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Small scale atmospheric variations sensed with very short baseline interferometry (VSBI) and microwave radiometry

G. Elgered and R. Haas

Abstract We have compared differential zenith wet delays, estimated between the 20 m telescope and the twin telescopes at Onsala, with linear horizontal gradients from a water vapour radiometer (WVR). The east and north gradients from the WVR are projected on to the baseline between the telescopes. The formal errors of the estimated differential zenith delays are comparable to the size of the estimated values. We obtain correlation coefficients for specific 24 h experiments in the range from 0 to 0.2, and the overall correlation is 0.1. Although the correlations are low, we use simulations to verify that they are in the expected range.

Keywords wet delay, horizontal gradients, microwave radiometry

1 Introduction

Three telescopes at the Onsala Space Observatory are regularly used in geodetic VLBI experiments: the 20 m radome enclosed telescope (ON) and the twin telescopes (OE and OW). The distance between the twin telescopes is approximately 75 m and they are in turn approximately 500 m southwest of the 20 m telescope, see Figure 1. The location of the Onsala telescopes close to the coast line suggests that there may occasionally be significant local horizontal gradients in the atmospheric water vapour content. Horizontal gradients estimated by collocated GNSS stations and a Water Vapour Radiometer (WVR) frequently reach a size of several millimetres (Elgered et al., 2019). In this study we address if it is reasonable to estimate the differential equivalent zenith wet delay (ΔZWD) between the 20 m telescope and the OTT telescopes. A series of 25 local Very Short Baseline Interferometry (VSBI) experiments has been carried out with these three telescopes in 2019 and 2020 (Varenius et al., 2021).

The ΔZWD relates to the horizontal linear gradient, G, projected on to the baseline, $\overline{b}$, between the telescopes via the scale height, h_s, of the wet refractivity and the distance between the telescopes:

$$\Delta \text{ZWD} = \frac{|\overline{b}|}{h_s} \cdot G \qquad (1)$$

Elósegui et al. (1999) and Zus et al. (2019) have estimated the scale height to be in the range from 1 to 3 km. Assuming a scale height of 2 km a typical gradient size inferred from the WVR observations of 1 mm, then corresponds to a ΔZWD of 0.25 mm over the approximately 500 m baseline between the telescopes. With this in mind we compare the horizontal gradients inferred from the data WVR with the ΔZWD estimated in the analysis using the interferometry data from the 20 m and the OTT telescopes.

In Section 2 we describe the VSBI and WVR data processing. In Section 3 we present the comparisons between the ΔZWD estimated from the interferometer data with the horizontal gradients estimated from the WVR data, and in Section 4 we assess the quality of the results using simulations based on the estimated observed parameters and their formal errors. Finally, the conclusions are given in Section 5.

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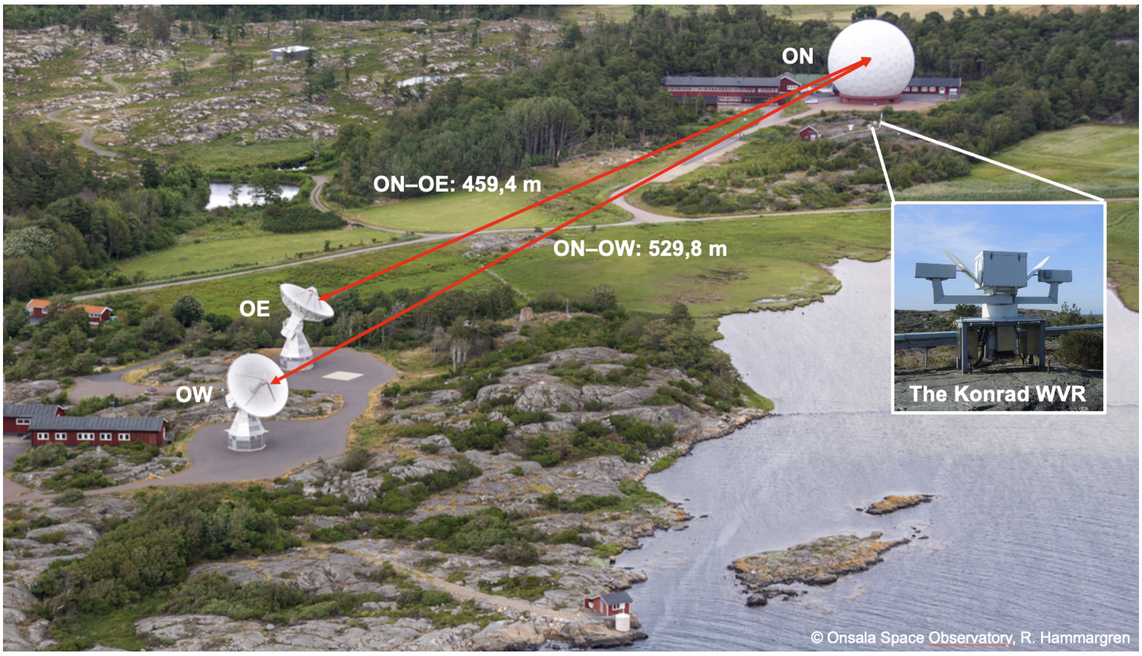

Fig. 1 The three telescopes used for geodetic VLBI at Onsala: the 20 m radome enclosed telescope and the twin telescopes. The WVR is located close to the 20 m telescope.

2 Input data

The VSBI data analysis was carried out using the ASCOT software (Artz et al., 2016) as follows:

- A group delay analysis was performed.
- The station coordinates were fixed for the 20 m telescope (ON) on VTRF2020b, but estimated for the twin telescopes (OW and OE).
- The reference clock was ON. Clock parameters for OE and OW were estimated every hour.
- The ZWD was fixed at OE and OW, based on the ground pressure referred to the reference points, and estimated for ON as a continuous piece-wise linear function updated every 5 min. We tested to carry out the analysis with different constraints for the ZWD, from 50 ps/h to 350 ps/h. All observations down to an elevation angle of 5° were used.
- EOP and radio sources were fixed according to IERS C04 and ICRF3.

The WVR data were analysed with our in house software as described by Elgered et al. (2019). However, the observing schedule was different during 2019 and 2020. The WVR was operated according to a 5 min long cycle, during which 52 observations were distributed over the sky at elevation angles from 25° and above (see Figure 2). This means that we had a good sky coverage in order to estimate linear horizontal gradients with a temporal resolution of 5 min. The reason for the high elevation cutoff angle was to avoid ground noise pickup. A drawback of the WVR is that data acquired during rain, or when the equivalent zenith liquid water content is larger than 0.7 mm, are inaccurate and therefore ignored. There were also several periods during the VSBI experiments when the WVR was unstable and these data were also deleted. A final requirement was that there had to be at least 40 of the scheduled 52 observations in a 5 min period in order to estimate gradients.

Both the WVR gradients and the differential zenith delays, ΔZWD, were estimated every 5 min. However, they were not synchronized, and as mentioned above there are also many data gaps in the WVR gradient time series. Therefore, in order to be used in the comparison, we required a maximum difference between the time epochs of the samples of $\pm$2.5 min. Finally, out of the original 6414 ΔZWD estimates, from the 25 experiments, we had 3044 matching gradients from the WVR for the comparison.

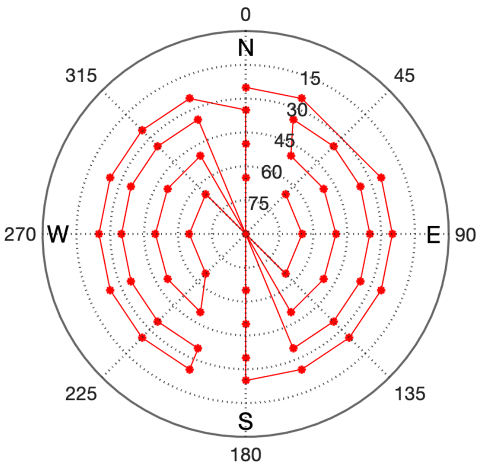

Fig. 2 One measurement cycle of the WVR consists of 52 observations. The cycle starts in the north direction with an elevation angle of 25° and is repeated every 5 min. The zenith point is only measured once, the first time it passes over zenith direction.

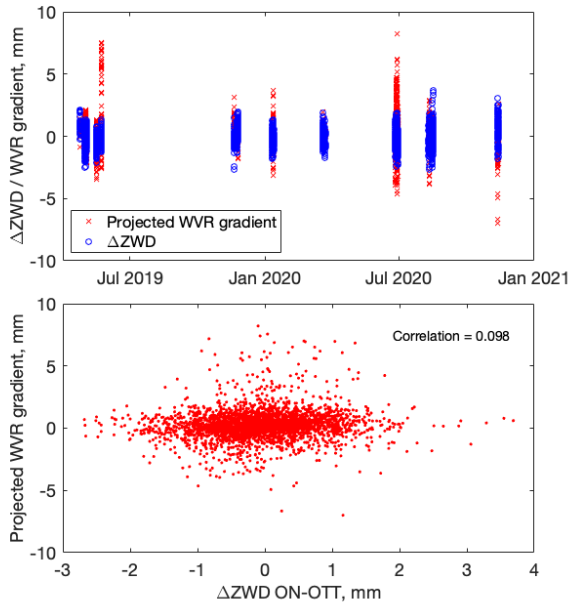

Fig. 3 All estimated projected WVR gradients and ΔZWD obtained when the constraint of 350 ps/h is applied in the VSBI analysis. Time series of the individual experiments (top) and a correlation plot (bottom).

3 Results

The results presented are based on the 3044 data pairs of projected WVR gradients and the ΔZWD from the VSBI experiments if nothing else is stated.

The estimated values and their formal uncertainties are summarised in Table 1. The formal uncertainties of the ΔZWD, from the VSBI analysis, are typically larger than the estimated values and the effect of course increase when the constraint is weaker. The uncertainties of the WVR gradients are scaled meaning that if the true wet delays in the different directions have deviations from the linear gradient model the uncertainties increase. Such deviations will be common during convection processes and the assumption of linear changes of the wet refractivity in a layered atmosphere will not be accurate.

The correlations for the whole dataset of 25 experiments and 3044 data points between the ΔZWD and the WVR gradient projected on to the OTT–ON averaged baseline are calculated for the three cases with different applied constraints. The correlation coefficients are 0.077, 0.109, and 0.098 for the constraints of 50 ps/h, 200 ps/h, and 350 ps/h, respectively. Given the small relative size of the atmospheric signal compared to the uncertainties we do not regard these differences as significant.

We find, as expected, that both the differential ΔZWD between the 20 m telescope and the OTT telescopes and the gradients estimated from the WVR are slightly larger during the warmer season when there is a higher water vapour content in the atmosphere. The time series and the correlation plot are shown in Figure 3 for the case when a constraint of 350 ps/h is applied.

The effect of using different constraints is further illustrated in Figure 4 where we present the data from two experiments, each one with a duration of 24 h, that show one of the highest correlations. A tighter constraint reduce the noise, but at the same time the possibility to catch and follow rapid changes are decreased. An overall result for all the experiments studied is that weakening the constraint results in larger ΔZWD values and more noise. In this specific case also the correlation decreases when the constraint is weaker but for the whole data set it seems as the advantage of being able to track short term variations is balanced by the increased noise.

Table 1 Statistics of ΔZWD and the WVR gradients projected on to the OTT–ON average baseline

ΔZWD constraint (ps/h)	Mean absolute (mm)	Maximum absolute (mm)	Mean formal error (mm)	Maximum formal error (mm)
50	0.34	1.70	0.36	0.98
200	0.49	3.09	0.61	1.59
350	0.58	3.91	0.76	2.01
WVR gradient (no constraint)	0.80	8.21	0.09	0.84

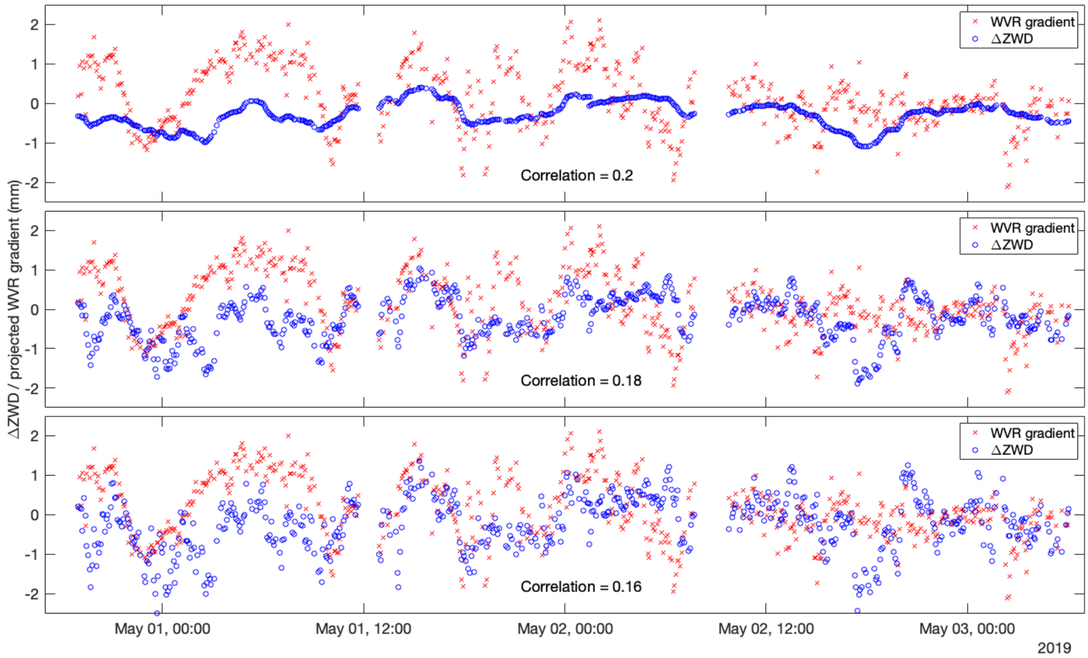

Fig. 4 An example of estimated ΔZWD (ON–OTT) and WVR gradients projected on to the ON–OTT baseline for two contiguous experiments (19APR30VB and 19MAY02VB). The applied constraints are 50 ps/h (top), 200 ps/h (middle), and 350 ps/h (bottom).

4 Simulations

In order to assess the results we carried out a couple simple simulations as follows.

- We generated a time series of projected WVR gradients with a mean value of zero and a gaussian distribution with a standard deviation (SD) equal to 0.5 mm.
- Using Eq. (1 with a scale height of 2 km and a baseline length of 500 m we calculated the corresponding time series of ΔZWD. These simulated time series of true values are then of course perfectly correlated.
- Gaussian noise with an SD of 0.1 mm was added to the WVR gradient time series and three different time series adding different SD were generated for the ΔZWD (0.3, 0.6, and 0.8 mm, based on the three different constraints in Table 1).
- The resulting correlation coefficients were 0.35, 0.18, and 0.15.

We note that the correlation obtained based on the values corresponding to the constraint of 350 ps/h is closest to the observed values. Our preliminary interpretation is that using a the tighter constraint, acting as a low pass filter, means that the temporal resolution shall be significantly lower than 5 min, which in turn means that the assumed size of the true WVR gradients shall also be smaller.

This is illustrated by another simulation. When reducing the SD of the assumed true WVR gradients from 0.5 mm to 0.2 mm, reducing the SD of the WVR gradient noise from 0.1 mm to 0.05 mm, and adding the ΔZWD noise of 0.3 mm (corresponding to the 50 ps/h constraint), the correlation becomes 0.14.

5 Conclusions and future work

Given the relative large values of the uncertainties compared to the estimated values, a relevant question is if it is motivated to solve for a ΔZWD when the baselines between the telescopes are as short as 500 m. Of course, the short baselines between the telescopes implicates that no large differences in the differential zenith delays are expected. Although the estimated differences are most of the time very small they may also absorb other errors in the observations and uncertainties in the models used, thereby hiding the possibility to identify the origin of such problems. This motivates the operation of a co-located WVR in order to estimate independent ZWD and gradients. These can than be used to search for large differences compared to the corresponding expected ΔZWD in order to identify and eliminate problems that are not necessarily caused by the atmosphere.

In this study we focused on the highest possible temporal resolution, defined by the gradients inferred from the WVR data. The primary goal was to assess if it would be meaningful to estimate differential zenith delays between the the Onsala 20 m telescope and the twin telescopes telescopes. However, from a geodetic point of view, i.e. in terms of the accuracy of the estimated geodetic parameters, a lower temporal resolution is possibly a better strategy. We have not yet addressed this question.

Future work in order to assess the modelling of the wet atmosphere is proposed to also analyse experiments where the Onsala telescopes are included in long baseline experiments, allowing estimates of the ZWD for each telescope, or for a combination of telescopes.

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