Appraising the effects of atmospheric aerosols and ground particulates concentrations on GPS-derived PWV estimates

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Highlights

• Mitigating aerosol/particulate pollution in a Nigerian city.
• CW-HAT200 particulate counter is validated.
• Significant relationship between GPS_{PWV} and aerosols/particulates.
• New mechanism for GPS_{PWV}- PM_{10} relationship.

Abstract

In 2016, three Nigerian cities were listed amongst the World's most polluted in terms of particulate matter (PM). Acknowledging Nigeria's limited resources for outdoor air pollution monitoring, this study attempts to investigate the effects on atmospheric aerosol optical depth and ground PM on GPS derived-precipitable water vapour estimates. The study utilized available GPS-derived precipitable water vapour (GPS_{PWV}), the moderate resolution imaging spectroradiometer aerosol optical depth ($MODIS_{AOD}$) and the ground level particulate matter of less than 10 microns (GPM) datasets for December 2015 – November 2016. All the datasets were tested for normality. To evaluate the atmospheric aerosol properties, the $MODIS_{PWV}$ estimates were pre-validated using the GPS_{PWV} measurements. The results revealed GPS_{PWV}-$MODIS_{PWV}$ agreement (R = 0.964; RMSE = 3.810 mm). The GPS_{PWV}-$MODIS_{AOD}$ analysis showed relationship ($R \leq -0.636$; $RMSE \leq 0.563$) for the atmospheric aerosol experiment, while the collocating GPS_{PWV}-GPM seasonal analysis also revealed significant correlation ($R < -0.660$). The correlation of combined seasonal datasets for the GPS_{PWV}-$MODIS_{AOD}$ and GPS_{PWV}-GPM relationships showed high negative correlation values of 0.79 and 0.68 respectively. The findings of this study is in agreement with similar related studies, as well as serve as future position accuracy for similar related studies.

Keywords: GPS PWV; MODIS AOD; Particulate Matter PM_{10}; Nigeria

1. Introduction

Atmospheric water vapour plays a crucial role in the Earth's climate system as well as the monitoring of aerosols/particulate properties (Solomon et al., 2010; Zhang et al., 2017). Despite its importance to a wide range of spatial and temporal atmospheric processes, it is one of the poorly understood components of the Earth's atmosphere (Boutiouta and Lahcene, 2013). Observational studies have reported that the intensity of aerosol particles contributes to climatic variables such as precipitation of liquid water and electrification of thunderstorms (Middey and Chaudhuri, 2013; Zhao et al., 2016). The significance of atmospheric studies for aerosol/water vapour projections has attracted earth observation satellites and global positioning system (GPS) approaches (Nordio et al., 2013; Ortiz de Galisteo et al., 2014).

Scientists have since embraced the concept of GPS meteorology as it provides the ability to measure atmospheric water vapour content for application in diverse topics such as atmospheric chemistry and global climate change (Bevis et al., 1992). GPS offers consistent and precise atmospheric information for precise-point positioning (PPP), ionospheric/tropospheric studies and general environmental assessments that can be used for sensing atmospheric water vapour contents (Zumberge et al., 1997). The GPS signals recorded using ground level continuous operating reference station (CORS), are usually subjected to various attenuations such as, multipath, ionosphere/troposphere delay and signal strength fluctuations. Some of these signal attenuations are presently being assimilated into models for aerosol evaluation.

Since the introduction of the space-based pollution monitoring instruments in the mid-90s, the instruments have continued to display increased user-friendly proficiency for atmospheric processes estimations in 4-dimensional resolution (Duncan et al., 2014; Tsay et al., 2016). Aerosols (particulates) are a composite combination of suspended solid and liquid elements (excluding cloud units) that are being monitored using satellite-based instruments (Gupta et al., 2006). They are an essential component of the climate system and a major concern of the earth's existing anthropogenic radiative force. To minimize these concerns, precise and regular appraisal of these aerosols distributions are necessary so as to regulate its negative impact on man's environment. Accurate monitoring of atmospheric processes such as aerosols and trace gases, are also vital for developing efficient local, regional or global climate models (Madrigano et al., 2013; Chew et al., 2016).

Air pollution remains a serious environmental challenge in many developing countries (Lau and He, 2017). Nigeria accommodates Africa's largest sophisticated population, many of whom continue to migrate to the high-density settlements that surround the urban cities. Three of its developing cities (Onitsha, Kaduna and Aba) were listed amongst the World's top ten most polluted cities (Figure 1), in terms of particulate matter of less than 10 microns (WHO, 2016). Nigeria is reported to have five air monitoring stations established by the Nigerian Meteorological Agency (NiMET) (UNEP, 2015), their operational status remains sceptical as the review of literature showed that there is no record of their data being utilized.

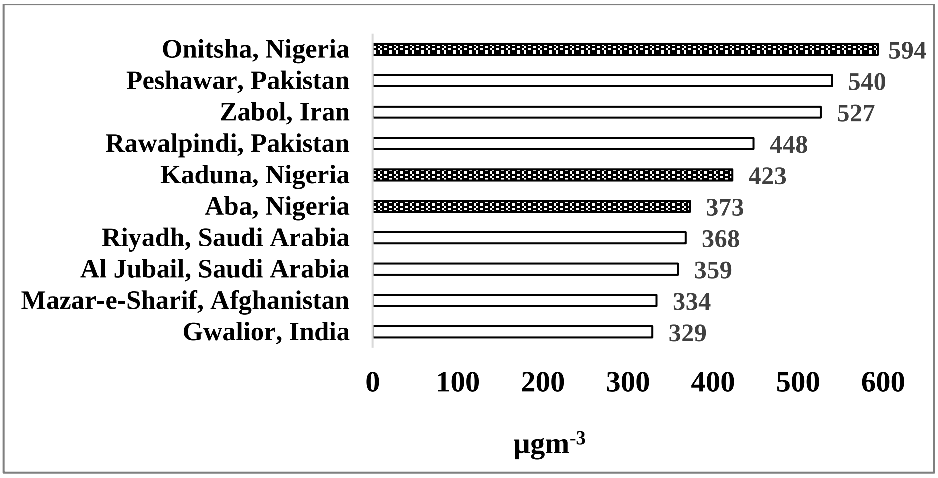

Figure 1. The World's 10 most polluted cities in terms of particulates less than 10 microns, modified after the (WHO, 2016). Shaded column highlight the Nigerian cities.

Satellite-based observations provide a comprehensive view of the earth's atmosphere (Streets et al., 2013) and serves as a practical means for the retrieval of both water vapour and aerosol estimates in a limited resources environment like Nigeria. If the precision and legitimacy of satellite-based estimates are to be verified, the availability of ground-based pollution network/dataset is crucial. Ground-based GNSS operates a meteorological technique whereby its signal delays can be used to derive PWV estimates (Boutiouta and Lahcene, 2013). GNSS remote sensing is becoming necessary due to the technical improvements applied to their inexpensive processing and easy-access of weather insensitive signals (Bonafoni and Biondi, 2016).

It is important for a country like Nigeria to exploit available resources for mitigating particulate air pollution. It is on this basis that this study utilizes seasonal variability of input parameters; GPS-derived precipitable water vapour, MODIS AOD estimates and ground PM measurements, to appraise the effect of atmospheric aerosols and ground particulates concentrations on GPS derived PWV estimates. This study plans to direct a latent position for Nigeria, on the practicability of its existing Nigerian global navigational satellite system reference network (NIGNET) for ground particulates and atmospheric aerosols monitoring. The data processing techniques are described as follows.

2. Methodology

2.1 Study Area

Nigeria established a GNSS Reference Network (NIGNET) through a joint collaboration between Nigeria's Office of the Surveyor General of the Federation (OSGOF) and the Africa Reference Frame (AFREF) programme (Ayorinde et al., 2016). The ABUZ station was utilized for the extraction of the GPS PWV estimates (Figure 2). The ABUZ station is hosted in the main campus of the Ahmadu Bello University Zaria, northern Nigeria. The climate within the study area is categorized into dry (October–

May) and wet (June–September) seasons. It is further characterized by the peak low temperature (14.1 °C) during the harmattan in January and the peak high temperature (35.2 °C) in April. The ABUZ Continuous Operating Reference Station (CORS) is a Trimble NETR8 receiver type with antenna TRM59800.00. The system(s) of observations are GPS and GLONASS. The vertical antenna height specification is 0.17m. The ABUZ station utilized in this study was adopted for two reasons. First, it is the only study location with collocating time-series atmospheric and ground particulates (aerosols) measurements, to achieve the study objectives. Secondly, Abbasy et al., (2017) have endorsed the practicability of utilizing a single GPS station for meteorological studies. The meteorological parameters (surface temperature and pressure) required for the ABUZ GPS derived PWV estimates were synchronized with an existing automatic weather observing station (AWOS). The derived PWV were extracted from GPS data obtained in Receiver Independent Exchange (RINEX) format. The ABUZ RINEX observation sampling frequency is 30 secs, and was accessed via NIGNET portal (http://www.nignet.net/data/RINEX).

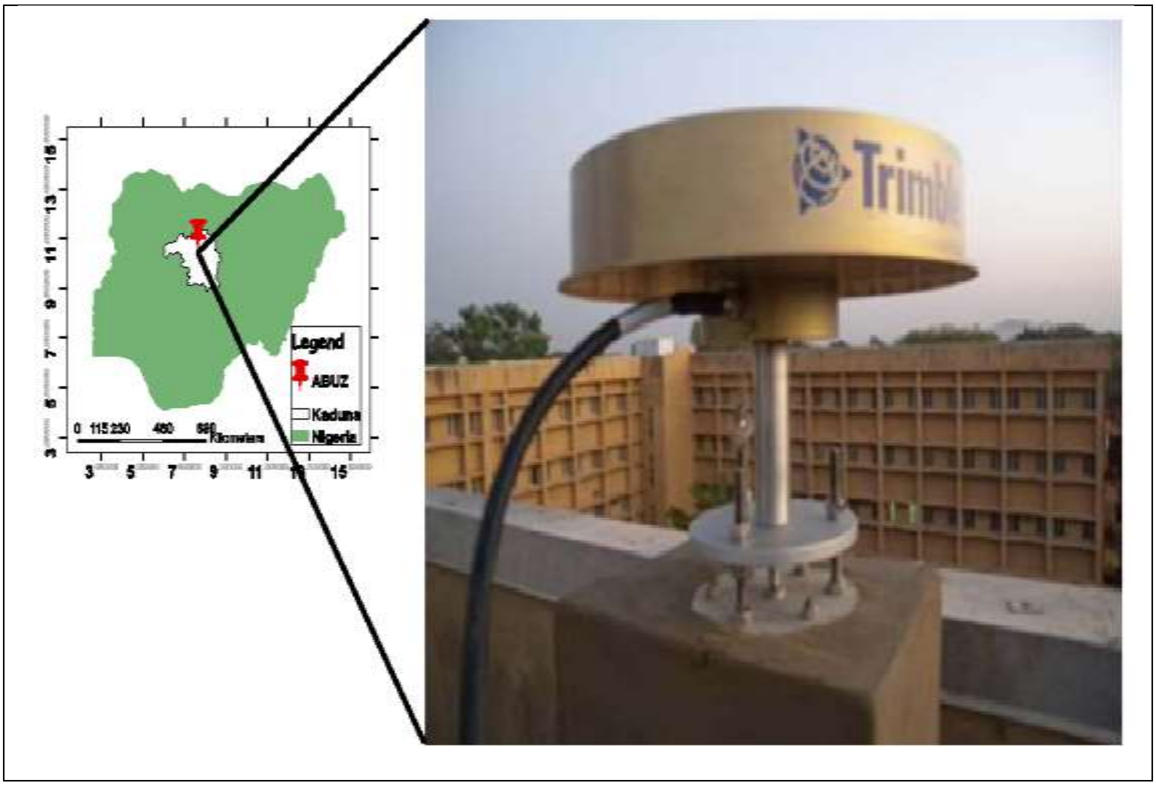

Figure 2. The ABUZ NIGNET station situated within the Ahmadu Bello University Main Campus, Zaria – Nigeria from which precipitable water vapor (PWV) will be extracted for this study

2.2 GPS PWV Estimates

To extract the PWV estimates for precise-point positioning (PPP), the GPS RINEX observation data was processed using WaSoft GNSS software designed by Wanninger (2000) and validated by Schröder et al. (2017). We utilized International GNSS service (IGS) final paths and earth revolution parameters for tropospheric delay derivation and antenna phase centre offsets. Satellite elevation mask of 10 degrees was adopted (Kouba, 2009). The Saastamoinen model (1972) plus random-walk mechanism from meteorologically sourced global pressure and temperature (GPT) model was employed as a *priori* tropospheric model while the zenith delay was processed via the Vienna mapping function (VMF) (Boehm et al., 2006). The WaSoft software is capable of determining the three dimensional data as well as tropospheric factors, which incorporates the Zenith Tropospheric Delay (ZTD).

We transferred atmospheric temperature and pressure to the ABUZ station from the nearby meteorological (AWOS) station using Equation [1] (Bai and Feng, 2003; Musa et al., 2011). We took into consideration the horizontal distance and observation height between the GPS and AWOS station (Table 1).

$$\left.\begin{array}{l} T_{GNSS} = T_{MSL} - 0.0065 \times H_{GNSS} \\ P_{GNSS} = P_{MSL}\left(1 - 0.0000226 \times H_{GNSS}\right)^{5.225} \end{array}\right\} \qquad [1]$$

Where T_{GNSS}; P_{GNSS} are the respective reduced temperature and pressure at the ABUZ station of interest, T_{MSL}; P_{MSL} are the respective temperature and pressure values at the automatic weather observing station (AWOS) mean seal level. The Equation (1) takes into consideration, possible variability in the sensitivity of temperature and pressure at the GNSS antenna height, H_{GNSS}.

Table 1. Properties of the ABUZ station and the matching AWOS station from which meteorological parameters were interpolated to the actual station level (modified after Isioye et al., 2017)

GNSS Station	GNSS station coordinate		AWOS station	AWOS station coordinate		Horizontal distance (m)	Station height (m)	
	Longitude (deg.)	Latitude (deg.)		Longitude (deg.)	Latitude (deg.)		GNSS	AWOS
ABUZ	7.65	11.15	Zaria	7.68	11.10	6855.03	705.05	655.00

To apply GNSS for meteorological purposes, it is necessary to scale down the Zenith Tropospheric Delay (ZTD) into its constituent fractions; the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The ZHD is majorly accountable for the ZTD (~ 90% using experimental models with given surface temperature and pressure). The ZWD is of meteorological importance, due to its significant relationship with humidity changes both spatially and temporally. The PWV can be derived from ZWD as described by Bevis *et al*. (1994) in Equation [2].

$$PWV = \frac{10^6}{R_W \rho_W \left(K_2^{'} + K_3 / T_m\right)} \times (ZTD - ZHD) \quad [2]$$

ρ_w - water density; R_w - water vapour specific gas constant {461.525 ± 0.003 [J kg^{-1} K^{-1}]}; k'_2 and k_3 - [refraction constants in K mb^{-1} (22.1 ± 2.2 K mb^{-1} and 373900 ± 0.012)]; T_m - weighted mean temperature in troposphere gauged in Kelvin; *PWV* - precipitable water vapour

The mean temperature (T_m) utilized for the extraction of the PWV estimate is described in Equation [3] below.

$$T_m = (T_0 - \beta H)\left[1 - \frac{\beta R}{g_m \lambda^{'}}\right] \quad [3]$$

T_o, β *and* λ are meteorological parameters; *H* – orthometric height in metres; $\lambda' = \lambda + 1$ (unit less); *R* is the gas constant for dry air (287.054Jkg^{-1}K^{-1}); g_m – gravity acceleration at the atmospheric column centroid in ms^{-2}.

Applying Saastamoinen (1972) model for the ZHD constituent and meteorologically sourced global pressure temperature (GPT) model, a simplified PWV (mm) relationship to ZWD is described in Equation [4] as follows:

$$PWV = ZWD \times \left[9.80392 - \frac{16917.64}{0.053499 T_s + 1739.07624}\right] \quad [4]$$

ZWD = zenith wet delay; T_s - surface temperature measured in Kelvin

2.3 Atmospheric Aerosol Estimates

MODIS is the most appropriate atmospheric satellite information for investigating aerosols with proficiency for local, regional and global scale air pollution monitoring (Ali et al., 2017). It comprises of 36 spectral bands for precise observation of atmospheric heat and humidity, as well as its constituents which include aerosols and trace gases (Misra et al., 2015). The algorithm for the MODIS aerosol optical depth (AOD) retrieval is centred on the theory of recording aerosol reflectance from reflectance at atmospheric top using Rayleigh path radiance and surface reflectance. This is expressed by Wong et al. (2008) using Equation [5].

$$\rho_{TOA}(\theta_o, \theta_s, \phi) = \rho_{ATM}(\theta_o, \theta_s, \phi, \tau_{Aer}, \tau_{Ray}, p(\theta), \omega_o) + \frac{T_{Tot}(\theta_o) \times T_{Tot}(\theta_s) \times \rho_{Surf}(\theta_o, \theta_s)}{1 - \rho_{Surf}(\theta_o, \theta_s) \times r_{Hem}(\tau_{Tot}, g)} \quad [5]$$

θ_o - peak slant of sun; θ_s - peak slant of satellite; ϕ – clockwise horizontal slant from meridian; $\rho(\theta)$ - phase function (angular dispersal of scattered light); ρ_{ATM} - atmospheric path reflectance; *g* - asymmetry parameter; τ_{Hem} (τ_{Tot}, g) - hemispheric reflectance; ω_o – single scattering albedo; τ_{Tot} (m_o) - total transmittance; ρ_{Surf} (θ_o,θ_s) - surface reflectance; τ_{Aer}, τ_{Ray} and τ_{Tot} - aerosol optical thickness, Rayleigh optical thickness, and overall optical thickness respectively.

The Rayleigh path radiance is obtained from Equation [6] by computing its spectral requirements and phase function, as described by Bucholtz (1995).

$$\tau_{Ray}(\lambda) = P \times \lambda^{-(Q+R\lambda+S/\lambda)} \times \frac{p(z)}{p_o} \qquad [6]$$

where P, Q, R, S are the standard atmospheric aggregate of Rayleigh scattering cross-section plus volume scattering coefficients while p(h), the appropriate height pressure is defined in Equation [7].

$$p(h) = p_o \times \exp\left[\frac{-29.87 \times g \times 0.75 \times h}{8.315 \times \left(T_S - g \times 0.75 \times h\right)}\right] \qquad [7]$$

Where h – altitude from digital elevation model; g – acceleration due to gravity and T_s – surface temperature

For the MODIS aerosol estimates, the deep blue level 3 version 5.1 aerosol products (http://disc.sci.gsfc.nasa.gov/SSW/#keywords=MYD08_D3 5.1) was adopted for its geophysical parameter, averaged into (-90.0° to +90.0°) latitude and (-180.0° to +180.0°) longitude grid cells (Tian et al., 2014). The variable [Deep_Blue_Aerosol_Optical_Depth_Land_Mean] takes convenience of the dark-exterior attributes at 0.47 μm blue wavelengths and frail dust penetration at 0.65 μm red wavelength (Shi et al., 2013; Misra et al., 2015). The downloaded MODIS precipitable water vapour variable (IR retrieval) datasets were accessed using Panoply software (Vollmer, 2010). The subset $MODIS_{AOD}$ and $MODIS_{PWV}$ estimates were then collocated over the ABUZ station using the Kriging interpolation mechanism (Araki et al., 2015; Li et al., 2016).

2.4 Ground Particulate Measurements

The use of efficient portable sensors for particulate matter (PM_{10}) measurements is getting major attention across the globe (Liu et al., 2014; Li and Biswas, 2017). The study utilized the validated Chinaway CW-HAT200 particulate counter, to obtain ground samples measurements for PM_{10} in (microgram per meter cube, μg m^{-3}) using the laser diode principle. The sample measurements were collected for the duration of 1 year (1 December 2015 – 30 November 2016) and collocated with the available daytime averaged ABUZ GPS_{PWV} and $MODIS_{AOD}$ estimates. Instrument background and pump flow was also examined prior to conducting each measurement session. The portable PM_{10} instrument were validated using the WHO air filter sampling technique, described in Efe and Efe (2008). The validation results are displayed in Figure 3.

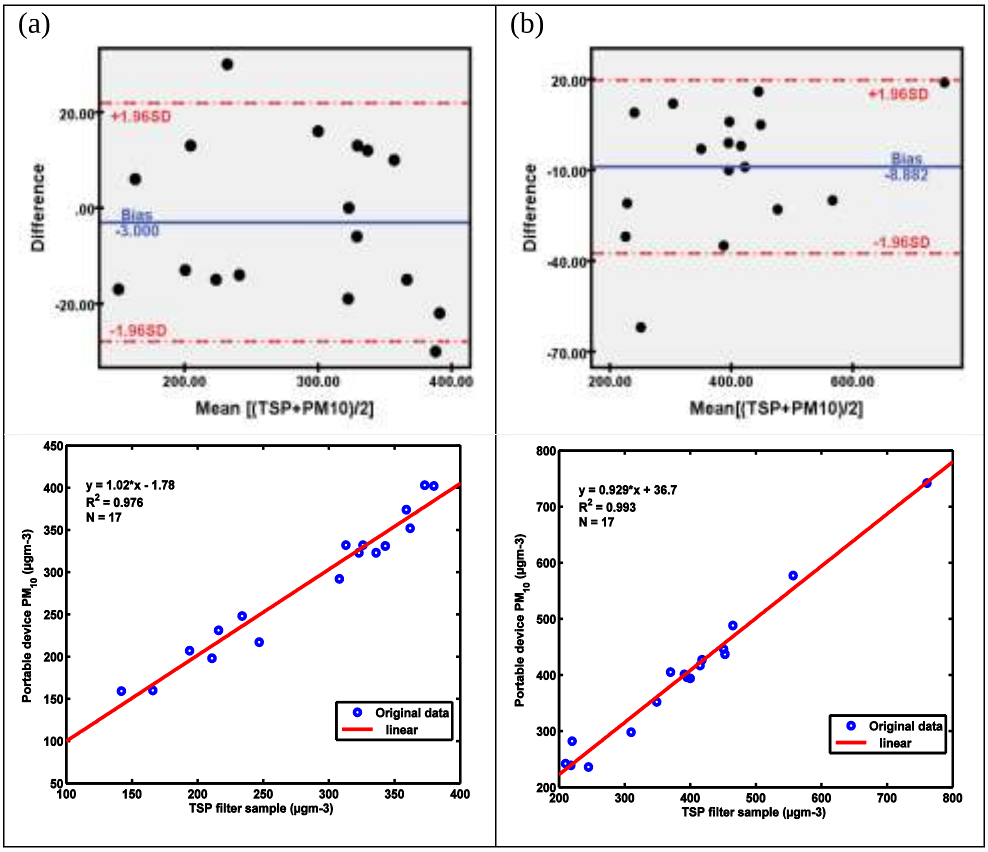

Figure 3. Agreement and linear regression plots showing the bias and coefficient of determination between the TSP and the CW-HAT200 particulate monitor samples at two sample sites (a) control site, (b) dense activity site (modified after Aliyu and Botai, 2018)

2.5 Data Analysis Approach

The study is interested in evaluating the effects of atmospheric aerosols and ground particulates concentrations on GPS_{PWV} estimates. Figure 4 highlights the flowchart which describes the steps taken to achieve this study. The datasets utilized in this study covered a duration of 1-year (December 2015 – November 2016).

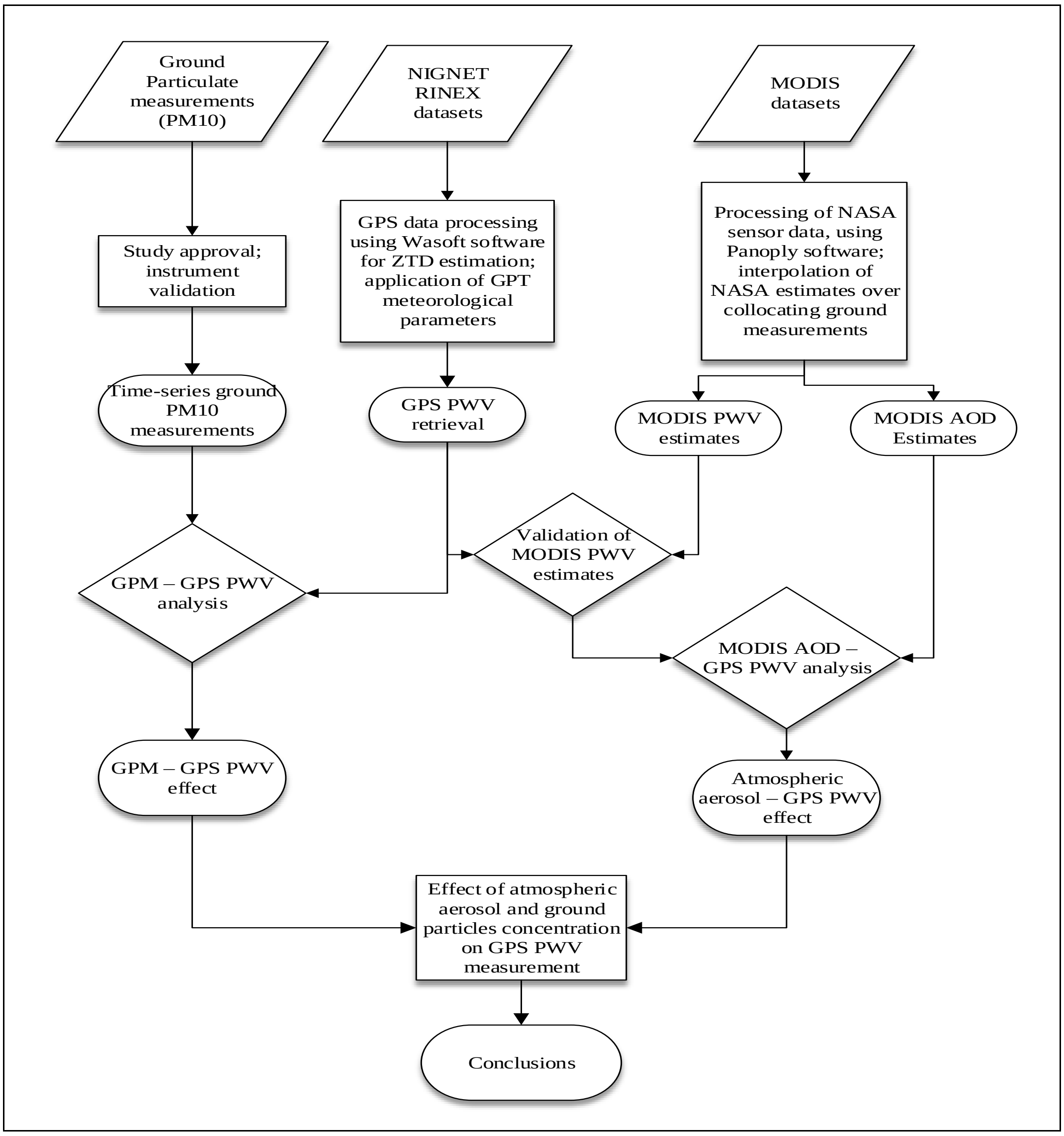

Figure 4. Flowchart of the data analysis steps

The assimilation process for aerosol estimation using GPS-derived PWV estimates involves three empirical steps (Equation 1 – 3). First, we determined the ZTD. It is the GNSS signal attenuation primarily responsible for indicating precipitable water vapour contents (Bevis et al., 1994; Rohm et al., 2014). Second, we utilized the GPS meteorology concept. This extracts the precipitable water vapour (PWV) from the GPS–ZTD estimates given that the atmospheric temperature and pressure at the ABUZ station is known (Isioye et al., 2017). Finally, we utilized literatures which indicated that water vapour takes out aerosol from the atmosphere that usually occur as a result of particulate matter (PM) floating in the air/gas or dissolved in water. PM are a major contributor of aerosol constituents in the troposphere from which the PWV is derived using the GPS ZTD signal (Lau and He, 2017). It has been established that PWV and particulates (aerosols) have a significant inverse relationship (Gui et al., 2017a). Furthermore, the degree of relationship between the PM and AOD quantities have established by literature. Their relationship can be determined using their level of correlation (Schäfer et al., 2008;

Yap and Hashim, 2013). This practical approach is acknowledged for examining PM concentration from satellite remote sensing AOD data. A full data processing technique for relating PM with AOD is discussed in Filip and Stefan (2011).

To ensure reliability of our results, we adopted four performance indicators to evaluate the GPS-derived PWV estimates for aerosol monitoring. The indicators include: alpha data reliability (Le Boennec and Salladarré, 2017), correlation coefficient (R) (Murphy, 1988) and root mean square error (RMSE) (Chai and Draxler, 2014). They are represented mathematically in Equations [8 – 10]. The alpha data reliability index computes the average factor by which observed measurements of interest differ from one another. The correlation (R) weighs the level of variability in the actual values that is explained by the model. RMSE expresses the difference between observations predicted by a model.

$$\alpha = \frac{N \cdot \overline{C}}{\overline{\upsilon} + (N-1) \cdot \overline{C}} \quad [8]$$

$$R = \frac{\sum_{i=1}^{n} \left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)}{\left[\sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2 \times \sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2\right]^{\frac{1}{2}}} \quad [9]$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2\right]^{\frac{1}{2}} \quad [10]$$

where N is the sample size, c is average covariance between the GPS_{PWV} estimates (O_i) and the predicting $MODIS_{PWV}$ and $MODIS_{AOD}$ estimates (P_i), ϑ is the average variance, O_i is time series of reference GPS_{PWV} estimates, P_i, is the time series of predicted $MODIS_{PWV}$ and $MODIS_{AOD}$ models, $\overline{O}$ and $\overline{P}$ denotes the averages of the reference and predicted model values; N indicates number of observation samples.

3. Results and Discussion

The distribution of the GPS-derived PWV (GPS_{PWV}) estimates over the ABUZ station was analysed for skewness and kurtosis. The GPS_{PWV} data revealed a skewness value (- 0.256) and kurtosis value (-1.509). The standard error across the GPS_{PWV} variables is 1.240 mm. This indicated that the GPS-derived PWV estimates were normal distributed with the 95% confidence interval. To further certify the assumption of normality, the Shapiro-Wilk's test based on an empirical standardization of the GPS_{PWV} observation residuals, was conducted. The test displayed a value of 0.890. For the $MODIS_{PWV}$, the value for skewness and kurtosis is -0.312 and -1.426 respectively. The Shapiro-Wilk's test of the $MODIS_{PWV}$ observation residuals is 0.882. These results did conclude that the GPS_{PWV} observations are normally distributed. Figure 5 illustrates the time-series data of the collocating average PWV estimates from the ABUZ and MODIS instruments for the time interval (1300 – 1415 h). The time series data revealed varying data breaches for the collocating observations. While the data gap for the ABUZ station is restricted to hardware issues, he MODIS breaches is as a result of the Lance-MODIS latency plus hardware issues.

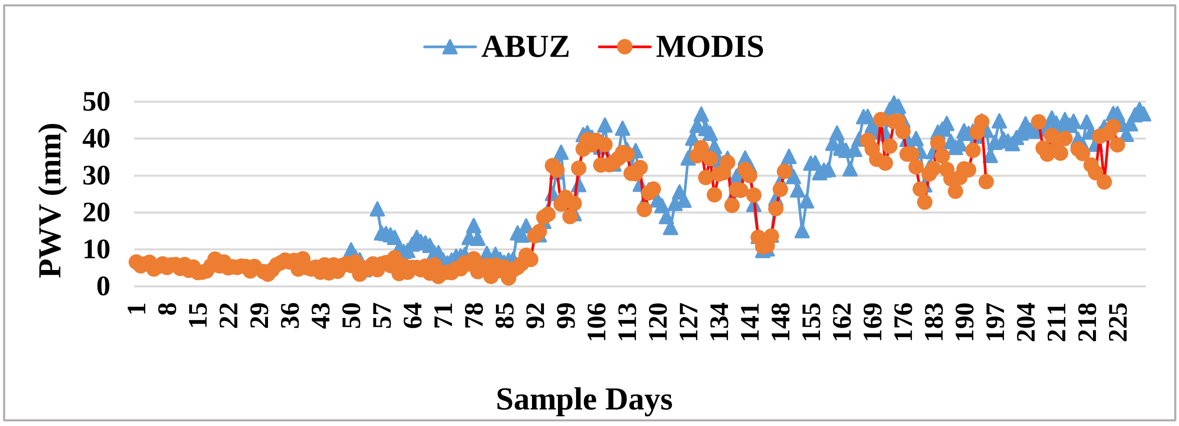

Figure 5. Time series of collocating average PWV from the ABUZ station and MODIS instrument for the study period (available sample days' equals 232)

3.1 Effects of $MODIS_{AOD}$ concentrations on GPS_{PWV}

Prior to the GPS_{PWV}-$MODIS_{AOD}$ investigation, we conducted a pre-validation of the MODIS instrument ($MODIS_{PWV}$) using the GPS_{PWV} measurements. The $MODIS_{PWV}$ estimates were extracted from the MODIS MYD08_D3 5.1 IR retrieval variable. We utilized available GPS_{PWV} data for the study period. The available datasets were categorized the data across seasons; December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). The time-analysis in Figure 5 showed that $MODIS_{PWV}$ recorded good correlating estimates when compared to the GPS_{PWV} estimates over the ABUZ station. Figure 6 displays the Bland-Altman agreement plot, linear regression and boxplots of the compared PWV residuals. The daily average PWV (mm) recorded across the collocated stations ranged from (4.60 – 49.66) and (2.25 – 45.09) for GPS and MODIS instrument respectively (Figure 6b).

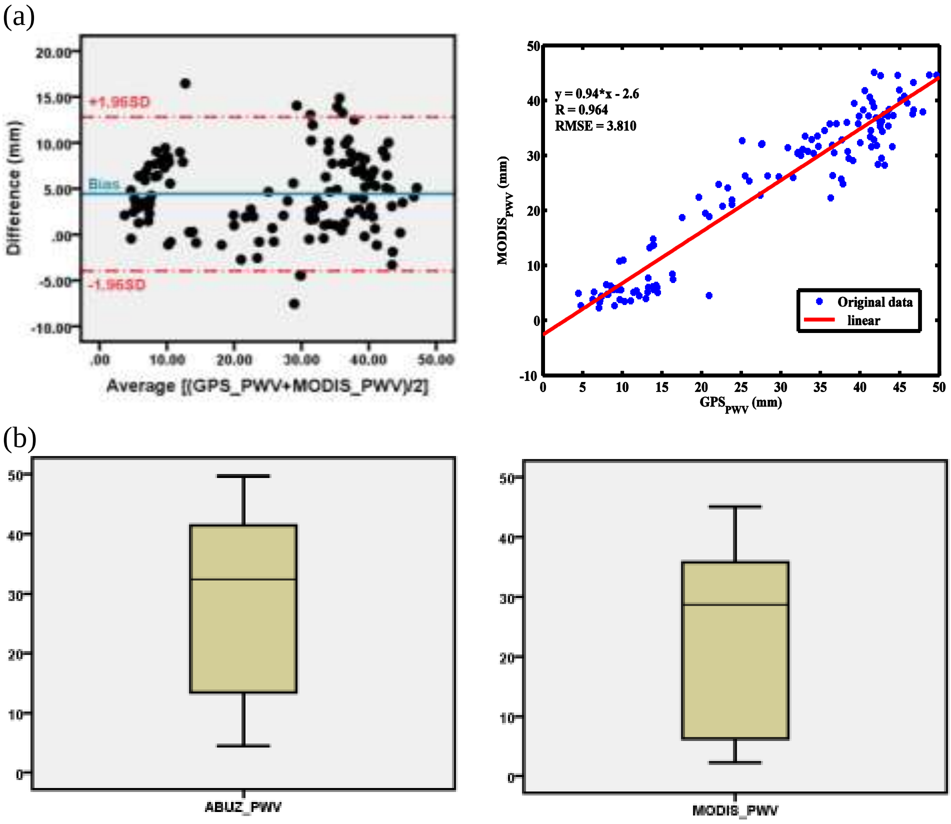

Figure 6. (a) Difference - linear regression plot of the GPS_{PWV} and $MODIS_{PWV}$ estimates (b) Boxplots showing the range of PWV values

The GPS data acquisition process revealed that there were no available datasets for SON season. From the Figure 5 and 6, we can see that the $MODIS_{PWV}$ estimates showed a good linear agreement with GPS_{PWV} estimates. Table 2 illustrates the GPS_{PWV}-$MODIS_{PWV}$ validation results. The descriptive revealed good GPS_{PWV}-$MODIS_{PWV}$ agreement at surface level (R = 0.96; RMSE = 3.81). This $MODIS_{PWV}$ validation is within the range of acceptable results, when compared to similar research findings on PWV validation (Tsidu et al., 2015; Gui et al., 2017b) but slightly lower than Ningombam et al., (2016). From Table 2, we can also conclude that the computed alpha reliability, correlation coefficient, root mean square error and bias, were within the range of PWV estimation with GPS positioning.

Table 2. Performance statistics between GPS_{PWV} and $MODIS_{PWV}$ retrievals estimates

GPS station	Season	α	R	RMSE (mm)	Bias (mm)
ABUZ	DJF	0.98	0.77	1.03	5.46
	MAM	0.99	0.93	3.42	2.94
	JJA	0.98	0.79	3.95	6.49
	Combined	0.97	0.96	3.81	4.41

To determine the effect of $MODIS_{AOD}$ concentrations on GPS_{PWV} estimates, $MODIS_{AOD}$ estimates was collected over the ABUZ station collocating with the GPS_{PWV} estimates for the study period. The $MODIS_{AOD}$ measurement over the ABUZ station, was obtained after the initial spatial boundary box sub-setting and subsequent Kriging interpolation described in Aliyu and Botai (2018). The descriptive statistics of the $MODIS_{AOD}$ estimates over the ABUZ station showed that the standard error of mean ranged from 0.04. The standard error of skewedness and kurtosis were computed as 0.17 and 0.34 respectively. The Shapiro-Wilk's test of normality (0.83) also indicated that the estimates are normally distributed over the ABUZ station. All the collocating data observations (GPS_{PWV} and $MODIS_{AOD}$) indicated strong reliability ($\alpha > 0.90$) over the ABUZ station. Figure 7 displays the time-series of the $MODIS_{AOD}$ measurements against the GPS_{PWV} estimates.

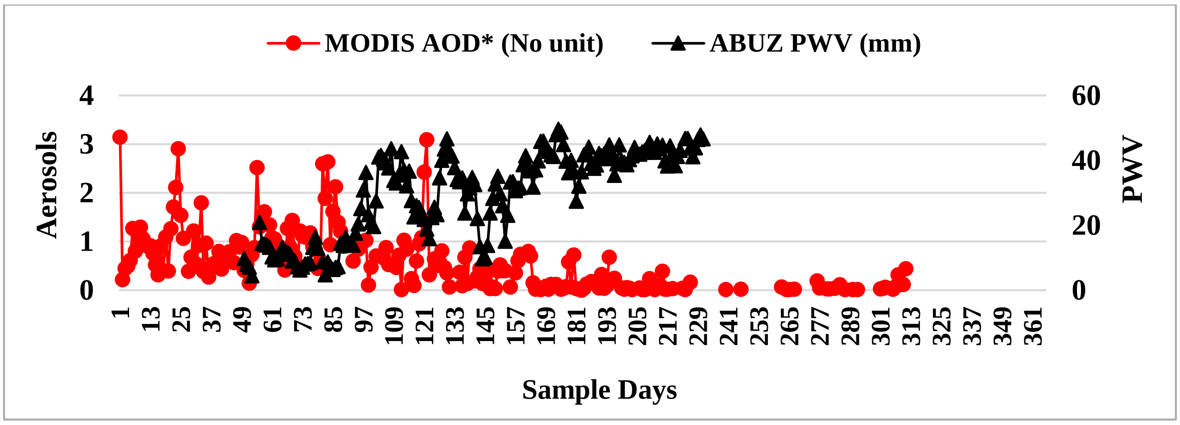

Figure 7. Time-series of the collocating averaged GPS_{PWV} estimates and $MODIS_{AOD}$ measurements

The GPS_{PWV} and $MODIS_{AOD}$ measurements were significant ($p < 0.05$). The GPS_{PWV} and $MODIS_{AOD}$ analysis showed good correlation performance ($R \leq -0.64$) with the JJA season recorded the better performance ($R = -0.79$; $\alpha = 0.999$; RMSE = 0.46). Our finding for the GPS_{PWV} - $MODIS_{AOD}$ analysis does agree with Gui et al. (2017a) that evaluated atmospheric aerosol (AOD) with PWV estimates from radiosondes and weather stations.

3.2 Effects of GPM Concentrations on GPS_{PWV}

Secondly, we evaluated the applicability of the GPS_{PWV} estimates derived from the ABUZ station for monitoring ground particulate matter (GPM) measurements. We utilized the available collocating GPM time-series data. The linear relationship of the GPS_{PWV} and GPM measurement is illustrated in Figure 8. Table 3 also displays the descriptive statistics of the collocating GPM measurements.

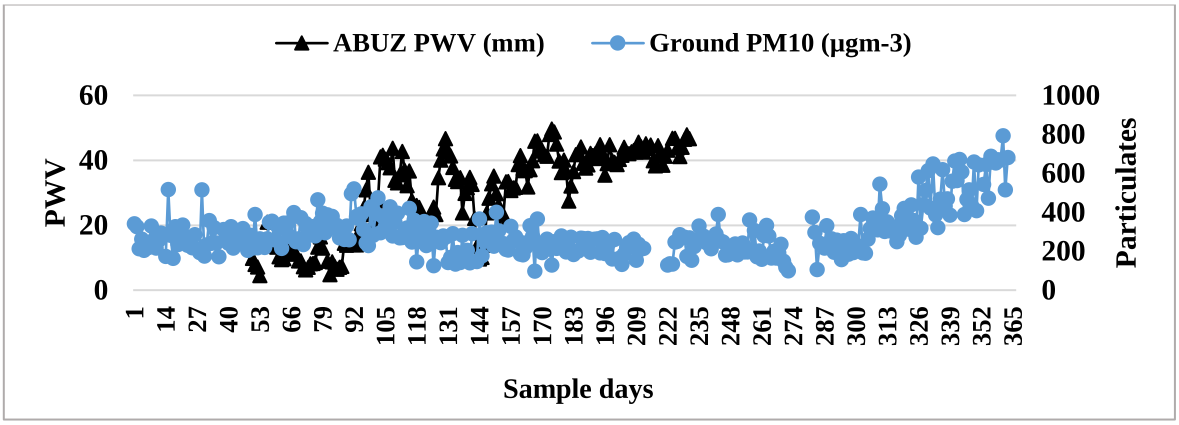

Figure 8. Time-series of the daily averaged GPS_{PWV} estimates and GPM measurements

In Table 3, we can see that the probabilities of datasets normality are greater than 0.05, thus the null hypothesis (H_0) is accepted. This indicates that the datasets are normal distributed as well as within satisfactory skewness and kurtosis. Also, the MAM and JJA season recorded higher GPM concentrations. This could be attributed to the massive construction activities that commenced within the study area.

Table 3. Descriptive statistics of collocating GPM measurements

Season	DJF	MAM	JJA
Mean (µg m^{-3})	309.08	300.94	224.01
SE of mean	12.24	10.99	9.71
SD	127.25	114.30	100.90
Skewness	1.12	0.49	0.167
Kurtosis	1.28	-0.12	-1.01
Shapiro-Wilk's Test	0.92	0.97	0.97

For the comparative results of the GPM concentrations against the GPS_{PWV} estimates. The GPS_{PWV} and GPM measurements were significant ($p < 0.05$). Similarly, the GPS_{PWV} and GPM analysis showed good correlation (R) range of values (-0.66, -0.67 and -0.79) for the DJF, MAM and JJA seasons. The GPS_{PWV}-GPM recorded the better relationship ($R = -0.79$; $\alpha = 0.99$; RMSE = 2.39) in the JJA season. This is also similar to the GPS_{PWV}-$MODIS_{AOD}$ comparison. This indicated that the presence of ground level particulates resulting from anthropogenic activities contributes significantly, to atmospheric aerosol concentration within the study area. There are very limited studies that analysed the GPS_{PWV}-GPM analysis. However, this correlation coefficient was satisfactory, if compared to AOD – PM_{10} study ($R = -0.70$) reported by Filip and Stefan (2011). Furthermore, the GPS_{PWV}-GPM investigation can contribute to the position accuracy for similar related studies in the future.

From the above-described results, we can conclude that the prediction of MODIS AOD and particulate matter, PM_{10} from GPS_{PWV} estimations, does provide convincing argument for the study location. The better performance of the GPS_{PWV}-GPM to the GPS_{PWV}-$MODIS_{AOD}$ can also attributed to the alternating humidity and cloud across the study seasons, as it may impact negatively on the MODIS retrievals thus responsible for observation variations.

4. Conclusions

With the World Health Organization reporting alarming particulate pollution level across Nigerian cities, this paper presents seasonal variability of the input parameters; GPS-derived precipitable water vapour, MODIS AOD estimates and ground PM measurements over Zaria, Nigeria for December 2015 - November 2016. We examined the effect of atmospheric aerosols and ground particulate matter concentrations on GPS derived precipitable water estimates. The collocating datasets utilized for this study revealed satisfactory results for skewness and normality. The MODIS-GPS pre-validation procedure results showed good agreement for GPS_{PWV}-$MODIS_{PWV}$ across the instruments. The analysis the GPS_{PWV}-$MODIS_{AOD}$ and the GPM_{PWV}-GPM measurements revealed promising relationships which were similar to related studies. The spatial variability of particulates/aerosols concentration within the Nigerian territory cannot be ignored, thus the need to explore available operational techniques for efficient pollution monitoring. Our study introduced a novel physical mechanism of the GPS PWV-PM relationship that can be utilized for future position accuracy. The incorporation of our findings will provide a basis for the improved analysis of the aerosol/particulates processes. These findings present an applicability of the Nigerian GNSS Reference Network (NIGNET) for monitoring ground particulates and satellite aerosol measurements. Thus, the Nigerian air pollution planners can begin to consider its NIGNET stations for aerosol monitoring, taking into consideration its limited air pollution monitoring capabilities.

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