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ORIGINAL ARTICLE

# Improvement in PWV estimation from GPS due to the absolute calibration of antenna phase center variations

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**Abstract** Climatology of column-integrated atmospheric water vapor over Spain has been carried out by means of three techniques: soundings, sun photometers and GPS receivers. Comparing data from stations equipped with more than one of these instruments, we found that a large discontinuity occurred on November 6, 2006, in the differences between the data series from GPS receivers and those from the other two techniques. Prior to that date, the GPS data indicate a wet bias of 2–3 mm for all stations when compared with sounding or photometer data, whereas after that date this bias practically reduces to zero. The root mean square error also decreases about half of its value. On November 6, 2006, the International GNSS Service adopted an absolute calibration model for the antennas of the GPS satellites and receivers instead of the relative one. This change is expected to be an improvement, increasing the accuracy of station position determination and consequently benefiting post-processing products such as zenith total delay from which the atmospheric water vapor content is calculated.

**Keywords** Phase center variations · GPS · Water vapor

## Introduction

When carrying out climatology of total column-integrated atmospheric water vapor content over Spain with soundings, sun photometers and GPS receivers, we find that on November 6, 2006, a great jump occurs in the differences between the data series from GPS receivers and those of the other two techniques.

Positioning by the Global Position System (GPS) is based on the distances between the electrical phase center of the ground receiver antenna and the GPS satellites antenna. It is well known that the antenna phase center depends on the wavelength of the signal and that it is not a stable point, but it varies with the elevation and azimuth angle of the outgoing and incoming radiation (Rothacher et al. 1995).

In order to overcome the phase center variation problem, antennas must be calibrated. Basically, there are two ways to do this: the relative and the absolute calibration. The relative calibration is based on taking one antenna as a reference and calculating the corrections for other antennas in comparison with the reference one. This method cannot correct for systematic error associated with the phase center variation (PCV) of the reference antenna (Schmid et al. 2004), thus only relative corrections can be obtained. The absolute calibration method is based on the determination of the absolute PCV of each antenna model (Wübbena et al. 2000). GPS antennas are a very critical error source, and a transition from relative to absolute PCVs would be an improvement, increasing the accuracy of station position determination (Schmid et al. 2005). On November 6, 2006, the International GNSS Service (IGS) adopted a model of absolute calibration to correct for PCV. This calibration is included in the procedure to calculate precise satellite orbits and the station coordinates (IGSMail-5438 2006; http://www.igscb.jpl.nasa.gov/mail/igsmail/2006/maillist.html).

The atmosphere increases the optical path length between GPS satellites and ground receivers, introducing a

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delay in the arrival time compared to signal propagation in vacuum. The tropospheric total zenith delay (ZTD) has two components: the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD). The ZHD is proportional to the amount of air and can be modeled and removed by knowing the surface atmospheric pressure at station level; and the wet ZWD is due to the presence of water vapor (Bevis et al. 1992). The ZTD can be calculated from GPS measurements using complicated geodetic inversions (Tralli et al. 1988; Herring et al. 1990). Subtracting the ZHD from the ZTD, the ZWD is obtained. Subsequently, this can be converted into total precipitable water vapor (PWV). One millimeter of PWV approximately produces a delay of 6.35 mm (Bevis et al. 1994). Thus, the GPS receiver network can be used to estimate the PWV (De Haan 2006).

According to the procedure described above, any error in the distance between GPS satellites and ground receivers is propagated to the travel time of the signal and consequently affects the accuracy of the ZTD and the PWV. It follows that an improvement in positioning should improve the PWV estimation accuracy. This study demonstrates this last statement by comparing PWV data before and after November 6, 2006, from GPS with the values provided by other techniques like soundings and sun photometers.

The following section presents the stations and data used. In Section "Result," we compare the PWV amounts measured by the three different techniques and discuss the results. The most important results are summarized in Section "Conclusions".

**Table 1** Geographic coordinates of the stations in latitude (north), longitude (west) and elevation in meters above sea level

| Station | GPS station | | | Sounding/photometer station | | |
|---|---|---|---|---|---|---|
| | Lat. | Lon. | Elev. | Lat. | Lon. | Elev. |
| Cáceres | 39°29′ | 6°21′ | 384 | 39°29′ | 6°21′ | 397 |
| Coruña | 43°22′ | 8°24′ | 12 | 43°22′ | 8°25′ | 58 |
| Santander | 43°28′ | 3°48′ | 48 | 43°29′ | 3°48′ | 52 |
| Madrid | 40°27′ | 3°57′ | 596 | 40°28′ | 3°35′ | 631 |

## Stations and data

We have used the data from the radio sounding stations run by the Meteorological State Agency of Spain (AEMET), sun photometers of the Aerosol Robotic Network (AERONET), and GPS receivers of the European Reference Frame (EUREF).

We selected four GPS receiver stations with a long data series and equipped, in the same location or in the near-by vicinity, with any of the other two instruments. Three GPS stations are supplied with radio sounding equipment (Coruña, Santander and Madrid), and the other one with a sun photometer (Cáceres). Table 1 shows the geographical coordinates of the locations of the stations.

PWV data from the radio soundings have been downloaded from the Web site of the University of Wyoming (http://www.weather.uwyo.edu/upperair/sounding.html). In the case of sun photometers, we have used the quality level 1.5 (cloud-screened) water vapor data from AERONET version 2 processing algorithm (http://www.aeronet.gsfc.nasa.gov/). Although level 2.0 data are quality assured, we have chosen level 1.5 because level 2.0 dataset has many gaps. Finally, for GPS receivers, the ZTD data have been obtained from EUREF Permanent Network Web site (http://www.epncb.oma.be/). From all the Analysis Centers of EUREF, we have selected the data generated by the National Geographic Institute of Spain (IGE) using the Bernese V5.0 software. Within the routine analysis of a network of ground-based GPS receivers, the tropospheric parameters are a by-product of the parameter estimation. In order to achieve the highest accuracy, the ZTD data is calculated with the final precise orbits of the satellites provided by the IGS (Kruse et al. 1999). The IGE processes the ZTD at all of its stations over Spain on an hourly basis. The ZTD is transformed in PWV knowing the pressure and temperature from a nearby meteorological station (Guerova 2003).

**Table 2** Statistics of the comparison for 2 year data before November 6, 2006

| Station | Instruments | Before November 6, 2006 | | | | | |
|---|---|---|---|---|---|---|---|
| | | Mean GPS | Mean S/F | BIAS | Relative BIAS % | RMAD % | RMSE |
| Cáceres | GPS/photometer | 16.92 | 14.91 | 2.01 | 12.3 | 13.5 | 2.72 |
| Coruña | GPS/sounding | 21.19 | 18.56 | 2.63 | 14.5 | 15.2 | 3.25 |
| Santander | GPS/sounding | 21.69 | 18.64 | 3.05 | 17.8 | 18.8 | 4.33 |
| Madrid | GPS/sounding | 15.82 | 13.92 | 1.91 | 15.4 | 16.9 | 2.64 |

The column *Instruments* indicates the two data sources. The statistics shown are the mean water vapor content in millimeters from GPS receivers (Mean GPS), the mean of the other techniques (Mean S/F), the difference (BIAS), the relative mean difference (Relative BIAS) and the relative mean absolute difference (RMAD) expressed in percentage, and the root mean square error (RMSE)

Soundings are usually launched twice a day, at 00 and 12 UTC. The soundings last approximately an hour and a half, but it takes to the balloon 30 min to pass across the lower 7,000 m of the troposphere, where most of the water vapor is present. Therefore, soundings provide a PWV data which is not an instantaneous measurement but a kind of average from the launch time (about 30–45 min before the nominal hour) to the final stage. It is not an actual average because in each instant a different atmospheric layer is measured.

The ability of soundings to provide accurate PWV data is limited, in fact, among all soundings data the relative humidity is the least reliable (Richner and Phillips 1982). The sounding PWD data are also affected by errors in temperature and pressure data and can present a dry bias in daytime caused by solar heating of the sensor (Miloshevich et al. 2006). Most soundings measure relative humidity with a precision of about 3.5% (Elliott and Gaffen 1991) and PWV with an accuracy of a few millimeters.

The photometer PWV is derived from direct solar transmittance measures in the 940-nm strong water vapor absorption band (Schmid et al. 1996; Halthore et al. 1997; Cachorro et al. 1998). The main error sources associated with this retrieval procedure depend on the determination of the calibration constant (Reagan et al. 1987; Bruegge et al. 1992) and in the modeling of water

**Table 3** Statistics for 2-year data after November 6, 2006

| Station | Instruments | After November 6, 2006 | | | | | |
|---|---|---|---|---|---|---|---|
| | | Mean GPS | Mean S/F | BIAS | Relative BIAS % | RMAD % | RMSE |
| Cáceres | GPS/photometer | 14.03 | 14.04 | −0.01 | −1.4 | 8.0 | 1.29 |
| Coruña | GPS/sounding | 19.07 | 19.02 | 0.05 | 0.0 | 6.6 | 1.60 |
| Santander | GPS/sounding | 19.77 | 19.59 | 0.18 | 0.9 | 6.9 | 1.66 |
| Madrid | GPS/sounding | 14.76 | 14.78 | −0.03 | −0.6 | 8.8 | 1.54 |

See Table 2 for additional explanation

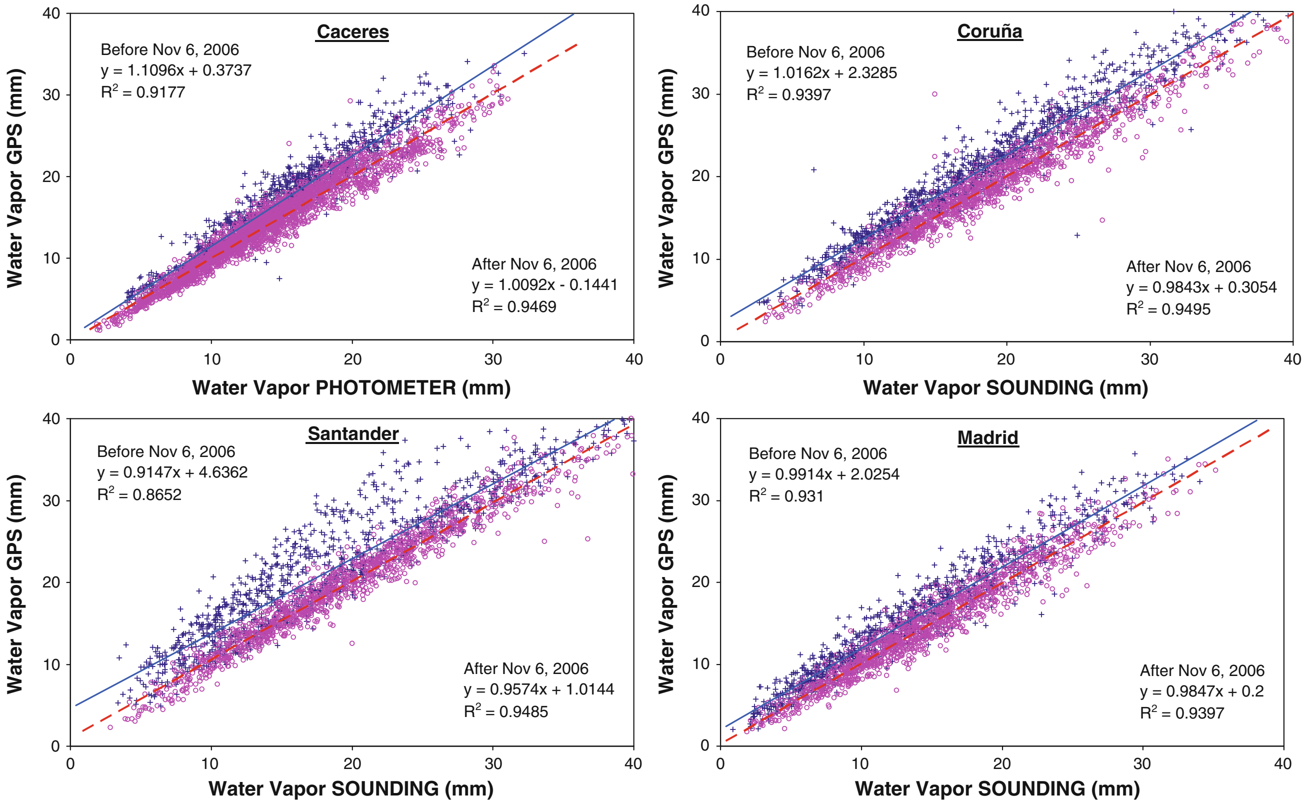

**Fig. 1** Regression line and correlation coefficient $R^2$ of the PWV data series obtained from GPS receivers and from soundings or sun photometers. The *blue crosses* and the *blue solid* line represent the data before November 6, 2006 and the *pink circles* and the *red dash line* the data after this date

vapor transmittance (Ingold et al. 2000). There are others related issues like cloudiness contamination, instrument characteristics, filter shape, filter aging, or filter central wavelength (Boyoke et al. 2006). In the case of AERONET (Smirnov et al. 2004) or similar photometers, the PWV retrieved for this technique is about 10%, but the uncertainty is very variable depending on the specific instrument used to measure the solar radiation in this band.

We selected 2 years of data before and after the change from relative to absolute antenna calibration to compare two series of the same length to avoid a bias. This is not the true of the Cáceres station, which began operating in July 2005. However, we include this station because is the only one equipped with a sun photometer in order to be able to illustrate the comparison with this technique.

In order to carry out the comparison, each sounding data has been paired with the closest GPS data after the actual time of the sounding launch, and each sun photometer data has been matched up with the closest GPS data taken at an interval of ±5 min. Thus, about 2,300 pairs of GPS-sounding data for each station and 3,750 pairs of GPS-photometer have been compared.

## Results

We compared for each location the GPS series data with the sounding or photometer series data and calculated the mean PWV, the mean difference (BIAS), the relative mean difference (Relative BIAS), the relative mean absolute difference (RMAD), and the root mean square error (RMSE). The mathematical expressions of these statistics can be found in the "Appendix".

Before the adoption of the absolute calibration model of PCVs (Table 2), the PWV obtained from GPS receivers is higher than the one obtained from the soundings or photometer in the four locations. This wet bias ranges between 1.91 and 3.05 mm and the relative bias between 12.3 and 17.8%. After November 6, 2006, (Table 3), the bias practically decreases to zero for all four sites, ranging between −0.03 and 0.18 mm. Also the RMAD and the RMSE decrease, the RMAD from a range of 13.5–18.8% to another of 6.6–8.8%, and the RMSE from 2.64–4.33 mm to 1.29–1.66 mm. On average, both quantities experience a drop of about 52%. These figures seem to indicate that the antenna relative calibration model overestimated the PWV GPS data by 2–3 mm.

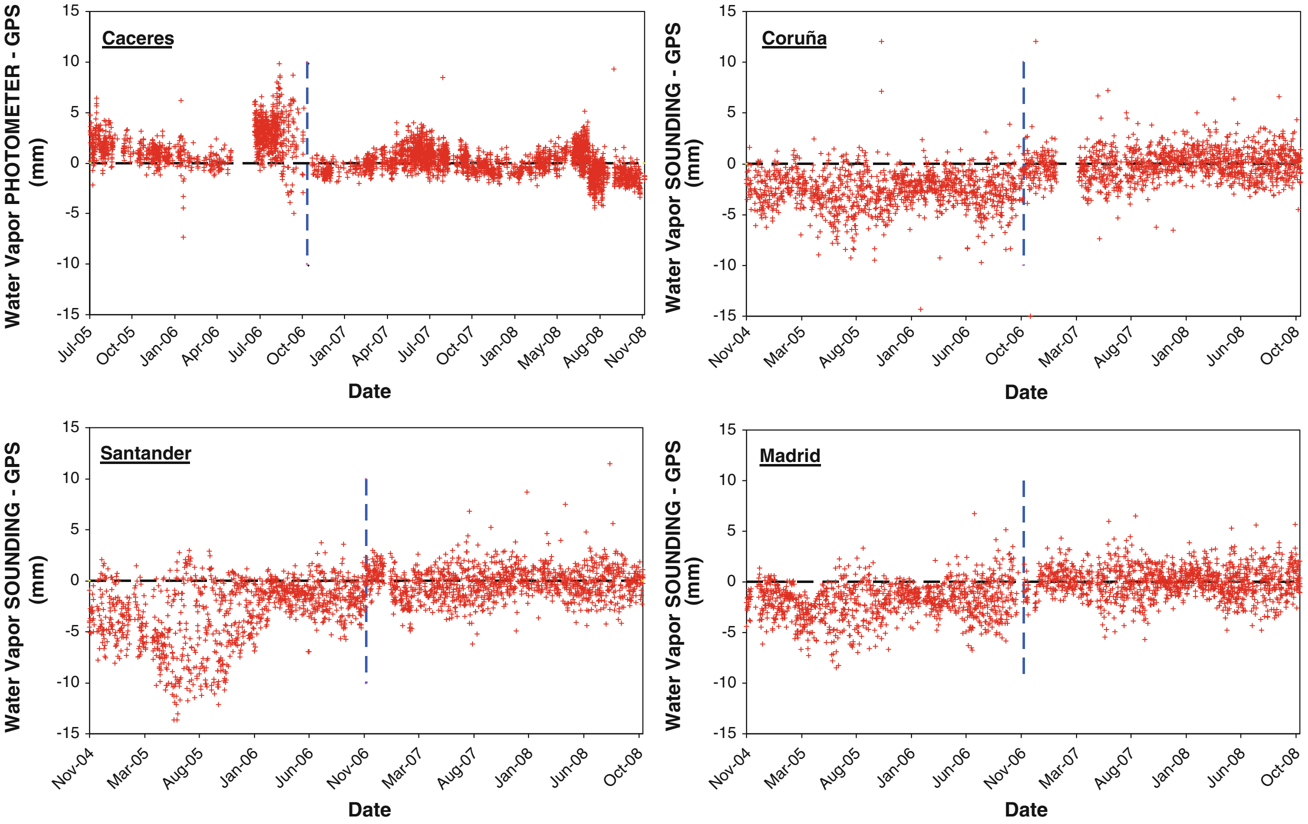

**Fig. 2** Time series of the PWV differences (expressed in millimeters) calculated from GPS data and the other techniques (sounding or sun photometer). The *vertical dash line marks* the November 6, 2006, date

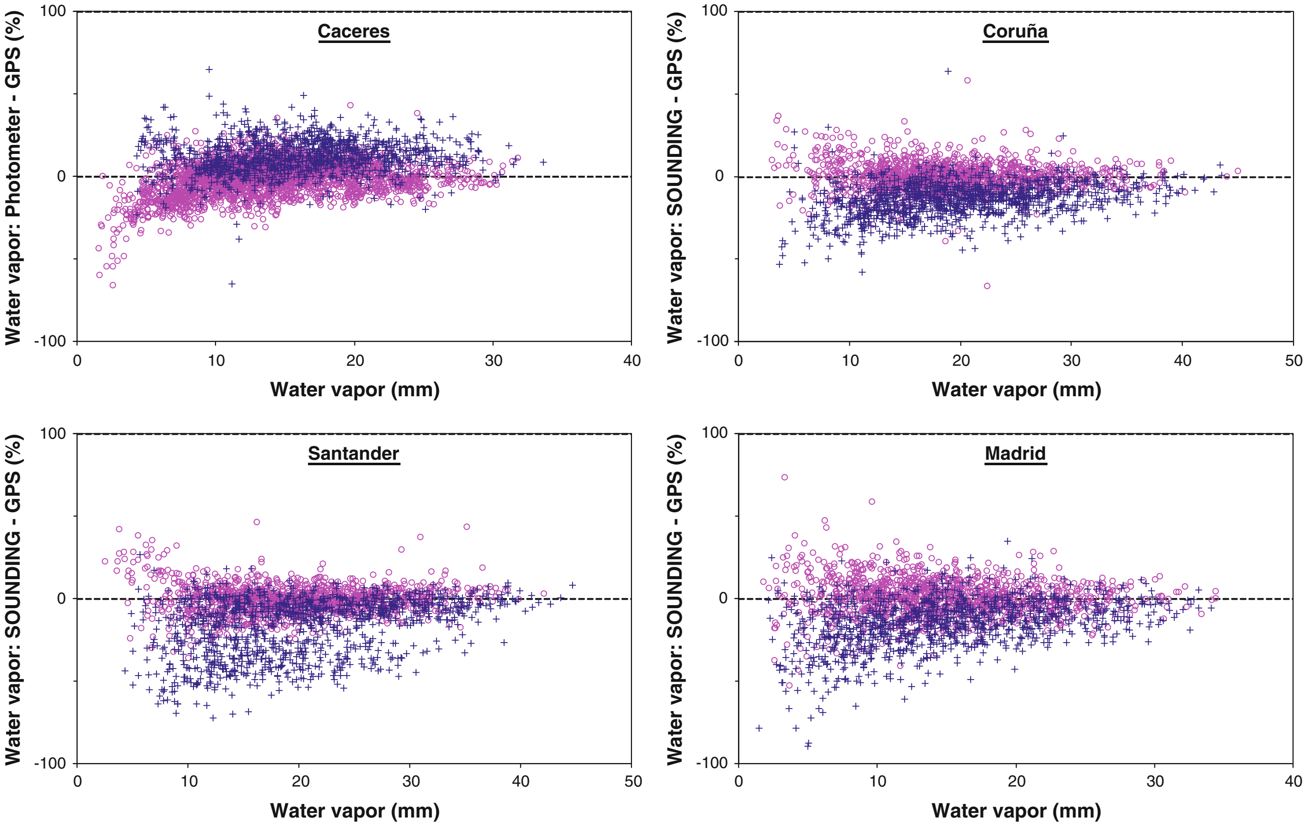

**Fig. 3** Relative differences (expressed as a percentage of the average) between the PWV data from the GPS receiver and from the other instrument versus the mean PWV. The *blue crosses* represent the data before November 6, 2006, and the *pink circles* the data after this date

Figure 1 shows the regression lines between the compared series before and after November 6 for each site. It can be observed how after this date the regression lines fit better to the diagonal. The figure also contains the values of the correlation coefficient ($R^2$), as well as the equation of the regression lines. After the cited date, the $R^2$ coefficients increase slightly, whereas the slopes of the regression lines are closer to the unit, and the Y-intercept values decrease.

If we plot the time series of the PWV differences from GPS data and the other techniques (Fig. 2), a significant jump can be observed. The data points experienced a shift and are oscillating around zero after November 6. This can also be observed in Fig. 3, where the differences are plotted versus the mean PWV. The shapes of the data points are similar, but there is a vertical shift.

In addition to the intrinsic error sources mentioned above, we have to keep in mind the different temporal resolution and the fact that they do not check the same atmospheric layer when comparing the PWV data from GPS, soundings or photometers. For GPS receivers and photometers, the measures are taken pointing toward the satellite constellation and the sun, respectively, and are subsequently projected onto the vertical, whereas soundings are drifted by the wind. All these produce noise in the comparisons of GPS-sounding and GPS-photometer (Fig. 2). We emphasize that in this study we are interested in a relative comparison before and after the change in the calibration model of PCVs rather than in an absolute one. Nevertheless, the root mean square errors obtained are in good agreement with the published ones by other authors (Ohtani and Naito 2000; Bokoye et al. 2003; Schneider et al. 2009).

As a result of switching from relative to absolute antenna calibration models, other authors point out differences in the station coordinates (higher in the vertical) and in the ZTD (Schmid et al. 2006; Bruyninx et al. 2006; Fotiou et al. 2008; Byun and Bar-Server 2009) ranging between 5 and 15 mm. Taking into account that 1 mm of PWV produces a delay in the incoming signal of approximately 6.35 mm when expressed in units of length, these figures can explain the differences in the PWV that we have found.

## Conclusions

A detailed comparison between PWV from GPS receivers, radio soundings and photometers in four different locations in Spain has been carried out using 2 years of data before and after November 6, 2006. At that date, the calibration model for the GPS antenna phase center variations was switched from relative to absolute.

Regardless of the technique used to compare with GPS data, the results show an improvement in PWV data after the absolute calibration model was established. Before November 6, 2006, the data calculated with the GPS ground receivers contained a systematic error, overestimating the PWV in 2–3 mm. After November 6, 2006, this wet bias practically decreases to zero. Also the root mean square error and the relative mean absolute differences reduce by one half, and the correlation coefficient increases slightly.

The results provide strong evidence that the new absolute calibration model is clearly unbiased as opposed to the relative calibration previously used. Thus, GPS technique appears to be a key method for water vapor monitoring, providing data with a better temporal and spatial resolution.

## Appendix

Definitions of statistics

$$\mathrm{BIAS} = \frac{\sum_{i=1}^{N} \mathrm{PWV}_i^{(\mathrm{GPS})} - \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}}{N_{\mathrm{data}}}$$

$$\mathrm{RelativeBIAS} = \frac{\sum_{i=1}^{N} 2 \times \frac{\mathrm{PWV}_i^{(\mathrm{GPS})} - \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}}{\mathrm{PWV}_i^{(\mathrm{GPS})} + \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}}}{N_{\mathrm{data}}} \times 100$$

$$\mathrm{RMDA} = \frac{\sum_{i=1}^{N} 2 \times \frac{\left|\mathrm{PWV}_i^{(\mathrm{GPS})} - \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}\right|}{\mathrm{PWV}_i^{(\mathrm{GPS})} + \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}}}{N_{\mathrm{data}}} \times 100$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} \left(\mathrm{PWV}_i^{(\mathrm{GPS})} - \mathrm{PWV}_i^{(\mathrm{Sound/Photo})}\right)^2}{N_{\mathrm{data}}}}$$

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