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Tropospheric Scintillation Predictions of the Nigerian Climate; A Case Study of Mowe, Ifo Local Government, South West Nigeria.

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Abstract

Signal deterioration will result from tropospheric scintillation in microwave communication connections with small fade margins. In tropical areas, very few scintillation research has been carried out. Twelve months (Jan 2014 – Dec 2014) of data obtained from the Tropospheric Data Acquisition Network (TRODAN) weather station in Mowe, Nigeria, with a frequency of 13 GHz and an elevation angle of 60.7° were used to study tropospheric scintillation. The data are processed, and the predictions of a few scintillations prediction models that are already in use were compared. Scintillation was seen to be at its peak in April and August with 0.95 dB and 0.88 dB respectively. The strongest intensities show skewness, which is also typical in the absence of rain. According to the analysis, the ITU-R model predicts the scintillation intensity for a fade at 0.01 % of the time to 1 percentage of time, with the lowest error rate. As Mowe is located in the tropical region of Nigeria, it is established in this study that ITU-R and Kasarawa have the best predictions for the climatic condition there. The observation has additional relevance because it is supported by the ITU-2003 R recommendation for the radio communication sector, which calls for a 99.99% availability percentage for quality of service. Accordingly, it will be anticipated that an additional fade margin of roughly 0.8 dB must be made to account for amplitude scintillation in the area. The data from this study will aid in determining the region's required antenna performance and size for satellite communication links to reduce fade.

Keywords: Troposhere, Scintillation, Models, Tropical, Mowe

1. Introduction

Most weather systems, dynamics, convection, turbulence, and clouds are found in the troposphere, the lowermost and most unstable layer of the atmosphere. 99% of the water vapor in the atmosphere is found in the troposphere, where concentrations change with latitudinal position (Willoughby, 2023). The troposphere's height fluctuates with altitude, being higher over warmer regions and lower over colder regions (Wallace and Hobbs, 2006.)

The effectiveness of communication systems is continuously hampered by the impact of the earth's atmosphere on electromagnetic wave propagation in space and the earth (Sanyaolu et al, 2020). A signal that suddenly changes in amplitude and phase is said to scintillate. Scintillation occurs when a signal passes through an area with fast changes in the dielectric properties in both space and time (Gibson, 2002). Scintillation is one of the processes that cause signal deterioration as it travels through the atmosphere of the earth. Since there is a need for extra bandwidth owing to the overcrowding on the lower frequency bands such as C and Ku bands, there is more focus on tropospheric scintillation (Dairo, et al., 2020). Tropospheric scintillation, an occurrence that causes millimeter radio waves in satellite communication systems to rapidly fluctuate in size and phase, and tends to have an impact on higher-frequency bands

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(Agunlejika, 2009; Akhondi, 2015). Rapid changes in the refractive index along the journey will cause fluctuations in the signal level received when the signal comes into contact with turbulence in the atmosphere (Mandeep et al, 2008; 2011). Scintillations are these erratic fluctuations that often revolve around the mean signal level (Ojo and Olurotimi, 2014).

Specifically, there are two types of scintillations namely Ionospheric scintillation and tropospheric scintillation (Timothy et al., 2003). Due to anomalies in the refractive index, tropospheric scintillation is the scintillation that affects the troposphere layer (Marzano and D'Auria 1998; Dao et al., 2013).

Season and daily weather conditions have an impact on tropospheric scintillation. Strong cloud turbulence is the principal cause of substantial scintillation effects on satellite communications (Dairo and Kolawole, 2017). Rapid amplitude and phase changes in the received signal are the outcome, and they have an impact on radio communications in earth orbit. The intensity of tropospheric scintillation has been observed to increase with carrier frequency over 10 GHz and to decrease with antenna size and elevation angle (Ojo and Falodun, 2012; Abdul, et al, 2013).

It is well known that various climatic variables, such as temperature, humidity, and differences in the refractive indices of the propagation media, have a substantial link with troposphere scintillation. The highest scintillation amplitudes for a given path are produced by high temperatures and humidity (Theerapatpaiboon, et., 2004). High humidity, constant temperature, and significant rainfall are characteristics of tropical climates, and as a result, they have larger scintillation amplitude than temperate ones (Adediji, and Ajewole, 2010).

Mowe, Nigeria has a humid tropical climate, with dry and rainy seasons that, respectively, take place between November and February, and March and October each year. High temperatures and humidity are characteristics of the dry season, whereas the rainy season is marked by an abundance of all types of precipitation. Additionally, the area is known for having high annual temperatures and humidity levels (Adediji et al, 2015).

Tropospheric scintillation has been considered to be most prevalent around noon especially when cumulus and cumulonimbus clouds are present along the propagation path which has been attributed to the non-uniform small-scale refractive index majorly caused by the disorder of aforementioned parameters in the troposphere (Omotosho et al, 2016) and usually occur in the summer afternoon (Mandeep and Islam, 2012). Tropospheric scintillation, which affects radio wave transmission whether there is rain or not (clear air or sky), is a severe issue that reduces the system's availability and dependability. Signals traveling through the atmosphere while fog, rain, water vapor, and oxygen are present exhibit this difficult degradation (Sanyaolu et al, 2020).

The signal-to-noise ratio suffers noticeably (up to several dB), and their effects worsen as the operating frequency rises. Scintillation effects, particularly those at high frequency and low elevation angles, must be carefully accounted for during link budgeting to obtain systems with low fade margins.

Omotosho (2016) established that specifically at percentages of exceedance above 1% unavailability which is about 87.5 hours of signal unavailability in an average year, measurements have shown that scintillation-induced fading at low elevation angles exceeds attenuation caused by rain. Meanwhile, A modified version of the ITU-R tropospheric scintillation model, presented by Famoriji (2014), is applicable to the frequency spectrum of a laser beam used in a free-space optical communication system.

Work on experimental analysis and model comparison of tropospheric scintillation was done by Ojo (2018). Four models; Otung , Karasawa, Van de Kamp, and, ITU-R, were contrasted with measured scintillation data acquired while traveling over a tropical climate in Nigeria. They found that, for Akure, the Karasawa model provided the most accurate predictions of scintillation intensity.

In Nigeria, scintillation-related scientific projects have been investigated by other researchers such as: (Agunlejika, et al., 2007; Adediji and Ajewole, 2008; Adebo, and Akindugbagbe, 2019; Ashidi, et al, 2019). Many potential prediction models have been the result of these investigations and others. There has also been published evidence of the relationship between frequency, antenna diameter, elevation angle, climatology of locations as the communication links' factors, Nevertheless, there is still much that has to be learned about tropospheric scintillation in other parts of the country, such as Mowe.

The objective of this research is to evaluate the tropospheric scintillation at Mowe, a tropical area in Nigeria. Based on the characterization and analysis of the time series EUTELSAT-36B Ku-band satellite signal, the estimation of the level of troposphere scintillation that could be experienced through Earth-space links in this location and comparisons with the current scintillation prediction models.

2. Method

Temperature, pressure, and relative humidity are only a few of the meteorological variables that were used in this study. The Tropospheric Data Acquisition Network (TRODAN) weather station, which is located in the extension of Redeemer's University's Physics department in Mowe (Lat 6.80º N, Lon 3.40º E), was used to gather data for the full year, from January 2014 to December 2014. Selecting the 13 Ghz Ku band of the Eutelsat satellite link with the elevation angle of 60^0.

The tropospheric scintillation phenomenon variations were separated from the tangle of fluctuations in the raw data using digital processing techniques. Some of the current scintillation prediction models were compared to the measured ground data (x).

Three models—the ITU-R, Otung, and Karasawa models (Karasawa, 1988a,1988b; Otung, 1996; ITU-R P.618-10, 2009) are taken into consideration in this study to estimate the variance of signal log-amplitude. The models represent the particular climatic conditions of the site and are based on monthly averages of the relative humidity, H (%), water vapour (e) and temperature, t (°C).

1.1. Prediction models

2.1.1 ITU-R Model

Based on observations, theoretical frequency dependency, and aperture averaging effects, the ITU-R P.618-10, 2009 scintillation model estimates the average scintillation intensity as the standard deviation of the deviation of signal fluctuation due to scintillation, asi over a minimum period of one month. The cumulative distribution of the fade tropospheric scintillation is represented by the model as follows:

$$\sigma_{pre} = \frac{\sigma_{ref} f^{\frac{7}{12}} g(x)}{\sin \theta^{1.2}} \tag{1}$$

where σ_{pre} is the standard deviation, σ_{ref} is the standard deviation of reference signal amplitude, and $g(x)$ is the antenna averaging factor.

$$\sigma_{ref} = 3.6\ X\ 10^{-3} + N_{wet}\ X\ 10^{-4}\ \text{dB} \tag{2}$$

$$\mathrm{N_{wet}} = 3.73\ x\ 10^5 \frac{e}{T^2} \tag{3}$$

e, the water vapour pressure, is calculated by

$$e = \frac{6.112H}{100} \exp\left(\frac{17.502t}{t+240.97}\right) \tag{4}$$

H (%) denotes relative humidity, and t (^{0}C) denotes air temperature.

The antenna averaging factor $g(x)$ is expressed as:

$$g(x) = \sqrt{3.86(x^2+1)} X\ sin\left[\frac{11}{6} \arctan\left(\frac{1}{x}\right)\right] - 0.78x^{\frac{5}{6}} \tag{5}$$

$$x = 1.222 \frac{D^2 f_{eff}}{L} \tag{6}$$

$$D_{eff} = \sqrt{\eta} D \quad \text{m} \tag{8}$$

where ɳ is the antenna efficiency and D is the earth station antenna diameter

$$L = \frac{2h_l}{\sqrt{sin^2\,\theta + 2.35\ X\ 10^{-4}} + sin\theta} \tag{9}$$

$$h_l = 1000\ m$$

The time percentage factor is calculated as

$$a(p) = -0.061(log\ p) + 0.072\ (\log p) - 1.71(\log p) + 3\ (0.01\%) < p < 50.0\% \tag{10}$$

where p is the percentage of time.

The fade depth of the scintillation is therefore expressed as

$$A(p) = a(p).\,\sigma_{pre}\ \text{dB} \tag{11}$$

2.1.2 Otung model

Otung (1996) researched tropospheric amplitude scintillation prediction. The worst-month cumulative distribution of scintillation fades and its annual distribution were both given. This model is a modified version of the ITU-R Model: it is expressed as:

$$a(p) = 3.6191exp\left[\frac{9.501X\ 10^{-4}}{p} - (0.40454 + 0.00285p)\ln(p)\right] \tag{12}$$

where p is the percentage of the time.

2.1.3 Kasarawa Model

The Karasawa (1988) model for the predicted scintillation intensity is given as:

$$a(p) = -0.061(log\ p)^3 + 0.072\ (\log P\ )^2 - 1.71(\log p) + 3.0 \tag{13}$$

where p is the percentage of the time.

Based on the fractional percentage error (E), each tropospheric scintillation's performance was evaluated where E is given as:

$$E = \left(\frac{x_{predicted} - x_{measured}}{x_{measured}}\right) X\ 100 \tag{14}$$

Calculating the root-mean-square De (RMS) requires the mean error (μe), and standard deviation, (σe). Its definition is as follows:

$$D_e = [(\mu_e)^2 + {\sigma_e}^2]^{1/2} \tag{15}$$

3. Results and Discussion

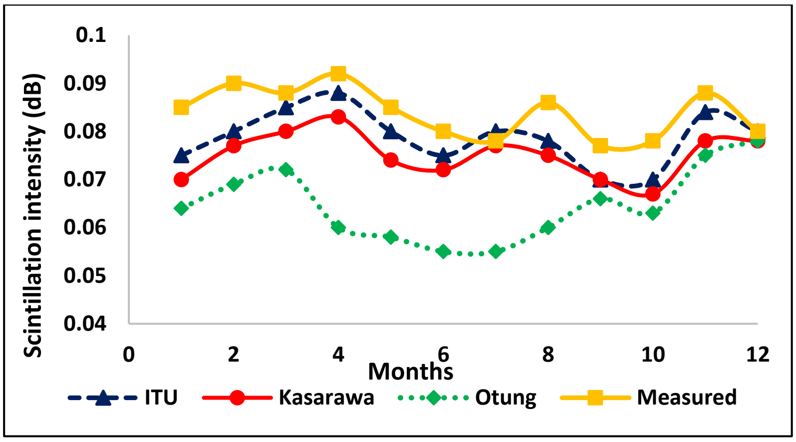

Figure 1: Scintillation intensity comparison between measured data and prediction models

Figure 1 compares the measured scintillation intensity to the three already in-use models. For the duration under consideration, the result has been presented for each of the months. Although it is clear that every model understates the scintillation intensity, the ITU and Kasarawa models do not deviate noticeably from the observations. In comparison to Kasarawa and ITU, the Otung model deviations are more significant. The best forecast comes from the ITU-R model, followed by the Kasarawa model. Scintillation was seen to be at its peak in April and August with 0.95 dB and 0.88 dB respectively. Wet seasons typically have higher mean values of scintillation intensity than dry ones. The wet component of the troposphere's refractivity, Nwet, nevertheless affects the average monthly scintillation intensity. The value peaks at 0.08 dB in October and then drops to 0.070 dB in July.

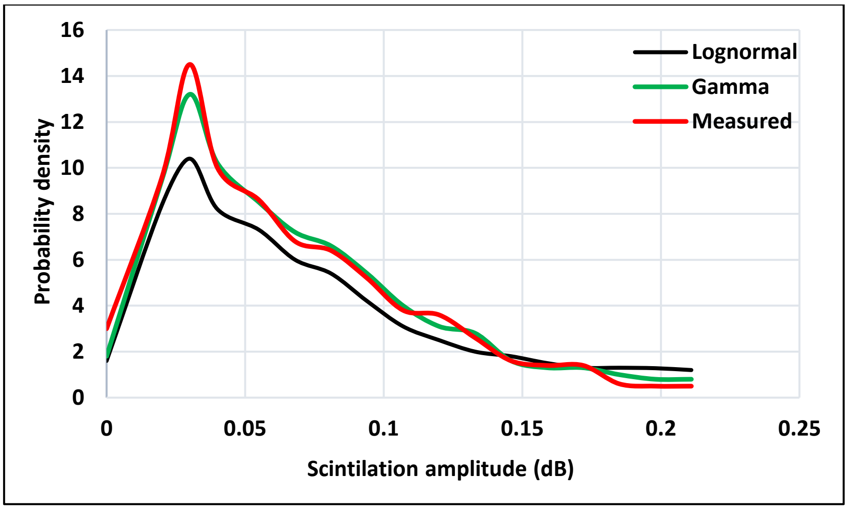

Figure 2. comparison of the measured scintillation amplitude with the probability densities of lognormal and gamma

Figure 2 depicts the long-term probability density of scintillation amplitude for a period of twelve months, with identical forms for the lognormal and gamma distributions. In comparison to a Gaussian distribution, the probability density function has a wider lower kurtosis, and positive skew for lengthy observational experimental data. The strongest intensities show skewness, which is also typical in the absence of rain since cumulus clouds can create a burst of powerful scintillation when they cross a path. Dry scintillation performed well under the Karasawa et al. (1988b) gamma model, and the lognormal deviates from the scintillation intensity measured by the probability density function.

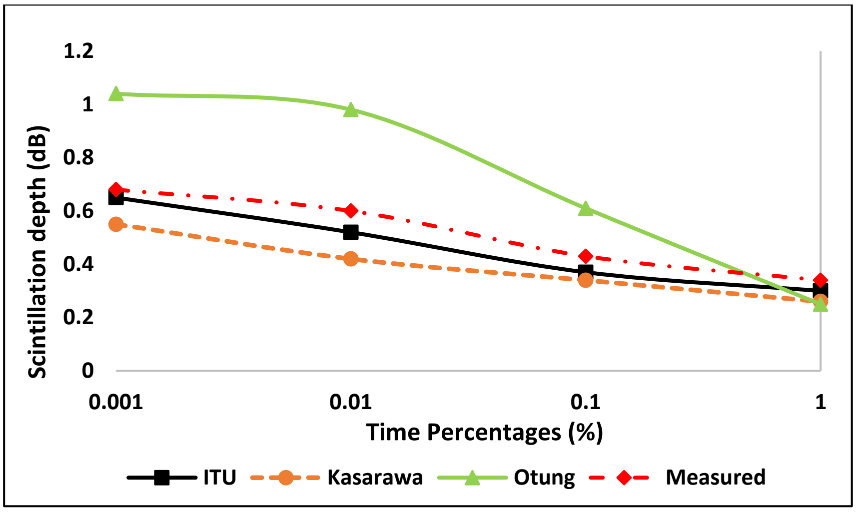

Figure 3: Scintillation fading depth comparison between measured data and prediction models

Figure 3 also analyses how well the scintillation prediction models performed for the scintillation depth of fade. Every model's scintillation intensity is determined for a specific period of time, ranging from 0.01% to 1% of the year. The figure shows the annual percentage exceedance of scintillation fade for Mowe, based on the scintillation amplitude prediction model for the time percentage exceedance between 1% and 0.001% in this study. From the curves, it can be seen that for the ITU-R model, the corresponding amplitudes for exceedances of 1%, 0.1%, 0.01%, and 0.001% are approximately 0.34 dB, 0.42 dB, 0.52 dB, and 0.76 dB respectively. It also shows that there is almost complete symmetry between measured and ITU-R models for fading scintillation. The similarity of the plot shape also indicated consistency in the way the ITUR and Kasarawa models performed in comparison to the measured. The observation has additional relevance because it is supported by the ITU-2003 R recommendation for the radio communication sector, which calls for a 99.99% availability percentage for quality of service. Accordingly, it will be anticipated that an additional fade margin of roughly 0.8 dB must be made to account for amplitude scintillation over this area.

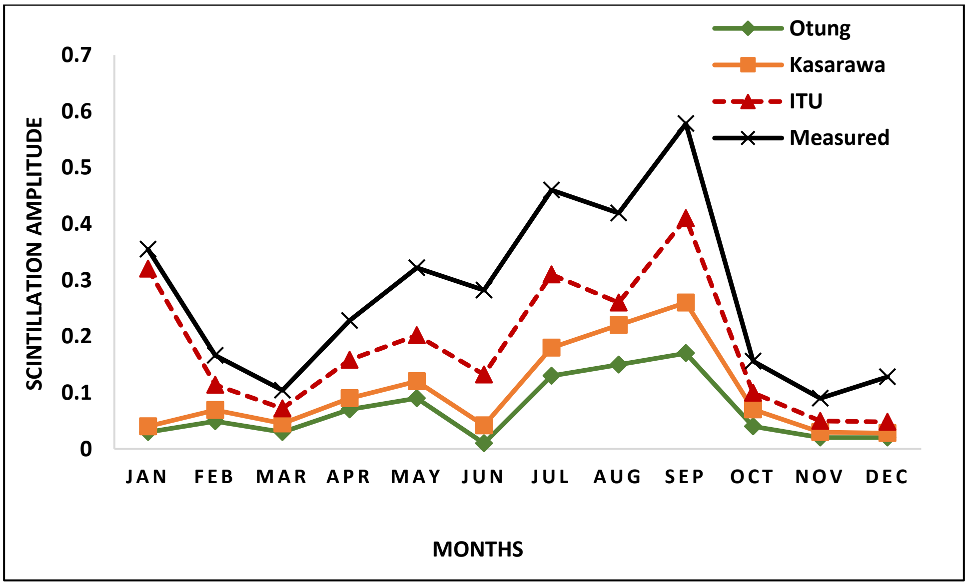

Figure 4. Comparison of predicted with the measured data for the fade scintillation at 0.01%

For the typical measurement period, predictions of the monthly scintillation amplitude are calculated at 0.01% of the time. A statistical parameter that describes the degree of the association between two variables was introduced as a correlation in the study. This was contrasted with the correlation results obtained using the measured tropospheric scintillation data and each forecast model. The fade scintillation equation is provided by the ITU-R, Otung, and, Karasawa, models to determine the scintillation amplitude.

In general, wet seasons have higher mean values for scintillation intensity than dry ones. The moist term of the troposphere refractivity continues to be a factor in the mean monthly scintillation intensity. The measured signal fading scintillation amplitude values and the Karasawa model are in roughly good agreement during the whole predicted % time. This is due to the fact that the model was created using data that was gathered during the dry season, where there was a strong correlation between the scintillation characteristics and the water vapour contribution effect on the refractivity index determined from the data on ground temperature and local humidity. Higher elevation angles and temperature were used in the model's development. The ITU model is modeled after the Karasawa model, however, the Otung model deviates greatly from other models, including the measured scintillation fading in this location.

Table 1: Comparison of the scintillation intensity percentage errors for every month over the typical year

	MODELS		
Months	**ITU**	**Kasarawa**	**Otung**
January	15.2	16.12	41.21
February	10.62	11.22	37.43
March	4.20	18.41	30.15
April	2.80	23.11	28.21
May	6.50	16.10	35.30
June	14.32	20.24	39.15
July	21.31	18.69	40.65
August	20.28	21.22	34.83
September	21.56	25.36	30.81
October	20.30	20.21	25.60
November	22.63	12.71	28.24
December	22.81	28.44	35.10

Table 4: The measuring site's overall averages, standard deviations, and RMS values over the typical year

	MODELS		
	ITU	**Kasarawa**	**Otung**
STD	7.41	10.34	11.03
MEAN	-20.65	-36.52	-50.68
RMS	26.7	37.45	51.28

The percentage relative error between the projected value and the measured value is computed using Mandeep et al., (2011) with reference to Tables 1 and Table 2. The RMS error rate for the best prediction between the analysed time frame is 26.7% for the ITU-R model, 37.45% for the second-best prediction from the Karasawa model, and 21.28% for the Otung model. In Table 1, the percentage error rate for ITU R ranges from 15 % to 22 % while that of Kasarawa ranges from 16 % to 28 %. The percentages error of Otung was seen to be the highest as it ranges between 35% to 41 %. ITU R and Kasarawa are still the best in predicting scintillation in this tropical area under consideration.

4. Conclusion

Models for forecasting the signal log-amplitude cumulative distribution and the scintillation intensity of tropospheric scintillation have both been investigated. The need for a better understanding of propagation degradation in satellite communication systems led to the development of this study on tropospheric scintillation intensity. Improved system design can result from greater understanding. The ITU-R, Otung, and Kasarawa models are employed to study how microwave radiations interact with turbulent medium and to also suggest which model best fits the region under consideration. The measurement from the earth station demonstrated that for Mowe's tropical environment, the ITU-R model provides the most accurate forecasts of tropospheric scintillation intensity.

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