Assessing Long Term Trends in the Atmospheric Water Vapor Content by Combining Data From VLBI, GPS, Radiosondes and Microwave Radiometry

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Summary: Consistent time series of integrated precipitable water vapor (IPWV) are important when estimating long term trends associated with climate change. Space geodetic and remote sensing techniques offer different advantages in terms of a long observation history, instrumental stability, and measurement uncertainty. We use four different techniques at the Onsala Space Observatory on the Swedish west coast namely geodetic VLBI, ground-based GPS, microwave radiometry, and radiosondes. The individual advantages and disadvantages are exploited to assess the long-term trend in the IPWV. A combined linear trend for the IPWV and the time period 1980-2002 is estimated to +0.17 ± 0.01 mm/yr.

1 Introduction

Water vapor in the atmosphere is one of the most effective so-called ”greenhouse gases”. Thus, consistent time series of integrated precipitable water vapor (IPWV) are an important data product for meteorology and climate research. Since changes in the atmospheric water vapor might be related to climate change scenarios originating to some extent from antropogenic influences, the monitoring of possible changes of IPWV is of major interest to society.

Different remote sensing and space geodetic techniques are sensitive to atmospheric water vapor and thus can contribute to this task. For example, trends in the IWPV have been derived from radiosonde data covering more than a decade of observations (Gaffen *et al.*, 1992). Also microwave radiometry observations covering more than 15 years have been used to derive long-term trends in the IWPV (Elgered and Jarlemark, 1998). Recently, many years of observations with the Global Positioning System (GPS) have been used to derive trends in the atmospheric water vapor content (Gradinarsky *et al.*, 2001). The possible importance of VLBI results for climate studies has also been pointed out (Niell *et al.*, 2001).

However, each of the above mentioned techniques has its specific advantages and disadvantages in terms of instrumental stability, long observation history, measurement uncertainty, temporal and spatial sampling. Therefore, a combination of results from complementing techniques promises to be a robust approach for the assessment of possible long term trends in the atmospheric water vapor content. For this purpose we use data obtained with several different techniques at the Onsala Space Observatory at the Swedish west coast. The observatory hosts collocated equipment for space geodetic and remote sensing techniques, i.e. for geodetic VLBI, the Global Positioning System (GPS) and microwave radiometry. Furthermore, radiosonde launches are performed at the Gothenburg-Landvetter Airport at about 37 km distance from the observatory. Thus, results for IPWV from these four techniques will be compared and combined.

Sections 2-5 of this paper describe the four different techniques, their specialities, advantages and disadvantages. They present the individual data analysis and the results derived for long term trends in IPWV from the individual techniques. In Section 6 we compare the results of the individual techniques and address the question of data sampling and complementing data sets. Section 7 deals with the combination of the results obtained with the four techniques. Finally, Section 8 briefly discusses the combination results and draws some conclusions.

2 Geodetic VLBI observations at the Onsala Space Observatory

The first successful Mark III geodetic VLBI observations were performed at the Onsala Space Observatory in 1980. Since then the observatory participates regularly in geodetic VLBI sessions and usually 20 to 30 individual VLBI sessions per year are observed. During the years the observatory also participated in a number of continuous campaigns, e.g. Cont94, Cont95, Cont96, Cont01 and Cont02. Nevertheless, the observation sessions unfortunately were not, and are not, on regular intervals. This is definitely a disadvantage of the technique and causes a sampling problem for the monitoring of the IPWV. Besides the temporal sampling, also the spatial sampling of VLBI is one of the techniques disadvantages. There are less than 150 telescopes world-wide that have been and are used for geodetic VLBI and 90% of them are located on the northern hemisphere. The number of telescopes that have been used for observations over a total time span of more than 10 years is less than 30. On the other hand, the VLBI technique has the advantage of high long term stability due to its stable instrumentation. Another advantage is that the relatively small amount of available VLBI data easily can be reprocessed for specific purposes using consistent assumptions and models.

The VLBI data used for this study were analysed using the Calc/Solve analysis software package (Ma *et al.*, 1990). Zenith wet delays (ZWD) were estimated every 1 hour, horizontal delay gradients (HDG) were estimated every 3 hours. The Niell mapping functions (Niell, 1996) were applied. The ZWD results were converted into IPWV results using a conversion formula based on the season and latitude of the station (Emardson *et al.*, 1998). Figure 1 shows the IPWV results obtained from VLBI, the upper plot the total values and the lower plot the corresponding formal errors. It is clearly visible that the measurement uncertainty decreased over the years. This is mainly due to increased number of observations per observation session and improved and optimised observation geometry.

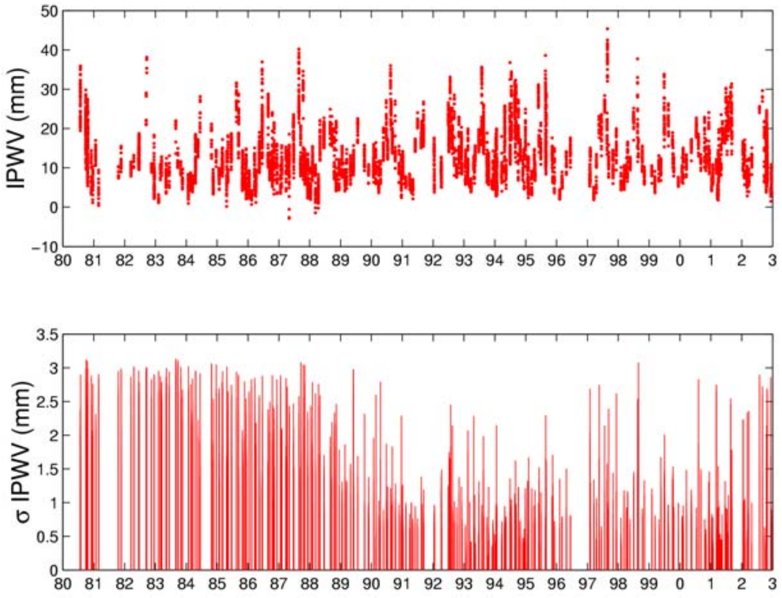

Figure 1: IPWV results derived from VLBI observations at the Onsala Space Observatory between 1980 and 2003.

3 Microwave Radiometry at the Onsala Space Observatory

Microwave radiometry measurements are performed at the Onsala Space Observatory with the water vapor radiometer (WVR) ASTRID since 1980 (Elgered *et al.*, 1991). The instrument is equipped with 2 channels with center frequencies at 21.0 and 31.4 GHz. It has two horn antennas with full width half power beams of 6 degrees. During the 1980ies the instrument was mainly operated during VLBI sessions only. Since 1993 the instrument is used almost continuously in a so-called ”sky-mapping mode”. In 1991/1992 the instrument was upgraded and mechanical parts and calibration loads were improved. Recently (Elgered and Haas, 2003, this volume), the instrument was upgraded again in terms of an improved data acquisition software. A disadvantage of the technique is that a long term stable calibration is rather difficult to achieve, as is the case for most instruments performing emission measurements. The data quality of the derived atmospheric parameters depends on the accuracy of the retrieval algorithms that are applied. The spatial sampling of ground based microwave radiometers is rather poor and many instuments in use are unique instruments. An advantage of the technique is that it gives direct and instantaneous measurements of atmospheric properties in any direction and the temporal sampling can be quite high.

The data acquired with the WVR Astrid at Onsala were analysed using the RadGrad software and zenith wet delays and gradients were estimated and averaged with a time resolution of 30 minutes. The ZWD were converted to IPWV as described before. Figure 2 shows the IPWV values derived from the WVR (upper plot) and their corresponding uncertainties (lower plot). These are assumed to be 5% of the total value, reflecting mainly uncertainties in the absolute calibration using the tip-curve method and the retrieval algorithms.

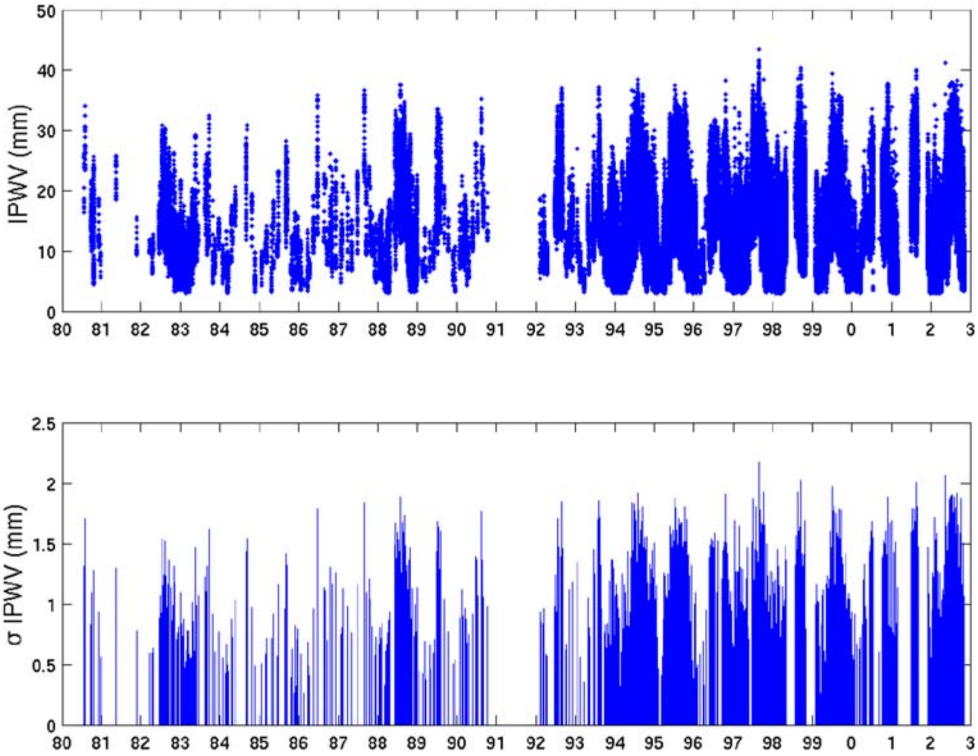

Figure 2: IPWV results derived from microwave radiometry at the Onsala Space Observatory with the water vapor radiometer (WVR) Astrid.

4 Global Positioning System observations at the Onsala Space Observatory

The first GPS-observations at Onsala were acquired during campaigns in the mid 1980ies. The site became a continuous site in the CIGNET network in late 1987 and later an IGS site. During the first years of operation a number of instrumental changes have occurred at the site, e.g. change of receivers and antenna foundation, which are a disadvantage of the technique. Since 1993 the site is part of the Swedish SWEPOS network performing continuous GPS observations. Here we will use the GPS data from the start of SWEPOS in August 1993. After this time, only one major change has occurred, a new hemispherical radome was installed on February 1, 1999. The GPS technique has the advantage to deliver continuous and almost uninterrupted time-series of atmospheric parameters during all types of weather. Besides the temporal sampling, GPS networks offer also a high spatial sampling since there are a large number of continuous GPS stations in national GPS networks almost worldwide.

Figure 3 shows results for IPWV obtained from GPS-observations at the Onsala Space Observatory. The data have been analysed using the Gipsy/Oasis II GPS analysis software (Webb and Zumberge, 1993) in the so-called ”precise-point-positioning” (PPP) technique (Zumberge *et al.*, 1997). The resulting total zenith delays (TZD) obtained for 5 minute intervals were first converted to ZWD by subtracting the zenith hydrostatic delay (ZHD) based on pressure data observed at the site and then converted to IPWV as described before. Figure 3 shows the IPWV values (upper panel) and their corresponding formal errors from the Gipsy output (lower panel). The uncertainties do not show any systematic behaviour.

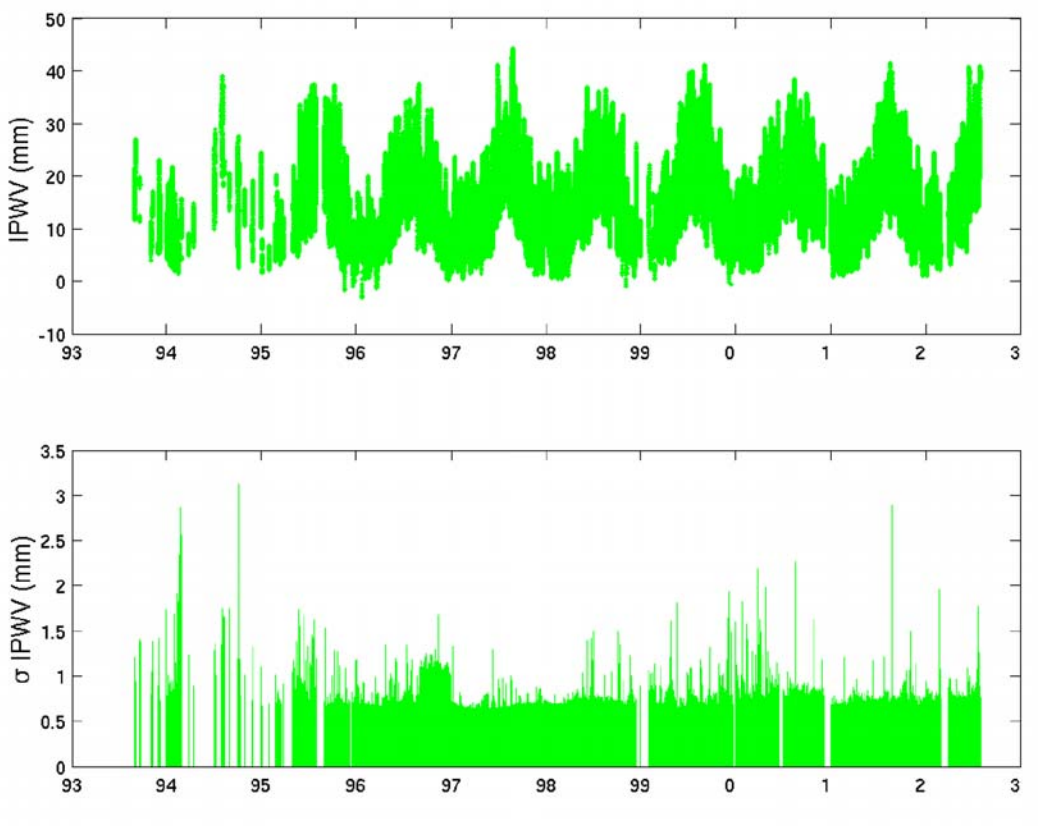

Figure 3: IPWV results derived from GPS observations at the Onsala Space Observatory.

5 Radiosonde observations at Landvetter airport

Radiosondes (RS) are a traditional measurement device for upper air observations in meteorology. The Swedish Meteorological and Hydrological Institute (SMHI) launches radiosondes at Landvetter airport at about 37 km distance from the Onsala Space Observatory every 6 to 12 hours. (The launching interval has varied over the years.) These radiosondes measurements have a long and continuous observation history. However, the type of radiosondes used has changed over the years. Before March 1986 the radiosonde type Vaisala RS18 was in use and since December 1985 the radiosonde type Vaisala RS80 is in use. During the four months December 1985 to March 1986 both types were used in parallel. The low but regular temporal sampling of 6-12 hours is not critical for long term monitoring since the time scales of air mass changes is typically a few days. The spatial sampling of radiosonde observations is however a limitation since the launches are expensive and often only performed at larger airports. The observations are available in form of atmospheric profiles of pressure, temperature, and humidity and thus give information on the vertical structure.

The data taken at Landvetter have been analysed using the in house developed CalcRS software. Figure 1 shows IPWV results from radiosonde launches at Landvetter for 1980 to 2003. The upper plot shows the IPWV results and the lower plot the corresponding accuracies. The accuracies are assumed to be 5% of the absolute value, based on measurement accuracies of the sensors used in the radiosondes (England *et al*., 1993).

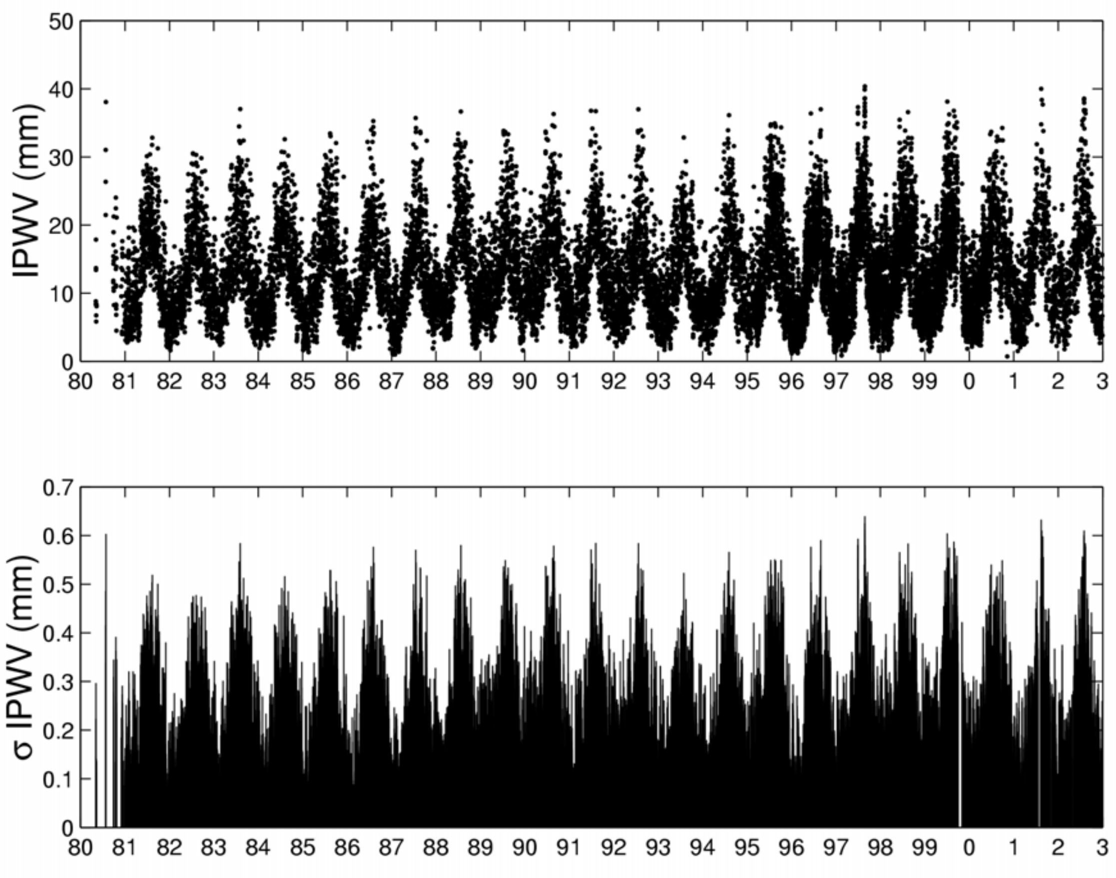

Figure 4: IPWV results derived from radiosondes (RS) launched at Landvetter airport

6 Comparing the four techniques

As a first approach the IPWV time series of each technique can be analysed individually. A simple first-order mathematical model is to estimate four parameters from a time series. These parameters are an offset (a_1), a rate (a_2), and a sine amplitude (a_3) and cosine amplitude (a_4) to describe an annual variation of the IWPV while fixing the period to be 365.25 days. For the estimation process the weighting of the data points is of importance. As seen in Figures 2 and 4, the WVR and the RS results have uncertainties on the order of 5 % of the total values. If these uncertainties were used as input for the weighting of the data points, this would lead to a systematic down-weighting of the winter periods since the IPWV values during winter are smaller than during summer. Figure 1 shows that the formal errors of the earlier VLBI observations are larger compared to the more recent ones. Thus, taking the formal errors into account for the weighting of the data points would down-weight the VLBI results obtained from observations performed in the 1980ies. Only the standard deviations of the GPS results do not show any systematic behaviour and could be used without having any systematic impact on the results.

Instead of using standard deviations for the weighting, it appears to be more appropriate to use the same weighting for all data points and to force the reduced chi-square to unity. Using this approach, the following results are obtained for the IPWV trend parameter (a_2):

Table 1: IPWV trends from four different space geodetic and remote sensing techniques.

Technique	Data period	Number of data points	IPWV trend (a_2)
VLBI	1980-2002	8477	+0.03 ± 0.01 mm/yr
WVR	1980-2002	212260	+0.13 ± 0.01 mm/yr
GPS	1993-2002	693127	+0.24 ± 0.01 mm/yr
RS	1980-2002	18597	+0.04 ± 0.01 mm/yr

The derived IPWV trends are statistically significant and positive for all techniques. However, VLBI and RS give only a slight increase, while WVR and GPS show significantly larger values. To understand this discrepancy it has to be noted that the individual input time series cover different time periods and have different temporal sampling. The VLBI time series is the most sparse one with only 20-30 observation sessions of 24 hours per year and a couple of continuous observation sessions of several days length. This is a clear undersampling of the IPWV variations during one year. For the first half of the time series the WVR was operated mainly only during VLBI session, but in the second half the instrument was operated nearly continuously. The GPS time series has the most regular sampling and almost continuous data. The RS time series is also quite regular, however the sampling is less frequent, than that of the other techniques, with one data point every 6 to 12 hours only. In the following it will be shown that the different sampling of the four techniques causes the significant differences in the derived IPWV trend parameters.

The question of the impact of the sampling on the trend results is closely related to the question of complementing time series. Here the question is, whether it is possible and reasonable to fill up gaps in the IWPV time series of one technique with values obtained by another technique. In this case the techniques would complement each other and the combined time series would give more robust and reliable results than each of the individual time series on its own. To address this question, it is useful to compare the four techniques pairwise and to use only data from epochs where both techniques have IPWV results. We therefore formed six datasets including pairwise results of two techniques each that were sampled at the same or close time epochs. We then used the simple mathematical model as described before and determined trend parameters for each of the two techniques involved in this pairwise comparison. The definition of what the same or close sampling means depends on the sampling frequency of the original individual time series. We required that the sampling epochs agreed within the shortest sampling interval length of the two techniques to be compared. Table 2 shows the results for IPWV trends derived from pairwise time series with synchronised sampling and the corresponding rms-differences.

Table 2: Pairwise comparison of the four different techniques using synchronized sampling epochs.

Comparison pair	Number of common data points	IPWV trend from (a) (mm/yr)	IPWV trend from (b) (mm/yr)	Bias (a)–(b) (mm)	RMS-diff. (mm)
VLBI (a), WVR (b)	1925	+0.19 ± 0.01	+0.13 ± 0.01	+0.43 ± 0.04	1.6
VLBI (a), GPS (b)	2045	–0.07 ± 0.01	–0.05 ± 0.01	–0.33 ± 0.03	1.3
VLBI (a), RS (b)	753	+0.05 ± 0.01	+0.03 ± 0.01	+0.60 ± 0.08	2.1
WVR (a), GPS (b)	128978	+0.31 ± 0.01	+0.31 ± 0.01	–0.57 ± 0.01	1.6
WVR (a), RS (b)	1755	+0.11 ± 0.01	+0.12 ± 0.01	+0.29 ± 0.05	1.7
GPS (a), RS (b)	7120	+0.25 ± 0.01	+0.20 ± 0.01	+0.96 ± 0.02	2.0

The pairwise comparison proves that the sampling is an important factor when deriving trends from the IPWV time series. The largest deviation seen is 0.06 mm/yr and the mean deviation is 0.03 mm/yr. We see that when the time series of two techniques have synchronised sampling epochs, the derived IPWV trends agree reasonably well. This becomes especially apparent in the comparison between VLBI and GPS. From each of the techniques itself a positive, but different IPWV trend was derived, see Table 1. The difference is more than 0.2 mm/yr. But using synchronised sampling epochs, both IPWV trends become negative and agree within 0.02 mm/yr. Thus, the two techniques VLBI and GPS appear to sense the same physical signal.

Regarding the pairwise differences between the techniques, there are only small systematic variations left, the biases between the techniques are less than 1 mm and the rms-differences are on the level of 1.3 to 2.1 mm. The conclusion from these comparisons is that it indeed appears to be reasonable to use the four techniques as complementing techniques for a combination approach.

7 Combining the four techniques

A nine parameter model was used for the combination of the complementing IPWV results of the four techniques. The model consisted of four individual offset parameters (b_1, b_2, b_3, b_4), one for each technique, a common rate parameter (b_5) for all techniques, a sine amplitude (b_6) and a cosine amplitude (b_7) to describe the annual variation for the three techniques collocated at the Onsala Space Observatory, and a sine amplitude (b_8) and a cosine amplitude (b_9) for the radisondes at Landvetter airport. All data points got identical weighting and the chi-square per degree of freedom was forced to unity. The numerical results are shown in Table 3.

The results show that the four techniques have individual offset values that differ within a total range of 0.5 mm. The pairwise differences between these offsets (biases) confirm the findings of Section 6. The tendencies (positive or negative bias) are the same while the abolute values are slightly different. The estimated annual signals for Onsala and Landvetter differ slightly. The total amplitude of the annual signal is larger for the three collocated techniques at Onsala (6.68 ± 0.01 mm) than for the radiosondes at Landvetter airport (6.43 ± 0.02 mm). The phase of the annual signal expressed in day of the year (doy) is earlier by three days for the three collocated techniques at Onsala (doy 240.1 ± 0.1) as compared to Landvetter (doy 243.1 ± 0.2). The common trend in IPWV was estimated to +0.17 ± 0.01 mm/yr. Figure 5 shows the combined solution.

Table 3: Estimated parameters of the nine parameter model: Four offset parameters (VLBI – b_1, WVR – b_2, GPS – b_3, RS – b_4) one common trend parameter (b_5), sine amplitude (b_6) and cosine amplitude (b_7) for the annual variation of the collocated techniques at Onsala (VLBI, WVR, GPS), and sine amplitude (b_8) and cosine amplitude (b_9) for the radiosondes at Landvetter airport.

b_1 (mm)	b_2 (mm)	b_3 (mm)	b_4 (mm)	b_5 (mm/yr)	b_6 (mm)	b_7 (mm)	b_8 (mm)	b_9 (mm)
11.22 ± 0.02	10.79 ± 0.02	11.29 ± 0.02	10.97 ± 0.02	0.17 ± 0.01	–3.67 ± 0.01	–5.59 ± 0.01	–3.25 ± 0.02	–5.55 ± 0.02

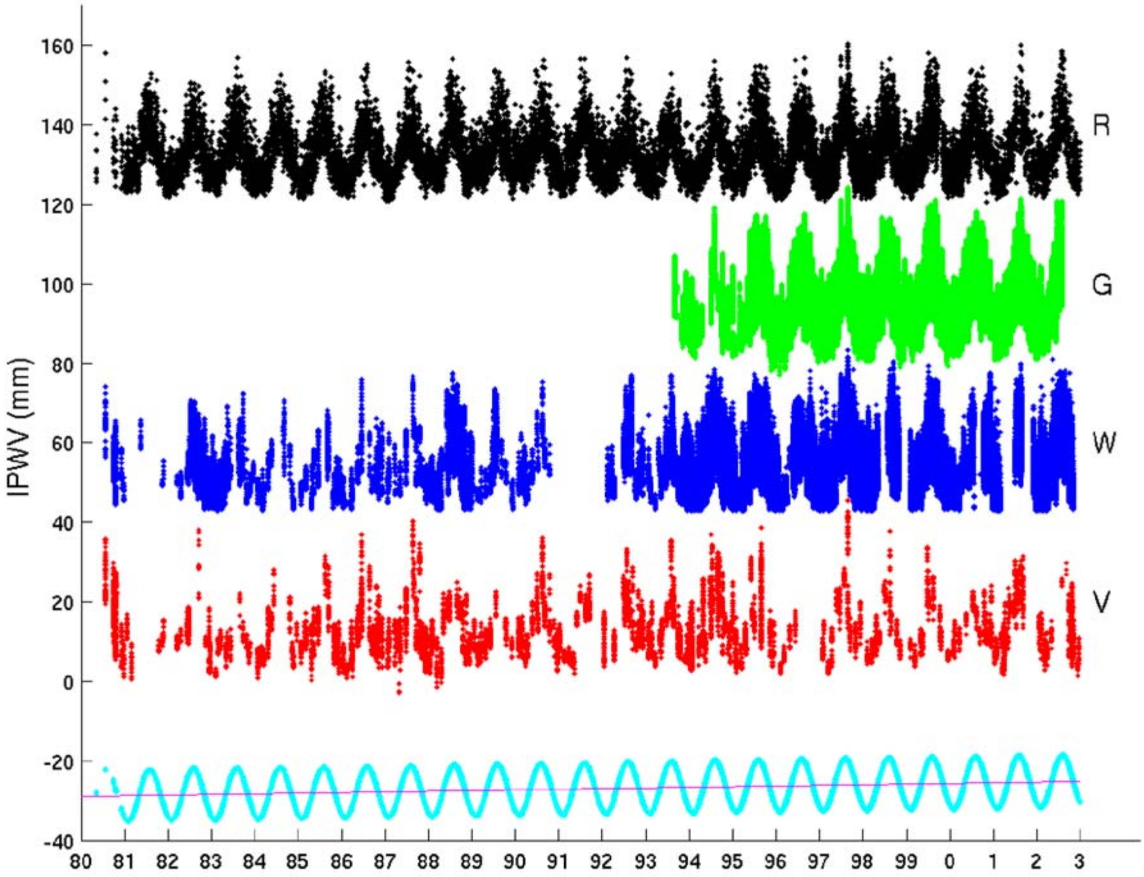

Figure 5: Combined time series of IPWV from four different techniques over 23 years. Shown are the original data sets, i.e. VLBI (V) without offset, WVR (W) offset by +40 mm, GPS (G) offset by +80 mm, RS (R) offset by +120 mm, together with the sinusoidal mean annual variation and the common linear trend (offset by –40 mm). The common trend in IPWV is +0.17 ±0.01 mm/yr.

8 Discussion and conclusion

Time series of IPWV derived from different space geodetic and remote-sensing techniques can be used to derive long term trends of the IPWV. Different techniques have their individual advantages and disadvantages in terms of long observation history, instrumental stability, temporal sampling and measurement accuracy and also give different results due to different sampling epochs. However, the comparison of IPWV results from different collocated space geodetic and remote sensing techniques at the Onsala Space Observatory shows that the techniques give similar results for synchronised sampling epochs. The agreement for IPWV trends is on the level of 0.05 mm/yr, the biases between the absolute IPWV values of the different techniques are less than 1 mm, and the rms differences are on the level of 1.3 to 2.1 mm when the absolute IPWV values are compared. The best agreement in terms of rms-differences is found between VLBI and GPS.

This investigation indicates that a combination of results from different complementing techniques is a useful and promising approach to derive long term trends in the atmospheric water vapor. Using the collocated techniques at the Onsala Space Observatory we derive an IPWV trend of +0.17 ± 0.01 mm/yr.

These results have been derived using very simple mathematical models. Future investigations will apply more advanced mathematical models that address the individual advantages and disadvantages of the individual techniques in more detail. This will for example include studying possible effects due to instrumental changes at the microwave radiometer. Robust estimates for long term trends in atmospheric water vapor will be derived.

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