REAL-TIME ZTD ESTIMATES BASED ON PRECISE POINT POSITIONING AND IGS REAL-TIME ORBIT AND CLOCK PRODUCTS

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ABSTRACT

The Geodetic Observatory Pecný routinely estimates near real-time zenith total delays (ZTD) from GPS permanent stations more than 12 years. Three additional ZTD products have been developed since 2009 – hourly GPS global, GPS+GLONASS regional and GPS real-time products. While the first two are based on data batch processing in a network mode using Bernese GNSS software, the last one exploits autonomous Precise Point Positioning epoch-wise processing technique. The latter is supported by GNSS real-time data and products and in-house developed G-Nut/Tefnut application. The software functionality supports troposphere estimation in post-processing, near real-time and real-time modes. Real-time ZTDs has been continuously processed in the demonstration campaign (Feb-Sept, 2013) for selected 36 European and global stations. Resulting ZTDs are characterized by mean standard deviations of 7 mm which already complies with the requirements from now-casting applications.

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 [1]. Produced ZTDs are exploited for weather forecasting models in several meteorological institutions today. On request from the UK Met Office in 2010, the GOP developed the first hourly updated global ZTD solution [2] in support of global numerical weather prediction (NWP). After one year evaluation the product is officially disseminated within the E-GVAP project [3] and later assimilated in the UK Met Office operational global model. In 2009, together with developing ultra-rapid GLONASS orbit product, the GOP developed GPS+GLONASS near real-time ZTD solution. This has been provided routinely since 2011 after the switching to IGS08 antenna phase centre model reducing GPS-GLONASS biases [4]. Based on a long-term product evaluation, we can confirm that still unofficial GPS+GLONASS ultra-rapids orbit product as provided by the International GNSS Service, IGS [5] is already suitable for an operational ZTD estimation.

All the above mentioned ZTD solutions are based on the batch data processing in network mode via least-square adjustment of double-difference observations. The Bernese GNSS software V5.0 [6] is used together with IGS ultra-rapid orbit products. New challenges came up with the latest standardization of the state-space corrections for real-time dissemination and with developing global real-time orbit and clock products. The IGS Real-Time Service, RTS [7] provides today highly robust and accurate real-time orbit and clock corrections which can be operationally used for the end-user applications.

The GOP real-time ZTD solution could have been developed utilizing alternative approach – the Precise Point Positioning, PPP [8] based on the IGS global real-time products and filtering epoch-wise un-differenced GNSS observations. In-house developed software application Tefnut derived from the G-Nut software library developed at GOP was used for this purpose [9].

In the first section we briefly present the G-Nut software library and G-Nut/Tefnut end-user application. The second section shows initial results of the new approach solution in simulated real-time mode. The third section describes first real-time demonstration for ZTD estimates performed at GOP in February-September, 2013. The fourth section shows the evaluation of the results from the demonstration campaign and the last section concludes the paper.

2. REAL-TIME SOFTWARE DEVELOPMENT

The G-Nut software library has been developed at GOP since 2011 [9]. The library is designed primarily for the analysing of GNSS data. It is aimed to support all multi-GNSS constellations, real-time and offline analyses, epoch-wise filtering as well as batch least-square adjustments. For a high flexibility, the library is written in C++ taking advantage of the object-oriented concept.

First end-user applications were derived, namely: *Anubis* – tool for GNSS data editing and monitoring, *Geb* – tool for precise positioning, *Tefnut* – tool for troposphere estimation and, recently, *Shu* – tool for troposphere modelling exploiting data from numerical weather models. In contrast to the G-Nut development library, the end-user applications are usually released under the GNU Public Licence V3.0 [10] and these can be downloaded from the web http://www.pecny.cz/.

3. OFFLINE TESTING CAMPAIGN

For evaluating real-time products and development of in-house software, we firstly setup a one-month benchmark campaign (April 2012). The data were processed in two ways – a) in simulated real-time mode (utilizing real-time products) and b) in post-processing mode (using final products). The solutions estimating coordinates in both static and pseudo-static (kinematic) modes were provided for the set of 11 stations selected in Europe. The resulting ZTDs were compared with respect to the EUREF final products.

Achieved standard deviations and systematic errors are summarized in Fig.1 and 2 for static and kinematic modes, respectively. Interestingly, the latter solution provided almost comparable results to the former one. The standard deviations can be found within the range of 6-9 mm for ZTD with a single exception of station POTS where a specific problem occurred. Such results already fulfill requirements from the nowcasting applications [11], and we believe, they can be still improved when optimizing the accuracy versus timeliness (5 min).

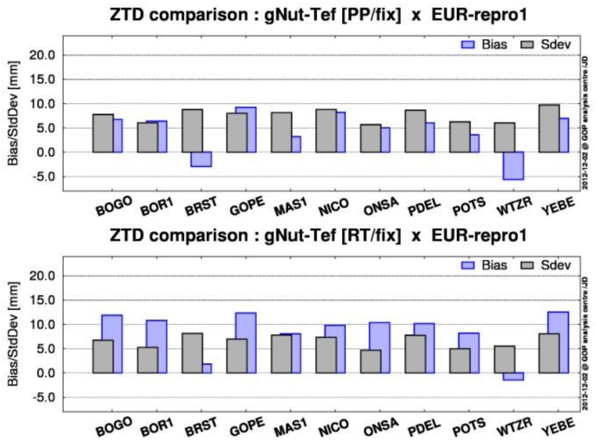

Figure 1. PPP ZTD comparisons with static coordinates based on final products (top) and real-time products (below).

Significant biases exist in all the solutions, which can be attributed mainly to the still existing precise model deficiencies in Tefnut software (e.g. satellite eclipse modeling, various tide models and some others). These are planned to be implemented in the second step of the development since primary goal was to provide required precision. The figures show biases estimated from a whole month, which can be easily eliminated in the pre-processing performed within the assimilation process - a bias estimation procedure usually applied for each ZTD processing centre for products from previous month [12].

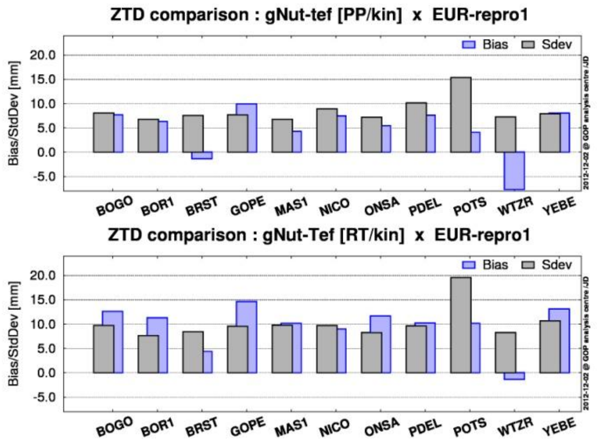

Figure 2. PPP ZTD comparisons with kinematic coordinates based on final products (top) and real-time products (bottom).

For completeness, the impact of the age of real-time corrections on the quality of estimated ZTDs was tested. The statistics in Fig.3 shows the decrease of ZTD accuracy due to precise real-time orbit and clock correction extrapolations for 10, 20, 30, 40, 50, 60 and 70 sec. Ten seconds in the extrapolation already shows the degradation in ZTD of about 1-2 mm (for standard deviation), while 60 sec of the extrapolation resulted already in twice lower ZTD accuracy. In reality, however, the ZTD can be delivered with the latency of up 5 min for nowcasting applications. For this reason, in the real-time campaign we setup 80 sec delay to be in a safe mode for the use of the corrections.

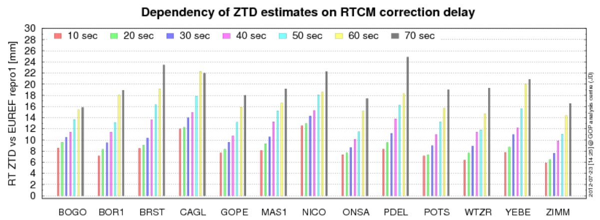

Figure 3. Decrease of ZTD accuracy due to precise real-time correction extrapolations (10, 20, 30, 40, 50, 60 and 70sec).

4. REAL-TIME DEMONSTRATION CAMPAIGN

In order to assess the quality of routinely estimated ZTDs based on the IGS real-time products [7], we have setup the testing campaign of 18 GNSS permanent stations in Europe and 18 in the world. Stations were selected according to their location, real-time data availability and the availability of reference ZTD values from EUREF and IGS final products.

The campaign was initiated in February 2013 using three selected global real-time products, see Tab.1. Two products were official IGS RTS combined solutions, while the third one was provided by CNES [13] representing a single-agency product contribution to the IGS RTS combination. The IGS01 stream is based on the epoch-wise clock and orbit combination approach provided by ESOC and the IGS02 is based on Kalman filter solution approach provided by BKG.

Table 1. Summary of used real-time global products

Stream ID	Update rates	Source	Remarks
IGS01	5s orbits, 5s clocks	IGS @ESOC	Combined product Epoch-wise approach
IGS02	60s orbits, 10s clocks	IGS @BKG	Combined product Kalman filter approach
CNS91	5s orbits, 5s clocks	CNES	Individual product

During the real-time ZTD solution, coordinates were estimated too, but usually tightly constrained. The real-time solution was reset every two months, results archived, ZTDs evaluated and software updated for new developments. Within this demonstration campaign the GPS data were used only. The processing sampling rate for estimating ZTD and coordinates was set to 10 seconds and the processing delay of 80 sec in order to avoid clock and orbit extrapolations (global products are usually delayed by 40-50 sec). The output included ZTD, coordinates, formal sigma and the number of observed satellites. The latter two could be efficiently used to filter out problematic epochs from the real-time processing. Increased formal ZTD sigma is usually a good indicator of any initialization period occurring after data gap or when a few satellites are observed.

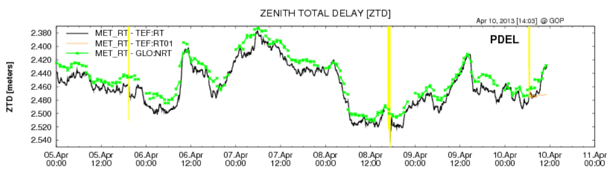

Figure 4. ZTD time-series at PDEL station showing near real-time network solution from Bernese GPS software (green) and real-time PPP solution by G-Nut/Tefnut application (black). Yellow lines indicate ZTD initialization after data gaps.

5. REAL-TIME PRODUCT EVALUATION

The real-time ZTDs data were evaluated during the period of February – September, 2013. Fig.4 shows sample ZTD time-series for station PDEL for new real-time PPP solution using Tefnut application and GOP operational NRT solutions using Bernese software and double-difference processing. Yellow lines display ZTDs during epochs identified as initializing periods usually after a data gap.

All real-time ZTDs have been evaluated with respect to the IGS/EUREF final products. Total and weekly biases and standard deviations were calculated from ZTD differences. Fig.5 displays weekly statistics for all global stations. After well-known initial problem, caused by incorrectly switched off solid earth tide model, the mean standard deviation over all stations steadily remains below 10 mm. The ZTD standard deviation improves in time which represents additional software improvements as well as the mean bias has decreased below 10 mm. It is valid when taking into account all global station while in Europe it still remains even more systematic.

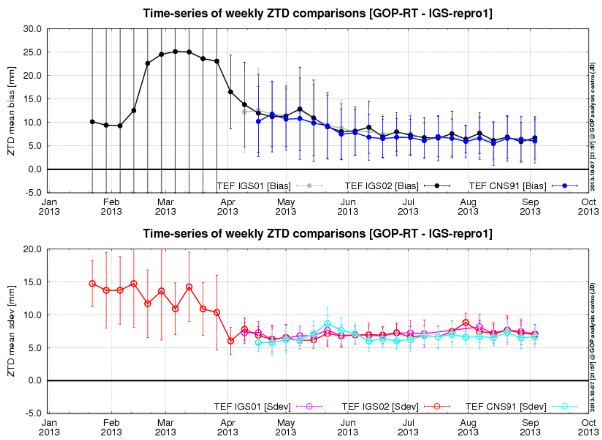

Figure 5. Weekly comparisons of real-time solutions with respect to IGS final ZTDs based on three products (IGS01, IGS02 and CNS91) – bias (top) standard deviation (bottom).

Figure 6 displays total statistics for real-time ZTDs from European stations compared with respect to the EUREF final tropospheric product.

More than a half-year real-time campaign evaluation demonstrated that real-time estimated ZTD can be characterized by standard deviation of 5-9 mm. Based on this we can state that the PPP real-time approach supported with the IGS real-time orbit and clock products already comply with the requirements for now-casting applications.

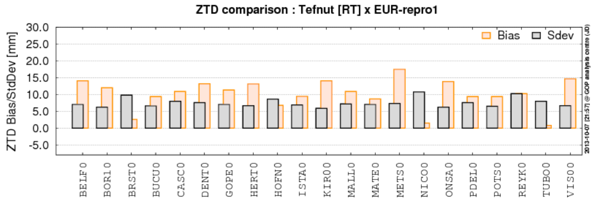

Figure 6. Total statistics (May-Sep, 2013) from real-time ZTD estimates compared to EUREF final tropospheric product.

6. CONCLUSION

New application G-Nut/Tefnut was developed at

Geodetic Observatory Pecny for the ultra-fast or real-time zenith delay monitoring with PPP technique and supported with the IGS Real-Time Service precise products. Offline simulated benchmark campaign over 44 days for eleven stations and the real-time campaign during February - August, 2013 for 36 European and global stations were performed at GOP. The tropospheric results were compared to the IGS and EUREF ZTD final products.

Achieved results demonstrate the real-time ZTDs can be routinely estimated with standard deviation of 6-9 mm in ZTD almost independent of location, when supported with current real-time precise orbit and clock corrections. Significant systematic errors, however, still remain in real-time estimates (values up to 17 mm), which are attributed mainly to the current software deficiencies of missing precise IERS models. These will be implemented and evaluated in the second phase of the development. After 6 months of the testing routine solution, GOP real-time ZTDs demonstrated a good stability of the product providing with the precision already complying with requirements for operational nowcasting applications.

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