Atmospheric VLBI: A method to validate long time series of water vapour content

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Abstract. We assess the possibility to validate time series of the atmospheric integrated water vapour (IWV) from GPS observations using geodetic VLBI at the Onsala Space Observatory in Sweden. An overall motivation is to determine the relation—and its uncertainties—between trends in the IWV with trends in the ground temperature. We find that the frequency of VLBI experiments is too low in order to validate estimated linear trends using data acquired over a ten year period. On the other hand, the VLBI method provides an accuracy of the same order, compared to using GPS or nearby radiosonde launches for validation of the IWV on an absolute scale. Further assessments using other, as well as larger, data sets are called for.

Keywords. VLBI, atmospheric water vapour, global wetting, global warming

1 Introduction

Water vapour is an important atmospheric gas in climate models. A specific question at issue is the relation between changes in the temperature and possible corresponding changes in the integrated water vapour (IWV). Following the Clausius-Clapeyron relation, assuming conservation of relative humidity, we obtain a relation for the IWV changes due to a change in the temperature of approximately 6 [%/K] (Trenberth et al., 2003). Analyses and comparisons of trends in the temperature and the IWV using the ERA40 model do not give an accurate assessment of this relation. This is argued to be due to artifacts in the global observing system of water vapour (Bengtsson et al., 2004). Accurate observations, and especially with a high long term stability, of the IWV as well as of the temperature are therefore important.

The possibility to infer the IWV from space geodetic observations has been demonstrated, with increasing quality, during the last twenty years. First by using geodetic VLBI data (e.g. Herring et al., 1990; Heinkelmann et al., 2007) and thereafter also based on GPS (e.g. Tralli & Lichten, 1990; Elgered et al., 2005). Ground-based GPS receiver stations provide a relatively high spatial resolution and results in close to real time, at least compared to VLBI. Therefore, the IWV estimates from GPS networks are nowadays used, and their impact assessed, in assimilation into numerical models for weather prediction. The absolute accuracy, and especially the long term stability of the GPS results is of fundamental importance for applications in climate research. In order to assess the stability of the GPS results an independent, preferably a more stable and accurate, method is called for. We here investigate to what extent geodetic VLBI is an appropriate method for this task. For this purpose we use geodetic VLBI and GPS data from the Onsala Space Observatory and radiosonde data from the Göteborg-Landvetter Airport.

In Section 2 we present an overview of the results recently obtained in terms of linear trends in the IWV using data acquired with the Swedish and Finnish ground-based GPS networks from 1996 to 2006. Section 3 describes the analysis of the geodetic VLBI experiments at Onsala. In Section 4 we compare the results of the estimated IWV using VLBI, GPS, and radiosondes. Section 5 contains the conclusions.

2 GPS estimates of IWV

2.1 Summary of estimated trends

Linear trends in the IWV were recently estimated using ten years of GPS data from the ground-based GPS networks in Sweden and Finland (Nilsson & Elgered, 2008). The trends were estimated from the IWV data using the following model:

$$\begin{aligned} V &= V_0 + a_1\, t + a_2 \sin(2\pi t) + a_3 \cos(2\pi t) \\ &\quad + a_4 \sin(4\pi t) + a_5 \cos(4\pi t) \qquad (1) \end{aligned}$$

where t is the time in years and the coefficients V_0, a_1, a_2, a_3, a_4, and a_5, are estimated using the method of least squares. The overall linear trends are identical to the estimated parameters a_1 for the different sites. These are shown in Figure 1. In general we see positive trends, except for the south-east part of Sweden.

The same type of six-parameter model is used throughout this paper to model also the ground temperatures of sites nearby the GPS receiver stations, and the equivalent zenith wet delay (ZWD) estimated from VLBI, GPS, and radiosonde data.

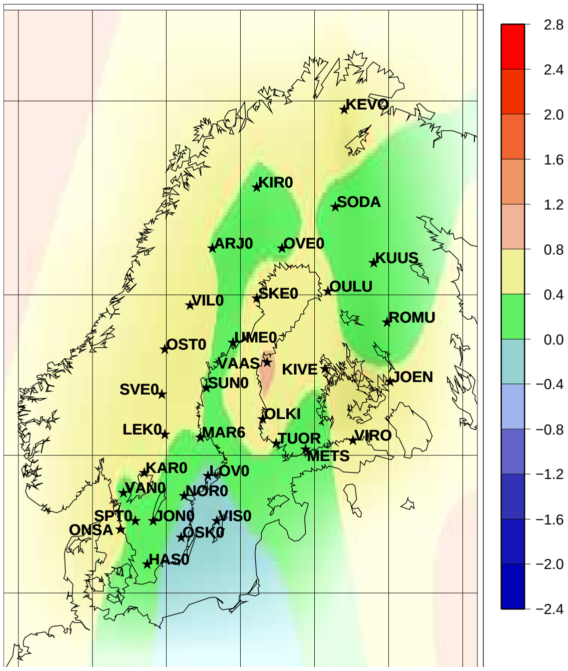

Figure 1. Estimated trends in the IWV from 1996 to 2006, from (Nilsson & Elgered, 2008).

2.2 On the relation between ground temperature and IWV

Space geodetic data offer a new and independent method compared to traditional meteorological observations. We expect that an increase in the temperature will correspond to an increase in the IWV. We analysed monthly means of ground

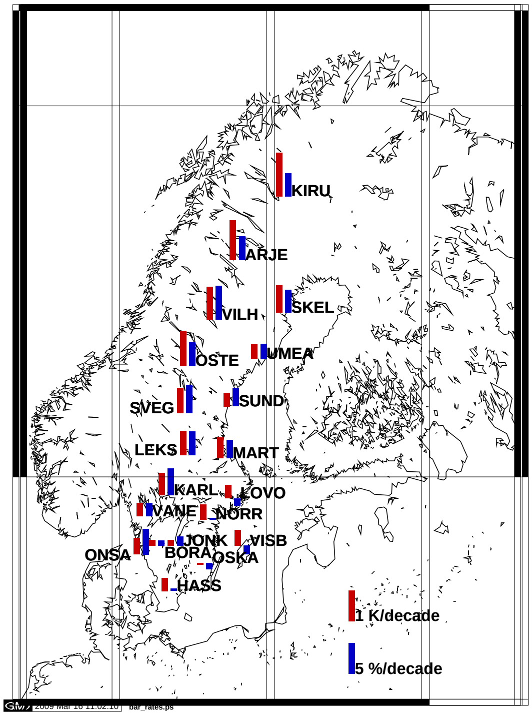

Figure 2. IWV trends from GPS sites in the Swedish GPS network and the corresponding trends in the ground temperature at nearby sites.

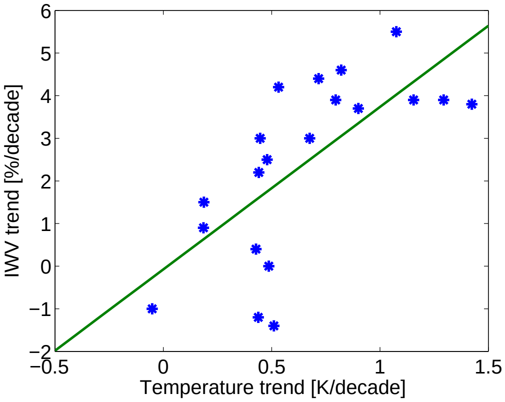

Figure 3. The relation of estimated IWV trends from GPS sites in the Swedish GPS network vs. the corresponding trends in the ground temperature at nearby sites.

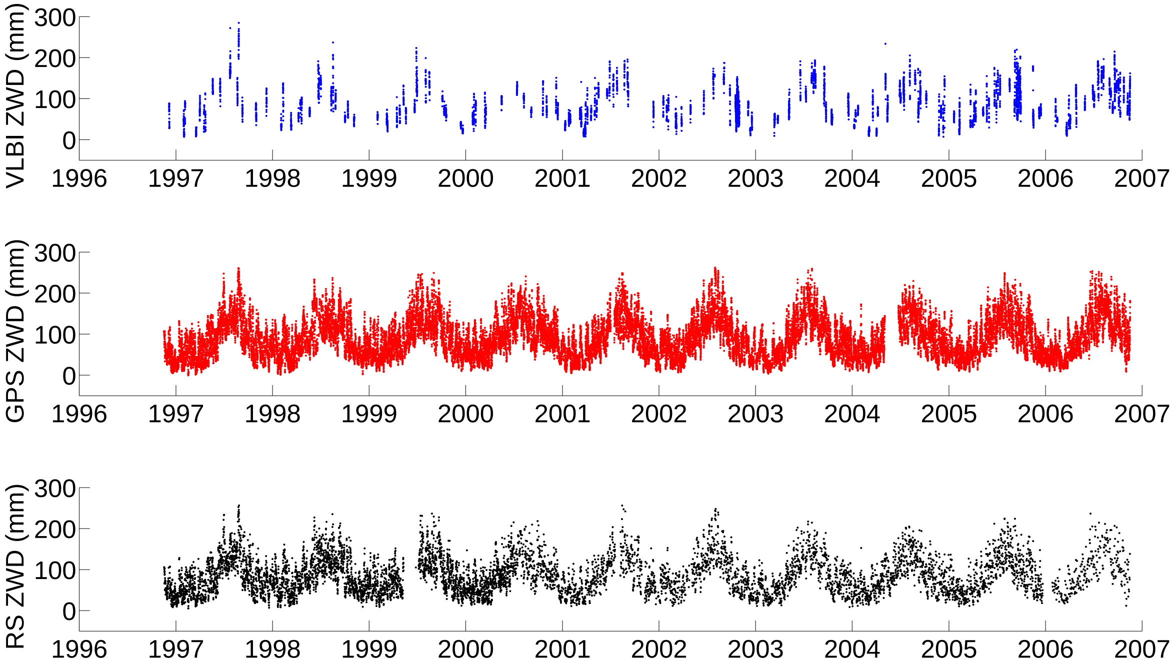

Figure 4. Time series of the equivalent zenith wet delay (ZWD) estimated from VLBI data (top), GPS data (middle), and radiosonde data (bottom).

temperatures from the observational network of the Swedish Meteorological and Hydrological Institute (SMHI) from the same ten year period as we have GPS derived IWV results. Linear trends were estimated also from these data and they are presented together with the IWV trends in the map in Figure 2.

A correlation plot between the trends is shown in Figure 3. The correlation coefficient of the data is 0.69, meaning that it has been shown that the two trends are correlated with a probability larger than 99%. It is also interesting to note that the linear slope is 3.8%/K. This indicates that the relative humidity is this area has not been conserved during the studied time period. Additional studies using different data sets are necessary in order to assess the uncertainty of this parameter.

In the remainder of this paper we will focus on the possibility to validate the IWV trend at Onsala, which is 0.58 kg/($m^2\cdot$ decade). This corresponds to a relative trend of 4.2%/decade, and a trend in the ZWD of 3.7 mm/decade. In the following we will use ZWD time series from VLBI and radiosonde observations to represent the IWV.

3 Geodetic VLBI data analysis

We will assess the use the ZWD estimated from VLBI data for the comparisons with the results from the other methods. The estimated time series of the ZWD originate from analyses of the global VLBI data set covering the period of interest: 17 Nov. 1996 – 16 Nov. 2006. In total 230 such 24 h long sessions included the Onsala telescope. The data were analysed with the CALC/SOLVE software (Ma et al., 1990). Radio source positions, station positions and velocities were estimated as global parameters, and earth rotation and orientation parameters as daily parameters. The necessary no-net-translation and no-net-rotation constraints were applied. Clock and atmosphere parameters were estimated as piece-wise linear functions with a 1 h resolution, and horizontal atmospheric gradients as piece-wise linear functions with a 3 h resolution. Solid earth tides, ocean loading and atmospheric loading were applied in the analysis. An elevation cutoff angle of 5 degrees was used in two different solutions, one using the NMF mapping functions (Niell, 1996), and another one using the VMF1 mapping functions (Böhm et al, 2006).

Figure 4 shows the time series of estimated ZWD from the VLBI analysis using the NMF

Table 1. Linear trends in the ZWD inferred from GPS and VLBI data from Onsala and radiosonde (RS) data from Landvetter airport.

Data source	Data points	Trend (mm/decade)
synchronizing VLBI and GPS		
VLBI (NMF)	2737	6.3 ± 0.4
VLBI (VMF1)	2737	6.6 ± 0.4
GPS	2737	9.9 ± 0.4
synchronizing VLBI and RS		
VLBI (NMF)	511	7.3 ± 0.8
VLBI (VMF1)	511	7.8 ± 0.8
RS	511	6.5 ± 0.8
synchronizing GPS and RS		
GPS	7914	5.4 ± 0.2
RS	7914	3.3 ± 0.2
synchronizing GPS(synchro2VLBI) and RS		
GPS	479	6.6 ± 0.8
RS	479	6.0 ± 0.8
unsynchronized (all) data *17 Nov. 1996 – 16 Nov. 2006*		
VLBI (NMF)	5746	6.4 ± 0.3
VLBI (VMF1)	5746	6.9 ± 0.3
GPS	41104	3.7 ± 0.1
RS	8500	3.1 ± 0.2

mapping function. Also included in this figure are the GPS and the radiosonde data. It is obvious that the relatively sparse sampling of the atmosphere with VLBI means that significant periods with potentially large deviations from the ZWD model can be missed compared to the other methods. In the next section these different time series will be compared.

4 Comparison results

In order to be able to compare the estimated ZWD trends from the different methods the data shall be acquired during the same time periods. As mentioned earlier, the VLBI data have a temporal resolution of 1 h during the experiments. The GPS data have a 2 h resolution, while the radiosonde data have a 6 h (1996– mid 2000), a 12 h (mid 2000 – end of 2005), and a 24 h temporal resolution (since 2006). The trend calculations are first based on synchronized data sets and then also estimated from the complete unsynchronized data sets. All estimated trends are presented in Table 1.

We note that all the estimated ZWD trends are positive, which is consistent with earlier studies using data from Onsala but acquired during different time periods (Haas et al., 2003).

Furthermore, we note that the trends estimated using the NMF or the VMF1 mapping functions in the VLBI analyses are not significantly different.

The presented uncertainties of the trends are one standard deviation (1σ) values, assuming uncorrelated white noise deviations from the model. These shall be considered as minimum values because a temporal correlation is expected for values closer than a couple of days (Nilsson & Elgered, 2008). This is especially true for the larger data sets, where the individual data points are closer in time.

Considering that the error bars maybe inflated by a factor of four, the disagreement between the different methods is reasonable. However, there are details that ought to be studied further.

For example, the trend obtained from the GPS data is significantly larger than the VLBI trend when using GPS data synchronized to VLBI experiments. On the other hand we obtain a consistent trend if the GPS data are synchronized to both the VLBI and the radiosonde data.

In order to study the accuracy of the three methods further, we calculate the root-mean-square (RMS) differences between data pairs of the different ZWD time series. These results are presented in Table 2.

Again we note that the impact of using the different mapping functions in the VLBI analyses is small. They only affect the ZWD bias, but at the level of 0.6 mm. As expected we also see the best agreement between the VLBI and the GPS results because the radiosondes are launched approximately 37 km from the Onsala site. Further conclusions are difficult to draw. The RMS differences are slightly larger for the VLBI–radiosonde calculation compared to the GPS–radiosonde result, suggesting that the GPS data are slightly more accurate, but we note that the difference is hardly significant when restricting the GPS–radiosonde comparison to the same periods as there are VLBI data available. In order to address this problem in more detail, further investigations are required based on other, as well as larger, data sets.

Table 2. RMS differences in the ZWD inferred from GPS, VLBI and radiosonde data acquired during the time period Nov. 1996–Nov. 2006.

Compared synchronized data Method 1 − Method 2	Number of data points	Mean ZWD[1] (mm)	RMS (mm)	Bias[2] (mm)
VLBI (NMF) – GPS	2737	91.3	7.5	−1.1
VLBI (VMF1) – GPS	2737	91.3	7.5	−0.5
VLBI (NMF) – radiosonde	511	86.2	11.4	−0.1
VLBI (VMF1) – radiosonde	511	86.2	11.3	+0.5
GPS – radiosonde	7914	84.6	10.2	+1.7
GPS – radiosonde (VLBI periods only)	479	85.6	10.7	+2.8

[1] The mean value is that of Method 2

[2] Method 1 − Method 2

5 Conclusions

Our preliminary analysis suggest that approximately monthly geodetic VLBI experiments do not give a sufficient temporal resolution in order to validate linear trends in the IWV estimated from ground-based GPS data at the Onsala site over a ten year period. However, when comparing the RMS differences between the ZWD from VLBI, GPS, and radiosonde data, we conclude that the VLBI data seem to be of a quality—in terms of accuracy—which is comparable to the other methods.

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