Assessment of Tropospheric Zenith Path Delay Time Series at the Romanian EUREF Permanent GPS Stations

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Abstract: *This paper investigates the tropospheric zenith path delay (ZPD) time series derived from the Global Data Assimilation System (GDAS) numerical weather model (NWM) for five EUREF permanent GNSS stations operated by the Romanian National Agency for Cadastre and Land Registration. The GDAS NWM extracted meteorological data were used to compute the ZPDs. The total ZPD agrees the EUREF ZPD product with RMS of 2.5 cm and is subject to some mean biases and discontinuities of up to 1.8 cm. The precision of GDAS NWM ZPD should be sufficient for all GNSS navigation solutions.*

Keywords: *EUREF, GNSS, GDAS, tropospheric zenith delay, numerical weather model.*

1. Introduction

The lower part of the atmosphere consists of three main layers: the troposphere (from sea level to a height of about 12 km), the tropopause (a thin boundary layer between 12 and 16 km) and the stratosphere (from 16 to 50 km). As far as GNSS applications are concerned, the troposphere is a neutral part of the atmosphere, which causes delay of the transmitted GNSS signals travelling through it. This effect is normally referred to as the tropospheric delay. Because of tropospheric delay the distance determined from the satellite signal between the user's receiver and satellite is longer than the geometrical distance resulted in case the signal would travel through vacuum.

Mathematically, the tropospheric delay along the signal path (ZPD) is determined by integration of the refractivity along the signal path

$$ZPD = 10^{-6} \int N ds \tag{1}$$

The refractivity can be determined using the following equation given by Thayer (1974):

$$N = k_1 \left(\frac{P_d}{T} \right) Z_d^{-1} + \left(k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \right) Z_w^{-1} \tag{2}$$

where k_1, k_2, k_3 are the refraction coefficients, P_d is the partial pressure of the dry air in hPa (mbar), T is the temperature in degrees of Kelvin, and e is the partial pressure of water vapor in hPa (mbar). Z_d and Z_w are the compressibility factors for dry air and water vapor respectively, and they account for the deviation of the gasses from an ideal gas. The first term in the above formula is called dry refractivity, since it depends only on the dry constituents, while the term in the last bracket is called wet refractivity.

Several sets of values for the empirical k-coefficients have been determined and there has been some dispute over which values are the best (Mendes, 1999). Bevis et al. (1994) provided a new set of the k-values based on a re-analysis of older experimentally determined coefficients (Table 1).

Davis et al. (1985) introduced another expression for the refractivity:

$$N = k_1 R_d \rho + \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2} \right) Z_w^{-1} \quad (3)$$

where the new coefficient is given as $k_2' = k_2 - k_1 M_w / M_d$. M_w and M_d are the molar mass of water vapor and dry air, respectively. The first term in Eq.(3), albeit it is *hydrostatic refractivity*, includes the effect of water vapor via the total density ρ. The last term is still based on the water vapor and is thus still called *wet refractivity*, although the term non-hydrostatic refractivity is also found in the literature.

Table 1 Refractivity coefficients from Bevis et al. (1994)

k_1 $[K / hPa]$	k_2 $[K / hPa]$	k_3 $[K^2 / hPa]$	k_2' $[K / hPa]$
77.60 ± 0.05	70.40 ± 2.2	373900 ± 12000	22.1 ± 2.2

Correspondingly to the hydrostatic and wet refractivity, the zenith path delay (ZPD) can now be divided into two parts:

$$ZPD = 10^{-6} \int N_h ds + 10^{-6} \int N_w ds = ZHD + ZWD \quad (4)$$

as a summation of the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD).

The hydrostatic part of the delay comprises approximately 90% of the total tropospheric delay, with a magnitude of about 2.3 m in the zenith direction (Spilker, 1996). It is possible to predict ZHD to better than 1 mm using ground pressure only accurate to 0.3 mbar. The wet component is smaller ranging from a few mm in dry artic areas or in deserts to 40 cm in tropical regions (Spilker, 1996). Unlike the hydrostatic component, the wet component is less predictable even with the surface measurements due to wide fluctuation of the water vapor in the atmosphere.

In GNSS positioning tropospheric effect can either be estimated together with the other parameters within GNSS data processing software packages (Bernese, Gipsy, Gambit) or computed by means of global tropospheric delay models based on climate data (Saastamoinen, Hopfield, MOPS). Some of the models are explicitly dependent on the surface meteorological data and others are site dependent (the latitude and the height are required).

The total tropospheric delay for a satellite signal at an elevation angle (E) can be computed from the delay in the zenith direction multiplied by a mapping function, $m(E)$, one for each component. Thus the slant propagation delay (SPD) can be written as:

$$SPD(E) = m_h(E) \cdot ZHD + m_w(E) \cdot ZWD \quad (5)$$

where $m_h(E)$ and $m_w(E)$ are the hydrostatic and wet mapping functions. The mapping factor is about 4 for 15° elevation angle, about 6 for 10° elevation, and about 10 for 5° elevation angle.

Several mapping functions have been proposed during the last decades such as Ifadis (1986), Herring (1992), Niell (1996). These mapping functions are adopted in the form of the continued fraction in $1/\sin E$ as given in Eq.(6) and determined for both hydrostatic and wet component.

The number of terms determines the accuracy of the function. Niell (1996) found that three terms are sufficient to hold the error to less than 1 mm for elevations down to 3°. However, the mapping functions differ in parameterization of the coefficients a, b and c.

$$M(E) = \frac{1 + \cfrac{a}{1 + \cfrac{b}{1 + c}}}{\sin E + \cfrac{a}{\sin E + \cfrac{b}{\sin E + c}}} \qquad (6)$$

More recently, some enhanced mapping functions have been introduced. Mapping functions like the Isobaric Mapping Function IMF (Niell, 2000), Vienna Mapping Functions VMF1 (Boehm, 2004) or Global Mapping Function GMF (Boehm et al., 2006) are based on data from numerical weather model (NWM) such as the ECMWF (European Centre for Medium-Range Weather Forecasts) model. Although all three NWM-based mapping functions use output of the ECMWF model, they differ in the easiness of parameter computation and the amount of data used from NWM.

The main purpose of this study is to compare the zenith path delays derived from numerical weather model (NWM ZPDs) obtained at the Romanian EUREF permanent GNSS stations to the EUREF ZPD product released with a latency of approximately 4 weeks. The files can be downloaded from the EUREF product directory at BKG[1] (Bundesamt für Kartographie und Geodäsie) since GPS week 1110 (April 15th, 2001). For the comparison a period of two years was used, i.e., February 2006 – February 2008.

Table 2 Approximate positions (latitude, longitude and ellipsoidal height) of the Romanian EUREF GNSS stations used for comparisons, during February 2006 – February 2008

Station	Name	ϕ	λ	h (m)
BACA	Bacau	46°34′	26°55′	219.2
BAIA	Baia Mare	47°39′	23°33′	271.0
BUCU	Bucuresti	46°34′	26°55′	219.2
COST	Constanta	44°10′	28°39′	46.1
DEVA	Deva	45°53′	22°55′	246.7

2. GNSS network in Romanian

Continuous development and improvement of satellite-based technologies and services in the last decades introduced the necessity for a new approach to maintain and develop the Romanian geodetic network. After 1990, the satellite-based techniques came to Romania and were included in different project applications that concerned geodesy, surveying, cadastre or geographical information systems. Among various projects, the most important is the one conducted by the Romanian National Agency for Cadastre and Land Registration (NACLR) aiming to establish, control, monitor and maintain a national network of GNSS permanent stations (RN-SGP).

The first step was done in 1999; the Faculty of Geodesy, at Bucharest Technical University of Civil Engineering established the first GPS permanent station with the help of the Bundesamt für Kartographie und Geodäsie from Frankfurt a.M., Germany. The station was first included in the European permanent network and later became also a member of the global International GNSS Service (IGS) network.

Between 2001-2003, five new permanent GPS/GNSS stations were installed in municipalities of Suceava, Cluj, Timişoara, Sibiu and Brăila and included in the national network along with the station from Bucharest. After 2003, the development process continued with

[1] ftp://igs.bkg.bund.de/

installation more GPS/GNSS receivers and including more permanent stations distributed homogenously over the Romania's territory (which has an area of approximately 237000 km^2). Nowadays, there are more than 30 GPS/GNSS permanent stations available and the development process continues till a density of 50 km is achieved[2].

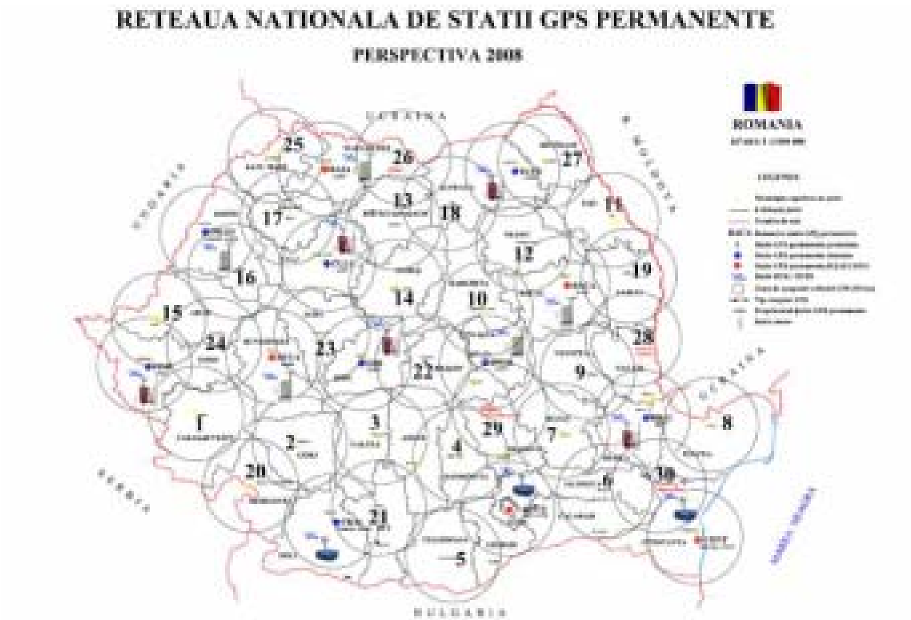

Fig 1. Perspective vision of the Romanian GNSS permanent station national network (RN-SGP) given by the Monitor and Control Centre (CMC) of the Romanian National Agency for Cadastre and Land Registration (NACLR) for the year 2008

This effort done by the Romanian authorities did not remain without international answer. Consequently, the EUREF organization decided to include four of the Romanian GNSS stations (BACA, BAIA, COST, DEVA) in its EUREF permanent network (EPN, established in 1995), starting from February 12th, 2006 (EUREF mail no. 2697[3]) in addition to the already included BUCU station. Moreover, discussions have been started on the creation of an EPN Local Analysis Centre located at Faculty of Geodesy in Bucharest.

3. Global Data Assimilation System model

The global GDAS numeric weather model used for this study is produced by the National Centers for Environmental Prediction (NCEP) of the US National Oceanic and Atmospheric Administration (NOAA). The system produces data with a temporal resolution of 6 hours with 3 h forecast cycles. This means that the final analysis takes place 4 times per day, i.e., at 00, 06, 12 and 18 UTC and serves as basis for predictions in 3 h intervals. The output data has a horizontal resolution of 1 degree × 1 degree and a vertical resolution of 23 pressure layers up to 20 hPa (Figure 2). The GDAS weather fields contain 35 different quantities, but the most interesting for this study were geopotential height (23 layers: 1000, 975, 950, 925, 900, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 50, 20 hPa), temperature (23 layers, same pressure layers as for geopotential height) and relative humidity (21 layers, same as the previous two quantities except the last two of 50 and 20 hPa).

[2] http://www.cngcft.ro/dgc/rnsgp.htm
[3] http://www.epncb.oma.be/ftp/mail

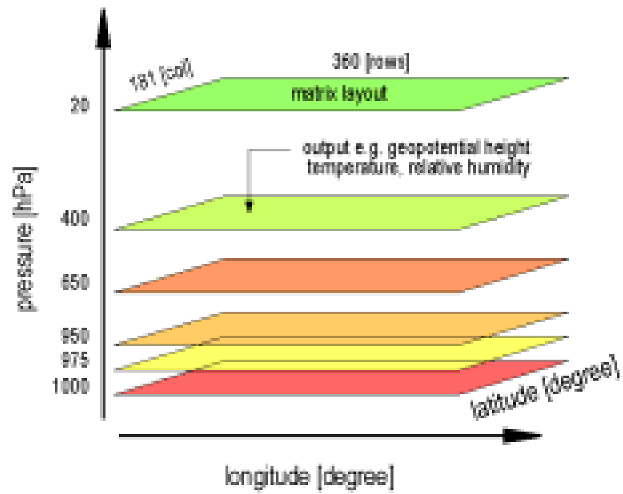

Fig 2. Data representation in the Global Data Assimilation System (GDAS) numerical weather model (NWM)

Schueler (2001) analyzed different approaches to extract meteorological data from a NWM. In brief, three main steps for data extraction might be carried out: (1) vertical interpolation that is performed with respect to the observing site height above mean sea level for all four nearest neighbouring horizontal grid points of a weather field. Pressure data are interpolated by an exponential function, while temperature and relative humidity are obtained by linear interpolation; (2) horizontal interpolation that is performed with all four neighbouring points using normalized weights defined by the reciprocal spherical distance between the observing site and grid point; and (3) temporal interpolation or interpolation in the time domain that is performed using either linear functions (when the forecast values are outputted) or cubic splines (in case of four epochs per day).

As mentioned earlier, many tropospheric models need meteorological information at the height of the observing site as input, with pressure being of an essential parameter for determination of hydrostatic zenith delay as showed in Davis et al. (1985)

$$ZHD = 0.002277 \cdot \frac{P}{1 - 0.00266 \cdot \cos(2\varphi) - 0.28 \cdot 10^{-6} h} \qquad (7)$$

while temperature and relative humidity are usually required in modelling the wet zenith delay as given in Saastamoinen (1973).

$$ZWD = 0.002277 \cdot \left(\frac{1255}{T} + 0.05 \right) \cdot e \qquad (8)$$

where P denotes the total pressure in hPa, T denotes the temperature in °K, e denotes the water vapor partial pressure in hPa, and (φ, h) representing the latitude and the height in meter at the observing site.

Because relative humidity is temperature dependent and water vapor partial pressure (e) is the quantity required in the computation of the wet component of the delay, the following equation is used to convert relative humidity (RH) to water vapor partial pressure (Leick, 1995):

$$e = 6.108 \cdot \frac{RH}{100} \cdot \exp\left(\frac{17.15 \cdot T - 4684}{T - 38.45} \right) \qquad (9)$$

4. Data analysis and discussions

The computation of the tropospheric delay was carried out using an application developed on the basis of the object-oriented approach in C++ programming language. The implemented computational procedure consists of three main steps. In the first step the meteorological data are extracted from GDAS NWM according with the position (geocentric latitude, longitude and orthometric height) and time for each station. In the second step, the hydrostatic and wet components are calculated based on Eqs.(7), (8) and (9), and in the third step the slant tropospheric delay is obtained by using GMF (NWM-derived mapping function). In case of zenith tropospheric delay calculation, the slant angle equals 90° and all mapping functions at zenith equals to unity.

4.1. Meteorological data comparison

Because three stations (BACA, BAIA and DEVA) are also equipped with meteorological sensors (MET 3A), a comparison of the GDAS extracted meteorological data was carried out with respect to the values collected by the in situ meteorological sensors, which according with MET 3A technical specifications have an accuracy of ±0.08 hPa for pressure from 620 to 1100 hPa, ±0.1°C for temperatures between –50 and +60°C and 2% accuracy for relative humidity at 25°C. Table 3 summarizes the statistics of this assessment. The mean bias and standard deviation of the differences between GDAS NWM extracted and in situ pressure data demonstrate a good agreement, with a maximum standard deviation of 0.85 hPa. This approximately corresponds to 2 mm uncertainty in the hydrostatic component. In addition, mean biases are also within acceptable limits for temperature, with a standard deviation less than 2.5°C. Furthermore, a good agreement is obtained for the relative humidity; only BAIA station is a bit out of range with a systematic error of 7.4. However, the standard deviations for the relative humidity at all three stations are larger than 10 %. This result may be caused by the fact that GDAS model is global and tends to smooth the extracted quantities, whereas the relative humidity depends mainly on local atmospheric conditions. Figure 3 shows the histograms of the differences between GDAS NWM and in situ meteorological parameters. As one can see, despite the fact that the NWM-extracted meteorological data may have some offsets with respect to the in situ observations, they are reliable and can be used to compute tropospheric delays in absence of in situ observation.

Table 3 Statistical results of the assessment of NWM-extracted meteorological parameters

Station name	Meteo quantity	Statistics					
		Mean	Min	Max	Std	RMS	Samples
BACA	P (hPa)	0.48	-4.00	4.40	0.84	0.97	17224
	T (°C)	0.15	-8.20	12.30	2.52	2.52	17224
	RH (%)	-3.35	-63.10	64.40	14.03	14.42	17224
BAIA	P (hPa)	-0.96	-4.90	2.60	0.63	1.14	16530
	T (°C)	-0.49	-9.70	7.80	2.21	2.26	16530
	RH (%)	-0.85	-49.50	56.50	12.90	12.93	16530
DEVA	P (hPa)	-0.75	-4.50	4.00	0.77	1.08	17079
	T (°C)	0.87	-8.20	12.80	2.90	3.02	17079
	RH (%)	-7.38	-77.60	50.60	15.83	17.47	17079

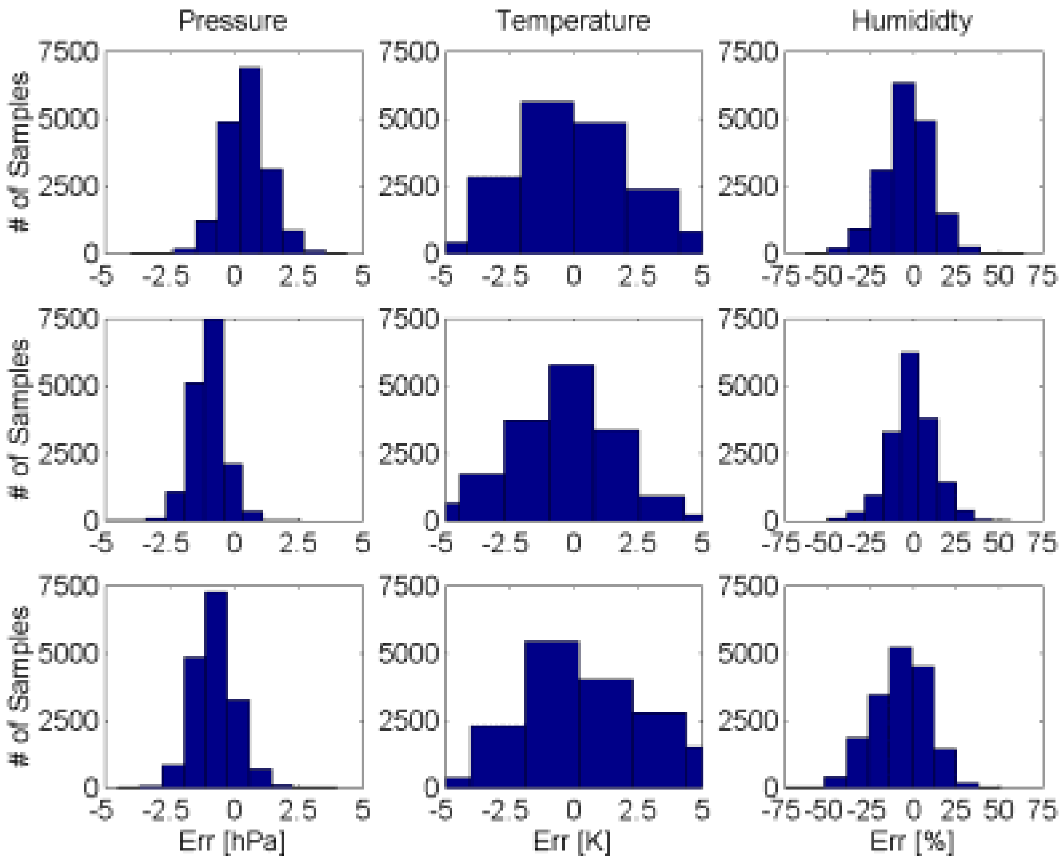

Fig 3. Histograms of the GDAS NWM-extracted and in situ meteorological parameters (pressure, temperature and relative humidity) for three of test stations: BACA (up), BAIA (middle) and DEVA (down)

4.2. GDAS NWM ZPD assessment

The extended network of EPN permanent stations, with its high number of Local Analysis Centres (LAC), motivated the decision to create a special project named "Troposphere Parameter Estimation" in which the EUREF ZPD product is generated as a by-product of the parameter estimation by the routine analysis. In the first step a combined solution is produced in post-processing mode similar to the combination of the SINEX[4] files for the derivation of the combined coordinate product. The EPN LACs contribute to the project with daily troposphere solutions on the basis of precise orbits. The combination is carried out following today's IGS standards: epoch-wise combination of the individual solutions as weighted mean with rigorous outlier detection in consecutive steps. Biases between the individual solutions and the mean have to be taken into account; this way jumps will be avoided if single observations of the individual solutions we missed. The output file (EURwwwwd.TRO[5]) contains the combined troposphere estimates with a hourly sampling rate. Since the precision of EUREF ZPD solutions is close to the precision of IGS SINEX ZPD estimates, i.e., 6 mm or better (Kouba, 2003) these values can be used as a reference for the assessment of GDAS NWM ZPDs.

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[4] SINEX is the acronym for Software INdependent EXchange
[5] wwwwd denotes the GPS week and day of the week

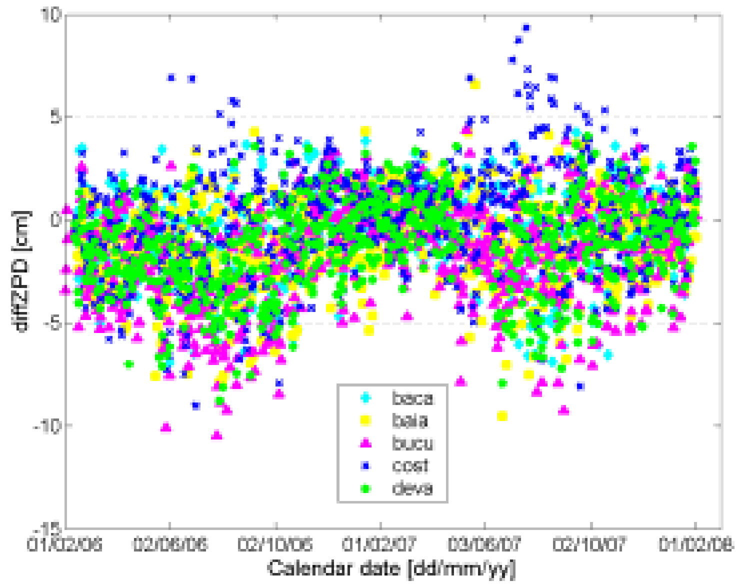

Fig 4. The GDAS NWM ZPD differences with respect to EUREF ZPD solutions for the Romanian EUREF GNSS test stations, only one (0-h UT) epoch is used for each day during the interval February 2006 - February 2008

Figure 4 shows the differences between GDAS NWM ZPD solutions and the EUREF ZPDs for the two-year considered time interval (February 2006 – February 2008). Some discontinuities can be seen for two stations (BUCU and COST), especially in the summer season, that go up to 10 cm. Figure 5 confirms the above results and also shows a seasonal feature by plotting the monthly differences statistics (mean bias and standard deviation). A special attention should be paid to the results for COST station. Due to closeness of this station to the Black Sea, the atmospheric water vapor measurements will record a higher variation compared with the stations located inside the country. This fact affects the wet component estimation. Both Figures 4 and 5 also confirm that the GDAS NWM tends to underpredict the ZPDs, at least for the case of Romanian territory.

Table 4 (left) shows the mean biases and standard deviations for the hourly differences of the GDAS NWM ZPD and EUREF ZPD solutions for all 5 Romanian EUREF stations. The largest standard deviation of the total ZPD differences is observed for stations BUCU and COST. While station COST presents the smallest mean bias, BUCU station mean bias is the largest. To prevent oversampling and causing rather too optimistic statistic, only the first (0-h UT) epoch of each day was used in Figure 4 and Table 4 (right).

Table 4 Means and standard deviations (1σ) of differences of the total ZPD of the GDAS NWM and EUREF solutions based on hourly data (left side) and at 0-h UT for February 2006 – February 2008

Station	Statistics (hourly data)				Statistics (only one epoch 0-h UT)			
name	Mean	Std	RMS	Samples	Mean	Std	RMS	Samples
BACA	-0.4	2.1	2.2	17272	-0.6	2.1	2.2	719
BAIA	-1.0	2.1	2.4	17291	-1.1	2.1	2.4	719
BUCU	-1.8	2.6	3.1	18015	-1.7	2.4	3.0	749
COST	0.1	2.6	2.6	16770	0.1	2.7	2.7	702
DEVA	-1.4	2.3	2.7	16962	-1.4	2.2	2.6	678

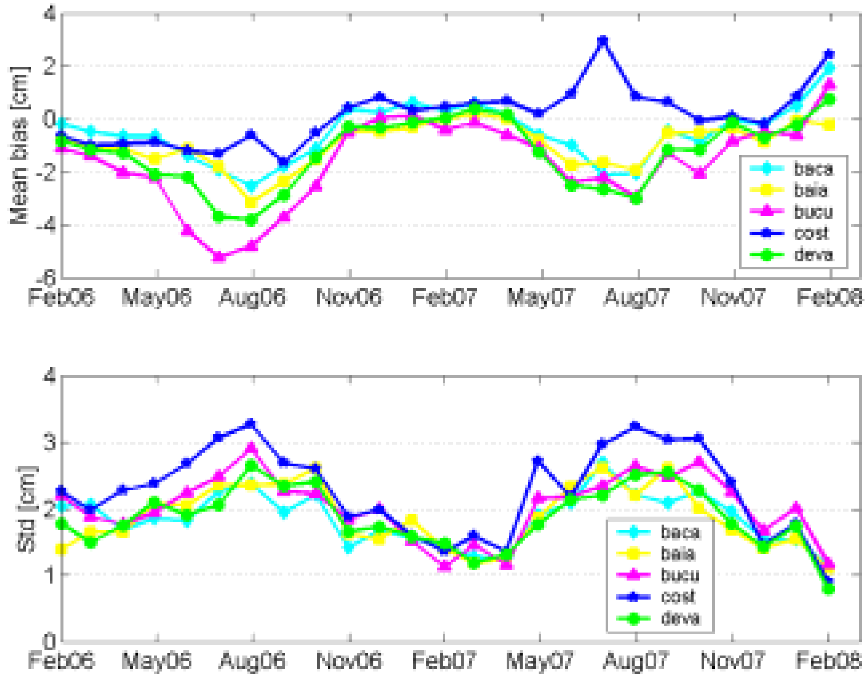

Fig 5. Monthly mean biases and standard deviations of the differences (GDAS NWM – EUREF) for the 5 Romanian EUREF GNSS stations, during February 2006 – February 2008. Hourly differences were considered in the monthly statistics

5. Conclusions

The GDAS NWM ZPDs estimated at the Romanian EUREF permanent GNSS stations demonstrate a good agreement with the EUREF solutions. There were, however, some notable exceptions of large differences and discontinuities, up to 10 cm, most of which were attributable to the NWM extracted meteorological parameters. While the NWM extracted pressure data were well compared (less then 0.85 hPa in standard deviation) with the in situ meteorological measurements, the temperature and especially relative humidity showed a poor agreement with sensors data. While temperature agreement was less then 3°C in standard deviation, the relative humidity agreement was around 15%. Poor estimation of the relative humidity also means poor estimation of the partial pressure of water vapor, which combined with temperature lead to less accurate estimation of the wet component of the tropospheric delay.

Since a medium resolution model was used in this investigation and the covered area was limited to 4° × 6° degrees, it is expected that a higher resolution model will improve these results. Even so, the fact that the GDAS NWM tropospheric delays agree the EUREF solutions at a level of 2-3 cm for any location almost in real-time, makes them useful not only for static, but also for kinematic and sub-meter positioning.

6. Acknowledgements

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7. References

1. *Bevis M., Businger S., Chriswell S., Herring T.A., Anthes R.A., Rocken C., and Ware R.H., 1994, GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water. Journal pf Applied Meteorology, 33:379-386;*
2. *Boehm J., Schuh H., 2004, Vienna mapping functions in VLBI analyses. Geophysical Research Letters 31:L01603. doi:10.1029/2003GL018984;*
3. *Boehm J., Werl B., and Schuh H., 2006, Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data. Journal of Geophysical Research 111:B02406;*
4. *Bruyninx C., 2004, "The EUREF Permanent Network: a multi-disciplinary network serving surveyors as well as scientists", GeoInformatics, Vol 7, pp. 32-35;*
5. *Davis J.L., Herring T.A., Shapiro I.I., Rogers A.E.E., Elgered G., 1985, Geodesy by radio interferometry: effects of atmospheric modelling errors on estimates of baseline length. Radio Science 20(6):1593–1607;*
6. *Herring T.A., 1992, Modelling atmospheric delays in the analysis of space geodetic data. In J. C. DeMunkand and T. A. Spoelstra (eds), Symposium on Refraction of Transatmospheric Signals in Geodesy, number 36, Netherlands Geodetic Commission Series, pp. 157–164;*
7. *Ifadis I., 1986, The atmospheric delay of radio waves: Modelling the elevation dependence on a global scale, Technical Report 38L, School of Electrical and Computer Engineering, Chalmers University of Technology, Gothenburg, Sweden;*
8. *Kouba J., 2003, A guide to using International GPS Service (IGS) products, a report prepared for IGS, February 2003; http://igscb.jpl.nasa.gov /igscb/resource/pubs/GuidetoUsingIGS Products;*
9. *Leick A., 1995, GPS Satellite Surveying, 2nd edn, John Wiley & Sons, Inc., New York, pp.220;*
10. *Mendes V.B., 1999, Modelling the neutral-atmosphere propagation delay in radiometric space techniques. PhD thesis. Department of Geodesy and Geomatics Engineering, Technical Report No.199, University of New Brunswick, Fredericton, New Brunswick, Canada;*
11. *Niell A.E., 1996, Global mapping functions for the atmosphere delay at radio wavelengths. Journal of Geophysical Research 101(B2):3227–3246;*
12. *Niell A.E., 2000, Improved atmospheric mapping functions for VLBI and GPS. Earth Planets Space 52(10):699–702;*
13. *Saastamoinen J., 1973, Contributions to the theory of atmospheric refraction. Bulletin Geodesique 105-107: 279–298; 383–397; 13–34;*
14. *Schueler T., 2001, On Ground-based GPS Tropospheric Delay Estimation. PhD thesis. Universität der Bundeswehr, Munchen, pp.197-205;*
15. *Spilker J.J., 1996, Tropospheric Effects on GPS, Global Positioning System: Theory and Applications Vol. I, Progress in Astronautics and Aeronautics Vol. 163, Spilker and Parkinson, pp. 517–546;*
16. *Thayer G., 1974, An Improved Equation for the Radio Refractive Index of Air. Radio Science 9(10):803–807.*