European GNSS troposphere monitoring for meteorological applications

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Abstract. Near real-time GNSS double-difference network processing is a traditional method still used within the EUMETNET EIG GNSS Water Vapour Programme (E-GVAP) for the atmosphere water vapour content monitoring in support of Numerical Weather Prediction. The standard production relies on estimating zenith tropospheric path delays (ZTDs) for GNSS ground stations with a 1-hour time resolution and a latency of 90 minutes. The Precise Point Positioning (PPP) method in real-time mode has reached the reliability and the accuracy comparable to the near real-time solution. The effectiveness of the PPP method relies on exploiting undifferenced observations from individual receivers, thus optimal use of all tracked systems, observations and signal bands, possible in-situ processing, high temporal resolution of estimated parameters and almost without any latency. The solution may implicitly include horizontal tropospheric gradients and slant tropospheric path delays for enabling the monitoring of a local asymmetry of the troposphere around each individual site. We have been estimating ZTD and gradients in real-time continuously since 2015 with a limited number of stations. Recently, the solution has been extended to a pan-European and global production consisting of approximately 200 stations. The real-time product has been assessed cross-comparing ZTDs and horizontal gradients at 11 collocated stations and by validating real-time ZTDs with respect to the final post-processing products.

1. Introduction
Nowadays, Global Navigation Satellite System (GNSS) is an established atmospheric sounding technique suitable for delivering Integrated Water Vapour content (IWV) obtained from ground stations in near real-time for Numerical Weather Prediction (NWP) in Europe. The concept of the so-called GNSS Meteorology was initially proposed in 1992 [1]. In 2001, the first operational analyses [2] [3] became available within the COST 716 Demonstration campaign [4]. Such a solution consisted of Zenith Total Delay (ZTD) parameters estimated using a piecewise constant model based on processing Global Positioning System (GPS) observations on hourly basis. In 2004, the EUMETNET GNSS Water Vapour Programme (E-GVAP, [5]) was established to coordinate a delivery of GNSS ZTDs with a latency of 90 minutes for their operational assimilations of ZTDs into European NWP models. During 2007-2009, first assimilations were developed, tested and adopted into operational services [6] [7].

Since 2008, further development has been focused on multi-GNSS analyses, namely GPS+GLONASS at that time. Only recently, the Galileo and BeiDou constellations became effectively
A high-resolution product with a short delivery latency was however enabled with a standardization of real-time corrections for the state-space representation and support of the Precise Point Positioning (PPP) method [10]. Since 2013, the IGS Real-Time Service (RTS, [11]) has provided accurate combined real-time orbit and clock corrections for GPS (GLONASS) which could have been used for real-time PPP processing for the atmosphere monitoring. The PPP approach offers many advantages: 1) high efficiency of the processing supporting even a decentralized approach, 2) epoch-wise stochastic filtering suitable for real-time applications with a high temporal resolution of estimated parameters, and 3) absolute values of all estimated parameters (ZTDs, linear horizontal gradients, and slant tropospheric delays) can be obtained directly from the PPP processing.

Advances in GNSS constellations (available satellites, signals, and services), high-accuracy data processing and error modelling concepts, developing software and optimizing strategies, provide new opportunities for optimal exploitations of GNSS data for atmospheric sciences. Ultra-fast and real-time products with a high temporal parameter resolution, low latency, characterizing a first-order anisotropy, or even line-of-sight delays from all visible satellites, will be available besides providing traditional products such as vertical tropospheric path delays, or integrated water vapour content [12], above individual stations. Although significant progresses in multi-GNSS, real-time, and asymmetry monitoring were achieved within the Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate (GNSS4SWEC, 2013-2017) EU collaborative project [13], the added values of GNSS troposphere monitoring suggest exploitation in support of public weather services [14].

This paper describes and evaluates recent developments and achievements in real-time atmospheric sounding with GNSS when briefly introducing a new application development towards a storm nowcasting demonstrator within public weather and hail suppression services in Bulgaria.

2. Real-time troposphere estimates
Past milestones as well as recent developments of real-time software and processing strategy are described in the following sections.

2.1. Real-time software development
The in-house G-Nut/Tefnut software has been developed since 2011 for estimating tropospheric parameters in real time, originally designed as a PPP client from the G-Nut software library [15]. First real-time operational ZTD results were obtained already during 2013 [16], i.e. shortly after the IGS announced the Real-Time Service (RTS). A half-a-year testing period served for the initial software validation and such operation resulted in many improvements in terms of the stability of the processing. At the end of the validation campaign, the solution achieved a precision of 6-10 mm (measured with the standard deviation compared to final GNSS tropospheric products), however, the parameters were still biased up to 15 mm depending on stations and products used. The latter was attributed to the quality of precise products and inconsistencies of models between the service and our PPP client solution. Anyway, such a precision has already achieved the minimum requirements specified for the GNSS ZTD estimates for NWP nowcasting applications (5 kg/m² of the IWV).

During the GNSS4SWEC project, a dedicated Benchmark campaign [17] and Real-time campaign [19] [18] were organized for an efficient collaboration of several groups from different institutions. The Benchmark campaign aimed at optimizing and validating generic processing strategies including
modelling and estimating horizontal gradients and slant delays, optimal utilization of multi-constellation data and products in both offline and simulated real-time modes. The Real-time campaign was designed for demonstrating, comparing and validating recently developed real-time software and processing strategies. It demonstrated that such solutions can be stable and precise enough for an operational product delivery. Both campaigns were extensively used improving of the G-Nut software, specifically for optimizing, comparing and validating: 1) estimation of horizontal gradients [19], 2) retrievals of tropospheric slant delays [20], 3) numerical weather models and predictions [17] [21], 4) provision of troposphere model for positioning [22], and others.

Recently, the G-Nut/Tefnut software has been further enhanced [23] for a) all-in-one strategy supporting the troposphere monitoring in near real-time processing (using hourly data files) and real-time processing (using real-time data streams) and 2) using undifferenced and uncombined observation models for a PPP multi-GNSS analysis [24]. Last but not least, the software has been enhanced for more optimal parallel data processing with an interactive control of threads and processes via a user console in real time, for decoding original data and product streams, and, for encoding tropospheric products to the standard format such as SINEX_TRO Version 2 [25]. Consequently, hundreds of stations can be processed now simultaneously (or thousands of stations in a distributed mode) while still keeping a fully consistent product output.

2.2. Real-time processing strategy

Until recently, a majority of the contributions to the EGVAP were generated with the least-square batch processing technique utilizing deterministic models (piecewise constant or linear) for tropospheric parameters. The G-Nut/Tefnut uses a stochastic modelling in the Kalman filter and backward smoother [26] which supports high-resolution parameter estimation updated e.g. with any new coming observation. Although the backward smoothing was designed for the post-processing solution, it can be specifically used in near real-time processing mode too [23].

Table 1 shows a summary of the processing strategy and models utilised at GOP for real-time troposphere monitoring. GPS code and phase observations from the ionosphere-free linear combination are used within a current operational solution when supported with real-time orbit and clock corrections from the IGS Real-time Service [11] or French Space Agency, CNES [27]. Observations above 7-degree elevation angle cut-off are used and weighted with an elevation-dependent factor. Input data at a 10-sec sampling rate are processed by a square root filter for estimating ZTDs and horizontal tropospheric gradients at every epoch, however, these are saved in the SINEX_TRO V2 format only at a 5-minute sampling rate. The state vector related to each individual station is updated every epoch and consists of the following parameters:

- station coordinates (estimated as static),
- receiver clocks corrections,
- zenith wet delays,
- tropospheric horizontal linear gradients in the north and east directions,
- intersystem bias for GLONASS and Galileo (if applicable), and
- initial phase ambiguities for all available satellites.

| Processing strategy          | Description                                                      |
|------------------------------|------------------------------------------------------------------|
| Observations                 | Undifferenced code and phase ionosphere-free linear combinations |
| Observation weighting        | Elevation dependent factor 1/sin(elevation)^2                     |
| Parameter                                      | Description                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------------|
| Elevation angle cutoff                        | 7 degrees                                                                   |
| Estimator                                     | Square root filter                                                          |
| Constellations                                | GPS (GLONASS, Galileo)                                                     |
| Data / parameter sampling rate                 | 10 seconds (RTCM) / 5 minutes (SINEX_TRO)                                   |
| Coordinates                                   | Simultaneously estimated (static values).                                   |
| Receiver clocks                               | Estimated epoch by epoch when utilizing the white noise process             |
| Initial carrier-phase ambiguity                | Float values estimated.                                                    |
| Attitude of satellites                         | Nominal attitude models, satellites note used during eclipsing events.      |
| Ionosphere                                    | First order eliminated by ionosphere-free combination                       |
| Troposphere                                   | • ZHD from the Saastamoinen model [28] based on atmospheric pressure from the GPT model [29] |
|                                              | • ZWD estimated when utilizing random walk process with the noise 5 mm/sqrt(hour) |
|                                              | • Gradients estimated using random walk process with the noise 0.5 mm/sqrt(hour) |
|                                              | • Mapping function for ZHD/ZWD: GMF model [30]                              |
|                                              | • Mapping function for gradients: Chen and Herring [31]                     |
| Antenna phase centre corrections               | • Receiver - antenna type offsets and variations                            |
| (IGS14 models)                                | • Satellite - antenna offsets                                              |
| Tides (IERS 2010 conventions, [32])            | • Solid earth tide model                                                   |
|                                              | • Ocean tide loading: FES2004 model [33]                                    |

3. **Real-time tropospheric parameter monitoring and validation**

Currently, tropospheric parameters for more than 200 GNSS stations in Europe and worldwide are estimated operationally in real-time. We identified 11 pairs of collocated stations and these are very useful for inter-comparisons of estimated values since the atmospheric effect should be the same at a unique site. Monitoring and validating GNSS real-time tropospheric delays are thus performed via 1) immediate visualizing products on the web portal, 2) cross-comparing of ZTDs and tropospheric horizontal gradients at several collocated stations, and 3) comparing real-time ZTDs with respect to the EUREF final tropospheric products.

3.1. **Web portal for monitoring real-time products**

Real-time tropospheric products, ZTDs and tropospheric horizontal gradients, are displayed on a portal at http://www.pecny.cz/RT-TROPO. This enables plotting and selecting various parameters, stations, sources or views:

- tropospheric products from one or more resources (or networks),
- geographical/table views of stations (display of attitude, data availability, source, metadata),
- time-series of real-time estimated tropospheric parameters (from one or more stations),
- combining/comparing tropospheric parameters (from several resources or different locations),
- evolution of tropospheric products during recent days, and others.
Figure 1 shows the portal with a map of all stations processed in real-time during June 6-10, 2021. The bottom time-series plot shows the availability of ZTDs from selected stations (green points). Figure 2 displays a detailed view for two collocated stations at Geodetic Observatory Pecný (GOPE and GOP6) which are located at a horizontal distance of less than 4 m. North and East tropospheric horizontal gradients from these two stations are plot together in yellow/red and dark/light blue colours, respectively. Although the gradients reach values up to 2.5 mm, they are obviously in a very good agreement while obtained independently from two independent data sources (stations) at the location.

Figure 2. Tropospheric horizontal gradient visualized for two collocated stations at Pecný site

3.2. Cross-comparison of ZTDs and horizontal gradients at collocated stations

Besides a visual inspection of tropospheric parameters at collocated stations on the web portal, a numerical cross-comparison was performed during January 2021 for both ZTDs and horizontal gradients. Such an evaluation represents a quality assessment of estimated parameters when using independent data sources for monitoring a common atmospheric effect at two close stations. Table 2
shows metadata and collocation information of 11 stations routinely available within the GOP real-time service since December 2020, hence, these were used for the product assessment.

Table 2. Collocated stations within the real-time troposphere solution

| Station pair | Receiver | Antenna (radome) | H distance | V distance |
|--------------|----------|------------------|------------|------------|
| GOPE (CZE)   | TRIMBLE ALLOY | TPSCR.G3 (TPSH) | 4.1 m      | 0.0 m      |
| GOP6 (CZE)   | SEPT POLARX5 | SEPCHOKE_B3E6 (SPKE) |          |            |
| HERS (GBR)   | SEPT POLARX5TR | LEIAR25.R3 (NONE) | 136.3 m    | 6.8 m      |
| HERT (GBR)   | LEICA GRX1200GGPRO | LEIAT504GG (NONE) |          |            |
| JOEN (FIN)   | JAVAD TRE_3 DELTA | ASH700936A_M (SNOW) | 4.9 m   | 0.0 m      |
| JOE2 (FIN)   | JAVAD TRE_3 DELTA | JAVRINGANT_DM (SCIS) |        |            |
| KIR0 (SWE)   | SEPT POLARX5 | JNSCR_C146-22-1 (OSOD) | 4.2 m | 0.0 m |
| KIR8 (SWE)   | TRIMBLE ALLOY | LEIAR25.R3 (LEIT) |          |            |
| MATG (ITA)   | LEICA GR10 | LEIAR25 (NONE) | 20.0 m    | -0.1 m     |
| MATE (ITA)   | LEICA GR30 | LEIAR20 (NONE) |            |            |
| METG (FIN)   | SEPT POLARX5 | TRM59800.00 (SCIS) | 2790.3 m  | 19.5 m     |
| MET3 (FIN)   | JAVAD TRE_3 DELTA | JAVRINGANT_DM (SCIS) |          |            |
| ONSA (SWE)   | SEPT POLARX5TR | AOAD/M B (OSOD) | 58.8 m    | -1.1 m     |
| ONS1 (SWE)   | TRIMBLE NETR9 | LEIAR25.R3 (LEIT) |          |            |
| SKE0 (SWE)   | SEPT POLARX5 | ASH701945C_M (OSOD) | 6.7 m | 0.1 m |
| SKE8 (SWE)   | TRIMBLE NETR9 | LEIAR25.R3 (LEIT) |          |            |
| SODA (FIN)   | JAVAD TRE_3 DELTA | AOAD/M_T (DUTD) | 12.8 m   | 1.0 m      |
| SOD3 (FIN)   | JAVAD TRE_3 DELTA | JAVRINGANT_DM (SCIS) |          |            |
| TSLE (FRA)   | TRIMBLE NETR9 | TRM59800.00 (NONE) | 1265.5 m | 1.5 m      |
| TSLG (FRA)   | SEPT POLARX5TR | TRM59800.00 (NONE) |          |            |
| VIS0 (SWE)   | SEPT POLARX5 | AOAD/M_T (OSOD) | 4.6 m     | -0.4 m     |
| VIS6 (SWE)   | TRIMBLE NETR9 | LEIAR25.R3 (LEIT) |          |            |

Figure 3 displays the time series of daily root-mean-square (RMS) of differences in ZTD (left) and gradients (right) obtained from the pairs of collocated stations. Note the time series for individual stations are displayed with offsets by 10 mm and 1 mm for the ZTD and gradients, respectively. A single peak visible on January 15, 2021 is attributed to the restart of the solution with a new convergence affecting all estimated parameters including reference coordinates for all the stations. Very good agreement was achieved during the entire period with the exception of the stations at Metsahovi (MET3 and METG) collocated at large vertical and horizontal distances. Table 3 then shows statistical results of tropospheric parameters estimated in real-time between collocated stations.

Figure 3. Daily RMS of ZTDs and horizontal tropospheric gradients differences at collocated stations.
Table 3. Statistics of ZTD and horizontal linear gradient differences at collocated stations

| Station pair | ZTD [mm] | N-grad [mm] | E-grad [mm] |
|--------------|----------|-------------|-------------|
|              | Bias     | SDEV        | RMS         | Bias     | SDEV        | RMS         | Bias     | SDEV        | RMS         |
| GOPE – GOP6  | -0.53    | 3.44        | 3.48        | 0.13      | 0.50        | 0.52        | -0.01    | 0.43        | 0.43        |
| HERS – HERT  | 3.07     | 4.17        | 5.18        | 0.01      | 0.47        | 0.47        | -0.17    | 0.47        | 0.50        |
| JOEN – JOE2  | -4.41    | 6.34        | 7.72        | -0.03     | 0.71        | 0.71        | 0.18     | 0.82        | 0.84        |
| KIR0 – KIR8  | -0.04    | 2.48        | 2.48        | -0.13     | 0.43        | 0.45        | 0.11     | 0.41        | 0.43        |
| MATG – MATE  | -1.21    | 2.94        | 3.18        | 0.15      | 0.52        | 0.54        | 0.03     | 0.51        | 0.51        |
| METG – MET3  | 5.72     | 4.47        | 7.26        | 0.18      | 0.67        | 0.70        | 0.12     | 0.82        | 0.82        |
| ONSA – ONS1  | 0.95     | 3.71        | 3.83        | -0.06     | 0.65        | 0.65        | 0.10     | 0.47        | 0.49        |
| SKE0 – SKE8  | -1.09    | 2.55        | 2.77        | -0.01     | 0.30        | 0.30        | 0.07     | 0.30        | 0.31        |
| SODA – SOD3  | 2.12     | 3.45        | 4.05        | 0.09      | 0.47        | 0.48        | -0.29    | 0.66        | 0.72        |
| TSLE – TLSG  | -1.26    | 4.36        | 4.53        | -0.08     | 0.74        | 0.74        | 0.12     | 0.66        | 0.68        |
| VIS0 – VIS6  | 0.42     | 2.83        | 2.87        | 0.11      | 0.42        | 0.44        | 0.02     | 0.33        | 0.34        |

3.3. Assessment of ZTDs with respect to EUREF final products

Validation of the GNSS real-time tropospheric delays were finally performed with respect to the EUREF final product combined from several analysis centres [34]. Unfortunately, only ZTDs can be validated as there is no combination of estimated horizontal gradients. Figure 4 displays a time series of ZTD RMS from several permanent stations included in the GOP real-time processing prior December 2021. The figure displays monthly ZTD RMS values (stations offset by 10 mm) during 2019-2021, and Table 4 eventually total statistical results.

![Monthly comparisons of real-time ZTD with EUREF combined solution](image)

**Figure 4.** Monthly RMS of ZTD differences between real-time and EUREF final products

Table 4. Statistics of ZTD differences from real-time and EUREF final product comparison

| Station | BIAS [mm] | SDEV [mm] | RMS [mm] |
|---------|-----------|-----------|----------|
| BRST    | 2.58      | 5.95      | 6.43     |
| NICO    | 3.15      | 6.04      | 6.53     |
| HERT    | 5.42      | 6.02      | 8.53     |
| WTZR    | 4.82      | 5.12      | 7.20     |
| HOFN    | 2.34      | 4.64      | 5.16     |
| POTS    | 4.28      | 5.08      | 6.82     |
| ONSA    | 4.91      | 4.66      | 6.76     |
| MATE    | 2.58      | 7.55      | 7.91     |
| GOPE    | 4.14      | 5.43      | 6.81     |
4. Storm demonstrator development

The World Meteorological Organization defines nowcasting as “detailed description of current weather and forecast up to 6 hours ahead of hazardous, high-impact weather phenomena” [35]. In Bulgaria, high-impact weather events, like intense precipitation, hail and thunderstorms, are common in the summer months and are associated with large economic losses. A recent study [36] demonstrated the added value of combining the instability indices with GNSS derived Integrated Water Vapour (IWV) for thunderstorm days in the warm part of the year from May to September 2010-2015, for the Sofia region. The results clearly indicated improvements in probability of detection and false alarm ratio scores for a classification function, combining instability indices and IWV.

Thunder and hail storm demonstrator (Storm Demo) is currently under development when exploiting the added value of NRT and RT GNSS tropospheric products for storm nowcasting in Bulgaria. Figure 5 presents the Storm Demo design concept. The demonstrator targets development of service centred at GNSS products for two regions with hail suppression operations, namely Northwestern and Central Bulgaria. As a part of the Storm Demo, operational real-time PPP processing with a latency of 5 minute will be conducted for the first time in Southeast Europe during the hail suppression season May-September 2021. Simulations with the Weather Research and Forecasting (WRF) model will be conducted twice a day and saved in the Sofia University Data Archive (SUADA, [37]). On the publicly accessible Storm Demo geoportal (http://suada.phys.uni-sofia.bg/?page_id=4838) actual values of GNSS and WRF derived IWV are visualised and continuously updated. Evaluation of the real-time products will be performed using reprocessed GNSS tropospheric products. The added value of the high temporal resolution of the GNSS tropospheric products will be investigated for selected storm cases. The Storm Demonstrator is still unique in Europe and will serve as a prototype for real-time provision of GNSS products for storm nowcasting.

5. Conclusions

Recent developments of the troposphere sounding with ground-based GNSS data processed in real-time proved that we are ready for an operational delivery of advanced tropospheric products, ZTDs and tropospheric horizontal gradients, with a high accuracy and time resolution, low latency and for many
stations. In December 2020, we extended the demonstration real-time processing into a pan-European (and global) scope including more than 200 GNSS stations.

For the product assessment, we first compared ZTDs obtained at 9 stations from the real-time processing and from the EUREF final ZTD product. The evaluation resulted in RMS of 5-8 mm for individual stations during the two-year period of a routine production. Second, we compared real-time ZTDs and horizontal gradients at 11 collocated stations assuming to obtain zero differences in atmospheric conditions within both stations. The comparison resulted in 3-6 mm and 0.5-0.8 mm for ZTDs and gradients, respectively. We can conclude, that the PPP method in real-time has reached the reliability and the accuracy comparable to near real-time solutions.

We are going to continue operating real-time processing with aim at serving for new meteorological applications among others. We believe, the development of the Storm nowcasting demonstrator in Bulgaria, briefly introduced in this paper, will open doors for further exploitations of advanced GNSS tropospheric products in nowcasting domain or others.

Acknowledgment(s)
We acknowledge the EUREF and IGS communities as well as many individual contributors for providing real-time data and precise products.

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