



Troposphere slant total delays of satellite signal from GNSS data and NWP model ray-tracing, their comparison and validation

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Abstract:

Permanent GNSS observations provide excellent data to derive the state of neutral atmosphere. The GNSS&METEO research group at Wrocław University of Environmental and Life Sciences (WUELS) in Poland participates in the COST ES1206 Action: “Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate” (GNSS4SWEK) and E-GVAP initiative as near real-time and real-time GNSS processing centre for troposphere research. The knowledge of spatial and temporal variation of troposphere cannot be obtained using the zenith troposphere delay only. GNSS signal delay estimation in direction to satellites makes possible the 4-dimensional modelling of troposphere, when multipath, residual antenna model uncertainty and noise is isolated and removed. Paper presents methodology and results of GNSS signal slant total delay estimation at WUELS using the Precise Point Positioning (PPP) and ray-tracing through the numerical weather prediction (NWP) model approaches. It presents also their comparison as well as an their quality assessment.

INTRODUCTION

The GNSS signal as it propagates from satellite to the receiver is subjected to the phase delay due to the presence of atmosphere. The GNSS signal troposphere phase delay is linked with the density of all gaseous constituents, including one of the most important - water vapour. Hence, the remote sensing of water vapour content in the troposphere with high temporal and spatial resolution applying inverse modelling of GNSS signal is feasible. Even though this technique is quite mature (e.g. Bevis et al., 1992; Rocken et al., 1993) the establishment of dense GNSS Continuously Operating Receiver Stations (CORS) and launching of new satellites constellations re-invented the ground –based GNSS observations as an important meteorological data source, bringing new opportunities and challenges. One of the challenges is the development of effective methodology to use new GNSS systems for estimation of troposphere parameters. Another challenge linked with GNSS meteorology processing, still unresolved word-wide, is estimation of direct satellite to receiver GNSS signal Slant Total Delay (STD), currently, only Zenith Troposphere Delay (ZTD) estimates are provided. Hence, important horizontal and vertical anisotropy of the troposphere around GNSS receiver is not resolved. Also, the time resolution and differencing technique of retrieved GNSS products, have not been established and varies between weekly (CODE), daily (BKG), hourly (E-GVAP) to real-time (SOUINNET), and between Double Difference (DD) (CODE) and Precise Point Positioning (SOUINNET). Therefore, the optimal GNSS products resolution for weather forecasting has not been thoroughly investigated. The GNSS processing side development should be matched by the investigations into the NWP model domain. However, the assimilations of GNSS ZTD observations in the NWP models performed by top meteorological institutes across Europe and USA have not been reproduced in Poland. Therefore the basic NRT ZTD should also be tested within the scope of this research, it is already provided by processing centre at the Wrocław University of Environmental and Life Sciences (WUELS). However, the main future objective of this research is the assimilation of multi-GNSS Slant Total Delays, with considerations of error budget and target time and space resolution.

RAY-TRACING THROUGH ALLADIN NWP MODEL

In the ray-tracing code, we assume the ray-path does not leave the plane of constant azimuth at given elevation angle to the satellite. The horizontal components of the delay are thus neglected due to their minor contribution, but significant computational load, making the ray propagation two-dimensional. The real ray-path is approximated by finite number of linear ray-pieces between radii with predefined spacing on WGS84 ellipsoid using Euler formula

$$R = \left(\frac{\cos^2 A}{M} + \frac{\sin^2 A}{N} \right)^{-1}$$

where A is ray-path azimuth, M and N are radii of curvature along meridian and prime vertical, respectively.

We follow height-dependent increments (Tab. 1) given by Rocken (2001) which require meteorological parameters to be vertically interpolated in order to obtain finer resolution. Both, atmospheric (P) and water vapor partial pressure (e) are interpolated exponentially from two nearest layers, while the temperature (T) uses constant lapse rate of 5°C/km. Horizontally, we find four nearest nodes for each ray to perform weighted mean interpolation, where weighting function equals to inverse distance with the power parameter set to two.

$$P_i = \frac{\sum p_i w_i}{\sum w_i}, \quad w_i = \frac{1}{(dx^2 + dy^2)}$$

The tropospheric delay is a function of refractive index which uses „best available” empirical coefficients of Rueger (2002)

$$N = (n - 1) \times 10^{-6}$$

$$N = k_1 \frac{P - e}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

International Standard Atmosphere (ISA76) is adopted above range of numerical weather prediction model to provide supplementary meteorological data up to 86 km.

Geometric elements of the ray-tracing system that need to be calculated for each ray coordinates are the geocentric angle ϕ which can be found based on spherical trigonometry and the global elevation angle θ

$$\theta_{i+1} = \arccos \left(\frac{R_i n_i \cos \theta_i}{R_{i+1} n_{i+1}} \right)$$

The electromagnetic delay is then calculated for given chord length (s) using mean refractive index between two consecutive rays yielding the total delay.

$$\tau_i = \sum s_i (n_i - 1) \times 10^6$$

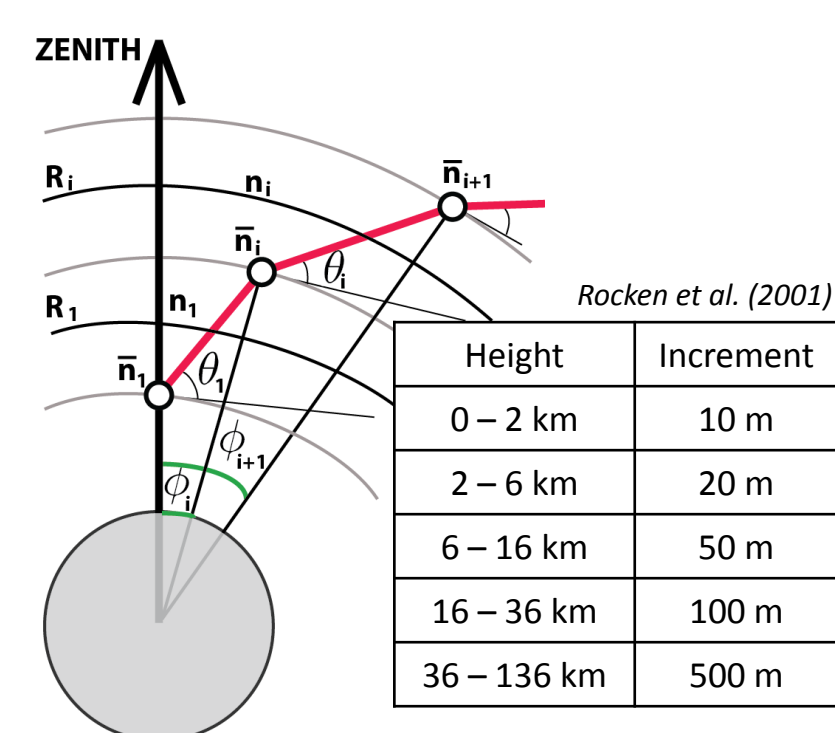


Fig. 1. Illustration of linear ray-tracing

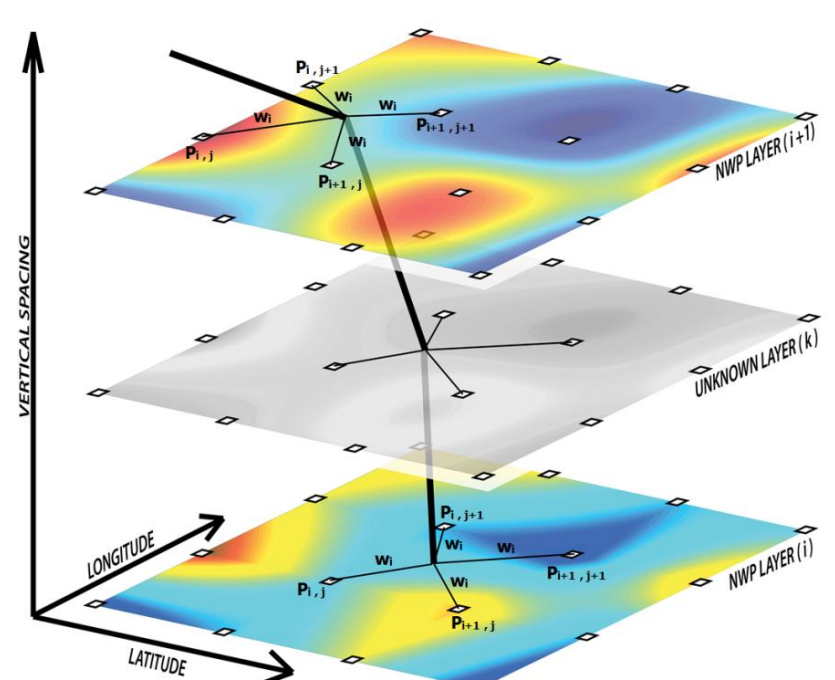


Fig. 2. Interpolation in NWP model domain

GNSS ESTIMATION

To test the methodology of slant troposphere delay estimation at WUELS, we used the COST ES1206 GNSS4SWEK benchmark campaign data for 2013, 125-180 day. The GOPE, KIBG, LDB0, LDB2, POTM, POTS, SAAL, WTZR, WTZS, WTZZ stations were selected (figure 3), where LDB0, LDB2 (Lindenberg, Germany) and POTM, POTS (Potsdam, Germany) as well as WTZR, WTZS, WTZZ (Bad Koetzting, Germany) are co-located, making three groups of stations for internal comparison.

Tab. 1. Summary of GNSS data processing strategy at WUELS

Strategy	Software	GNSS	Elevation cut-off	Mapping function	Products	ZTD / gradients interval
PPP	Bernese 5.2	GPS	3 °	VMF1/ Chen & Herring	CODE final	2.5 min/1h

Processing of GNSS data was done using Bernese GNSS Software 5.2 in PPP mode. Zenith troposphere delays estimated each 2.5 minute were relatively constrained on the level of 1 mm over last 15 minutes and the horizontal ZTD gradients (estimated in 1h interval) were constrained on 0.1 mm over last 2 hours (table 1). Calculation of slant delays was done using the formula (Dach et al., 2015) and a priori ZHD value as well as mapping functions coefficients from VMF1 model:

$$\tau_{t,a,z} = ZHD_{apr}(t) * mf_{Dry}(z) + ZWD_{Est}(t) * mf_{Wet}(z) + \frac{\partial mf_{Grad}}{\partial z} (G_N \cos(a) + G_E \sin(a))$$

$$STD = \tau_{t,a,z} + \epsilon \quad \epsilon = MP + APC_{res} + noise$$

Resultant slant delay (STD) is obtained from τ and post-fit residuals ϵ from the PPP least squares estimation. The post-fit residuals include the multipath effect (MP), residual antenna phase centre uncertainty (APC) and remaining noise. Figure 4a presents example map of averaged residuals from 55 days in 2013 with corresponding map of standard deviation (Fig. 4 b).

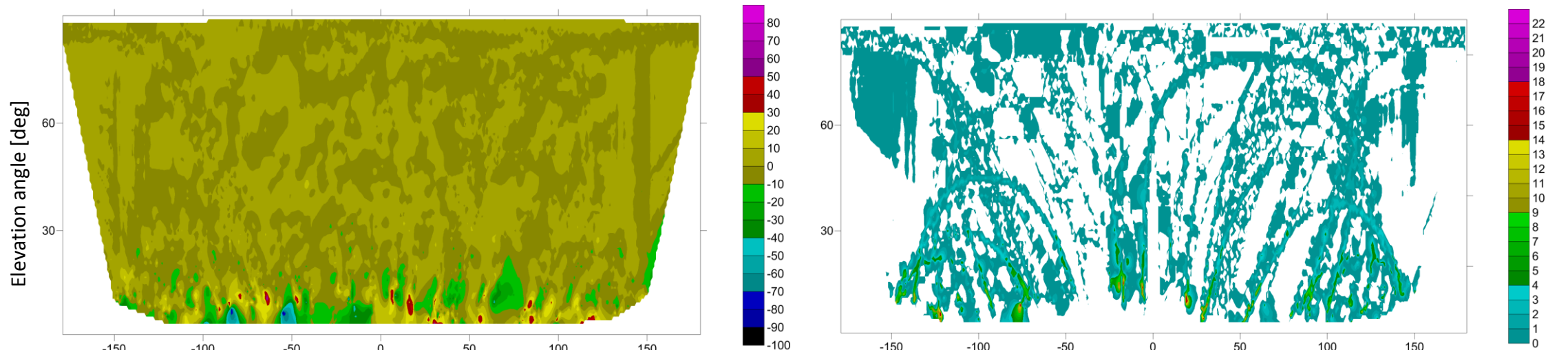


Fig. 4a, 4b. Map of bias (a) and standard deviation (b) of PPP post-fit residuals on station GOPE period 125-180 DOY of 2013, interval 2.5 min

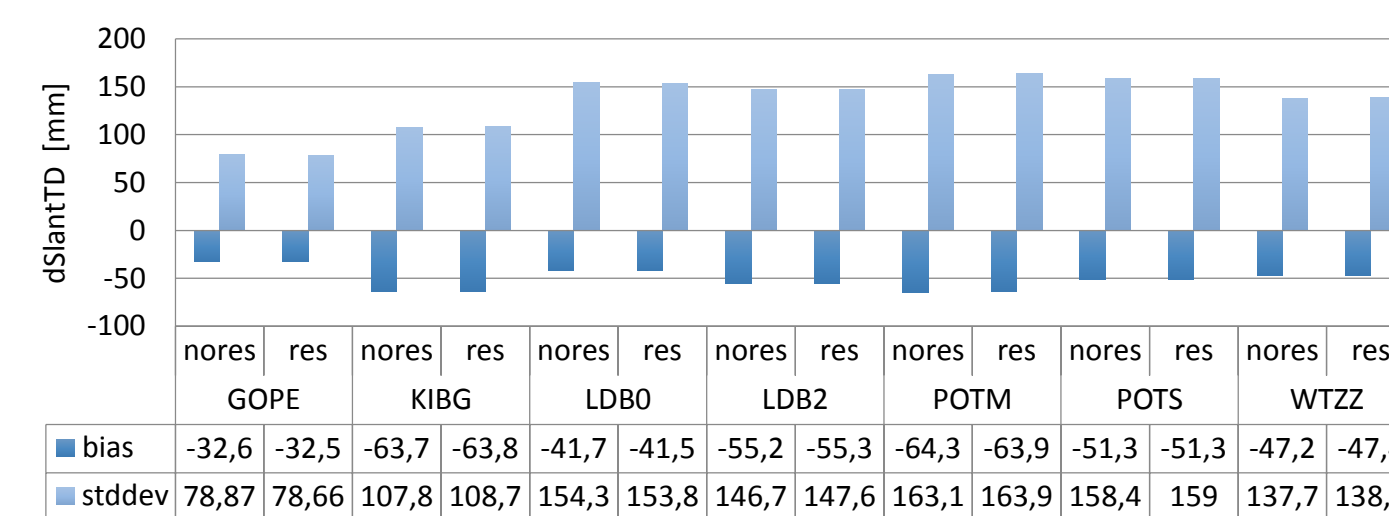


Fig. 5. Statistics of discrepancies between WUELS slants total delays from PPP and from ray-tracing through ALLADIN-CZ model

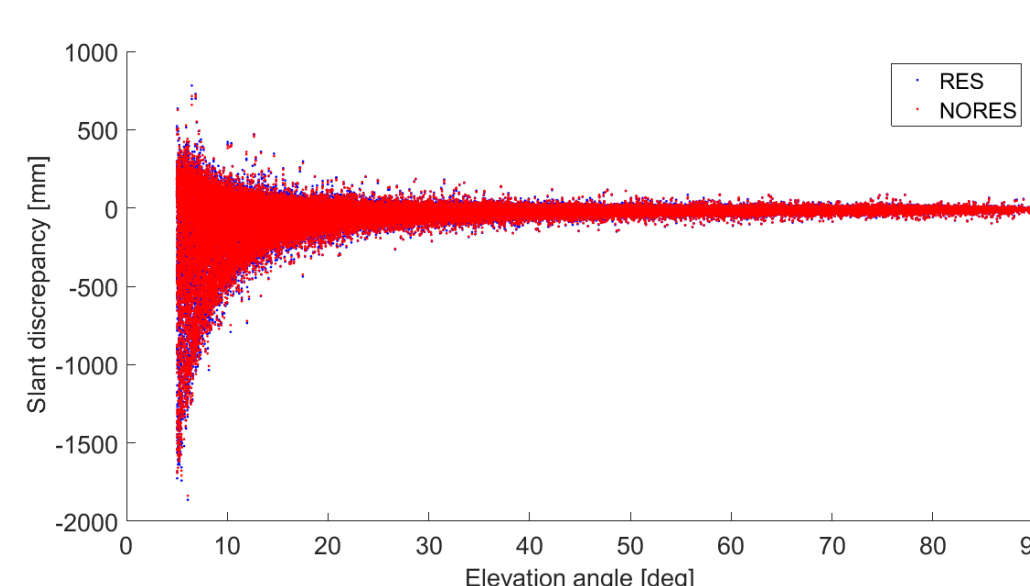


Fig. 6. Results of slant total delay comparison (PPP vs ray-tracing), 7 stations, 55 days, interval 1h

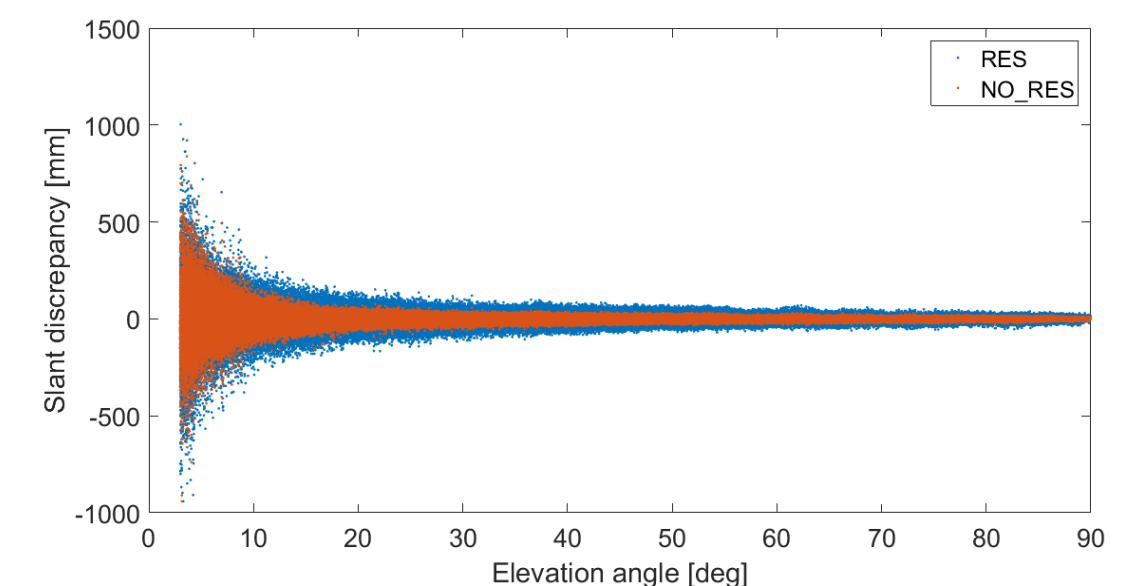


Fig. 7. Results of slant total delay comparison (PPP WUELS vs PPP TU Wien), 7 stations, 55 days, interval 2.5min

SUMMARY

Presented results prove that the strategy of slant total delay estimation at WUELS is correct. Comparison with external GNSS derived results (TUW) as well as with ray-tracing results revealed, that slant delays obtained at WUELS agree with GNSS and ray-tracing data on the same level. The future work covers the post-fit residual analysis towards extraction of multipath signal, and application of slants to the numerical weather prediction systems for improving the weather forecasts.

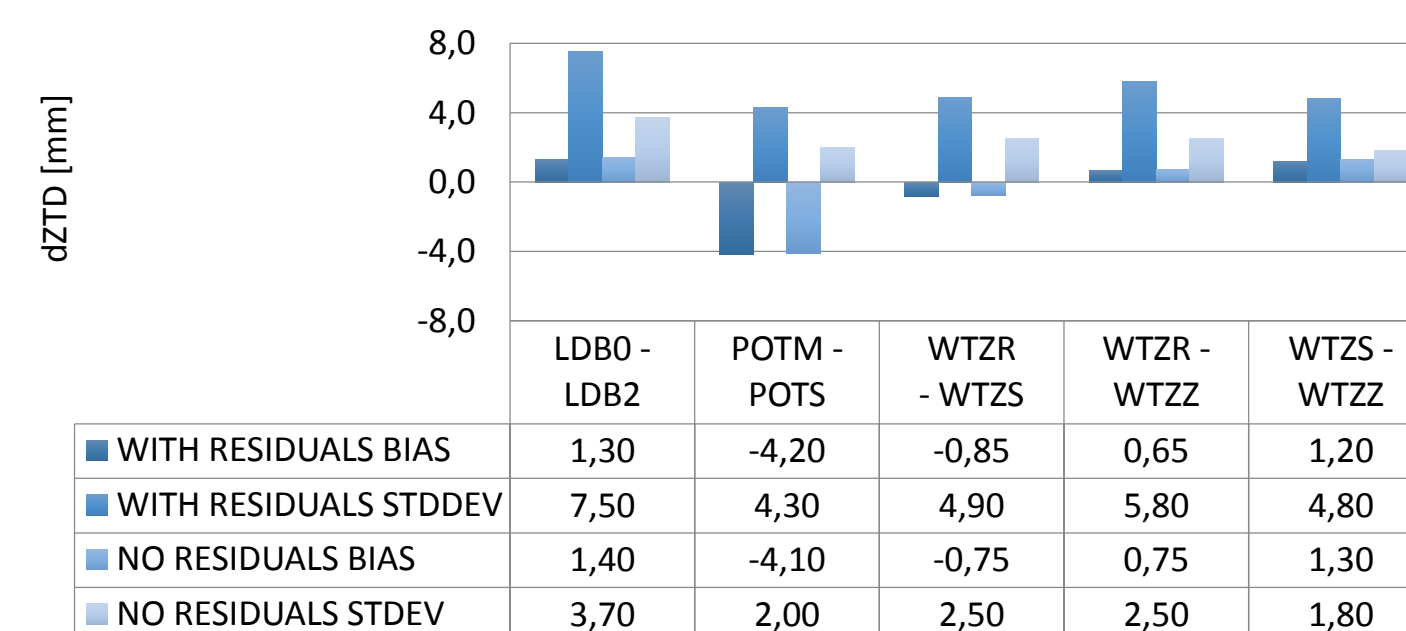


Fig. 8. Statistics of discrepancies between ZTDs obtained from WUELS PPP slants for close-neighbour stations, 55 days, interval 2.5 min

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