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The Status of GNSS Data Processing Systems to Estimate Integrated Water Vapour for Use in Numerical Weather Prediction Models

F. Ahmed · F. N. Teferle · R. M. Bingley · D. Laurichesse

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Abstract Modern Numerical Weather Prediction (NWP) models make use of the GNSS-derived Zenith Total Delay (ZTD) or Integrated Water Vapour (IWV) estimates to enhance the quality of their forecasts. Usually, the ZTD is assimilated into the NWP models on 3-hourly to 6-hourly intervals but with the advancement of NWP models towards higher update rates e.g. 1-hourly cycling in the Rapid Update Cycle (RUC) NWP, it has become of high interest to estimate ZTD on sub-hourly intervals. In turn, this imposes requirements related to the timeliness and accuracy of the ZTD estimates and has lead to a development of various strategies to process GNSS observations to obtain ZTD with different latencies and accuracies. Using present GNSS products and tools, ZTD can be estimated in real-time (RT), near real-time (NRT) and post-processing (PP) modes. The aim of this study is to provide an overview and accuracy assessment of various RT, NRT, and PP IWV estimation systems and comparing their achieved accuracy with the user requirements for GNSS meteorology. The NRT systems are based on Bernese GPS Software 5.0 and use a double-differencing strategy whereas the PP system is based on the Bernese GNSS Software 5.2 using the precise point positioning (PPP) strategy. The RT systems are based on the BKG Ntrip Client 2.7 and the PPP-Wizard both using PPP. The PPP-Wizard allows integer ambiguity resolution at a single station and therefore the effect of fixing integer ambiguities on ZTD estimates will also be presented.

F. Ahmed, F. N. Teferle
Geophysics Laboratory, University of Luxembourg,
L-1359 Luxembourg, Luxembourg
E-mail: furqan.ahmed@uni.lu

R. M. Bingley
Nottingham Geospatial Institute, University of Nottingham,
Nottingham NG7 2TU, United Kingdom

D. Laurichesse
Centre National d'Etudes Spatiales, 31401 Toulouse, France

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1 Introduction

Atmospheric water vapour is a primary greenhouse gas and plays an important role in the formation of weather systems and climate change. Global Navigation Satellite System (GNSS) signals experience a propagation delay, which, along with other factors, is also related to the amount of water vapour in the lower atmosphere. Hence GNSS observations can be processed to estimate this delay with millimetre-level accuracy and together with surface meteorological data can be used to compute the amount of atmospheric water vapour on various temporal and spatial scales (e.g. Bevis et al, 1994). The term "GNSS Meteorology" refers to the assimilation of GNSS-derived atmospheric information in NWP models as well as the combination of NWP model output and GNSS observations while issuing the forecasts. GNSS Meteorology has in general a positive impact on the quality of weather forecasts (e.g. Bennitt and Levick, 2011; De Haan, 2011; Gutman et al, 2004; Vedel et al, 2004). Long-term analysis of GNSS data is also being used for climatological studies (e.g. Nilsson and Elgered, 2008; Stende, 2006). The EUMETNET EIG GNSS water vapour programme (E-GVAP) is a programme for collection and distribution of NRT ground based GNSS data for operational meteorology since 2005 (http://egvap.dmi.dk). Analysis centres located all over Europe submit NRT GNSS-derived delay and IWV solutions to E-GVAP for validation, monitoring and research. The Troposphere Working Group of the International GNSS Service (IGS) (Dow et al, 2009) produces a high-precision GPS-based troposphere product,

Table 1 General characteristics of GNSS processing systems at UL. BSW5.2 denotes the Bernese GNSS Software 5.2, BSW5.0, the Bernese GPS Software 5.0, BNC2.7 the BKG Ntrip Client 2.7, and PPPW the PPP-Wizard.

System	Update Cycle	Output Sampling	Processing Engine
PP	Post-processed	1 hour	BSW5.2
NRT	Hourly	15 min	BSW5.0
RT-I	10 min	1 sec	BNC2.7
RT-II	10 min	5 sec	PPPW

known as the IGS Final Troposphere product. The current version of this product is produced at the United States Naval Observatory (USNO) and contains ZTD estimates obtained using the precise point positioning (PPP) strategy (Zumberge et al, 1997) in form of 27-hour long sessions with a sampling interval of 5 minutes (Byram et al, 2011). Beginning from 1997, the IGS Final Troposphere product was initially based on the network processing strategy but later in 2007, the PPP strategy was adopted for its production which had advantages over the older approach (Byun et al, 2009). In this paper we will refer to the current version of this product as IGFT. The Potential of Precipitable Water Vapour Measurements using Global Navigation Satellite Systems in Luxembourg (PWVLUX) is a research project which aims at studying the potential for the use of GNSS in operational meteorology and climatology in Luxembourg and its surrounding areas (the Greater Region). Under the framework of this project, various data processing systems have been established at the University of Luxembourg in collaboration with the University of Nottingham to estimate ZTD and IWV from GNSS observations in PP, NRT, and RT modes. Some characteristics of these systems are shown in Table 1.

The COST Action 716 (Elgered et al, 2005) developed various user requirements for GNSS meteorology which specify threshold and target values on timeliness, accuracy and resolution, etc, of ZTD and IWV estimates for use in NWP nowcasting (Table 2) (Offiler, 2010). The accuracy requirements for IWV can be translated to their equivalent for ZTD (6 mm target and 30 mm threshold). If the RMS of the bias from IGFT is considered as a measure of relative accuracy, the obtained ZTD solutions can be compared to these requirements.

In this paper, we provide the current status of these systems along with their characteristics. Furthermore, we carry out a comparative analysis of these systems with IGFT and the accuracy requirements for GNSS meteorology. To read about the comparisons of GPS-derived ZTD estimates with those from other, non-GPS techniques, we refer the reader to Teke et al (2011).

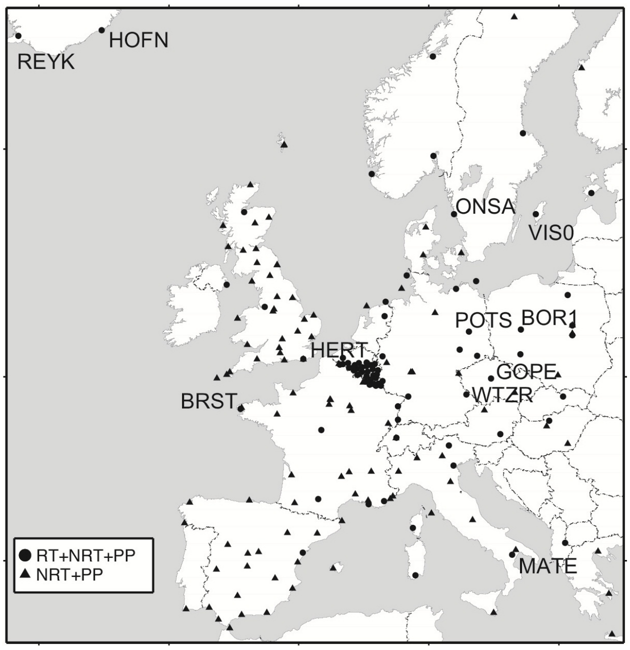

Fig. 1 Network of GNSS stations in Western Europe processed by the PP-, NRT-, and RT-systems at UL (global stations are not shown).

2 Processing Systems

Since 2011 the University of Luxembourg has established a number of GPS processing systems for the routine estimation of ZTD in collaboration with the University of Nottingham and the Centre National d'Etudes Spatiales. The hourly NRT system is based on Bernese GPS Software 5.0 (BSW5.0) (Dach et al, 2007, 2009) and uses double differencing to process a Europe-wide network (Figure 1). A sub-hourly NRT system with an update cycle of 15 minutes is also based on BSW5.0 and is used to process 15 minutes RINEX files created from RT streams. It currently does not contribute to any meteorological activities and therefore it has not been considered for assessment in this study. The two RT systems use the PPP strategy and are based on the Federal Agency for Cartography and Geodesy (BKG) Ntrip Client (BNC) 2.7 (Weber, Mervart, 2012) and the PPP-Wizard (Laurichesse, 2011) software packages. The PP system has been implemented using the Bernese GNSS Software 5.2 (BSW5.2) (Dach, 2013) and also uses PPP. Table 3 summarizes some specific characteristics of the various processing systems.

3 Accuracy Assessment of the ZTD Estimates

The results from the hourly NRT system are submitted to E-GVAP as test solution UL01. E-GVAP allows a comparative analysis of the ZTD and IWV time series on a station-by-station basis and for an entire solution using the modelled

Table 2 User requirements for GNSS Meteorology as outlined by COST Action 716 (Offiler, 2010).

	Integrated Water Vapour (IWV)	
	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 (6 mm in ZTD)	5 kg/m^2 (30 mm in ZTD)
Timeliness	5 min	30 min

Table 3 Specific characteristics of GNSS processing systems at UL

System:	PP	NRT	RT-I	RT-II
GNSS Used	GPS	GPS	GPS	GPS
Processing Strategy	PPP	Double Differencing	PPP	PPP
Receiver PCV Correction	Yes	Yes	No	No
Receiver PCO Correction	Yes	Yes	Yes	No
Satellite PCV Correction	Yes	Yes	No	Yes
Satellite PCO Correction	Yes	Yes	No[a]	No[a]
Coordinates Computed	Yes	Yes	Yes	No
Input Raw Data Format	Daily RINEX	Hourly RINEX	RTCM-3 streams	RTCM-3 streams
Input Orbit/Clock Products	CODE Final	IGS Ultra-rapid	IGS02 (RTIGS)	CLK9B (CNES)
Ambiguity Resolution	No	No	No	Yes

[a] In the RT 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.

values from the NWP model of the Royal Netherlands Meteorological Institute (KNMI) as a reference. A recent ZTD and IWV time series from the UL01 solution in comparison with other solutions for the GNSS station Visby (VIS0) are shown in Figure 2. For this period and station, UL01 ZTD has a mean bias of -0.84±14.81 mm with the ZTD from the KNMI NWP model. We note that for the stations used in this study (shown with 4-character ID in Figure 1), ZTD from UL01 has a mean bias of 3.71±11.90 mm with that from the KNMI NWP model. This compares well with the 3.42±9.95 mm computed for all other E-GVAP analysis centers processing these stations.

Besides this comparison of the hourly NRT solution to other E-GVAP solutions we have also carried out an evaluation with regards to IGFT. In order to do so we extracted a 20-day long (April 20 to May 10, 2013) data set containing ZTD estimates from the solutions of the RT-I, RT-II, NRT and PP processing systems at UL. The selected GNSS stations belong to the IGS and the choice of stations was based on the availability of RT observation data and the maximum number of epochs common in all the solutions. Figure 1 shows the network of all GNSS stations in Europe included in the processing by the systems and identifies the eleven stations, with their 4-character ID, which were used in this analysis.

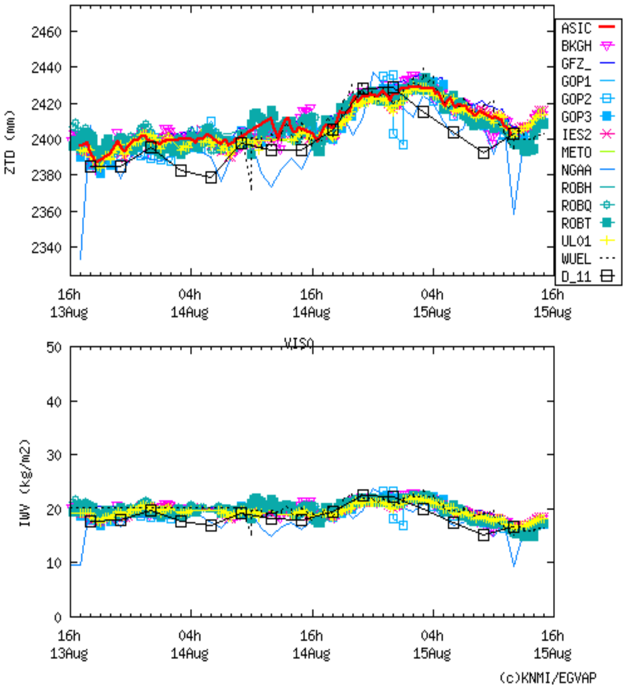

Fig. 2 E-GVAP ZTD (top) and IWV (bottom) time series comparison for station VIS0 from 2013-08-13 16:00UTC to 2013-08-15 16:00UTC. The UL01 solution is shown in yellow (http://www.egvap.dmi.dk).

After the extraction of the data set, the ZTD time series were formed and compared. Figure 3 shows the example time series for BOR1, HOFN, POTS and VIS0 obtained by the four systems and IGFT. For clarity we have introduced artificial offsets in the figure. It is clearly visible that all five solutions generally follow the same pattern. Some data gaps are visible in all solutions and not just in the RT-I, RT-II and NRT ones, which is an indication that also the delayed processes of the PP and IGFT solutions could not recover these data. It is also visible that the scatter of the solutions varies. This is most pronounced for RT-II, which shows many short-term variations. As these are not evident in the other solutions, these are an artifact of the PPP-Wizard software. It is also suggested that the ZTD variations, on temporal scales from a day to a few days, are fairly consistent between the RT-II, NRT, PP and IGFT solutions. Only for the RT-I solution the ZTD estimates are somewhat smoothened due to the constraints in the Kalman filter approach used by BNC2.7. This is apparent when rapid changes in the ZTD estimates occur, e.g. around day 7 for HOFN or days 5 and 6 for VIS0. The value of the troposphere white noise sigma (equal to 1e-5 m/s) used in BNC2.7 could be another possible reason for the delays or smoothness in the RT-I solution. On the other hand, there is no suggestion that the NRT, PP and IGFT solutions cannot track rapid variations as well as the RT-II solution.

Based on the 11 stations selected in this study we compute various statistics by taking the common epochs from the UL and IGFT reference data sets (Table 4). It can be seen that the PP and NRT systems show mean differences to the IGFT of -0.86±4.44 mm and -0.27±5.18 mm, respectively, whereas the mean differences of the RT-I and RT-II ZTD estimates to those from IGFT are 8.60±27.97 mm and 60.40±37.26 mm, respectively. The IGFT reference solution is based on BSW5.0 and thus the two solutions using the same software, i.e. PP and NRT, might have an advantage in this comparison. The large bias for RT-II 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, so resulting in a mis-match between the constrained coordinates of the survey marker and the ZTD estimation at the antenna phase center. This issue will need to be addressed. Furthermore, the lack of receiver antenna phase center variation corrections in RT solutions is believed to be one of the reasons for the larger short-term variations (scatter) in their ZTD estimates. Although a bias in the ZTD can be overcome during their assimilation into NWP models, these short-term variations and variations in the standard deviation (SD) would clearly be undesirable. Even though the RT-II solution has a large bias and variability, it can be seen that among the two RT solutions, it is more sensitive to rapid changes and tracks ZTD variations similarly well as the NRT, PP and IGFT solutions.

In favour of the RT-II system using the PPP-Wizard is the fact that it is capable of resolving the integer ambiguities in RT PPP. In order to study the effect of integer ambiguity resolution on the ZTD estimates, another RT solution for the same stations and time period has been obtained after disabling the ambiguity resolution feature in the PPP-Wizard. Using the same RT products a mean difference of 0.39±5.47 mm has been observed between the ambiguity float and ambiguity fixed solutions. Although this is a small effect, the RT-II fixed solution was improved over the float solution.

Considering the averaged RMS difference between each solution and the IGFT as a measure of its absolute accuracy, the achieved accuracies have been compared to the GNSS meteorology user requirements for NWP nowcasting as outlined in COST Action 716. As a result of this comparison, it was found that the PP and NRT systems meet the target requirements, RT-I system meets the threshold requirements whereas the RT-II system currently exceeds the threshold requirements.

4 Conclusions

The four ZTD and IWV estimation systems at the University of Luxembourg have been introduced and their relative accuracy has been assessed by comparing them to solutions from E-GVAP and the IGS Final Troposphere (IGFT) product. We showed that the near real-time (NRT) systems show good agreement at the few millimetre level with estimates from E-GVAP, and that the post-processing (PP) and NRT systems show a sub-millimetre level agreement to IGFT. The agreement of the real-time (RT) estimation systems RT-I and RT-II to IGFT is on the order of tens of millimeters. For RT-II this 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 of offsets and variations, a circumstance which will need to be adressed urgently. Nevertheless, using the PPP-Wizard the integer ambiguities can be resolved for RT PPP, which provided a slight improvement to the ambiguity-fixed solution of RT-II. Finally, when comparing these results to the GNSS meteorology user requirements for NWP nowcasting as outlined in COST Action 716, we can conclude that the PP and NRT systems meet the target requirements, RT-I system meets the threshold requirements whereas the RT-II system currently exceeds the threshold requirements.

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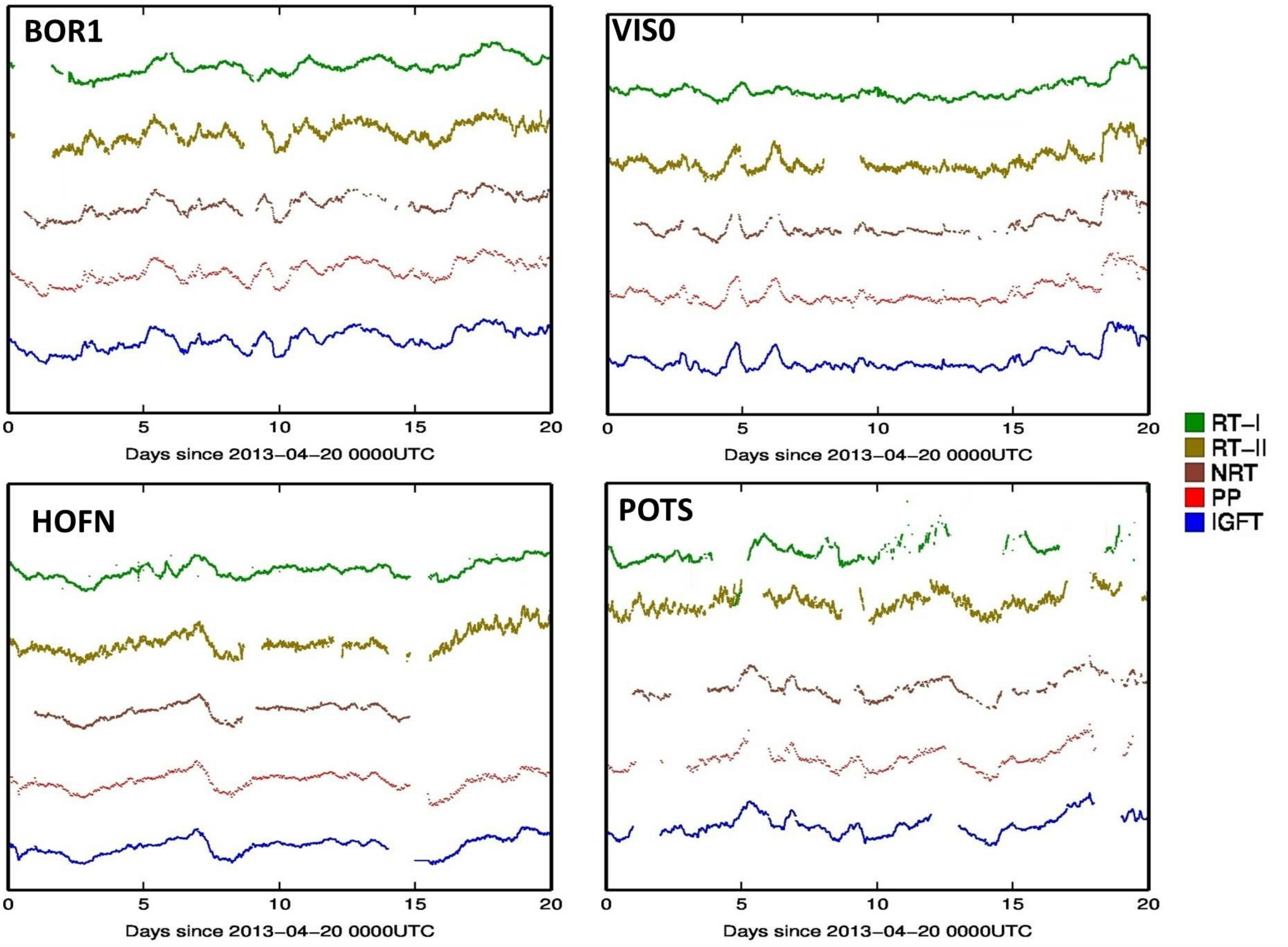

Fig. 3 ZTD time series for the stations BOR1, VIS0, HOFN and POTS obtained using the PP, NRT, RT-I and RT-II systems at UL compared to IGFT.

Table 4 Accuracy of the ZTD estimation systems relative to IGFT and their comparison to the user requirements for NWP nowcasting

System	Mean [mm]	SD [mm]	RMS [mm]	Difference from required target [mm]	Difference from required threshold [mm]	Remarks
PP	-0.86	4.44	5.19	-0.81	-24.81	Meets the target
NRT	-0.27	5.18	5.43	-0.57	-24.57	Meets the target
RT-I	8.60	27.97	30.42	24.42	-0.42	Meets the threshold
RT-II	60.40	37.26	47.81	41.81	17.81	Exceeds the threshold

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