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

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Abstract

The use of observations from Global Navigation Satellite Systems (GNSS) in operational meteorology is increasing worldwide due to the continuous evolution of GNSS. The assimilation of near real-time (NRT) GNSS-derived zenith total delay (ZTD) estimates into local, regional and global scale numerical weather prediction (NWP) models is now in operation at a number of meteorological institutions. The development of NWP models with high update cycles for nowcasting and monitoring of extreme weather events in recent years, requires the estimation of ZTD with minimal latencies, i.e. from 5 to 10 minutes, while maintaining an adequate level of accuracy for these. The availability of real-time (RT) observations and products from the IGS RT service and associated analysis centers make it possible to compute precise point positioning (PPP) solutions in RT, which provide ZTD along with position estimates.

This study presents a comparison of the RT ZTD estimates from three different PPP software packages (G-Nut/Tefnut, BNC2.7 and PPP-Wizard) to the state-of-the-art IGS Final Troposphere Product employing PPP in the Bernese GPS Software. Overall, the ZTD time series obtained by the software packages agree fairly well with the estimates following the variations of the other solutions, but showing various biases with the reference. After correction of these the RMS differences are at the order of 0.01 m. The application of PPP ambiguity resolution in one solution or the use of different RT product streams shows little impact on the ZTD estimates.

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 vapour (IWV) using surface meteorological data [1]. 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 (e.g. [2],[3]).

As of today, the NRT ZTD estimates are assimilated into local, regional and global scale NWP models that are run with hourly update cycles and produce long-term (up to a few days) weather forecasts. However, with the developments of high update-rate NWP models, for example, the Rapid Update Cycle (RUC) and the Real-Time Meso Analysis High Resolution Rapid Refresh (RTMA-HRRR) models; in order to use ZTD estimates for nowcasting and monitoring of extreme short-term weather changes, it is desired to obtain these with a minimal latency, e.g. 10 or even 5 minutes while maintaining a certain level of accuracy. The COST Action 716 specified various user requirements for GNSS meteorology which define threshold and target values on timeliness, accuracy and resolution etc. of ZTD and IWV estimates for use in nowcasting and climate monitoring.

Table 1 summarizes the user requirements for nowcasting. The typical value of the dimensionless conversion factor Q 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. 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.

Table 1 User requirements for GNSS Meteorology (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/m^2	5 kg/m^2
Timeliness	5 min	30 min

In this paper, we have compared the ZTD estimates obtained in RT using three PPP software packages (described in the next section) with the high precision GPS-based troposphere product known as the IGS Final Troposphere Product [4] (hereafter mentioned as IGFT) in order to assess the accuracy of these estimates. The effect of integer ambiguity resolution on ZTD estimates has also been studied using two different versions of the software package called PPP-Wizard.

Real-Time Data and Products

For RT GNSS applications, the broadcast ephemeris, and the orbit and clock corrections to it are available in RT from the IGS Real-Time Service as well as other RT analysis centers. 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. The RTCM-SSR real-time streams are composed of various types of messages and their description is available at http://igs.bkg.bund.de/ntrip/orbits.

The availability of RT orbit and clock correction information in form of the RTCM-SSR messages and the RT observation data makes it possible to perform RT PPP. Table 2 provides some characteristics of the product streams used for this study and the RTCM v3 messages contained by them (http://rts.igs.org/products/, http://www.ppp-wizard.net/caster.html).

Table 2 RT Correction Streams used in this study

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
CLK91	Orbit/Clock Correction	1059, 1060, 1065, 1066	CNES
CLK9B	Orbit/Clock Correction + Corrections for Integer Ambiguity Resolution	1059, 1060, 1065, 1066	CNES

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The Real-Time PPP Systems

This section provides a brief description of the three RT PPP software packages used in this study namely the BKG Ntrip Client, PPP-Wizard and the G-Nut/Tefnut Software Library.

BKG Ntrip Client

The BKG Ntrip Client (BNC), developed by the Bundesamt für Kartographie und Geodäsie (BKG) [5], is capable of performing PPP in RT (RTPPP). For this study, version 2.7 of the BNC has been used to perform RTPPP using streams of code plus phase observations, broadcast ephemeris and corrections for satellite orbits and clocks. During the process in BNC, the corrections from the RT streams are applied to the broadcast ephemeris. Along with the precise position estimates, the total tropospheric delay estimates can also be obtained as one of the outputs.

PPP-Wizard

To promote their ambiguity fixing strategy, CNES developed "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 which can be used to fix ambiguities in RTPPP mode [6]. In order to study the impact of ambiguity fixing on the ZTD estimates, two versions of PPP-Wizard were used in this study. One version has the ambiguity fixing feature enabled and the other has it disabled.

G-Nut/Tefnut Softwrae Library

The G-Nut software library [7] 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 were already derived for meteorology and climatology (Tefnut), geodesy and seismology (Geb) and GNSS quality check (Anubis). In this paper we used G-Nut/Tefnut software that is capable of estimating GNSS tropospheric parameters in RT, NRT and post-processing modes.

Methodology

The real-time processing for this study was simultaneously performed at the University of Luxembourg (UL) and the Geodetic Observatory Pecny (GOP). UL generated the solutions from BNC2.7 and PPP-Wizard whereas GOP generated the solutions using Tefnut application from the G-Nut software library.

The selection of 22 globally distributed stations from the IGS Real-Time GNSS network used for this comparison is shown in Figure 1. A dataset containing real-time 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.

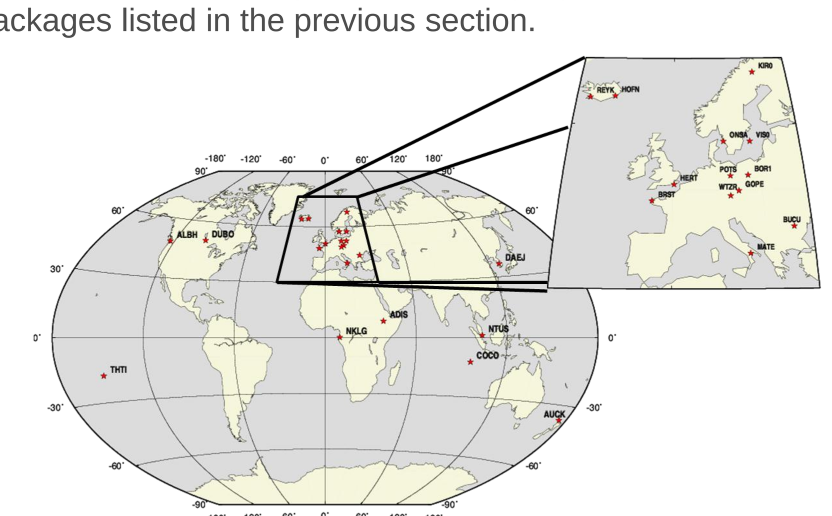

Figure 1 IGS Real-Time GNSS stations used in this study

The configuration and characteristics of the software packages used during the RT processing are shown in Table 3.

Table 3 Processing characteristics of the RT PPP Software Packages

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 (Chao's coefficients)	GMF
Receiver PCV Correction	No	No	Yes
Receiver PCO Correction	Yes	No	Yes
Satellite PCV Correction	No	Yes	Yes
Satellite PCO Correction	No*	No*	Yes
Coordinates Computed	Yes	No	Yes
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

Results

This section shows the results of the comparison of RT ZTD estimates and the effect of ambiguity resolution. We will below refer to the BNC2.7 solution using the IGS01 product as BN01, BNC2.7 solution using the IGS02 product as BN02, the PPP-Wizard (ambiguity float) solution as PWFL, the G-Nut/Tefnut solution using the IGS01 product as GN01, the G-Nut/Tefnut solution using the IGS02 product as GN02, and the G-Nut/Tefnut solution using the CLK91 product as GN91. Figure 2 shows a 3-week ZTD time series for four stations obtained from the above mentioned RT solutions and the IGFT. The time series from every individual solution has been plotted with an artificial offset for visibility purposes. It can be seen that the various time series follow the same pattern. 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 ZTD time series.

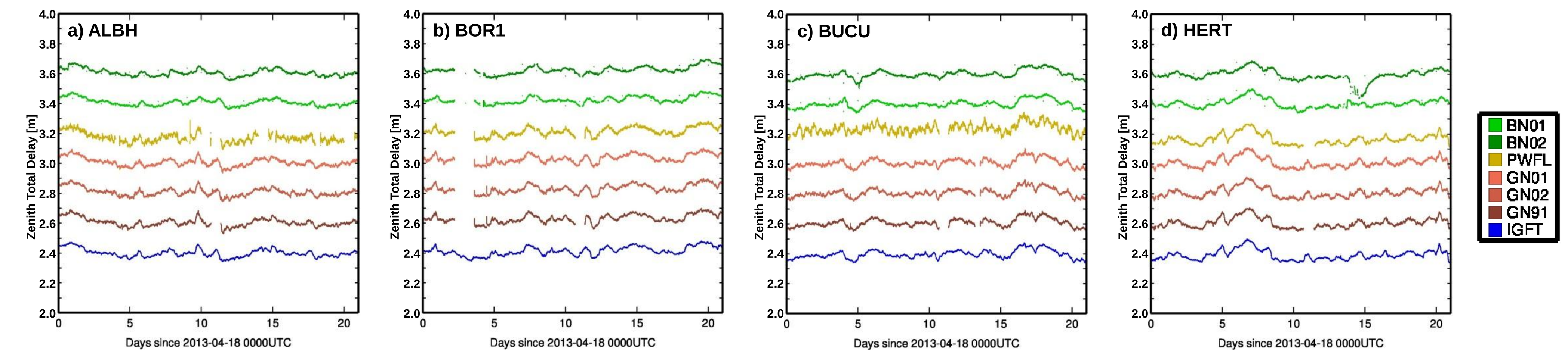

Figure 2 ZTD Time Series obtained using the RT solutions and IGFT for stations a) ALBH, b) BOR1, c) BUCU, d) HERT

The overall biases between the RT PPP ZTD estimates from the individual RT solutions and the IGFT are shown in Table 4. The PPP-Wizard's ambiguity float solution (PWFL) has the largest mean bias of 6.81 ± 2.42 cm. Here it is important to mention that PPP-Wizard was originally designed to estimate the positions of moving receivers and it does not apply the correction for receiver antenna phase center offsets. 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.

Table 4 Biases in RT PPP ZTD solutions to IGFT

Solution	Mean [cm]	STD [cm]	RMS [cm]
BN01	3.17	4.61	11.82
BN02	0.21	3.24	1.86
PWFL	6.81	2.42	18.52
GN01	1.16	0.82	1.43
GN02	1.11	0.80	1.38
GN91	1.00	0.83	1.29

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. In PWFX, only those epochs have been included in the evaluation for which the number of fixed ambiguities is greater than or equal to 4. The comparison of the biases in RT PPP ZTD of PWFL and PWFX solutions with respect to IGFT is shown in Table 5 and the statistics for the difference between the float and fixed solutions are shown in Table 6. The station-wise values of the difference between the float and fixed solution is shown in Figure 3.

Table 5 Differences in RT PPP ZTD of PWFL and PWFX with respect to IGFT

PWFL (ambiguity float)		PWFX (ambiguity fixed)	
Mean [cm]	STD [cm]	Mean [cm]	STD [cm]
6.81	2.42	6.21	4.62

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 the user requirements for nowcasting mentioned in the Introduction section. Table 7 shows this comparison for each RT solution generated in this study. It can be seen from this table that BN02, GN01, GN02 and GN91 meet the threshold requirement for relative accuracy whereas BN01 and PWFL exceed the threshold.

Table 7 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	11.82	11.22	8.82	Exceeds the threshold
BN02	1.86	1.26	-1.15	Meets the threshold
PWFL	18.52	17.92	15.52	Exceeds the threshold
GN01	1.43	0.83	-1.58	Meets the threshold
GN02	1.38	0.78	-1.62	Meets the threshold
GN91	1.29	0.69	-1.71	Meets the threshold

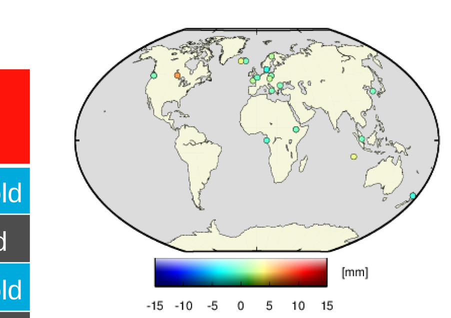

Figure 3 Station-wise magnitude of the difference between PWFL and PWFX

Table 6 Difference in RT PPP ZTD between PWFL and PWFX

Mean [cm]	STD [cm]	RMS [cm]
0.61	4.66	2.03

Discussion and Conclusions

The RT PPP ZTD estimates from three different software packages were compared using the IGS Final Troposphere Product as reference. In terms of standard deviation, it was seen that the solution from the G-Nut/Tefnut software library has the best agreement with the reference. After G-Nut/Tefnut solutions, the solutions from BNC2.7 are the next closest to the reference. Among the BNC2.7 solutions, a lower bias has been found for the solution computed using the correction stream containing 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 with the reference because of the fact that it currently does not apply corrections for receiver antenna phase centre offsets during processing. 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 nowcasting by using RMS bias to IGFT as a measure of relative accuracy. It was seen that GN01, GN02, GN91 and BN02 fulfill the threshold requirements on ZTD accuracy whereas BN01, and PWFL (and PWFX) exceed this threshold.

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