Ku-Band scintillation over Akure, Nigeria

Ayodeji Gabriel Ashidi
Department of Physics, Federal University of Technology, PMB 704, Akure, Nigeria
E-mail: agashidi@futa.edu.ng

Keywords: scintillation intensity, peak-to-peak amplitude, radio beacons

Abstract
Relationship between scintillation intensity ($\sigma_\chi$) and peak-to-peak amplitude ($\chi_{pp}$) is important for mitigating scintillation effects on any communication link. This study employs linear, logarithmic and polynomial functions for fitting $\sigma_\chi$ and $\chi_{pp}$ in order to determine the best model for describing the variation of the former with the latter. It also examines the frequency of occurrence of scintillation intensity and the suitable probability density function for characterizing its distribution. Data used spanned 24 months, and were obtained from measurement of EUTELSAT W4/W7 satellite beacons on 12.245 GHz frequency, 1 s integration time and 53° elevation angle, at the Department of Physics, Federal University of Technology, Akure (07°17’N, 005°18’E, 358 m) Nigeria. Results show that logarithmic function performed best in modelling $\chi_{pp}$ from $\sigma_\chi$ as indicated by high coefficient of determination and minimal root mean square error values. Strong scintillation events ($\sigma_\chi > 0.5$) were also found to occur less frequently as sample interval increased. Lastly, lognormal, gamma and generalised extreme value (GEV) models were found suitable for describing $\sigma_\chi$ distribution.

1. Introduction

Radiowaves propagating through the atmosphere do experience many degrading effects, among which is scintillation; a phenomenon that is often perceived as fast fluctuations in radiowaves parameters (amplitude, phase, angle and time of arrival, etc). At Ku-band frequencies and above, scintillation originates in the troposphere due to variation in temperature, pressure, and water vapor content, which cause perturbations in radio refractivity [1]. Also, scintillation imposes a significant degree of degradation on some satellite links such as those operating above ultrahigh frequency (UHF), low angles of elevation and outage margins, as well as very small aperture terminals (VSATs). Similarly, systems with low availability and those operating in low-rainfall region are susceptible to scintillation effects [2, 3]. Two important measures of scintillation phenomenon on any communication system include (i) scintillation intensity ($\sigma_\chi$), and (ii) peak-to-peak amplitude ($\chi_{pp}$). The former is the standard deviation of scintillation amplitude $\chi$ over a short measurement interval, while the latter is the sum of maximum enhancement ($\chi_+$) and the modulus of maximum fade ($\chi_-$) within the same sampling interval. The relationship between this two is important for developing effective fade mitigation architecture, just as a strong positive correlation between them is expected [2–4].

Limited studies have been conducted on scintillation in Nigeria, some of which include [5–7], and this current work attempts to expand the scope by determining a simple empirical relation between two measures used in characterizing scintillation, as well as the frequency of occurrence of its intensity.

1.1. Quantification of scintillation
Early studies on scintillation measurement employed S4 index and SI index for its computation. They are expressed in equations (1) and (2) respectively [2]:

$$S4 = \sqrt{\overline{A^2} - (\overline{A})^2}/(\overline{A})^2$$

(1)

$$SI = (A_{\text{max}} - A_{\text{min}})/(A_{\text{max}} + A_{\text{min}})$$

(2)
where $A$ represents the received signal amplitude averaged over a short time interval during which prevailing weather condition is approximately constant.

Scintillation is considered weak or strong depending on whether $S4/SI$ value is less or greater than 0.5 respectively [2, 8]. More recently, however, scintillation amplitude, $\chi$, is obtained from relative signal level, $A$, by implementing a moving average algorithm. Prior to this, $A$ must have been passed through a Butterworth digital high-pass filter of order six [3, 4]. The moving average output is expressed in equation (3) as:

$$\chi(n) = 20 \log_{10}[A(n)/\bar{A}(n)]$$  \hspace{1cm} (3)$$

The cutoff frequency, $f_c$, of the filter is dependent on the number of averaging points, $M$, and integration time, $\Delta t$, as expressed in equation (4) [4, 9]:

$$f_c = \frac{0.443}{M\Delta t}$$  \hspace{1cm} (4)$$

Scintillation intensity, $\sigma_\chi$, was thereafter computed from amplitude, $\chi$, over seven sampling intervals $i = 1, 5, 10, 15, 20, 30$ and 60 min using equation (5). While peak-to-peak amplitude, $\chi_{pp}$, was obtained from equation (6) in the same intervals [2].

$$\sigma_\chi = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (\chi_i - \bar{\chi})^2 \right]^{1/2}$$  \hspace{1cm} (5)$$

$$\chi_{pp} = \chi_{max} - \chi_{min}$$  \hspace{1cm} (6)$$

2. Data and methodology

Location of study is the Department of Physics, Federal University of Technology, Akure, Nigeria ($07^\circ 17'N, 005^\circ 18'E, 358$ m). Measurement of radio beacons on EUTELSAT W4/W7 at frequency 12.245 GHz, with 90 cm parabolic antenna and 53°E elevation using Tektronix Y400 NetTek spectrum analyzer was carried out. Beacon signal samples are recorded continuously at one second integration time. Data spanning 24 months (covering 2017 and 2018) were employed for the study. The $\chi_{pp}$ data for one year were grouped into bins, based on the corresponding $\sigma_\chi$ value, in 0.1 dB sizes, between 0 and maximum $\sigma_\chi$ value for that interval. For each group, the intensity value is equal to the center of the bin size, while the peak-to-peak amplitude value is equal to the average $\chi_{pp}$ value of that group [2].

3. Results and discussion

3.1. Variation of intensity with amplitude

Table 1 shows a typical distribution of scintillation intensity ($\sigma$) and corresponding peak-to-peak amplitude ($\chi_{pp}$) at different measurement interval $i$ for the year 2017. In order to best describe the relationship between the peak-to-peak

| $\sigma_\chi$ (dB) | $\chi_{pp}$ at different intervals |
|-------------------|----------------------------------|
| 0.05              | 0.24 0.20 0.22 0.36 0.37 0.39 —  |
| 0.15              | 0.98 1.04 1.08 1.12 1.13 1.19 1.18 |
| 0.25              | 1.06 1.04 1.32 1.30 1.42 1.35 1.34 |
| 0.35              | 1.47 1.59 1.73 1.87 1.89 2.00 2.01 |
| 0.45              | 1.77 2.03 2.46 2.36 2.59 2.21 2.10 |
| 0.55              | 2.26 2.05 2.34 2.38 2.50 2.54 2.08 |
| 0.65              | 2.50 2.53 2.43 2.58 2.53 2.66 2.46 |
| 0.75              | 2.46 2.48 2.48 2.56 2.57 2.68 2.42 |
| 0.85              | 2.64 2.57 2.54 2.77 2.69 2.85 2.75 |
| 0.95              | 2.75 2.71 2.65 2.81 2.75 2.92 2.81 |
| 1.05              | 2.75 2.70 2.75 2.81 2.72 2.88 2.79 |
| 1.15              | 2.70 2.70 2.75 2.77 2.72 2.76 3.01 |
| 1.25              | 2.80 2.83 2.91 2.92 2.87 3.14 —   |
| 1.35              | 2.98 3.04 3.07 — 3.19 —  —   —   |
| 1.45              | 3.22 3.10 —  —  —  —  —  —  —   |
amplitude and scintillation intensity, as well as determine the best equation to represent their relationship, attempt was made to fit the parameters of $\sigma$ and $\chi_{pp}$ using three different models—linear, logarithmic and polynomial (order 2). A plot of $\chi_{pp}$ versus $\sigma$ for the 1 min measurement interval is shown in figures 1(a) to (c). A sample equation and

**Figure 1.** (a) linear; (b) logarithmic and (c) quadratic relationship between peak-to-peak amplitude ($\chi_{pp}$) and scintillation intensity ($\sigma$).
χ corresponds to weak and strong scintillation events respectively. The lognormal model is recommended for use over the polynomial model because the former offers superior R² values at other measurement intervals than the latter. Nevertheless, all the models established that a very strong relationship exists between σχ and χpp as well as scintillation intensity (σ). Also, prediction of χpp in the shorter interval (1–15 min) from the interval s σχ, and vice versa, can be done with better accuracy than the longer measurement intervals (above 15 min).

The developed prediction models in each of the 7 sampling intervals were validated against measured peak-to-peak scintillation amplitude (χpp) and scintillation intensity (σχ) of 2018. Figures 2(a) to (c) show the plot of the predicted against the measured scintillation peak-to-peak amplitude for linear logarithmic and polynomial models respectively. Table 2 also shows the coefficient of determination (R^2) values for the performance evaluation of the validation and error analysis of each model. The superiority in performance of the lognormal and polynomial models over the linear model is once again established through stronger coefficients of determination (R^2*) values and lower error margins. The core responsibility of σχ is to provide an insight into the degree of fluctuations above and below the average level of the received signal amplitude over a measurement interval [2, 4, 8, 10]. This provides the system engineer with a tool to estimate and mitigate the impact of scintillation-induced fade, thus making the derived empirical models very important. Also, σχ = 0 implies that each signal sample received within the sampling interval are of equal value. Such scenario is practically impossible except the receiver unit’s quantization interval is excessively large. Small and large values of σχ correspond to weak and strong scintillation events respectively [2]. Also, empty groups of χpp that correspond to large values of σχ with increasing sampling interval (as shown in table 1) implies that strong scintillation is generally a short-lived phenomenon [2–4]. Also, χpp is further important for quantifying the impact of scintillation on communication system if symmetry in the distribution of its amplitude fluctuations is assumed.

### Table 2. Regression and validation statistics for linear: logarithmic: and quadratic relationships between peak-to-peak amplitude (χpp) and scintillation intensity (σ).

| Distribution | Model | \(a\) | \(b\) | \(R^2\) | \(R^2*\) | RMSE |
|--------------|-------|-------|-------|--------|--------|------|
| Linear \((\chi_{pp} = a\sigma + b)\) | Int. 1 | 2.067 | 0.685 | 0.871 | 0.890 | 0.305 |
| | 5 | 1.917 | 0.907 | 0.824 | 0.836 | 0.372 |
| | 10 | 1.963 | 0.979 | 0.782 | 0.802 | 0.402 |
| | 15 | 0.782 | 0.968 | 0.779 | 0.749 | 1.104 |
| | 20 | 1.893 | 1.118 | 0.743 | 0.752 | 0.454 |
| | 30 | 2.209 | 1.008 | 0.738 | 0.785 | 0.460 |
| | 60 | 1.977 | 1.176 | 0.737 | 0.857 | 0.385 |
| Logarithmic \((\chi_{pp} = a\ln(\sigma) + b)\) | Int. 1 | 1.036 | 2.828 | 0.961 | 0.935 | 0.241 |
| | 5 | 0.998 | 2.915 | 0.981 | 0.966 | 0.169 |
| | 10 | 0.981 | 2.982 | 0.971 | 0.966 | 0.164 |
| | 15 | 1.005 | 3.078 | 0.976 | 0.969 | 0.164 |
| | 20 | 0.963 | 3.058 | 0.957 | 0.953 | 0.196 |
| | 30 | 1.029 | 3.175 | 0.975 | 0.976 | 0.145 |
| | 60 | 1.048 | 3.078 | 0.966 | 0.984 | 0.124 |
| Polynomial \((\chi_{pp} = a\sigma^2 + b\sigma + c)\) | Int. 1 | −1.731 | 4.663 | 0.034 | 0.961 | 0.961 | 0.213 |
| | 5 | −2.078 | 5.034 | 0.126 | 0.966 | 0.987 | 0.175 |
| | 10 | −2.471 | 5.424 | 0.170 | 0.941 | 0.939 | 0.244 |
| | 15 | −3.216 | 6.327 | 0.059 | 0.972 | 0.968 | 0.309 |
| | 20 | −2.633 | 5.583 | 0.235 | 0.927 | 0.915 | 0.318 |
| | 30 | −3.157 | 6.312 | 0.117 | 0.965 | 0.852 | 0.517 |
| | 60 | −1.537 | 3.976 | 0.681 | 0.959 | 0.593 | 0.663 |
This implies that scintillation fade depth and enhancement are equal to $0.5 \chi_{pp}$. Models in table 2 therefore serve as means to calculate such important communication link parameter from the more readily measurable scintillation intensity.

Figure 2. Validation of (a) linear; (b) lognormal; (c) Polynomial equations for predicting peak-to-peak scintillation amplitude for selected measurement intervals. Also shown in dotted lines are the linear regression models for each interval.
3.2. Frequency of occurrence of scintillation intensity

Figures 3 (a) to (c) give typical discrete sequence plot of the frequency of occurrence of scintillation intensity ($\sigma_X$) for 1, 30 and 60 min respectively. Although the frequency curves of all measurement intervals have the same
Figure 4. Annual probability density function of scintillation intensity fitted to lognormal, gamma and GEV pdfs for (a) 1; (b) 20; (c) 60 min interval.
pattern, it is important to note how stronger intensities continued to record fewer strong scintillation events as the measurement interval increased. The value of the maximum observed intensity also decreased notably with increasing sampling interval. All these point to the fact that strong scintillations are short-lived phenomena showing significant dependence on the length of sampling interval.

This trend was also reported in previous research, notably [8–10] to mention just a few. From the analysis of frequency of occurrence of scintillation intensity, it becomes obvious that ‘strong scintillations are short-lived phenomena, which tend to occur in bursts lasting for only a few minutes at the most’ [2, 4]. Also, similarity in the frequency of occurrence curves of $\sigma_\chi$ for different sampling intervals suggest that similar distribution function is required for its characterization [2]. This was demonstrated by plotting the pdf of scintillation intensity and fitting same to lognormal, gamma and generalized extreme value (GEV) models, as shown in figure 4. It can also be seen that the shape, scale and location parameters of the models reflect dependence on sampling/measuring intervals as the height of the pdf curves were seen to decrease steadily as measurement interval increased. This is due to the fact that fewer strong scintillation ($\sigma > 0.5$) events remained in the dataset for each successive measurement interval, thereby affecting the ratio of mean to standard deviation and compelling the continuous drop in the height of the pdf curves.

4. Conclusion

This work has examined the variation of scintillation intensity with peak-to-peak amplitude as well as the frequency of occurrence of scintillation, and its distribution characteristics. Of the three models employed, the logarithmic model performed best, compared to linear and polynomial models, for estimating $\chi_{pp}$ from $\sigma_\chi$; returning highest $R^2$ and least RMS error values. Coefficient of validation also reinforced the suitability of the three models. Similarly, bulk of the occurrence of scintillation intensity fall within the weak scintillation regime, implying that occasional-use satellite services can leverage on this to avoid the few periods of strong scintillation activities. Similarity in the shape of the discrete sequence plots of $\sigma_\chi$ indicates that uniform pdf is adequate for characterizing $\sigma_\chi$ irrespective of the length of sampling interval. The models developed in this study provide a means of calculating $\chi_{pp}$ which is a useful communication link parameter, from the more readily measurable $\sigma_\chi$.

Acknowledgments

The author is grateful to the communication research group, Department of Physics, Federal University of Technology, Akure.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Ayodeji Gabriel Ashidi @ https://orcid.org/0000-0002-5864-4250

References

[1] Ippolito Louis J 1989 Propagation Effects Handbook for Satellite Systems Design: A Summary of Propagation Impairments on 10 to 100 GHz Satellite Links with Techniques for System Design 1082 (USA: National Aeronautics and Space Administration, Scientific and Technical)
[2] Otung I E 1995 Amplitude scintillation of Ka-band satellite signals Doctoral Dissertation University of Surrey
[3] Otung I E, Al-Nuaimi M O and Evans B G 1998 Extracting scintillations from satellite beacon propagation data IEEE Trans. Antennas Propag. 46 1580–1
[4] Karasawa Y, Yamada M and Allnutt J E 1988 A new prediction method for tropospheric scintillation on Earth-space paths IEEE Transactions on Antennas and Propagation 36 1608–14
[5] Ashidi A G, Ojo I S, Adediji A T and Ajewole M O 2017 Characterization of Ku-band Amplitude Scintillation on Earth–Space Path over Akure, SW Nigeria XXXIXth General Assembly and Scientific Symposium, URSI (Montreal, Canada) (http://ursi.org/proceedings/procGAI7/papers/Paper_F24-5(1888).pdf)
[6] Ashidi A G, Dada J B and Lawal Y B 2020 Spectral analysis of Ku-Band scintillation dataset for satellite communication in a tropical location 2020 Int. Conf. in Mathematics, Computer Engineering and Computer Science (ICMCECS) (Piscataway, NJ) (IEEE) pp 1–5
[7] Adebo B and Akindugbogbe J 2019 Prediction of Tropospheric Scintillation over some Selected Locations in Nigeria Journal of American Science 15 72–7
[8] Ortgies G 1985 Probability density function of amplitude scintillations Electron. Lett. 21 141
[9] Otung I E 1996 Prediction of tropospheric amplitude scintillation on a satellite link IEEE Trans. Antennas Propag. 44 1600–8
[10] Mandeep S J, Syed I S H, Kiyoshi I, Kenji T and Mitsuyoshi I 2006 Analysis of tropospheric scintillation intensity on Earth to space in Malaysia Amer J. App. Sci. 3 2029–32