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Intercomparison and Validation of GNSS-IWV Derived with G-Nut and Bernese Software

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Abstract. GNSS is an important source of meteorological data. GNSS measurements can provide tropospheric Zenith Wet Delays (ZWD) over wide area covered with permanent stations. In addition, when using surface synoptical data, GNSS can provide Integrated Water Vapor (IWV) which is very valuable information utilized in weather forecasts and severe weather monitoring.

Hence, there is a need to test and validate various algorithms and software used for ZWD estimation. In this research, the accuracy of the ZWD estimates was tested using two different software packages: Bernese GNSS Software v.5.2 and G-Nut/Tefnut. In addition, their computational load was evaluated. The GNSS data were obtained from POTS permanent station, which is located in Potsdam, Germany. To validate the estimation results, the derived ZWD was transformed into the IWV, and afterwards compared to the reference IWV measured by the collocated Microwave Radiometer. In addition, the ZWD estimates were also compared to the EUREF final solution.

Keywords: PPP, ZTD, IWV, GNSS meteorology.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

The troposphere is the medium that delays electromagnetic waves, including the Global Navigation Satellite System (GNSS) signals. In order to achieve high accuracy of satellite positioning, that delay must be measured. Delay of the GNSS signal is usually measured across the zenith direction above the receiver (zenith total delay, ZTD). The zenith delay consists the hydrostatic component (ZHD), which is connected to the dry gas pressure and temperature, and the non-hydrostatic, wet component (ZWD), which is caused by the water vapor contained in the troposphere. ZHD can be computed using the global atmosphere model, while ZWD could be estimated as the difference between ZTD given by the GNSS observation and the modeled hydrostatic delay:

$$ZWD = ZTD - ZHD.$$

The ZTD estimation based on GNSS measurements is widely used method since early 90' (Bevis *et al.* 1994; Jin *et al.* 2005; Wielgosz *et al.* 2013; Rohm *et al.* 2014). The precise positioning techniques based on the accurate satellite orbit parameters allows to determine (or estimate) parameters mentioned above. Using this estimates and the synoptic data (surface temperature and the troposphere refraction indexes) the ZWD can be transformed into the integrated water vapor (IWV) content in troposphere which is one of the most important parameter for the meteorologists. Determining and mapping the IWV and ZTD is source of the desirable data. This could be the basis for creating the numerical weather models and the advantage of the near real time measurements is very useful for weather forecasts (Karabatić *et al.* 2011).

In over two decades, the satellite geodesy and the meteorology developed close cooperation in Europe (Douša *et al.* 2016). Good example of that kind of cooperation is the COST ES1206 action "GNSS4SWEC – Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate". The action took aim in addressing new and improved capabilities from concurrent developments in both the GNSS and meteorological communities. The main objective of the Action is to enhance existing and develop new, ground-based multiGNSS tropospheric products, assess their usefulness in severe weather forecasting and climate monitoring, and to improve GNSS accuracy through enhanced atmospheric modelling (COST Action ES1206… 2012). The action developed advanced tropospheric products based on multi-GNSS water vapour estimates. One of the main part of the action was the Benchmark Campaign – collecting the GNSS meteorological radar data for 430 permanent stations in Central Europe for two months period in 2013 that covered the occurrence of severe weather events that have caused the flooding in the region. The achievements of the Benchmark Campaign improved the approach to activities from real-time monitoring and forecasting of severe weather, to climate research (Douša *et al.* 2016).

Development of GNSS research and advancements in computational methods allowing to obtaining efficient troposphere data, created new possibilities and new challenges. One of them is the necessity of developing the precise data processing tools. Hence, regarding the future scientific near-real time applications, it is important to test several software and answer the question which is more accurate and effective. The main purpose of this research was to test computational load and capabilities of two different software in the field of the ZTD estimation using the GNSS observations processed in the PPP mode.

The most common procedure of GNSS-based ZTD estimation is the processing of double-differenced (DD) observations. This approach reduces some geometry-related errors, e.g., satellite and receiver clock errors. The other approach (zero-difference, ZD) involves the observational data from a single receiver with addition of precise geodetic products: orbit clock and clock corrections, solid Earth tides, antenna phase center corrections, etc. (Petit, Luzum 2010). This technique is called PPP (Precise Point Positioning (Zumberge *et al.* 1997)) and its advantage is that the position can be determined with high accuracy with use of only one GNSS receiver. The PPP technique is a proven and well tested way to determine the troposphere parameters (Karabatić 2011). However, unlike in the double-difference approach, the hardware biases have to be taken into account. The International GPS Service (IGS) provides necessary products that are required by PPP. In PPP technique, the standard observation model is based on ionosphere-free linear combination of code and carrier phase observations. Basic PPP observation model is given by equations (Zumberge *et al.* 1997):

$$P_{if} = \rho + c(dT - dt) + Tr,$$

$$\Phi_{if} = \rho + c(dT - dt) + Tr + \lambda_{if} N_{if},$$

where P_{if} is the ionosphere-free combination of code measurements; Φ_{if} is the ionosphere-free combination of carrier-phase measurements in metric units; ρ is the geometric distance between satellite and receiver antenna phase centers; c is the vacuum speed of light; Tr is the neutral atmosphere delay; dT and dt are the ionosphere-free receiver and satellite clock errors, respectively; λ if is the ionosphere-free effective carrier-phase wavelength; and N_{if} is the ionosphere-free carrier-phase ambiguity parameter (Héroux, Kouba 2001).

The IGS products gave us information about satellite position and clock corrections, hence in the epoch to epoch data processing, positioning equation can be solved with high accuracy. In the PPP technique it is necessary to estimate the troposphere delay, thus there are various examples of software that allow to achieve the ZTD/ZWD estimates during the positioning process. The most popular scientific software that is widely used for troposphere modelling is Bernese GNSS Software (Dach *et al.* 2015). The Bernese software is a scientific software package meeting highest quality standards for geodetic and further applications based on Global Navigation Satellite Systems (GNSS) (Dach *et al.* 2015). Bernese is the multipurpose software that is designed to wide analysis and research based on the GNSS. It is possible to estimate The Zenith Path Delays in the Bernese GNSS Software both in the Double Difference mode and using the Precise Point Positioning technique, and both solutions gives very good results. The usability and the quality of the Bernese data processing is proven by the numerous articles (Wielgosz *et al.* 2011). The advantage of this software is implementation of various troposphere models and mapping functions that could be evaluated. This allows to perform various examinations and tests.

The second scientific software package that was used in this research is recently developed and still improved G-Nut created in the Geodetic Observatory Pecny, particularly one of its components – Tefnut. G-Nut software library has been written in C++ and designed for the GNSS data processing using PPP technique. Tefnut is one of the G-Nut core library's part aimed for monitoring of the troposphere, in particular to support numerical weather forecasting, now-casting or climatology (Vaclavovic *et al.* 2013). It is the end-user application designed to estimate tropospheric path delays in postprocessing or real-time mode. The application is released under the GNU General Public Licence.

Methodology

The accuracy of results given by those two software depends mainly on the quality of the precise orbit parameters and clock corrections that are used for the estimation in the PPP mode. The highest quality IGS final products with 30 second interval were used in this research.

The resulting ZTD values and ZWD estimates were evaluated. The first step was the comparison of the total delay to the official EUREF data. This data is used by the numerous institutions over the world, therefore it was considered as a good reference.

Another source of the reference data is the Microwave Radiometer. Such device is collocated with the tested GNSS receiver in Potsdam. Wet delay, estimated as the difference between the observed total delay and hydrostatic delay computed from the a priori model, were converted into the Integrated Water Vapor (IWV) content in the troposphere. Such conversion was proposed in the 1992 by Bevis as the solution of the following formula by Bevis (Bevis *et al.* 1994):

$$IWV = \frac{ZWD}{10^{-8}\left(k_2^{'} + \frac{k_3}{T_m}\right)R_w},$$

where: *ZWD* is Zenith Wet Delay in meters, *k* are empirical coefficients, *Tm* is the mean temperature above the observation site in Kelvins, *Rw* is gas constant for wet air, equals 461.525 [$J \cdot K^{-1} \cdot kg^{-1}$]. The important thing in this equation are the *k* coefficients, that corresponds the refractive indexes of the troposphere (Bevis *et al.* 1994). In numerous investigations, much attention was paid to this topic. In the early 50' Ernest Smith and Stanley Weintraub determined the accurate coefficients based on the many previous results (Smith, Weintraub 1953). Afterwards, there were, among the others, Bevis (Bevis *et al.* 1994) and Rueger (Rueger 2002) that continued the topic of empirical estimation of the refractive indexes of the troposphere, and their results was more and more accurate. Relying on the recent research it was considered to apply for the research the coefficients provided by the Rueger (Hordyniec 2014). The k coefficient are presented in the Table 1:

Table 1. *k* coefficient values by Rueger 2002

Coefficient	Rueger values
k_1	77.695 $(K \cdot hPa^{-1})$
k_2	71.97 $(K \cdot hPa^{-1})$
k_3	3.754 $10^5(K^2 \cdot hPa^{-1})$

The k'_2 coefficient is given by the equation:

$$k_2' = k_2 - k_1 \frac{Mw}{Md},$$

where *Mw* and *Md* are molar masses for wet and dry air that equal to 18.0152 and 28.9644 [g/mol], respectively. The Mean Temperature [*Tm*] from the equation is computed from the temperature registered [*T*] on the surface by the equation of Bevis (Bevis *et al.* 1994):

$$Tm = 70.2 + 0.72 \cdot T[K].$$

The temperature was registered for the Potsdam permanent receiver site.

The ZWD converted into the IWV was compared to the measurements of the microwave radiometer. Microwave radiometers have the advantage of measuring the IWV directly, along the path to each observed satellite. Then the slant values are transformed into the water vapor content along the zenith path. However there is also the big disadvantage – excessive sensitivity to the particular weather conditions such as rain and the other precipitation. The precipitation can cause occurrence of the outliers that makes the device useless. Nonetheless, the radiometers was designed as the "superstation" dedicated to water vapor measurements, and their accuracy is proven (Niell et al. 2001).

The statistics on the comparison of the determined ZTDs to the EUREF solution and the IWV estimates to the radiometer data are included in the next section.

Results

Software and data configuration

In this research, two time series of the GNSS observations from the permanent station in Potsdam were tested. The time series covered the following periods: 03.05–13.05.2015 and 11.06–24.06.2015. Those time series are long enough to point out their main characteristics. The GNSS observation data were processed in two software Bernese v.5.2 and G-Nut/Tefnut, using the same configuration.

The receiver coordinates were determined in the PPP technique in 30 second interval. The computations were performed based on the final IGS solutions: precise orbit parameters (sp3) and clock corrections (clk) with the 30 second interval as well. The initial sigma for the coordinates equals 1 m. Minimum elevation cutoff for satellites was 10°. Based on that configuration the tropospheric path delays were determined. The a priori model for the hydrostatic part of the troposphere were Saastamoinen model (Saastamoinen 1972) with use of the standard meteorological parameters from the Global Pressure and Temperature (GPT). The slant delays were transformed using the Global Mapping Function (Boehm *et al.* 2007). Initial sigma for the ZTD were set to 0.5m. The interval for the ZTD was 300 seconds. The ZWD was converted into the IWV based on the meteorological data registered for the receiver site using Rueger (Rueger 2002) *k* coefficients.

The reference data for the ZTD – the EUREF. The IWV values for the comparison were derived by the microwave radiometer localized in Potsdam. The radiometer time series was subjected to the outliers check, deleting values exceeding 40 kg/m^2 and then the values exceeding the median + standard deviation of the time series. That operation allowed to get rid of the noise caused by the precipitation.

The ZTD comparison

The comparison of the computed ZTDs to the reference data is shown on the Figure 1 and Figure 2. One can notice the high correlation, especially in the Bernese software solution. In some parts of the G-Nut/Tefnut solution, the residuals are visibly higher, and the chart is less similar to the reference line. The Bernese is more stable in the troposphere delay estimation task.

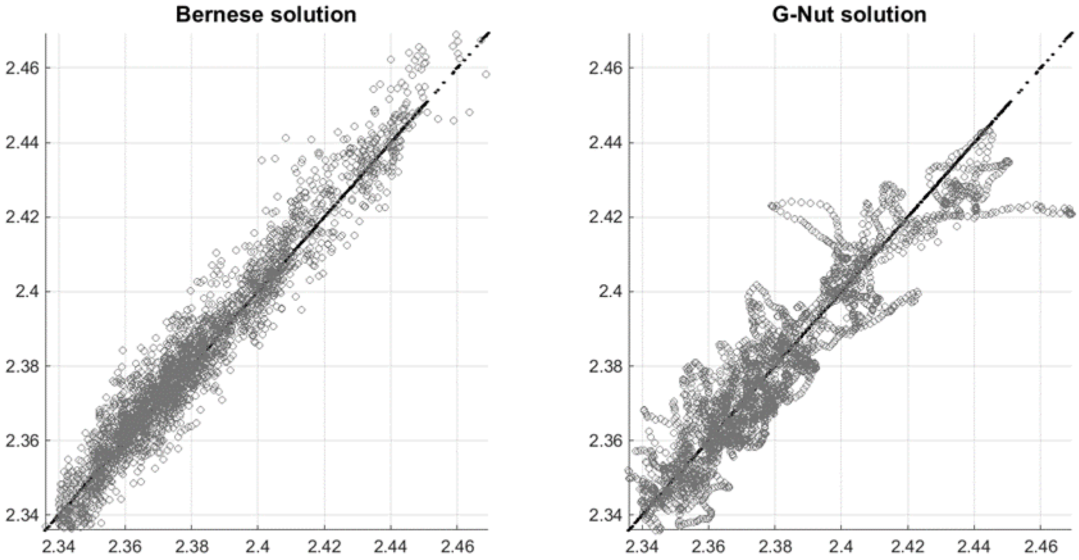

Fig. 1. Comparison of the ZTDs computed by the Bernese GNSS software (left),
G-Nut/Tefnut software (right), to the EUREF reference data; time series 03.05 – 13.05.2015

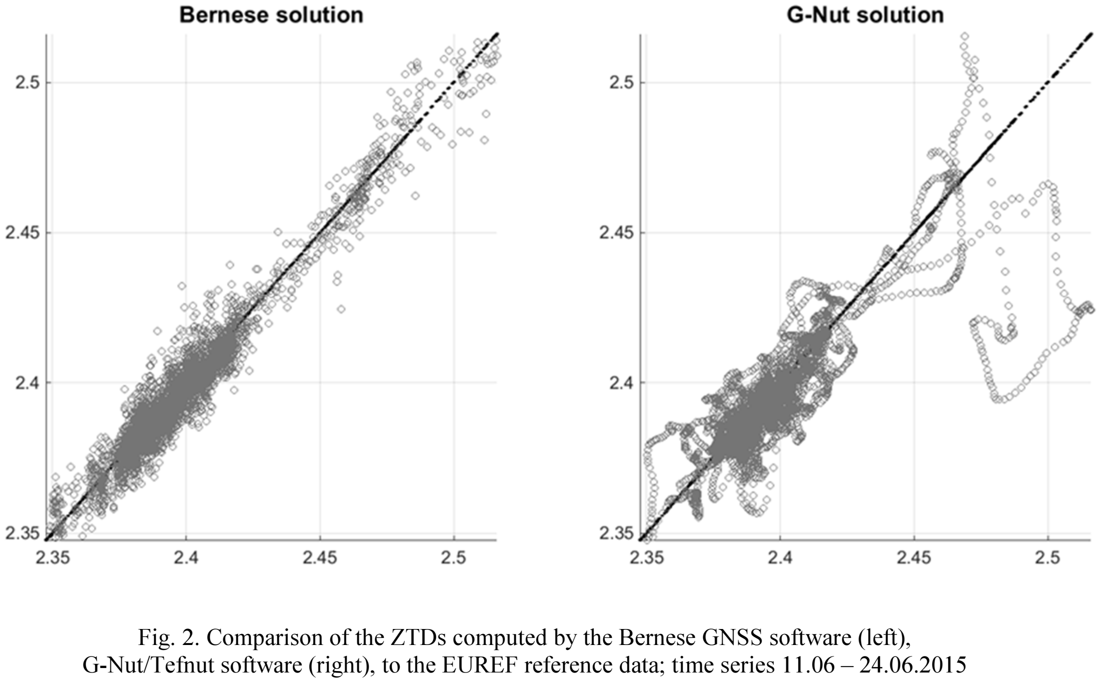

Fig. 2. Comparison of the ZTDs computed by the Bernese GNSS software (left),
G-Nut/Tefnut software (right), to the EUREF reference data; time series 11.06 – 24.06.2015

The Figure 3 and Figure 4 presents the residuals for the ZTDs – epoch to epoch difference between the reference and the computed values. On those charts there is especially visible that the results are very similar except of the few cases. The data is highly correlated which is confirmed by the statistics shown in the Table 2 and Table 3. Both software gives satisfying results with the slight advantage of the Bernese software, which has less outliers. For both software, over 90% of the residuals fits between –0.03 and +0.03.

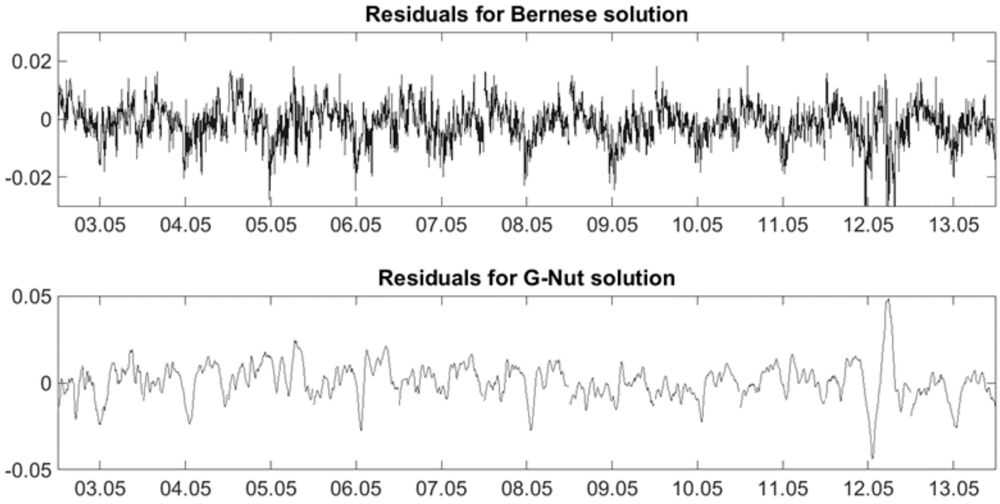

Fig. 3. Residuals between the EUREF and the Bernese GNSS software (top), and G-Nut/Tefnut software (bottom); time series 03.05 – 13.05.2015

Table 2. Statistics for the ZTD comparison); time series 03.05 – 13.05.2015

	Correlation	Mean	Median	Max	Min	Std
Bernese	0.973	-0.001	-0.001	0.018	-0.034	0.006
G-Nut/Tefnut	0.923	0.001	0.001	0.048	-0.044	0.010

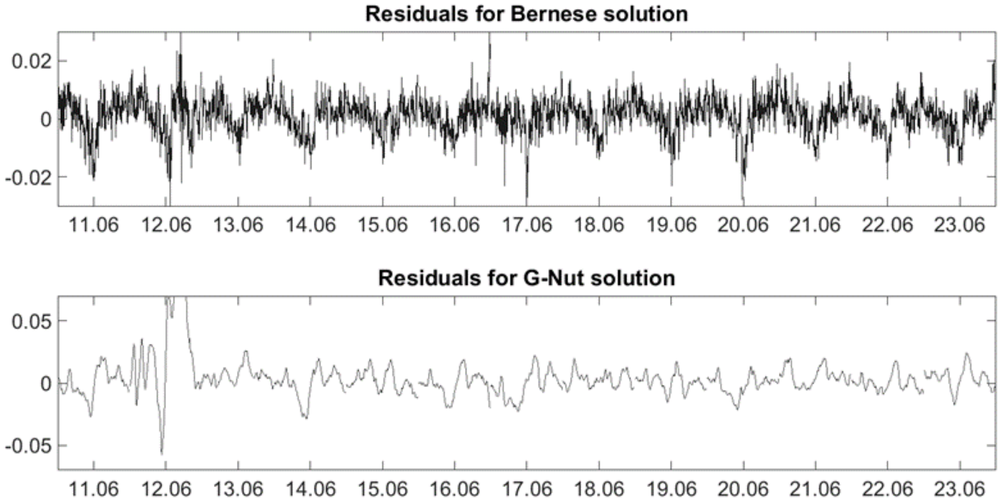

Fig. 4. Residuals between the EUREF and the Bernese GNSS software (top), and G-Nut/Tefnut software (bottom); time series 11.06 – 24.06.2015

Table 3. Statistics for the ZTD comparison; time series 11.06 – 24.06.2015

	Correlation	Mean	Median	Max	Min	Std
Bernese	0.973	0.001	0.002	0.033	–0.036	0.006
G-Nut/Tefnut	0.822	0.003	0.002	0.093	–0.058	0.015

The IWV comparison

For the IWV compared to the radiometer data, the results are slightly worse. This is visible on the Figure 5 and Figure 6 and the Table 4 and Table 5 containing the statistics. The correlation is lower by about 5%, and the residuals are relatively higher. It may be caused by the computation methods imperfection (the tropospheric refraction indexes, ZWD estimation) or by the unstable work of the microwave radiometer during the rainfall as well.

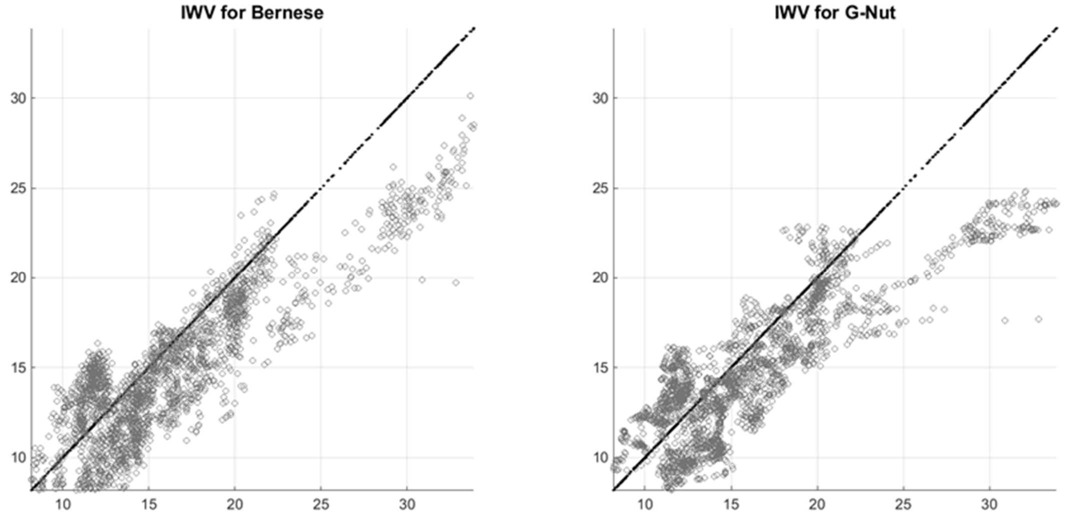

Fig. 5. Comparison of the IWVs computed by the Bernese GNSS software (left), G-Nut/Tefnut software (right), to the microwave radiometer reference data; time series 03.05 – 13.05.2015

Table 4. Statistics for the IWV comparison; time series 11.06 – 24.06.2015

	Correlation	Mean	Median	Max	Min	Std
Bernese	0.870	1.450	1.338	13.086	–4.410	2.550
G-Nut/Tefnut	0.848	1.348	1.191	15.128	–4.752	2.771

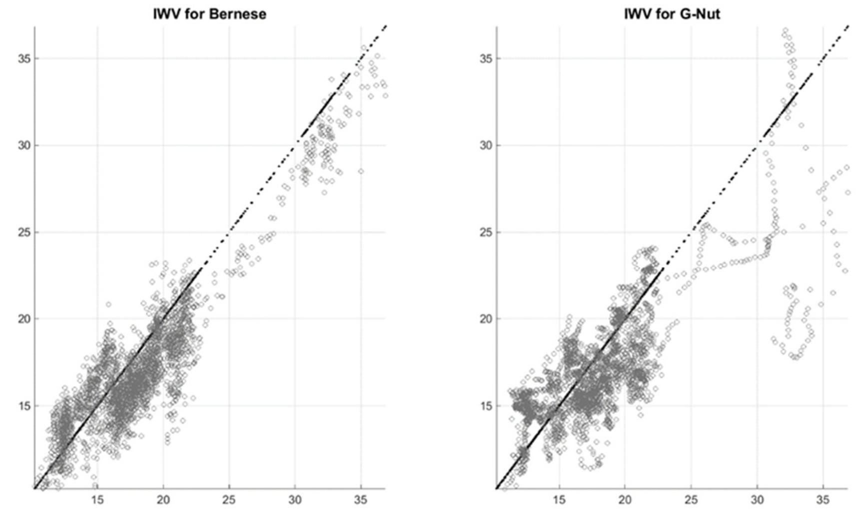

Fig. 6. Comparison of the IWVs computed by the Bernese GNSS software (left), G-Nut/Tefnut software (right), to the microwave radiometer reference data; time 11.06 – 24.06.2015

Table 5. Statistics for the IWV comparison; time series 11.06 – 24.06.2015

	Correlation	Mean	Median	Max	Min	Std
Bernese	0.910	0.926	1.088	7.465	–4.987	1.843
G-Nut/Tefnut	0.777	0.888	0.839	15.331	–8.068	2.796

Conclusions

The Bernese GNSS software gives slightly better results and has better performance than the G-Nut/ Tefnut software. Although, both of the packages give satisfying results after deleting few outliers.

The performance in the ZTD determination with use of the tested software is much better than the ZWD estimation itself. The ZWD values transformed into the IWVs has worse correlation to the reference radiometer data than the ZTDs compared to the official EUREF solution. However it could be connected with the radiometer hardware errors caused by the precipitation.

The research has proven the utility and accuracy of the tropospheric parameters derived by the tested software.

The accuracy of the test results allow to implement such operations in the meteorology and weather monitoring, as well as to the precise positioning purposes.

Important thing is that the Bernese GNSS software is more complex and multipurpose toolkit, while the G-Nut/Tefnut software is more user-friendly, because the operator has to input only the important parameters and the GNSS observation files in the RINEX format. It is easier to use Tefnut if the purpose is only the troposphere parameters estimation.

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