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Comparative Analysis of Real-Time Precise Point Positioning Zenith Total Delay Estimates

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Abstract

The continuous evolution of Global Navigation Satellite Systems (GNSS) meteorology has led to an increased use of associated observations for operational meteorology worldwide. In order to enhance short-term weather forecasts, meteorological institutions have developed modern low-latency Numerical Weather Prediction (NWP) models which assimilate GNSS-derived Zenith Total Delay (ZTD) estimates. Usually, the assimilation of the ZTD in NWP models is performed in 3-hourly to 6-hourly cycles. However, the development of NWP models with faster assimilation cycles, e.g. 1-hourly assimilation cycle in the Rapid Update Cycle (RUC) NWP model, has increased the interest of the meteorological community towards sub-hourly ZTD estimates. For such NWP models, a number of GNSS processing strategies allow the provision of these ZTDs in real-time (RT), but only at a loss in accuracy. The suitability of RT ZTD estimates obtained from three different Precise Point Positioning (PPP) software packages has been assessed by comparing them to the state-of-the-art IGS Final Troposphere Product as well as collocated radiosonde observations. The time series of the ZTD obtained by the three software packages follow the same pattern. The comparison has shown that the ZTD estimates obtained by BNC2.7 show a mean bias of 0.21 cm to the reference, and those obtained by the G-Nut/Tefnut software library show a mean bias of 1.09 cm. Whereas, the ambiguity float and ambiguity fixed solutions obtained by PPP-Wizard have mean biases of 6.81 cm and 6.21 cm, respectively. The large biases in the time series from PPP-Wizard are due to the fact that this software has been developed for kinematic applications and hence does not apply receiver antenna eccentricity and PCO corrections on the observations. Application of the eccentricity and PCO corrections to the a priori coordinates has resulted in a 66% reduction of bias in the PPP-Wizard solutions. The biases are found to be stable...
over the whole period of the comparison which is a criteria (rather than the magnitude of the bias) for the suitability of ZTD estimates for use in NWP nowcasting. A millimeter-level impact on the ZTD estimates has also been observed in relation to ambiguity resolution.

Keywords:
GPS, GNSS, Real-Time, Zenith Total Delay, Precise Point Positioning, Ambiguity Resolution
Introduction

The observations from Global Navigation Satellite Systems (GNSS) can be used to study the state of the troposphere at a given location and time by estimating the respective amount of zenith total delay (ZTD) and converting this to integrated water vapor (IWV) using surface meteorological data (Bevis et al., 1994). Both of these GNSS-derived tropospheric parameters (ZTD and IWV) can further be assimilated into numerical weather prediction (NWP) models having a positive impact on the quality of weather forecasts (Bennitt and Levick, 2011; de Haan, 2011; Gutman et al., 2004; Vedel et al., 2004). As of today, the Global Positioning System (GPS) is the most widely used GNSS in operational meteorology. However, research is on-going for the inclusion of other GNSS in meteorological applications. Therefore, in the following text, the term GNSS would refer to GPS unless otherwise stated.

Over the last decade, a number of international research projects and programmes in Europe (Elgered, 2001; Huang et al., 2003), North America (Smith et al., 2007) and Asia (Iwabuchi et al., 2000) have investigated the use of GNSS-derived near real-time (NRT) ZTD estimates in NWP models. Since 2005, the EUMETNET EIG GNSS water vapor programme (E-GVAP) enables various analysis centers across Europe to submit their NRT ZTD estimates for assimilation into the NWP models of the partner meteorological institutions (Vedel et al., 2012). In late 2012, another European project “COST Action ES1206: Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)” (Jones et al., 2012) was approved to investigate GNSS meteorology further in the light of modern challenges and developments.

As of today, the NRT ZTD estimates are assimilated into local, regional and global scale NWP models that are run with 3-hourly to 6-hourly update cycles and produce long-term (up to a few days) weather forecasts. However, with the developments of high update-rate NWP models, e.g. the Rapid Update Cycle (RUC) (Benjamin et al., 2010) and the Real-Time Meso Analysis High Resolution Rapid Refresh (RTMA-HRRR) (Benjamin et al., 2013), and in order to use the ZTD estimates for NWP nowcasting and monitoring extreme short-term weather
changes, it is desired to obtain them with a minimal latency of 10 or even 5 minutes while maintaining an accuracy of 5 to 30 mm.

The real-time (RT) transport of GNSS observational data and products is carried in the formats specified by the Special Committee 104 (SC104) of the Radio Technical Commission for Maritime Services (RTCM) (http://www.rtc.org, Heo et al., 2009) using the Network Transport of RTCM via Internet Protocol (NTRIP) (Weber et al., 2006). Since December 2012, the Real-Time Service (RTS) of the International GNSS Service (IGS) (Caissy et al., 2012; Dow et al., 2009) and its associated analysis centers are making RT orbit and clock products officially available to the GNSS community. These products include the broadcast ephemeris and the orbit and clock corrections. The IGS together with RTCM-SC104 have defined different formats for the dissemination of observation and correction data in RT. The format for observation data messages is called RTCM-3 and that for orbit and clock correction messages is called RTCM-SSR where SSR stands for State Space Representation (Weber et al., 2012; Wübben, 2012). The RTCM-SSR real-time streams are composed of various types of messages.

Using the RT data and products, ZTD can be estimated in RT but different strategies result in different accuracies of the obtained ZTD estimates. The availability of orbit and clock products in RT triggers the possibility to perform Precise Point Positioning (PPP) (Zumberge et al., 1997) in RT. Although both the double differenced (DD) and PPP processing strategies can be implemented in RT, PPP is highly suitable for RT processing due to being computationally more efficient.

Various error sources can affect the accuracy of the GNSS-derived ZTD estimates. In PPP processing, the ZTD is more sensitive to the radial component of the orbit error, whereas in DD processing, it is more sensitive to the tangential component of the orbit error (Douša, 2012). Although the first-order ionospheric delay is eliminated using the linear combination of the measurements from two different carriers, there remains still a smaller effect from the higher order terms of the ionosphere delay especially during the times of high solar activity. There is a linear dependency between the daily mean of the total electron content (TEC)
unit and the estimated vertical position (Fritsche et al., 2005). If the error in ZTD is approximated as one third of the vertical position error (Hill et al., 2009), it would mean that an increase of the TEC unit from 25 to 175 will result in a ZTD error ranging from 0.6 mm to 4 mm if higher-order ionospheric corrections are not applied. Furthermore, errors in the a priori zenith hydrostatic delay (ZHD) caused by the use of inaccurate surface pressure values could result in an error of -0.1 mm/hPa to -0.2 mm/hPa in vertical position estimates (Tregoning and Herring, 2006) and this could also lead to an error in the ZTD. Antenna related errors, e.g. phase center offsets and variations (PCV) and radome geometry, also lead to errors in the vertical position and the ZTD estimates. Byun and Bar-Sever (2009) and Thomas et al. (2011) have shown that differences in the estimated ZTD with and without the PCV corrections may vary from 2 to 10 mm. The tropospheric mapping functions (MF), which are used to map the tropospheric delay from other angles (slant) to zenith, also have an elevation-dependent effect on the corresponding ZTD, although the effect of the MF reduces with an increase in any elevation cut-off angle used for observations (Ning, 2012).

Fixing of integer phase ambiguities enhances the precision of the position estimates. In the DD strategy, common errors are removed and it becomes easier to identify and fix such integer ambiguities. However, for un-differenced observations, it was not possible to fix the integer phase ambiguities until recently (Geng et al., 2010). Amongst others, the Centre National d’Etudes Spatiales (CNES) has developed strategies to fix integer ambiguities of un-differenced phase measurements by first fixing the difference between the ambiguities on the two carrier frequencies and then fixing the remaining ambiguity in a global network solution (Loyer et al., 2012). To date, only few studies have been performed to study the impact of ambiguity resolution on the GNSS-based ZTD estimates and some of them are based on in-house software and products (Shi and Gao, 2012, Li et al., 2014).

We have evaluated the suitability of RT-PPP ZTD estimates for meteorological applications through a comparison with the IGS Final Troposphere Product and collocated radiosonde observations. These estimates have been obtained by three different PPP software packages using RT orbit and clock products from the IGS
RTS as well as from the individual analysis center CNES. The effect of integer ambiguity resolution on ZTD estimates has also been studied. All the software packages and products used are freely available.

The next sections describe the RT-PPP software packages, the RT data and products, and the reference solutions used in this study followed by results, discussion and conclusions.

**Real-Time PPP Systems**

The real-time processing for a selection of GNSS stations and time periods was simultaneously performed at the University of Luxembourg (UL) and the Geodetic Observatory Pécny (GOP). UL generated the solutions from BNC2.7 and PPP-Wizard whereas GOP generated the solutions using the Tefnut application from their G-Nut software library.

The BKG Ntrip Client (BNC), developed by the Bundesamt für Kartographie und Geodäsie (BKG) (Weber and Mervart, 2012), is capable of performing PPP in RT (RT-PPP). For this study, version 2.7 of the BNC has been used to perform RT-PPP using streams of code plus phase observations, the broadcast ephemeris and corrections for satellite orbits and clocks. During the processing in BNC, the corrections from the RT streams are applied to the broadcast ephemeris. Along with the precise position estimates, the ZTD estimates can also be obtained as one of the outputs. The recent study by Yuan et al (2014) is also based on this software package, however, they have modified it to implement some precise bias models such as ocean tide loading, receiver antenna PCV and computation of hydrostatic and wet mapping functions from Global Pressure and Temperature 2 (GPT2) model (Lagler et al., 2013).

To promote their ambiguity fixing strategy, CNES developed the “Precise Point Positioning with Integer and Zero-difference Ambiguity Resolution Demonstrator (PPP-Wizard)” and started to produce a RT product containing corrections for integer ambiguity resolution which can be used to fix ambiguities in RT-PPP mode (Laurichesse, 2011).
The G-Nut software library (Václavovic et al., 2013) has been developed at the Geodetic Observatory Pecny (GOP) since 2011 in order to support development of high-accuracy GNSS analysis. Several end-user applications have been derived for meteorology and climatology (Tefnut), geodesy and seismology (Geb) and GNSS quality checking (Anubis). We have used the G-Nut/Tefnut software which is capable of estimating GNSS tropospheric parameters in RT, NRT and post-processing modes (Douša and Václavovic, 2014).

All the above mentioned software packages use the Kalman filter approach. The configuration and characteristics of the software packages used in this study are shown in Table 1. For the BNC2.7 and PPP-Wizard solutions, the a priori coordinates of the stations were computed by a 20-day average of coordinates obtained using PPP with the Bernese GPS Software 5.0 (Dach et al., 2007). The G-Nut/Tefnet does not need a priori coordinates, however, if precise station coordinates are available, they can be introduced into the processing as a priori values. In this campaign, G-Nut/Tefnet was used without introducing a priori coordinates. During the RT data processing, BNC2.7 computed the receiver coordinates (unconstrained) in every epoch whereas the version of PPP-Wizard used for this study did not estimate the receiver coordinates in order to reduce the number of unknown parameters. Hence in the PPP-Wizard solution, the coordinates were fixed to the values provided a priori and the ZTD was estimated every 5 seconds. The G-Nut/Tefnet software applied simultaneous coordinate and ZTD estimations. The former were tightly constrained to remain stable over time while the latter were constrained loosely to optimally balance between stable and reliable tropospheric parameter estimates.

The convergence time of the RT-PPP solutions (coordinates and ZTD) is generally between 20 to 60 minutes depending on the quality of the station data and satellite constellation, etc. if no precise a priori coordinates are provided. However, as mentioned above, for PPP-Wizard and BNC2.7, the a priori coordinates were provided and hence the convergence time was not significant. For G-Nut/Tefnet, the results were filtered to include only the epochs after the convergence time.
The software packages mentioned here are meant for RT and kinematic applications and therefore do not employ the most precise bias models, e.g. ocean tide loading and higher-order ionospheric corrections, etc.

**Real-Time Data and Products**

The network of GNSS stations used in this study comprises 22 globally distributed IGS stations which provide RT observation data (Figure 1). Table 2 provides the relevant station information. Only GPS observations have been used in this study. Table 3 provides some characteristics of the RT product streams used for this study.

**Reference Datasets**

The first reference dataset used to compare the RT-PPP ZTD estimates is the IGS Final Troposphere Product (hereafter termed IGFT) generated by the U.S. Naval Observatory (USNO) (Byram et al., 2011). The IGFT is based on the final IGS orbit and clock products and contains the ZTD estimates computed by processing 27-hour observation window using PPP with the Bernese GPS Software 5.0 at an output sampling interval of 5 minutes. The second reference dataset consists of the ZTD estimates derived from the observations of radiosondes (RS) collocated with 5 selected GNSS stations. The ZHD and ZWD at the RS locations have been corrected for height differences (to the GNSS station height) using the methods described in (Douša and Elias, 2014) and (Gyori and Douša, 2013) respectively. However, no correction has been applied for the horizontal separation between the GNSS station and the collocated RS. Table 4 shows the selection of the RS sites along with their horizontal and vertical distances to the respective GNSS stations. The ZTD from GNSS observations (at the 5 stations shown in Table 4) has then been compared to the ZTD from the corresponding RS.

The statistics for the comparisons have been computed using only the common epochs in the respective datasets.
Results

A dataset containing RT-PPP ZTD estimates for the previously described network of stations and a time-period of 31 days (2013-04-18 to 2013-05-18) was obtained using the software packages listed in the previous section. For brevity, we will below refer to the BNC2.7 solutions using the IGS01 products as BN01, the BNC2.7 solutions using the IGS02 products as BN02, the PPP-Wizard (ambiguity float) solutions as PWFL, the G-Nut/Tefnut solutions using IGS01 products as GN01, and the G-Nut/Tefnut solutions using IGS02 products as GN02. Table 5 gives an overview of the product streams and software used in each of the solutions. IGS01 and IGS02 (tested with BNC2.7 and G-Nut/Tefnut) streams contain single-epoch and Kalman filter combined solutions, respectively and could help studying any impact of the combination approaches on the RT-PPP ZTD estimates. Although the PPP-Wizard is also able to ingest the IGS01 and IGS02 product streams in non ambiguity-fixing mode, however, it was tested only with the CLK9B stream in order to examine the impact of ambiguity fixing only by keeping all other parameters in the fixed and float solutions consistent. Various technical problems, often related to data communication, compromise the transfer of real-time data and lead to gaps in the observation data and hence 100% of the data is not available in real-time, which results in gaps in the RT-PPP ZTD time series. Table 6 shows the percentage of ZTD estimates obtained from each of the RT solutions for each station.

On average, the RT-PPP ZTD estimates were available for 78% of the selected time period from BNC27, 65% from PPP-Wizard, and 92% from G-Nut/Tefnut. The lower amount of available RT-PPP ZTD estimates from PPP-Wizard is due to missing data and product streams caused by a temporary network related issue at UL from 2013-05-10 to 2013-05-18. Apart from the missing data, another reason for missing estimates for some epochs is that during the PPP convergence period after a data gap, the ZTD estimates with large formal sigma are rejected.

Internal Evaluation

For all the stations used in this study, the RT-PPP time series obtained from all the solutions follow the same pattern. Figure 2 shows the time series of the RT-PPP ZTD estimates obtained from the above mentioned RT solutions and the IGFT for
four stations, and Figure 3 shows the time series of the difference between the RT-PPP ZTD estimates and the IGFT for these stations. The ZTD and difference time series of PWFL solution in Figures 2 and 3 have been plotted after removing the mean bias (considering the fact that the bias in the ZTD is removed before NWP assimilation however, it is important that the bias is stable over time). The gap in the PWFL time series around day 11 for all 4 stations is due to a temporary interruption in the CLK9B product stream. For the station BOR1 (top right), the gap in the time series for all the RT solutions around day 3 is due to interruption of data stream from that station for this period. The gap in the GN01 and GN02 solution for the station BUCU (bottom left) around day 14 is due to an interruption in the data stream at that time at GOP.

The overall biases between the RT-PPP ZTD estimates from the individual RT solutions and the IGFT are shown in Table 7. It could be seen that the G-Nut/Tefnut solutions (GN01 and GN02) have a better stability (i.e. lower standard deviation) of the mean bias as compared to the BNC2.7 solutions (BN01 and BN02). It should be noted that the two G-Nut/Tefnut solutions used the same strategy, software and data access, so any difference in results reflects the stability and reliability issues related to the applied products. Similarly, for the two BNC2.7 solutions, same processing strategy was used and the only difference was in the applied products. However, unlike the G-Nut/Tefnet solutions, the mutual difference (in terms of bias) between the two BNC2.7 solutions is relatively larger. One possible reason for the lower bias in BN02 as compared to that in BN01 could be the use of a Kalman Filter combination orbit/clock correction stream (IGS02) rather than a correction stream with single epoch solution (IGS01) as in BN01. The RMS of the difference between the RT-PPP ZTD from the BNC software and that from the IGFT as shown by Yuan et al., 2014 is lower than that found in this study and this is because of the fact that they have implemented ocean tide loading corrections, improved mapping function and receiver antenna PCV correction in their version of BNC. The PPP-Wizard’s ambiguity float solution (PWFL) has the largest mean bias which is a consequence of the fact that the PPP-Wizard currently does not allow the application of antenna up eccentricity (height) and receiver antenna phase center models for offsets and variations, hence resulting in a mis-match between the constrained coordinates of
the survey marker and the ZTD estimation at the antenna phase center. Table 8 shows the station-wise biases in PWFL with respect to the up eccentricities of the antenna ARP. However, for the assimilation into NWP models, it can be argued that the standard deviation of the ZTD is of more importance than the bias, because any station-specific biases are corrected for during the screening process before the assimilation. Also, aforementioned mean biases of the RT-PPP ZTD solutions (calculated over all stations) have less significance than that of the standard deviations because the biases vary with location and characteristics of the station.

As mentioned earlier, the PPP-Wizard is capable of resolving integer ambiguities in RT-PPP. In order to study the effect of integer ambiguity resolution on the RT-PPP ZTD estimates, another RT solution for the same stations and time period as above was obtained using PPP-Wizard with the ambiguity resolution feature. We term this solution as PWFX. Keeping in view the time needed for ambiguity convergence, only those epochs (≈ 40% of the total) from PWFX have been included in the evaluation for which the number of fixed ambiguities is greater than or equal to 4. The difference between the RT-PPP ZTD of PWFL and PWFX solutions was found to be 0.61 ± 4.66 cm with an RMS of 4.93 cm. The observed impact of ambiguity resolution on ZTD is approximately 6 mm which compares well to, e.g., the 20% (4 to 5 mm) impact observed by Geng et al. (2009). The recent study by Li et al. (2014), which is based on their in-house software and products, also reported on the non-significant differences between the RT-PPP float and fixed solutions after sufficiently long times of convergence, however, it demonstrated the usefulness of ambiguity fixing for the rapid re-initialization of an RT-PPP estimation system (e.g. after an interruption in data stream).

To verify the claimed reason for the large bias in the PPP-Wizard solutions, i.e. the lack of ARP eccentricity and PCO corrections, another processing experiment (for a different 1-week long period) using the PPP-Wizard was conducted in which the coordinates were corrected for ARP eccentricities and the PCO prior to processing. The L₁ and L₂ PCOs have been combined by using the ionosphere free linear combination, i.e.
where $f_1 = 1575.42 \text{ MHz}$, $f_2 = 1227.60 \text{ MHz}$ and $PCO$ values are in millimeters.

Integer ambiguity fixing was also applied during this experiment. We name the PPP-Wizard solution from this new experiment as PWFX2. The RT-PPP ZTD estimates from PWFX2 were then compared to the corresponding IGFT estimates. The bias between IGFT and PWFX2 was found to be $2.33 \pm 2.76 \text{ cm}$ (in contrast to $6.81 \pm 2.42 \text{ cm}$ for IGFT−PWFL) with an RMS of $4.60 \text{ cm}$ (in contrast to $14.96 \text{ cm}$ for IGFT−PWFL). This implies that after applying the ARP eccentricity and PCO corrections to the a priori coordinates, the mean bias between the ZTD estimates from PPP-Wizard and IGFT has been reduced by approximately 66% and the RMS of this bias has been reduced by approximately 70%.

**External Evaluation**

The statistics from the comparison of GNSS-derived ZTD and RS-based ZTD are summarized in Table 11. In terms of standard deviation, the G-Nut/Tefnut solutions show the best agreement to the RS-based ZTD whereas, in terms of the mean bias, BNC2.7 solutions show the best agreement to the RS-based ZTD. The BNC2.7 solutions show mean biases between 1 to 2 cm, whereas G-Nut/Tefnut and PPP-Wizard solutions show mean biases between 2 to 3 cm with the RS-based ZTD. Figure 4 shows the time series of GNSS-derived and RS-based ZTD estimates for the station HERT as an example. It can be seen that all the time series follow the same pattern and both the GNSS-derived and RS-based ZTD are sensitive to the variations in a similar fashion. This is also the case for the other 4 stations not shown in Figure 4. The time series of the difference between the RT-PPP ZTD solutions and the RS-based ZTD for the station HERT are show in Figure 5.

**Discussion**

The COST Action 716: Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Analysis, which was a demonstration project to
study the potential of ZTD products from ground-based GPS networks for NWP and climate monitoring, specified various user requirements (Offiler, 2010) for GNSS meteorology which define threshold and target values on timeliness, accuracy and resolution etc. of ZTD and IWV estimates for use in NWP nowcasting and climate monitoring. These requirements are widely accepted for quality control during operational use. Table 9 summarizes the current user requirements for NWP nowcasting however, during the new COST Action ES1206 (GNSS4SWEC), these requirements will be revised. The typical value of the dimensionless conversion factor $Q$ (Askne and Nordius, 1987) used for the conversion of Zenith Wet Delay (ZWD) to IWV is approximately 6 and therefore 1 kg/m$^2$ of IWV is equivalent to about 6 mm of ZTD (Tomasz et al., 2006). Using this equivalence, the accuracy requirements for IWV can be translated to their equivalent for ZTD which are 6 mm (0.6 cm) target and 30 mm (3 cm) threshold values. Considering the IGFT as the truth and the RMS of the bias of each solution from IGFT as a measure of its relative accuracy, the obtained RT-PPP ZTD solutions can be compared to these requirements. Table 10 shows this comparison for each RT solution generated in this study.

It can be seen from Table 10 that BN02, GN01 and GN02 meet the threshold requirement for relative accuracy whereas BN01 and PWFL exceed the threshold. Although the application of the ARP eccentricity and PCO corrections on the coordinates prior to processing has improved the relative accuracy of the PPP-Wizard solution, it currently exceeds the threshold requirements for NWP nowcasting.

**Conclusions**

The suitability of RT-PPP ZTD estimates from three different software packages for operational meteorology was assessed through a comparative analysis using the IGS Final Troposphere Product and RS data as references. In terms of standard deviation, it was seen that the solutions from the G-Nut/Tefnut software library achieves the best agreement with the reference. The solutions from BNC2.7 are the next closest to the reference. Among the BNC2.7 solutions, lower biases have been found for the solutions computed using the correction stream containing a Kalman Filter combination (IGS02) rather than the one computed
using a single-epoch solution correction stream (IGS01). The ambiguity float solution from the PPP-Wizard has the largest bias to the reference because of the fact that it currently does not apply receiver ARP eccentricity and PCO corrections during processing. However, the application of ARP eccentricity and PCO corrections on the coordinates prior to processing leads to 66% reduction in this bias. Integer ambiguity resolution using the PPP-Wizard seems to have a millimeter-level effect on the RT-PPP ZTD estimates.

The RT-PPP ZTD solutions were compared to the established user requirements for NWP nowcasting by using RMS bias to IGFT as a measure of relative accuracy. It was found that GN01, GN02, and BN02 fulfill the threshold requirements on ZTD accuracy whereas BN01, and PWFL, PWFX (and PWFX2) exceed this threshold. The RT-PPP ZTD solutions were also compared to RS-based ZTD and an agreement of 1 to 3 cm in terms of bias and 1 to 4 cm in terms of standard deviation was found between the two.

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Table 1 Configuration of the software packages used in this study

| Software                      | BNC2.7          | PPP-Wizard       | G-Nut/Tefnut     |
|-------------------------------|-----------------|------------------|------------------|
| Update Cycle                  | Real-time       | Real-time        | Real-time        |
| Output Interval                | 1 second        | 5 seconds        | 5 seconds        |
| GNSS Used                      | GPS             | GPS              | GPS              |
| Strategy                       | PPP             | PPP              | PPP              |
| A-priori ZHD Model            | Saastamoinen    | Constant (2.37 m)| Saastamoinen     |
| Troposphere Mapping Function   | 1/cos(z)        | GPS STANAG       | GMF              |
| Receiver PCV Correction        | No              | No               | Elevation dependent only |
| Receiver PCO Correction        | Yes             | No               | Yes              |
| Satellite PCV Correction       | No              | Yes              | Yes              |
| Satellite PCO Correction       | No*             | No*              | No*              |
| Coordinates Computed Correction| Yes             | No               | Yes              |
| Ocean Tide Loading Correction  | No              | No               | No               |
| Input Raw Data Format          | RTCM-3          | RTCM-3           | RTCM-3           |
| Input Orbit/Clock Correction Format| RTCM-SSR        | RTCM-SSR         | RTCM-SSR         |
| Input Broadcast Ephemeris Format| RTCM-SSR        | RTCM-SSR         | RTCM-SSR         |
| Ambiguity Resolution          | No              | Yes              | No               |

* In the correction streams used, the satellite’s position refers to the ionosphere free phase center of its antenna and therefore the satellite antenna PCO correction is not necessary.
| Station | IERS DOMES Number | Receiver Type       | Antenna and Radome | ARP Eccentricity (Up) [m] |
|---------|------------------|---------------------|--------------------|--------------------------|
| ADIS    | 31502M001        | JPS LEGACY          | TRM29659.00        | 0.0010                   |
| ALBH    | 40129M003        | AOA BENCHMARK ACT   | AOAD/M_T           | 0.1000                   |
| AUCK    | 50209M001        | TRIMBLE NETR9       | TRM55971.00        | 0.0550                   |
| BOR1    | 12205M002        | TRIMBLE NETRS       | AOAD/M_T           | 0.0624                   |
| BRST    | 10004M004        | TRIMBLE NETRS       | TRM57971.00        | 2.0431                   |
| BUCU    | 11401M001        | LEICA GRX1200GGPRO  | LEIAT504GG         | 0.0970                   |
| COCO    | 50127M001        | TRIMBLE NETR8       | AOAD/M_T           | 0.0040                   |
| DAEJ    | 23902M002        | TRIMBLE NETRS       | TRM59800.00        | 0.0000                   |
| DUBO    | 40137M001        | TPS NETG3           | AOAD/M_T           | 0.1000                   |
| GOPE    | 11502M002        | TPS NETG3           | TPSCR.G3           | 0.1114                   |
| HERI    | 13212M010        | LEICA GRX1200GGPRO  | LEIAT504GG         | 0.0000                   |
| HOFN    | 10204M002        | LEICA GR25          | LEIAR25.R4         | 0.0319                   |
| KIRA    | 10422M001        | JPS EGGDT           | AOAD/M_T           | 0.0710                   |
| MATE    | 12734M008        | LEICA GRX1200GGPRO  | LEIAT504GG         | 0.1010                   |
| NKLG    | 32809M002        | TRIMBLE NETR9       | TRM59800.00        | 3.0430                   |
| NTUS    | 22601M001        | LEICA GRX1200GGPRO  | LEIAT504GG         | 0.0776                   |
| ONSA    | 10402M004        | JPS E_GGD           | AOAD/M_B           | 0.9950                   |
| POTS    | 14106M003        | JAVAD TRE_G3TH DELTA| JAV_RINGANT_G3T   | 0.1206                   |
| REYK    | 10202M001        | LEICA GR25          | LEIAR25.R4         | 0.0570                   |
| THTI    | 92201M009        | TRIMBLE NETR8       | ASH701945E_M       | 1.0470                   |
| VIS0    | 10423M001        | JPS EGGDT           | AOAD/M_T           | 0.0710                   |
| WTZR    | 14201M010        | LEICA GRX1200+GNSS  | LEIAR25.R3         | 0.0710                   |
Table 3 Real-time correction streams ([http://rts.igs.org/products/](http://rts.igs.org/products/), [http://www.ppp-wizard.net/caster.html](http://www.ppp-wizard.net/caster.html))

| Stream    | Content                                      | Message Types   | Provider |
|-----------|----------------------------------------------|-----------------|----------|
| RTCM3EPH  | Broadcast Ephemeris                          | 1019, 1020, 1045 | BKG      |
| IGS01     | Orbit/Clock Correction (single epoch solution) | 1059, 1060      | ESA      |
| IGS02     | Orbit/Clock Correction (Kalman filter combination) | 1057, 1058, 1059 | BKG      |
| CLK9B     | Orbit/Clock Correction + Corrections for Integer Ambiguity Resolution | 1059, 1060, 1065, 1066 | CNES    |
Table 4 The selected radiosondes used for comparison

| GNSS Station ID | RS ID (WMO) | Vertical Separation (GNSS-RS) [m] | Horizontal Separation [km] |
|----------------|-------------|-----------------------------------|---------------------------|
| BUCU           | 15420       | 53                                | 4.0                       |
| COCO           | 96996       | -37                               | 1.8                       |
| HERT           | 03882       | 32                                | 4.0                       |
| THTI           | 91938       | 97                                | 3.4                       |
| VIS0           | 02591       | 33                                | 2.0                       |
Table 5 Combinations of software package and product streams used in RT-PPP ZTD solutions

| Solution | Software Used   | Ephemeris Stream Used | Orbit/Clock Product Used |
|----------|-----------------|-----------------------|--------------------------|
| BN01     | BNC2.7          | RTCM3EPH              | IGS01                    |
| BN02     | BNC2.7          | RTCM3EPH              | IGS02                    |
| PWFL     | PPP-Wizard      | RTCM3EPH              | CLK9B                    |
| GN01     | G-Nut/Tefnut    | RTCM3EPH              | IGS01                    |
| GN02     | G-Nut/Tefnut    | RTCM3EPH              | IGS02                    |
Table 6 Percentage of available RT-PPP ZTD epochs in different solutions

| Station | BN01 | BN02 | PWFL | GN01 | GN02 |
|---------|------|------|------|------|------|
| ADIS    | 75   | 67   | 64   | 94   | 94   |
| ALBH    | 97   | 95   | 55   | 95   | 95   |
| AUCK    | 91   | 86   | 68   | 97   | 96   |
| BOR1    | 87   | 87   | 63   | 92   | 91   |
| BRST    | 88   | 86   | 68   | 98   | 98   |
| BUCU    | 98   | 98   | 68   | 85   | 84   |
| COCO    | 60   | 86   | 65   | 95   | 95   |
| DAEJ    | 96   | 96   | 67   | 96   | 96   |
| DUBO    | 98   | 97   | 64   | 98   | 98   |
| GOPE    | 92   | 92   | 64   | 93   | 93   |
| HERT    | 93   | 91   | 68   | 98   | 98   |
| HOFN    | 93   | 90   | 67   | 97   | 97   |
| KIR0    | 90   | 89   | 66   | 98   | 98   |
| MATE    | 61   | 52   | 65   | 83   | 82   |
| NKLG    | 52   | 53   | 69   | 99   | 99   |
| NTUS    | 53   | 74   | 68   | 99   | 98   |
| ONSA    | 88   | 86   | 66   | 99   | 98   |
| POTS    | 56   | 52   | 68   | 98   | 98   |
| REYK    | 73   | 77   | 61   | 91   | 91   |
| THTI    | 61   | 47   | 68   | 99   | 99   |
| VIS0    | 94   | 95   | 68   | 84   | 84   |
| WTZR    | 81   | 81   | 61   | 89   | 89   |
| Solution | Mean [cm] | STD [cm] | RMS [cm] |
|----------|-----------|----------|----------|
| BN01     | 3.17      | 4.61     | 6.04     |
| BN02     | 0.46      | 2.72     | 2.92     |
| PWFL     | 6.81      | 2.42     | 14.96    |
| GN01     | 1.16      | 0.82     | 1.43     |
| GN02     | 1.11      | 0.80     | 1.38     |
| Station | ARP Eccentricity (UP) [cm] | PWFL Bias [cm] |
|---------|---------------------------|----------------|
| ADIS    | 0.10                      | 3.14           |
| ALBH    | 10.00                     | 2.20           |
| AUCK    | 5.50                      | -3.29          |
| BOR1    | 6.24                      | 4.66           |
| BRST    | 204.31                    | 54.58          |
| BUCU    | 9.70                      | 9.09           |
| COCO    | 0.40                      | -4.78          |
| DAEJ    | 0.00                      | -0.77          |
| DUBO    | 10.00                     | 2.15           |
| GOPE    | 11.14                     | 5.73           |
| HERT    | 0.00                      | 2.53           |
| HOFN    | 3.19                      | 4.92           |
| KIR0    | 7.10                      | 12.45          |
| MATE    | 10.10                     | 5.85           |
| NKLG    | 304.30                    | 64.74          |
| NTUS    | 7.76                      | -75.81         |
| ONSA    | 99.50                     | 26.03          |
| POTS    | 12.06                     | 6.11           |
| REYK    | 5.70                      | 4.78           |
| THTI    | 104.70                    | 13.67          |
| VIS0    | 7.10                      | 5.05           |
| WTZR    | 7.10                      | 6.73           |
Table 9 User requirements for GNSS meteorology (NWP nowcasting)

| Parameter             | Target               | Threshold       |
|-----------------------|----------------------|-----------------|
| Horizontal Domain     | Europe to National   |                 |
| Repetition Cycle      | 5 min                | 1 hour          |
| Integration Time      | MIN(5 min, rep cycle)|                 |
| Relative Accuracy     | 1 kg/m²              | 5 kg/m²         |
| Timeliness            | 5 min                | 30 min          |
Table 10 Comparison of RT relative accuracies to user requirements of GNSS meteorology

| RT Solution | ZTD relative accuracy [cm] | Difference from required target [cm] | Difference from required threshold [cm] | Remarks             |
|-------------|-----------------------------|--------------------------------------|----------------------------------------|---------------------|
| BN01        | 6.04                        | 5.44                                 | 3.04                                   | Exceeds the threshold |
| BN02        | 2.92                        | 2.32                                 | -0.08                                  | Meets the threshold  |
| PWFL        | 14.96                       | 14.36                                | 11.96                                  | Exceeds the threshold |
| GN01        | 1.43                        | 0.83                                 | -1.58                                  | Meets the threshold  |
| GN02        | 1.38                        | 0.78                                 | -1.62                                  | Meets the threshold  |
| PWFX2       | 4.64                        | 4.04                                 | 1.64                                   | Exceeds the threshold |
Table 11 Statistics of comparison between GNSS-derived and RS-based ZTD

| RT-PPP Solution | Mean (GNSS-RS) [cm] | STD (GNSS-RS) [cm] | RMS (GNSS-RS) [cm] |
|-----------------|---------------------|--------------------|--------------------|
| BNC (IGS01)     | 1.40                | 3.44               | 4.41               |
| BNC (IGS02)     | 1.71                | 3.19               | 4.30               |
| PPP-Wizard*     |                     |                    |                    |
| (fixed)         | 2.76                | 3.12               | 5.23               |
| Tefnut (IGS01)  | 2.17                | 1.32               | 3.04               |
| Tefnut (IGS02)  | 2.12                | 1.29               | 3.01               |

*The solution after application of eccentricity and PCO corrections and ambiguity resolution
Figure 1 IGS real-time stations used in this study
Figure 2 Time series of the RT-PPP ZTD estimates and IGFT for the stations ALBH, BOR1, BUCU and HERT
Figure 3 Time series of the difference between the RT-PPP ZTD estimates and IGFT for the stations ALBH, BOR1, BUCU and HERT
Figure 4 Time series of the RT-PPP ZTD estimates and RS-based ZTD for the station HERT
Figure 5 Time series of the difference RT-PPP ZTD and RS-based ZTD estimates for the station HERT