Refined and site-augmented tropospheric delay models for GNSS applications

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IGS Workshop, 8 – 12 February 2016, Sydney, NSW, Australia

1. Introduction

This poster shows that the performance of tropospheric delays from **empirical troposphere models** such as GPT2w (Böhm et al., 2015) can be **augmented by incorporating in situ measurements** of temperature *T* and water vapor pressure *e*. As is generally known, the hydrostatic part of the delay can determined very accurately by measuring pressure *p* directly at the site. The wet part, however, is not so straightforward to determine, as surface measurements of water vapor pressure are not necessarily representative for the air masses above. Nevertheless, **if** there is **no possibility to access** real-time information from **numerical weather models** (NWM), surface measurements of *T* and *e* may still cause a significant increase in accuracy of the wet delay compared to the empirical-only approach. For this purpose we have developed a new method of augmenting empirical zenith wet delays and **tested** it successfully **for 55 GNSS stations throughout the globe for 2013**, utilizing meteorological data from two different sources: a) from close-by weather stations and b) from in-situ measurements from the IGS.

2. Tropospheric delay modeling

The general concept of modeling tropospheric delays is as follows:

$$\Delta L = \Delta L_h^z * mf_h + \Delta L_w^z * mf_w$$

For IGS sites, there is the possibility to derive the zenith total delay ΔL^z from the **IGS products**. The hydrostatic zenith delay ΔL^z_h can be calculated from the in situ measured *p* using the equation by Saastamoinen (1972), while the hydrostatic and wet mapping functions mf_h and mf_w are taken from VMF1 (Vienna Mapping Functions 1, Böhm et al. (2006)). In consequence, the **high-precision ΔL^z_w** can then be determined by simply rearranging the equation.

3. Augmentation of ΔL^z_w

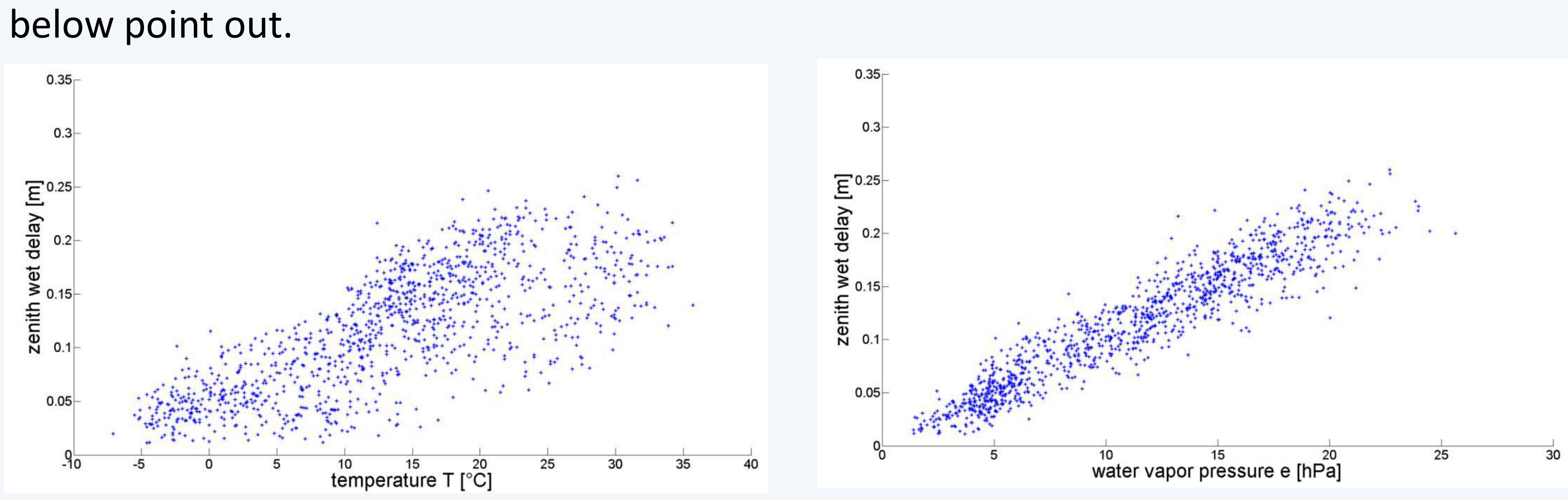
However, there is not always the possibility to exploit real-time data, what prohibits all of the above steps. Instead, one has to use empirical models which are of significantly poorer accuracy. All required quantities can be derived from the **empirical troposphere model GPT2w**, with the **empirical zenith wet delay ΔL^z_w** being calculated by the **formula of Askne and Nordius (1987)** using humidity parameters from GPT2w. However, this empirical ΔL^z_w can be augmented by additional in situ measurements of *T* and *e*. For this reason, we have developed the following **two models**:

$$1.)\ \Delta L_w^z = L^z_{w_{GPT2w}} + M * (T - T_{GPT2w})$$

$$2.)\ \Delta L_w^z = L^z_{w_{GPT2w}} + M_1 * (T - T_{GPT2w}) + M_2 * (e - e_{GPT2w})$$

L^z_w .... augmented zenith wet delay
$L^z_{w_{GPT2w}}$ .... empirical zenith wet delay from Askne and Nordius (1987)
M, M_1, M_2 .... universal, global coefficients
T_{GPT2w}, e_{GPT2w} ...... empirical temperature and water vapor pressure
T, e .... in situ measured temperature and water vapor pressure

When measuring *T* directly at the site, ΔL^z_w can be improved slightly by applying equation (1). Additional measurement of *e* and applying equation (2) yields a significant improvement. Moreover, in negligence of the formulae above, the measured *e* can likewise be inserted directly into the formula by Askne and Nordius (1987) instead of the empirical *e*, what yields similar results (chapter 5).
The augmentation of the empirical ΔL^z_w is possible, as it is **distinctively correlated with *T* and *e***, as the figures below point out.



Plots showing the correlation between T and ΔL^z_w (left) and e and ΔL^z_w (right) for IGS station BZRG in Bolzano, Italy. The applied meteorological data comes from a weather station 6 kilometers away from the GNSS station.

Averaged over all 55 GNSS stations and all 1460 epochs of 2013, the resulting **correlation coefficients** are **0.65 for $T/\Delta L^z_w$** and **0.85 for $e/\Delta L^z_w$**. The globally valid weighting coefficients M, M_1 and M_2 were determined ahead of this investigation in least squares adjustments using ray-traced delays through NWM from 2009-2014 for 19 Very Long Baseline Interferometry (VLBI) stations (Landskron et al., 2015). The table below shows their values.

coefficient	value	unit
M	0.0018	[m/°C]
M_1	0.0005	[m/°C]
M_2	0.0092	[m/hPa]

Acknowledgements:
The authors would like to thank the Austrian Science Fund (FWF) for financial support within the project RADIATE VLBI (P25320).

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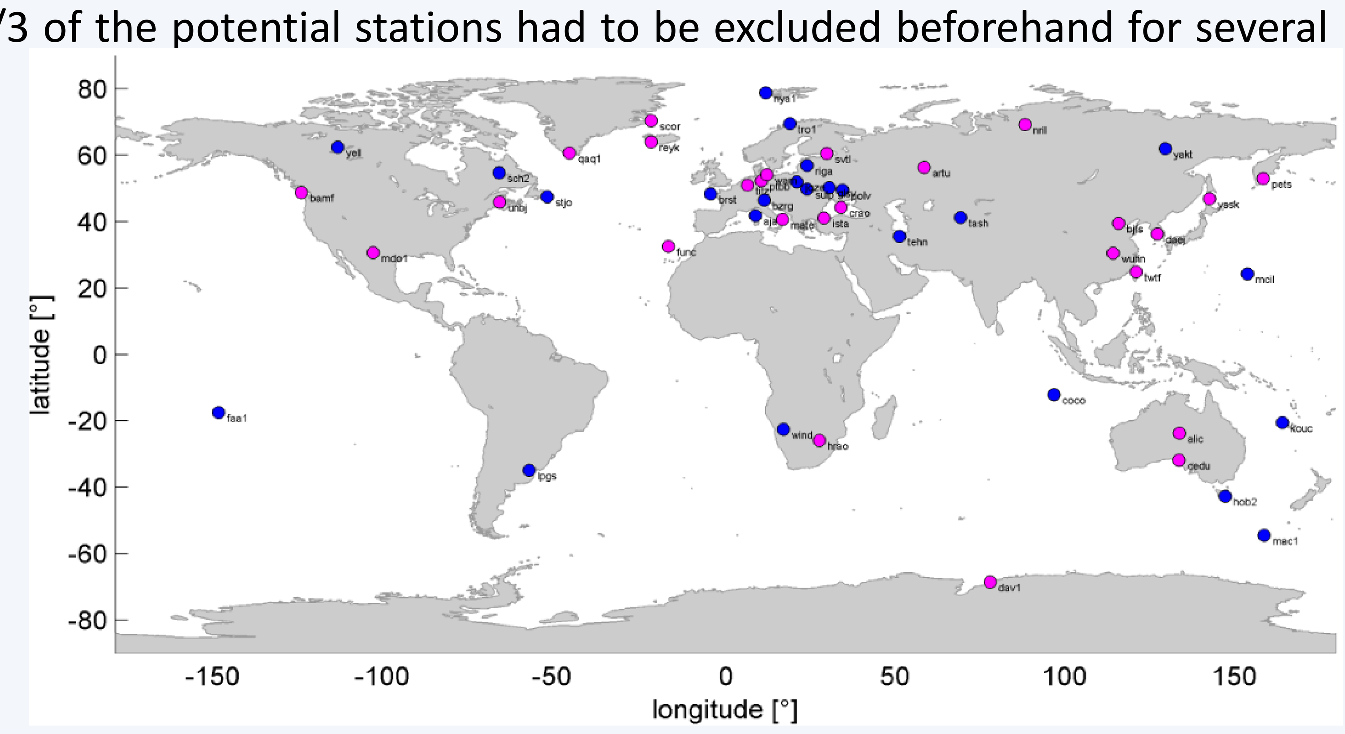
4. Meteorological data

Overall, data of 55 IGS stations was processed, each covering 4 epochs per day in 2013. ***T*, *p* and *e*** come **from two different sources**:

(a) close-by weather stations: 29 stations (blue dots), **high quality**, at maximum 10 km horizontally and 100 m vertically away from the respective GNSS station

(b) in situ measurements provided by the IGS: 26 stations (pink dots), available only for a few of the IGS stations, **moderate quality**, ~1/3 of the potential stations had to be excluded beforehand for several reasons:

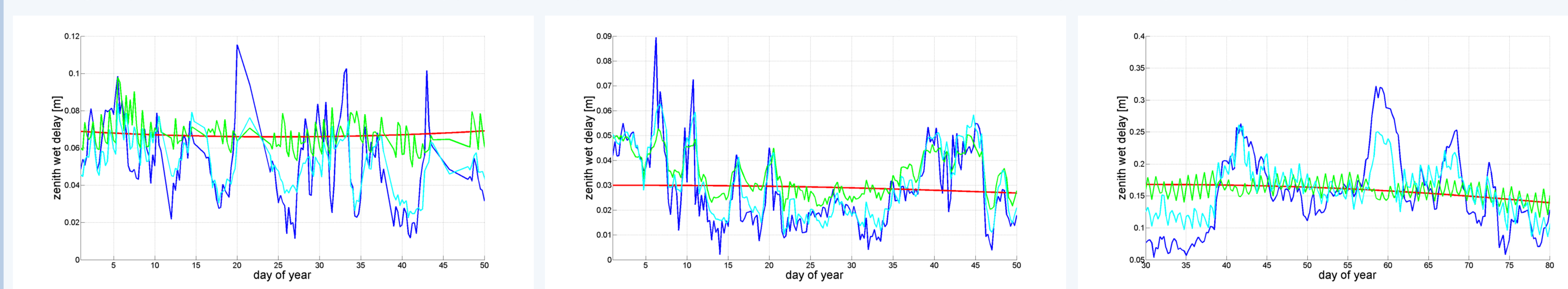
- Entirely wrong *p*, *T* or *e* measurements (11 stations)
- Occasionally wrong *p*, *T* or *e* measurements (2 stations)
- Wrong dates



Since this in situ meteorological data is operationally used for determining precipitable water vapor (PWV), it is quite surprising that the quality is so poor.
As a consequence, the remaining data has to be treated with caution as well, therefore the meteorological data from the weather stations (a) is regarded to be more trustworthy.

5. Results

In order to assess the quality of the augmented ΔL^z_w, reference values have to be defined. These are the **high-precision ΔL^z_w** introduced in section 2. For the upcoming comparisons, they **are** regarded to be the **"true" ΔL^z_w**. In the figures below, the augmentation performance is depicted for three GNSS stations (left to right): BZRG (Bolzano, Italy), NYA1 (Ny Alesund, Svalbard) and ALIC (Alice Springs, Australia).



dark blue line: "true" ΔL^z_w, red line: empirical ΔL^z_w, green line: (1) empirical ΔL^z_w + T, light blue line: (2) empirical ΔL^z_w + T, e

In general, it can be seen that information about ***T* explains only short-time variations of ΔL^z_w**, while additional **knowledge of *e*** helps getting **much closer to the "real" values**. However, the extremes in ΔL^z_w are quite often not modelled very well. Averaging over all 55 stations and 1460 epochs and comparing the results to the true ΔL^z_w yields the following tables:

approach	mean abs. diff [cm] (a)	mean abs. diff [cm] (b)
empirical only	2.8	2.8
(1) empirical +T	2.7	2.6
(2) empirical + T, e	2.0	2.1

approach	Corr. Coeff. (a)	Corr. Coeff. (b)
empirical only	0.70	0.73
(1) empirical +T	0.73	0.76
(2) empirical + T, e	0.86	0.86

Both tables show a distinct improvement of the ΔL^z_w when using the augmentation approaches. Inserting the measured *e* directly into the formula by Askne and Nordius (1987) yields very similar results, being only marginally worse than approach (2).

6. Conclusions

The commonly accepted opinion in tropospheric delay research is that the zenith wet delay ΔL^z_w cannot be described by surface measurements only. However, it can thus be approximated, as results for the **augmentation of empirical zenith wet delays using in situ measured meteorological data clearly reveal an improvement in accuracy**. When the user has the possibility to **measure *T*** at the site, an **improvement of ~5%** is possible; when there is **also** a **humidity** sensor, an **improvement of up to 30%** may be achieved. All GNSS applications which do not have access to real-time NWM data, but have meteorological sensors available may benefit from this augmentation. The prerequisite is the usage of **accurate and reliable meteorological sensors**. **Best performance** of the augmentation approach is achieved **in dry regions**; for sites where there are high amounts and variations of water vapor, such as stations in the tropics or on islands, it performs not so well.

References:

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