Proceedings of the Estonian Academy of Sciences,
2014, **63**, 1, 37–47
doi: 10.3176/proc.2014.1.07
Available online at www.eap.ee/proceedings

PHYSICS

Column water vapour: an intertechnique comparison of estimation methods in Estonia

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Received 12 September 2013, revised 23 December 2013, accepted 25 January 2014, available online 14 March 2014

Abstract. Despite different techniques for the estimation of column integrated water vapour (precipitable water, PW) no method has yet been identified as the most accurate or the reference one. In this work we report intercomparisons between four PW estimation methods – radiosonde, Aerosol Robotic Network (AERONET), Global Positioning System (GPS), and High Resolution Limited Area Model (HIRLAM). Two intensive observation periods at Tõravere, Estonia, were used: 22 June–6 November 2008 and 9–12 August 2010. During the longer campaign, only observations by GPS, AERONET, and HIRLAM were performed. An agreement with average difference less than 2.2% among all three methods was established. However, compared to HIRLAM and GPS, the AERONET method overestimated PW by 5–9% at PW < 12 mm and underestimated it by 6–10% at PW > 25 mm. In addition, the consistency test applied indicated that previously reported uncertainty in AERONET-measured PW is too high. During the shorter but more complex campaign, data obtained with all four methods were available. Although the average differences between PW from radiosonde and three other methods were <5%, the discrepancy between single measurements reached 33%. Relatively low temporal and spatial resolution of the HIRLAM grid as well as launching sparseness of radiosondes caused higher scatter from the other methods. The study suggests that besides radiosonde, as a traditional meteorological tool, the most reliable PW estimation can be made by GPS.

Key words: water vapour, precipitable water, AERONET, GPS, HIRLAM, radiosonde.

1. INTRODUCTION

Water vapour is an important item in debates on climate change and possible global warming. Although it constitutes only 0.001% of the planet's water resource, it is the major radiative and dynamic element in the atmosphere. Considering the entire vertical cross section of the atmosphere, it is often quantified as the column integrated water vapour or precipitable water (PW), equal to the thickness of the layer of liquid water if all water vapour per unit area were condensed. Its SI-unit, kg/m^2, is equivalent to the millimetre. Accurate estimation of the spatial and temporal distribution of PW represents a significant challenge in current meteorological practice.

In this research we report on our results of intercomparison of PW estimation by three methods – Aerosol Robotic Network (AERONET), Global Positioning System (GPS), and High Resolution Limited Area Model (HIRLAM) during a longer, 4.5-month period, and by four methods – radiosonde, AERONET, GPS, and HIRLAM during a short, four-day period. Both campaigns were performed at Tõravere (Estonia), the longer one on 22 June to 6 November 2008, the shorter on 9–12 August 2010. This well-equipped actinometric station is included into the Basic Surface Radiation Network (BSRN) where PW is an indispensable input in studies of radiation and aerosol regime (McArthur, 2005).

Until the 1990s, radiosonde was a traditional worldwide and actually the only routine instrument for the evaluation of PW. The advantage of radiosonde is

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retrieval of vertical profiles, for a number of levels z, of wind, relative humidity, and temperature at the same cast of sounding. After a cast, PW is calculated according to the vertical profile of absolute humidity, $a(z)$:

$$\mathrm{PW} = \int_0^{\infty} a(z)dz. \tag{1}$$

Because of progress in the construction of humidity sensors used in radiosondes, homogeneous time series of PW are not available. For this reason it is difficult to determine long-term trends and climatic effects (Maurellis and Tennyson, 2003).

The uncertainty in radiosonde estimated PW depends on the type of the sonde. With the often used Vaisala RS90 sondes and the 95% confidence level, the uncertainty is about 8% (Jakobson, 2009).

In our shorter field campaign, which was held together with Estonian military forces, the GRAW DFM-06 (Germany) sondes were used (GRAW, 2013). These are GPS sondes without a pressure sensor. According to our estimations based on the accuracy of GRAW sondes in observations of vertical humidity profiles, the uncertainty in PW retrievals is about 4% (at 95% confidence level) in typical Estonian summer conditions when PW = 20–30 mm.

Once developed by Fowle (1912) already 100 years ago, the spectroscopic technique for PW estimation was not widely used until 1993 when AERONET was started and currently covers, with its Cimel photometers, about 400 sites in 50 countries across all seven continents. The method involves measurements at 940 nm which enables estimation of PW. Although solar photometry provides higher spatial and temporal resolution than radiosonde soundings, their measurements require a clear solar disc, offering thereby only daytime data biased towards cloud-free conditions. Due to low elevation angles of the sun and cloudiness, the method is less applicable during winter at high latitudes. In AERONET 1–2 winter months are usually used for the service and laboratory calibration of photometers. The uncertainty in AERONET-derived PW retrievals has been estimated to be 10% (Holben et al., 2001). It should be noted with gratitude that the AERONET products are still freely available at http://aeronet.gsfc.nasa.gov/.

Over the last two decades some other PW estimation methods have become increasingly available, e.g. the GPS meteorology, databases of numerical weather prediction (NWP), ground-based upward-looking microwave radiometry, remote sensing from satellites (Bevis et al., 1992, 1994; Cucurull et al., 2000; Campmany et al., 2010). In this list the GPS method is special for its ability to provide high temporal frequency of a few minutes at all weather types. This frequency is high enough to describe extreme cases of fast PW variations caused by substitution of air masses over a certain location, e.g. monitoring the progress of PW during the passage of a typhoon (Song and Grejner-Brzezinska, 2009). The spatial resolution of the method, around a given location, depends solely on the density of the ground network of GPS-stations (Glowacki et al., 2006).

Although originally designed for 3D navigation, GPS was soon implemented in geodesy for precise horizontal and vertical positioning. In these applications tropospheric water vapour is known as a source of additional noise which is hard to predict. Further development in atmospheric research (the beginning of GPS meteorology) introduced a different paradigm – this noise can be used in navigation as an important source of information for quantifying PW. Now several comprehensive suites of programmes are available, e.g. GAMIT, GIPSY-OASIS, BERNESE, which besides traditional geodetic products (surveying, monitoring of crustal deformations, sea level motions, etc.), allow estimation of PW (Bevis et al., 1992; Webb and Zumberge, 1993; Dach et al., 2007; Herring et al., 2010).

The uncertainty in the PW estimation by GPS has many origins, including the density of the ground-based GPS network nearby, azimuthal asymmetry of the atmosphere above the site, and quality of input meteorological data. A total root-sum-square error in PW estimates using GPS has been shown to be slightly above the 1 mm level using data from the Swedish and Finnish networks (Emardson et al., 1998; Jakobson et al., 2009). Using GAMIT software, the "formal error" was calculated for every single measurement of PW. As our campaigns confirm, its average is 1.1 mm.

The "total atmospheric delay" (in millimetres) of the signal emitted by a GPS satellite consists of two parts, "hydrostatic delay" and "wet delay". The former depends on air mass between the receiver and satellite and can be expressed as a function of ground atmospheric pressure. The latter depends on the amount of water vapour along the path of the signal. These three parameters, in standard procedures of PW calculations, are referred to the zenith direction: zenith total delay (ZTD), zenith hydrostatic delay (ZHD), and zenith wet delay (ZWD).

Omitting here details in derivation of ZHD and ZWD (Bevis et al., 1992; Ning, 2012), PW is related to ZWD through a conversion factor, Q:

$$\mathrm{PW} = \frac{\mathrm{ZWD}}{Q}, \tag{2}$$

where Q can be found by the following equation (Askne and Nordius, 1987):

$$Q = 10^{-8} \rho_{\mathrm{w}} R_{\mathrm{w}} \left(k_2' + \frac{k_3}{T_{\mathrm{m}}} \right). \tag{3}$$

Here ρ_w is the density of liquid water, 1000 kg/m^3; R_w is the specific gas constant for water vapour, 461.5 J/(kg·K); $k_2' = 22.1 \pm 2.2$ K/hPa; $k_3 = 373\,900 \pm 1200$ K^2/hPa; T_m is the mean temperature of the atmosphere. In our work, T_m is evaluated through the surface air temperature, T_s (Bevis et al., 1992):

$$T_m = 70.2 + 0.72\,T_s, \tag{4}$$

where the temperatures are in kelvins. It is estimated that the uncertainty of the mean temperature of the atmosphere, $u(T_m)$, is about 2%. The uncertainty of the conversion factor, $u(Q)$, is given as (Ning, 2012)

$$u(Q) = 10^{-8}\rho_w R_w \sqrt{\left(\frac{u(k_3)}{T_m}\right)^2 + u^2(k_2') + \left(k_3\frac{u(T_m)}{T_m^2}\right)^2}. \tag{5}$$

The total uncertainty of PW is now calculated as follows (Ning, 2012):

$$u(\mathrm{PW}) = \sqrt{\left(\frac{u(\mathrm{ZTD})}{Q}\right)^2 + \left(\frac{2.2767u(P_0)}{f(\lambda,H)Q}\right)^2 + \left(\frac{P_0 u(c)}{f(\lambda,H)Q}\right)^2 + \left(\mathrm{PW}\frac{u(Q)}{Q}\right)^2}, \tag{6}$$

where P_0 and $u(P_0)$, in hPa, denote the ground pressure and its uncertainty; $u(\mathrm{ZTD})$ is estimated by standard procedures of the software package; $u(c) = 0.0015$ represents an uncertainty of the technical parameter c, omitted above for the sake of brevity (Ning, 2012). Inserting the latitude, $\lambda = 58.26°$, and the height above the geoid, $H = 96.3$ m, for Tõravere, we obtain the value of f via the equation (Saastamoinen, 1972)

$$f(\lambda, H) = 1 - 2.66\times10^{-3}\cos(2\lambda) - 2.8\times10^{-7}H. \tag{7}$$

According to the technical information about the barometer used at Tõravere, the uncertainty in pressure $u(P_0) = 0.17$ hPa.

Applying Eq. (6) to every single measurement yields the average $u(\mathrm{PW}) = 1.2$ mm. In our experiment this value coincides with the average "formal error" (as a rough estimate of 1σ) calculated by the GAMIT software.

Our fourth method was calculation of PW from the operational weather forecast HIRLAM, whose database actually consists of two parts. First, it is updated four times daily, at 00, 06, 12, and 18 UTC, by reports from meteorological networks, and second, it produces forecasts for 03, 09, 15, and 21 UTC.

The estimation of uncertainty in PW retrievals by NWP models (e.g. HIRLAM) is complicated. Apparently, the uncertainty depends, besides the density of the ground-based meteorological network, also on the closeness of upper-air sounding stations and daily frequency of ascents. The data from GRAW radiosondes launched at Tõravere were not assimilated in HIRLAM analyses. Nine radiosonde stations are located closer than 500 km to Tõravere (58.26°N, 26.47°E, 70 m) (Fig. 1). Radisondes are launched twice a day at six of these stations: Voejkovo (Russia, 305 km, 00 + 12 UTC), Velikie Luki (Russia, 328 km, 00 + 12 UTC), Jokioinen (Finland, 329 km, 00 + 12 UTC), Bologoe (Russia, 447 km, 00 + 12 UTC), Jyväskylä (Finland, 461 km, 06 + 18 UTC), and Visby (Sweden, 484 km, 00 + 12 UTC). Radisondes are launched once a day at 00 UTC at Harku (Estonia, 165 km), Skriveri (Latvia, 197 km), and Kaunas (Lithuania, 410 km). Sparseness of the operational radiosonde network and low frequency of ascents limit the performance quality of vertical temperature, humidity, atmospheric pressure, and wind profiles in the NWP fields, including the estimation of PW.

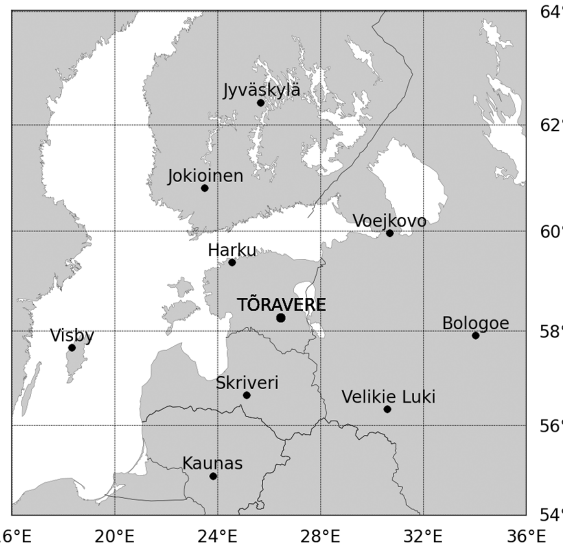

Fig. 1. Map of the nine radiosonde stations closer than 500 km to Tõravere. The data from all of these stations were assimilated to the HIRLAM model.

2. PREVIOUS INTERCOMPARISONS OF PW ESTIMATIONS

Comparisons between different PW estimation techniques usually involve only two methods. For example Tregoning et al. (1998) compared GPS and radiosonde PW estimates during two months, November and December of 1995, in Tasmania. Inside the observed limits, PW = 5–30 mm, the root-mean-square difference (RMSD) between these methods was 1.5 mm. In terms of simple biases, the radiosonde measurements were observed to be only 0.6 mm "wetter" than the GPS solutions.

Similar research has been completed on the Korean Peninsula for two years by Kwon et al. (2007), who examined the accuracy of GPS-derived PW in a humid region. Precipitable water ranged from 5 mm in winter to over 70 mm in the hot rainy season. Compared to Tregoning et al. (1998), the mean offset was opposite and the radiosonde estimated atmospheric column was 1.5 mm "drier" than the GPS, with RMSD = 2.5 mm.

Comparing GPS and radiosonde data during 2003–2004 at 98 stations around the world, Wang et al. (2007) found that radiosonde measurements were on average 1.08 mm (5.5%) drier than those of GPS. The dry bias was primarily related to the Vaisala RS80A sondes, but not to the GRAW sondes (used at ten stations).

Ning et al. (2012) compared radiosonde and GPS estimates for a 10-year period at ten sites in Finland and Sweden. They concluded that the mean difference of ZWD was 0.8 mm (radiosonde showing higher values). Considering a rough estimate proposed by Bevis et al. (1994), $\mathrm{PW}/\mathrm{ZWD} = Q \approx 0.15$, this corresponds to only 0.1 mm in PW.

Comparisons between PW retrievals from radiosondes and sun photometers revealed considerably larger discrepancies. Halthore et al. (1997) compared AERONET Cimel sun photometer and radiosonde measurements during one month, July 1993, at Wallops Island (US), where PW ranged from 10 to 55 mm. They registered systematic differences of 10% with radiosonde showing higher values. Later, in April 1994, these authors carried out comparison between the same instruments for Oklahoma where PW ranged from 5 to 35 mm. Here, on the contrary, the sun photometer yielded 9.2% higher PW values than radiosonde. However, it should be noted that the processing algorithms of AERONET were substantially updated in 2005 (e.g. the absorption of direct solar beam by NO_2 was taken into account). The resulting PW retrievals by Version 2 showed a 13–19% decrease in PW from the previous Version 1 values (Holben, 2005).

The list of works on verification of simulated PW by operational NWP systems is brief. An excellent and perhaps the most comprehensive experiment on the spatial scale of 100–1500 km in northern Europe, to compare PW time series from HIRLAM simulations with estimates from ground-based GPS receivers, was done by Yang et al. (1999). The observational data were calculated from GPS measurements using 25 sites in Sweden and Finland over a four-month period, August–November 1995.

In frames of individual GPS sites the mean bias between PW (HIRLAM) and PW (GPS) ranged from −1.4 mm (GPS as a reference instrument was "wetter" by 11%) to 2.1 mm (GPS "drier" by 14%). The mean PW (GPS) averaged over the entire data set, i.e. over 11 244 paired numbers of data, was 13.6 mm, which was closely matched to the PW (HIRLAM) mean of 13.7 mm, implying almost no deviation in the HIRLAM representation.

In this experiment (Yang et al., 1999), the overall average scatter of HIRLAM predictions, in regard to GPS, was characterized by the RMSD equal to 2.4 mm (18%). We now use this result and the law of propagation of uncertainty for a rough calculation of uncertainty in PW simulations by HIRLAM:

$$\sqrt{u^2(\mathrm{GPS}) + u^2(\mathrm{HIRLAM})} = 2.4. \qquad (8)$$

Inserting $u(\mathrm{GPS}) = 1.0,\ 1.1,\ 1.2,\ 1.3,\ 1.4$ mm, we obtain that $u(\mathrm{HIRLAM}) = 2.2,\ 2.1,\ 2.1,\ 2.0,\ 1.9$ mm, respectively. According to the review given by Jakobson et al. (2009), the mean uncertainty in the PW values from GPS measurements, $u(\mathrm{GPS})$, is slightly above the 1-mm level. This leads to an evaluation $u(\mathrm{HIRLAM}) \approx 2.1$ mm, which we used, as a first approximation, in our estimations.

In December 1996 an analogous intensive two-week campaign, but in southern Europe and on a smaller spatial scale (5–50 km) at high topographic relief, was performed at Madrid Sierra, Spain (Cucurull et al., 2000). The ability of the HIRLAM model to calculate PW values was validated using GPS measurements from five sites with the geoid altitude of 600–1030 m. The PW (GPS) ranged from 4 to 24 mm. The uncertainty in PW (GPS) was calculated to be about 1 mm. The uncertainty of PW (HIRLAM) was evaluated to vary from 1.4 to 2.1 mm. In drier situations, below PW (GPS) values of 10 mm, there was a tendency to get markedly, often by 6 mm, higher PW (HIRLAM) estimates. In contrast, when the GPS measurements were higher than 15 mm, the PW (HIRLAM) values became up to 4.5 mm lower than PW (GPS). The experiment was also supported by 00 + 12 UTC radiosonde launches from Barajas (suburb of Madrid with the international airport). The GPS-measured and radiosonde-measured PW values agreed with each other within 1.6 mm RMSD, but the radiosonde PW estimates were generally lower than those obtained using GPS and HIRLAM.

Different methods to evaluate PW as a critical input for a good estimate of aerosol optical depth in Norrköping, Sweden, were compared in the careful analysis by Carlund et al. (2003). It was found that, on average for April–July 1997, PW (HIRLAM) was a little higher than PW (radiosonde), but the difference was small, less than 1 mm.

Nevertheless, on the basis of the cited and other reports (e.g. Glowacki et al., 2006; Thomas et al., 2011), focusing on validating PW estimates by different sensors and products, we cannot yet decide which method is closer to the "true PW value". Indeed, GPS, providing almost continuous 24-h PW observations in all weather conditions, shows its growing strength.

Some doubts with regard to the usefulness of the GPS-derived PW are possibly due to site-specific problems when the meteorological and GPS stations are located not exactly at the same place but separated by some tens of kilometres. Obviously, further studies on the accuracy and capacity of different PW estimation methods are needed.

3. DATA SETS

In frames of this research, two observation campaigns were performed at Tõravere, Estonia. During the considerably longer campaign, from 22 June to 6 November 2008, only the PW retrievals by AERONET, GPS, and HIRLAM were available. The GPS database included 3264 hourly averaged PW values on 139 days. The AERONET database consisted of 1067 Level 2.0 measurements on 71 days. The shortest time interval between successive photometric observations was 2 min and the longest, due to cloudiness, 14 days. The HIRLAM database, including both its parts (reports from the meteorological networks and predictions), enables the retrieval of humidity profiles and therefore, PW calculations, with a 3-h step, at 00, 03, 06, ..., 21 UTC. The HIRLAM (Version 7.1.2) method produced 1105 PW values for 138 days. Retrievals from GPS and HIRLAM were linearly interpolated to the times when the AERONET-measured PW values were available.

During the shorter campaign, on 9–12 August 2010, data obtained by means of four methods, radiosonde, AERONET, GPS, and HIRLAM, were available. The Estonian Defence Forces launched 17 sondes with the time interval of 3 h. The GRAW DFM-06 sondes provided information with the frequency of 1 s, about pressure, relative humidity, temperature, wind direction and speed, up to an altitude of about 36 km. According to the manufacturer, the uncertainty in sonde's relative humidity does not exceed 5%. Being affected by cloudiness and solar elevation, the AERONET sun photometer recorded PW irregularly. In clear solar disc conditions, depending on the elevation of the sun, the frequency of observations was 2–15 min. For intercomparison with other methods, hourly means for AERONET and GPS measurements were calculated.

Besides finding the largest discrepancies between single measurements, in order to quantify and evaluate the rate of differences between pairs of methods, six simple statistical tests were employed. First, we calculated the mean bias difference (MBD[mm] and MBD[%]), which reveals the average systematic deviation, overestimation or underestimation, of PW by the method y compared to the method x (or reference in this comparison):

$$\mathrm{MBD[mm]} = \frac{1}{N}\sum_{i=1}^{N}(y_i - x_i), \tag{9}$$

$$\mathrm{MBD[\%]} = \frac{1}{N}\sum_{i=1}^{N}\frac{y_i - x_i}{x_i}100. \tag{10}$$

Here N denotes the number of concurrent measurements during the campaign. Ideally, when there is neither over- nor underestimation by the method y with regard to the reference method x, zero values for MBD[mm] and MBD[%] should be obtained.

Scatter between the two methods was quantified by RMSD[mm] and RMSD[%]:

$$\mathrm{RMSD[mm]} = \left\{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right\}^{1/2}, \tag{11}$$

$$\mathrm{RMSD[\%]} = \left\{\frac{1}{N}\sum_{i=1}^{N}\frac{(y_i - x_i)^2}{x_i^2}\right\}^{1/2}100. \tag{12}$$

As the overestimations and underestimations in part compensate each other in Eq. (9), $\mathrm{MBD} < \mathrm{RMSD}$.

The fifth statistical test was calculation of a slope, a, for least-squares linear fits, $y = ax$.

In order to quantify the rate of consistency of two simultaneous estimations of PW, we used a concept proposed by Immler et al. (2010). In our research we specified this test as follows. Two independent simultaneous measurements of PW, x_i and y_i, with standard uncertainties u_x and u_y, respectively, were considered. The rate of consistency of measurements was checked according to fulfilment of inequality:

$$|x_i - y_i| < k\sqrt{u_x^2 + u_y^2}, \tag{13}$$

where the coverage factor, $k = 1, 2, 3$, is a numerical multiplier to obtain an expanded uncertainty (IOS, 1995). The terminology for checking the consistency of x_i and y_i is given in Table 1.

If the condition by Eq. (13) is not valid even for $k = 3$, the pair of measurements is considered as inconsistent.

Table 1. Terminology for checking a pair of independent measurements for consistency

Fulfilment of condition, Eq. (13)	Evaluation
$k = 1$	Strong consistency
$k = 2$	Moderate consistency
$k = 3$	Weak consistency

4. RESULTS

4.1. The campaign from 22 June to 6 November 2008

Figure 2 shows PW values obtained at Tõravere, Estonia, from 22 June to 6 November 2008, by GPS, AERONET, and HIRLAM. It appears that during the summer months (June, July, and August) the values were about 10 mm higher than during the following months. The transition from relatively warm air masses to considerably colder air occurred in the middle of September. A maximum value of PW, 42.8 mm, was registered by GPS on 13 August, when the air mass with a high humidity content (especially at an altitude of 1.5–4 km) arrived from Spain and France. A minimum value of PW, 4.7 mm, was also determined by GPS on 5 November, when the air mass at Tõravere originated from the cold, polar region (back-trajectories were calculated using HYSPLIT).

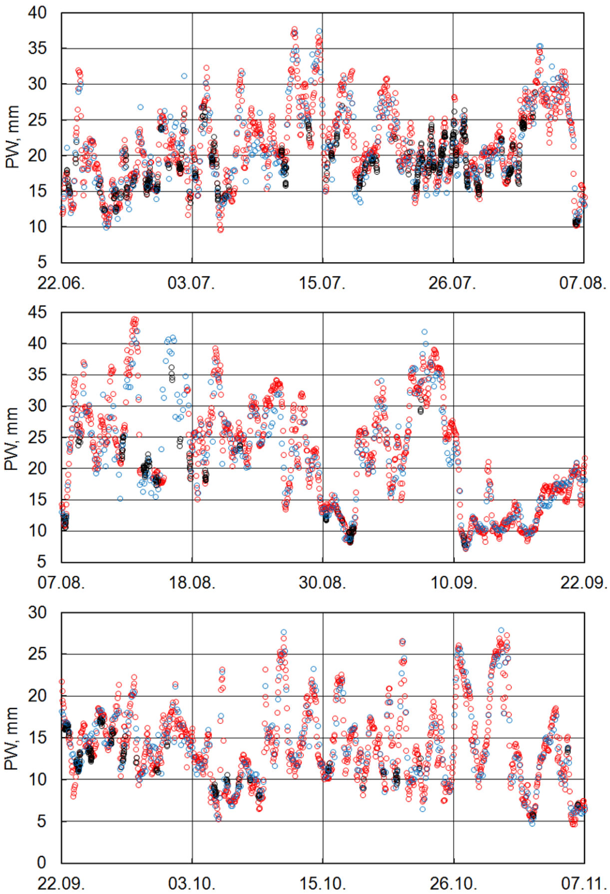

Fig. 2. Evolution of PW estimated by three methods at Tõravere during the first campaign, from 22 June to 6 November 2008. The number of points: GPS (red) – 3264; AERONET (black) – 1067; HIRLAM (blue) – 1105. Note that a different scale is used on each of the plots.

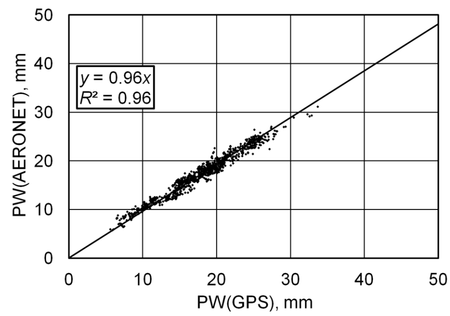

Fig. 3. Comparison of PW retrieved by AERONET and GPS at Tõravere, from 22 June to 6 November 2008 (1038 points, 71 days). The deviation of data from the best fit line becomes evident at values below 12 mm and above 25 mm.

Three figures illustrate the linear fits and correlations between the three methods mentioned above. The linear fit through zero, as an ideal relation in case of the value of the slope $a = 1$, was used. As can be seen from Fig. 3, the comparison of PW obtained with AERONET and GPS is best described by the formula

$$\mathrm{PW(AERONET)} = 0.96\ \mathrm{PW(GPS)}, \qquad (14)$$

which is characterized by the coefficient of determination $R^2 = 0.96$, RMSD = 1.2 mm (6.7%) and MBD = –0.5 mm (–2.2%), with GPS showing higher PW values.

Figure 3 shows that differences between PW estimated by these methods are visually most notable at PW values below 12 mm (when AERONET evaluated PW somewhat higher than GPS) and over 25 mm (when AERONET underestimated PW). In fact, a similar conclusion has been drawn by Smirnov et al. (2004) from the AERONET team, describing the relation between these methods with the formula

$$\mathrm{PW(AERONET)} = 0.92\ \mathrm{PW(GPS)} + 1.5, \qquad (15)$$

where the coefficient of determination was also $R^2 = 0.96$. More recently, PW measurements by these techniques have been compared by De Mazière et al. (2009), who obtained the linear regression

$$\mathrm{PW(AERONET)} = 0.82\ \mathrm{PW(GPS)} + 2.7, \qquad (16)$$

where the coefficient of determination $R^2 = 0.92$. If we force to pass the best fit lines of these previous studies through zero, the slope of the lines would increase, thus providing the evidence of deviation of data from the best fit line that is similar to our results. If we add an intercept to our formula, we get

$$\mathrm{PW(AERONET)} = 0.89\ \mathrm{PW(GPS)} + 1.3. \qquad (17)$$

Figure 4 compares the AERONET outputs with its HIRLAM counterparts. It can be calculated that the

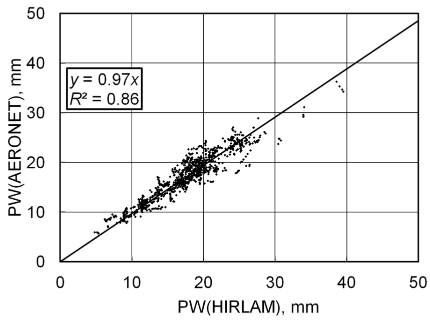

Fig. 4. Comparison of PW retrieved by AERONET and HIRLAM at Tõravere, from 22 June to 6 November 2008 (1066 points, 71 days). Similar deviation of data from the best fit line becomes evident, as was the case in comparing PW estimated by AERONET and GPS.

linear regression for comparison between PW obtained with AERONET and HIRLAM is

$$\mathrm{PW(AERONET)} = 0.97\ \mathrm{PW(HIRLAM)}, \qquad (18)$$

where the coefficient of determination $R^2 = 0.86$, RMSD = 1.8 mm (10.1%) and MBD = –0.3 mm (–1.0%), with HIRLAM showing higher PW values.

The data points in Fig. 4 are more scattered than in previous comparison. This refers to the shortfall of HIRLAM to describe the variability of PW as accurately as GPS. A similar deviation of data from the best fit line to the one shown by comparison of PW values estimated by AERONET and GPS becomes evident. These evidences suggest that compared to GPS, AERONET overestimates PW by 5% at values below 12 mm and underestimates PW by 6% at values over 25 mm. Compared to HIRLAM, these numbers are 9% and 10%, respectively.

As revealed by Fig. 5, the data points between PW (HIRLAM) and PW (GPS) are evenly scattered around the best fit line, but points are more dispersed than in previous relations. The relation between these methods can be described with the formula

$$\mathrm{PW(HIRLAM)} = 0.98\ \mathrm{PW(GPS)}, \qquad (19)$$

where the coefficient of determination $R^2 = 0.91$, RMSD = 2.2 mm (11.3%) and MBD = –0.2 mm (–0.2%), with GPS showing higher PW values.

This result is also in a good agreement with the study conducted by Cucurull et al. (2000), who found that GPS-derived PW is 0.4 mm higher than HIRLAM-modelled PW, with RMSD of 2 mm. Nevertheless, our investigation does not show a tendency for HIRLAM values to be higher than PW estimates by GPS below 15 mm.

Table 2 summarizes the results of the first study period.

A consistency test using the concept proposed by Immler et al. (2010) was carried out (Table 3). The pairs of datasets that involved AERONET showed an extremely high rate (>87%) of "strong consistency" and very low "weak consistency" (0–1%). Since the sum

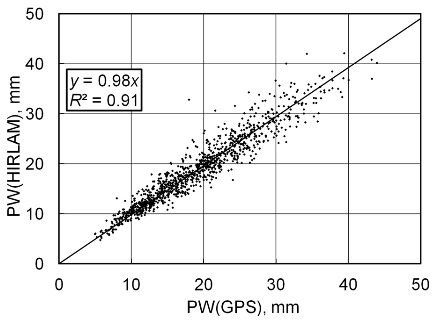

Fig. 5. Comparison of PW retrieved by HIRLAM and GPS at Tõravere, from 22 June to 6 November 2008 (1057 points, 135 days). In contrast to previous comparisons, the slope of the best fit line is closest to 1, while the RMSD is highest.

Table 2. Slopes (*a*) for linear fits, $y = ax$, mean bias differences (MBD) and root-mean-square differences (RMSD) between three PW estimation methods at Tõravere, 22 June–6 November 2008. The uncertainty of the slope is given at 95% confidence level. *N*, the number of coupled observations

Pair of methods	*N*	Slope (*a*)	MBD[mm]	MBD[%]	RMSD[mm]	RMSD[%]
AERONET (*y*) vs GPS (*x*)	1038	0.96 ± 0.003	–0.5	–2.2	1.2	6.7
HIRLAM (*y*) vs GPS (*x*)	1057	0.98 ± 0.006	–0.2	–0.2	2.2	11.3
AERONET (*y*) vs HIRLAM (*x*)	1066	0.97 ± 0.006	–0.3	–1.0	1.8	10.1

Table 3. A consistency analysis based on Eq. (13) for Tõravere, 22 June–6 November 2008. The rate of consistency is calculated as per cent of all possible fulfilments of conditions

Pair of methods	Strong consistency, %	Moderate consistency, %	Weak consistency, %	Inconsistency, %
AERONET vs GPS	93	7	0	0
HIRLAM vs AERONET	87	12	1	0
HIRLAM vs GPS	76	20	3	1

of "weak consistency" and "inconsistency" is much less than the assumed 4.5% and the "strong consistency" is much higher than 68%, the results show that the uncertainty in AERONET-estimated PW should be considerably smaller than 10%, previously reported by Holben et al. (2001). Two simultaneous estimations of PW by HIRLAM and GPS are reasonably consistent, indicating neither systematic effects nor incorrect evaluation of uncertainty.

4.2. The campaign of 9–12 August 2010

For the short campaign, data obtained by all four methods, radiosonde, AERONET, GPS, and HIRLAM, were available (Fig. 6). Keeping in mind the historical role of radiosonde in the investigation of column humidity, we considered it as a preliminary reference in this campaign.

Lower PW values in the first hours of 11 August were due to invasion of colder and drier air from Scandinavia. Higher PW values on 12 August were generated by the transport of warm and moist southern air from the Balkan Peninsula, which initially reached Estonia at altitudes above 2 km.

Comparison of single PW estimates by different methods revealed unexpectedly large discrepancies. The largest one, 9.1 mm, occurred on 12 August when the PW estimate by GPS was 37.3 mm, but only 28.2 mm by HIRLAM. The situation was opposite on 10 August when the GPS estimate was "drier" by 7.3 mm than the HIRLAM estimate.

Discrepancies between the GPS and radiosonde methods reached 7 mm and again, in both directions. Obviously, GPS-measured PW had the most "unquiet character" during these four days, showing the lowest as well as the highest PW value, 21.3 and 37.3 mm, respectively.

Discrepancies between the HIRLAM and radiosonde methods reached 7.6 mm on 12 August, 15 UTC: PW (radiosonde) = 35.9 mm against PW (HIRLAM) = 28.3 mm. Profiles of absolute humidity in Fig. 7 provide the reason for this difference.

However, no relationships between vertical humidity profiles and PW discrepancies were found. Positive as well as negative biases occurred for relatively similar profiles.

During the shorter campaign, the four different methods enabled generation of six different pairs. Intercomparison of their performance, in terms of the slope, MBD, and RMSD, is given in Table 4. The GPS method gave the closest values to radiosonde, being "drier": MBD = −0.2 mm (−0.7%). In terms of the scatter from radiosonde, AERONET was the best method: RMSD = 1.7 mm (5.5%). With MBD = −0.6 mm (–1.7%), AERONET showed slightly higher systematic deviation from radiosonde compared to GPS. The largest average systematic deviation from radiosonde, towards "drier" estimations, was demonstrated by HIRLAM: MBD = −1.5 mm (−4.8%). In the other three possible pairs (the three lowest lines in Table 4) agreement between the methods is described by MBD less than 4%. The MBD values of HIRLAM–GPS, as well as AERONET–HIRLAM, were considerably larger than at the longer campaign (–3.2% vs −0.2% and 3.9% vs 1.0%, respectively). However, the results that reflect the differences between AERONET and GPS ($a = 0.96$, MBD = 2.1%) agree well with the outcome of the longer campaign ($a = 0.96$, MBD = 2.2%).

As seen from Table 5, checking the pairs of independent measurements for consistency with Eq. (13) revealed the highest consistency in pairs which involved AERONET. In all these pairs – AERONET vs radiosonde, AERONET vs GPS, HIRLAM vs AERONET – Eq. (13) was true for $k = 1$ in more than 79% of cases, thus the data may be called "strongly consistent".

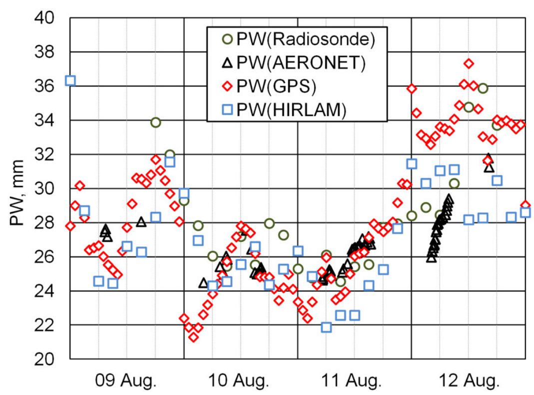

Fig. 6. Evolution of PW estimated by four methods, radiosonde, AERONET, GPS, and HIRLAM, at Tõravere during the 2010 campaign.

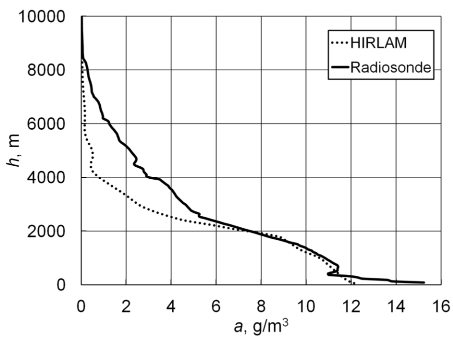

Fig. 7. Profiles of absolute humidity a, 12 August 2010, 15 UTC, Tõravere, Estonia. On the ground and at an altitude of 2–8 km HIRLAM gave considerably lower PW values than radiosonde.

Table 4. Slopes (a) for linear fits, $y = ax$, mean bias differences (MBD) and root-mean-square differences (RMSD) between four PW estimation methods at Tõravere, 9–12 August 2010. The uncertainty of the slope is given at 95% confidence level. N, the number of coupled observations

Pair of methods	N	Slope (a)	MBD[mm]	MBD[%]	RMSD[mm]	RMSD[%]
HIRLAM (y) vs radiosonde (x)	25	0.94 ± 0.04	−1.5	−4.8	3.0	9.6
GPS (y) vs radiosonde (x)	25	0.99 ± 0.05	−0.2	−0.7	3.2	11.1
AERONET (y) vs radiosonde (x)	11	0.97 ± 0.04	−0.6	−1.7	1.7	5.5
AERONET (y) vs GPS (x)	25	0.96 ± 0.04	−0.8	−2.1	2.6	8.3
HIRLAM (y) vs GPS (x)	25	0.94 ± 0.05	−1.3	−3.2	3.6	12.7
AERONET (y) vs HIRLAM (x)	11	1.02 ± 0.07	0.7	3.9	2.8	11.0

Table 5. A consistency analysis based on Eq. (13) for Tõravere, 9–12 August 2010. The rate of the consistency is calculated as per cent from all possible fulfilments of conditions

Pair of methods	Strong consistency, %	Moderate consistency, %	Weak consistency, %	Inconsistency, %
HIRLAM vs radiosonde	60	28	8	4
GPS vs radiosonde	48	36	12	4
AERONET vs radiosonde	82	18	0	0
AERONET vs GPS	79	14	7	0
HIRLAM vs GPS	58	30	9	3
HIRLAM vs AERONET	86	14	0	0

In addition, in pairs AERONET vs radiosonde and HIRLAM vs AERONET there was not a single case when the measurements were “weakly consistent” or “inconsistent” (Eq. (13) not true for $k = 2$ and $k = 3$, respectively). Similarly to the longer campaign, the results confirm that the previously estimated uncertainty u(AERONET) = 10% is too high. The other three pairs of methods all included one case in which two measurements were defined as “inconsistent”.

5. CONCLUSIONS

The aim of the current research was to find linear fits and correlations between four measurement methods of PW – GPS, AERONET, HIRLAM, and radiosonde. A survey of column integrated water vapour was based on measurements and modelling data gathered at Tõravere, Estonia, during two campaigns.

During the first campaign, while analysing the data obtained by AERONET, GPS, and HIRLAM on 22 June–6 November 2008, PW evaluated by GPS was 2.2% higher than by AERONET and 0.1% higher than by HIRLAM. In spite of the small bias from the other methods, systematic deviation of AERONET-derived PW became evident. Compared to data of HIRLAM and GPS, AERONET overestimated PW by 5–9% at values below 12 mm, and underestimated PW by 6–10% at values over 25 mm. The RMSD between the PW estimates by HIRLAM and the other two methods was higher than between AERONET and GPS. Relatively low temporal and spatial resolution as well as launching sparseness of radiosondes resulted in a method “not as accurate” as other techniques compared.

During the second campaign, on 9–12 August 2010, the GPS, AERONET, HIRLAM, and radiosonde methods were compared. Deriving information from 17 GRAW radiosonde measurements, which were used as a preliminary reference, it was concluded that PW closest to radiosonde was obtained by means of GPS. Moreover, GPS was well correlated with all three methods, providing PW which did not exceed a difference of 3.2%. The results that reflected the differences of PW estimated by HIRLAM and the other three methods were slightly higher.

By checking the pairs of independent measurements for consistency, both campaigns indicate that previously reported uncertainty in AERONET-measured PW is too high. The results of the longer campaign suggest that the uncertainty is only about 3%.

On the whole, considering previous statements about systematic deviations of AERONET and higher scatter in comparisons which involved HIRLAM, GPS is the most accurate alternative to the radiosonde method for estimation of PW. The results of our research are encouraging for the possible use of GPS atmospheric products in the near future in Estonia, along with more frequently used techniques. To compare PW estimated by GPS with radiosonde measurements gathered over a longer period, further analysis of data from the Suurupi GPS-station (since 1996) and the radiosonde data from the nearby Harku site, separated by 14.6 km, is needed.

ACKNOWLEDGEMENTS

Our particular gratitude goes to teams of AERONET, EEA, HIRLAM, and the Estonian Land Board, who provided data for this research. The survey was supported by the Estonian Science Foundation (postdoctoral grant JD189 and grant 7347), European Social Fund's Doctoral Studies and Internationalisation Programme DoRa, carried out by the Foundation Archimedes, a project "Estonian radiation climate" of the European Regional Development Fund as well as targeted financing by the Estonian Ministry of Education and Research (project SF0180038s08). We would like to thank the anonymous reviewers for their valuable comments and suggestions that improved the quality of the paper.

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Õhusamba niiskussisaldus: määramisviiside võrdlus Eesti andmetel

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Hoolimata mitmetest õhusamba niiskussisalduse (sadestatav veeaur, PW) määramisviisidest, pole ükski neist siiani defineeritud kui referentsmeetod. Käesoleva töö eesmärgiks oli võrrelda ja leida seosed nelja meetodi – Global Positioning System (GPS), Aerosol Robotic Network (AERONET), High Resolution Limited Area Model (HIRLAM) ning raadiosondeerimine – vahel. Töös on kasutatud mõõtmisandmeid kahest perioodist: 1) 22.06.–06.11.2008 ja 2) 09.–12.08.2010. Pikemal mõõtmisperioodil kasutati GPS-i, AERONET-i ja HIRLAM-i mõõtmistulemusi. Nende kolme meetodi vahel leiti kokkulangevus, mille kohaselt oli PW keskmine erinevus väiksem kui 2,2%. Võrreldes AERONET-i fotomeetriga mõõdetud PW väärtusi GPS-i ja HIRLAM-i andmetega, ülehindas AERONET sadestatavat veeauru 5–9%, kui PW < 12 mm, ning alahindas 6–10%, kui PW > 25 mm. Lühemal perioodil kasutati kõigi nelja meetodi mõõtmistulemusi. Kuigi PW keskmine erinevus raadiosondi kui traditsioonilise mõõtmisvahendi ja teiste meetodite vahel oli väiksem kui 5%, ulatusid erinevused üksikväärtuste vahel kuni 33%-ni. Tulenevalt HIRLAM-i mudelandmete suhteliselt väikesest ajalisest ja ruumilisest resolutsioonist ning hõredalt paiknevatest lähipiirkonna raadiosondeerimise jaamadest ilmnes mudelandmete kõrvutamisel GPS-i ja AERONET-i mõõtmistega suurem hajuvus kui viimastel omavahel. Töö autorid leiavad, et PW väärtusi iseloomustas kõige täpsemini GPS.