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**Key Points:**

- We develop a new RT GPS water vapor processing system
- PPP ambiguity fixing with RT satellite orbit, clock, and phase delays
- Our results are very promising and demonstrate RT ZTD/IWV accuracy

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# Real-time GPS sensing of atmospheric water vapor: Precise point positioning with orbit, clock, and phase delay corrections

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**Abstract** The recent development of the International Global Navigation Satellite Systems Service Real-Time Pilot Project and the enormous progress in precise point positioning (PPP) techniques provide a promising opportunity for real-time determination of Integrated Water Vapor (IWV) using GPS ground networks for various geodetic and meteorological applications. In this study, we develop a new real-time GPS water vapor processing system based on the PPP ambiguity fixing technique with real-time satellite orbit, clock, and phase delay corrections. We demonstrate the performance of the new real-time water vapor estimates using the currently operationally used near-real-time GPS atmospheric data and collocated microwave radiometer measurements as an independent reference. The results show that an accuracy of 1.0 ~ 2.0 mm is achievable for the new real-time GPS based IWV value. Data of such accuracy might be highly valuable for time-critical geodetic (positioning) and meteorological applications.

## 1. Introduction

It is well known, that atmospheric water vapor is fundamental for the transfer of energy in the atmosphere and for the formation and propagation of precipitation events. Water vapor is highly variable in space and time depending on the complex interplay of several phenomena like convection, precipitation, turbulence, etc. It remains one of the most poorly characterized meteorological parameters, because this important quantity is often inadequately covered by conventional and satellite observations due to various limitations [*Gendt et al.*, 2004].

Remarkable progress in using of Global Navigation Satellite Systems (GNSS), in particular GPS, for monitoring of atmospheric water vapor has been achieved during the last decades [*Bevis et al.*, 1992; *Rocken et al.*, 1997; *Fang et al.*, 1998]. Various studies have demonstrated that GPS could provide accurate water vapor estimates in both postprocessing and near-real-time (NRT, generally 1–2 h latency) modes, which are comparable to the measurements of meteorological sensors [*Dick et al.*, 2001; *Gendt et al.*, 2004; *Dousa*, 2001; *Karabatic et al.*, 2011]. GNSS have several significant advantages compared to the traditional observing systems, including low operating expense, all-weather operability, and high temporal/spatial coverage. As a notable example, in the framework of the European EUMETNET EIG GNSS water vapour programme (http://egvap.dmi.dk/) project more than 2400 GNSS sites are continuously operated, providing hourly updated tropospheric Zenith Total Delays (ZTD) for assimilation into numerical weather prediction (NWP) models. A positive impact of GPS-derived tropospheric products on NWP has been demonstrated in several studies [e.g., *Haan et al.*, 2004; *Gutman et al.*, 2004; *Shoji et al.*, 2011; *Karabatic et al.*, 2011]. Several European projects such as WAVEFRONT, MAGIC, and European Cooperation in Science and Technology (COST-716) [*Elgered et al.*, 2005] have all demonstrated the ability of GNSS to serve as an accurate atmospheric water vapor sensor for meteorological applications.

However, many innovative applications such as now-casting of severe weather events or regional short-term forecast systems could potentially benefit from more rapid updates of the atmospheric state. A transition from deferred-time to real-time GPS data analysis can provide a significant contribution in this context. The development of real-time tropospheric products is one of the most important topics within the new European Earth System Science and Environmental Management COST Action ES1206 "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)" which started in May 2013 with 33 participating countries (http://www.cost.eu/domains_actions/essem/Actions/ES1206).

Two processing strategies are mainly used in (near) real-time or postprocessed GPS water vapor estimation: the baseline/network approach using double-differenced observations [*Rocken et al.*, 1997; *Hernandez-Pajares et al.*, 2001; *Iwabuchi et al.*, 2006] or the precise point positioning (PPP) [*Zumberge et al.*, 1997] approach using undifferenced (UD) observations [*Gendt et al.*, 2004; *Karabatic et al.*, 2011]. The network approach has been successfully used in real-time applications as most of the errors can be effectively cancelled out (e.g., satellite clock errors) or reduced (e.g., orbit errors) during the differencing process [*Lee et al.*, 2013]. However, the network approach is time consuming and particularly difficult for real-time data analysis (rapid update and super low latency, e.g., few seconds) of several hundreds or thousands of ground stations. Furthermore, insufficient separation between GPS stations can lead to the filter divergence. The PPP approach has been proved to be effective in the deferred-time mode [*Byun and Bar-Server*, 2009], but it was limited in real-time applications because precise ephemeris such as the International GNSS Service (IGS) final ephemeris were generally unavailable in real time.

Thanks to the recent development of the IGS Real-Time Pilot Project (RTPP), real-time precise satellite orbit, and clock products are now available online (launched in April 2013), and thus, the interest in real time PPP technique has greatly increased [*Caissy et al.*, 2012]. Especially, integer ambiguity fixing approach for PPP has been developed in recent years to improve its performance [*Ge et al.*, 2008; *Geng et al.*, 2012; *Li et al.*, 2013]. Deutsches GeoForschungsZentrum (GFZ), as one of the IGS real-time analysis centers, is operationally generating real-time orbits, clocks, and uncalibrated phase delays (UPDs) for the ambiguity-fixed PPP service using the recently developed Earth Parameter and Orbit determination System – Real Time (EPOS-RT) software [*Ge et al.*, 2008]. Based on these real-time products, we developed a real-time GPS ZTD/Integrated Water Vapor (IWV) estimation technique might be of special interest for time-critical meteorological applications such as nowcasting and longer-range numerical weather prediction. The new real-time IWV processing is now implemented at GFZ and runs in PPP ambiguity fixing mode for a large number of stations. We present initial validation results of the new real-time ZTD and IWV estimates using the established NRT ZTD products and the collocated radiometer observations as a reference.

## 2. Real Time GPS Data Analysis

In recent years an increasing number of GPS stations have been set up to provide data in real time. These GPS networks provide a great opportunity for real-time GPS IWV estimation where the processing delay is typically at the level of a few seconds or less. The observation equation of the UD carrier phase can be expressed as:

$$L = \rho_g - t^s + t_r + \lambda(b_r - b^s + N) - I + T + \varepsilon. \tag{1}$$

where $s$ and $r$ refer to satellite and receiver, respectively, $t^s$ and $t_r$ are the clock biases, $N$ is the integer ambiguity, $b_r$ and $b^s$ are the UPDs, $\lambda$ is the wavelength, $I$ is the ionospheric delay, $\varepsilon$ denotes measurement noise and multipath, and $\rho_g$ denotes the geometric distance. The phase center offset and variation, tidal loading, and phase windup can be corrected according to the existing models [*Ge et al.*, 2008]. The tropospheric delay $T$ consists of the dry and wet components and both can be expressed by their individual zenith delay and mapping function,

$$T = M_h \cdot Z_h + M_w \cdot [Z_w + \cot(e) \cdot (G_N \cdot \cos(a) + G_E \cdot \sin(a))]. \tag{2}$$

The dry delay $Z_h$ can be computed rather accurately using the Saastamoinen model and meteorological data, the zenith wet delay $Z_w$ and gradient parameters are estimated in the GPS data processing. $M_h$ and $M_w$ are the dry and wet coefficients of the global mapping function (GMF) [*Böhm et al.*, 2006]; $e$ and $a$ are the elevation and azimuth angle; $G_N$ and $G_E$ are the gradients in north and east directions.

Within the framework of the IGS RTPP, data from a global real-time network of more than 100 stations is available and the related data transfer links for the observation retrieving and product casting were established [*Caissy et al.*, 2012]. Furthermore, several Real-Time Analysis Centers (RTAC) were established and have been running operationally to contribute their real-time orbit and clock products for comparison and combination. Most of the RTAC use a processing procedure similar to that for generating the IGS ultrarapid orbits, but the update time of 6 h could be shortened for a better orbit accuracy. GFZ provides an ultrarapid product updated every 3 h for real-time users. The satellite clock products are estimated every 5 s together with receiver clock, ambiguity, and zenith tropospheric delay parameters with fixed or tightly constrained satellite orbits and station coordinates.

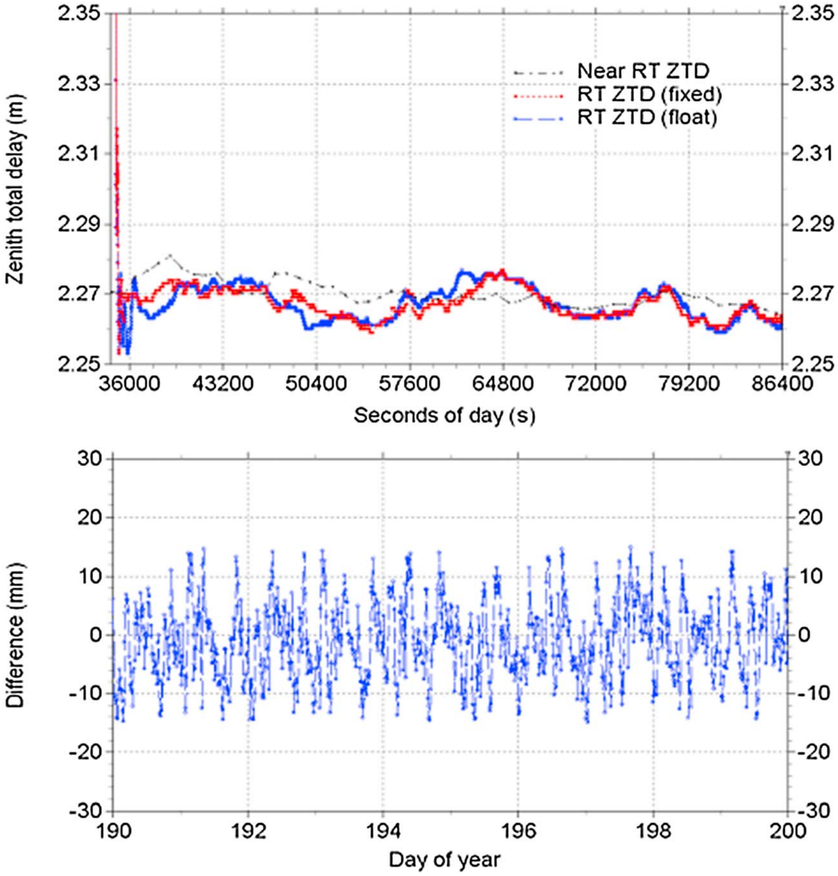

**Figure 1.** Comparison of the real-time ZTD and NRT ZTD products at SAPOS station 0256 (Munich). (a) The real-time ZTD values (5 May 2013, DOY 125) derived from ambiguity fixed PPP is shown by the red curve. The near real-time ZTD product is drawn by the black curve. The real-time ZTD derived from traditional PPP float solution is also shown for comparisons with the blue curve. (b) The difference between real-time ZTD (fixed solution) and NRT ZTD for the period of 10 days (DOY 190-200, 2013).

For recovering the integer feature of the UD ambiguities at user-end, UPD corrections are also estimated and transmitted to users [*Li et al.*, 2013].

With the received real-time corrections of GPS satellite orbit, clock, and UPD, the corresponding terms can be calculated and the observation equation can be expressed as

$$-(M_w\cdot[Z_w + \cot(e)\cdot(G_N\cdot\cos(a) + G_E\cdot\sin(a))]) - t_r - \lambda\cdot N + I = \rho_g - L - t^s + \lambda(b_r - b^s) + M_h\cdot Z_h + \varepsilon \quad (3)$$

The station coordinates are tightly constrained or fixed to known values. The receiver UPD can be easily separated by adapting one UD ambiguity to its nearest integer. The estimated parameter vector **X** can be expressed as

$$\mathbf{X} = \left(Z_w\ G_N\ G_E\ t_r\ (\mathbf{N})^T\ (\mathbf{I})^T\right)^T. \quad (4)$$

**N** is integer ambiguity vector for all the visible satellites, **I** is ionospheric delay vector. A sequential least squares filter is employed to estimate the unknown parameters for real-time processing. The tropospheric zenith wet delay and associated northern and eastern horizontal gradients are modeled as a random walk process. The receiver clock $t_r$ is estimated epoch-wise as white noise. The carrier-phase ambiguities **N** are fixed to integers using integer estimation methods [*Li et al.*, 2013]. The ionospheric delays are taken as estimated parameters for each satellite and at each epoch by using dual-frequency carrier phase and pseudorange observations. A strict data quality control procedure is employed, including preprocessing, robust filter, and residual editing in real time.

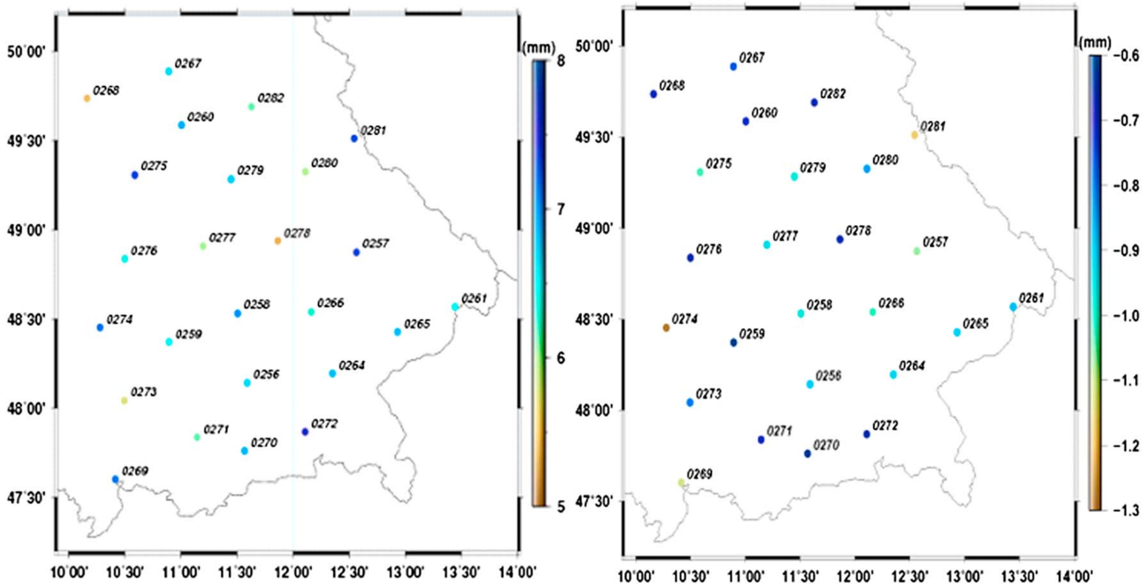

**Figure 2.** (left) The RMS values and (right) the mean biases of the ZTD differences (DOY 190-200, 2013) retrieved from real-time PPP and NRT procedure. Data from the SAPOS subnetwork of 25 GPS stations in Bavaria are used here.

In the GPS IWV estimation, the quantity of greatest interest is $Z_w$, the discrete formulation of $Z_w$ can be modeled as follows

$$Z_{w,t} - Z_{w,t-1} = q_t, q_t \sim N\left(0, \sigma_{\mathrm{qt}}^2\right). \tag{5}$$

Here $q_t$ is the tropospheric change from the previous to the current epoch, $\sigma_{\mathrm{qt}}^2$ is the variance of $q_t$, and the noise intensity is about $5 \sim 10\ \mathrm{mm}/\sqrt{\mathrm{hour}}$.

Once $Z_w$ is accurately estimated, it can be directly related to the IWV [*Askne and Nordius*, 1987]:

$$\mathrm{IWV} = \Pi(T_m) \cdot Z_w. \tag{6}$$

$\Pi(T_m)$ depends on the atmospheric mean temperature $T_m$ and can be calculated from surface meteorological measurements. Its value is typically around 0.15 and can vary up to 15%.

## 3. Accuracy Evaluations Using the Established NRT Products

Taking the operational real-time PPP service, developed at GFZ, as example [*Ge et al.*, 2008; *Li et al.*, 2013], the data streams of about 80 globally distributed IGS stations are processed in real time by using the EPOS-RT software for generating and broadcasting orbit, clock, and UPD products for the PPP ambiguity fixing service. From the IGS real-time combination and comparison, the user range error of the orbit and clock is about 0.1 ns. Based on these corrections, data streams from the SAPOS network (1Hz sampling rate) in Germany were processed in real time to generate ZTD and IWV estimates as described in section 2. The established deferred-time products of GFZ were used for accuracy evaluation of the new real-time ZTD products.

GFZ has more than 10 years experience in GPS ground-based monitoring of atmospheric IWV. Beginning with several field campaigns this experience has been extended to the operational determination of water vapor in near real time with an accuracy of about 1 mm for the IWV. Currently, the data of ~350 German GPS stations are analyzed hourly at GFZ and ZTD/IWV products are available with a delay of about 30 min. The temporal resolution of these data sets is 15 min. All these operationally running hourly updated products are based on the batch processing using the GFZ EPOS software [*Gendt et al.*, 2004]. The NRT ZTD products are now assimilated operationally by several European weather services.

The real-time ZTDs derived from PPP solution are compared with our NRT ZTD products and the results for SAPOS station 0256 (Munich) on DOY 125, 2013 are shown as examples in Figure 1a. The real-time ZTD series

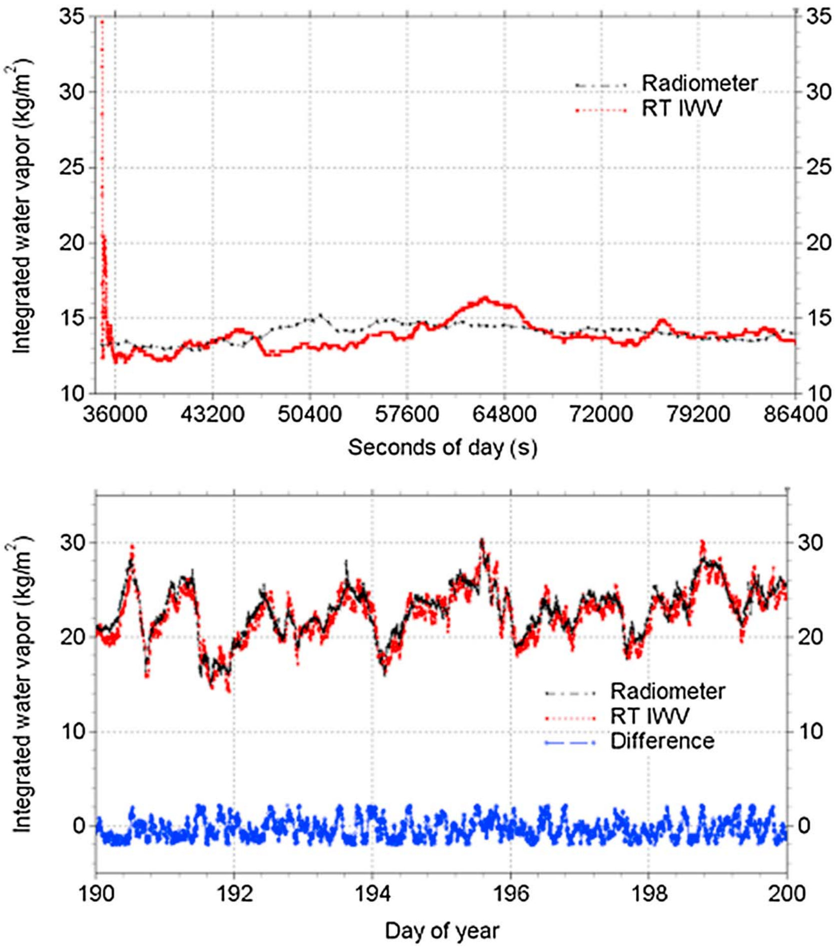

**Figure 3.** Comparison of integrated water vapor from real-time PPP and the collocated GFZ microwave radiometer at Potsdam. The real-time IWV values derived from ambiguity fixed PPP are represented by the red curve. The IWV measurements from microwave radiometer are indicated by the black curve. (a) The IWV comparison for DOY 125, 2013. (b) The IWV comparison for a period of 10 days (DOY 190-200, 2013) together with their differences which are shown in blue.

derived from the PPP fixed solution are shown by the red curve, while the NRT ZTD results are shown by the black curve. The comparison shows that the real-time ZTD after convergence agrees quite well with the NRT results with a difference about several millimeters. The real-time ZTD derived from the PPP float solution is also shown in the same figure and the comparison indicates that integer ambiguity fixing can significantly improve the ZTD estimates at the beginning (first hours). It is useful for the rapid (re-)initialization (when receiver activation or signal interruption for most of the satellites) of a real-time water vapor system and important for time-critical applications. We can also find that no significant difference between PPP float and fixed solutions remains after a sufficiently long time of convergence (e.g., several hours).

Figure 1b shows the difference series between the real-time ZTD (with integer ambiguity fixing) and the NRT ZTD product for station 0256 during a period of 10 days (DOY 190-200, 2013). We calculated the root-mean-square (RMS) values of the ZTD differences retrieved from real-time PPP and NRT procedure. The RMS for the station 0256 is about 6.7 mm (the mean bias is about $-0.9$ mm and the standard deviation is about 6.64 mm). The results of 25 GPS stations (Bavarian) are shown in Figure 2 and the RMS values range from 5 mm to 8 mm, which is about 1 mm in integrated water vapor.

## 4. Validation With Water Vapor Radiometer

The IWV data products, generated by the real-time analysis were validated using independent observations from a microwave radiometer. The GFZ microwave radiometer (Humidity And Temperature Profiler, Radiometer Physics

GmbH), which is operated in the vicinity of the Potsdam GNSS station (~10 m distance), observes the water vapor lineshape at six frequency channels between 22.24 and 27.84 GHz and a window channel at 31.4 GHz. It provides IWV and liquid water data along the respective line of sight.

The comparisons of real-time GPS IWV derived from the PPP fixed solution and radiometer measurements with the collocated GFZ microwave radiometer and GPS station are displayed in Figure 3. The results of the day 125 of 2013 are shown as examples in Figure 3a. The real-time IWV series derived from PPP fixed solution are represented by the red curve, while the radiometer measurements are shown by the black curve. We started the new real-time IWV procedure at about 9:30 of that day, so we can clearly see an initialization stage for ambiguity fixing. After a short convergence of about 10 min, the real-time IWV displays an excellent agreement with the radiometer results with a difference of about 1.0 ~ 2.0 mm.

Figure 3b shows the time series of real-time IWV (with ambiguity fixing) and radiometer measurements during a period of 10 days (DOY 190-200, 2013). Within this period the filter was running continuously and the real-time IWV data do not contain the initialization period. The results show a good consistency and the differences are in general smaller than 3.0 mm. The IWV differences between real-time PPP and radiometer measurements are presented by the blue curve and the RMS value is about 1.4 mm (with a slight bias of −0.25 mm). We conclude that the real-time ambiguity-fixed PPP can quickly provide accurate IWV estimates with a single GPS receiver. This demonstrates the potential of real-time GPS IWV for the detection of rapidly evolving meteorological phenomena, e.g., frontal passages.

## 5. Conclusions and Discussions

In this study, we develop a real-time GPS IWV estimation technique using PPP with real-time satellite orbit, clock, and phase delay corrections, which is especially suitable for analyzing dense GPS networks with a large number of stations. We present initial validation results and evaluate the accuracy of the new real-time ZTD and IWV estimates using the established NRT ZTD products and collocated radiometer measurements as a reference.

The results from the German SAPOS network show a high consistency between the established deferred-time and the new real-time ZTD products. The RMS of their differences is about 1 mm in integrated water vapor. Comparisons with water vapor radiometer measurements show that the real-time GPS IWV estimates have an accuracy of about 1.0 ~ 2.0 mm. These initial results are very promising and demonstrate the huge potential of real-time tropospheric products for meteorological applications, like improving short-term precipitation forecast. Further analysis of long-term IWV series (e.g., few years) derived from real-time PPP and comparisons with more water vapor radiometers will be in focus of future work.

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