TRENDS IN THE ATMOSPHERIC WATER VAPOUR ESTIMATED FROM TWO DECADES OF GROUND-BASED GPS DATA: SENSITIVITY TO THE ELEVATION CUTOFF ANGLE

Tong Ning[1], Gunnar Elgered[2], and Stefan Heise[3]

[1]*Lantmäteriet, SE-801 82, Gävle, Sweden*
[2]*Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden*
[3]*GFZ German Research Centre for Geosciences, Section 1.1: Space Geodetic Techniques, Telegrafenberg, 14473 Potsdam, Germany*

ABSTRACT

We have analysed 20 years of data from 13 GPS sites in Sweden and Finland, using two different elevation cutoff angles, 10° and 25°, to estimate the atmospheric integrated water vapour (IWV). Then we estimated the linear long-term trends of IWV which were compared to the corresponding trends from the radiosonde data at 7 nearby (< 120 km) sites and the trends given by the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA-Interim). The IWV trends given by the GPS elevation 10° and 25° solutions show similar results when compared to the trends from the radiosonde data, with correlation coefficients of 0.71 and 0.74, respectively. When compared to the IWV trends obtained from ERA-Interim, the GPS solution for the 25° elevation cutoff angle gives a significantly higher correlation (0.90) than the one obtained for the 10° solution (0.53). The results indicate that a higher elevation cutoff angle is meaningful when estimating long term trends, and that the use of different elevation cutoff angles in the GPS data processing is a valuable diagnostic tool for detection of any time varying multipath impacts.

Key words: integrated water vapour, elevation cutoff angle, GPS, radiosondes, ERA-Interim.

1. INTRODUCTION

Atmospheric water vapour contribute to one of the most important climate feedback processes and therefore can be used as an independent data source for monitoring climate change. This requires accurate observations with a long-term stability in order to have a high accuracy of the estimated trends in the atmospheric water vapour. With a relatively high temporal resolution, continuously improving spatial density, and less expensive receivers, ground-based GNSS networks have been identified as a useful technique to obtain long-term trends in the integrated amount of water vapour (IWV) in the atmosphere. A realistic and reliable IWV trend can only be obtained from homogeneous data. The observations obtained from the ground-based GNSS stations may contain the inconsistencies due to effects of signal multipath which are correlated to the change of reflective properties, e.g. growing vegetation [1] and the cutting of trees and/or different soil moisture [2]. In addition signal multipath effects are highly elevation dependent and are worse for observations at low elevation angles. Therefore the selection of the elevation cutoff angle used in the GNSS data processing can have a significant impact on the resulting IWV trend. Using 14 years of GPS data from 12 sites in Sweden and Finland, *Ning and Elgered* [3] found that a higher elevation cutoff angle (25°) gives the best agreement between the GPS-derived IWV trends and the ones obtained from radiosonde profiles at nearby launching sites.

In this work, we carried out a similar study as done by *Ning and Elgered* [3] but using 20 years of data. Two different elevation cutoff angles (10° and 25°) were used in the GPS data processing. The data sets of GPS, radiosonde, and ERA-Interim, are discussed in Section 2. Section 3 presents the results, first from the IWV comparison and thereafter for the trends estimated from the different data sets. Section 4 gives the conclusions.

2. DATA SETS AND ANALYSIS

2.1. GPS

We have analysed 20 years (from 1 January 1997 to 31 December 2016) of GPS observations acquired from 8 sites from the Swedish network (SWEPOS) and 5 sites from the Finnish reference network (FinnRef) (see Figure 1). Table 1 lists the details about the GPS data processing. We did not apply elevation-angle-dependent weighting in the GPS data processing because we are interested in studying systematic effects introduced by observations at low elevation angles. It is also noted that we did not include corrections for higher-order terms in the ionospheric delay in the data processing. The impact of

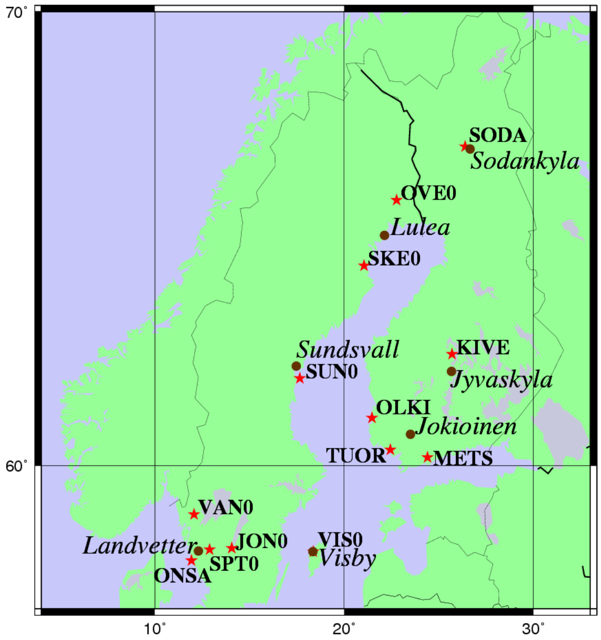

Figure 1. The geographic location of the 13 GPS sites (red stars) and the 7 radiosonde sites (black dots).

the higher-order terms on the resulting IWV estimates is however insignificant over a long time series [4].

2.2. Radiosonde

Measurements from seven radiosonde sites (see Figure 1) were obtained from `https://ruc.noaa.gov/raobs/`. The data consist of vertical profiles of pressure, temperature, and humidity. We linearly interpolated these profiles up to 12 km at intervals of 50 m, and integrated the absolute humidity in order to calculate the IWV. Radiosondes are at the most launched four times per day (but more common is two times per day) and the profiles are reported at the nominal time epochs 0:00, 6:00, 12:00, and 18:00 UTC.

Table 1. Models used in the GPS data analyses.

Model	
GPS software	GIPSY v6.2 [5]
Strategy	Precise Point Positioning [6]
Mapping function	Vienna 1 2006 (VMF) [7]
Elevation cutoff	10° and 25°
Elevation weighting	No
Ocean loading	FES 2004 [8]
Antenna PCV	igs08_1740.atx
Ambiguity resolution	Yes

Table 2. Known station-related changes.

Site	Date of change	Type of change
JON0	2002-08-23	Antenna change
METS	2010-08-19	Antenna change
METS	2013-06-28	Antenna change
ONSA	1999-02-02	Radome change
SKE0	2003-09-27	Antenna change
SKE0	2008-03-14	Antenna change
SPT0	2007-06-09	Eccosorb® change
SPT0	2016-08-23	Antenna change
VAN0	2003-03-30	Radome change

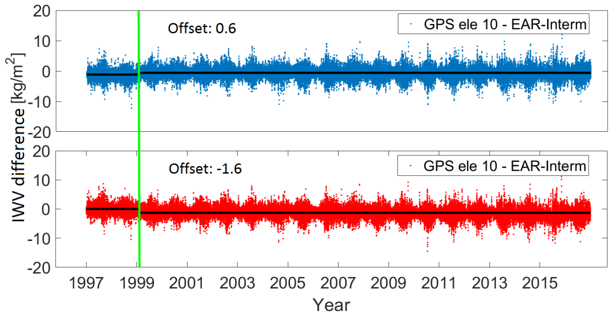

Figure 2. The IWV difference between the ERA-Interim data and the data obtained from the GPS 10° elevation cutoff solution (up), and the one given by the GPS 25° elevation cutoff solution (below), for the IGS site ONSA .

2.3. ERA-Interim data

As the most recently developed reanalysis product by the ECMWF, ERA-Interim, provides the IWV time series with a temporal resolution of 6 h and a horizontal resolution of about 50 km [9]. In order to reduce the IWV offset due to the difference between the model height and the GPS antenna height, we carried out a vertical interpolation of the ERA-Interim data to the height of the antenna where a cubic spline vertical interpolation using the lapse rate in the boundary layer was used [10]. A horizontal interpolation was also implemented using the IWV from the four grid points that surround the GPS site. In addition a temporal interpolation of the ERA-Interim data were applied in order to have the same temporal resolution as in the IWV time series from the GPS data.

2.4. Interventions in GPS time series

In this work we address the question if there are multipath, or other antenna environment, effects on the resulting trends. Therefore any known interventions in the GPS observations due to, e.g., an antenna change and/or

Table 3. The IWV comparison between radiosonde data and the GPS data before and after the corrections for the interventions in the GPS time series.

Elevation 10° solution − Radiosonde				
	Before corrections		After corrections	
GPS site	Mean difference [kg/m^2]	Standard deviation [kg/m^2]	Mean difference [kg/m^2]	Standard deviation [kg/m^2]
JON0	0.63	2.11	0.71	2.12
METS	−0.09	1.86	−0.13	1.86
ONSA	−0.40	1.62	−0.55	1.60
SKE0	−0.19	1.93	0.08	1.92
SPT0	0.02	1.23	0.38	1.19
VAN0	0.22	2.37	0.31	2.36
Elevation 25° solution − Radiosonde				
JON0	0.48	2.20	0.63	2.20
METS	−0.22	1.99	−0.04	1.98
ONSA	−0.16	1.81	0.21	1.74
SKE0	0.36	2.07	0.56	2.06
SPT0	1.45	1.38	1.44	1.36
VAN0	0.82	2.47	0.67	2.46

a radome change, need to be corrected for before we calculate the IWV trends. There are in total 6 GPS sites which have known station-related changes over the investigated time period. The types of such changes and the corresponding dates of the changes are listed in Table 2. As shown most of interventions are due to antenna changes while two of them are due to radome changes. One intervention consists of adding a microwave absorbing material to the antenna at the SPT0 site.

It is noted that the magnitude of the IWV offsets caused by interventions might be different from different elevation cutoff solutions. Figure 2 depicts the time series of the IWV differences between the GPS and the ERA-Interim data for the ONSA site. It is clear that the offsets, due to a radome change, for the two elevation cutoff solutions have different signs and magnitudes.

The corrections caused by the known interventions in the GPS data were carried out using the mean values estimated from the difference between GPS IWV and ERA-Interim IWV. Thereafter all results are presented using the GPS IWV which have been corrected for the known interventions. Table 3 shows the mean and standard deviation of the IWV difference between the radiosonde data and the GPS data before and after the corrections for the interventions. It is clear that for the most of sites the IWV mean difference change significantly after the offset correction on the GPS data while the standard deviations of the difference show almost no changes. The level of the change on the mean difference before and after correction is based on many factors, i.e., the number of the changes in the GPS IWV and the date of the changes, as well as the magnitude of the offset.

2.5. Trend estimation

We estimated linear trends in the IWV using the model [11]:

$$\begin{aligned} y &= y_0 + a_1\, t + a_2 \sin(2\pi t) + a_3 \cos(2\pi t) \\ &\quad + a_4 \sin(4\pi t) + a_5 \cos(4\pi t) \end{aligned} \tag{1}$$

where y and t are the IWV and the time in years (from 1 Jan. 1997 at UTC 0:00), respectively. The parameters y_0 and a_1 are the mean and the linear trend of the IWV, respectively; a_2 and a_3 are the annual component coefficients, and a_4 and a_5 are the semi-annual component coefficients. All unknown coefficients are determined through the method of least squares.

For some radiosonde stations the launch frequency decreases dramatically over the years. As a result there is a varying temporal resolution in the data obtained from these stations. In order to avoid the possible difference in the estimated IWV trend due to this, a data synchronisation is necessary. This was done by using the GPS and the ERA-Interim data acquired simultaneous to the launches from the radiosonde site.

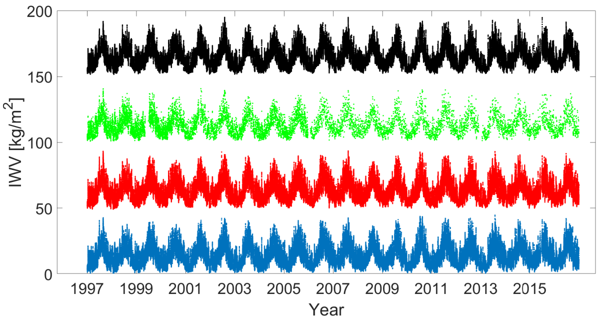

Figure 3. Time series of the IWV derived from the different techniques at the IGS site ONSA. Note that offsets of 50, 100, and 150 kg/m^2 have been added to the time series from GPS elevation 25° solution (red), radiosonde (green), and ERA-Interim (black), respectively. No offset is added to the time series from the GPS elevation 10° solution (blue)

3. RESULTS

3.1. IWV comparison

One example of the IWV time series estimated from GPS, radiosonde, and ERA-Interim at the IGS site ONSA is shown in Figure 3. The radiosonde data were obtained from the Landvetter airport which is located 37 km away from ONSA. It is clear that the IWV derived from the GPS and the ERA-Interim data are most regularly sampled while the RS-derived IWV has a lower temporal resolution.

Figure 4 depicts comparisons of IWV estimates obtained from the different data sets. Note that one radiosonde site can be compared to multiple GPS sites. The comparisons show, as expected, that the standard deviation of the IWV difference increases as the distance between the GPS and the radiosonde site becomes larger. In addition the IWV differences between the GPS elevation 25° solution and the other two techniques give a larger standard deviation than the one given by the GPS elevation 10° solution. This is due to larger formal errors of the individual IWV estimates caused by a worse satellite geometry and the reduced number of the observations when applying a higher elevation cutoff angle in the GPS data processing.

3.2. IWV trend comparison

Before comparing the trends obtained from the different data sets, we calculated the corresponding trend uncertainties for the GPS data from two different elevation solutions. The resulting uncertainties are shown in Figure 5. In the top panel the trend uncertainties were obtained using the formal error of the GPS estimates assuming a white noise behaviour. However this type of uncertainty only indicates how the estimated trend differs from what would be expected if there is no other errors, or deviations, in the IWV data compared to the model. As a result the uncertainties obtained from two elevation solutions have very small values (∼0.015 kg/(m^2·decade) for 25° solution and ∼0.005 kg/(m^2·decade) for 10° solution). Actually the estimated IWV trends should have rather large uncertainties caused by the true short term variation (the natural variability of the weather) which of course not are described by the model. In order to calculate the trend uncertainty after taking these short term variation into account, we used a model which was presented by *Nilsson and Elgered* [11]. The resulting uncertainties are given in the bottom panel of Figure 5 where the two elevation solutions show similar and significant trend uncertainties varying between 0.20 and 0.25 kg/(m^2·decade).

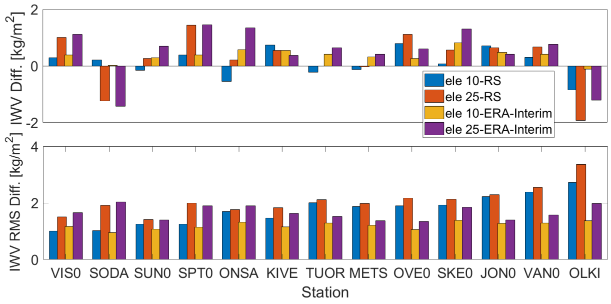

Figure 4. The mean (up) and the RMS (below) of the IWV differences for two different elevation cutoff angles. The sites (from left to right) are sorted by increasing distance between the GPS site and the radiosonde site.

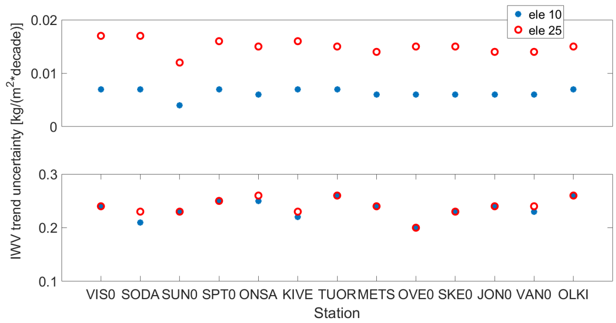

Figure 5. The uncertainties of the IWV trends obtained using the formal error of the GPS estimates and assuming a white noise behaviour (up), and after rescaling and taking the short term temporal correlation of the IWV into account (bottom).

The IWV trends estimated for each GPS site and for each one of the two elevation solutions and the synchronised trends obtained from the ERA-Interim data and the radiosonde data are listed in Table 4. Again note that one radiosonde site can be compared to multiple GPS sites. Overall a homogenous result is shown for all estimated trends which is positive (except one with a very small negative value). Compared to the others the ERA-Interim trends show a smaller variation (from 0.07 to 0.53 kg/(m^2·decade)) over all sites. It is clear that the trend differences between the GPS data and others are compa-

Table 4. The estimated IWV trends from all data sets.

GPS site	Radiosonde site	Distance [km]	Number of paired observations	Trend [kg/(m^2·decade)]			
				GPS 10°	GPS 25°	Radiosonde	ERA-Interim
VIS0	Visby	1	11007	0.07	− 0.05	0.08	0.07
SODA	Sodankylä	12	10756	0.45	0.50	0.29	0.34
SUN0	Sundsvall	35	15338	0.18	0.22	0.40	0.30
SPT0	Landvetter	37	11436	0.17	0.25	0.32	0.30
ONSA	Landvetter	37	11420	0.21	0.23	0.32	0.34
KIVE	Jyväskylä	47	9947	0.27	0.28	0.10	0.26
TUOR	Jokioinen	73	11644	0.53	0.66	0.79	0.53
METS	Jokioinen	83	12366	0.41	0.40	0.65	0.44
OVE0	Luleå	90	10805	0.20	0.50	0.41	0.44
SKE0	Luleå	90	10926	0.29	0.37	0.42	0.40
JON0	Landvetter	105	11636	0.23	0.24	0.31	0.28
VAN0	Landvetter	114	11584	0.28	0.40	0.33	0.33
OLKI	Jokioinen	119	10655	0.87	0.50	0.68	0.38

rable to the trend uncertainties after taking the short term temporal correlation of the IWV into account (see Figure 5). In addition we observed that the trend differences between the GPS data and the radiosonde data show no clear correlation to the site distance where the maximum distance is shorter than 120 km.

Figure 6(a) depicts the comparison of the IWV trends between the radiosonde data and the ones given by the GPS data for two different elevation solutions. Similar correlation coefficients (0.71 and 0.74) are observed for the GPS elevation 10° and 25° solutions, respectively.

The GPS IWV trends were also compared to the ones obtained from the ERA-Interim data. A higher correlation coefficient (0.9) is seen for the GPS elevation 25° solution than the one (0.53) for the 10° solution (see 6(b)). This low correlation however is mainly due to the estimated trend for one GPS site (OLKI). If we remove OLKI from the comparison, the correlation coefficient for the GPS 10° solution will increase significantly, to 0.74.

4. CONCLUSION

We have processed 20 years of GPS data acquired from 13 GNSS sites in Sweden and Finland, using the two elevation cutoff angels of 10° and 25°, to estimate the IWV and its linear long-term trends. The GPS-derived IWV trends were compared to the trends obtained from the radiosonde data at 7 nearby ($<$ 120 km) sites and the ones given by the ERA-Interim data.

The results show that due to the larger formal errors of the individual IWV estimates a larger standard deviation is seen in the IWV difference between the GPS elevation 25° solution and the other two techniques.

We also show that the larger formal error of the individual IWV estimates is not the limiting factor for the uncertainty of the estimated IWV trend. The results show similar correlation coefficients, of 0.74 and 0.71, when comparing the trends obtained from the GPS elevation 25° and 10° solutions with the ones obtained from the radiosonde data. A significantly higher correlation is seen for the GPS 25° solution compared to the 10° solution when the two are compared to the IWV trends given by the ERA-Interim data.

The results indicate that using different elevation cutoff angles is a valuable diagnostic tool that can be used for the validation purpose and detection of the possible multipath impacts. When we use the GPS data to monitor the long-term change of the IWV, e.g. as linear trends, it is recommended that we apply at lease two different elevation cutoff angles in the data processing. Ideally the IWV trends obtained from the two different elevation solutions should be the same if there is no significant multipath, or any other elevation dependent phenomena in addition to the atmosphere, that effects the observations.

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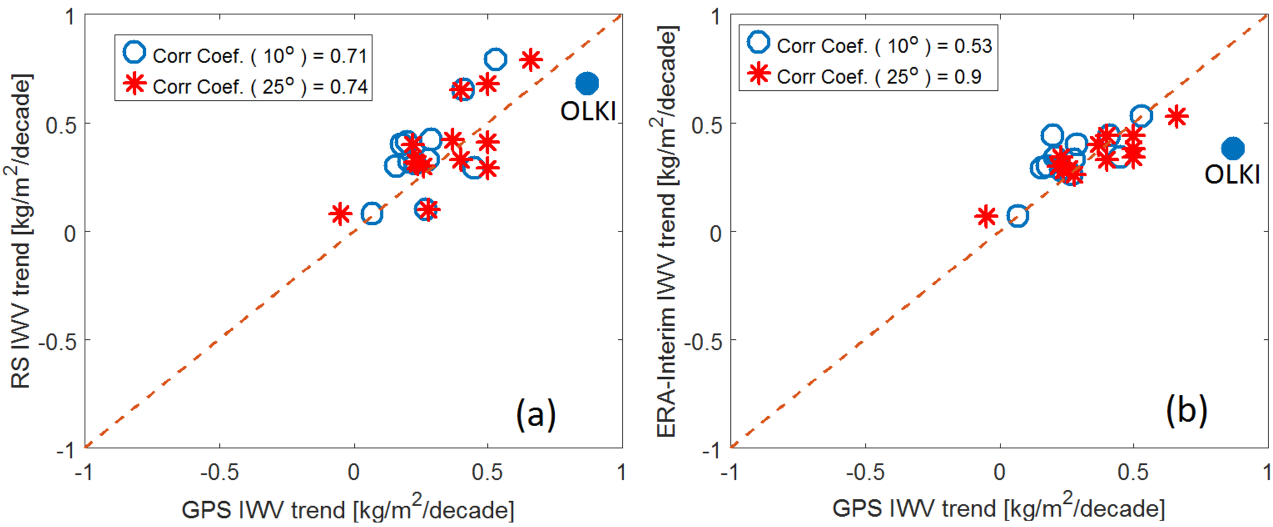

Figure 6. Correlations between the IWV trends from the GPS and the radiosonde data (a), and the ERA-Interim data (b) for 10° and 25° elevation cutoff angles. The dashed lines show the perfect agreement. The trend estimated for the site OLKI is indicated by the filled blue circle.

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