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Validation of GPS derived integrated water vapor (IWV) of the atmosphere on the Georgia's territory

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A B S T R A C T

The delay in radio signals from the Global Navigation Satellite System (GNSS) is proportional to the integrated water vapor (IWV) in the atmosphere above the GNSS site. In this paper some peculiarities of atmospheric water vapor distribution derived from 7 GPS located on Georgia's territory are presented. We calculate ZPD data these GPS and converted into IWV using observed surface pressure and mean atmospheric column temperature obtained from the surface meteorological stations of Georgia's NHMS. The same variables have been obtained from the ECMWF ERA interim reanalyzes – for two years 2014-2015 period and compared with station observations. As radiosonde data for Georgia's stations are not available GPS derived IWV values were compared to the IWV from the ECMWF ERA interim reanalyses with a special focus on the monthly averaged difference (bias) and the standard deviation of daily differences. This comparison shows that the GPS derived IWV values are well suited for the validation of ERA interim reanalyzes of IWV. For most GPS stations, the IWV data agree quite well with the analyzed data indicating that they are both correct at these locations. Larger differences were mainly found in less humid areas during warm periods of year.

Keywords: GNSS delay, Integrated water vapor, ERA interim, Specific humidity, Time series, Satellite

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Introduction

Global Navigation Satellite Systems (GNSS) not only revolutionized positioning, navigation and timing, but also provided an accurate sensor of the most common meteorological parameter, water vapor. A deeper understanding of the mechanisms distributing water vapor through the atmosphere and of water the vapor effects on atmospheric radiation and circulation is vital to estimate long-term changes in climate. This understanding is hampered by the fact that water vapor is the most variable of the major constituents of the atmosphere and our ability to measure time-varying global and regional water vapor distributions is still severely limited [1].

The NRT (near-real time) GNSS delay data contain information about the amount of water vapour above the GNSS sites. Surface based GPS-based measurements of zenith path delay (ZPD) can be used to derive vertically integrated water vapour (IWV) of the atmosphere. Surface based GPS-based measurements offer possibility to provide data at similar quality under all weather conditions. Regional networks, established all around the world providing temporally high resolved information of the integrated atmospheric water vapour with vertical profiling by satellite occultation techniques.

With the surface based technique, dual-frequency signals are collected at ground-based receivers and used to obtain the signal delay and thus the integrated water vapour along the path from the GPS satellites to the receiver [2-3]. It is interesting to note that this possibility occurred whilst exploring the cause of errors in geodetic measurements [4-5].

This "geodetic noise" is a valuable meteorological signal, as the so-called wet delay is nearly proportional to the quantity of water vapor integrated along the signal path, which in turn can be transformed into an estimate of precipitable water. Given accurate delay measurements, precipitable water can be recovered with an accuracy of - 1 mm.

Radio signals from Global Navigation Satellite System (GNSS) slow down and bend, when passing from a GNSS satellite to a ground based receiver, causing a delay of the signals compared to a no atmosphere situation. The largest part of the delay is from the ionosphere, but this part is easily subtracted, due to its dispersive (frequency dependent) nature, and the fact that the GNSS satellites emit at two frequencies. The remainder of the delay is due to the neutral atmosphere, near the surface of earth [6-8].

A specially weighted average of the delays toward the individual satellites can be considered as zenith total delay (ZTD). The ZTD is typically given as a distance, corresponding to the actual delay multiplied by the speed of light, equal to the apparent extra distance the signals have been traveling.

It can be divided into two terms. The first term is the zenith hydrostatic or zenith dry delay (ZHD), which is proportional to the pressure at the GNSS receiver site. The second term is the zenith wet delay (ZWD), which is proportional to the integrated water vapor (IWV) above the GNSS site, and which depends weakly on the temperature and humidity profile above the site.

Water vapor plays a key role in formation of climate factors and some of the most important weather phenomena on Georgia's territory. This important meteorological parameter is not well studied yet, because of a big lack of humidity observations, mostly on upper atmosphere layers. Except of some valuable research devoted to atmospheric humidity temporal and spatial distribution on Georgia's territory [9].

Usage of ground based GNSS data is one means by which to improve this situation. We have 24 GNSS operating sites in Georgia with about 8 year period archived observations. For this study, we select 7 of them, located closely to automated weather stations (AWS), to avoid horizontal interpolation of surface pressure and temperature measured by AWS for calculation of vertically integrated water vapour with GAMIT/GLOBK software. GNSS and AWS locations, with corresponding elevations are presented on the map. Vertical interpolation of meteorological parameters from AWS elevation to GNSS ones was performed. This is a pilot investigation of GNSS derived meteorological parameters for country. Validity of the results was obtained by comparison of GNSS derived IWV against ECMWF ERA interim reanalyzes Total column water vapor (TCWV) parameter.

GPS observations and data processing

To obtain integrated water vapor (IWV) we selected 7 ground-based GPS station from the network operated by Georgian National Agency of Public registry (NAPR). All the available data at these 7 sites during the 2 year period of 2014–20215 has been analyzed along with the 12 far field IGS stations to reduce the influence of the strong correlation of tropospheric parameters. The NAPR stations distributed along territory of Georgia, which covers humid/dry and low/high elevation areas (Fig 1).

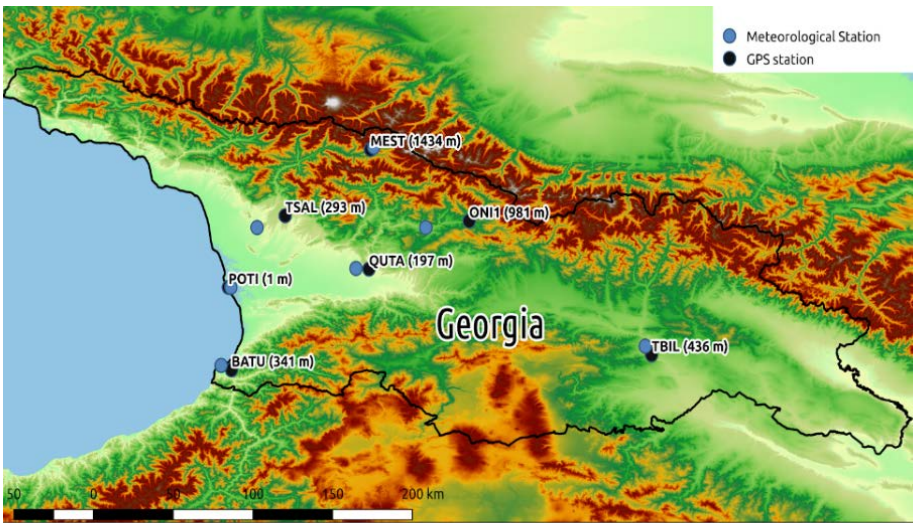

Fig. 1. *The map shows GPS and Meteorological stations location with the labeled name of the station and elevation in meters.*

We process GPS data using the GAMIT/ GLOBK software package [11] developed at the Massachusetts Institute of Technology, which uses double-difference phase observations to determine baseline distances between ground-based receivers and satellites. GPS satellite signal is delayed when it propagates through the atmosphere. Significant delay directly attributed to the passage of the signal to troposphere, which can be decomposed into a hydrostatic (dry) and a non-hydrostatic (wet) delay. Since these delays change with the elevation angle, the signal with low elevation angle has a longer delay through the troposphere than one with high elevation angle. The mapping functions VMF1 (Vienna mapping function) are applied to transform slant tropospheric delays into the zenith tropospheric delay (ZTD). The zenith hydrostatic delay (ZHD) accounts for nearly 90% of the total tropospheric delay and can be estimated more accurately if the surface pressure and temperature data is applied. In the absence of in situ meteorological sensor, we used vertically interpolated pressure data of the nearest station of the Georgian National Environmental Agency network with the average horizontal distance 10km. Zenith wet delay (ZWD) can be estimated by subtracting ZHD from the ZTD. Finally, ZWD can be converted to precipitate water vapor (PWV) using the following formula:

PWV=Π × ZWD

where can be calculated based on the for

$$\Pi = \frac{10^6}{\rho_\omega R_v (k_2 - \frac{k_3}{T_m}}$$

where ρ_ω is the density of liquid water, Rv is the specific gas constant for water vapor, k_2 and k_3 are the refractivity constants and T_m is the weighted mean temperature of the atmosphere given by

$$T_m = \frac{\int\left(\frac{e}{T}\right)dz}{\int\left(\frac{e}{T^2}\right)dz}$$

where e is the partial pressure of water vapor and Tis absolute temperature along the zenith path. The integral intervals are from the earth surface to the atmospheric top. Simply, T_m can be estimated [12] using the surface temperature measurement T_s and was interpolated from the nearest meteorological station:

$$T_m = 70.2 + 0.72T$$

ERA interim reanalysis

ERA-Interim is the latest global atmospheric reanalysis produced by the ECMWF [13]. ERA-Interim covers the period from 1 January 1989 onwards, and continues to be extended forward in near-real time. An extension from 1979 to 1989 is currently in preparation. Gridded data products include a large variety of 3-hourly surface parameters, describing weather as well as ocean-wave and land-surface conditions, and 6-hourly upper-air parameters covering the troposphere and stratosphere. Vertical integrals of atmospheric fluxes, monthly averages for many of the parameters, and other derived fields have also been produced [14-15].

The ERA-Interim atmospheric model and reanalysis system uses cycle 31r2 of ECMWF's Integrated Forecast System (IFS), which was introduced operationally in September 2006, configured for the following spatial resolution:

60 levels in the vertical, with the top level at 0.1 hPa;

T255 spherical-harmonic representation for the basic dynamical fields;

a reduced Gaussian grid with approximately uniform 79 km spacing for surface and other grid-point fields.

For comparison we extracted Total column water vapor (TCWV) from Era Interim archive at 6 hour time steps four times per day starting at 00 UT.

ZPD from GPS is usually measured instantaneously at 2 hour time steps starting at 01 UT. In order to obtain ZPD values at the 6 hourly times, the two ZPD measurements before and after the 6 hour time are averaged, i.e. the GPS results are mean values over four hourly intervals (e.g. a ZPD value at 12 UT is the average of the measurements at 11 UT and 13 UT). If only one of these two ZPD measurements is available, it alone represents the 6 hour time.

Validation strategy and obtained results

The GPS derived IWV cannot be compared directly with the IWV data from the reanalysis data. That information from different sources are averaged over different areas (GPS by some 100 km2 and ERA over an area of 10000 km2) and the GPS stations heights usually do not agree with the topography used in the ERA. Thus, it is necessary to interpolate ERA IWV not only horizontally but also vertically to the position of the GPS station. The horizontal interpolation of all OA values used, e.g. IWV or model height h, to a station coordinates is done by a weighted linear interpolation from the surrounding four grid boxes with the center coordinates i. In order to compare the horizontally interpolated OA IWV values to the GPS derived IWV values, they have to be vertically interpolated from the model surface height to the GPS station height, more precisely the IWV difference between the model surface height and GPS station height has to be estimated. It is assumed that the mean relative humidity of the two lowest OA model levels (j = 1, 2) is representative for the atmospheric layer near the surface, especially at the station height *hS* and the model surface height *h(Xs)*. As only the specific humidity *q* is stored in the archive at model levels, the relative humidity r for both layers j with the pressure *pj* has to be computed [16-20].

The adjustment of the ERA interim IWV to the GNSS station height is obtained by the integration of specific humidity (q) over the height difference between the GPS station and the model surface.

$$IWV_{ERA} = IWV_{\chi_s} + \sum_{i=1}^{n} \frac{q(h_{i-1}) + q(h_i)}{2} (h_{i-1} - h_i)$$

This integration is numerically done in 30-m steps, which generally corresponds to a pressure difference smaller than 4 hPa and IWV 2 mm.

$$h_0 = h(\chi_s),\ h_1 = h(\chi_s) + 30m,\ \ldots h_n = h_s$$

Corrected and averaged ERA interim and GNSS IWV 6 hourly data set was compared for 2014-15 period. Daily Biases were calculated and monthly statistics derived from daily ones have been analyzed. This comparison shows that the GNSS derived IWV values are well suited for the validation of ERA IWV and presented graphs are demonstrate such results (Fig.2 of individual GNSS and ERA interim IWV).

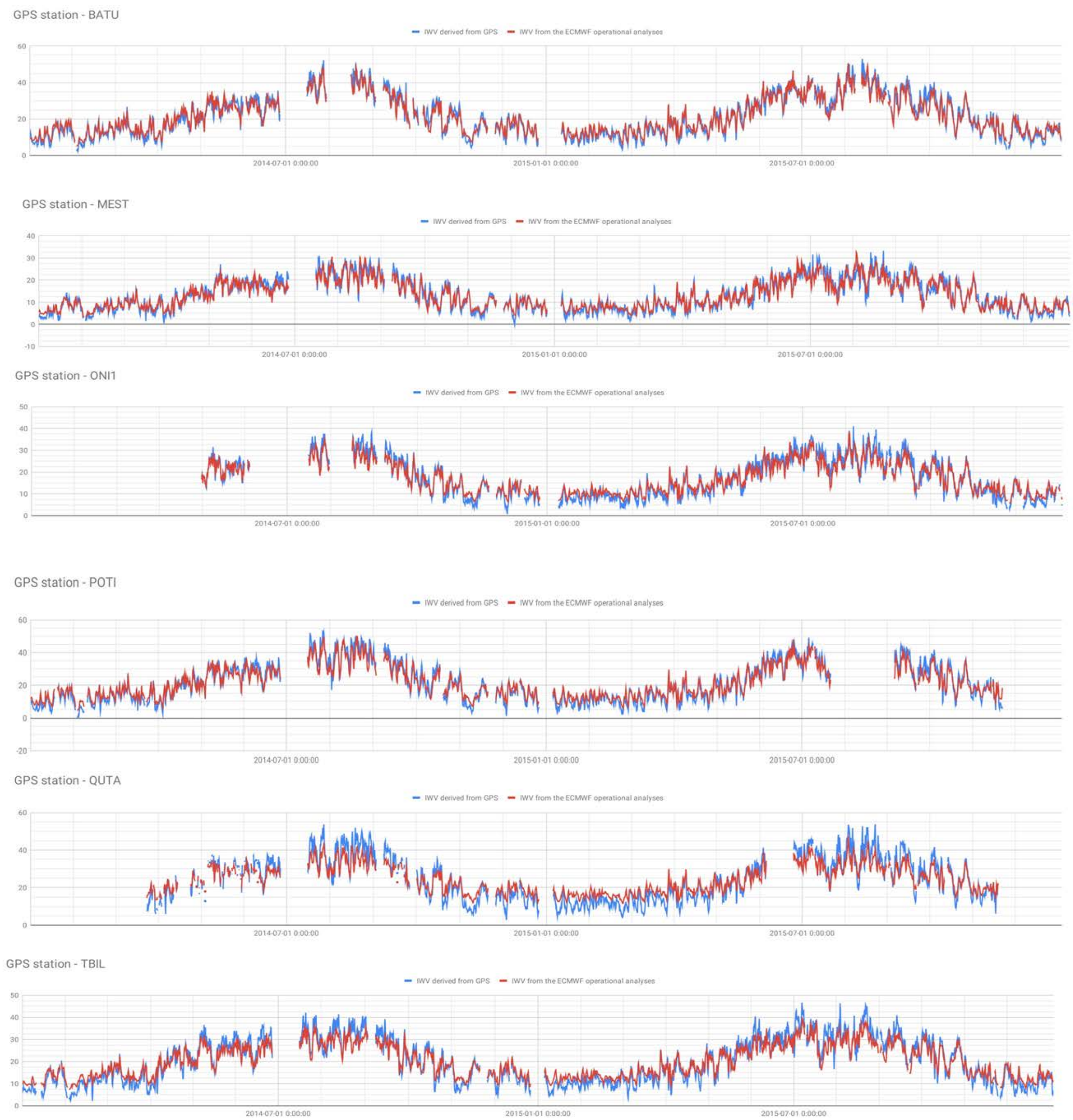

Fig. 2. *Time series of IWV derived from GPS and IWV from the ECMWF reanalysis*

For most GPS stations, the IWV data agree quite well with the analysed data indicating that they are both correct at these locations. From the graphs can be concluded, that in cold months GPS derived IWV have negative biases on all stations, as blue color is dominant in such a months, when in summer GPS overestimates water vapour and this dry bias is more evident on dryer stations (Qutaisi and Tbilisi). The Table 1 Shows the mean seasonal and annual biases and correlations, from where ones again we can see that in winter GPS derived IWV lower than IWV from Era across all stations and it is higher in summer, and this mean error is close to ± 2mm.

Table. 1. *Mean seasonal and annual biases and correlation between ERA and GPS mean daily IWV data*

Winter	spring	summer	autumn	year	statistics
-1.9	-0.7	2.15	0.4	0.0098	bias
0.8196	0.9202	0.8697	0.8834	0.906	correlation

On annual span mean error is almost 0 (0.0098) and Correlation also high. Fig. 3 also proves that all mean daily values over all sites are highly correlated and well fitted in regression model.

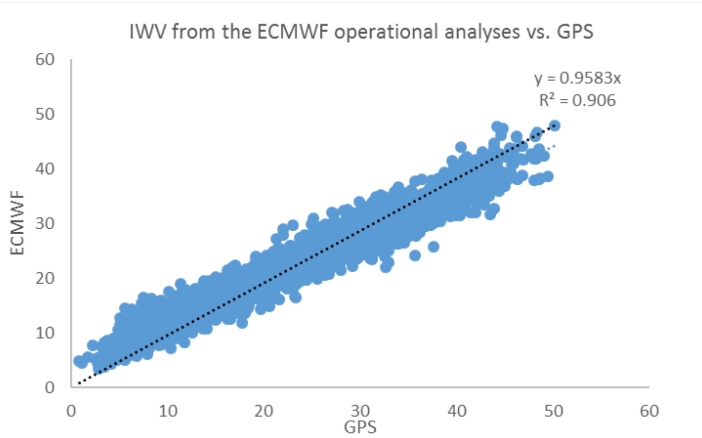

Fig. 3. *Scatterplot of GPS derived and Era interim mean daily integrated water vapor (IWV)*

Table 2 represents monthly RMSE of mean daily bias on the analyzed sites. It's evident that deference between GNSS stations and ERA interim IWV are higher on all stations for summer period. It should be mentioned that despite errors are small, results should be filtered taking into account uncertainty in the GPS derived IWV due to GPS measurements of ZPD (< 0.7 mm) and the use of surface pressure measurements from surrounding areas (0.5 mm).

Table. 2 *Monthly RMSE of mean daily bias for the 7 GNSS stations*

Stations	1	2	3	4	5	6	7	8	9	10	11	12
Tbilisi	4.2	3.1	2.7	2.6	3.1	3.8	3.7	5.1	4.2	2.4	2.5	2.5
Kutaisi	5.3	4.5	4.6	3.3	2.8	4.2	6	6.8	5.1	3.3	4.3	4.7
Poti	2.7	2.8	2.3	2.1	2.3	3.4	4.8	5	4.5	3.3	2.8	2.7
Mestia	1.5	1.2	1.3	1.4	1.5	2.4	2.7	2.1	2	1.7	1.1	1.6
Oni	2.5	2.1	2.1	1.9	2.2	3.1	3.3	4	3.1	2.1	2.1	2.4
Batumi	1.9	1.5	1.9	2.2	2.7	3.4	3.9	4	3.8	2.3	1.8	1.9
Tsalenjikha										3.2	2.4	2.1

Conclusion

This initial validation show that the GNSS derived IWV values are well suited for the validation of ERA IWV and presented graphs and tables are demonstrate such results. For most GPS stations, the IWV data agree quite well with the analyzed data indicating that they are both correct for the locations. This tendency is valid for all stations for all seasons and annually. It is noteworthy that all stations showed negative deviations during the winter season and dry biases during the summer and this tendency is more evident on dryer stations (Qutaisi and Tbilisi). From our results maximum RMSE values have been obtained on the stations where we had less difficulties with orography and horizontal pressure interpolations, which additionally gives errors in GPS derived IVW calculations, but on the stations from drier climate zones. It should be also mentioned, that this two stations are in urban areas and this possible effect worst to be investigated.

Acknowledgements

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