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Comparison of techniques for Integrated Precipitable Water measurement in the polar region

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Abstract: Tropospheric delay estimates (tropospheric product) for selected International GNSS Service (IGS) and EUREF Permanent Network (EPN) stations made it possible to asses two areological techniques in the polar region (mainly in Greenland). Integrated Precipitable Water (IPW) – important meteorological parameter is derived from GPS tropospheric solutions by a known procedure for GPS stations. To convert from the wet part of tropospheric delay (ZWD) to IPW, the relation between 2 m temperature and the so-called mean temperature of the atmosphere above was derived using local radiosonde data for nearby GPS stations. Sunphotometer data were provided by AERONET (NASA AErosol RObotic NETwork). IPW comparisons lead to the determination of a systematic difference between the techniques of GPS IPW and sunphotometer data (not present in the case of RAOBs). IPW measured by sunphotometer CIMEL (Cimel Electronique) is several percent smaller than IPW from GPS (both IGS and EPN solution). The bias changes seasonally and is a function of atmospheric temperature. It signals some systematic deficiencies in solar photometry as the IPW retrieval technique. CIMEL IPW shows some temperature dependent bias also in relation to radiosoundings.

Keywords: water vapour, GNSS meteorology, precipitable water vapour, sunphotometer, radiosounding, polar research, Greenland

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1. Introduction

Water vapour is an extremely important component of the water cycle and plays a crucial role in many meteorological, climatological and environmental processes (such as evapotranspiration, condensation, precipitation, thermodynamic latent heat release, cloudiness and its impact on insolation, etc.) as acknowledged in numerous sources even at the textbook level (e.g. Shelton, 2009; McIlven, 2010; Salby, 2012). The average value of IPW for the Earth is about 25 mm but average precipitation amounts to about 1000 mm which exhibits clear evidence of high dynamics of hydrological processes (45 evaporation-condensation cycles in one year). Water vapour contributes to the greenhouse gas effect more than carbon dioxide (but of course lasts in the atmosphere for a short time). In a warmer atmosphere saturation water vapour pressure is higher and likewise water vapour density for the same relative humidity. Water vapour is both climate change agent and indicator (see e.g. Kruczyk, 2014). Integrated precipitable water, i.e. column water content in the whole of the atmosphere, provides a convenient measure of water vapour and is obtained by means of measurements by a variety of techniques.

There are several completely different techniques to observe/measure water vapour content in the atmosphere:

- in-situ meteorological measurements (various termohigrometers, capacity sensors etc.),
- radiosonde/dropsonde (direct measurements from the device moving through the atmosphere),
- Water Vapour Radiometry (WVR) – remote sensing possible both from ground and satellite platforms,
- LIDAR (especially Raman and DIAL types),

– Fourier Transform Infrared Spectrometry (FTIR),
– sun photometry (with a rare lunar variety),
– differential optical absorption spectrometry (DOAS),
– GNSS meteorology (described in detail below).

The main aim of this paper is to compare three of these techniques in the case of the polar region – Greenland. Here is a short description of the techniques tackled.

Atmospheric refraction of the Global Positioning System (GPS) L-band navigational signal manifests itself as tropospheric delay of pseudorange. For a GPS measurement taken for a satellite at zenith and a receiver located at sea level, the Zenith Tropospheric Delay (ZTD), in units of length, amounts to approximately 2.3 m. The ZTDs need to be properly taken into account when high accuracy of determined station coordinates is required, i.e. at the level of several millimetres. Due to limited accuracy of existing ZTD models, precise applications of GPS positioning (geodynamics, geodetic reference frames) require the estimation of ZTDs in the process of the adjustment of GPS observations, together with other parameters, like station coordinates, phase ambiguities, etc. (Hoffmann-Wellenhof et al., 2008; chapter 5.3). Because of temporal variability, ZTDs are usually estimated every hour for each station in the case of EPN (24 parameters for a daily session). For the IGS PPP solution there are 12 parameters each hour. Tropospheric delay is estimated together with coordinates. The GPS-derived ZTDs obtained from the networks of permanent GPS stations maintained for most precise scientific applications are also used for the purpose of atmospheric research and are the basis of GPS meteorology (Duan et al., 1996). ZTD is a sum of Zenith Wet Delay (ZWD) and Zenith Hydrostatic Delay (ZHD). ZWD, which is about 10% of ZTD, depends mostly on the content of water vapour along the path of signal propagation and is highly variable both spatially and temporally. ZHD depends mostly on surface atmospheric pressure, and can be computed at the several millimetre accuracy level from the existing ZHD models using surface meteorological data (Saastamoinen formula with gravitational correction as a function of surface atmospheric pressure is applied).

Integrated Precipitable Water (IPW) – sometimes denoted simply as PW – is a valuable meteorological parameter describing the quantity of water vapour in the vertical direction over the station in millimetres of liquid water after condensation. A related parameter – Integrated Water Vapour (IWV) – is also used; it has the same value as IPW but is expressed in another unit of measure, i.e. kg/m^2. IPW can be calculated from ZTD by separating Zenith Hydrostatic Delay and Zenith Wet Delay before calculating IPW from previously obtained ZWD with the use of a numerical coefficient dependent on the so called "mean temperature" (along the vertical profile of the atmosphere) (Rocken et al., 1993; Bevis et al., 1994). The procedure is presented in detail in the next section.

On the other hand IPW can be determined from vertical humidity data, i.e. radiosounding data or numerical weather prediction models by integrating water vapour density. IPW can also be obtained from the measurements of atmospheric radiation in infrared using radiometers and photometers (see below). A number of studies have shown that IPW estimates from ground-based GPS observations and meteorological/aerological data give the same level of accuracy as aerological techniques. GNSS-derived IPW is the basis of a new discipline called GNSS meteorology, which is developing so dynamically and is such an abundant field for various types of research that it takes a full publication to present the state of the art (see e.g. Böhm and Schuh, 2013).

A number of studies have also shown that IPW estimates from ground-based GPS observations and meteorological/aerological data give the same level of accuracy as radiosondes and microwave radiometers (see e.g. Vedel et al., 2001). In this work both radiosoundings and another water vapour data source – sun photometer – are tested in exceptional conditions: at the polar region of Greenland.

The fundamental aerological technique is balloon soundings called radiosounding. GPS and RAOB comparisons in the form of ZTD are provided by Vedel in the frame of EPN (see the 2nd www in the References).

Integrated Precipitable Water for a radiosounding profile can be obtained by numerical integration of average water vapour density (calculated from temperature and relative humidity for each level *j* and averaged between registered levels, from surface reading $j = 0$ up to the last level N):

$$IPW = \sum_{k=1}^{N} \overline{\rho_{wv}(j-1, j)}(h_j - h_{j-1}) \qquad (1)$$

CIMEL-318 sun photometer is an important tool in aerosol research (Halthorne et al., 1997; Holben et al., 1998; Holben et al., 2001). CIMEL is an automatic/robotic sun tracking photometer (solar powered) produced by Cimel Electronique (www.cimel.fr). These multifunctional devices are operated in the framework of the AERONET (AErosol RObotic NETwork) programme coordinated by NASA and CNRS (www.aeronet.net). The globally distributed network of over 100 sites provides assured aerosol optical properties to monitor atmosphere, environment and validate remote sensing satellite retrievals. A sun photometer is a multichannel radiometer which measures many air properties (mostly aerosols) registering absorption of 8 line bands of solar spectra (340, 380, 440, 500, 675, 870, 940 and 1020 nm nominal wavelengths; potentially also 1640 nm). The automatic Sun and sky scanning radiometers make direct Sun measurements with a 1.2° full FOV every 15 min. The direct Sun measurements take 8 seconds to scan all 8 wavelengths, with a motor driven filter wheel positioning each filter in front of the detector resulting in 3 measurements at each wavelength within a one minute period. These solar extinction measurements are then used to compute aerosol optical depth at each channel by means of comparing measurements of sky radiance with off-band wavelengths (with no absorption). CIMEL gives also IPW values (precisely – slant values in the direction to the Sun). The bandpass of ion assisted deposition interference filters (spectral windows breadth FWHM) of most channels is 10 nm and includes many individual lines of water vapour molecular spectral transitions (vibrational-rotational). Water vapour channels used by CIMEL are centred on 940 nm and 1020 nm (940 nm channel used solely to retrieve precipitable water). The relationship used to estimate the PW from the water vapour transmittance T_{wv} is:

$$T_{wv} = e^{-a(m \cdot IPW)^b} \qquad (2)$$

The two constants a and b are related to the water vapour channel used and m is the relative optical airmass.

Spectrometric detection and measurements of water vapour (in this case called CWV – column water vapour) are demanding tasks because of the complexity of the instruments calibration (e.g. Schmid et al., 2001). CIMEL instruments use parameters (e.g. zero airmass voltages) from reference instruments calibrated at Mauna Loa Observatory every 3 months. From the point of view of GNSS meteorology CIMEL is an independent source of IPW.

Several investigations have been carried out to evaluate sunphotometer IPW by other techniques, also GNSS (see e.g. Pérez-Ramírez et al., 2014). They acknowledge the relatively low accuracy of IPW measured by sunphotometer (IPW bias of about 10%). There is ongoing work with the procedure of IPW retrieval from sunphotometer measurements (Alexandrov et al., 2009). Most comprehensive inter-technique comparison (dealing mostly with satellite devices) achieved better GNSS-CIMEL agreement but also reports some CIMEL IPW bias dependent on IPW value (Van Malderen et al., 2014).

There are several papers concerning GNSS meteorology in polar regions (see e.g. Vazquez and Brzezinska, 2012). The author performed investigations on IPW technique comparison in the case of a dedicated solution for a non-EPN station operated permanently (but not included in EPN) by the Insitute of Geophysics of the Polish Academy of Sciences at Hornsund, Svalbard (Kruczyk and Liwosz, 2015).

2. GNSS tropospheric solutions and IPW determination

Several tropospheric solutions are routinely provided as a result of the International GNSS Service (IGS) and EUREF Permanent Network (EPN) services. In this research the author used the new IGS tropospheric product calculated by Byun and Bar-Sever, JPL, and from 2011 by Byram, USNO (see Byun and Bar-Sever, 2009) as well as the EPN (http://www.epncb.oma.be) standard product of the EPN network created as iterative weighted mean of individual analysis centres' solutions. The EPN combination (EUR) was made by Söhne (see Söhne and Weber, 2009) and Pacione (for details see: Pacione et al., 2011). The map in Figure 1 shows the location of analysed stations.

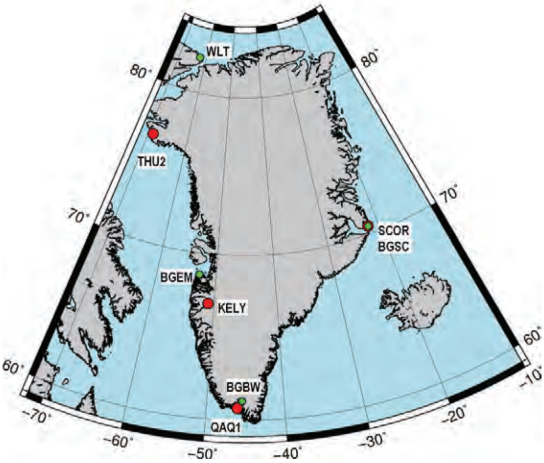

Fig. 1. GNSS stations used (red): THU2/THU3 – Thule, SCOR – Scoresbysund/ Ittoqqortoormiit, KELY– Kangerlussuaq and QAQ1 – Qaqortoq / Julianehaab and corresponding radiosounding points (green)

Integrated precipitable water, i.e. the total column of water vapour (as liquid) is determined from ZTD solution by a widely known procedure involving first the separation of Wet Delay by calculation of Hydrostatic Delay

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD} \tag{3}$$

Physically ZHD is defined as follows:

$$\mathrm{ZHD} = \int_0^{p_s} \frac{R_d k_1}{g} pd \tag{4}$$

where p_s is the surface atmospheric pressure, R_d is specific gas constant for dry air, g is the acceleration of gravity, and empirical constant $k_1 = 7.76 \cdot 10^{-7}$ [K/Pa]. In this work the Saastamoinen formula (Saastamoinen, 1972) with gravitational correction is used – ZHD is a function of surface atmospheric pressure

$$\mathrm{ZHD} = 2.2779\ p/\mathrm{f}(\varphi, H) \tag{5}$$

where p is atmospheric pressure, function f reproduces changes in gravity with latitude φ and ellipsoidal height H in kilometres, and can be derived employing effective gravity and effective height (Davis et al., 1985)

$$\mathrm{f}(\varphi, H) = (1 - 0.00266\cos 2\varphi - 0.00028H) \tag{6}$$

In the next step the obtained ZWD is transformed into IPW using the coefficient κ dependent on “mean temperature”

$$\mathrm{IPW} \approx \kappa \cdot \mathrm{ZWD} \tag{7}$$

with κ given as follows:

$$1/\kappa = 10^{-6}(k_3/T_m + k_2')R_v \tag{8}$$

where R_v is the specific gas constant for water vapour, T_m is “mean temperature” (through the vertical profile of atmosphere), k_i are empirical coefficients (given e.g. in: Davis et al., 1985). Coefficient κ of a value about 1/6.4 depends on temperature vertical profile but it can be estimated as a function of surface temperature at the GNSS station (Bevis et al., 1992).

$$T_m = \frac{\int_S (P_v/T)ds}{\int_S (P_v/T^2)ds} \approx \frac{\int_{h_0}^{\infty} (P_v/T)dh}{\int_{h_0}^{\infty} (P_v/T^2)dh} \tag{9}$$

One can model mean temperature as a linear function of surface temperature. Normally the linear model proposed by Bevis et al. (1992) is used; but in order to obtain higher accuracy it is better to use radiosounding profiles for the particular place. It is also possible to calculate T_m from a numerical weather prediction model. For example mean temperature is available at the Technical University of Vienna (for www see References) where they are computed from ECMWF (European Centre for Medium-Range Weather Forecasting) model operational analysis of pressure level data. As the IPW derivation procedure is quite sensitive to T_m values, the author used radiosounding data to obtain a local linear model for mean temperature (Table 1) as a function of surface atmospheric temperature T_s measured at the GNSS station at 2 m height. The polar tropopause, which is lower and relatively warmer in relation to the surface than tropopause for mid-latitudes makes the procedure particularly important in the case of polar stations. Soundings were performed in Greenland in the vicinity of 3 stations (at 207 km distance in the case of KELY); the nearest radiosounding point is in Northern Canada (Alert, Ellesmere Island, Nunavut). Figure 2 presents the fit of linear formula for two radiosounding stations in Greenland and the Bevis

Table 1. Mean temperature model for selected radiosounding points close to Greenland IGS/EPN stations, for the period of 2012–14

Radiosounding point	Nearby GNSS points	Distance [km]	Mean temperature formula [K] and difference STDEV	Number of radiosoundings
04339 BGSC Ittoqqortoormiit	SCOR	1	$T_m = 62.2 + 0.74 \cdot T_s \pm 4.0$	2122
04270 BGBW Narsarsuaq	QAQ1	62	$T_m = 70.4 + 0.71 \cdot T_s \pm 4.4$	2158
04220 BGEM Aasiaat	KELY	206	$T_m = 12.1 + 0.92 \cdot T_s \pm 3.4$	2159
071082 WLT Alert (Nunavut, Canada)	THU2/THU3	675	$T_m = 96.0 + 0.62 \cdot T_s \pm 6.2$	2449

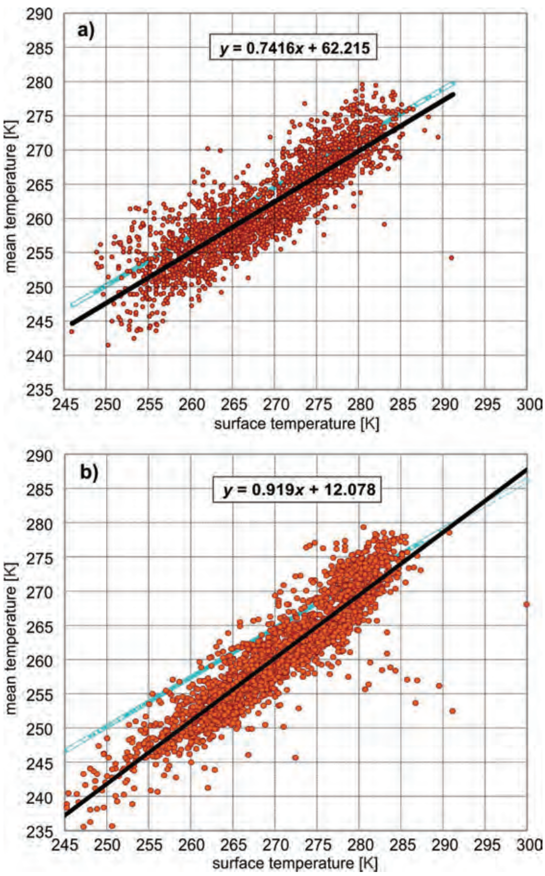

Fig. 2. Mean temperature vs. surface temperature for a) Ittoqqortoormiit (04339 BGSC), and b) Aasiaat (04220 BGEM), 2012–2014 (2122 and 2159 soundings respectively), the fit of linear formula (black line) and Bevis formula (blue line)

formula (which has been obtained for lower latitudes of continental USA). The local formula is obviously better.

For the separation of ZWD direct measurements of meteorological parameters at GNSS stations are needed. Unfortunately the GNSS stations equipped with meteorological sensors are quite sparse (as for the Greenland stations local meteorological measurements are not provided for KELY).

Both meteorological data which are recorded in time intervals of 5 min, and ZTD estimates over 5 minute intervals (in the case of the IGS solution) have been averaged in hourly intervals to obtain IPW. Only hourly data are the subject of IPW comparisons described below.

Figure 3 shows annual series of IPW hourly values calculated from the IGS tropospheric solution

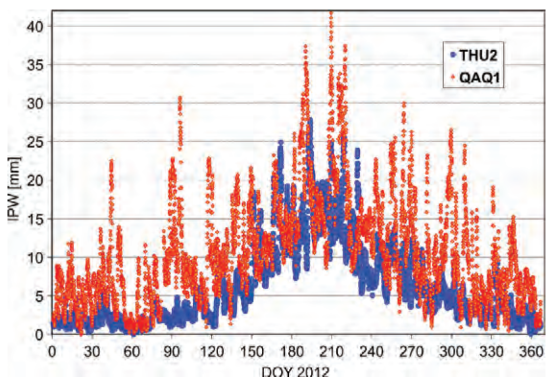

Fig. 3. Hourly GNSS IPW estimates in 2012 for THU2 (Thule) and QAQ1 (Ittoqqortoormiit); IGS tropospheric product

for Thule (THU2) and Qaqortoq (QAQ1) – located at opposite sides of the giant island – in 2012. This graph even provides some details to describe the local climate: for QAQ1 (southern tip of Greenland) is much warmer and more variable than THU2 (far to the north). In polar regions IPW (if much smaller than in the tropics) exhibits strong seasonal and short time (i.e. several days) variability because of dramatic changes in insolation and influence of local atmospheric masses taking part in global circulation.

3. IPW from IGS/EPN tropospheric solutions and CIMEL sun-photometer comparisons

CIMEL automatic sun tracking photometers are operated in the framework of the AERONET programme in the vicinity of all four GNSS sites presented on the map in Figure 1. Unfortunately measurements at Narsarsuaq (near QAQ1) are seriously incomplete and measurements at Kangerlussuaq (near KELY) cannot be effectively used because meteorological measurements here are not available to precisely calculate IPW. To calculate IPW for GNSS site that does not record meteorological data one can use meteorological data from the sounding taking into account height difference or use some numerical weather prediction data. In such a case the precision needed to compare the techniques can never be achieved. For polar stations (especially Thule – far north of Greenland) CIMEL measurements are only possible when the Sun is high enough over the horizon – so only data (IPW measurements) for the period from the second half of March till late September are available (see Fig. 4).

IPW differences (ΔIPW) for Thule will be investigated with the greatest attention because the techniques are almost collocated. The distance between CIMEL Thule and THU2/THU3 GNSS stations is only 2 km. Annually averaged results for both IGS and EPN solution in 6 subsequent years are listed in Table 2.

The sign of IPW difference (CIMEL – GPS) changes from positive to negative with growing IPW value (Fig. 5) also the histogram of differences is asymmetric (Fig. 6).

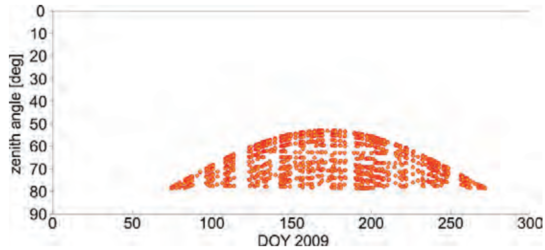

Fig. 4. Zenith angle of CIMEL measurements in 2009 at Thule ($\varphi = 76.5°$)

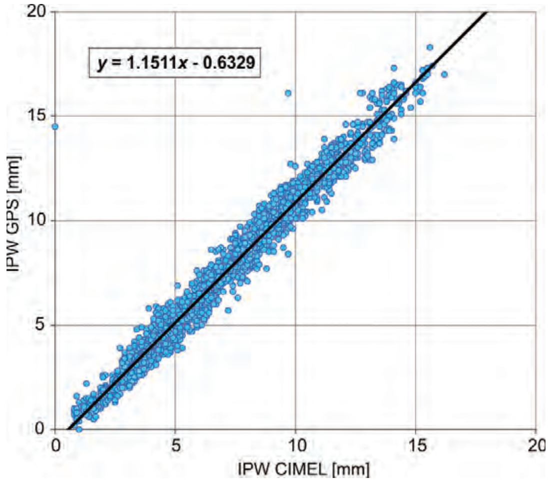

Fig. 5. IPW (CIMEL vs. GPS) for Thule (THU2) for 2009–2011

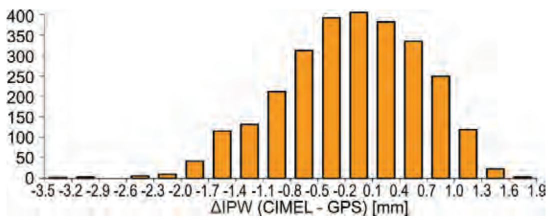

Fig. 6. IPW difference (CIMEL – GPS) for Thule (THU2) for 2009–2011 (2740 points)

The crucial point of this experiment – systematic annual change in IPW difference (between CIMEL-318 sunphotometer and IPW at GPS point) – is best illustrated in Figures 7 and 8. Annual averages (details in Table 2) and the scatterplot (Fig. 5) only suggest some inter-technique systematic bias, but time changes of IPW difference neatly follow seasons and temperature.

Table 2. Comparison of IPW from CIMEL and GPS at Thule (differences: CIMEL – GPS) EPN tropospheric combination and IGS tropospheric product (hourly averages of 5 minute estimates)

Year	GPS solution	IPW average difference [mm]	Difference STD [mm]	Difference RMS [mm]	GPS estimates	CSPHOT measurements
2009	THU2 IGS	–0.30	0.74	0.80	1247	3034
	THU3 IGS	–0.37	0.73	0.82	1177	2817
	THU3 EUR	–0.63	0.80	1.02	1202	2888
2010	THU2 IGS	–0.05	0.62	0.62	875	2184
	THU3 IGS	–0.12	0.62	0.63	888	2212
	THU3 EUR	–0.43	0.60	0.74	874	2176
2011	THU2 IGS	–1.23	0.62	1.38	618	1658
	THU3 IGS	–1.24	0.62	1.39	618	1658
	THU3 EUR	–1.30	0.66	1.46	618	1658
2012	THU2 IGS	–0.10	0.54	0.54	892	2865
	THU3 IGS	–0.12	0.55	0.56	892	2865
	THU3 EUR	–0.16	0.54	0.57	905	2915
2013	THU2 IGS	–0.60	0.80	1.00	1088	3294
	THU3 IGS	–0.54	0.73	0.91	1071	3285
	THU3 EUR	–0.63	0.72	0.96	1113	3403
2014	THU2 IGS	–0.88	0.76	1.16	858	2505
	THU3 IGS	–0.89	0.78	1.18	844	2470

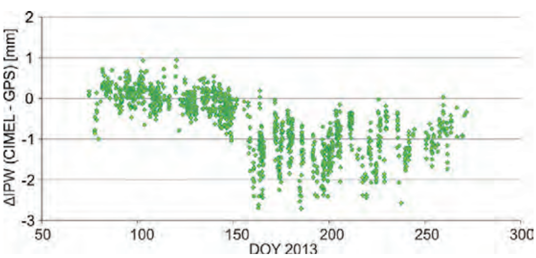

Fig. 7. IPW difference (CIMEL-GPS) for Thule (THU3) in 2013, EPN tropospheric combined solution; 1113 points

IPW difference has almost the same characteristics in two separate years, and two independent GPS solutions: EPN tropospheric product (combination of individual analysis centre standard network solutions (by Bernese 5.2) and IGS tropospheric product (PPP solution by GIPSY-OASIS). The only difference is the number of simultaneous measurements available. Also THU2 shows almost identical results. Intriguing seasonal changes in IPW differences (CIMEL – GPS) can be best explained by the most obvious environmental factor – atmospheric temperature. There is clear dependence of IPW difference on temperature registered at GPS stations, best perceptible with a smaller number of points, i.e. during a single year (Fig. 9). There is no such dependence of IPW difference on zenith angle (its daily range also changes with season, Fig. 10).

Results presented clearly signal some systematic deficiencies in solar photometry as an IPW retrieval technique. Lack of IPW difference and zenith angle rather excludes a change in optical atmospheric properties as a possible cause. The probable reason for this phenomenon is a change in optical filter characteristics in sunphotometers working in extreme polar conditions. There is probably some

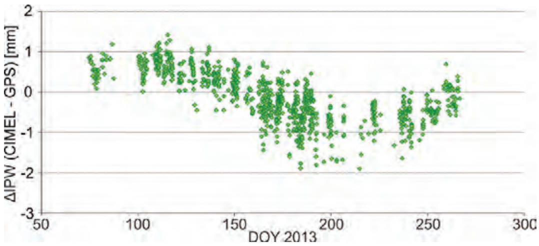

Fig. 8. IPW difference (CIMEL – GPS) for Thule (THU3) in 2010, IGS tropospheric solution

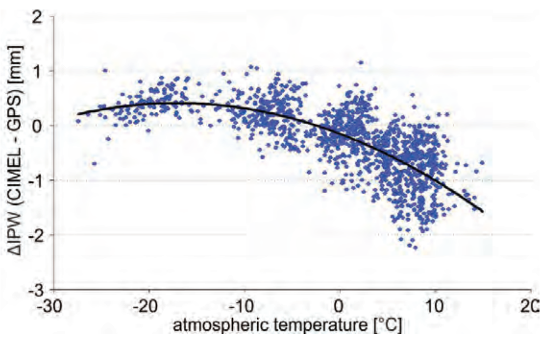

Fig. 9. IPW difference (CIMEL – GPS) for Thule (THU2) in 2009 as a function of atmospheric temperature, IGS tropospheric solution

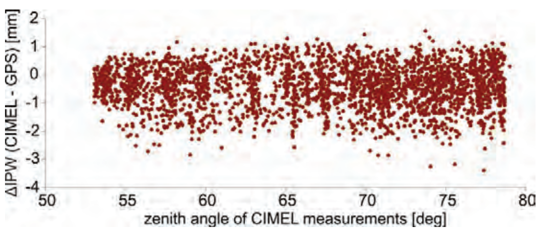

Fig. 10. IPW difference (CIMEL – GPS) for Thule (THU2) in 2009–2011 as a function of zenith angle of the Sun (CIMEL measurement), IGS tropospheric solution

change in the band pass filter characteristics in the non-thermostaticised device (A. Pietruczuk – personal communication).

Next the results are presented of an analogic comparison for CIMEL Ittoqqortoormiit and GPS at Scoresbysund (SCOR). This time the distance between CIMEL Ittoqqortoormiit and SCOR GNSS station is 9.7 km; the location is on the eastern side of Greenland at Greenland's Sea shore.

Dependence of IPW differences on temperature both for Thule and Scoresbysund are put together in Figure 11. In both cases data from a 3 year period were used (for Thule the same period as in Figures 6 and 9). In the case of difference between Ittoqqortoormiit (CIMEL) and Scoresbysund (SCOR GNSS station) this effect (of temperature dependence of the IPW differences) is less conspicuous but still present. Points are located in Eastern Greenland (on the warmer side of the island) 6° of latitude to the south in relation to Thule – so less extreme temperatures are encountered there.

4. GNSS IPW and sunphotometer IPW vs. radiosoundings

It is a common standard in GNSS meteorology to compare GPS IPW with radiosoundings. In this work the EPN combined tropospheric solution and IGS tropospheric product are the object of such a procedure.

There are two methods to compare IPW from the GNSS solution and radiosounding observations. First is to compare GNSS IPW obtained with local meteorological measurements (only where they are available). The second – possible for all GNSS stations near the radiosounding point – is to use surface meteorological readings from radiosounding to obtain IPW at the GNSS point taking into account the difference in orthometric heights. Hence one needs barometric correction to atmospheric pressure (see e.g. Andrews, 2010; chapter 2.3).

$$\frac{p_2}{p_1} = e^{-(h_2 - h_1)/H_e} \tag{10}$$

where: p_1 and p_2 is the atmospheric pressure at the heights h_1 and h_2, respectively, H_e is pressure scale height

$$H_e = \frac{R_a T}{g} \tag{11}$$

R_a – universal gas constant per unit mass, T temperature [K] and g – gravity.

The results of such an IPW RAOB – GPS comparison are presented in both versions (GPS meteo and RAOB meteo) for selected polar and subpolar stations in 2011 for EPN combined tropospheric product (Table 4). RAOB IPW bias depends on the radiosounding point – GNSS station distance and their latitude.

Table 3. Comparison of IPW from CIMEL Ittoqqortoormiit and GPS at Scoresbysund (SCOR) (differences: CIMEL – GPS); EPN tropospheric combination and IGS tropospheric product (hourly averages of 5 minute estimates)

Year	GPS solution	IPW average difference [mm]	Difference STD [mm]	Difference RMS [mm]	GPS estimates	CSPHOT measurements
2010	IGS	–0.16	0.48	0.51	647	1803
2011	IGS	0.08	0.49	0.49	312	777
2012	IGS	0.06	0.67	0.68	1262	4205
	EUR	0.07	0.71	0.71	1281	4281
2013	IGS	0.18	0.54	0.57	1036	3474
	EUR	0.22	0.50	0.54	1056	3538
2014	IGS	0.22	0.64	0.67	1128	3757
	EUR	0.25	0.50	0.56	1128	3757

Table 4. Comparison results of IPW from radiosoundings and GPS at selected stations (bias: RAOB – GPS); EPN combined tropospheric product (EUR) in 2011, for TIXI IGS solution; stations sorted by latitude

Radiosounding point	GPS	Distance [km]	Bias [mm]	Difference STD [mm]	Difference RMS [mm]	No of points
local meteo at GPS station						
4270 GL Narsarsuaq	QAQ1 43007M001	52.0	–0.10	1.55	1.55	715
4339 GL Ittoqqortoormi	SCOR 43006M002	9.7	0.27	0.73	0.78	594
4018 IS Keflavikurflug	REYK 10202M001	41.1	–0.18	1.18	1.19	691
3238 UK Albemarle	MORP 13299S001	26.4	–0.65	1.39	1.54	325
10113 DE Norderney	BORJ 14268M002	31.6	0.48	2.60	2.65	336
meteo from radiosounding						
4220 GL Aasiaat	KELY 43005M002	207.3	1.02	2.00	2.24	716
4270 GL Narsarsuaq	QAQ1 43007M001	52.0	–0.59	1.39	1.51	715
4339 GL Ittoqqortoormi	SCOR 43006M002	9.7	0.65	1.05	1.24	697
1004 NO NY-ALESUND II	NYA1 10317M003	3.4	0.49	0.82	0.95	385
1415 NO Stavanger	STAS 10330M001	24.2	0.57	1.44	1.55	666
1241 NO Orland	TRDS 10331M001	51.0	1.46	1.91	2.41	704
4018 IS Keflavikurflug	REYK 10202M001	41.1	1.60	1.47	2.17	690
2591 SN VISBY AEROLOG	VIS0 10423M001	7.2	1.32	1.54	2.03	671
21824 RU Tiksi	TIXI 12319M001	15.0	1.92	1.79	2.62	694
3238 UK Albemarle	MORP 13299S001	26.4	–0.21	1.62	1.64	439
3913 UK Castor Bay	BELF 13240M001	32.7	0.95	1.49	1.77	532
10113 DE Norderney	BORJ 14268M002	31.6	0.50	2.55	2.60	353

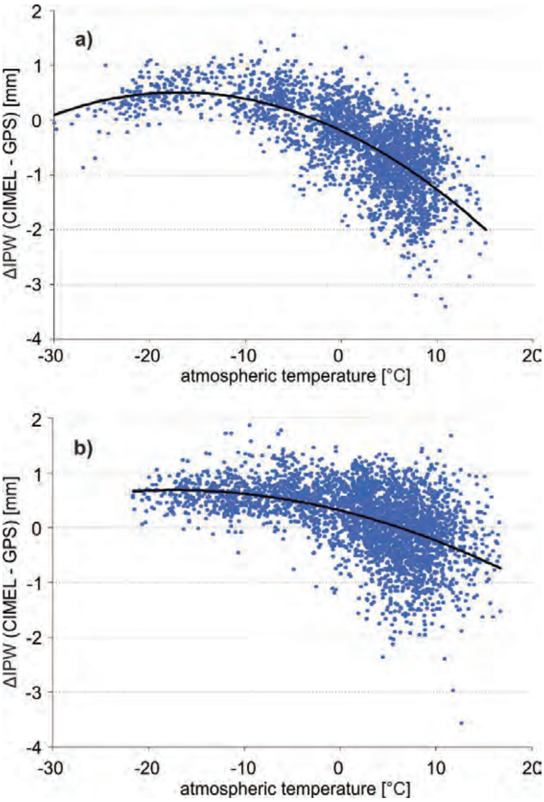

Fig. 11. IPW difference (CIMEL – GPS) for a) Thule-THU2 for 2009–2011, and b) Ittoqqortoormiit – Scoresbysund (SCOR) for 2012–2014 as function of atmospheric temperature, IGS tropospheric solution

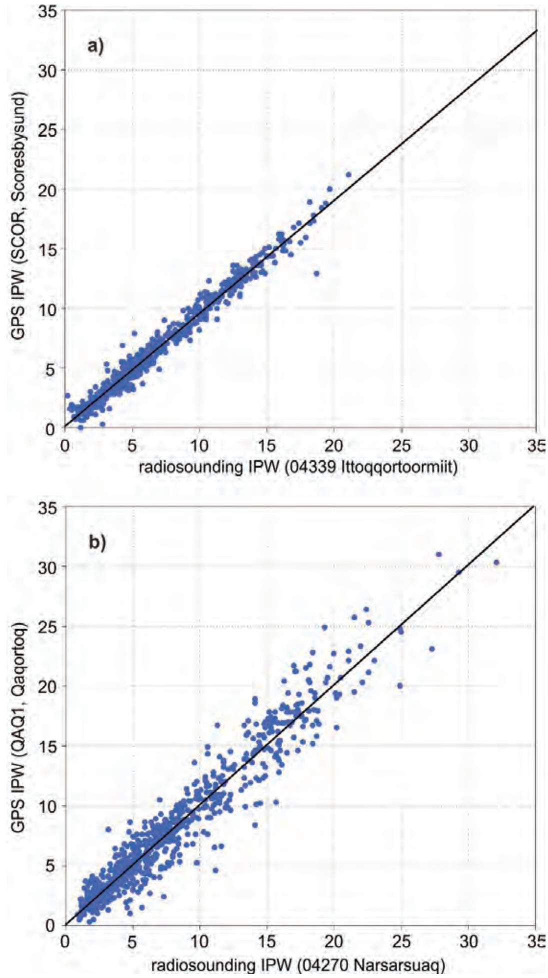

Fig. 12. IPW (RAOB vs. GPS) for a) Ittoqqortoormiit (04339 BGSC) – Scoresbysund (SCOR), and b) Narsarsuaq (04270 BGBW) – Qaqortoq (QAQ1) in 2012; distance in the first case is only 1 km, in the second: 62 km

Conformity of radiosounding and GPS derived IPW is of no surprise. Also for more distant stations (Narsarsuaq–Qaqortoq) quite good results with slightly greater dispersion were obtained (see Fig. 12).

There is no such seasonal periodicity (or temperature dependence) in IPW differences as in the case of CIMEL (Fig. 13). However, some periodicity of about 2 months can be observed in the series and needs further investigation.

Finally there is a possibility to directly compare aerological techniques, i.e. CIMEL sun-photometer and radiosoundings. The main problem here is a small number of common points: radiosoundings are performed only twice a day and only daily soundings at 12 UTC can be used. In the case of Ittoqqortoormiit in the period of 2010–2014 there are only 343 common points. Nevertheless IPW

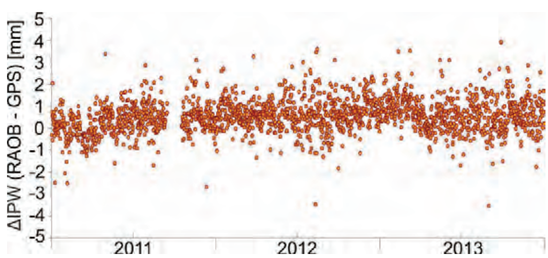

Fig. 13. IPW difference (RAOB – GPS) for Ittoqqortoormiit (04339 BGSC) – Scoresbysund (SCOR) IGS tropospheric solution, 2011–2013

difference once more exhibits temperature dependence (Fig. 14). The distance Ittoqqortoormiit – 04339 BGSC is only 600 m.

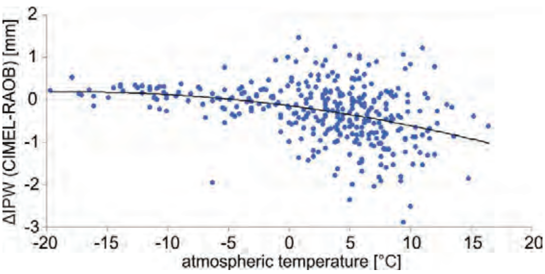

Fig. 14. IPW difference (CIMEL – RAOB) Ittoqqortoormiit – 04339 BGSC for 2010–2014 as a function of atmospheric temperature, IGS tropospheric solution

Conclusions

IPW – this valuable meteorological parameter can be obtained both by classical aerologic techniques and derived from tropospheric solutions/products and treated as a reference to aerology. Three independent techniques have been tested to obtain Integrated Precipitable Water at four points in Greenland: GPS solution, radiosounding and CIMEL sunphotometer.

To calculate IPW for four GNSS stations, a local model of the mean temperature was developed using radiosoundings performed nearby by meteorological services. The linear formulae for mean temperature obtained in some cases considerably differ from the formulae obtained by Bevis et al. (2012) for stations in mid-latitudes because of the polar tropopause which is lower and relatively warmer in relation to the surface than tropopause for mid-latitudes.

CIMEL sunphotometer IPW and IPW values derived from standard solutions of IGS and EPN (combined solution) show relatively good agreement but also some biases of 2–7 %. IPW bias shows seasonal dependence (especially in the case of Thule), which signals some systematic deficiencies in solar photometry as an IPW retrieval technique. A probable cause of this phenomenon is a change in optical filter characteristics in sunphotometer working in extreme polar conditions.

Averaged IPW difference for RAOB – GPS is relatively small and show no dependence on temperature. The attempt to compare aerological techniques (CIMEL and RAOB) brings a similar temperature – IPW difference dependence but results are less pronounced.

In the polar environment with different sun visibility, GPS constellation geometry and temperature range, IPW series obtained by GPS and aerology show some characteristic discrepancies. There is empirical basis to claim that the GPS solution gives us at least as reliable results of IPW in the polar region as expert aerological techniques.

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References

Alexandrov M.A., Schmid B., Turner D.D., Cairns B., Oinas V., Lacis A.A., Gutman S.I., Westwater E.R., Smirnov A., Eilers J., (2009): *Columnar water vapor retrievals from MFRSR data*, J. Geophys. Res., 114, D02306, doi:10.1029/2008JD010543.

Andrews D.G., (2010): *An Introduction to Atmospheric Physics,* Second Edition, Cambridge University Press.

Bevis M., Businger S., Herring T.A., Rocken Ch., Anthes R.A., Ware R.H., (1992): *GPS Meteorology' Remote Sensing of Atmospheric Water Vapor*

Using the Global Positioning System, J. Geophys. Res., Vol. 97, D14, pp. 15787–15801.

Böhm J., Schuh H., (2013): *Atmospheric Effects in Space Geodesy*, Springer Heidelberg New York Dordrecht London, doi: 10.1007/978-3-642-36932-2.

Byun S.H., Bar-Sever Y.E., (2009): *A new type of troposphere zenith path delay product of the international GNSS service*, J. Geod. (2009) 83: pp. 367–373, doi: 10.1007/s00190-008-0288-8.

Davis J.L., Herring T.A., Shapiro I.I., Rogers A.E., Elgered G., (1985): *Geodesy by radio interferometry: Effects of atmospheric modelling errors on estimates of baseline length*, Radio Sci., 20, pp. 1593–1607 doi:10.1029/RS020i006p01593.

Duan J., Bevis M., Fang P., Bock Y., Chiswell S., Businger S., Rocken C., Solheim F., Van Hove T., Ware R., McClusky S., Herring T.A., King R.W., (1996): *GPS meteorology: direct estimation of the absolute value of precipitable water*, J. Applied Met., 35, pp. 830–838. doi:10.1175/1520-0450.

Halthore R.N., Eck T.F., Holben B.N., Markham B.L., (1997): *Sunphotometric Measurements of Atmospheric Water Vapor Column Abundance in the 940-nm Band*, J. Geophys. Res., 102, pp. 4343–4352.

Holben B.N., Eck T.F., Slutsker I., Tanre D., Buis J.P., Setzer A., Vermote E., Reagan J.A., Kaufman Y.J., Nakajima T., Lavenu F., Jankowiak I., Smirnov A., (1998): *AERONET – A federated instrument network and data archive for aerosol characterization*, Rem. Sens. Env., 66(1), pp. 1–16.

Holben B.N., Tanre D., Smirnov A., Eck T.F., Slutsker I., Abuhassan N., Newcomb W.W., Schafer J., Chatenet B., Lavenue F., Kaufman Y.J., Castle J.V., Setzer A., Markham B., Clark D., Frouin R., Halthore R., Karnieli A., O'Neill N.T., Pietras C., Pinker R.T., Voss K., Zibordi G., (2001): *An emerging ground-based aerosol climatology: Aerosol Optical Depth from AERONET*, J. Geophys. Res., 106, pp. 12067–12097.

Hofmann-Wellenhof B., Lichtenegger H., Wasle E., (2008): *GNSS – Global Navigation Satellite Systems GPS, GLONASS, Galileo, and more,* Springer Wien NewYork.

Kruczyk M., (2014): *Integrated Precipitable Water from GNSS as a climate parameter*, Geoinformation Issues, Vol. 6, No 1(6), pp. 21–35.

Kruczyk M., Liwosz T., (2015): *Integrated precipitable water vapour measurements at Polish Polar Station Hornsund from GPS observations verified by aerological techniques*, Reports on Geodesy and Geoinformatics, Vol. 98, pp. 1–17; DOI: 10.2478/rgg-2015-0001.

van Malderen R., Brenot H., Pottiaux E., Beirle S., Hermans C., De Mazière M., Wagner T., De Backer H., Bruyninx C., (2014): *A multi-site techniques intercomparison of integrated water vapour observations for climate change analysis,* Atmospheric Measurement Techniques Discussions, Vol. 7, Issue 2, pp. 1075–1151.

Van der Marel H., (2004): *COST-716 demonstration project for the near real-time estimation of integrated water vapour from GPS,* Physics and Chemistry of the Earth, Parts A/B/C, 29, pp. 187–199.

McIlven R., (2010): *Fundamentals of Weather and Climate*, Second Edition, Oxford University Press.

Pacione R., Pace B., de Haan S., Vedel H., Lanotte R., Vespe F., (2011): *Combination Methods of Tropospheric Time Series*, Adv. Space Res., 47(2), pp. 323–335, doi: 10.1016/j.asr.2010.07.021.

Rocken C., Ware R., van Hove T., Solheim F., Alber C., Johnson J., Bevis M., Businger S., (1993): *Sensing atmospheric water vapor with the Global Positioning System*, Geophys. Res. Lett., 20, 2631.

Saastamoinen J., (1972): *Atmospheric Correction for the troposphere and stratosphere in radio ranging of satellites*, The Use of Artificial Satellites for Geodesy Geophysics Monograph Series, (ed.) S.W. Henriksen et al., pp. 247–251.

Salby M.L., (2012): *Physics of the Atmosphere and Climate*, Cambridge University Press.

Shelton M.L., (2009): *Hydrometeorology. Perspectives and Applications*, Cambridge University Press.

Schmid B., Michalsky J.J, Slater D.W., Barnard J.C., Halthore R.N., Liljegren J.C., Holben B.N., Eck T.F., Livingston J.M., Russell P.B., Ingold T., Slutsker I., (2001): *Comparison of columnar water-vapour measurements from solar transmittance methods*, Applied Optics, Vol. 40, No 12, pp. 1886–1896.

Söhne W., Weber G., (2009): *Status Report of the EPN Special Project "Troposphere Parameter Estimation"*, EUREF Publication No 15 Mitteilungen des Bundesamtes für Kartographie und Geodäsie 42(15), pp. 79–82.

Vazquez G.E., Brzezinska D., (2012): *GPS-PWV estimation and validation with radiosonde* *data and numerical weather prediction model in Antarctica*, GPS Solutions, doi:10.1007/s10291-012-0258-8.

Vedel H., Mogensen K.S., Huang X.-Y., (2001): *Calculation of zenith delays from meteorological data, comparison of NWP model, radiosonde and GPS delays*, Phys. Chem. Earth, Vol. 26, No 6–8, pp. 497–502.

WWW References

AERONET data: http://aeronet.gsfc.nasa.gov/data_menu.html

Radiosonde ZPD biases (EPN): http://www.epncb.oma.be/_networkdata/radiosonde_zpd_biases.php

Mean temperature data (TU Wien): http://ggosatm.hg.tuwien.ac.at/DELAY/ETC/TMEAN

Porównanie technik pomiarów kolumnowej zawartości pary wodnej w obszarze polarnym

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Streszczenie: Rozwiązania troposferyczne IGS i EPN zostały wykorzystane do przetestowania dwu technik pomiarów aerologicznych dla stacji GNSS w regionie polarnym (Grenlandia). Parametr meteorologiczny jakim jest scałkowana zawartość pary wodnej (IPW) został pozyskany za pomocą standardowej procedury opisanej w literaturze. Do przeliczania IPW z wilgotnej części opóźnienia opracowano lokalny model temperatury średniej (zależność linowa względem temperatury na wysokości 2 metrów nad powierzchnią ziemi) wyznaczony z radiosondowań prowadzonych w sąsiedztwie stacji GNSS. Pomiary fotometryczne udostępnia sieć pomiarów aerozoli AERONET działająca pod egidą NASA. Porównania kilkuletnich szeregów IPW wykazują systematyczne różnice między IPW z GNSS a fotometrem słonecznym (ale nie radiosondażem). IPW z fotometru jest nie tylko średnio kilka procent mniejsza niż z GNSS ale różnica ta zmienia się wraz z porami roku i temperaturą (co jest szczególnie widoczne w warunkach polarnych). To wykazuje pewien istotny problem z fotometrią słoneczną jako techniką pomiarów kolumnowej pary wodnej. Fotometr wykazuje systematyczną różnicę IPW (zależną od temperatury atmosferycznej) także w stosunku do wyników radiosondażu.

Słowa kluczowe: para wodna, meteorologia GNSS, kolumnowa (scałkowana) zawartość pary wodnej, fotometr słoneczny, radiosondaż, badania polarne, Grenlandia