Statistical investigation of refractivity and path delay in a semi temperate region

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Abstract. Of the many impairments that affect quality of signals propagated at frequencies above 10 GHz, attenuation of electromagnetic waves by rain is the major impediment system engineers and designers have to overcome. Path delay and refractivity are two major factors to be considered alongside rain attenuation. Hence, this paper investigates the relationship between refractivity and path delay, and the results are used to predict path delay in Jos (09°57’N, 08°58’E, 1192m), a semi temperate region of Nigeria. In this research, daily meteorological data, collected from October 2013 to September 2014, was statistically analysed for refractivity and path delay. The values of the refractivity index was estimated with ITU-R prediction model, and path delay was computed afterwards. The statistical analysis of the least square regression model revealed that the month of July to September experienced variation as envisaged with respect to R² and adjusted R. This variation took place in at the peak of raining season and this is attributed to rain attenuation. There was no variation observed between the variables from the month of October to June which appears to be dry season. Pearson correlation showed a strong correlation between the variable under study as all the correlation coefficient value stood above 0.99. There was correlation between refractivity and path delay as increase in refractivity led to increase in path delay and path delay is more prominent in the wet season due to impairments such rain attenuation. The result obtained in this research could be used to plan and deploy fade mitigation techniques for microwave links in the region.

Keywords: Radio refractivity, Satellite communication, Tropospheric Scintillation, path delay.

1. Introduction
In recent times, the continuous increasing demand for speedy, dependable and adaptable wireless communication over the internet, has led to an increasing demand for higher frequency bands above 10 GHZ [1]. Two core benefits derived from the use of higher frequency bands are: - reduced congestion in the lower frequency bands; and the availability of larger bandwidths to accommodate more broadband services, at higher frequencies [2, 3].

Author [4] noted that, system operators and radio engineers find these frequencies are attractive and desirable to deploy their technologies. However, the systems are easily degraded by some tropospheric constituents of which rain is the principal factor [1]. Some other degrading factors such as crosstalk or inter-system interference are considered secondary because, the effect of rain is so severe that it leads to a total outage (or unavailability) of the radio link.[1].
Rapid fluctuations in meteorological parameters such as temperature, pressure and relative humidity affect the transmission of radio signals in the atmosphere [5, 6]. When the meteorological parameters fluctuate, the refractive index of the air in the atmosphere changes rapidly; these rapid changes are measured by the refractivity index, N, expressed in equation (3). Refractivity leads to various radio wave propagation incidents such as ducting, scintillation, refraction and fading [7].

Many research studies [4, 8, 9] have expressed refractivity as a function of atmospheric meteorological parameters in the lower atmosphere (the troposphere). The troposphere extends from the earth surface to an altitude of about 10m at the earth poles and 17 m at the equator [10]. Authors [11] studied variation of tropospheric refractivity at Nsukka in South Eastern Nigeria; while [12] studied diurnal and seasonal variation of surface refractivity over Nigeria.

Authors [9] presented about 3m variation due to refractivity in mountainous coastal waters; over X-band line-of-sight paths. The authors opined that seasonal variation of refractivity gradient could cause microwave systems unavailability. The study of atmospheric refractivity over Abuja Nigeria [8] were based on relative humidity, temperature and pressure. Some other refractivity works were based on radiosonde station data in Nigeria [1, 4, 6, 9, 13, 14]. Here, sensors were mounted on a radio transmitter at some locations to measure atmospheric data. They observed that refractivity values were higher during the rainy season and lower in the dry season.

With these in mind, this paper investigates the relationship between refractivity and path delay, after which results will be used in modelling path delay in Jos (09°57’N, 08°58’E, 1192m), a semi temperate region of Nigeria, from October 2013 to September 2014. The results will be useful for future forecasting in system planning, development of millimetre wave communication and prediction of occurrence of signal outages during transmission due to rainfall in Guinea Savanna location. This research provides system designers with additional information and input parameters to design satellite systems in the tropical regions such as Nigeria [13].

2. Method
For this study, the measurement of data was carried out in Gold and Base – near Airforce Military School (AFMS), Jos with coordinates (09°896’N, 08°858’E, 1192 m), located on the plateau with a guinea savanna climate in North Central, Nigeria. Jos has an average annual temperature of 22.8°C and average annual rainfall of 1160 mm [15]. The measurement was taken as described in [15, 16]. The Davis Vantage Vue the weather station consists of an integrated sensor suite (ISS) and weather link data logger; which was used to measure and record one-minute temperature, pressure and humidity values over the period of one year (October 2013 to September 2014). Table 1 gives the description of experimental site and radio parameters for the Ku-band link as specified by authors [15, 17, 18].

Table 1: Characteristics of experimental site and parameters for the Ku-band link [15, 17]

| Measurement Site            | Gold and Base, Jos, (09°57’N, 08°58’E, 1192m) |
|----------------------------|-----------------------------------------------|
| Climate Region of the Site  | Guinea Savanna                                 |
| Max/ Ave/ Min Temperatures  | 29.8°C / 22.8°C/ 17°C                          |
| Satellite Name / Number     | EUTELSAT; W4/ W7 (DSTV Multi-choice)           |
| Satellite Signal Frequency  | 12.245 GHz                                    |
| Symbol Rate                 | 27.509 bps                                    |
| Satellite Elevation (orbital)| 036E                                          |
| Satellite Geo-station Lookup| 037.3E                                        |
| Antenna Diameter            | 90cm                                          |
| Rain Equipment / Integration time | Davis Vantage Vue Integrated Sensor Suite (ISS) |
|                            | Weather Station and Weather Link              |
2.1 Calculation of Path Delay from Refractivity

The monthly and annual values of wet term of refractivity (Nwet) were computed from the measured meteorological data of temperature, pressure, and relative humidity following the method described by [6]. The wet term of refractivity, Nwet was obtained using the ITU-R in [18] as described in equations (1) to (9):

\[ N_{wet} = 3.732 \times 10^5 \left( \frac{e}{T^2} \right) \]  
\[ N_{dry} = 77.6 \frac{P}{T} \]  
\[ N = 77.6 \frac{P_d}{T} + 72 \frac{e}{T} + 3.732 \times 10^5 \frac{e}{T^2} \]

\( P_d \) is the partial pressure of the other components (mainly oxygen and nitrogen) \( T \) is the absolute temperature (K). The water vapour pressure \( e \), is derived from the humidity, \( H \), and the saturation water vapour pressure, \( e_s \) as [6]:

\[ e = \left( \frac{H \times e_s}{100} \right) \]  
Where, the saturation water vapour pressure, \( e_s \) (hpa)

\[ e_s = a \exp \left( \frac{bt}{t+c} \right) \]  
where \( a = 6.112, \ b = 17.50, \ c = 240.97 \), and \( t \) is the Celcius temperature.

Path Delay \( \Delta L \) was thus calculated using equation (6) derived by [19]:

\[ \Delta L = 10^{-6} \int_{l=0}^{L} N(l) \, dl \]  
where \( N(l) \) is the refractivity at position \( l \) on the path, and according to [20] \( N(l) \) is given as:

\[ N(l) = (n - 1) \times 10^{-6} \]  
Where \( n \) is the refractive index. To calculate slant path \( l \), [21] in [3] gave the expression for \( l \), in equation (8) as:

\[ l = \frac{H-\Phi}{\sin \theta} \]  
where \( H \) is the rain height, \( \Phi \) is the station altitude and \( \theta \) is the look up angle [18]. Davis weather station Jos has its rain height of 4.86m [15], station altitude of 1.192 km and antenna look up angle of 56.5° respectively. Substituting these into the slant path expression given by [9] as:

\[ l = \frac{4.86 \text{km} - 1.192 \text{km}}{\sin 56.5^\circ} = 4.399 \text{km} \]

The modelling was achieved using Microsoft excel statistical package and SPSS to find the refractivity, path delay and also test the relationship between refractivity and path delay in the data.

3. Results and discussion

The maximum and minimum values of refractivity for each month are summarised in Table 2. The hourly time series of path delay [19] for the months October 2013 to September 2014 are shown in
figure 1 (a) – (l), while Table 3 presents the minimum and maximum path delay, from the graph, for each month.

It was observed that the refractivity values of the months of July, August and September are most dominate except for November which has the highest maximum refractivity value. Comparing the wet and dry seasons, July – a month in the wet season recorded the highest refractivity value for the region as compared to November - a month in the dry season. Also, April and March recorded the lowest value of refractivity for wet and dry seasons respectively. Months that fall into the rainy season all have higher maximum refractivity values as compared to the dry season which suggests they are more prone to signal loss and scintillations.

Table 2. Monthly maximum and minimum values of refractivity in Jos

| Month      | Maximum Refractivity (N_{max}) | Minimum Refractivity (N_{min}) | Month      | Maximum Refractivity (N_{max}) | Minimum Refractivity (N_{min}) |
|------------|--------------------------------|--------------------------------|------------|--------------------------------|--------------------------------|
| Oct 2013   | 301.41                         | 267.64                         | Apr 2014   | 300.54                         | 254.41                         |
| Nov 2013   | 357.20                         | 280.01                         | May 2014   | 302.42                         | 268.16                         |
| Dec 2013   | 299.67                         | 260.53                         | Jun 2014   | 301.92                         | 276.75                         |
| Jan 2014   | 298.68                         | 258.32                         | Jul 2014   | 303.02                         | 280.31                         |
| Feb 2014   | 296.82                         | 255.87                         | Aug 2014   | 302.23                         | 286.00                         |
| Mar 2014   | 299.69                         | 254.93                         | Sep 2014   | 302.11                         | 270.08                         |
Figure 1(a – l): Path Delay Time Series for Oct 2013 to Sep 2014.

Table 3. Monthly maximum and minimum values of path delay in Jos [20]

| Month  | Maximum path delay (m) | Minimum path delay (m) | Month  | Maximum path delay (m) | Minimum path delay (m) |
|--------|------------------------|------------------------|--------|------------------------|------------------------|
| Oct 2013 | 1.88                   | 1.67                   | Apr 2014 | 1.88                   | 1.59                   |
| Nov 2013 | 2.23                   | 1.75                   | May 2014 | 1.89                   | 1.67                   |
| Dec 2013 | 1.87                   | 1.63                   | Jun 2014 | 1.88                   | 1.73                   |
| Jan 2014 | 1.86                   | 1.72                   | Jul 2014 | 1.89                   | 1.75                   |
| Feb 2014 | 1.85                   | 1.60                   | Aug 2014 | 1.89                   | 1.79                   |
| Mar 2014 | 1.87                   | 1.59                   | Sep 2014 | 1.89                   | 1.69                   |
Path delay values where highest in November – a month in the dry season and July – a month in wet season. The path delay values increases as refractivity increases and the wet months experience higher refractivity and path delay than the dry months with the exception of November.

Table 4 presents the model summary of the predictor variable path delay with the independent variable refractivity for the month of October 2013 to September 2014 using both the least square regression model and the Pearson correlation. Data analysis of samples collected from Gold and Base, Jos was conducted through statistical analysis executed using Ordinary Least Square Regression to ascertain the variation between the predictor variable path delay and the dependent variable refractivity from the month October 2013 to September 2014.

It was revealed that there is no variation between the variable from the month of October to June which appears to be dry season. Findings revealed that the month of July to September experienced variation as envisaged with respect to $R^2$ and adjusted $R$. This variation took place in at the peak of raining season and this is attributed to rain attenuation. Findings from the statistical analysis also revealed that there is strong correlation between the variable under study as all the correlation coefficient value stood above 0.99 representing 99%. The path delay is strongest in the rain season which means poor signal reception will be experienced as a result of this.

Table 4: Regression and Correlation analysis of Refractivity and Path Delay Oct 2013 – Dec 2014

| Months     | Regression Analysis of Refractivity and Path Delay | Correlation Result of Refractivity and Path Delay |
|------------|--------------------------------------------------|--------------------------------------------------|
| Oct 2013   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| Nov 2013   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| Dec 2013   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| Jan 2014   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| Feb 2014   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| March 2014 | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| April 2014 | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| May 2014   | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| June 2014  | R = 1.00 $R^2 = 1.00$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |
| July 2014  | R = 1.00 $R^2 = 0.99$ Adjusted $R^2 = 0.99$     | Path Delay = 0.99                                  |
| August 2014| R = 0.99 $R^2 = 0.98$ Adjusted $R^2 = 0.98$     | Path Delay = 0.99                                  |
| Sept 2014  | R = 1.00 $R^2 = 0.99$ Adjusted $R^2 = 1.00$     | Path Delay = 1.00                                  |

4. Conclusion
Since the spectrum at lower frequency bands is congested, there is an ever-increasing demand for higher bandwidth [24]. The preponderance of higher frequency bands such as Ku-, K- and Ka- bands is becoming popular for deploying satellite communication services. At these frequencies, various impairments cause signal to fade; the worst of these impairments is rain attenuation. Rain attenuation occurs when the raindrop scatters and absorbs part or all of the signal radiated power [22]. The ITU-R model was used in this research to calculate refractivity and path delay due to rain over Ku band links in Jos. Procedures described in [17, 18] and [23] were applied to the data. The statistical analysis executed using the least square regression model revealed that the month of July through September 2014 experienced variation as envisaged with respect to $R^2$ and adjusted $R$. This variation took place in at the peak of the rainy season and this is attributed to rain attenuation while there is no variation between the variable from the month of October to June which appears to be dry season. Pearson correlation revealed that there is strong correlation between the variable under study as all the correlation coefficient value stood above 0.99. There is correlation between refractivity and path delay as increase in refractivity led to increase in path delay and path delay is more prominent in the wet season due to
impairments such rain attenuation. In future studies, the predicted values of path delay could be compared with the measured radio propagation data obtained from the location. However, the results obtained in this research may be used to plan and design of terrestrial and space satellite links [7]; especially in the deployment of fade mitigation techniques for reliable microwave communication links [15].

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