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Acheampong, A.A.; Fosu, C.; Amekudzi, L.K.; Kaas, Eigil

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A. A. Acheampong*, C. Fosu, L. K. Amekudzi, and E. Kaas

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Abstract: Signals from Global Navigational Satellite Systems (GNSS) when integrated with surface meteorological parameters can be used to sense atmospheric water vapour. Using gLAB software and employing precise point positioning techniques, zenith troposphere delays (ZTD) for a GPS base station at KNUST, Kumasi have been computed and used to retrieve Precipitable Water (PW). The PW values obtained were compared with products from ERA-Interim and NCEP reanalysis data. The correlation coefficients, r, determined from these comparisons were 0.839 and 0.729 for ERA-interim and NCEP respectively. This study has demonstrated that water vapour can be retrieved with high precision from GNSS signal. Furthermore, a location map have been produced to serve as a guide in adopting and installing GNSS base stations in Ghana to achieve a country wide coverage of GNSS based water vapour monitoring.

Keywords: GNSS; integrated water vapour; numerical weather prediction; precipitable water; reanalysis model

1 Introduction

Climate change and variability are impacting greatly on human existence and the challenge for research is to understand the processes influencing such change. There are numerical weather predictions (NWP) models that have been used to study weather and climatic patterns (Lynch, 2008; Buizza, 2002; Shuman, 1978). These NWP models use winds, heat transfer, radiation, relative humidity and surface meteorological parameters as input to describe rising earth surface temperature, increasing greenhouse gases, precipitations, decreasing ice and other geophysical phenomena (Soos, 2010).

Unlike other greenhouse gases, water vapour coupled with its atmospheric concentration is not significantly influenced by direct anthropogenic activities (USGS, 2011; Seidel, 2002). This is because water vapour contributes to climate change through natural evolution and feedback mechanism. Again its contents in the atmosphere is highly variable both in space and in time due to temperature changes, atmospheric circulation and micro-physical processes (Pottiaux, 2010). According to Solomon et al. (2007), an estimated 70% of the recent rises in atmospheric temperature are attributed to water vapour feedback.

The amount and distribution of water vapour in space (horizontal and vertical) is a major parameter in the development of NWP models and its importance cannot be underestimated. Sensing and measurement of water vapour by conventional methods such as radiosondes, hygrometers, microwave radiometers, sun photometers are affected by meteorological conditions. In addition they are expensive and have coverage limitations. Again water vapour is under sampled in current operational meteorological and climate observing systems (Pichelli et al., 2010; Pierdicca et al., 2009; Gendt et al., 2003). Making available ne-resolution and accurate 2D and 3D water vapour field measurements would lead to substantial improvements in NWP model initialization (Sahoo et al., 2013).

Over two decades ago Global Navigation Satellite Systems (GNSS) signals were used to retrieve water vapour Bevis et al. (1992). The GNSS technique characterizes the propagation delays on the signals caused by the neutral atmosphere or troposphere and the magnitude of the delayed component is directly proportional to the atmospheric water vapour. This method is highly accurate irrespective of adverse meteorological conditions and with modeling capabilities to estimate errors with high temporal and spatial resolution. Moreover, GNSS receivers used in this application have little or no maintenance requirements and supports operational fore-casting of atmospheric conditions. This paper investigates how the GNSS meteorological concepts can be used to sense atmospheric water vapour to boost surface meteorological...
2 Methodology

Sensing meteorological parameters using GNSS signals can be achieved using either ground-based surface network of GNSS receivers or aboard low Earth orbiting satellites (De Haan and Van Der Marel, 2008). The later approach is known as radio occultation technique. For this work delayed signals due to tropospheric and stratospheric effects was used retrieved atmospheric Integrated Water Vapour (IWV).

Figure 1 gives an overview of the general concept. This technique is based on the precise determination of tropospheric\(^1\) delays, an output of GNSS data processing (Bosy et al., 2011). When not mitigated tropospheric delays can introduce range errors of 2.3 m to 9.3 m for a satellite at the zenith down to 15° elevation angle, and about 20 - 28 m for those between 5o and observer horizon (Leick, 2003; El-Rabbany, 2002).

Figure 1: Water vapour distribution and atmospheric layers in relation to GNSS satellites. X; Y; Z are coordinates of satellites and antenna positions, T is the epoch of observation, PCV are phase center values of transmitting and receiving antenna, ZTD is the zenith tropospheric delays

\(^1\) Actually the delays also include a very small contribution from the stratosphere.

2.1 Mathematical Models

Following Seeber (2003) the ideal delay observation equation would be:

\[ \Delta R = R_{\text{sat}} - R_{\text{rec}} \]

where \(R_{\text{sat}}\) is the true distance from the satellite to the receiver and \(R_{\text{rec}}\) is equal to the actual recorded signal transit time multiplied by the speed of light in vacuum, \(c\). However, in addition to the lower atmosphere contributing to the delay, several other processes influence the measured delay. So, considering all contributions to the observed code phase, \(p(t)\), Eq. (1) and carrier phase, \(\phi(t)\), Eq. (2) the real situation can be formulated as

\[ p(t) = R_s^t + c(\delta t_s - \delta t_r) + d_{\text{ion}} + \Delta L_{\text{at}}(\epsilon) + \zeta + d_{\text{orb}} \]

\[ \phi(t) = R_s^c + c(\delta t_s - \delta t_r) + \lambda \eta - d_{\text{ion}} + \Delta L_{\text{at}}^c(\epsilon) + \zeta + d_{\text{orb}} \]

where:
- \(R_s^t\) – Receiver Satellite distance in vacuum - Satellite and receiver position need to be accurately known;
- \(\delta t_s - \delta t_r\) – Satellite and receiver clock errors - Eliminated using double differences or precise IGS clock products;
- \(\eta\) – Unknown initial phase ambiguities - Needs to be resolve into either fixed integer or float;
- \(d_{\text{ion}}\) – Ionospheric delay - Eliminated using dual frequency ionosphere-free combination;
- \(c\) – speed of light in vacuum;
- \(\lambda, d_{\text{orb}}, \zeta\) – wavelength of the carrier phase, orbital errors and excess noise from receivers vicinity;
- \(\Delta L_{\text{at}}(\epsilon)\) – Tropospheric delays at elevation angles, \(c\) – Elevation angles.

The main differences between the code and carrier phases observables are for the wavelengths, carrier phases are shorter than code phases. Measurement noises are also small for carriers than code phases. There are ambiguities to be resolved in carrier measurements and the ionospheric propagation delays the code measurements but advances the carrier measurements.

For the purposes of GNSS meteorology, greater emphasis is given to the slant tropospheric delays, which are converted to zenith tropospheric delays (ZTD) using appropriate mapping functions (Bohm et al., 2006; Niell, 1996), when all other errors have been dealt with. The zenith tropospheric delays can be split into two components, the zenith hydrostatic delays (ZHD) and zenith wet delays (ZWD).

\[ ZTD = ZHD + ZWD \]

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IWV and Precipitable Water (PW) can then be retrieved from the computed ZWD values. The ZTD is the same as 
\[ \Delta L_a^i(\varepsilon) \] mapped onto the zenith. They are computed by 
first considering ray bending due to refractivity of the at-
mospheric medium making actual path taken by the signal 
greater than the geometric path as shown in Ning (2012); 
Schuler (2006); Bevis et al. (1992); Elgered et al. (1991):

\[ \Delta L_a^i = \int n(s) \cdot ds - \int ds \]  

where, \( \Delta L_a^i \) is total slant delay from satellite, \( i \) to receiver’s 
antenna, \( a \), at elevation angle, \( \varepsilon \); \( n \) is index of atmospheric 
refraction; \( ds \) is differential increment in distance with re-
spect to the line of sight; \( atm \) and \( vac \) are atmospheric and 
vacuum media.

Expressing \( n \) in terms of refractivity \( N \), which is the 
sum of refractivities of the dry gases and water vapour in 
the atmosphere, where \( N = 10^6(n - 1) \), and ignoring all 
other terms which are zero in the zenith direction, Eq. (4) 
becomes:

\[ \Delta L_a^i(\varepsilon) = 10^{-6} \int n(s) \cdot ds = 10^{-6} \int N_d(s) + N_w(s) \cdot ds \]  

The refractivity of the atmosphere is a function of its 
temperature, pressure, water pressure and independent to 
microwave frequencies below 40 GHz (Nilsson et al., 2013).
Thayer (1974) expressed \( N \) as:

\[ N = k_1 \frac{p_d}{T} Z_d^{-1} + k_2 \frac{e}{T} Z_w^{-1} + k_3 \frac{e}{T^2} Z_w^{-1} \]  

where \( p_d \) and \( e \) are partial pressures of the dry gases and 
water vapour in hPa, \( T \) is absolute temperature in Kelvins;
\( Z_d^1 \) and \( Z_w^1 \) are inverse are compressibility factors for dry 
and moist air respectively and are used to describe the 
deviation of the atmospheric constituents from an ideal 
gas; \( k_1, k_2 \) and \( k_3 \) are constants based on laboratories 
estimates and Bevis et al. (1994) found them to be \( k_1 = 7760 \pm 0.05 \) K/hPa, \( k_2 = 7740 \pm 2.2 \) K/hPa, \( k_3 = 373900 \pm 1200 \) K²/hPa and \( k_2 = 22.10 \pm 2.2 \) K/hPa. The compress-
ibility factor as shown in Nilsson et al. (2013) for ideal gas, 
\( Z = 1 \), and other \( j^\text{th} \) constituent of air is given by:

\[ Z_j = \frac{PM_j}{\rho_jRT} \]  

where is \( M_j \) is the molar mass and \( R \) is the universal gas 
constant. From Eq. (6) the first term is ZHD, caused by the 
induced dipole moment of the dry gases and the remaining 
terms are ZWD, caused by the water vapour molecules 
(Ning, 2012).

From the equation of state for ideal gases, we found out that 
\( p_d/T = R_d\rho_d \), where, \( R_d \) is the specific gas con-
stant of the dry constituent, \( R_d = R/M_d, R \) is the universal 
gas constant and \( M_d \) is the molar mass of the dry gases). 
Using simple approximations and the assumption of hy-
drostatic equation being valid for total pressure and not 
for partial pressures Davis et al. (1985) reformatted Eq. (6) 
to be:

\[ N = k_1 R_d \rho + k_2' \frac{e}{T} + k_3' \frac{e}{T^2} \]  

\( k_2' \) which has been given earlier is derived by \( k_2' = k_2 - \) 
\((M_w/M_d)k_1 \) and \( M_w \) is the molar mass of water vapour; \( \rho \) 
is the total density of dry gases and water vapour.

When all the slant delays are mapped onto the zenith 
direction, zenith hydrostatic delays, \( ZHD = \Delta L_a^z \) can be 
obtained by considering the assumption that hydrostatic 
equilibrium have been satisfied (Davis et al., 1985):

\[ \frac{dp}{dh} = -\rho(h)g(h) \]  

where \( g \) is the acceleration due to gravity in the vertical 
direction; \( p \) is the total pressure. The resultant integration of the 
first term in Eq. (7) gives:

\[ \Delta L_a^z = (10^{-5} k_1 p_g s_{01}^{-1}) \cdot P_g \]  

where \( P_g \) is the total ground pressure in hPa, \( g_m \) is grav-
itational acceleration at the mass centre of a vertical col-
umn of the atmosphere. Saastamoinen (1972) defines \( g_m = \) 
\((9.784 \pm 0.001 \text{ m/s}^2) \cdot f(\theta, H), \) and \( f(\theta, H) = (1 - 2.66 \cdot 10^{-3} \cos(\theta) - 2.8 \cdot 10^{-7} H). \) The parameters \( \theta \) and \( H \) are 
the latitude of the site in degrees and surface height above 
the geoid in meters respectively.
Substituting all the constants in Eq. (9), the expression for solving ZHD in units of length becomes:

$$\Delta L_d^z = 0.002277(1 + 0.0026 \cos 2\theta + 0.000284H) \cdot P_s.$$  

(10)

### 2.2 Precipitable Water Computation

The software gLAB® (Hernandez-Pajares et al., 2010) outputs the slant delays mapped onto the zenith. With ZTD already computed and knowledge of precise the coordinates of the antenna position (θ, H) and surface pressure values from nearby weather station, $ZWD = \Delta L_w^z$ can be computed using Eq. (3) and (10). Two parameters are used to refer to the atmospheric water vapour content, these are Integrated Water Vapour (IWV) in units of kg m$^{-2}$ which refers to the quantity of the atmospheric water vapour over a specific location and Precipitable Water (PW) is used to express the height of an equivalent column of liquid water in units of length. Bevis et al. (1992) gives IWV as

$$\text{IWV} = \int_0^\infty p_v(h)dh = \frac{1}{R_w} \int_0^\infty \frac{e(h)}{T(h)}dh$$  

(11)

where $p_v$ is the partial density of water vapour in kg/m$^3$; the height h in metres and $R_w$ is the specific gas constant for water vapour in J/(kg K). PW relates to IWV by diving with the density of liquid water, $\rho_w$. $\text{PW} = \text{IWV}/\rho_w$. Again IWV is related to the ZWD using a dimensionless quantity as conversion factor, $\Pi$:

$$\text{IWV} = \frac{\Delta L_w^z}{\Pi}, \quad \text{PW} = \frac{\Delta L_w^z}{\rho_w \cdot \Pi}$$  

(12)

From Eq. (5) and considering the second and third terms of Eq. (7), the wet delays become:

$$\Delta L_w^z = 10^{-6} \int_0^\pi (k_2 e(z) T(z) + k_3 e(z) T(z)^2)dz$$  

(13)

substituting the constants and introducing a mean temperature, $T_m$, which is defined by Bevis et al. (1992) as: $T_m = 0.72 T_s + 70.2$, where $T_s$ is the surface temperature. The conversion factor finally becomes:

$$\Pi = 10^{-6} \rho_w R_w (k_2 + \frac{k_3}{T_m})$$  

(14)

Bevis et al. (1994) computed $\Pi$ to be approximately 0.15, but this dimensionless constant is a function of season, location, and weather. The minimum and maximum values can have a range with variation of over 20% (Liou et al., 2001). For this study, 0.1629 was used for $\Pi$.

### 3 Data Processing

GPS data were processed using gLAB® (Hernandez-Pajares et al., 2010) software in Precise Point Positioning (PPP) mode and the estimate the ZTD values. The processing stages were:

1. Acquisition of GPS and surface meteorological data;
2. Precise receiver and orbit positions obtained from global GNSS analyses centres;
3. Eliminate ionosphere effect;
4. Introduce (Phase center correction values, Ocean Tide effects, Relativistic corrections...) and
5. Finally estimate Zenith Path Tropospheric Delay which is used to derive IWV and PW.

### 3.1 gLAB Software

gLAB® has been developed at the Research group of Astronomy & Geomatics at the Technical University of Catalonia in Barcelona, Spain. It is a multi-purpose package that runs on Windows and Linux operating systems and used to process and analyse GNSS data. The license is free on an "as is" basis without warranties or conditions of any kind. gLAB is a complete GNSS analysis tool for both educational and professional purposes. gLAB allows a full customization of its options and provides precise point positioning capabilities on the centimetre level. The software is able to output solutions of different application parameters including receiver position, satellite position and velocities, Satellite-receiver geometric distances, corrections to Satellite and receiver clocks, Relativistic Clock Correction, Wind-up correction Troposphere nominal correction and delays, Ionosphere correction, Relativistic path range correction and Solid Tides Correction. Processing can be done in standard and precise point positioning mode for static and kinematic receivers. Backward filtering is also supported to reduce errors associated with solution convergence. gLAB offers three different modules for processing:

1. Data Processing Core (DPC) - For all the processing
2. Graphic User Interface (GUI) - To customize options
3. Data Analysis Tool (DAT) - Graphics

Sample screenshots of the software during execution is shown in Fig. 3. Both the processing core and the plotting tool can be executed independently from the GUI. The latest release is gLAB version 2.0.0 in the year 2010 (Hernandez-Pajares et al., 2010).
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### 3.2 KNUST GPS Station

A Sokkia® GSR 2600 18 channeled receiver and a SOK600 antenna mount on the roof of the New Engineering block was used to log data for the study. The station has been logging data since March 2013, with a three month break from June to August. The precise coordinates of the antenna position as computed using the gLAB® software is shown in Table 1.

<table>
<thead>
<tr>
<th>Base Station</th>
<th>Coordinates</th>
<th>WGS 84</th>
<th>UTM (38N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>6333147.7419 +0.0022</td>
<td>6°40’21.6906’’</td>
<td>E 654586.674</td>
</tr>
<tr>
<td>Y</td>
<td>-17204.4837 +0.0109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>-78239.3222 +0.0004</td>
<td>k = 296.340</td>
<td></td>
</tr>
</tbody>
</table>

In accepting the ZTD values computed with gLAB, a comparison with International GNSS Service (IGS) ZTD products and gLAB derived values for the IGS station in Yamoussoukro, Cote d’Ivore² was done. Figure 4 shows plots of ZTD values against time of day for some selected days in October, 2013, and Table 2 give results of descriptive statistics run on the two ZTD values. With the exception of the different software used (i.e. IGS analysis centres use GIPSY and Bernese software (Byun and Bar-Sever, 2009; Dach et al., 2007; Bohm et al., 2006)), similar parameters were used for data processing. The parameters were an elevation cut-off of 7°, simple nominal tropospheric correction and Niell mapping functions (hydrostatic and wet), 24 hour data time span and 300 secs data rate were implemented in gLAB. Others were precise orbits and clocks products and corrections due to Earth orientation and antenna phase center.

Considering the plots in Fig. 4, the initial differences in the ZTD values from gLAB are due to time delay in resolving all ambiguities in the phase solutions. Again the differences observed in the plots of the two datasets can be attributed to the different approaches in ZTD computations, gLAB uses PPP techniques as opposed to differential/baselines from the IGS servers. From the results in Table 2, and correlation coefficients ranging between 0.893 – 0.916 the computed ZTD values from gLAB compares favourably with that of from IGS Servers. Hence, ZTD values from gLAB can be used for our study and analysis.

### 4 PW Comparison

The Precipitable Water (PW) values computed using the methodology and models described above were compared with global Re-analysis data from National Centers for Environmental Prediction (NCEP) and European Centers for Medium Range Weather Forecast (ECMWF) Era-Interim (Fig. 5). Correlation analyses were run and resulting, r, values of 0.839 for gLAB and ERA-Interim and 0.729 for gLAB and NCEP. The PW values computed with gLAB correlates better with ERA-Interim as opposed to NCEP. Figure 6 shows the correlation plots of computed PW for KNUST and values extracted from ERA-Interim and NCEP global reanalysis data. The correlation coefficients of this study gave values higher than those obtained for similar exercises across the African region. Bock et al. (2007) worked on comparing PW values computed from 9 International GNSS service stations across Africa with global re-analysis, radiosondes and AERONET data spanning a 3-year period, an averaged r values of 0.81 and 0.67 were obtained for ERA-40 and NCEP respectively. They further identified that the standard deviation, σ, decreases and correlation increases when the averaging period for data samples increases. These results clearly show that more

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² Yamoussoukro Tracking Station, YKRO, with IERS DOMES number of 32601M001 (http://igscb.jpl.nasa.gov/network/site/ykro.html)
work has to be done to indicate whether the global reanalysis models are oversampling or under-sampling precipitable water over Ghana. Similar assignments have been carried out in the past (Mims et al. (2011); Bokoye et al. (2003); Motell et al. (2002); Yoshihara et al. (2000)) all geared towards the comparisons of PW values retrieved from GPS, radiosonde, sun photometers, radiometers and other sensing approaches. Their concluding remarks show higher correlation for GPS against the conventional methods and thus proves that GPS offer a cheaper and accurate alternative in sensing water vapour.

To improve weather prediction and precipitation forecasting, this study proposes a collaborative effort between Ghana Meteorological Agency (GMet) and the Survey and Mapping Division of the Lands Commission of Ghana to adopt GNSS meteor. This concept can serve dual purpose of providing precise coordinates, differential corrections for PNT applications as well as PW for uploads into NWP servers. To deploy a system using a network of GNSS receivers to sense water vapour, 1° resolution in horizontal plane (approximately 110 km) for Ghana was considered. Again, GNSS meteorological concepts require surface data – pressure and temperature, for computation of PW. Merging these two assumptions and using the locations of GMet
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5 Conclusion

At such an early stage in the project, this paper has outlined the procedures in retrieving Precipitable Water from GPS Base station data. The gLAB software implements algorithms that compute the ZTD values based on PPP techniques, precise clocks and orbit products. Initial results from this study that compared retrieved PW from GNSS and reanalysis products clearly indicates good agreement between the two global reanalysis data. This study is not meant to conclude or recommend one reanalysis product over the other but to give an indication of its sampling of atmospheric parameters in our subregion. Results show a stronger correlation between ERA-Interim and gLAB retrieved PW estimates than NCEP Reanalysis over the study area. To affirm this position, more data needs to be logged and a longer time series considered.

Again, the study has a broader aim of using a network of continuously operation GNSS stations to map water vapour at high resolutions for operational weather prediction Ghana. The fullest potential of GNSS meteorology will be realized when these two state institutions, Survey and Mapping Division works closely with the Ghana Meteor Agency through data and knowledge sharing.

References
