Real-time zenith tropospheric delays in support of numerical weather prediction applications

Jan Dousa[a,*], Pavel Vaclavovic[a]

[a]*NTIS – New Technologies for Information Society*
Research Institute of Geodesy, Topography and Cartography,
Ústecká 98, 250 66 Zdiby, the Czech Republic

Abstract

The Geodetic Observatory Pecný (GOP) routinely estimates near real-time zenith total delays (ZTD) from GPS permanent stations for assimilation in numerical weather prediction (NWP) models more than 12 years. Besides European regional, global and GPS and GLONASS solutions, we have recently developed real-time estimates aimed at supporting NWP nowcasting or severe weather event monitoring. While all previous solutions are based on data batch processing in a network mode, the real-time solution exploits real-time global orbits and clocks from the International GNSS Service (IGS) and Precise Point Positioning (PPP) processing strategy. New application G-Nut/Tefnut has been developed and real-time ZTDs have been continuously processed in the nine-month demonstration campaign (February – October, 2013) for selected 36 European and global stations. Resulting ZTDs can be characterized by mean standard deviations of 6-10 mm, but still remaining large biases up to 20 mm due to missing precise models in the software. These results fulfilled threshold requirements for the operational NWP nowcasting (i.e. 30 mm ZTD). Since remaining ZTD biases can be effectively eliminated using the bias-reduction procedure prior to the assimilation, results are approaching the target requirements in terms of relative accuracy (i.e. 6 mm in ZTD). Real-time strategy and software are under the development and we foresee further improvements in reducing biases and in optimizing the accuracy within required timeliness. The real-time products from the International GNSS Service were found accurate and stable for supporting PPP-based tropospheric estimates for the NWP nowcasting.

Keywords: GNSS, Zenith Tropospheric Delay, real-time analysis, Precise Point Positioning, numerical weather prediction nowcasting

1. Introduction

The Geodetic Observatory Pecný (GOP) of the Research Institute of Geodesy, Topography and Cartography has been routinely estimating zenith total delay (ZTD) parameters from European GPS permanent stations in near real-time (NRT) since 2001 (Dousa, 2001). The GOP ZTD products are disseminated via the Global Telecommunication System of the World Meteorological Organization to meteorological institutions worldwide. The products are currently assimilated into numerical weather prediction (NWP) models in Météo France and the UK Met Office and exploited in other ways at some other agencies. In 2010, first hourly global ZTD solution (Dousa and Bennitt, 2013) was developed at GOP in support of global NWPs. One year later, after the product thorough evaluation, it was officially switched to the operational mode and it started to be routinely assimilated into operational global NWP models. In 2009, along with the developing ultra-rapid GLONASS orbits for the International GNSS Service (IGS) (Dow et al., 2009), GOP implemented near real-time GPS+GLONASS solution. It has been routinely provided since 2011 after adopting the IGS08 antenna phase centre model which reduced well-known GPS – GLONASS biases in ZTD (Dach et al., 2011), (Dousa, 2012). Based on this product we could state that GNSS ultra-rapid orbit products, provided so far by the IGS unofficially, have proven to be reliable for operational ZTD retrievals too.

All the above mentioned ZTD solutions are based on data analysis in a batch network mode using the least-square adjustment and double-difference observations. The Bernese GNSS software V5.0 (Dach et al., 2007) was used for the processing together with support of the IGS ultra-rapid orbits (Springer and Hugentobler, 2001). We did not utilize the Precise Point Positioning (PPP) method developed by Zumberge et al. (1997) which required an access to precise satellite clocks along with predicted orbits. Gendt et al. (2003) demonstrated that ZTD using PPP, supported with hourly updated precise satellite clocks, gives results comparable to those from the network solution. The precise clock product usable for NRT solution was, however, not publicly available at that time. The situation changed with the definition of the state-space correction

*Corresponding author
Email address: jan.dousa@pecny.cz (Jan Dousa)
URL: http://www.pecny.cz (Jan Dousa)

format for real-time dissemination that was standardized by the Radio Technical Commission for Maritime Service (RTCM, 2013). During last years, the IGS coordinated development of global real-time orbit and clock products exploiting individual contributions from several institutions in order to guarantee its high robustness and availability. At the end of 2012, the IGS launched its Real-Time Service (RTS) (Caissy et al., 2012) and declared the product as official. Thanks to these developments, PPP could have been implemented and recently used at GOP.

One of the well-known disadvantages of the PPP method, however, still remains – a long convergence interval of about 20–30 minutes. It is related to the difficulty of integer ambiguity resolution due to the presence of so called uncalibrated phase biases (Ge et al., 2008). Several strategies has been implemented in order to speed up the PPP convergence, but they require additional products, such as uncalibrated phase delays used in Ge et al. (2008) and Geng et al. (2010) or integer-clock corrections, see e.g. (Mervart et al., 2008), (Laurichesse et al., 2009), (Collins et al., 2010). The integer ambiguity resolution is thus available and the convergence time was reduced to about 10 minutes. The resolution of narrow-lane ambiguities, which are highly correlated with the other parameters such as receiver clocks, coordinates and tropospheric parameters, remained difficult using a shorter interval. Another recent studies overcame the PPP limitation by providing additional products, such as undifferenced L1 and L2 regional augmentation corrections from several reference stations up to a distance of 80-150 kilometres (Ge et al., 2012). Li et al. (2013) demonstrated the PPP Regional Augmentation (PPP-RA) for the instantaneous ambiguity resolution if supported with additional corrections derived from a regional reference network. This was already able to compete with the network RTK systems in terms of the first-time-to-fix interval when supporting even longer distances to reference stations.

In this paper we present a new GOP solution of real-time ZTD estimates that applies the PPP approach and un-differenced observations. The G-Nut/Tefnut software was developed for this purpose as a PPP client that uses global precise products publicly available from the internet. Ambiguities are not resolved to integer values, but ZTDs from a convergence interval after data gap can be eliminated since they are showing high formal errors.

Motivations for using the PPP consisted of several advantages when compared to the standard network processing strategy

1. highly efficient solution that may be processed for each station separately or, alternatively, in a decentralized mode provided that relevant products and software are distributed,
2. approach suitable for epoch-wise real-time filtering and supporting high-resolution tropospheric parameters,
3. direct support of absolute tropospheric zenith total delay estimates as well as additional parameters for monitoring atmospheric asymmetry around the stations – horizontal gradients or slant delays.

In particular the parameters of asymmetry modelling are considered as rewarding products for future support of NWP nowcasting or severe weather event monitoring.

After this introduction, the second section introduces the software development used in this work. The third section summarizes initial results from the new approach analysing a time-limited benchmark campaign in an offline mode. The fourth section describes a demonstration campaign provided for the assessment of a routine real-time solution. The results are summarized in the last section.

2. Software development

The results, presented in the paper, were achieved using the in-house application named Tefnut which was derived from the G-Nut software library developed at GOP (Vaclavovic et al., 2013). The G-Nut library is designed primarily for the GNSS data analyses, but recently we introduced modules for the processing of selected data from numerical weather models. The library aims at supporting all GNSS constellations, real-time and offline processing mode, epoch-wise filtering as well as batch least-square adjustment. For a high flexibility, the library is written in C++ taking advantage of the object-oriented concept.

While the pre-processing of carrier-phase observation has been properly implemented, the first stage of the library development missed several models for a high-accuracy analysis. These are foreseen for completing in the second development phase. Available models in the G-Nut/Tefnut application include solid earth tides, phase wind-up effect, receiver and satellite antenna phase centre offsets and variations, empirical tropospheric models, relativity correction due to the ellipticity of the GPS orbits, detection of eclipsing satellites for rejecting affected observations. Magnitudes of missing models recommended at the IERS Conventions (2010) are expected to reach at maximum a few centimetres in up coordinate components. For example, an error of 3 cm in the station height produces a relative error of 1 cm in ZTD according to the rule-of-thumb suggested by Beutler et al. (1988), thus we may expect systematic errors up to 2 cm in ZTDs.

Opposed to the G-Nut software library, which has not been publicly distributed yet, most of user applications derived from the library are released under the GNU Public Licence version 3.0 and they can be downloaded from the web http://www.pecny.cz/. Current applications support multi-GNSS data editing and quality monitoring (Anubis), precise static or kinematic positioning (Geb), precise troposphere monitoring (Tefnut), troposphere model parametrization based on NWP (Shu) and others will follow in future.

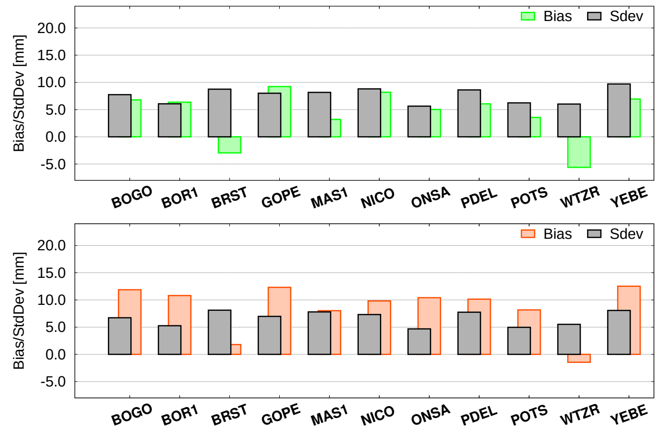

Figure 1: PPP ZTD biases and standard deviations (StdDev) with static coordinates estimated using final products (top) and real-time products (below)

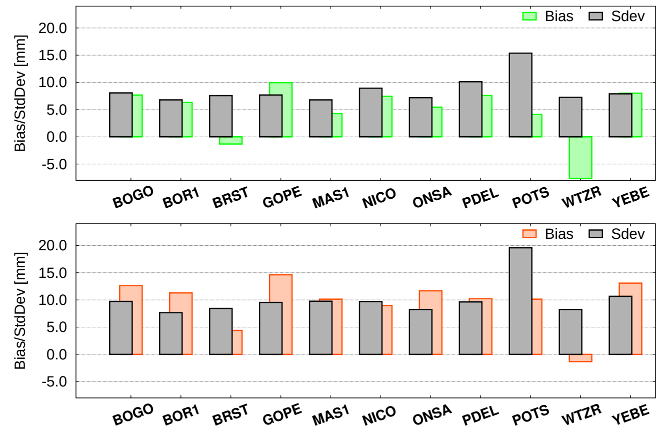

Figure 2: PPP ZTD biases and standard deviations (StdDev) with pseudo-kinematic coordinates estimated using final products (top) and real-time products (below)

3. Benchmark campaign for initial testing

In order to evaluate real-time products as well as in-house software development, first we set up a benchmark campaign over 44 days (March – April, 2012). The data were processed in two ways a) in simulated real-time mode utilizing the IGS real-time products and b) in offline mode utilizing the IGS final products. Eleven stations were selected in Europe. The coordinates were estimated in all solutions simultaneously with tropospheric parameters, however, we distinguished two modes for station positions – static and pseudo-kinematic. In the first strategy receiver coordinates were estimated as a single set of parameters during the processing period. In the latter strategy we aimed at estimating coordinates for each epoch independently although no real changes were expected because data from reference stations were processed only.

Results from the initial benchmark campaign were not iterated since the main focus was to identify readiness of real-time ZTD estimates using PPP approach with IGS RTS products. Further improvements concern the processing robustness, data and product availability and progress in the software development. These are now monitored on a routine basis within the real-time demonstration campaign described in Sect. 4.

ZTDs from the benchmark campaign were compared with respect to the EUREF final products (Soehne et al., 2009). Achieved standard deviations and systematic errors for individual stations are shown in Fig. 1. The offline and simulated real-time mode is demonstrated at top and bottom plot, respectively. Overall stability of the tropospheric estimates in both solutions achieved the precision represented by standard deviations below 10 mm. Existing large biases for most of the stations reached the magnitude of 15 mm which may be attributed to the missing models. The values represent averages over 44-day campaign meaning that the biases may be easily identified and eliminated in a bias-reduction scheme applied for each station, analysis centre and sliding window over the last month, Bennitt and Jupp (2012).

Figure 2 shows similar results as Fig. 1, but for the pseudo-kinematic mode. Interestingly, these provide almost comparable results to the static solution which is challenging for a potential future use of troposphere estimates from receivers on moving platforms. A problem was identified for the station POTS which we assumed to appear due to unknown problem in the pre-processing step affecting the stability of the real-time filter in a kinematic mode only.

According to the ZTD standard deviations at the level of 6-10 mm, the results were identified as fulfilling the threshold requirements for NWP nowcasting in terms of the relative accuracy initially defined in the project TOUGH (2005). Anyway, we believe that further improvements in terms of eliminating systematic errors and optimizing accuracy versus timeliness (5 min) could be still achieved.

For the completeness, the benchmark served for assessing of an impact of the age of real-time global orbit and clock corrections on the quality of estimated ZTDs. The statistics in Fig. 3 shows the increase of ZTD standard deviation due to precise real-time orbit and clock corrections extrapolated ahead for 10 s, 20 s, 30 s, 40 s, 50 s, 60 s and 70 s. The 10-second extrapolation already shows the degradation in ZTD standard deviation of about 1-2 mm while the 60-second extrapolation resulted in a twice lower accuracy of ZTD. In reality, however, the ZTD can be delivered with the latency of up to 5 minutes for NWP nowcasting. For this reason, in the real-time campaign we set up 80 s delay to be in a safe mode for the use of the corrections.

4. Demonstration campaign for real-time service

In order to assess the quality of routinely estimated ZTDs based on the IGS real-time products, we have set

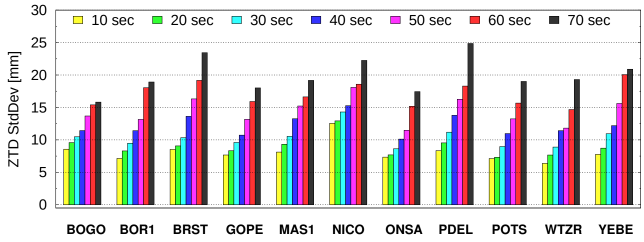

Figure 3: Decrease in ZTD accuracy due to extrapolating real-time precise corrections ahead for 10 s, 20 s, 30 s, 40 s, 50 s, 60 s and 70 s

Table 1: Global products used in the real-time demonstration campaign are summarized for mountpoint identifications associated to the product ID, update rate of disseminated corrections, agency or analysis center (AC) and additional remarks on individual products

Product ID /mountpoint	Update rate	Source /agency	Remarks
IGS01/IGS01	5 s orbits, 5 s clocks	IGS /ESOC	epoch-wise combination
IGS02/IGS02	60 s orbits, 10 s clocks	IGS /BKG	Kalman filter combination
CNS91/CLK91	5 s orbits, 5 s clocks	AC /CNES	individual AC product

up the demonstration campaign immediately after achieving expected results from the initial benchmark. In the following sections we describe the campaign design and processing strategy, we evaluate tropospheric parameters and, finally, we discuss the results.

4.1. Campaign design

Demonstration campaign was primarily designed for a continuous monitoring of the processing stability and availability of real-time data and global real-time products. For this reason we selected eighteen GNSS permanent stations in Europe and eighteen in the world. The selection was done according to the station location, real-time data availability and the presence of reference ZTD parameters from the EUREF and IGS final tropospheric products.

The campaign was initiated in February 2013 using three selected global real-time products, see Tab. 1. Two products are the IGS RTS official combinations and the third one represents an individual analysis centre (AC) product contribution to the IGS. Although two IGS combined solutions use the same set of contributing products, they are distinguished due to applied strategy, correction parametrization and combination software. The IGS01 product (stream mountpoint IGS01) is based on a single-epoch clock and orbit combination developed in ESOC (Agrotis et al., 2010) with 5 s update rate for clock and orbit offset corrections in the combined RTCM message. The IGS02 product (stream mountpoint IGS02) is based on the Kalman filter approach developed in BKG (Mervart and Weber, 2011) with clock offset corrections updated every 10 s while orbit offset corrections and their rate of change updated every 60 s. The CNS91 product (stream mounpoint CLK91) developed in CNES (Laurichesse, 2011) provides a similar correction scenario like the IGS01 product, i.e. every 5 s for both clock and orbit corrections. More details about combined products can be found at http://rts.igs.org/products.

The G-Nut/Tefnut enables to analyse a group of stations in parallel using several threads. We started three processes within the demonstration campaign, each for 36 stations applying three global products and the same settings. In addition, three other processes were started for a pseudo-kinematic mode, but only for 5 selected European stations, and these have not been evaluated for ZTD estimates. All real-time processes within the demonstration campaign were reset every two months in order to archive products, extract and evaluate ZTDs and update software with recent developments and bugs fixed.

4.2. Processing strategy

Along with the real-time ZTD estimates the station coordinates are solved for too, however, tightly constrained to keep its stable solution. Within presented results of the demonstration campaign GPS data were used only. The sampling rate for the estimating ZTD and coordinates was set to 10 s. The processing delay of 80 s was applied in order to avoid clock and orbit extrapolations (global products are disseminated with the latency of 40–50 s).

The tropospheric model was initialized with zenith hydrostatic delay calculated using the Global Pressure and Temperature model (GPT), Boehm et al. (2007). Zenith hydrostatic and wet delays were mapped to a satellite direction using the Global Mapping Function (GMF) developed by Boehm et al. (2006). The tropospheric parameters were effectively constrained based on an initial empirical test taking into account a priori observation sigma and processing sampling rate. The elevation angle cut-off 7 deg was applied and all observations weighted with respect to the elevations using $1/(\cos z)^2$ function.

Since code and carrier phase data were analysed together, a thorough pre-processing was necessary. Its main purpose was the detection of cycle slips and the reconstruction of coherency between code and phase observations caused by receiver clock jumps. For detecting carrier-phase cycle slips, various epoch-difference linear combinations were compared to defined threshold and new ambiguity parameter was set whenever the criteria is exceeded. While large cycle slips can be identified, small ones, over a few cycles only, could remain unrecognized and for this purpose the outlier rejection was implemented too. We applied iterative approach when observation with the largest post-fit residual are removed first. If all satellites were affected by a common cycle slip, a receiver clock jump was recognized and compensated using algorithm based on comparing time differenced code and phase data (Guo and Zhang, 2013). Correcting these effect avoided any repetitive initializations.

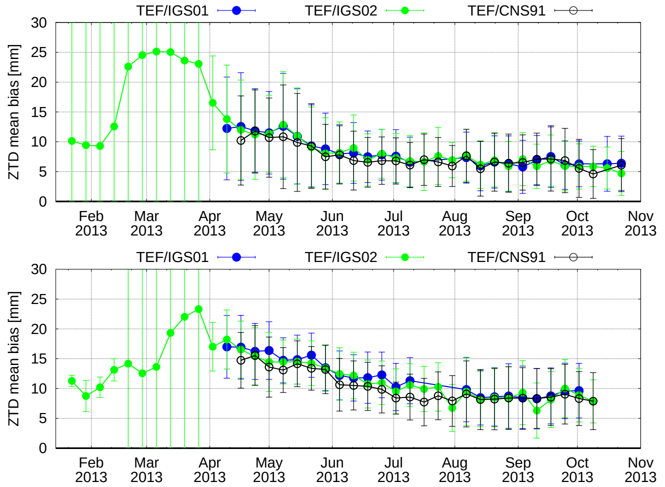

Figure 4: Tefnut ZTD weekly mean biases over all stations compared to the IGS (top) and EUREF (bottom) final products; bars show uncertainties of mean biases and standard deviations

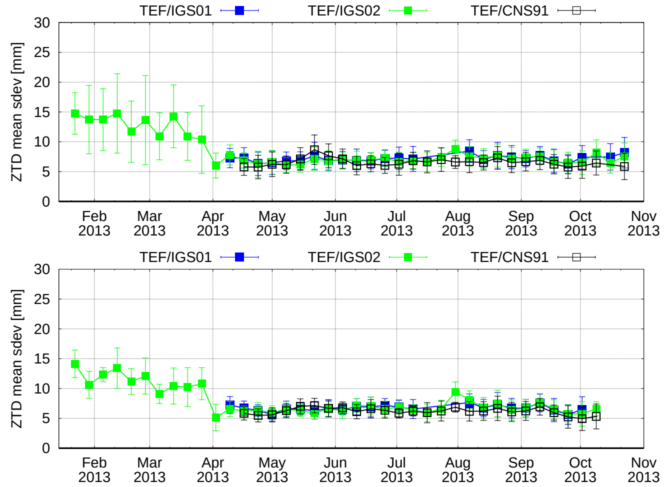

Figure 5: Tefnut ZTD weekly mean standard deviations over all stations compared to IGS (top) and EUREF (bottom) final products; bars show uncertainties of mean biases and standard deviations

The G-Nut/Tefnut output included ZTD, coordinates, formal sigmas and numbers of observed satellites. The latter two were effectively used to filter out problematic epochs from the real-time processing. Increased formal ZTD sigma in epoch-wise processing was a good indicator for identifying the initialization periods, after data gaps occurred or whenever a few satellites were observed only.

4.3. Evaluation of real-time ZTDs

The real-time ZTD data were evaluated from the demonstration campaign during the period of February – October, 2013. All extracted ZTDs were compared with respect to the EUREF (Soehne et al., 2009) and IGS (Byram et al., 2011) final tropospheric products in three modes - total over the entire period, on a weekly basis and on a hourly basis, i.e. data filtered with respect to the hour of day. The comparisons were done for ZTD values utilizing the GOP tropospheric database system – GOP-TropDB (Gyori and Dousa, 2013).

Figures 4 and 5 display weekly mean ZTD biases and mean ZTD standard deviations, respectively, over all stations when compared to IGS (top) and EUREF (bottom) products (uncertainties are shown using bars in both plots). The problem of large individual station systematic biases during the initial period (February – March, 2013) arose due to incorrectly switch off the solid earth tide model. In general, bias variations were more significant in the global comparison than in the European one. Since the end of March 2013 the mean bias has decreased significantly in both comparisons (global and European) as well as standard deviations have become stable at the level below 10 mm. The progressive improvements can be attributed mainly to the software developments which concerned a better performance during data decoding, carrier-phase cycle slip detection, receiver clock jump reparation, observation outlier rejection and others. No significant changes were made in terms of the precise model implementations - these are planned for the upcoming months after completing software robustness in various situations. In the evaluation we could observe only a bit of a typical decrease of ZTD precision during the summer months characteristic by increased humidity. The effect is shadowed by the lower precision of real-time ZTDs (i.e. standard deviation of 6-10 mm) with respect to NRT solutions achieving 3-6 mm (Dousa and Vaclavovic, 2013).

Figures 6 and 7 display total statistics for real-time ZTDs compared to the EUREF and IGS tropospheric product, respectively. The biases are shown at top plots while standard deviations at bottom plots. All three global products were compared during the entire period of April – October, 2013, i.e. the initial period with well-known bug was excluded from all further comparisons. Besides large biases, which are individual for each station and positive in general, the achieved standard deviations are rather consistent over all European stations. A single value exceeding 10 mm was found at the station REYK (Iceland). It should be noted that standard deviations are slightly larger than in weekly comparisons, where biases are separated on a weekly basis, while in the total comparison these are constant over the entire period. Thus any temporal variability in systematic errors due to the missing models is included directly in all estimated standard deviations.

Larger values of standard deviations can be also seen in the global comparison. A few stations exceeded 10 mm and a single station UNSA (South America) resulted in 18 mm standard deviation. Slightly worse precision in the global solution can be attributed to several aspects. First, the lower accuracy of real-time orbit and clock products in a global scale is due to the fact that Europe is extremely well covered with data supporting precise and stable corrections over the region in global products. Second, a higher variability in atmospheric conditions causes lower accuracy

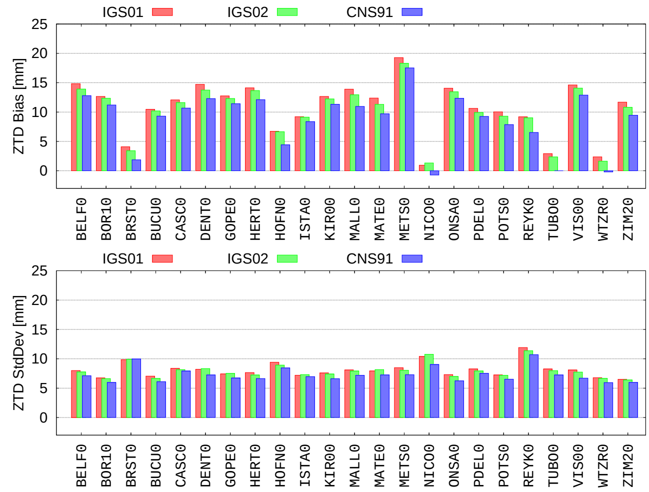

Figure 6: Tefnut ZTD comparisons with respect to EUREF final products - biases (top) and standard deviations (bottom)

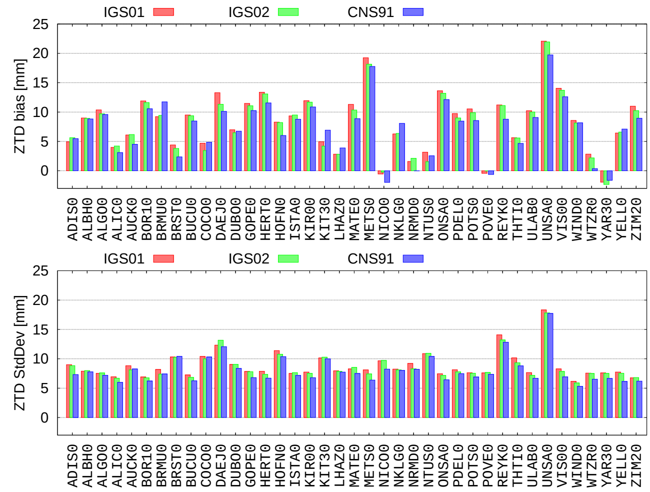

Figure 7: Tefnut ZTD comparisons with respect to IGS final products - biases (top) and standard deviations (bottom); bars show uncertainties of mean biases and standard deviations

at stations in the tropical belt with overall higher humidity and atmospheric pressure variation. Third, the availability of global data meaning more frequent loss of lock due to data gaps, increased latency and others affecting the continuity of the processing. The geographical distribution of all global stations compared to the IGS products is shown in Fig. 8 with biases and standard deviations at top and bottom plots, respectively.

Finally, we have compared real-time ZTDs on an hourly basis meaning that during the period of April – October 2013 all values were filtered and compared according to hour of day. Figure 9 plots mean biases (top) and mean standard deviations (bottom) over all compared stations. Standard deviations are similar for both EUREF and IGS comparisons, i.e. European and global, and generally does not expose variation over a day. This is not true for the biases, which reveal a clear diurnal variation and larger positive values in Europe. This can be clearly attributed to the modelling deficiencies in the application exciting a regional effect.

As concerns the standard deviation, both European and global real-time solutions already fulfil the requirements for NWP nowcasting provided that remaining systematic errors can be eliminated on a monthly basis in a bias-reduction scheme prior to the exploitation in meteorology as shown in Bennitt and Jupp (2012). Half-year results from the real-time demonstration campaign can be characterized with the standard deviation of 6-10 mm. We can state that the PPP real-time approach supported with the IGS real-time orbit and clock products complies with initial requirements defined NWP nowcasting.

4.4. Real-time product assessment

Figures 6 and 7 showed that the individual global orbit and clock corrections by CNES performed slightly better, in terms of ZTD statistics, than using IGS combined products. In accordance, when estimating pseudo-kinematic coordinates in real time we usually observed better stability when using CNES global product rather than using any of IGS combined products. It is demonstrated in Fig. 11 showing a sample of pseudo-kinematic positioning with simultaneous tropospheric estimates during July 2, 2013 using GOPE observations and all three global products – IGS01 (top), IGS02 (middle) and CNS91 (bottom).

In case of post-processing orbit and clock products, the IGS typically give the best accuracy and more robust and complete results than the ones obtained with the individual analysis centre (AC) solutions (Kouba, 2009). However, when concerns the real-time products, we observed slightly better results from an individual AC then from any of the combination approach within IGS. Although this combination aims mainly at the high product robustness and availability, this may indicate a potential space for improving the combination process in terms of the weighting of individual AC contributions.

4.5. Availability of produced ZTDs

Real-time tropospheric parameter estimates depend on the production and dissemination of real-time observations from the receiver, availability of real-time global precise orbit and clock products and an overall robustness of the processing strategy including indispensable data preprocessing and outlier rejection procedures.

Figure 10 shows a percentage of extracted ZTD parameters available for the comparison. The percentages do not include any ZTD results from periods of unstable solution identified merely by a large formal error. The criterion was set up to 6 mm while in normal situation the formal errors are usually at the level of 1 mm. Situation with large formal errors occur typically in the PPP initialization phase which takes approximately 30 minutes after a cold start or a data gap. Alternatively, a large formal error occurs

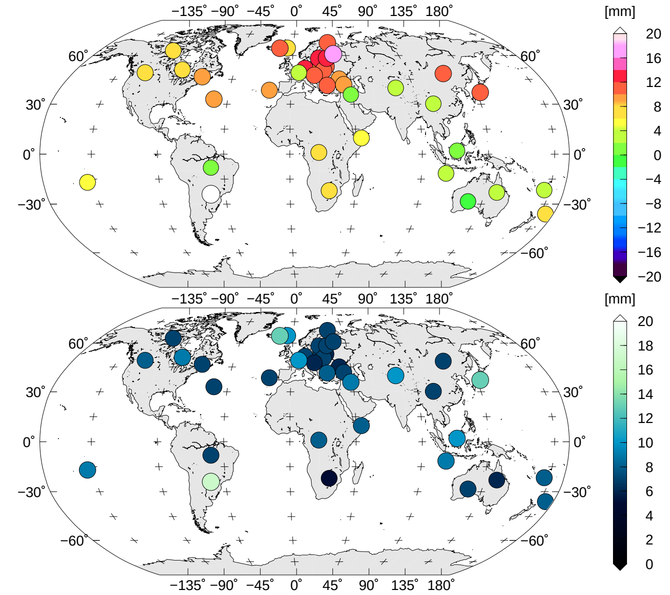

Figure 8: ZTD geographical real-time ZTD evaluation with respect to IGS final product during April-October, 2013 – bias (top) and standard deviation (bottom)

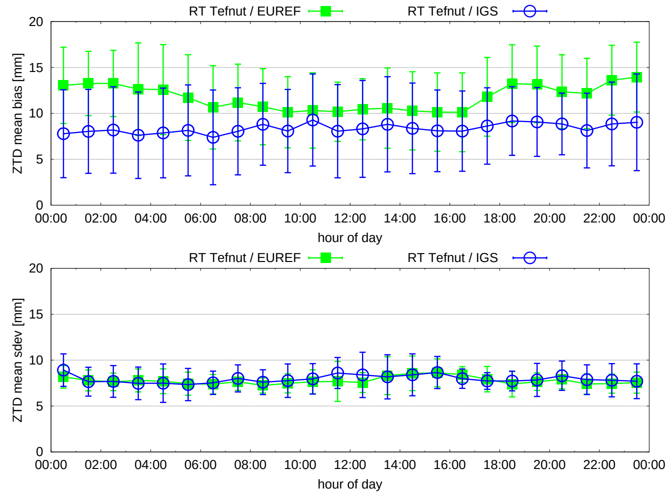

Figure 9: Real-time Tefnut ZTD mean bias (top) and standard deviations (bottom) with respect to IGS and EUREF final products based on hourly comparisons (March – October, 2013)

if a few satellites are available, i.e. those observed at the station and supported with the global precise corrections.

The figure shows a sample availability of ZTDs based on the CNES product during June – July, 2013. The availability is above 95 % for most of the stations that are reliable for real-time data provision. Such results can be assessed as very good when considering a long chain of various potential disrupting effects. The solutions based on IGS combined products showed only a slightly better availability.

In the figure we clearly identify problems specific to 1) data flow from individual stations represented by blank records in a line, 2) data overall dissemination problems, which is indicated with a decrease of overall ZTD availability in a column and 3) low availability of individual precise products can be visible comparing columns in figures for different products.

5. Conclusion

The main focus of this paper was to demonstrate availability and initial quality of real-time tropospheric estimates, which can be used for NWP nowcasting and for severe weather monitoring.

New application G-Nut/Tefnut developed at the Geodetic Observatory Pecný was described in brief, in particular to support real-time GNSS processing. The library and the user application are still under development which concerns a) the implementation of precise models compliant with the IERS 2010 conventions and b) the optimization of ultra-fast ZTD estimates in terms of achievable accuracy under the requested timeliness.

Offline simulated benchmark campaign over 44 days was provided for an initial assessment of the software and selected global precise products. The tropospheric estimates were compared with the IGS and EUREF ZTD final products. The results already showed that the quality of ZTD complies with the threshold requirements for the operational NWP nowcasting – the relative accuracy of 5 kg/m^2 in integrated water vapour (IWV) with the 60 minutes repetition cycle and the 30 minutes product latency. This roughly corresponds to the 30 mm in ZTD when approximating the conversion factor defined by Bevis et al. (1994).

The current precision of real-time ZTD estimates can be characterized with the standard deviation of 6-10 mm almost independent of location. This is not far from the target requirements for the operational NWP nowcasting defined as 1 kg/m^2 for IWV ($\approx$ 6 mm in ZTD) and 5 minutes for the repetition cycle and 5 minutes for the latency. Existing systematic errors are attributed mainly to the incomplete observation model in the G-Nut/Tefnut application, but it was shown to be enough stable so that they can be eliminated in a monthly bias-reduction procedure prior the use in meteorology.

The results achieved in the offline benchmark were confirmed in the first real-time demonstration campaign evaluated for the period of February – October 2013. The G-Nut/Tefnut was used to process 36 stations exploiting three precise orbit and clock products within the IGS Real-Time Service. Current real-time products are already reliable for the developing operational monitoring system for troposphere in support of meteorological applications.

We still foresee various possibilities to improve real-time processing strategy and software as well as we expect further enhancements in the IGS real-time combined products and in overall data and product availability. We assume that future improvements in ultra-fast tropospheric

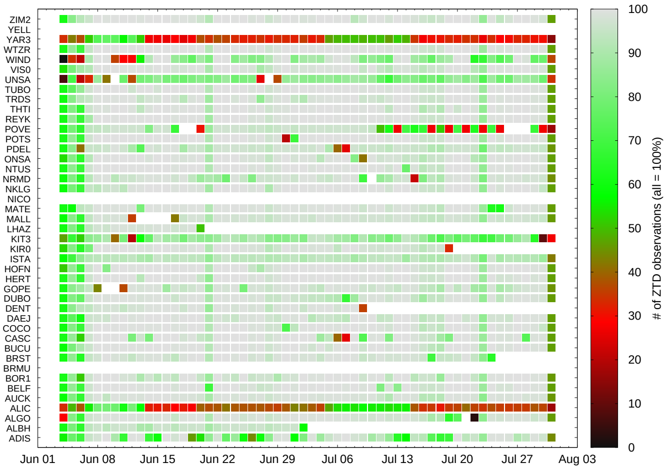

Figure 10: Real-time GNSS data, precise CNES products and tropospheric estimates availability during the two months of the demonstration campaign (June-July, 2013)

estimates, and not necessarily provided in real time, could achieve the accuracy requested by the target requirements for the operational NWP nowcasting.

Acknowledgements

The development of the G-Nut/Tefnut software and real-time tropospheric product was supported by the Czech Scientific Foundation (P209/12/2207). The assessment of the real-time and multi-GNSS solutions was done within the COST ES1206 project (GNSS4SWEC-CZ). The data from GOPE station used in real-time testing were provided with support of the CzechGeo project (No. LM2010008). We are thankful to the EUREF and IGS community providing data and products used in this work, in particular products of precise global orbit and clock corrections supported by individual contributing agencies. The authors warmly thanks to Dr Denis Laurichesse from the CNES for providing the individual global precise product.

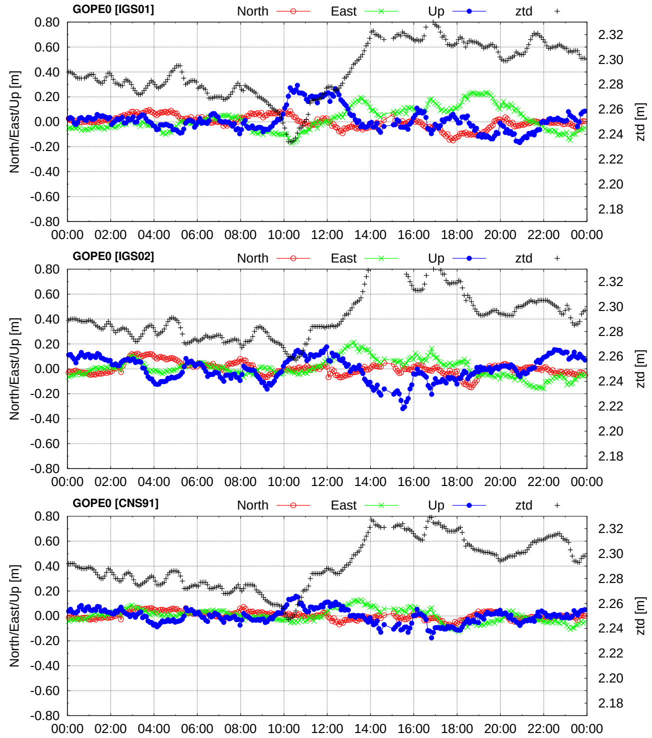

Figure 11: Pseudo-kinematic real-time solution for coordinates and troposphere at GOPE station supported with different orbit and clock products on July 2, 2013 - IGS01 (top), IGS02 (middle) and CNS91 (bottom)

References

Agrotis, L., Alfaro Sanz P., Dow, J., Zandbergen, R., Svehla, D., Ballereau, A. ESOCs RETINA System and the Generation of the IGS RT Combination presented at the IGS Analysis Workshop, Newcastle, United Kingdom, June 28 July 1, 2010.

Bennitt, G.V., Jupp, A. Operational assimilation of GPS Zenith total delay observations into the UK Met Office numerical weather prediction models. Mon. Weather Rev., 140(8), 2706–2719, 2012.

Beutler, G., Bauersima, I., Gurtner, W., Rothacher, M.,Schildknecht, T., Geiger, A. Atmospheric refraction and other important biases in GPS carrier phase observations. The University of New South Wales, Kensington, New South Wales, Australia : Atmospheric Effects on Geodetic Space Measurements, F.K. Brunner (ed). Monograph 12, School of Surveying, 1988.

Bevis, M., Businger, S., Chiswell, S., Herring, T.A., Anthes, R.A., Rocken, C., Ware, R.H. GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water. J Appl. Meteor., 33, 379–386, 1994.

Boehm, J., Niell, A., Tregoning, P., Schuh, H. Global mapping function (GMF): a new empirical mapping function based on numerical weather model data. Geophys. Res. Lett., 33:L07304, 943–951, doi:10.1029/2005GL025546, 2006.

Boehm, J., Heinkelmann, R., Schuh, H. Short note: a global model of pressure and temperature for geodetic applications. J Geod., 81:10, 679–683, doi:10.1007/s00190-007-0135-3, 2007.

Byram, S., Hackmann, C., Tracey, J. Computation of a High-Precision GPS-Based Troposphere Product by the USNO, In: Proceedings of the 24th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2011), 2011.

Caissy, M., Agrotis, L., Weber, G., Hermandez-Pajares, M., Hugentobler, U. Innovation: Coming Soon: The International GNSS Real-Time Service, GPS World, 2012.

Collins, P., Bisnath, S., Lahaye, F., Heroux, P. Undifferenced GPS Ambiguity Resolution Using the Decoupled Clock Model and Ambiguity Datum Fixing, Navigation, J Inst. Navig., 57(2), 2010

Dach R., Hugentobler, U., Fridez, P., Meindl, M. Bernese GPS Software V5.0. User manual, Astronomical Institute, University of Bern, 2007.

Dach, R., Schmid, R., Schmitz, M., Thaller, D., Schaer, S., Lutz, S., Steigenberger, P., Wuebbena, G., Beutler, G. Improved antenna phase center models for GLONASS. GPS Solut 15:49–65, doi:10.1007/s10291-010-0169-5, 2011.

Dousa, J. Towards an Operational Near real-Time Precipitable Water Vapor Estimation, Phys. Chem. Earth., Part A, 26(3), 189–194, 2001.

Dousa, J., Bennitt, G.V. Estimation and evaluation of hourly updated global GPS Zenith Total Delays over ten months, GPS solut., 17, 453–464, 2013.

Dousa, J. Development of the GLONASS ultra-rapid orbit determination at Geodetic Observatory Pecny, in: Geodesy of Planet Earth, Kenyon, S., Pacion, M.C., Marti, U. (eds.), IAG Symposia, Springer, 136, 1029–1036, 2012.

Dousa, J., Vaclavovic, P. Long-term evaluation of new ground-based GNSS tropospheric products. Submitted to the IAG Symposia Series of the IAG Scientific Assembly 2013 in Potsdam, Springer (submitted in 2013).

Dow, J.M., Neilan, R.E., Rizos, C. The International GNSS Service in a Changing Landscape of Global Navigation Satellite Systems, J. Geod., 83(3–4), 191–198, 2009.

E-GVAP project, available at web http://egvap.dmi.dk

Ge, M., Gendt, G., Rothacher, M., Shi, C., Liu, J. Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations. J. Geod., 82(7):389–399, doi:10.1007/s00190-007-0187-4, 2008.

Ge, M., Dousa, J., Li, X., Ramatschi, M., Nischan, T., Wickert, J. A Novel Real-time Precise Positioning Service System: Global Precise Point Positioning With Regional Augmentation J Global Pos. Syst., 11(1):2–10, doi:10.5081/jgps.11.1.2, 2012.

Gendt, G., Dick, G., Reigber, C., Tomassini, M., Liu, Y., Ramatschi, M. Near Real Time GPS Water Vapor Monitoring for Numerical Weather Prediction in Germany. J Meteorol. Soc. Japan, 82:361–370, (2004)

Geng, J., Meng, X., Dodson, A., Teferle, F. Integer ambiguity resolution in precise point positioning: method comparison, J. Geod., 84:569–581, doi:10.1007/s00190-010-0399-x, 2010.

Guo, F., Zhang, X. Real-time clock jump compensation for precise point positioning, GPS solut., 2013.

Gyori, G., Dousa, J. GOP-TropDB development for tropospheric product evaluation and monitoring - design, functionality and initial results, International Association of Geodesy Symposia, Rizos, C. and Willis, P. (eds), Springer (submitted paper), 2013.

IERS Conventions. Petit, G., Luzum, B. (eds.). (IERS Technical Note; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 179 pp., 2010.

Kouba, J. A guide to using International GNSS Service (IGS) products, available at the IGS Central Burau web: http://www.igs.org/overview/pubs.html, 2009.

Laurichesse, D. The CNES Real-time PPP with undifferenced integer ambiguity resolution demonstrator, In: Proceedings of the ION GNSS 2011, September 2011, Portland, Oregon, 2011.

Laurichesse, D., Mercier, F., Berthias, J.P., Broca, P., Cerri, L. Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination, Navigation, J Inst. Navig., 56(2), Summer 2009.

Li, X., Ge, M., Dousa, J., Wickert, J. Real-time precise point positioning regional augmentation for large GPS reference networks, GPS solut., 18(1), 61–71, 2013.

Mervart, L., Lukes, Z., Rocken, C., Iwabuchi, T. Precise Point Positioning With Ambiguity Resolution In Real-Time, In: Proceedings of ION GNSS 2008, the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation, Savannah, September 16-19, 397–405, 2008.

Mervart, L., Weber, G. Real-time Combination of GNSS Orbit and Clock Correction Streams Using a Kalman Filter Approach . In: Proceedings of ION GNSS 2011, the 24th International Technical Meeting of the Satellite Division of The Institute of Navigation, Portland, Oregon, September 1923, 2011, pp. 707711.

RTCM Standard 10403.2. Differential GNSS (Global Navigation Satellite Systems) Services - Version 3 (February 1, 2013). RTCM Paper 104-2013-SC104-STD (not freely available).

Springer, T.A., Hugentobler, U. IGS ultra rapid products for (near) real-time applications, Phys. Chem. Earth., Part A, 26(6–8), 623–628, 2001.

Soehne, W., Figurski, M., Szafranek, K. Homogeneous Zenith Total Delay Parameter Estimation from European Permanent GNSS Sites, presented at EUREF 2009 symposium, Florence, Italy, May 27-30, Available at http://www.epncb.oma.be/_documentation/papers, 2009.

TOUGH Targeting Optimal Use of GPS Humidity Measurement for Meteorology, (Deliverable D10, User requirements), Available at http://web.dmi.dk/pub/tough/.

Vaclavovic, P., Dousa, J., Gyori, G. G-Nut software library - state of development and first results, Acta Geodyn. Geomater., 10(4), 431–436, 2013.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., Webb, F.H. Precise point positioning for the efficient and robust analysis of GPS data from large networks, J Geoph. Res., 102, 5005-5018, 1997.