weights for each contributing solution to be used in the final combination step. This last step will provide the combined NRT ZTD estimates, their standard deviation and site/analysis centre specific biases. The combination fails if after the first or second combination level the ACs get less than 3.

### **3 NRT Combined ZTD validation**

The performance of the method has been tested by comparing NRT ZTD combined estimates with respect to radiosonde ZTD and EUREF Post-Processing combined solutions (http://epncb.oma. be/\_dataproducts/products/sitezenithpathdelays/) on the E-GVAP Super Site network. Super Site data have already been used in previous validation studies [5]. Data between July 2008 and August 2009 were used.

Radiosonde profiles are provided by the Danish Meteorological Institute as an independent data set to validate GPS ZTD data. The data are exchanged between EUREF and EUMETNET for scientific purposes based on a Memorandum of Understanding between the two mentioned organizations [8]. The amount of data used in the comparison varies from each site and ACs and it depends on the availability of AC NRT solutions in the considered epoch.

The monthly variation of the individual and combined (hereafter ASIC) ZTD bias and standard deviation for Payerne (PAYE, Switzerland), Zimmerwald (ZIMM, Switzerland), Camborne (CAMB, England) and

Yebes (YEBE, Spain) Super Site vs radiosonde is shown in Figure 3. Payerne and Zimmerwald sites are collocated with the same radiosonde (06610, 0 km from PAYE, 40 km from ZIMM) with the former rather closer to the radiosonde launching site. Among all the Super Sites, CAMB is the closest (0,6km) while YEBE is the most distant (45km). The standard deviation, computed over all the observations available in the analyzed period, ranges from 5 mm to 14 mm in agreement with previous comparisons

Eliminato: s



reported in [6] where more than 3 years of radiosonde observations were considered. Some effects in the standard deviation can certainly be attributed to atmospheric thermal cycle (usually better agreement in winter than in summer). Partly they are also due to the distance to the radiosondes (usually worse agreement if the distance is long). Beside the seasonal variations, the biases seem to be slightly negative meaning that GPS is slightly too dry by 4 till -10 mm. All analysis centers <u>have been using absolute</u> antenna models, as recommended by the IGS since November 2006 (GPS week 1400). GFZ is the only exception, since it uses relative antenna models [1]. Using these relative antenna models, GPS-derived ZTDs seemed to be too wet compared to radiosondes [5].

In Figure 2, the monthly variation of the individual and combined ZTD for each Super Site versus the EUREF post-processed solutions is shown, where a small but positive bias is visible for all the stations which means that the post-processed solutions are even dryer (1-4 mm, standard deviation 2-5 mm) compared to the NRT solutions. It could be due to a different way of dealing with the ambiguities in the data reduction process. Most of the individual solution used in the EUREF Post-Processing combined are 'ambiguity-fixed' solutions, while the individual NRT solutions used in the ASIC combination are 'ambiguity-float' (exception LPT NRT contribution).





Figure 2: Combined NRT versus EUREF Post-Processed solutions - Monthly basis (top) and std (bottom)



Figure 3: PAYE, ZIMM, CAMB and YEBE GPS ZTD versus radiosonde



Furthermore, a bias time series analysis has been performed for each Super Site and AC using a 14-month dataset. The histograms of the differences between individual AC-ZTD estimates and combined ZTDs (see an example in <u>Figure 4</u> for Medicina Super Sites and ASI, GOP, GFZ, and LPT ACs) are all symmetric with a bell shape. This suggests that all the bias values behave in a similar manner to a normally distributed independent samples. As far as GFZ MEDI, a mean value of 6 mm is detected which corresponds to the value that Gendt and Nischan [2] found checking the differences in the ZTD estimates generated using absolute and relative PCV models.

## 4 Summary

We proposed a method for combining NRT GPS derived ZTDs which is applied in NRT and on hourly basis to all the solutions delivered within E-GVAP and we described how it may be used for detecting problems in the data processing.

In E-GVAP II phase the combined solutions may be used in the active quality control and they even be distributed for assimilation into numerical weather prediction models. We demonstrate that they are of higher quality than the individual AC ZTDs. Timeliness is the only drawback for their real use, since you need to wait for all the contributing solutions to get the combined one. Clearly they will be useful in the general validation, as well as post processed ZTDs.

Within E-GVAP another combination is delivered based on a Kalman filtering method [3]. Despite the different mathematical method applied, these two combined solutions agree quite well [7].

Commento [PR2]: Verifica stampa sul pdf Commento [PR3]: Verifica stampa sul pdf Commento [PR4]: Verifica stampa sul pdf Commento [PR5]: Verifica stampa sul pdf Eliminato: 3 Formattato: Tipo di carattere: Non Corsivo Commento [PR6]: Verifica stampa sul pdf The validation of ZTD estimates, which are based on absolute antenna phase center models, with respect to radiosonde observations over  $15_{\rm F}$  month dataset shows that GPS is slightly 'too dry'. This conclusion is opposite to the findings when relative PCVs were applied. The intra-technique validation (GPS combined NRT and GPS EUREF combined Post-Processed) shows a small (3-4 mm) positive bias visible for all the stations.

Eliminato: 4

#### Acknowledgments

We acknowledge all E-GVAP ACs for providing the ZTD data used in this work and all the GNSS site owners providing raw data for processing by the ACs. W. Shone and E. Brockmann are acknowledged for their useful comments and suggestions.

### References

- [1] Dick, G., 2008: private communications.
- [2] Gendt, G., and T. Nischan, 2006: First Validation of new IGS Products Generated with Absolute Antenna Models. IGS Workshop 2006.
- [3] Keshim, M., 2006: Sequential combination of tropospheric time series, GPS Solut, Vol.11 37-47, 2007.
- [4] Offiler D., 2008: Format Specification for COST-716 Processed GPS Data. Available online at http://egvap.dmi.dk/support/ formats /cost\_format\_v21.pdf.
- [5] Pacione, R., F. Vespe and B. Pace, 2009: Near Real-Time GPS Zenith Total Delay validation at E-GVAP Super Sites, In: Ihde, J. and H. Hornik (Eds): Subcommision for the European Reference Frame (EUREF), Brussels, 2008, BGG Vol.1, 2009.
- [6] Pacione, R., F. Vespe, 2008 "Comparative Studies for the Assessment of the Quality of Near Real-Time GPS- Derived Atmospheric Parameters" Journal of Atmospheric and Oceanic Technology Vol.25, No. 5, 701-714.
- [7] Pacione, R., B.Pace, H. Vedel, S. De Hann, R. Lanotte, F.Vespe (2009): Combination methods of tropospheric time series, Proceeding of 2nd International Colloquium - Scientific and Fundamental Aspects of the Galileo Programme, Padua, Italy, 2009.
- [8] Pottiaux, E., E. Brockmann, W. Soehne, and C. Bruyninx 2009: The EUREF EUMETNET Collaboration: First Experiences and Potential Benefits. In: Ihde, J. and H. Hornik (Eds): Subcommision for the European Reference Frame (EUREF), Brussels, 2008, BGG Vol.1, 2009.