An Evaluation of Real-Time Zenith Total Delay Estimates

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Abstract

The use of modern low-latency Numerical Weather Prediction (NWP) models by meteorological institutions to improve now-casting operations requires the accurate and timely estimation of the Zenith Total Delay (ZTD). Observations from Global Navigation Satellite Systems (GNSS) can be processed to obtain such ZTD estimates. As of now, meeting the established requirements on the latency (as low as 5 min) and accuracy (up to a few millimeters) of the ZTD for its use in now-casting applications stands as a challenge. However, using, for example, the real-time orbit and clock products from the recently established IGS Real-Time Service, it is possible to estimate the ZTD by different processing strategies and each strategy can result in a different level of accuracy. The Bundesamt für Kartographie und Geodäsie Ntrip Client (BNC) can provide ZTD estimates in real-time using precise point positioning (PPP) without integer ambiguity resolution. Recently, the Centre National d'Etudes Spatiales (CNES) has released a modified version of BNC which produces ZTD estimates in real-time with integer-PPP, i.e.. PPP with integer ambiguity resolution using their integer-recovery clock and widelane phase bias information.

In this study, we present a preliminary comparison of the real-time ZTD estimates obtained from two different GNSS processing systems to those obtained from a near real-time system.

Introduction

It is widely known that the delay encountered by GNSS signals while passing through the atmosphere can be manipulated to estimate the amount of water vapour in the troposphere. This information can then be fed into numerical weather models for use in weather forecasting. In Europe the EUMETNET EIG GNSS water vapour programme (E-GVAP)[1] is a series of research projects to study the use of near real-time (NRT) GNSS data for numerical weather prediction (http://egvap.dmi.dk) since 2005. Analysis centres located all over Europe submit NRT GNSS-derived delay and Integrated Water Vapour (IWV) solutions to E-GVAP for validation, monitoring and research. "UL01" is a test solution which is generated at the University of Luxembourg and submitted to E-GVAP. The Europe-wide network of GNSS stations processed by UL01 is shown in Figure 1. Figure 2 shows recent ZTD and IWV time series from UL01 (yellow) in comparison with other solutions for the GNSS station Kings Lynn (KING). For this period and station, UL01 has a mean bias of 1.9 mm and a standard deviation (SD) of 10.9 mm. We note that for the ten stations used by the real-time systems UL01 has a mean bias of 10.5 ± 13.7 mm. This compares well with the 12.1 ± 13.4 mm computed for all other E-GVAP analysis centers processing these stations. The key features of UL01 are listed in Table 1.

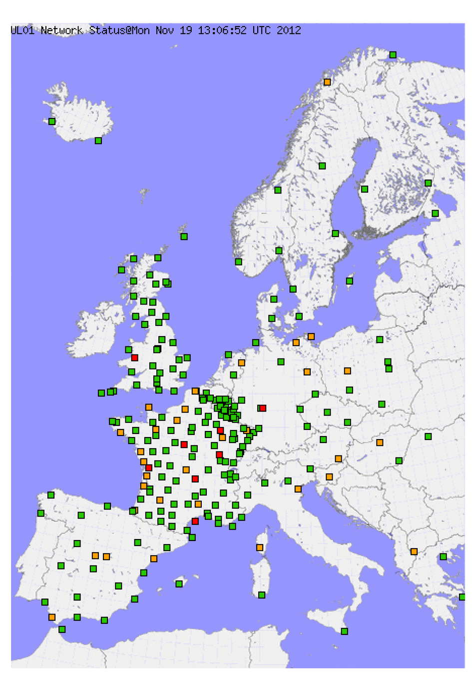

Figure 1: Network of stations processed by UL01 (E-GVAP, 2012)

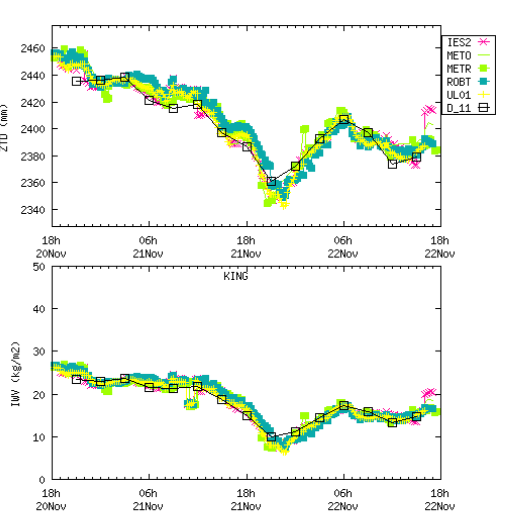

Figure 2: Time series of ZTD (top) and IWV (bottom) computed by UL01 (yellow) and other E-GVAP analysis centers for station KING from 2012-11-20 18:00UTC to 2012-11-22 18:00UTC (E-GVAP, 2012)

Table 1: Features of the NRT processing system UL01

Characteristics of UL01	
Update Cycle	1 hour
Processing Engine	Bernese GPS Software 5.0[2]
GNSS Used	GPS
Development Language(s)	Perl, Python
Input Raw Data	RINEX 2.11 (hourly)
Input Products	IGS Ultra-Rapid
Antenna Calibration	Absolute
Mapping Function	NMF
Input Meteorological Data	Hourly file of meteorological data
Outputs	• ZTD estimates • IWV estimates (COST-716) • 2D Plots • Animations

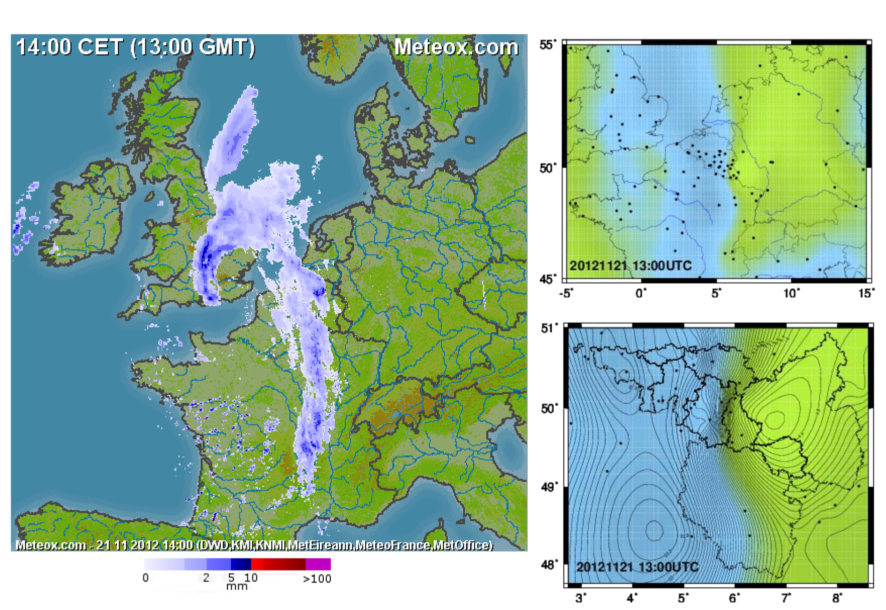

Figure 3: Comparison of weather radar (left) and UL01 IWV (right) at 2012-11-21 13:00UTC. Top Right: European scale, Bottom Right: Magnified view over the Greater Region

Figure 3 compares the 2D IWV (kg/m²) maps generated by UL01 for the Europe-wide network to the weather radar picture of precipitation (millimeters) taken from www.meteox.de. The black dots in the IWV maps represent the ground-based GNSS stations included in the processing. It can be seen that the zones with the largest gradients in IWV overlap with the fore-front of the precipitation events identified by the weather radar.

GNSS Meteorology Requirements

The European Cooperation in Science and Technology (COST) funded the "COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications"[3] from 1999 to 2004. Along with an assessment of the operational potential of the use of ground-based near real-time GPS observations in meteorology, it also established the user requirements on the GPS derived ZTD and IWV for their use in meteorology. Some of those requirements are listed in Table 2.

Table 2: User requirements for GNSS Meteorology as outlined by COST Action 716

Mode	Repetition Cycle		Accuracy		Timeliness	
	ZTD	IWV	ZTD	IWV	ZTD	IWV
Nowcasting		5 min ~ 1 hour		1 ~ 5 kg/m²		5 ~ 30 min
Numerical Weather Prediction	15 min ~ 1 hour		3 ~ 10 mm		30 min ~ 1.5 hours	
Climate Monitoring		1 hour		1 kg/m²		1 ~ 2 months

The Real-Time Processing Systems

The real-time processing systems process data from a Europe-wide network of 80 GNSS stations. This network contains stations from the IGS, EUREF, RGP, SPSLux and WALCORS real-time networks with a densification over Luxembourg and the Wallonie, Belgium. Out of these 80 stations, 10 stations with the least data gaps have been selected for this study. The black dots in Figure 4 show locations of all the 80 stations whereas the 4-character names indicate the 10 selected stations.

Figure 4: Real-time network and selected stations

We now introduce the two real-time processing software packages used in this study.

BKG Ntrip Client 2.6

The BKG Ntrip Client (BNC)[4] is capable of performing precise point positioning (PPP) in real-time. For this study, BNC has been used to perform real-time PPP 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 real-time 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. For this study, a sigma value of 1×10^{-5} m/s was used to describe the expected variation of the ZTD as estimated by BNC2.6.

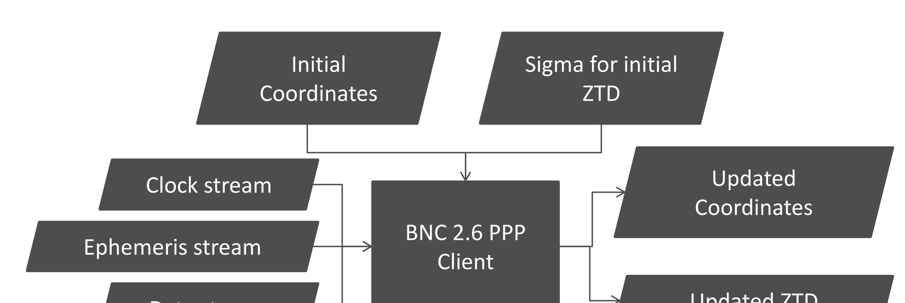

Figure 5: Flowchart showing ZTD estimation based on BNC 2.6 PPP Client

Table 3: Features and configuration of BNC 2.6

BNC 2.6	
Update Cycle	Real-time
Output Interval	1 second
GNSS Used	GPS
Input Raw Data	Real-time streams (RTCM 3)
Input Clock Stream	CLK11 (IGS)
Input Ephemeris Stream	RTCM3EPH (IGS)

Precise Point Positioning With Integer and Zero-difference Ambiguity Resolution Demonstrator

The Precise Point Positioning With Integer and Zero-difference Ambiguity Resolution Demonstrator (PPP-Wizard)[5] is a real-time processing software developed by CNES and is capable of performing PPP with undifferenced integer ambiguity resolution (i-PPP). It is based on a modified version of BNC v2.4. The version of PPP-Wizard used for this study does not estimate the receiver coordinates in order to reduce the number of unknown parameters.

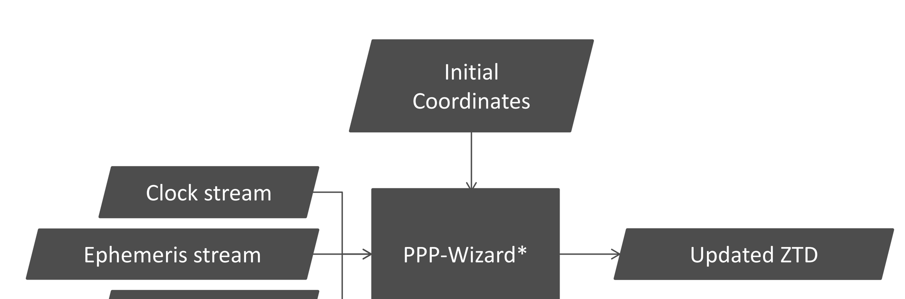

Figure 6: Flowchart showing ZTD estimation based on PPP-Wizard

Table 4: Features and configuration of PPP-Wizard

PPP-Wizard	
Update Cycle	Real-time
Output Interval	5 seconds
GNSS Used	GPS
Input Raw Data	Real-time streams (RTCM 3)
Input Clock Stream	CLK9B (CNES)
Input Ephemeris Stream	RTCM3EPH (IGS)

*For this study, PPP-Wizard has been modified to estimate only the ZTD. However, the original version of the PPP-Wizard also estimates the coordinates.

Real-Time Systems Comparison: Preliminary Results

In this section, we compare the ZTD estimates obtained by BNC v2.6 and the PPP-Wizard to those from the hourly near real-time system (UL01). The comparison has been performed for 10 stations from the IGS and EUREF permanent networks for the time period of 2012-11-14 00:00UTC to 2012-11-21 00:00UTC. UL01 provides ZTD estimates with a sampling interval of 15 minutes whereas BNC2.6 and the PPP-Wizard provide estimates with sampling intervals of 1 second and 5 seconds, respectively.

Figure 7 shows the ZTD time series for 4 out of the 10 stations obtained from UL01, BNC2.6 and PPP-Wizard. Figure 8 shows the correlation plots between the near real-time (UL01) and the real-time (BNC2.6, PPP-Wizard) ZTD time series shown in Figure 7. From the dataset obtained from the PPP-Wizard, only those epochs have been taken into account for which the number of solved ambiguities is greater than 4.

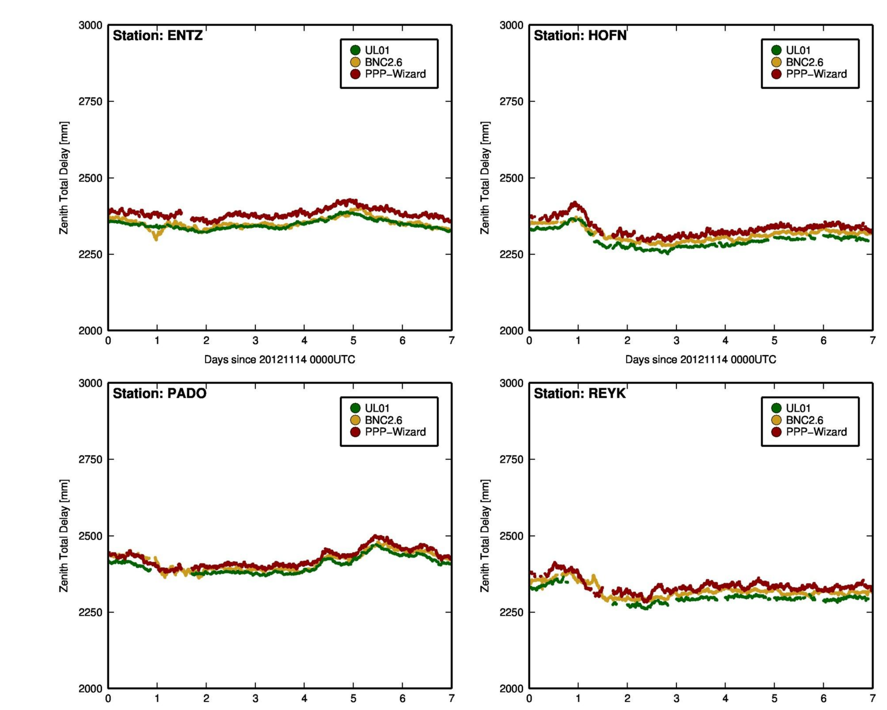

Figure 7: Comparison of ZTD time series obtained from UL01, BNC2.6 and the PPP-Wizard for 4 stations for 2012-11-14 00:00UTC to 2012-11-21 00:00UTC

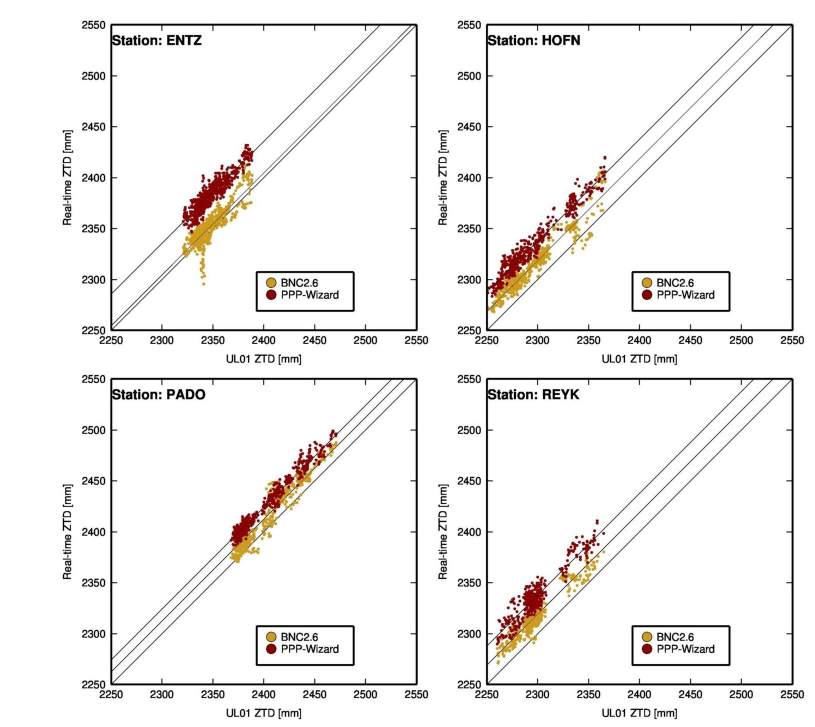

Figure 8: Correlation plots comparing ZTD estimates obtained from BNC2.6 and the PPP-Wizard to UL01 for 4 stations for 2012-11-14 00:00UTC to 2012-11-21 00:00UTC

In this The statistics for this comparison have been computed by taking the common epochs from all the three 7-days long datasets. Table 5 and Figure 9 summarize the results of comparison between UL01 and BNC2.6. This comparison has shown a mean bias of 10.7 ± 8.3 mm with an average RMS of 19.8 mm in the ZTD estimates. This translates to an error of about 3.3 kg/m² in IWV. Here it is worthwhile to mention that during PPP processing, BNC does not apply corrections for the effects of ocean and atmospheric loading.

Table 5: Statistics for the difference between real-time (BNC2.6) and near real-time ZTD estimates

Station	Bias[mm]	SD [mm]	RMS [mm]
CAGZ	8.70	8.81	12.39
ENTZ	4.54	8.95	10.04
GOPE	13.87	18.42	23.06
HOFN	18.54	7.90	20.15
INVR	12.63	28.90	31.54
MATE	-7.94	25.28	26.50
ORID	8.64	8.22	11.92
PADO	12.32	8.59	15.02
POTS	16.83	21.38	27.21
REYK	18.95	6.96	20.18

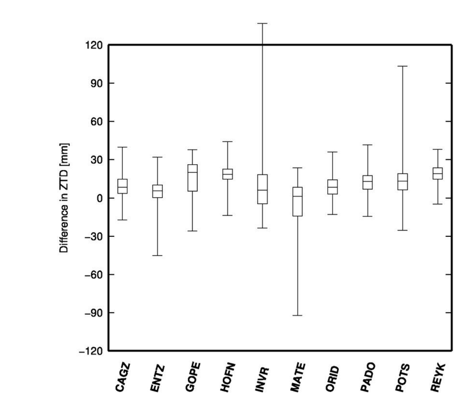

Figure 9: Box-and-Whisker plot showing statistics for comparison between UL01 and BNC2.6

Table 6: Statistics for the difference between real-time (PPP-Wizard) and near real-time ZTD estimates

Station	Bias[mm]	SD [mm]	RMS [mm]
CAGZ	65.31	9.02	65.93
ENTZ	35.53	6.64	36.14
GOPE	59.64	6.84	60.03
HOFN	37.85	38.43	6.66
INVR	47.46	8.32	48.18
MATE	60.13	7.64	60.62
ORID	46.09	6.83	46.59
PADO	24.25	5.47	24.85
POTS	58.02	7.20	58.46
REYK	37.89	8.31	38.79

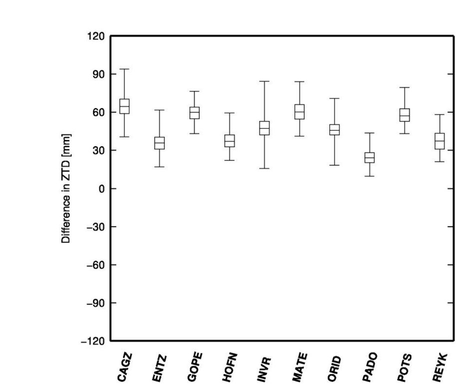

Figure 10: Box-and-Whisker plot showing statistics for comparison between UL01 and PPP-Wizard

The results of the comparison between UL01 and the PPP-Wizard have been summarized in Table 6 and Figure 10. This comparison has shown a mean difference of 47.2 ± 10.4 mm with an average RMS of 44.6 mm in the ZTD or 7.4 kg/m² in IWV.

Conclusions

The accuracy of the real-time ZTD estimates obtained by BNC 2.6 and the PPP-Wizard has been assessed by comparing them to the near real-time ZTD estimates from UL01. For BNC 2.6, this comparison resulted in a mean bias of 10.7 mm with a standard deviation of 8.3 mm whereas for the PPP-Wizard, the mean difference was found to be 47.2 mm with a standard deviation of 10.5 mm in ZTD.
The achieved accuracies of ZTD (or IWV) estimates were then compared to the user requirements for GNSS Meteorology as described by the COST Action 716 by considering the averaged RMS difference as a measure of absolute accuracy. For the estimates obtained by BNC 2.6, the IWV accuracy of 3.3 kg/m² would meet the requirements for now-casting whereas the estimates obtained by the PPP-Wizard of 7.4 kg/m² in IWV would exceed the accuracy requirements for now-casting. More work is required to identify the nature of the large mean bias of this real-time system.

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