

WROCŁAW UNIVERSITY **OF ENVIRONMENTAL** AND LIFE SCIENCES

International Association of Geodesy (IAG), Commission 4 Symposium

POSITIONING AND APPLICATIONS









Direct spatial interpolation of GNSS troposphere products

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Introduction

Spatial interpolation of GNSS derived troposphere parameters is required when zenith total delay or its gradients are required for positioning augmentation or transfer onto user position in meteorology applications. To interpolate the troposphere parameters (ZTD, PWV or temperature or relative humidity) the weighted average method is commonly used (Zheng et al., 2005; Igondova and Cibulka, 2010; Wilgan et al., 2014 and literature cited there). Here is presented the ZTD and its horizontal gradients interpolation method based on weighted average method.

Temperature, pressure and relative humidity transfer onto user height

If the meteorological parameters (P - pressure, t – temperature in Celsius, RH – relative humidity) are given for the mean sea level (MSL), the parameters at the station's height H may be calculated using formulas (Klein Baltink et al., 1999):

 $P = P_0 (1 - 2.26 * 10^{-5} H)^{5.225}$ $t = t_0 - 0.0065 * H$ $RH = RH_0 * exp(-6.396 * 10^{-4} * H)$ $e = \frac{RH}{100} * exp(-37.2465 + 0.213166 * (t + 273.15) - 0.000256808 * (t + 273.15)^2)$

ZTD transfer to the rover position

Interpolation tests

The test procedure was performed in Polish regional network (ASG-EUPOS + SmartNet) (Fig. 2). All stations (268) were used in the test, but the stations located outside the circle with a given radius (r) were downweighted to 0. As the true ZTD for comparison, the time-series of ZTDs were selected and excluded from interpolation for stations (GDA1/GDAN, JLGR, KLUC, NWT1, STAR, WROC, ZYWI), where GDA1/GDAN, STAR, KLUC and WROC are located in lowlands and the JLGR, NWT1, ZYWI are in the mountainous area. The radius (r) from interpolated stations was increased from 50km to 200km, the interpolated ZTDs were calculated with the statistics of ZTD differences with respect to true interpolated ZTD time-series. Test was performed with hourly resolution on the data calculated during three weeks with different ionosphere conditions: 24-30.10.2014 (solar

maximum activity); 14-20.03.2015 (geomagnetic Fig.2. Map of stations selected for interpolation tests from storm); 12-18.09.2015 (solar quiet activity). regional Polish network (black filled dots)

ZTD parameter estimated at the GNSS station may be transferred onto other station, if it will be reduced according to the height or pressure difference between stations. Here we use the Saastamoinen (1973) model to calculate the reduction of ZTD according to the pressure and temperature difference:

$$ZHD = 0.0022767 * \frac{P}{1 - 0.00266 * \cos(2\phi) - 0.28 * 10^{-6} * h}$$
$$ZWD = 0.0022767 * \left(P * \left(\frac{1225}{t + 273.15}\right) + 0.05\right) * e$$

ZTD = ZHD + ZWD $dZTD_{ij} = ZTD_i - ZTD_j$ $ZTD_i = ZTD_i^{REF} + dZTD_{ij}$

ZTD from Saastamoinen formulae for base (j) and rover (i) stations allows to calculate the model difference (dZTD) of ZTD between base and rover stations and finally the ZTD at the rover position using the ZTD^{REF} estimated at the reference station from GNSS observations.

ZTD interpolation

Zenith total delay interpolation have been done using the weighted average method on ZTDs transferred from reference stations located within the radius (r) around rover position:

$$ZTD_{interpolated} = \frac{\sum_{i=1}^{n} (ZTD_i * w_i)}{\sum_{i=1}^{n} w_i}$$

The weight functions (W1 - W4) tested during the study were:

$$W1(L, m_{ZTD}, \Delta H)_i = \begin{cases} 5.681 * exp\left(-\left(\frac{L+1382}{1051}\right)^2\right) * (\Delta H * m_{ZTD})^{-1} \\ 0, if \ L > r \end{cases}$$

 $W2(L, m_{ZTD}, \Delta H)_i = \begin{cases} \frac{L^{-2}}{m_{ZTD} * \Delta H} \\ 0, if \ L > r \end{cases}$ $W3(L, m_{ZTD}, \Delta H)_i = \Big\{ \overline{m_{ZTD} * \Delta H} \Big\}$ (0, if L > r)

 $W4(L, m_{ZTD}, \Delta H)_i = \Big\{ \overline{m_{ZTD} * \Delta H} \Big\}$

The first tested weight function was related to the Gaussian model of relation between ZTD correlation coefficients and distance between stations (Fig. 1) and the inverse of ZTD mean error and height difference between stations. L [km] is the distance between stations, and $\ensuremath{\mathsf{m}_{\text{ZTD}}}$ is the ZTD mean formal error at reference station calculated using the Bernese GNSS Software v. 5.2.

The second to fourth weight functions were the inverse of: distance from reference station to the user position (gained by the 2 to 4 power) and the inverse of ZTD mean error and height difference between stations.



(0, if L > r)

Troposphere impact on GNSS signal is correlated on two stations and the correlation level is decreasing with the increase of a distance between them. To determine the dependence of two













aph of interpolated ZTD gradient (E) time series for station STAF

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Fig. 3 Example time series of transferred and interpolated ZTDs (left) and N (middle), E (right) horizontal gradients for station STAR during 14-20.03.2015 period



Fig. 1. Correlation coefficients of ZTD time series calculated from ASG-EUPOS hourly data (125 stations, 120 days of 2013)

ZTD time-series correlation coefficient with the distance between stations, estimation of Pearson correlation coefficient was performed in Matlab on ZTD time series from ASG-EUPOS network in Poland with 1h interval over 120 days of 2013. Correlation coefficient was calculated using sliding time window with 1h step of movement and window length of 24, 48, 72, 96, 144 and 216 hours.

Total number of calculated correlation coefficient samples was 2500. All correlation coefficients were plotted against distance between stations (Fig. 1). Shape of obtained point cloud (Fig. 1) represents Gaussian type. The trend line was then fitted into data, which resulted with the estimation of Gaussian curve coefficients (a, b, c).

ZTD horizontal gradients interpolation

Interpolation of horizontal ZTD gradients was performed using the weighted average method as in the ZTD tests, but without calculating the model differences. To test the dependence of different weight functions on interpolation results, it was decided to use the functions related to exponential of distance between stations (W1), inverse of distance (W2), inverse of height difference (W3) and inverse of mean gradient error (W4).

 $W1(L)_{i} = \begin{cases} 5.681 * exp\left(-\left(\frac{L+1382}{1051}\right)^{2}\right) \\ 0, if \ L > r \end{cases}$ $W2(L)_{i} = \begin{cases} L^{-1} \\ 0, if \ L > r \end{cases}$ $W3(\Delta H)_{i} = \begin{cases} \Delta H^{-1} \\ 0, if \ L > r \end{cases}$ $W4(m_{grad})_{i} = \begin{cases} m_{grad}^{-1} \\ 0, if \ L > r \end{cases}$

	VVI VV2 VV3 VV4	VVI VV2 VV3 VV4	
Mean [mm] Stddev [mm] Mean [mm] Stddev [mm]	Mean [mm]	Stddev [mm]	

Fig. 4 Plots of ZTD (left) and N (middle), E (right) gradient components interpolation statistics (three test weeks)

Summary

Figure 4 presents the summary statistics for all ZTD interpolation tests. It is visible there, that interpolation performed on the closest stations gives the best results in terms of mean difference and standard deviation of differences. The first weight function (W1 - Gaussian) produces the highest standard deviation of 9.16 mm, minimum standard deviation was recorded (7.45 mm) for the fourth weight function (W4). Minimal mean ZTD difference (-0.506 mm) was obtained with the fourth weight function (W4). The first weight function (W1) gives the biggest mean ZTD difference (-1.068 mm).

Tests of spatial ZTD interpolation prove, that it is possible to interpolate the ZTDs with the systematic error (bias) from 0.506 to 1.068 mm and 7.451 to 9.163 mm (standard deviation) respectively. Accuracy of interpolated ZTD on the level of 1 cm is sufficient for RTK or PPP positioning augmentation.

Gradient interpolation test revealed, that interpolation performed on the closest stations (L < 50 km) gives the best results in terms of mean difference and standard deviation of differences. The first weight function (W1 -Gaussian) produces the lowest mean difference in north gradient component of -0.064 mm with standard deviation of 0.217 mm, minimum standard deviation was recorded (0.202 mm) for the second weight function (W2 – inverse of distance). For the east component the minimum difference (0.01 mm) is obtained for fourth function (W4 – inverse of gradient error) with standard deviation of 0.236 mm. Minimum standard deviation of differences (0.208 mm) was obtained with the second weight function (W2 – inverse of distance).

Acknowledgement

The research has been supported with ESA project "Higher Order Ionospheric modeling campaigns for precise GNSS" applications - HORION" (Contract No. 4000112665/14/NL/Cbi).

This work has been supported by the Wroclaw Center of Networking and Supercomputing (http://www.wcss.wroc.pl): computational grant using Matlab Software License No: 101979