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# Near Real-Time GPS Zenith Total Delay validation at E-GVAP Super Sites

ROSA PACIONE
e-GEOS, Centro di Geodesia Spaziale, Matera, Italy

FRANCESCO VESPE
Agenzia Spaziale Italiana, Centro di Geodesia Spaziale, Matera, Italy

B. PACE
Sistematica S.p.A., Centro di Geodesia Spaziale, Matera, Italy

*Summary*. – The EUMETNET GPS Water Vapour Programme (E-GVAP) has been set-up to collect, on the European scale, GPS ground-based tropospheric Zenith Total Delay (ZTD) estimates in Near Real-Time (NRT) for taking GPS meteorology in Europe to an operational status and delivering high quality GPS ZTD observations to the meteorological community. The number of operational GPS sites used in E-GVAP is more than 800, therefore there is the need, within E-GVAP community, to define a network of Super Sites, whose data must be analyzed by all analysis centers. It allows to make comparisons between processing centre solutions and validation against independent meteorological observations. First results, based on a 5-month long time series, on NRT GPS ZTD validation at E-GVAP Super Sites w.r.t. radiosonde observations show that GPS is drier than radiosonde for all analysis centers which are applying absolute phase center variations in their routine GPS processing. The analysis of the hourly post-fit phase residuals, output of the NRT data processing done with a standard technique of network adjustment fixing IGS Ultra-Rapid (IGU) products, is used to study the ZTD accuracy at the late boundary of the time span of the considered IGU products. The outcome of this analysis is useful to get an indication of the IGU update frequency.

## 1. – INTRODUCTION

Recent developments in GPS data processing have allowed the estimation of Zenith Total Delay, the delay of the neutral atmosphere or ZTD, with a high degree of accuracy using continuously operating GPS networks. From this delay, Integrated Water Vapor (IWV) can be derived by means of additional meteorological information, in particular observed pressure or numerical weather prediction model pressure.

On a European scale, collection of ground based GPS delay measurements in Near Real-Time was started around the beginning of this century, primarily as a result of the work related to EC COST ACTION 716 [5], followed by the scientific project TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology, http://tough.dmi.dk).

In April 2005, the EUMETNET GPS Water Vapour Programme (E-GVAP) has been set-up 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. Today, UK Met Office and Meteo France use NRT GPS ZTD in their operational forecasts. Other met agencies plan to start utilizing GPS ZTD data in their operations, since impact experiments indicate an improvement of the rain forecasts and of other meteo fields (e. g. wind and temperature) [11].

Currently, 10 E-GVAP Analysis Centers (ACs) are processing raw 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), 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).

In section 2, E-GVAP Super Sites are defined and the results of the GPS ZTD validation based on 5-month long time series are described. The validation is done both with respect to different GPS solutions, thus assessing the GPS internal accuracy, and to radiosonde observations.

Radiosonde data are often used to estimate the accuracy of GPS-derived atmospheric parameters considering short time scale (from several weeks to several years) of radiosonde data covering different regions of the world and to assess their degree of reliability. In [10] an extensive validation analysis of GPS ZTD data is deeply described. Discrepancies between radiosonde and GPS found in this and similar studies available in literature are often a result of errors in radiosonde humidity records. Such errors have been identified in [18] taking advantage of the long-term stability of the GPS data necessary for climate investigation.

In section 3, the accuracy of GPS NRT ZTD w.r.t. IGU products is evaluated and conclusions are drawn in section 4.

## 2. – E-GVAP SUPER SITES

The number of operational GPS sites used in E-GVAP has steadily increased to more than 800 sites (see the web page http://egvap.dmi.dk/).

Based on a recommendation from the E-GVAP expert team on data processing of expert geodesists, a set of Super Sites has been introduced (fig. 1), thus enabling quicker identification of many types of problems with the processing that can arise.

The Super Sites have been selected on the base of the following criteria: RINEX data should be available at least in 20 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.

The E-GVAP ACs apply different strategies for their NRT estimation of GPS ZTD and used different softwares, with different set-ups for the processing. They are relatively free to organize the processing in an optimized way. We refer to the [5] for a description of possible processing techniques.

At ASI Centro di Geodesia Spaziale (CGS), each Super Site is analyzed in NRT and in Post-Processing (hereafter PP) mode using GIPSY-OASIS II software [20] for data reduction. The NRT data processing is performed with a standard technique of network adjustment. The IGS [2] Ultra Rapid orbits are kept fixed but checked and "bad" satellites or stations are automatically excluded on the base of the analysis of the post-fit phase observation residuals, as suggested in [14]. When detected, a noisy station is not analyzed for the next 24 hours. A 24-hour sliding window approach for data handling is applied with a sampling rate of 5 minutes and an elevation cut-off angle for the data of 10°. The Zenith Wet Delay 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 PP solutions 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 [9]. For PP daily solutions, whose main features are reported in [8], the analysis is carried out by using the Precise Point Positioning approach [17], fixing Jet Propulsion Laboratory (JPL) fiducial-free satellite orbits, clocks and earth orientation parameters. The main aim of the PP solution is to provide both ZTD estimates useful for climate applications and site coordinates to fix in the NRT data processing. This is a necessary condition to get a more stable ZTD time series. 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 [13]) are needed to fulfill the requirement of retrieving IWV at an accuracy level of 0.5 kg/m2 [1].

In [10] the accuracy of ASI GPS Near Real-Time products have been assessed considering a 3-yr-long ZTD time series. The outcome of that analysis are used as terms of reference in the investigation described in paragraphs 2.1 and 2.2.

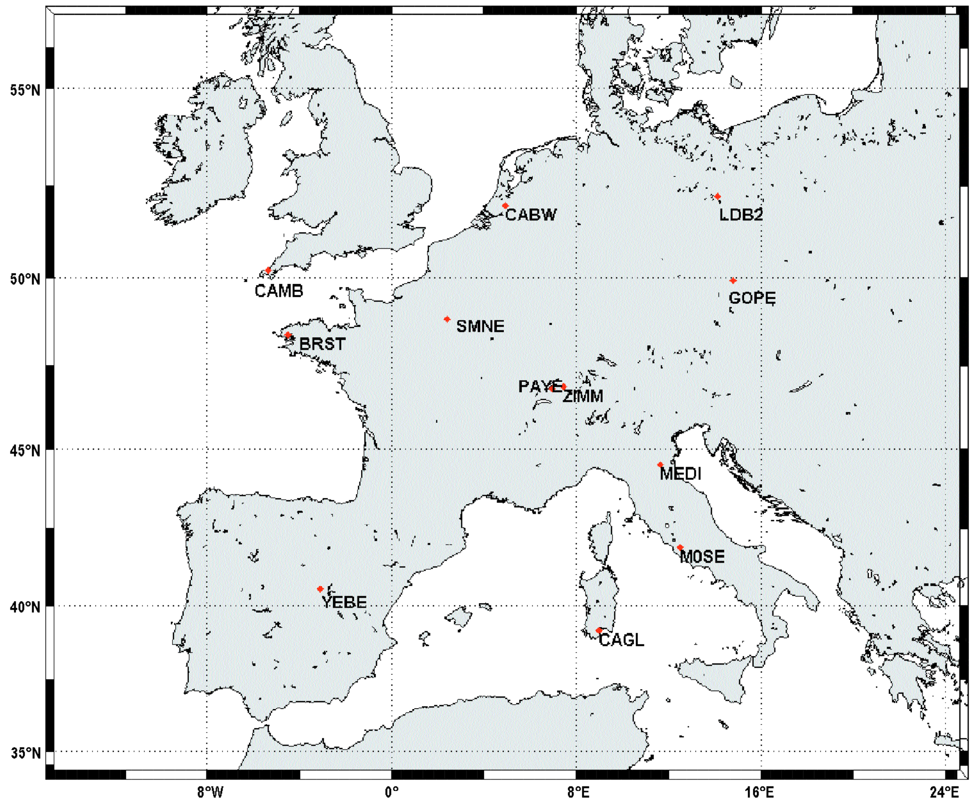


Fig. 1 – E-GVAP Super-Sites geographical location. In May 2008, two other Super Sites have been added: Milo (MILO, Italy) and Onsala (ONSA, Sweden), not shown in the figure.

### 2.1. - Super Sites internal validation

A 5-month long time series (November 2007 - March 2008) of Super Site ZTD data is considered for GPS internal validation. Pair wise comparison of individual NRT solutions over the whole period is done considering ASI solution as reference.

For each Super Site, the mean bias and standard deviation of the pair wise comparison using all observations available over the considered period are reported in table 1 and table 2, respectively. In fig. 2, the monthly variation in the ZTD bias and standard deviation for Cagliari (CAGL, Italy) and Medicina (MEDI, Italy) Super Sites is shown. The ZTD standard deviation ranges from 4 mm to 8 mm in agreement with what found in [10]. It is an indication of the precision which can be now achieved by the GPS technique. As far as the bias is concerned, it ranges from -12 mm to 2 mm considering all Super Sites. The larger bias (see table 1) w.r.t. GFZ can be explained because GFZ is still applying GPS relative phase center variations (PCV) [4] while all the other ACs are applying absolute values as recommended by IGS.

Gendt and Nischan [6] checked the differences in the Zenith Total Delay estimates generated using absolute and relative PCV models. For ~190 stations and 2 weeks of data, they found a mean bias of about –6 mm. Generally, this bias is depending on the antenna/radome type used at the station. Taking into account this mean bias, the bias in ASI versus GFZ comparison gets comparable to the other values reported in table 1.

Table 1 – Bias in the pair wise comparisons of the individual NRT solution using all observations available from November 2007 to March 2008. ASI solution is assumed as reference (unit in mm)

| | BKG | GFZ | GOP | KNMI | LPT | METO | SGN | SGN1 |
|---|---|---|---|---|---|---|---|---|
| BRST | – | –9.5 | –3.6 | –2.3 | –3.0 | –1.7 | –3.9 | –3.9 |
| CAGL | –3.6 | –7.5 | –1.2 | –0.6 | –0.4 | –0.3 | –0.9 | –0.9 |
| CAMB | – | – | –0.3 | 0.7 | – | 0.9 | –1.1 | –1.1 |
| GOPE | –5.3 | –10.3 | –4.2 | –3.1 | –1.6 | –4.3 | –6.2 | –6.2 |
| LDB2 | –8.4 | –12.1 | –4.2 | –7.1 | – | – | –9.7 | –9.7 |
| MEDI | 1.9 | –6.1 | 0.2 | 1.7 | 2.1 | 1.8 | –0.2 | –0.2 |
| M0SE | – | – | 0.6 | –0.4 | – | – | –1.3 | –1.3 |
| SMNE | – | –8.7 | –1.2 | –2.6 | –4.2 | –1.0 | –3.2 | –3.1 |
| YEBE | – | –6.3 | –1.4 | 0.9 | – | 1.5 | 0.2 | 0.2 |
| ZIMM | –2.0 | –6.8 | –1.6 | 0.1 | –1.1 | 0.7 | –1.5 | –1.4 |

Table 2 – Standard deviation in the pair wise comparisons of the individual NRT solution using all observations available from November 2007 to March 2008. ASI solution is assumed as reference (unit in mm)

| | BKG | GFZ | GOP | KNMI | LPT | METO | SGN | SGN1 |
|---|---|---|---|---|---|---|---|---|
| BRST | – | 5.9 | 5.2 | 4.7 | 5.0 | 5.4 | 6.4 | 6.5 |
| CAGL | 6.2 | 6.0 | 5.5 | 5.7 | 5.6 | 5.7 | 5.9 | 5.9 |
| CAMB | – | – | 6.1 | 5.7 | – | 6.1 | 6.2 | 6.2 |
| GOPE | 8.6 | 7.9 | 7.7 | 7.4 | 6.9 | 8.2 | 8.0 | 7.9 |
| LDB2 | 7.3 | 6.9 | 6.4 | 6.4 | – | – | 7.0 | 6.9 |
| MEDI | 5.7 | 6.3 | 5.7 | 5.3 | 5.6 | 5.9 | 6.0 | 6.0 |
| M0SE | – | – | 4.8 | 4.4 | – | – | 5.0 | 5.0 |
| SMNE | – | 5.1 | 5.4 | 4.2 | 4.7 | 5.2 | 5.9 | 5.9 |
| YEBE | – | 6.2 | 5.7 | 5.5 | – | 5.7 | 5.6 | 5.6 |
| ZIMM | 5.3 | 5.1 | 4.6 | 4.7 | 4.8 | 5.3 | 5.5 | 5.5 |

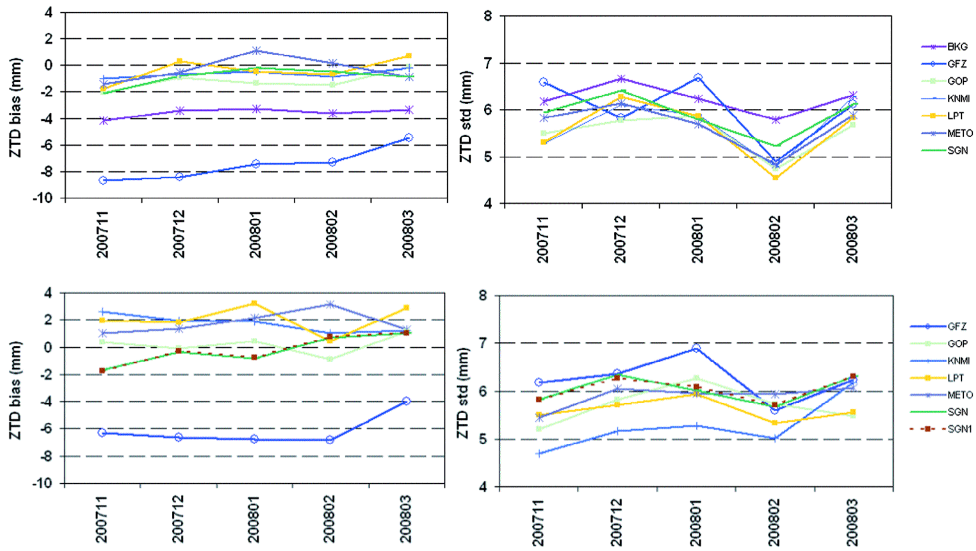


Fig. 2 – Cagliari (top) and Medicina (bottom) Super Site: pair wise comparisons in terms of monthly ZTD bias (left) and standard deviation (right) between individual NRT solutions. ASI solution is assumed as reference.

### 2.2. - Super Sites validation w.r.t. Radiosonde observations

GPS and radiosonde-derived ZTD estimated at Super Sites are compared for the period November 2007 – March 2008. Radiosonde profiles are provided by the Danish Meteorological Institute as independent data set to validate GPS ZTD data and are exchanged between EUREF and EUMETNET for scientific purposes [12]. In table 3 are reported the GPS and radiosonde code, the horizontal distance and the altitude difference between the GPS antenna and the radiosonde launch. The amount of data used in the comparison varies from each site and ACs and it depends on the availability of AC NRT solution in the considered epoch.

In fig. 3 the monthly variation in the ZTD bias and standard deviation for Brest (BRST, France), Medicina (MEDI, Italy) and Yebes (YEBE, Spain) Super Site is shown.

The standard deviation, computed over all observations available in the analyzed period, ranges from 5 mm to 14 mm in agreement with previous comparisons reported in [10] where more than 3 years of radiosonde observations were considered (see fig. 4).

As far as the bias is concerned, a wide and well-routed literature exists assessing that radiosondes are drier than GPS for time periods between 1999 and 2006. Almost all of the radiosondes used are Vaisala, one exception is Zimmerwald where Meteolabor radiosondes are launched. The Vaisala dry bias is well known and it has been discussed in [19], [15] and [16]. Most of these comparisons are based on GPS analyses which used relative antenna models for the ZTD estimation. From this comparison, we notice that GPS is drier than radiosonde for all the ACs. GFZ is the only exception. It was already described (see section 2.1) that GFZ is using relative antenna models whereas all other analysis centers used the absolute antenna models, which are recommended by IGS since November 2006 (GPS week 1400). This outcome is found also in [7] and [3] and needs to be deeply investigated especially to understand the dependence from the equipment (antenna/radome type) installed at the GPS site and in order to investigate possible seasonal variations, which also can be contributed to the radiosonde observations.

Furthermore, a residual analysis has been performed for each Super Site and AC on GPS minus radiosonde data. The histograms (get using normalized residual time series, see an example in fig. 5 for Cagliari Super Sites and ASI AC) are all symmetric, bell shape. This suggests that all the residual values behave in a similar manner to normally distributed independent samples.

Table 3 – GPS and radiosonde table. Distance is the horizontal distance between the radiosonde launch and the GPS antenna, (GPS - RS) height is he altitude difference between the GPS antenna and the radiosonde launch

| GPS site | RS code | Distance [km] | (GPS – RS) height [m] |
|---|---|---|---|
| BRST | 07110 | 10 | –85 |
| CAMB | 03808 | 0.6 | 0 |
| CAGL | 16560 | 15 | 187 |
| GOPE | 11520 | 29 | 181 |
| LDB2 | 10393 | 5 | 5 |
| MEDI | 16144 | 15 | –1 |
| M0SE | 16245 | 27 | 40 |
| PAYE | 06610 | 8 | 8 |
| SMNE | 07145 | 32 | –86 |
| YEBE | 08221 | 45 | 288 |
| ZIMM | 06610 | 40 | 417 |

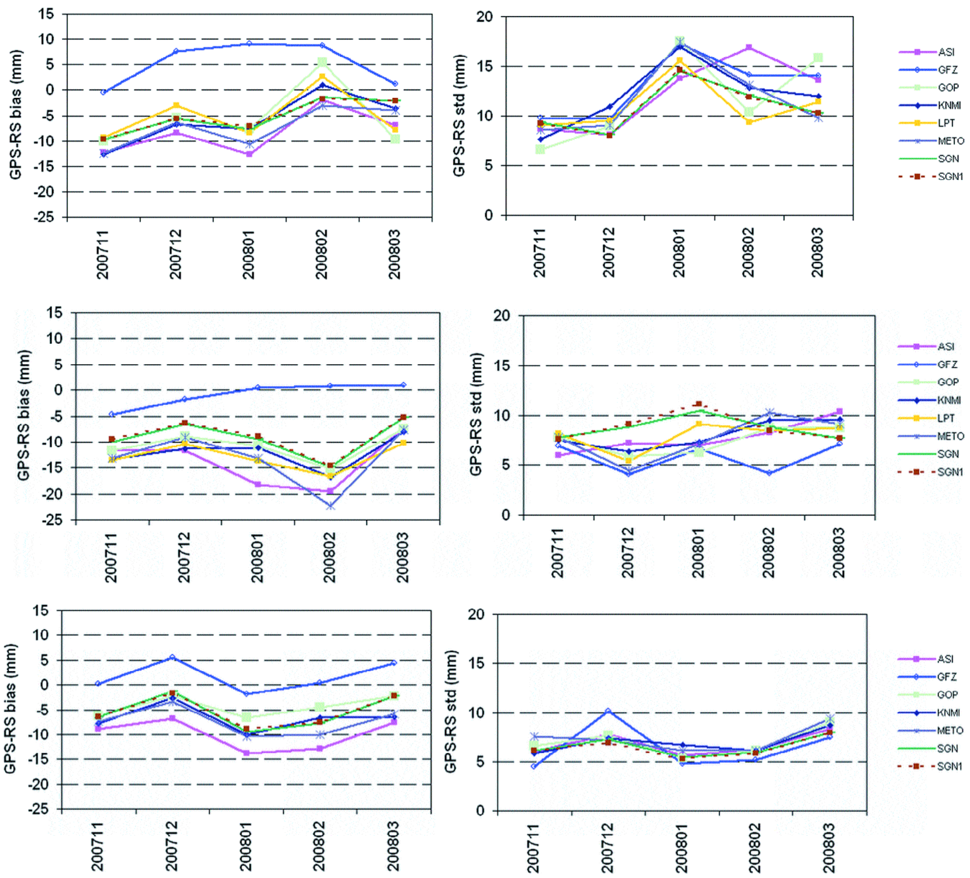


Fig. 3 – Brest (top), Medicina (middle) and Yebes (bottom) Super Site: ZTD monthly bias (left) and standard deviation (right) between GPS and radiosonde observations.

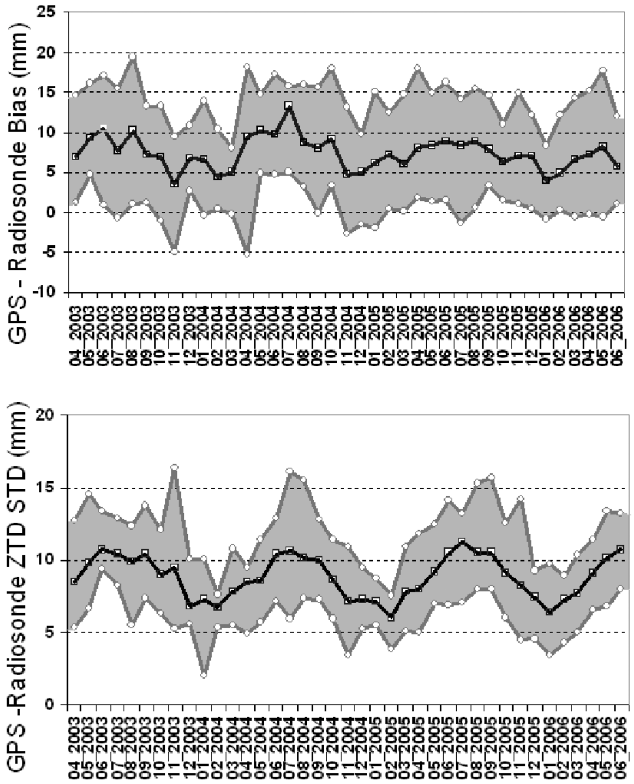


Fig. 4 – Monthly variation in ZTD bias (top) and std (bottom) of GPS versus radiosonde for the period April 2003-June 2006 and 13 stations (black line). Among then the following Super Sites are involved: CAGL, GOPE, MEDI, M0SE, YEBE and ZIMM. The grey area lies between the minimum and maximum values.

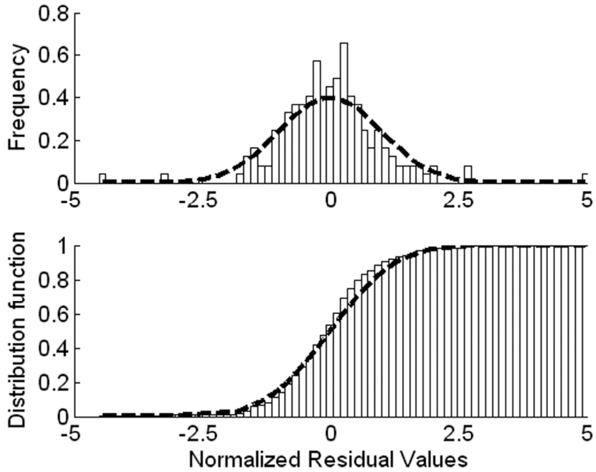


Fig. 5 – Residual Histogram and Normal Probability Plot for Cagliari Super Site and ASI AC. The bold lines are the theoretical values.

## 3. – ACCURACY OF NRT ZTD W.R.T. IGU PRODUCTS

The estimation of NRT GPS ZTD is based on IGS Ultra Rapid (IGU) orbits which are updated four times daily, that is at 03:00, 09:00, 15:00 and 21:00 UTC. Within E-GVAP community a discussion arises if NRT ZTD accuracy could be improved in case of IGS delivers Ultra Rapid orbits more frequently. The analysis of the hourly post-fit phase residuals can be used to investigate if there is a degradation in the ZTD accuracy at the late boundary of the time span of the considered IGU products.

For this, 5 GPS weeks (1471-1475/08MAR16-08APR19) are considered. Mean and standard deviation of epoch-wise post-fit phase residuals RMS values, w.r.t. every hour of the day, have been computed for all satellites and receivers. The hourly post-fit phase residuals are outputs of the NRT processing described in Section 2. Since a network approach is applied, these residuals are not influenced by any corresponding clock values but are influenced by the quality of the input data (that are IGU products and GPS data).

In fig. 6 mean and standard deviation of epoch-wise post-fit phase residuals RMS values, are shown for a sub-set of stations. The mean of the hourly post-fit phase residuals ranges from 5 mm to 8 mm with an increase of the order of a couple of mm just one hour before switching to the new IGU products, that is at 02:00, 08:00, 14:00, 20:00 UTC. The related standard deviation is ranges from 0.5 to 1 mm increasing of approximately 4-6 times at the late boundary of the time span of the considered IGU products, depending on the considered site. Similar results have been obtained analyzing satellite post-fit phase residuals. Such increase in the standard deviation shows that the process gets less stable at these hours of the day and seems to suggest that IGU orbits should be updated every 4 hours, at least when the described processing scheme is applied. This outcome needs to be confirmed by a cross-check investigation into epoch-wise post-fit phase residuals output of the different strategies with several softwares and set-ups used by the ACs when estimating ZTD.

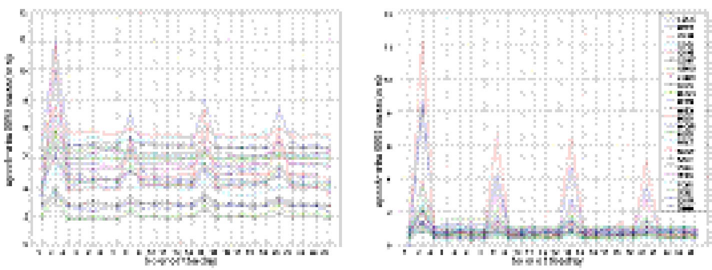

Fig. 6 – Hourly mean (left) and standard deviation (right) of epoch-wise post-fit phase residual RMS values.

## 4. – CONCLUSION

The ground based GPS technique is a useful tool for monitoring atmospheric parameters and for capturing their temporal variability. Data from E-GVAP Super Sites are processed in Near Real-Time mode by all analysis centres and the estimated ZTD is validated considering a 5-month long time series. In the GPS internal validation a larger bias is found w.r.t. GFZ which is due to the inconsistently used antenna phase center model (relative model in case of GFZ and absolute antenna model for all other analysis centers). The comparisons w.r.t. radiosonde observations show, for all ACs, which are applying absolute PCVs values in their routine processing, that the GPS estimates are drier than radiosonde-derived ZTDs. A deeper investigation, considering a longer time series, is necessary to point out any dependence of this GPS dry bias due to the equipment installed at the GPS site and to study possible annual variations.

The analysis of the hourly post-fit phase residuals is used to study the ZTD accuracy at the late boundary of the time span of the considered IGU products which are fixed in the data reduction process. The outcome of this analysis could be useful to get an indication of the IGU update frequency.

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