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# GPS Water Vapor Estimation Using Interpolated Surface Meteorological Data from Australian Automatic Weather Stations

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**Abstract.** The existing GPS tracking networks established primarily for surveying, geodesy and navigation purposes may also be used for meteorology studies. This research uses hourly surface temperature and pressure (T & P) observations from Australia for GPS Precipitable Water Vapor (PWV) estimation. The paper outlines the basic meteorological data requirements, and presents experimental results to show the comparison between interpolated and observed T and P values, and agreement between GPS-PWV estimates, using surface meteorological data and radiosonde PWV results. Data analysis of 36 data points in the Victoria region has demonstrated that the Ordinary Kriging method is preferable to pressure interpolation, resulting in an overall standard deviation of 0.40 mbar in pressure or 0.15mm in PWV estimation. We use the interpolated T and P measurements for four Australian IGS GPS sites to estimate GPS-PWV and compare against the radiosonde PWV results for the closely located radiosonde observations. 195 comparisons from all the sites have shown that GPS-PWV estimates agree with the Rad-PWV solutions at an average mean difference of –0.604 mm and RMS of 1.74mm for the tested stations. This agreement level is considered very reasonable. The experimental study shows a possible way to develop GPS meteorology and applications with the existing meteorological data network. This could save significant costs in installation of GPS-Met sensors.

**Keywords:** GPS meteorology, perceptible water vapor, pressure, interpolation, radiosondes.

## 1 Introduction

To estimate atmospheric water vapor from GPS data, surface meteorological observations collected at GPS sites are required. Ideally a dedicated meteorological sensor is installed together with the GPS antenna. However, this involves additional cost at the level of one-third or half of the geodetic GPS receiver cost. To take advantage of the existing GPS tracking networks and individual stations which are established and operated primarily for surveying, geodesy and navigation applications, it is worthwhile seeking alternative solutions, which either bypass the need for surface meteorological data, or use surface meteorological data from other sources.

Within Australia, there are currently over 30 permanent GPS reference stations providing hourly GPS data from the International GPS Services GPS tracking network and the Victoria GPS network (GPSnet), which can generate hourly GPS Zenith Total Delay (ZTD) parameters. However, hourly estimation of precipitable water vapor (PWV) depends on surface meteorological measurements. This research seeks to take advantage of surface temperature and pressure data from the Australian Automatic Weather Station (AWS) network operated by Bureau of Meteorology (BOM). The AWS network currently consists of over 1600 land sites across Australia, of which about 400 sites provide hourly updated temperature and pressure observations.

While some of the GPS sites are co-located to the AWS stations and radiosonde stations of the Australian Upper-Air Network, many others are located within the proximity of a number of weather stations. To be able to make use of the hourly surface meteorology data from the AWS network to determine GPS-PWV, we first need to assess the accuracies of interpolated temperature and pressure or derived Zenith Total Delay (ZTD) with meteorological observations from a local or regional ground AWS network. Secondly, we should verify these GPS-PWV measurements against radiosonde PWV results for some stations, in order to understand the consistence of derived GPS-PWV solutions to the external PWV solutions, such as radiosonde PWV solutions. In this paper, we present a case study using 36

AWS sites in Victoria and New South Wales to address the accuracy problem, and compare the GPS and radiosonde PWV results for Alice Spring, Darwin, Hobart and Townsville stations to verify the consistency of the results. The paper concludes with a summary of major research findings.

## 2 Accuracy Requirements For Surface Meteorological Data

### 2.1 Principles of GPS PWV Estimation

From GPS data, we can get the Zenith Total Delay (ZTD) estimates, which consist of Zenith Wet Delay (ZWD) and Zenith Hydrostatic (Dry) Delay (ZHD):

$$ZTD = ZWD + ZHD \tag{1}$$

ZHD can be calculated easily through surface meteorological observations using empirical models that have been developed for this need. The most popular models are the Saastamoinen (SAAS) (Saastamoinen, 1973), Hopfield (Hopfield, 1971) and Black (Black, 1978) models, defined as follows:

$$\begin{gathered} d_S^z = 0.2277 \cdot \frac{P}{F(\varphi, H)} \\ F(\varphi, H) \equiv 1 - 0.0026 \cdot \cos(2\varphi) - 0.00028 \cdot H \end{gathered} \tag{2}$$

$$\begin{gathered} d_H^z = 1 \cdot 552(h - H) \cdot \frac{P}{T} \\ h \equiv 40.082 + 0.14898 \cdot (T - 273.16) \end{gathered} \tag{3}$$

$$d_B^z = 0.2343 \cdot (T - 4.12) \cdot \frac{P}{T} \tag{4}$$

Where φ is the latitude of the station in radian, H is the station height above mean sea level in km, P is the surface air pressure in hPa, T is the absolute temperature in Kelvin, and h is the height of the upper edge troposphere in km. The subscripts S, H and B denote that the ZHD is from the SAAS, Hopfield, and Black model respectively.

After ZHD is calculated, directly subtract ZHD from ZTD to obtain ZWD:

$$ZWD = ZTD - ZHD \tag{5}$$

ZWD can then be convert to PWV using:

$$PWV = \Pi(T_m) ZWD \tag{6}$$

Where $\Pi(T_m)$ is a dimensionless quantity given by the mean weighted temperature of the atmosphere.

Eq. (2) to (6) show that all the above ZHD models require surface meteorological measurements, including air pressure and temperature. Hence the errors in surface meteorological data affect the ZHD estimates, and thus the ZWD and PWV estimates. In order to secure millimeter accuracy for the PWV, the admissible error in the surface meteorological measurements is defined.

### 2.2 Influence of Meteorological Measurements Errors

#### 2.2.1 Influence of Pressure Error

Assume T is accurately known in Eq. (2)-(4), then the impact of the uncertainty in the pressure measurement P on the ZHD can be evaluated using the variance propagation law for all the above models, which give (Liu, 2000):

$$\sigma_{d_S} = \frac{0.2277}{F(\varphi, H)} \cdot \sigma_P \tag{7}$$

$$\sigma_{d_H} = (0.2312 - \frac{0.9520 + 1.552 \cdot H}{T}) \cdot \sigma_P \tag{8}$$

$$\sigma_{d_B} = (0.2343 - \frac{0.9653}{T}) \cdot \sigma_P \tag{9}$$

In the above relationships, a large coefficient of $\sigma_P$ produces a large effect on the ZHD. This will be the case when φ is minimum and H is maximum in Eq. (7), whereas H is minimum and T is maximum in Eq. (8), and T is maximum in (9). Now, if we use φ =0° and H=5km in (7), H=0km and T=333.16K in Eq. (8) and Eq. (9), we obtain:

$$\sigma_{d_S} = 0.2286 \cdot \sigma_P \tag{10}$$

$$\sigma_{d_H} = 0.2283 \cdot \sigma_P \tag{11}$$

$$\sigma_{d_B} = 0.2314 \cdot \sigma_P \tag{12}$$

Where $\sigma_d$ is in cm and $\sigma_P$ is mbar.

In order to secure millimeter accuracy for the PWV, the contribution of ZHD estimates due to pressure error should be small enough to be neglected when compared with other error sources. Tab. 1 shows the influence of pressure error on the GPS PWV estimation, whose standard accuracy is 1mm. Assuming a ZHD error of 1mm leads to a PWV estimation accuracy of 0.15 mm. This contribution is not significant when compared with the total GPS PWV estimate accuracy of 1mm. From Tab. 1, we see that if the pressure measurement is accurate to 0.4 hPa or better, the contribution to the PWV error increase is about 1%, which may be negligible. To keep the pressure error contribution within 5% and 10% the pressure error must be below 0.80hPa and 1.20hPa, respectively.

Tab. 1 Influence of pressure error on PWV estimation.

| Pressure Error (hPa) | ZHD Error (mm) | PWV error (mm) | Total PWV Error (mm) |
|---|---|---|---|
| 0.40 | 0.92 | 0.15 | 1.01 |
| 0.80 | 1.84 | 0.30 | 1.04 |
| 1.20 | 2.76 | 0.45 | 1.10 |
| 2.00 | 4.60 | 0.75 | 1.25 |
| 3.00 | 6.90 | 1.125 | 1.51 |

### 2.2.2 Influence of the Temperature Error

Assume the pressure P is known, the effects of the uncertainty of temperature measurements on the calculated ZHD for the above models are given by:

$$\sigma_{d_S} = 0 \tag{13}$$

$$\sigma_{d_H} = (1.552 \cdot H + 0.9520) \cdot \frac{P}{T^2} \cdot \sigma_T \tag{14}$$

$$\sigma_{d_B} = \frac{0.9653 \cdot P}{T^2} \cdot \sigma_T \tag{15}$$

Obviously, the ZHD is independent of temperature in the SAAS model. As before, we fix H, P and T to their extreme values to see the maximum effect of the temperature error on the ZHD. Again for T=223.16K, P=1200mbar and H=5km we obtain:

$$\sigma_{d_H} = 0.2099 \cdot \sigma_T \tag{16}$$

$$\sigma_{d_B} = 0.0233 \cdot \sigma_T \tag{17}$$

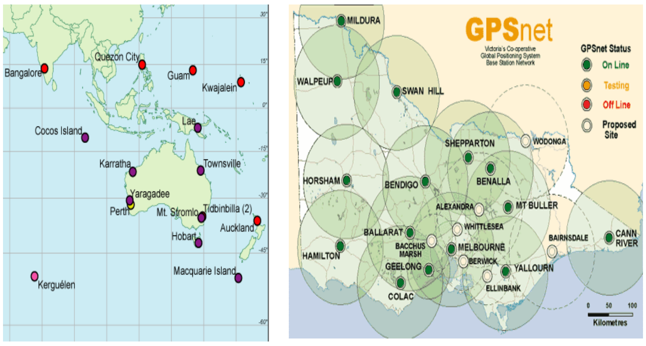

Fig. 1 Continuously operating GPS stations providing hourly GPS data files that could be available for GPS meteorology research in Australia. Includes 14 stations operated by International GPS services (IGS), and the Victoria GPSnet of 22 stations.

Because the temperature is not a variable in the SAAS model, its error will not affect the computed ZHD, but Hopfield and Black models are influenced by this error. Once again, in order to assure millimeter accuracy in the ZHD, we should have the temperature precision better than 0.5K in the Hopfield model and 5K in the Black model.

## 3 Description of Surface Meteorological Data and Interpolation Procedures

Fig. 1 illustrates the current continuously operating GPS stations providing hourly GPS data files available for GPS meteorology research in Australia, which includes 14 stations operated by International GPS services (IGS), and the 22 Victoria GPSnet stations (15 operating sites and 7 proposed sites). Fig. 2 shows the distribution of about 400 hourly updated weather observation stations across Australia, including about 60 sites in Victoria (as shown in the right side of the figure). From these two figures, it can be seen whilst many GPS sites in GPSnet are located close to the AWS sites, others are located within the proximity of a number of weather stations. Therefore, we can either use the meteorological data collected hourly at the closest site for PWV estimation, or use the interpolated measurements instead. Generally, a method is needed to interpolate the temperature and pressure at the GPS site with measurements from surrounding AWS sites. Because the vertical variability of pressure is sensitive to the altitude of the station, the pressure and temperature measurements given at different altitudes have to be converted to the common reference level, which is often Mean Sea Level. As a result, the interpolated parameters at any point refer to this reference level. These parameters must then be converted to the station level of the GPS station, in order to generate the PWV measurements for that station. In the following discussion, we establish the relationships between the meteorological parameters of different levels, followed by the interpolation method and results.

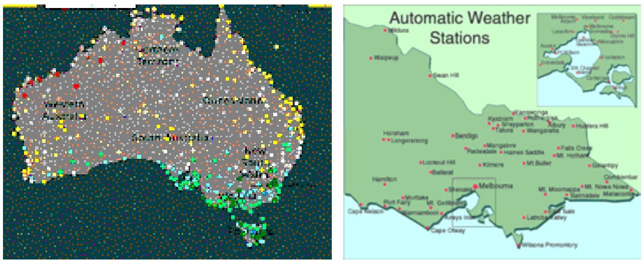

Fig. 2 Distribution of about 400 hourly updated automatic weather stations (AWS) across Australia, including about 60 sites in Victoria as shown in right.

### 3.1 Data Conversion Between a Reference Level and Station Level

Klein Baltink et al. (1999) gave the following relationships between values at station level and mean sea level (MSL):

$$
\begin{aligned}
P_{SL} &= P_{MSL}(1-2.26\cdot 10^{-5}\cdot H)^{5.225}\\
T_{SL} &= T_{MSL} - 0.0065\cdot H \qquad (18)\\
RH_{SL} &= RH_{MSL}e^{-6.396\cdot 10^{-4}\cdot H}
\end{aligned}
$$

Where H is the station height above sea level. The reverse computation can be rewritten as follows:

$$
\begin{aligned}
P_{MSL} &= P_{SL}/(1-2.26\cdot 10^{-5}\cdot H)^{5.225}\\
T_{MSL} &= T_{SL} + 0.0065\cdot H \qquad (19)\\
RH_{MSL} &= RH_{SL}/e^{-6.396\cdot 10^{-4}\cdot H}
\end{aligned}
$$

Fig. 3 illustrates the two steps to obtain the pressure and temperature at the GPS sites: first, deducting the MSL measurements from the Station Level pressures and temperatures at all the AWS sites, and second, deducting the Station Level pressures and temperatures at the GPS sites from the MSL pressures and temperatures.

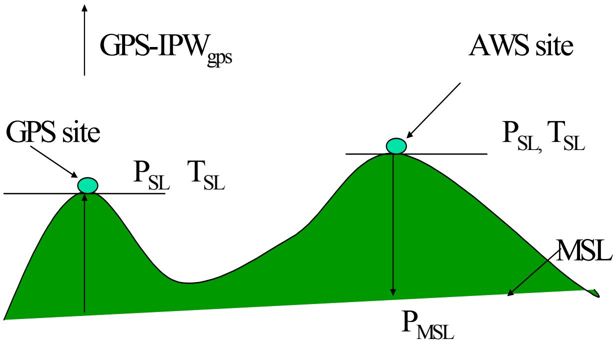

Fig. 3 Deduction of T and P at AWS station level to MSL, then to GPS station level.

### 3.2 Interpolation Methods and Results with a Local Network

Interpolation is a common tool to generate data at points without observations using values of nearby samples. There are many interpolation methods available in geodetic texts and references. Jarvis and Stuart (2001) suggest Ordinary Kriging (OK) also known as Punctual Kriging (Dorsel and LaBreche, 1997). Our analysis has shown that the OK method provides the optimal interpolation results for surface meteorological measurements.

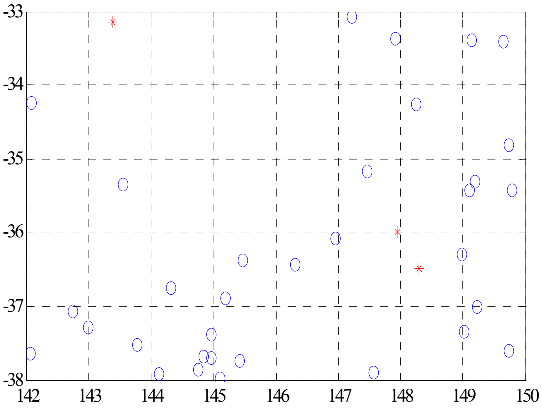

Fig. 4 Network of 36 hourly updated AWS sites, covering the area between 33°S and 38°S and between 140°E and 150°E in Australia. Asterisks indicates outlying points.

Fig. 4 shows the network of 36 hourly updated AWS sites, covering the area between 33°S and 38°S and between 140°E and 150°E in Australia. For each station the data file contains the station name, latitude and longitude in degrees, day and time of recording data, temperature in °C, relative humidity in %, MSL or QNH pressure in mbar, etc. The observations are updated every hour and acquired for use without quality control. A total of 45 hourly data points were collected for this experimental study.

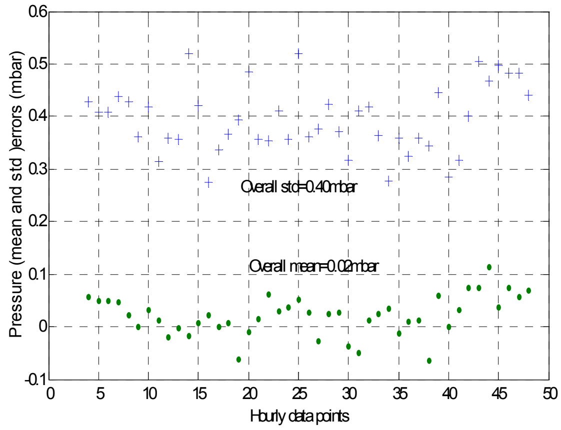

Fig. 5 Interpolated pressures standard deviation (STD) and mean values over the 33 data points against time, excluding three outlying data points.

To evaluate the interpolation results, we compare the interpolated pressure and temperature for each point using all other data points in the network, with the observed pressure and temperature. Experimental results have shown that interpolation using linear Variograms provides the optimal interpolation results in terms of overall standard deviation and RMS values. These values are computed from the differences between interpolated and observed pressure and temperature. Of the 36 data points, three have been identified to contain biases over many hourly measurements. Fig. 5 gives the overall standard deviation (STD) and mean errors over the 33 data points against the time, excluding three outlying data points.

Tab. 2 summarizes the statistics of these errors and provides the predicted ZHD and PWV errors, resulting from interpolated pressure errors. It is observed that for this particular AWA network, the overall interpolated pressure accuracy is about 0.40 mbar, which leads to a PWV estimation accuracy of 0.15 mm. This contribution is not significant, when compared with the total GPS PWV estimate accuracy of 1.0mm. In conclusion, using hourly surface meteorological measurements for GPS meteorological applications in Australia is feasible, if the quality control issues can be addressed.

Tab. 2 Summary of interpolated pressure errors and predicted ZHD and PWV errors.

| | Interpolated pressure errors (mabr) | Predicted ZHD error (mm) | Predicted PWV error (mm) |
|---|---|---|---|
| Min | -1.35 | -3.2 | -0.49 |
| Max | 1.96 | 4.5 | 0.69 |
| Mean | 0.021 | 0.05 | 0.01 |
| Std | 0.40 | 0.92 | 0.15 |
| RMS | 0.40 | 0.92 | 0.15 |

## 4 GPS Water Vapor Experiments and Results

### 4.1 Experimental Description

The purpose of presenting GPS water vapor experimental results from an Australian network is to assess the overall consistency of GPS PWV with radiosonde PWV solutions, for closely located stations where surface meteorological measurements for GPS sites can be interpolated from the surrounding AWS sites.

GPS tracking data were collected on a daily basis from the fifteen ARGN stations, operated by Geosciences Australia (formerly Australian Land Information Group - AUSLIG). The GPS tracking data were collected at a rate of 30 seconds. This network operates primarily for geodetic and geodynamic purposes, and does not provide surface meteorological data. 45 days (from 13 May to 30 June 2002) worth of data were retrieved and processed for this experiment. The radiosonde data at Alice Springs, Darwin, Townsville and Hobart were collected for the same period from the Australian Bureau of Meteorology (BOM). Radiosondes were released once or twice daily at about UTC 2300 or 1500 from the four sites. For each GPS/radionsonde site, hourly T and P data from the surrounding AWS sites were used to interpolate the T and P values. GPS zenith tropospheric delays were estimated every 30 min using GAMIT software, to match radiosonde release times and the 60 min meteorological data interval. Tab. 3 lists the separations between the GPS radiosonde sites.

Tab. 3 Separations between GPS and Radionsonde sites.

| | ΔH(m) | ΔS (km) |
|---|---|---|
| Alice springs | -41.5 | 14 |
| Darwin | -44.3 | 53 |
| Townsville | -22.8 | 30 |
| Hobart | 5.7 | 13 |

As discussed previously, T and P should be interpolated at mean sea level, and then deduced at the station level of the GPS sites.

### 4.2 Daily GPS Data Processing

GPS data were processed with GAMIT version 10.07 (MIT and SIO, 2002) using conventional 24-hour sessions, although the software is capable of handling variable session lengths starting at arbitrary times. The zenith tropospheric delays of each site were estimated every 30 minutes within each 24-hour session. The precise GPS orbits and Earth Orientation Parameters (EOP) were obtained from the International GPS Service (IGS) and International Earth Rotation Service (IERS) respectively. It is very important that tight constraints are placed on parameters such as orbits, EOP, and site positions, to the maximum extent of known confidence so that zenith delays may be estimated properly, since the tropospheric delay is strongly coupled to the site vertical component, which is in turn coupled to orbits, while the orbits are coupled to the EOP.

### 4.3 Experimental Results and Discussions

ZTD was estimated every 30 min using GPS tracking data of 24 hours from all the GPS sites. Two sets of meteorological measurements were then used to compute ZHD. One set is extracted from the closest AWS sites, the separations are shown in Tab 3. The other set is the interpolated results from the surrounding AWS sites. PWV was also estimated from radiosonde data that contains pressure, temperature and relative humidity profiles of all the layers above the site. As outlined in other research (give example references), the accuracy of radiosonde PWV observations is estimated to be about 1.2mm. Fig. 6 plots GPS-PWV estimates against Rad-PWV estimates at Alice Springs, Darwin, Hobart and Townsville stations respectively. Fig. 7 demonstrates the agreement with a scatter-plot for all the four sites. The

MEAN, RMS and STD, MAX and MIN values for the PWV differences for all the four stations are summarized in Tab. 4. All 195 comparisons between the GPS-PWV and Rad-PWV estimates show good agreement, and are in the range of ±6mm.

Tab. 4 Overall consistency of GPS PWV with interpolated T and P and Radiosonde PWV.

| | Ordinary Kringing Interpolated T &P(mm) |
|---|---|
| Max (GPS- Rad) | 5.60 |
| Min(GPS- Rad) | -5.93 |
| # of \|GPS-RAS\| > 4mm | 6 |
| Mean (Rad-GPS) | -0.60 |
| Std. dev (Rad-GPS) | 1.65 |
| RMS (Rad-GPS) | 1.74 |

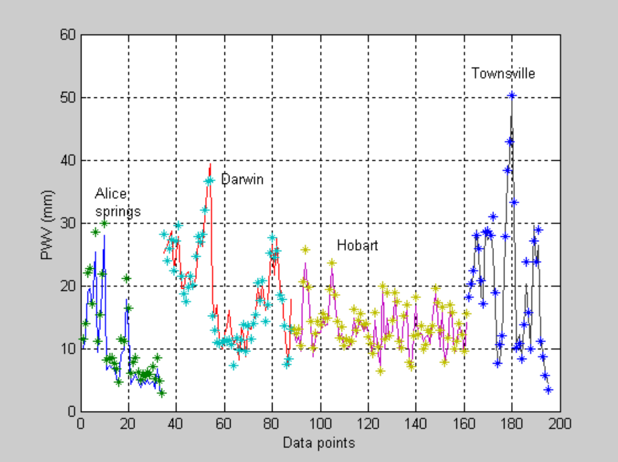

Fig. 6 GPS-PWV estimates against Rad-PWV estimates at Alice Springs, Darwin, Hobart and Townsville stations respectively.

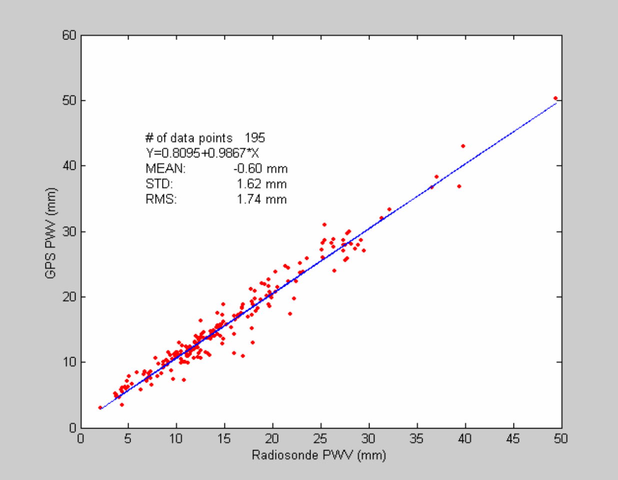

Fig. 7 Scatter-plot for four sites comparing GPS-PWV solutions against the radiosonde estimates, with interpolated T and P.

## 5 Summary

This paper has experimentally demonstrated the feasibility of using surface temperature and pressure hourly observations from the Australian Automatic Weather Stations (AWS) network for GPS Precipitable Water Vapor (PWV) estimation. Data analysis with 36 data points from the Victoria region has demonstrated that the Ordinary Kriging method with Linear Variograms is preferable for pressure interpolation, resulting in the overall standard deviation of 0.40 hPa in pressure or 0.15mm in PWV estimation.

This study used data from four GPS sites and co-located radiosonde sites over a period of about (how many?) months. The results have shown that GPS-PWV estimates agree with the Rad-PWV solutions at an average mean difference of 0.604 mm and RMS of 1.74mm for 195 comparisons. The agreement is perhaps slightly worse than the theoretical RMS of 1.56mm. However, the quoted results were obtained from radiosonde and AWS data sites located tens of kilometers apart and without pressure quality measures, this consistency is considered reasonably good. In other words, the experimental results indicate a possible way to develop GPS meteorology and applications with the existing meteorological data network, instead of using new meteorological sensors. This could save significant costs in installation of GPS-Met sensors.

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