# Refined and site-augmented tropospheric delay models in the analysis of VLBI observations


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## 1. Summary


In this poster, two standard approaches in the modeling of tropospheric delays are **enhanced**: the standard **estimation of horizontal tropospheric gradients** is extended to higher orders so that the azimuthal-dependent variations are modeled more precisely. Moreover, the standard approach of using the **empirical delay model GPT2w** (Global Pressure and Temperature 2 wet) is **enhanced by in-situ measurements of meteorological quantities** such as temperature, pressure and water vapor pressure. The quality of the different approaches is eventually determined on the one hand by investigating baseline length repeatabilities (BLR) for the continuous VLBI campaign in 2011 (CONT11) and on the other hand by comparisons to slant delays from ray-tracing using the ray-tracer RADIATE through numerical weather models by the European Centre for Medium-range Weather Forecasts (ECMWF).


## 2. Calculation of gradients

Three different equations are presented which allow the calculation of the slant delays including azimuthal variation:

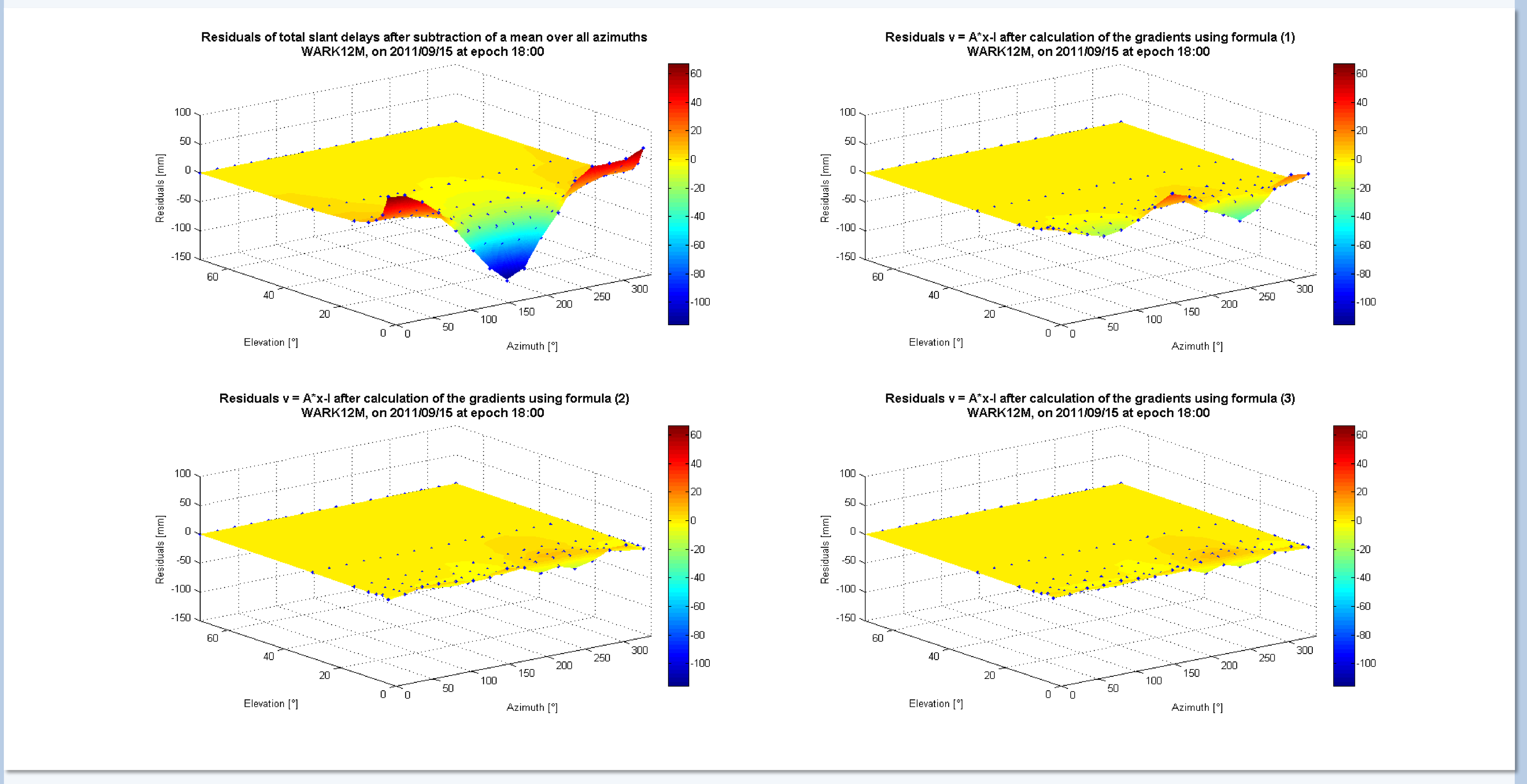
$$(1) \quad \Delta L(a,e) = \Delta L_0(e) + mf_g(e)[G_n \cos(a) + G_e \sin(a)] \qquad \text{(Standard)}$$

$$(2) \quad \Delta L(a,e) = \Delta L_0(e) + mf_g(e)[G_n \cos(a) + G_e \sin(a) + G_{n_2} \cos(2a) + G_{e_2} \sin(2a)]$$

$$(3) \quad \Delta L(a,e) = \Delta L_0(e) + mf_g(e)[G_n \cos(a) + G_e \sin(a) + G_{n_2} \cos(2a) + G_{e_2} \sin(2a) + G_{n_3} \cos(3a) + G_{e_3} \sin(3a)]$$

*a, e.............azimuth, elevation*
*ΔL(a,e).......total delay with gradients*
*$\Delta L_0(e)$........total delay without gradients*
*$mf_g$............gradient mapping function*
*$G_n$, $G_e$.........north and east gradient*
*$G_{n_2}$, $G_{e_2}$,*
*$G_{n_3}$, $G_{e_3}$ ......additional gradient variables*

Equation (1) is the well-known and generally used gradient model by Chen and Herring (1997) whereas equations (2) and (3) are extensions in the form of a progression. Tropospheric delays were calculated by the ray-tracer RADIATE (Hofmeister and Böhm 2014) at **16 constantly distributed azimuths** (0°:22.5°:360°) and **7 elevations** (3°, 5°, 7°, 10°, 15°, 30°, 70°) for each of the **14 VLBI stations participating in CONT11.** The resulting delays were then plugged in in a least squares adjustment in order to determine the gradient coefficients.
Figure 1 shows the **residuals between the ray-traced slant delays and those calculated** by using the three gradient equations for VLBI station WARK12M.




Averaged over all stations and epochs of the CONT11 campaign, the remaining **residuals** compared to the case of applying no horizontal gradients are only **31%** when using equation (1), **22%** when using equation (2) and **20%** when using equation (3).
In VLBI analysis, horizontal gradients can be used in two ways: either as a priori gradients and/or they can be estimated within the VLBI analysis in a least squares adjustment. In the following, the new gradient coefficients are applied as a priori gradients in a VLBI analysis using the Vienna VLBI Software (VieVS, Böhm et al. 2012) for CONT 11. To assess the quality of the results, BLR are calculated for each case:

| a priori gradients | a.) [cm] | b.) [cm] |
|---|---|---|
| none | 1.20 | 1.07 |
| using gradient formula (1) | 1.10 | 1.05 |
| using gradient formula (2) | 1.09 | 1.03 |
| using gradient formula (3) | 1.09 | 1.04 |

a.) mean BLR for the case of NO additional estimation in VLBI analysis
b.) mean BLR for the case of additionally estimating the gradients in VLBI analysis using gradient formula (1)

It can be seen that the **BLR are lowest (best) for** using a priori gradients calculated by **formula (2)**.

As a consequence of this study for the test period of CONT11, it would certainly make sense to think about a **revision of the description of the azimuthal asymmetry**. The additional **gradient variables $G_{n_2}$ and $G_{e_2}$** can be provided in near-real time in the same way as the gradients $G_n$ and $G_e$. The additional provision of the gradient variables $G_{n_3}$ and $G_{e_3}$, however, is not reasonable.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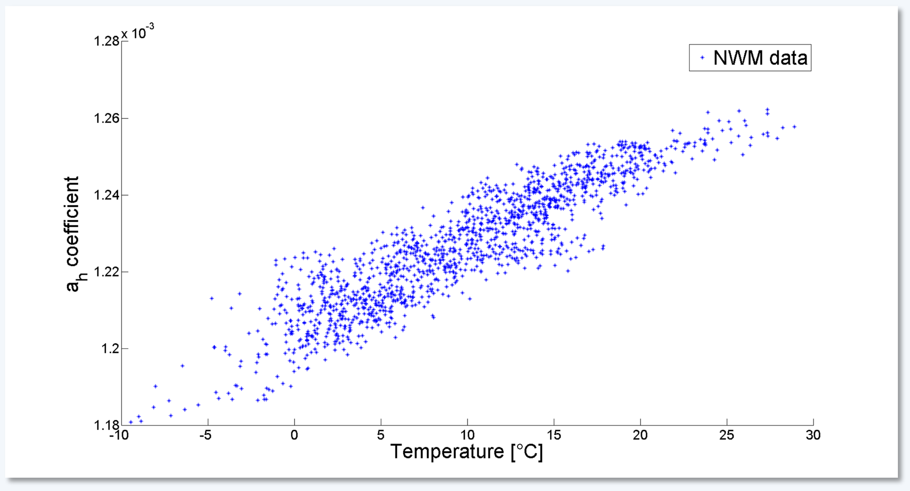
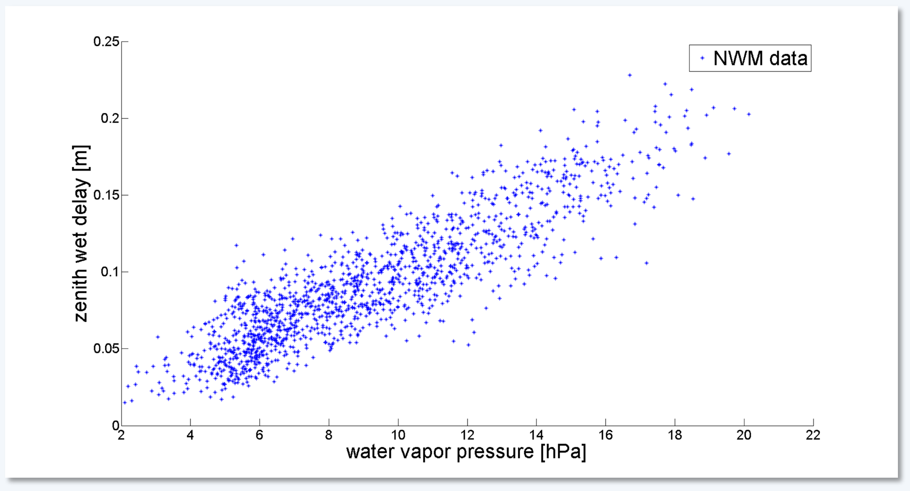
## 3. Site-augmented improvement of GPT2w

The recently published empirical delay model GPT2w (Böhm et al. 2015) provides values for temperature *T*, pressure *p*, water vapor pressure *e* and mapping function coefficients $a_h$ and $a_w$ (amongst others) for any point on Earth. The figures below show that there is a clear **correlation between *T* and $a_h$** (left) **as well as between *e* and the zenith wet delay** (*zwd*, right):




Hence, we found that the **performance of GPT2w can be augmented by including in-situ measurements of *T* and *e***, which are inserted in the formulas below to improve $a_h$ and *zwd*. The idea here is to bring the values closer to those from the Vienna Mapping Function (VMF1, Böhm et al. 2006) and from ray-tracing.

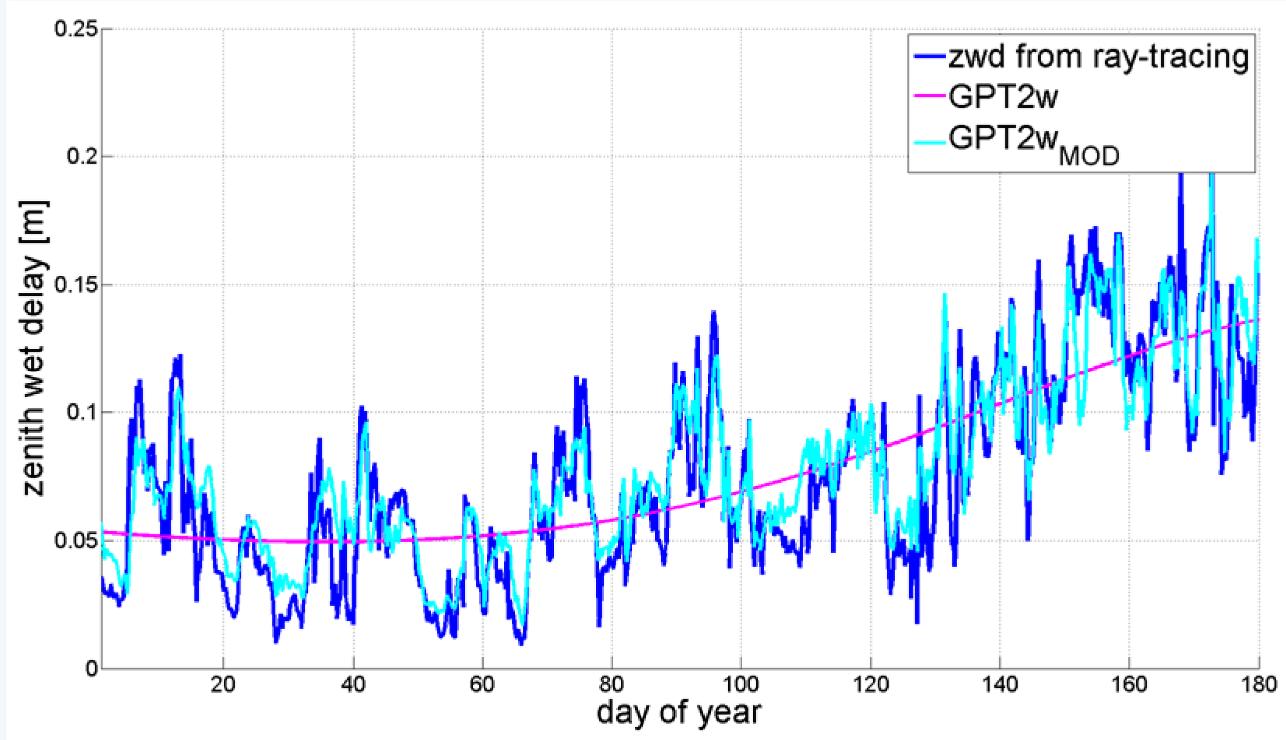
$$(4) \quad a_h = M_{a_h} * (T_{VMF1} - T_{GPT2w}) + a_{h_{GPT2w}}$$

$$(5) \quad zwd = M_{zwd} * (T_{VMF1} - T_{GPT2w}) + zwd_{GPT2w}$$

$$(6) \quad zwd = M_{zwd_1} * (T_{VMF1} - T_{GPT2w}) + M_{zwd_2} * (e_{VMF1} - e_{GPT2w}) + zwd_{GPT2w}$$

*$M_{a_h}$, $M_{zwd}$, $M_{zwd_1}$, $M_{zwd_2}$........universal, global coefficients*
*$T_{VMF1}$, $e_{VMF1}$............................T and e from the VMF1 files (NWM)*
*$T_{GPT2w}$, $e_{GPT2w}$, $ah_{GPT2w}$..........T, e and $a_h$ from GPT2w*
*$zwd_{GPT2w}$................................zenith wet delay calculated with the formula by Askne and Nordius (1987) using e from GPT2w*

Values for $M_{a_h}$, $M_{zwd}$, $M_{zwd_1}$ and $M_{zwd_2}$ were calculated in a least squares adjustment for 6 years of VMF1 data of 18 globally distributed stations. Thus we get improved, more realistic values for $a_h$ and *zwd,* what fits the resulting delays better to the respective delays from VMF1 and ray-tracing, which are regarded as the desired values. This is shown in an example for the first half of 2011 of station WETTZELL in the figure beside (the new approach is henceforth referred to as $GPT2_{MOD}$):




Measurement of *p* enables a very accurate calculation of the zenith hydrostatic delay (*zhd*). The following tables eventually show mean differences in the delays with respect to slant hydrostatic delays (*shd)* at an elevation of 5° from VMF1 and to *zwd* from ray-tracing, respectively. *T*, *p* and *e* from NWM are used as the in-situ measured values here, *zhd* is directly calculated from *p*.

| Mapping function | Δshd [cm] |
|---|---|
| GPT2w | 1.6 |
| $GPT2w_{MOD}$ (T measured) | 1.2 |

| Mapping Function | Δzwd [cm] |
|---|---|
| GPT2w | 2.6 |
| $GPT2w_{MOD}$ (*T* measured) | 2.5 |
| $GPT2w_{MOD}$ (*T* and *e* measured) | 1.7 |

In summary, it can be stated that in-situ **measurement of *T* yields an improvement of the $a_h$ coefficient by one quarter** and a slight improvement of the *zwd*, while additional **measurement of e improves the *zwd* by one third** on average compared to GPT2w.

## 4. Outlook

Upcoming tasks are the implementation of the new a priori gradients in VieVS as well as investigations, whether additional gradient variables can be estimated in the VLBI analysis together with the present quantities (*zwd*, $G_n$, $G_e$, *dUT1*,..). This will yield distinct improvements in the modeling of azimuthal asymmetries. Furthermore, the site-augmented GPT2w presented in chapter 3 will be made operational as well. In this field, more research will be done with using more precise *zwd* from GNSS analysis, since the site-augmented GPT2w is particularly advantageous for GNSS observations and analysis, where no access to information of NWM is possible.

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