# REFINED AND SITE-AUGMENTED TROPOSPHERIC DELAY MODELS FOR GNSS

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## ABSTRACT

In this paper we suggest a new method of modeling zenith wet delays by using information of the empirical troposphere delay model GPT2w plus in-situ measurements of temperature, pressure and/or water vapor pressure. Tropospheric delays estimated from GNSS data were used to determine the correlation with in-situ measured meteorological data and in further consequence to improve the empirical model. In order to assess the accuracy of this site-augmented approach, comparisons are made for a global station network with respect to high-precision zenith wet delays derived from GNSS data. Thus, it turns out that the modeled zenith wet delays are improved by up to one third on average compared to the empirical approach. The new model can be successfully applied to all GNSS range measurements and therefore of course also to Galileo observations.

Key words: GNSS; zenith wet delay; empirical troposphere model; GPT2w; site-augmentation.

## 1. INTRODUCTION

Appropriate modeling of tropospheric delays is one of the major challenges in the analysis of Global Navigation Satellite Systems (GNSS) observations, such as GPS, GLONASS or Galileo. Although the hydrostatic part of the tropospheric delay can be determined quite accurately from measuring pressure directly at the GNSS station, the wet part is not that straightforward to determine. Since the water vapor content of the air masses above the site cannot be described by surface measurements only, the zenith wet delay ($\Delta L_w^z$) can only be roughly approximated. To date, the basic way of approximating the zenith wet delay from surface measurements is by using the formula by Askne & Nordius [1]:

$$\Delta L_w^z = 10^{-6} * (k_2^{'} + \frac{k_3}{T_m}) * \frac{R_d * e}{(\lambda + 1) * g_m} \qquad (1)$$

where $e$ is the water vapor pressure, $T_m$ the mean temperature weighted with the water vapor pressure, $\lambda$ the decrease rate of the water vapor pressure, $R_d$ the specific gas constant for dry constituents, $g_m$ is the gravity acceleration whereas $k_2^{'}$ and $k_3$ are fixed, empirical coefficients. $e$, $T_m$ and $\lambda$ can be taken from empirical troposphere models, also referred to as blind troposphere models, such as GPT2w [2], what allows the calculation of empirical zenith wet delays.

The idea behind the site-augmented approach is the fact that there is a clear correlation between the zenith wet delay above the station and in-situ measured temperature and water vapor pressure. The empirical zenith wet delays calculated by the formula by Askne & Nordius [1] (Eq. (1)) can then be improved by incorporating the in-situ measured meteorological quantities. Albeit the zenith wet delay is highly variable both temporally and spatially, meteorological measurements directly at the GNSS station can be used to significantly improve the modeled zenith wet delay with respect to the empirical values. This is particularly important for GNSS applications in case there is no access to real-time information about the state of the troposphere derived from numerical weather models (NWM).

## 2. DATA

For this investigation, we utilized GNSS data from the IGS final tropospheric SNX-TROPO products and meteorological data from close-by weather stations. To ensure that the meteorological data is representative also for the site of the GNSS station, special requirements had to be met; that is, only GNSS stations which are maximally 10 km horizontally and 100 m vertically apart from the closest weather station were used. Thus, the 29 IGS stations, as shown in Fig. 1, are chosen.

At four epochs at each day in 2013, we have the zenith total delays $\Delta L^z$ at GNSS stations as well as pressure $p$, temperature $T$ and water vapor pressure $e$ at weather stations available. Pressure values were extrapolated from the height level of the weather station to those of the GNSS site using a simple, exponential pressure decrease rate. Inserting them to the formula by Saastamoinen [5] as refined by Davis et al. [3] (Eq. (2)) allows very accurate calculation of the zenith hydrostatic delay $\Delta L_h^z$:

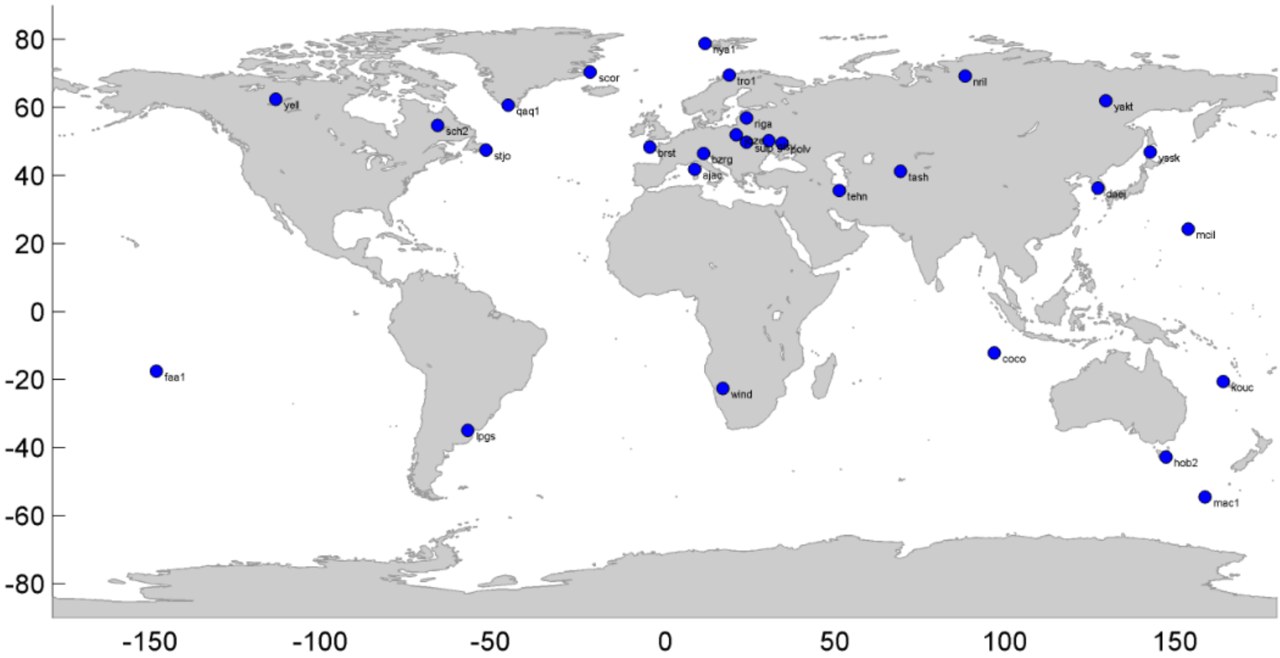


*Figure 1. The 29 IGS stations which are used for testing the performance of site-augmented GPT2w. Selection of those stations is done so as to ensure best possible global coverage. Unfortunately, none of the stations in the tropics meets the requirements concerning the vicinity to a meteorological station. However, there are five stations on islands which have similar characteristics as tropic stations with respect to the amount and variability of water vapor what makes them worthy representatives for the lacking tropics stations.*

$$\Delta L_h^z[m] = \frac{0.0022768 \cdot p[hPa]}{1 - 0.00266 \cdot cos(2\theta) - 0.28 \cdot 10^{-6}h} \quad (2)$$

where $\theta$ is the latitude and $h$ is the height of the site. Subtracting the thus obtained zenith hydrostatic delays $\Delta L_h^z$ from the zenith total delays $\Delta L^z$ yields the zenith wet delays $\Delta L_w^z$. These serve as the reference values, so to speak the "true" values, which are to be approximated by the site-augmented approach using the in-situ measured meteorological data.

Unlike pressure $p$, the temperature $T$ and water vapor pressure $e$ values were adopted unalteredly from the weather station due to the very slight differences.

## 3. CORRELATION BETWEEN THE QUANTITIES

Investigations show that there is a clear correlation between $e$ and $\Delta L_w^z$ and also $T$ and $\Delta L_w^z$, as shown in Figs. 2 and 3.

Averaged over all 1460 epochs and all 29 stations, the correlation coefficient between $e$ and $\Delta L_w^z$ is 0.85, and 0.65 between $T$ and $\Delta L_w^z$. This obvious correlation provides the basis for the site-augmentation of GPT2w.

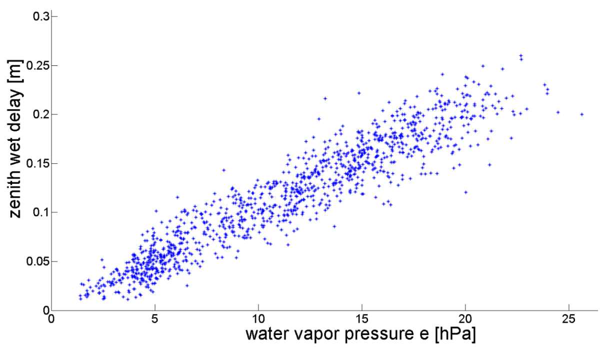


*Figure 2. Figure outlining the correlation between water vapor pressure $e$ and zenith wet delay $\Delta L_w^z$ for station bzrg (Bolzano, Italy).*

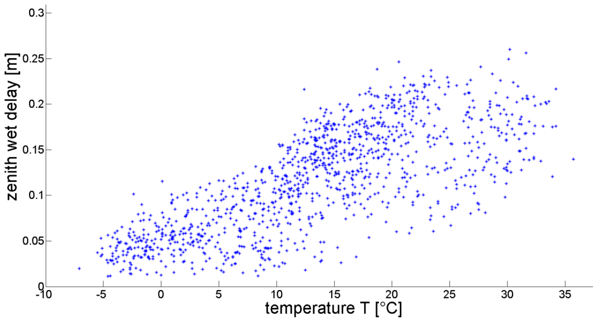


*Figure 3. Figure outlining the correlation between temperature $T$ and zenith wet delay $\Delta L_w^z$ for station bzrg (Bolzano, Italy). The correlation is not as distinct as in Fig. 2, however, it is still visible.*

## 4. AUGMENTATION APPROACHES

In general, we distinguish between two approaches of augmenting the zenith wet delay $\Delta L_w^z$: the first is an augmentation based on measurements of temperature $T$ (Eq. (4)), the second covers the more accurate augmentation when having both $T$ and $e$ available (Eq. (5)). Eq. (3) marks the empirical way without any in-situ measurements, that is, just applying Eq. (1) using the values from GPT2w.

$$\Delta L_w^z = \Delta L_{wGPT2w}^z \tag{3}$$
$$\Delta L_w^z = \Delta L_{wGPT2w}^z + M * (T - T_{GPT2w}) \tag{4}$$
$$\Delta L_w^z = \Delta L_{wGPT2w}^z + M_1 * (T - T_{GPT2w}) + M_2 * (e - e_{GPT2w}) \tag{5}$$

In addition, there is the possibility to insert the measured $e$ directly into Eq. (1), what yields very similar results as those from Eq. (5) as shown later.

The globally valid coefficients $M$, $M_1$ and $M_2$ were determined ahead of this investigation in least squares adjustments using numerical weather model (NWM) data from 2009-2014 for 19 Very Long Baseline Interferometry (VLBI) stations [4]. Their values are shown in Tab. 1.

*Table 1. Values for the $M$ coefficients determined in least-squares adjustments.*

| coefficient | value | unit |
|---|---|---|
| $M$ | 0.00178 | [m/°C] |
| $M_1$ | 0.00049 | [m/°C] |
| $M_2$ | 0.00915 | [m/hPa] |

Inserting those coefficients in the Eqs. (4) and (5) eventually enables the augmentation of the zenith wet delay $\Delta L_w^z$.

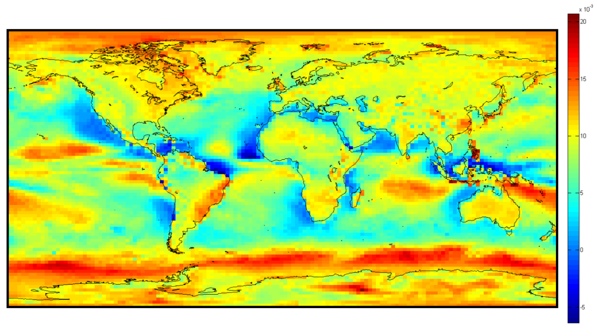

*Figure 4. Mean values for the geographically dependent $M_2$ coefficients. As can be seen, the values are highly variable especially offshore while being fairly constant onshore.*

Apart from those universal, globally valid $M$ coefficients it was also tested whether the determination of geographically and seasonally dependent coefficients makes sense. They were calculated on a 2.5°x2.0° global grid and given annual as well as semi-annual variations. Fig. 4 shows a global grid for mean values of coefficients $M_2$.

However, no systematics could be found in the seasonal variation and also the application of only the geographically dependent coefficients did not bring any improvement, therefore this approach is not considered in the following.

## 5. RESULTS

Results for the augmentation of the zenith wet delay clearly reveal an improvement in accuracy, as the values get closer to the "true" values than the empirical ones. In order to assess the performance of the augmentation, comparisons are made for three GNSS stations in meteorologically very diverse regions: station *bzrg* in temperate latitudes, station *coco* as an example for a station at a location with very high water vapor content and station *nya1* in the high north, where there is very low water vapor content.

In Fig. 5 for IGS station *bzrg* in Bolzano, Northern Italy it can be seen that the $\Delta L_w^z$ is very well approximated at some epochs and not so well in others. Nevertheless, the general statement of this figure is that the augmentation using Eq. (4) captures the very short time variations quite well, but has problems with medium time variations. Measuring and applying also $e$ (that is, Eq. (5)) mostly handles also those longer-time variations.

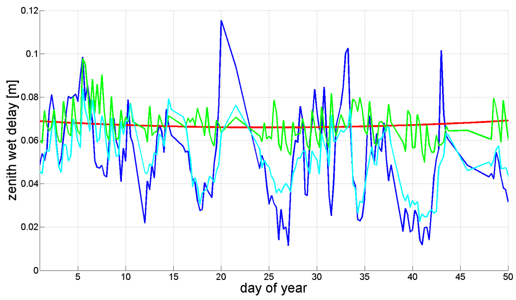


*Figure 5. Comparison of $\Delta L_w^z$ from various sources for the IGS station in Bolzano, Italy for the first quarter of 2013: the "true" $\Delta L_w^z$ (dark blue), the empirical $\Delta L_w^z$ (red), the $\Delta L_w^z$ augmented by using in situ measured T (green) and the $\Delta L_w^z$ augmented by using in situ measured T and e (light blue).*

In Fig. 6, a more complicated scenario is depicted. The IGS station *coco* on the Cocos Islands in the Indian Ocean is subjected to a very humid climate, what negatively influences the performance both of the calculation of $\Delta L_{wGPT2w}^z$ and of the site-augmentation. As a consequence, the augmentation using $T$ only does not visibly improve the empirical $\Delta L_w^z$, also the augmentation using $T$ and $e$ performs not as well as in Fig. 5.

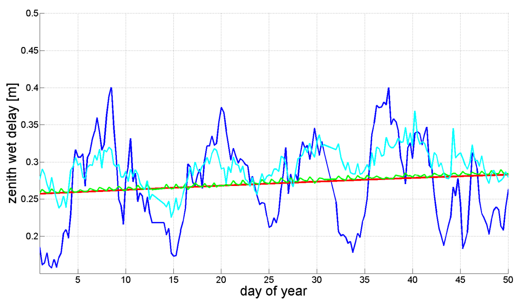


*Figure 6. Comparison of $\Delta L_w^z$ from various sources for the IGS station on the Cocos Islands for the first quarter of 2013: the "true" $\Delta L_w^z$ (dark blue), the empirical $\Delta L_w^z$ (red), the $\Delta L_w^z$ augmented by using in situ measured T (green) and the $\Delta L_w^z$ augmented by using in situ measured T and e (light blue).*

As a third example, the zenith wet delays for the station *nya1* on Svalbard are compared (Fig. 7). Owing to the very dry climate at these high latitudes, the augmentation works out very well, significant improvements can be already achieved by measuring only $T$.

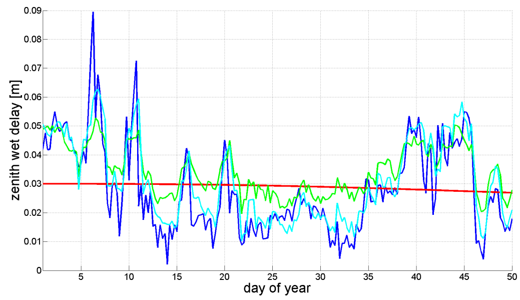


*Figure 7. Comparison of $\Delta L_w^z$ from various sources for the IGS station in Ny Alesund on Svalbard for the first quarter of 2013: the "true" $\Delta L_w^z$ (dark blue), the empirical $\Delta L_w^z$ (red), the $\Delta L_w^z$ augmented by using in situ measured T (green) and the $\Delta L_w^z$ augmented by using in situ measured T and e (light blue).*

To draw final conclusions about the performance of the augmentation, zenith wet delays averaged over all epochs and stations need to be considered. For that reason, differences between the reproduced zenith wet delays and the "true" zenith wet delays from IGS were determined. In the first comparison shown in Tab. 2, averaged absolute differences are shown as calculated by $mean(|\Delta L_{wIGS}^z - \Delta L_w^z|)$.

*Table 2. Absolute differences between the reproduced $\Delta L_w^z$ and $\Delta L_{wIGS}^z$ averaged over all epochs and stations. For in situ measurement of T and e there are two possibilities of augmentation: (a) insert T and e in Eq.* (5) *or (b) insert e directly into Eq.* (1).

| approach | mean abs. diff. [cm] |
|---|---|
| no in situ measurements | 2.8 |
| in situ meas. of T | 2.7 |
| in situ meas. of T and e (a) | 2.0 |
| in situ meas. of T and e (b) | 2.0 |

This shows quite distinctively what was already assumed when interpreting Figs. 5-7: in situ measuring $T$ and inserting into Eq. (4) improves $\Delta L_w^z$ slightly, while additional measurements of $e$ improves them significantly. When measuring both $T$ and $e$, it makes no noticeable difference whether approach (a) or (b) is applied. Although improvement by applying Eq. (4) is fairly small, it is however sensible as it is more likely to have temperature sensors at or near GNSS stations than humidity sensors.

Viewing the augmentation performance for each of the 29 IGS stations (Figs. 8 and 9) reveals that measuring $T$ improves the $\Delta L_w^z$ for all stations but two and works best for high-latitude sites. Additional inclusion of $e$ yields significant improvement for all stations.

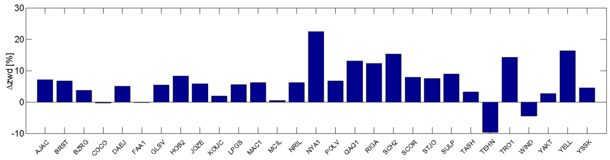


*Figure 8. Station-wise improvement by the augmentation when measuring only temperature (Eq. (4)).*

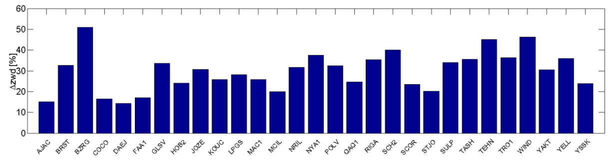


*Figure 9. Station-wise improvement by the augmentation when measuring both temperature and water vapor pressure (Eq. (5)).*

Another way to compare the results is to determine bias and standard deviation for the averaged zenith wet delays, as depicted in Tab. 3.

*Table 3. Bias and standard deviation of the differences between the reproduced $\Delta L_w^z$ and $\Delta L_{wIGS}^z$ averaged over all epochs and stations. Again, for in situ measurements of T and e there are two possibilities of augmentation: (a) insert T and e in Eq. (5) or (b) insert e directly into Eq. (1).*

| approach | bias [cm] | std. dev. [cm] |
|---|---|---|
| no in situ measurements | -0.1 | 3.5 |
| in situ meas. of T | -0.1 | 3.4 |
| in situ meas. of T and e (a) | -0.2 | 2.5 |
| in situ meas. of T and e (b) | -0.2 | 2.5 |

In here, the bias values are not necessarily meaningful for assessing the performance of augmentation, but comparing the respective standard deviations reveals the same message as Tab. 2.

In order to further strengthen this message, correlation coefficients between each approach and the $\Delta L_{wIGS}^z$ are calculated (Tab. 4). This proves, again, that including meteorological measurements significantly improves the resulting $\Delta L_w^z$.

*Table 4. Correlation coefficients between the reproduced $\Delta L_w^z$ and $\Delta L_{wIGS}^z$ averaged over all epochs and stations. Again, for in situ measurement of T and e there are two possibilities of augmentation: (a) insert T and e in Eq. (5) or (b) insert e directly into Eq. (1).*

| approach | corr. coeff. |
|---|---|
| no in situ measurements | 0.70 |
| in situ meas. of T | 0.73 |
| in situ meas. of T and e (a) | 0.86 |
| in situ meas. of T and e (b) | 0.86 |

## 6. CONCLUSIONS

Overall, the investigations showed that the blind tropospheric model GPT2w is well suited for site-augmentation by inclusion of in situ measured meteorological data. If there is the possibility of measuring temperature $T$ directly at the site or at a weather station close by, the accuracy of the resulting zenith wet delays $\Delta L_w^z$ is enhanced by approximately 5%. In case there is also a humidity sensor at the site, then the respective water vapor pressure $e$ can be determined which improves the resulting zenith wet delays $\Delta L_w^z$ by approximately 29%. It hardly makes any difference whether this augmentation is done by applying Eq. (5) or by directly inserting the measured $e$ directly into Eq. (1). Best performance of this site-augmentation is achieved in arid regions such as temperate and high latitudes, although it (slightly) improves the zenith wet delays also in humid regions as in the tropics or on islands.

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## REFERENCES

[1] Askne J., Nordius H., 1987, *Estimation of tropospheric delay for microwaves from surface weather data*. Radio Science, Vol. 22, Issue 3, 379386

[2] Böhm J., Möller G., Schindelegger M., Pain G., Weber R., 2015, *Development of an improved blind model for slant delays in the troposphere (GPT2w)*. GPS Solutions, 1 (2014), pp. 433-441

[3] Davis, J.L, Herring T.A., Shapiro I.I., Rogers A.E.E., and Elgered G. , *Geodesy by Radio Interferometry: Effects of Atmospheric Modeling Errors on Estimates of*

*Baseline Length*, Radio Science, Vol. 20, No. 6, pp. 1593-1607

[4] Landskron, D., Hofmeister A., Böhm J., *Refined and site-augmented tropospheric delay models in the analysis of VLBI observations*, Poster: IUGG 2015 General Assembly, Prague, 2015/06/22-2015/07/02

[5] Saastamoinen, J., 1972, *Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites].* In S.W. Henriksen et al., editors, *The use of Artificial Satellites for Geodesy*, Vol. 15, pp. 247-251, AGU, Washington, D.C.