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:

\[ \Delta L = \Delta L_{\text{hydro}} + \Delta L_{\text{wet}} \]

For IGS sites, there is the possibility to derive the zenith total delay \( \Delta L_z \) from the IGS products. The hydrostatic zenith delay \( \Delta L_{\text{hydro}} \) can be calculated from the in situ measured \( p \) using the equation by Saastamoinen (1972), while the hydrostatic and wet mapping functions \( m_f \) and \( m_w \) are taken from VMF1 (Vienna Mapping Functions 1, Böhm et al. (2006)). In consequence, the high-precision \( \Delta L_{\text{wet}} \) can then be determined by simply rearranging the equation:

\[ \Delta L_{\text{wet}} = \Delta L_{\text{hydro}} - \Delta L_{\text{wet}} \]

When measuring \( T \) directly at the site, \( \Delta L_{\text{wet}} \) 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 directly inserted into the formula by Askne and Nordius (1987) instead of the empirical \( e \), what yields similar results (chapter 5).

The augmentation of the empirical \( \Delta L_{\text{wet}} \) is possible, as it is distinctively correlated with \( T \) and \( e \), as the figures below point out.

Averaged over all 55 GNSS stations and all 1460 epochs of 2013, the resulting correlation coefficients are 0.65 for \( T/\Delta L_{\text{wet}} \) and 0.85 for \( e/\Delta L_{\text{wet}} \). The globally valid weighting coefficients \( M_1 \) 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.

<table>
<thead>
<tr>
<th>coefficient</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_1</td>
<td>0.0018</td>
<td>[m/K]</td>
</tr>
<tr>
<td>M_2</td>
<td>0.0005</td>
<td>[m/KPa]</td>
</tr>
</tbody>
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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 \( \Delta L_{\text{wet}} \), reference values have to be defined. These are the high-precision \( \Delta L_{\text{wet}} \) introduced in section 2. For this purpose, we use the "true" \( \Delta L_{\text{wet}} \). In the figures below, the augmentation performance is depicted for three GNSS stations (left to right): BZRG (Bolzano, Italy), NVA1 (Ny Alesund, Svalbard) and ALIC (Alice Springs, Australia).

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

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>empirical only</td>
<td>2.8</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>(1) empirical + T</td>
<td>2.7</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>(2) empirical + T, e</td>
<td>2.0</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Both tables show a distinct improvement of the \( \Delta L_{\text{wet}} \) 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 \( \Delta L_{\text{wet}} \) 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: