MODELING ZENITH DELAYS AND INTEGRATED WATER VAPOUR

Paweł Hordyniec [1]

Abstract

GNSS (Global Navigation Satellite System) is one of such techniques that allows continuous remote monitoring of atmosphere by analyzing the satellite signal noises. The major distortions comes from the troposphere, the closest layer to the Earth's surface. Its impact can be assessed by the knowledge of meteorological parameters at the observation site, which are pressure, temperature, and water vapour content. To provide these quantities, various methods have been developed that differ in spatial and temporal resolution, accuracy, input parameters etc.

This paper describes the most common sources of meteorological parameters: in-situ measurements, empirical atmosphere models such as UNB3m (University of New Brunswick), Global Pressure and Temperature (GPT and GPT2), standard atmosphere model of Berg as well as Numerical Weather Prediction (NWP) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). These models are used to determine troposphere delay components and total amount of water vapour along GNSS signal path by providing surface meteorological parameters. Based on analyses performed over territory of Poland at ASG-EUPOS reference stations of GBAS, COAMPS delivers very accurate parameters in terms of *bias* and *root mean square error* for both ZHD (-3.54 ±12.50mm) and ZWD (0.52 ±10.03mm), with meteorological observation available in 1-hour interval.

Keywords

atmosphere model, GNSS meteorology, IWV, NWP, troposphere delay

1 TROPOSPHERE DELAY MODELING

Main source of the GNSS signal noise is caused by the troposphere and results in troposphere delay, which is determined in the zenith direction between a satellite and a receiver. For this reason it is called Zenith Total Delay (ZTD). The total delay consists of two independent mediums and by separation into components – hydrostatic and wet – the delay can be expressed as a sum of Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD):

$$ZTD = ZHD + ZWD \tag{1}$$

The usual amount of ZTD is about 2.3m and most of this delay (90%) includes the hydrostatic part. Because the delay is a function of meteorological parameters, modeling the state of the atmosphere is the way to reduce the troposphere impact. ZHD is a pressure-dependent parameter that can be modeled with high accuracy by Saastamoinen [1] equation:

$$ZHD = \frac{0.0022767 \cdot p}{1 - 0.00266 \cdot \cos 2\varphi - 0.00000028 \cdot h} \tag{2}$$

where p is the surface pressure in hPa, φ is the station's latitude, h is the ellipsoidal height in meters.

Appropriately, the Saastamoinen's equation for the wet part reads as follows:

$$ZWD = 0.002277 \cdot \left(\frac{1255}{T} + 0.05\right) e \tag{3}$$

where T is the temperature in Kelvins, e is the water vapour partial pressure in hPa. In contrast to ZHD, the wet component is very difficult to model. Rapid changes of water vapour partial pressure, both in time and space, has an effect on high variability in ZWD. On the other hand, the amount of ZWD in the total delay is rather small. Therefore the variation might not be noticeable in final results.

For the reason that the wet component is highly related to water amount in the atmosphere, it is possible to convert ZWD into Integrated Water Vapour (IWV), which is commonly used parameter in meteorology. It describes the total amount of water on a vertical column between a satellite and an observation site.

$$IWV = \frac{ZWD}{10^{-6}\left(k_2' + \frac{k_3}{T_m}\right) \cdot R_w} \tag{4}$$

where ZWD is Zenith Wet Delay in meters, k are empirical coefficients, T_m is the mean temperature above the observation site in Kelvins, R_w is gas constant for wet air, which equals to 461.525 J · K^{-1} · kg^{-1}. The empirical constants were defined in a number of investigations. The coefficients depend on index of refractivity that can be expressed as variables of partial pressures (dry and wet) and temperature. Several solutions are gathered in Table 1, with best available coefficients of Rueger [2] that are used for analysis purposes of this study.

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Reference	k_1 $[K \cdot hPa^{-1}]$	k_2 $[K \cdot hPa^{-1}]$	k_3 $10^5[K^2 \cdot hPa^{-1}]$
Smith and Weintraub [3]	77.607	71.6	3.747
Bevis et al. [4]	77.600	70.4	3.739
Rueger 'best available' [2]	77.695	71.97	3.754

***Tab. 1** empirical coefficients*

The supplementary k'_2 coefficient is received from other coefficients and constants:

$$k'_2 = k_2 - k_1 \frac{M_w}{M_d} \quad (5)$$

where M_w and M_d are molar masses for wet and dry air that equal to 18.0152 and 28.9644 g/mol, respectively.

Instead of calculating separately each of delay components from a priori Saastamoinen model, the total delay ZTD can be defined directly from GNSS observations and data processing. In the next step, by subtracting the total delay and its hydrostatic part, the wet part will be derived, which is widely used method. Figure below summarizes these two available ways for ZWD determination, with ZWD to IWV conversion.

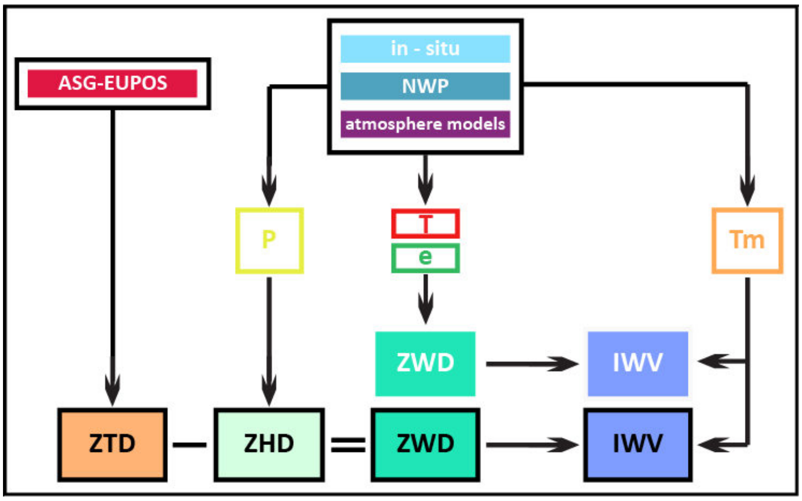

***Fig. 1** Methodology scheme*

As shows Figure 1, corresponding meteorological parameters are required to determine the delay components and IWV. When using a priori Saastamoinen model for ZHD determination, only surface pressure measurements are needed. If ZTD cannot be derived from GNSS processing, a priori ZWD is calculated from partial water vapour pressure and temperature. Additionally, mean temperature *Tm* is used in final conversions.

2 SOURCES OF METEOROLOGICAL PARAMETERS

In this paper, three main sources of meteorological data are utilized: in-situ; Numerical Weather Prediction (NWP) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) [5]; and empirical atmosphere models: Global Pressure and Temperature GPT [6] and GPT2 [7]; UNB3 modified [8]; model of Berg [9].

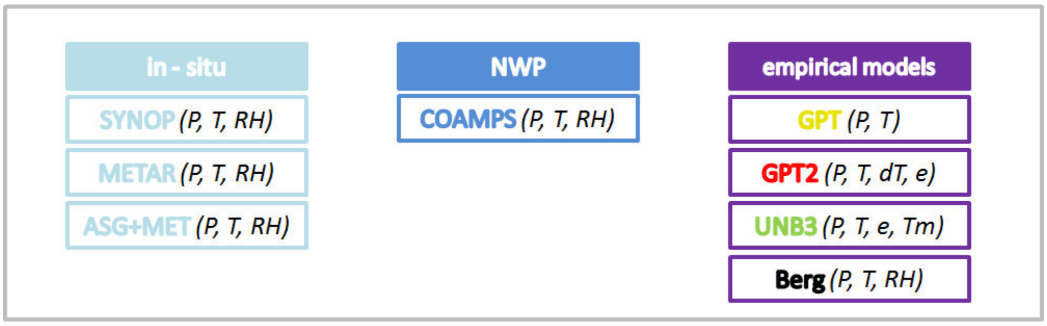

***Fig. 2** Meteorological sources*

The first group is represented by in-situ observations, which are pressure, temperature, and relative humidity collected from synoptic stations SYNOP belonging to Polish Institute of Meteorology and Water Management (49 stations), METAR (METeorological Aerodrome Report) stations at airports (9 stations), and ASG-EUPOS stations equipped with meteorological sensors (6 stations). In-situ data have 1-hour temporal resolution. Because all calculations are carried out in points of ASG-EUPOS network, the parameters have to be interpolated from their origin to desired location, except ASG+MET sites. The average distance between meteorological stations is 70km. Thus, the NN (nearest neighbor) method is utilized, with height correction for temperature and pressure.

For the data of COAMPS, all parameters are determined in station's coordinates throughout interpolation from grid nodes with 13km horizontal resolution. Pressure, temperature, and relative humidity are provided with 1-hour interval based on forecast launched at 00 and 12 UTC.

The empirical atmosphere models, often called "blind", provide appropriate parameters at given location, demanding only the coordinates (φ, λ, h) and the day of year (DOY). The model of Berg requires only the station's height, but the outcomes are constant in time. For the other cases, the resolution is annual, with annual and semiannual amplitudes of parameters for GPT2.

2.1 Water vapour partial pressure and mean temperature

To compute ZWD using a priori Saastamoinen model, the water vapour partial pressure is required. Unfortunately, such parameter is unspecified in the majority of sources. Thus, the equation of Clausius-Clapeyron is used to compute *e* on the basis of relative humidity data, temperature, and constants:

$$e = \frac{RH}{100} \cdot e_0 \cdot \exp\left(\frac{L}{R_e} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \tag{6}$$

where T_0 = 273.15K is the temperature of freezing, e_0 = 6.11hPa is the water vapour partial pressure for T_0, $L = 2.83 \cdot 10^6$ J/kg is the latent heat of vaporization, $R_e = 461$ $J \cdot K^{-1} \cdot kg^{-1}$ is specific gas constant for water vapor. based on forecast launched at 00 and 12 UTC.

To calculate the mean temperature, the linear function of surface temperature is utilized. However, to ensure high accuracy, *Tm* has to be defined for vertical pole above the site as a function of water vapour partial pressure and temperature with height derived from radio-soundings or interpolation from NWP vertical profiles. The "virtual" mean temperature is given in Kelvins by the equation of Bevis et al. [10]:

$$T_m = 70.2 + 0.72 \cdot T \tag{7}$$

3 CASE STUDY

The components of the total delay are calculated for the period from December 1st, 2012 to January 31th, 2013. ZTD measurements are known every hour for 121 stations of ASG-EUPOS network, including neighboring abroad sites. Thus, hourly meteo-observations are essential to provide homogeneous ZHDs. In the following section, the components calculated from in-situ data are considered as reference for comparative analyses. For this purpose, values of *bias* and *root mean square error* are used for comparisons. These are means calculated from the whole dataset for every chosen solution: in-situ, NWP, and empirical models with separation on each model. The results are referenced to stations labeled by numbers.

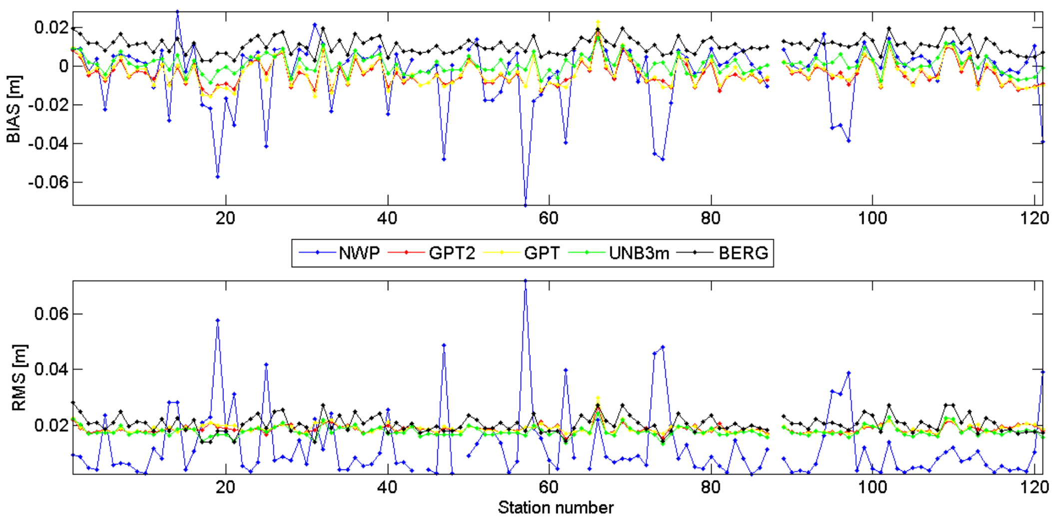

Fig. 3 *mean bias and rms of ZHD w.r.t ZHD in-situ*

Figure 3 shows the accuracy of models for ZHD component. There are some residuals seen for NWP. Usually, these refer to abroad stations or locations at high altitudes, where COAMPS may not provide sufficient accuracy for pressure in this case. If the stand-off stations were discarded, the *bias* and *rms* would not exceed 1cm, whereas it can be as high as 6cm. The most erroneous empirical model is the model of Berg, with *bias* and *rms* up to 2cm. The remaining ones are very similar in terms of *rms*, but the most unbiased is UNB3m (0.94mm).

Figure 4 for station CLIB (Liberec) is crucial to understand, how empirical models work. On the example of a priori plots (left) for the wet component, GPT2 and UNB3m are insignificantly changing in time for short periods, and as was written before, Berg is constant by its definition. Regardless the small biases apply to ZHD, and thus - the pressure, the models are only averaging the parameters in annual scale. The plots for non a priori ZWD (right), besides almost constant ZHDs for atmosphere models, are very close to COAMPS' characteristic. Their differences (dZWD) arise from ZHD's accuracy. This proofs Figure 5.

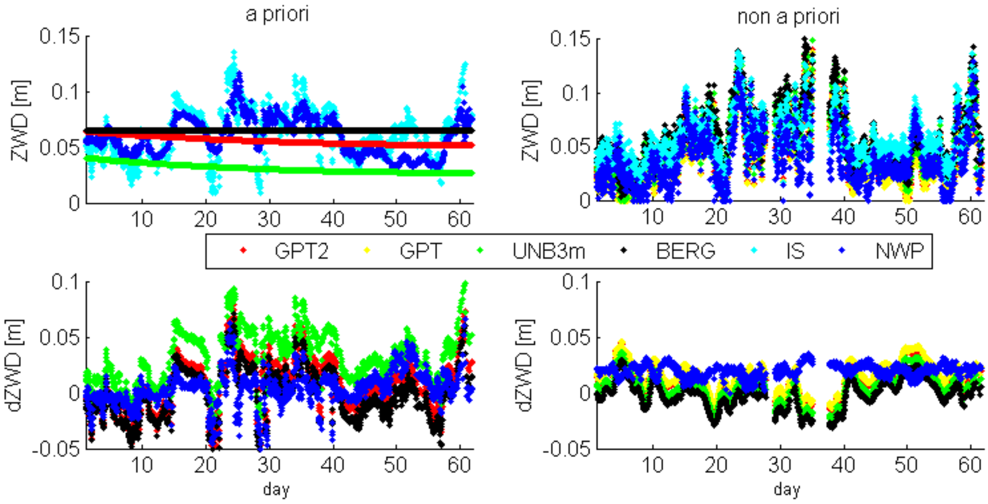

Fig. 4 *ZWD's differences for station CLIB (17) w.r.t. ZWD in-situ*

The *root mean square errors* are actually the same as for ZHD, while *biases* are the exact opposites (Figure 5). Thus, estimation of ZWD by subtracting the modeled ZHD from measured ZTD causes only minimal errors (see Table 2). Therefore, the estimated ZWD for in-situ data is taken to further comparisons as reference (best case scenario).

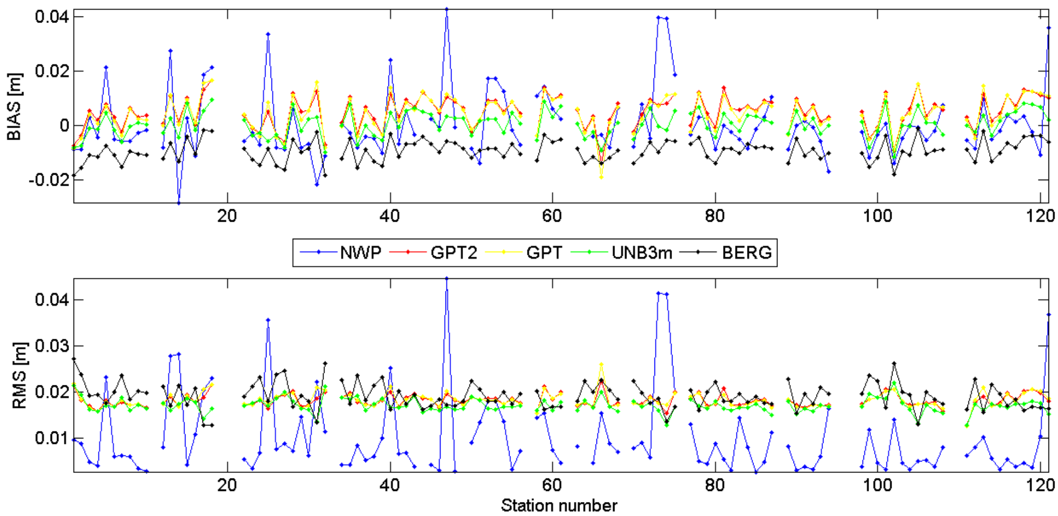

Fig. 5 *mean bias and rms of ZWD from ZTD-ZHD w.r.t ZWD in-situ*

If ZTD measurements are unavailable, ZWD will need to be calculated from a priori model using meteorological parameters. Due to the fact the outputs of GPT are only pressure and temperature, there is no GPT ZWD a priori.

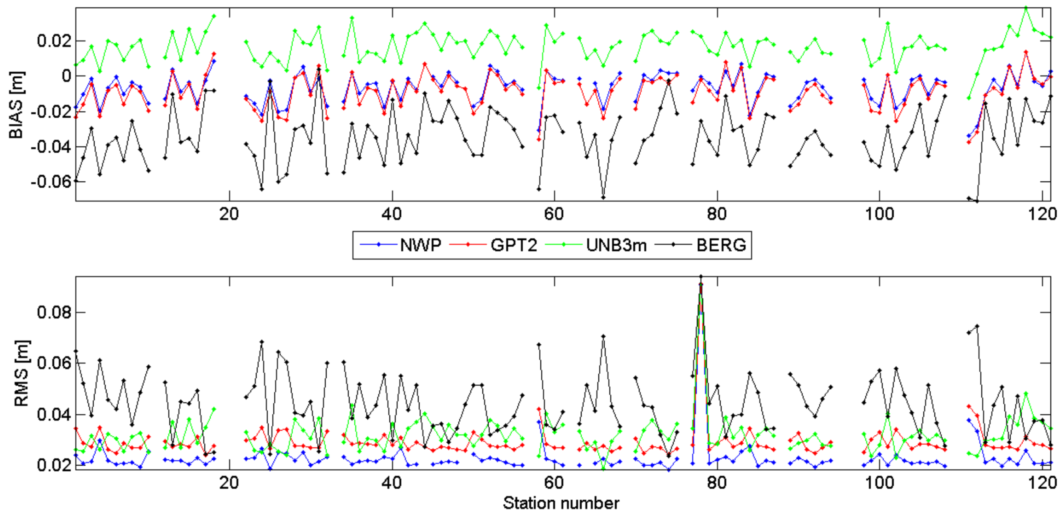

***Fig. 6** mean bias and rms of ZWD a priori w.r.t ZWD in-situ non a priori*

The exceptional *rms* error with over 9cm occurs for station No. 78 – OPLE (Opole). It is caused by low accuracy of ZTD measurements at this site, while the comparison is made with respect to ZWD non a priori using in-situ parameters. The best agreement in *bias'* residuals is seen between GPT2 empirical model and COAMPS forecast. UNB3m's results are mostly underestimated, because the overall *bias* is positive. The *rms* errors for a priori solution are ranging from minimum 23mm for COAMPS up to over 44mm, when parameters of Berg's model are utilized. Comparing the results of a priori ZWD, *rms* grows over twice as much as *rms* of estimated ZWD.

Component	Solution	NWP	GPT2	GPT	UNB3m	BERG
ZHD	Saastamoinen	-3.54 ±12.50	-3.86 ±18.60	-3.47 ±18.76	0.94 ±17.77	10.62 ±20.38
ZWD	ZTD-ZHD	0.52 ±10.03	4.81 ±18.05	4.30 ±18.12	0.40 ±16.99	-9.44 ±19.08
ZWD	Saastamoinen	-6.49 ±23.02	-9.00 ±29.39	-	16.83 ±32.07	-34.55 ±44.63

***Tab. 2** mean bias and rms [mm] w.r.t. in-situ data (Zenith Delays)*

To summarize the performed analyzes, Figure 7 is used to show the difference in spatial distribution of ZWD component, both estimated and modeled from a priori Saastamoinen model. The maps show the realization for NWP COAMPS. As we can see, the estimated ZWD is irregular. Correlation with topography is hardly visible. On one hand ZWD is at very low level for mountainous areas (e.g. NWTG, ZYWI). On the other hand, similar values of this component occur at the location of Masurian Lake District (sites LAMA, OLST), which is a lowland. For ZWD a priori, spatial distribution is smooth and grows from the east to the west of the country.

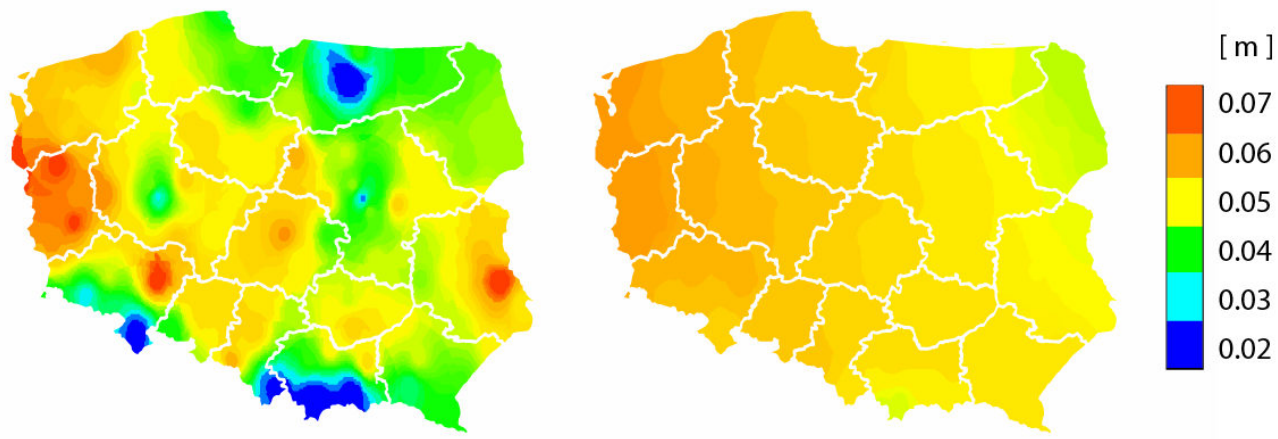

***Fig. 7** ZWD estimated (left) and a priori (right) for COAMPS*

The conversion to IWV from ZWD is performed for both, a priori and estimated results of the wet component. IWV is expressed in kg/m^2 that is equal to linear value of millimeter. The outcomes are presented for few chosen stations with different ellipsoidal heights:

- DRWP (Drawsko Pomorskie, PL) *h = 171.1m*
- DZIA (Działdowo, PL) *h = 206.6m*
- ELBL (Elbląg, PL) *h = 52.7m*
- GANP (Poprad Ganovce, SK) *h = 746.0m*

There is obvious error for NWP COAMPS on station GANP, which is located in Slovakia at very high altitude (*rms* 36kg/m^2). This case confirms mismodeling already shown for pressure. Station labeled by No. 25 (Fig. 3), which is GANP, has mean *bias* about -4cm, what means overestimation of ZHD with respect to „real“ data (in-situ). The error was transferred to ZWD (estimated) (Fig. 5) causing too low value for the wet part. This is because the calculated ZHD using COAMPS‘ pressure was higher than the total delay and thus, ZWD from subtraction must not be negative. The results for a priori method are over twice more biased, except the model of Berg. There are no significant differences between models in terms of *rms* error, whereas for non a priori IWV it is possible to group models into three diverse sets: least accurate with model of Berg, moderate (GPT, GPT2, UNB3m), and distinctly different NWP (with the exception of mismodeled sites).

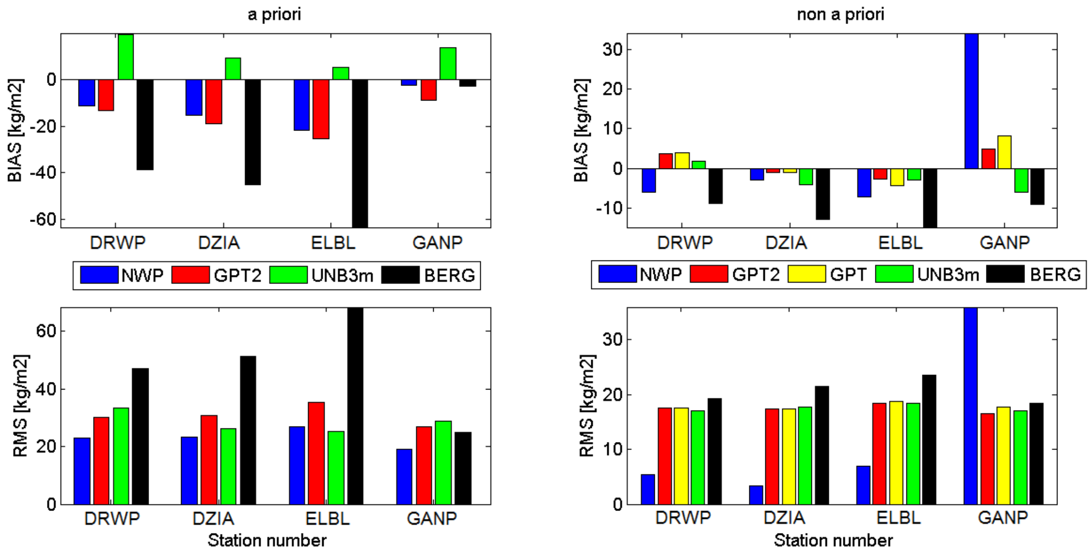

Fig. 8 *mean bias and rms [kg/m^2] of IWV's w.r.t. estimated IWV in-situ*

The overall accuracy of COAMPS is -6.57 ±23.24kg/m^2 a priori and 0.53 ±10.15kg/m^2 non a priori, respectively (Table 3). GPT models have very similar errors for estimated IWV. Smaller *bias* and *rms* holds UNB3m. Same as ZWD a priori, the results for IWV a priori are also less accurate. This is due to ZWD, which is required to derive IWV and is not error-free. Therefore, to provide the final errors, ZWD's *biases* and *rms* are taken into account.

Component	Solution	NWP	GPT2	GPT	UNB3m	BERG
IWV	non a priori	0.53 ±10.15	4.87 ±18.26	4.35 ±18.33	0.61 ±17.19	-9.67 ±19.37
IWV	a priori	-6.57 ±23.24	-9.11 ±29.74	-	17.06 ±32.46	-34.62 ±44.88

Tab. 3 *mean bias and rms [kg/m^2] w.r.t. in-situ data (IWV)*

The research proofs that Numerical Weather Prediction model COAMPS is the best replacement when the direct observations are unavailable. It has high resolution in time (1H) and space (13km grid). On the other hand, the data's acquisition process is highly complicated and equipment-demanding. Additionally, NWP is inaccurate for sites at high altitudes. In turn, the empirical models are easily accessible, while the parameters are calculated based on the coordinates. The temporal resolution is still reduced to one observation a day. The a priori solution used in analyzes is very inaccurate method and causes even doubled errors.

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