Statistical Analysis of Tropospheric Scintillation of Satellite Communication Signals using Karasawa and ITU-R Models

O. F. Dairo[1]
Dept. of Physical Sciences
Redeemer's University
Ede, Osun State, Nigeria
[1]dairof@run.edu.ng

L. B. Kolawole[2]
Dept. of Physical Sciences
Redeemer's University
Ede, Osun State, Nigeria
[2]kolawolel@run.edu.ng

***Abstract*—The climatology of the tropics coupled with its deep convective evolution at the equatorial troposphere has continued to draw significant attention to the effects of scintillation on satellite communication signals. Dearth of signal degradation data perceived as scintillation fade depth is pronounced in the tropics. In particular, the effect of tropospheric scintillation on two major satellite providers, namely NigComSat-1R and Eutelsat, were considered. Karasawa and ITU-R statistical models were used. Twelve months data were collected from the Tropospheric Data Acquisition Network stations with geo-spatial coverage representing Nigerian climatic zones. The variability is □9% for both models in the monsoon climate, and □158%–180% in warm semi-arid climate for both ITU-R and Karasawa, respectively. Scintillation intensity was highest in the monsoon climate with values of 1.31dB, 1.51dB and 18.72 dB using ITU-R, and 0.88 dB, 1.06 dB and 27.05 dB using Karasawafor Eutelsat, NigComSat-1R and low elevation satellites.**

Keywords--Microwave, Radio refractivity, Satellite communication, Tropical climate, Tropospheric scintillation.

I. INTRODUCTION

The ubiquitous of satellite communication has extended its applications horizon far beyond intercontinental communication services and satellite television. The new frontiers include augmented reality, remote sensing, atmospheric monitoring and space exploration among others. In fact, a host of defense related applications rely on real-time satellite services. The increasing demand for these services has continued to place a demand on the availability and reliability of satellite communication networks [1], [2]. The advent of satellite communications, pioneered in the C-band, witnessed minimal celestial and atmospheric propagation impairments within 1 GHz – 10 GHz window [3]. However, the high cost of large antenna size (30 m) and other debilitating factors, namely interference, congestion and crowding of the geostationary orbit slots for C-band soon ushered in higher frequency Ku (12 GHz to 18GHz) and Ka (26GHz to 40GHz) bands [4], [5]. The higher frequency regimes offer high bandwidth but with a drawback of atmospheric impairments. With the exception of signal attenuation by gaseous absorption lines, impairments such as scintillation increase dramatically with frequency. The signal degradation is perceived as enhancements and fades of the signal intensity about its mean level at the receiver [6]–[10].

Scintillation is the rapid fluctuations of the received signal parameters, namely amplitude, phase, angle of arrival and polarization due to spatial-temporal irregularities of the transmission medium. The atmosphere, being the medium of propagation of radio waves, is a not a lossless medium. The ionospheric and tropospheric layers of the atmosphere are, in particular, responsible for scintillation. Ionospheric scintillation is caused by localized irregular plasma structures, which results in small-scale fluctuations in refractive index. This scintillation degenerates rapidly at microwave frequencies because as path length or in homogeneity strength increases, the spatial coherence diminishes by multiple self interference, and the peak-to-peak fluctuations slowly begin to decrease [8], [11]. On the other hand, tropospheric scintillation is produced by refractive index fluctuations in the first few kilometers of the troposphere [5]. This is caused by high humidity gradient and temperature inversion layers. The effects are diurnally and seasonally dependent on the local climate.

The pronounced turbulent mixing of air masses [12], random distribution of hydrometeors [13], [14] and unpredictable climatic changes observed in the tropics, particularly pre-monsoon to post-monsoon evolutions of the West African monsoon (WAM) [15]–[17], makes scintillation in this region a major source of concern [4], [5]. The near equatorial latitudes are exposed to high solar insolation and the monsoon circulation. Hence the region is characterized with hot, humid and highly convective climate. The impact of WAM drives forced convection along the West African coast, laden with turbulence and thunderstorms. These processes drive the deep convection over the equatorial tropics.

978-1-5090-6422-9/17/$31.00 ©2017 IEEE

II. Meteorogical Data Collection

The meteorological parameters input used to study the spatiotemporal variability of scintillation intensity in the three major climatic zones over Nigeria were obtained from Tropospheric Data Acquisition Network (TRODAN). The climatic zones, namely monsoon 2009, tropical savanna 2009 and semi-arid 2010-2012 climates are representative of the latitudinal variation from the coastal area in the south to the Sahelian boundary in the north of Nigeria. The following parameters are used to characterize scintillation intensity at Ku band (11 – 15 GHz): the amplitude deviation y in dB; the variance, σ^2, and the standard deviation, σ of the log-amplitude; the predicted variance, σ^2_p, and standard deviationσ_p [18]–[22] for NigComSat-1R and Eutelsat 36B – used by commercial digital satellite television (DSTV) in Africa.

III. Tropospheric Scintillation Prediction Models

Classical scintillation models are statistical models used to calculate either a probability density function or a cumulative distribution function of the log-amplitude of the fluctuation or the variance of the log-amplitude. These models assumed that the short-term probability distribution function of the log-amplitude is Gaussian [18]. They are grouped as scintillation variance prediction models and lognormal scintillation prediction models model or simply lognormal. Among the statistical models [19]–[21] in use for prediction of long-term standard deviation are the Karasawa [22] and International Telecommunication Union – Radio communication (ITU-R) models [23]–[28]. Both prediction models are used to calculate the standard deviation of signal fluctuation due to scintillation using the wet term of the surface radio refractivity, N_{wet} [25],averaged at least over a month, as input parameter. Other scintillations prediction models presented very high error rates and are not suitable for predicting the scintillation intensity in the tropics [23]-[24].

IV. Results and Analysis

A marked variability was observed in the tropospheric scintillation intensity of the climates over Nigeria from the southern monsoon climate through the central tropical savanna to the northern semi-arid climate. The northward migration of the WAM from the coastal region in the south to the Sahelian north can be observed in the trend of variance distribution.

A. Variance of Distribution over Lagos (Geo. 6.5 ºN, 3.5 ºE)

Scintillation fade depth trends observed over Lagos showed that the standard deviation of signal fluctuation due to scintillation were quasi-sinusoidal for both prediction models.

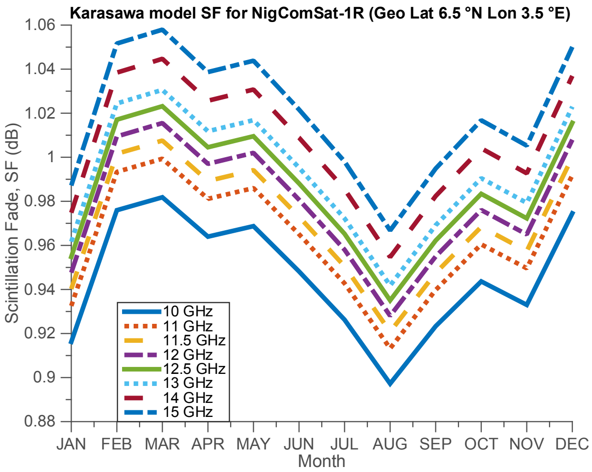

Figure 1. Karasawa NigComSat-1R fade depth in Lagos at θ = 44.2º

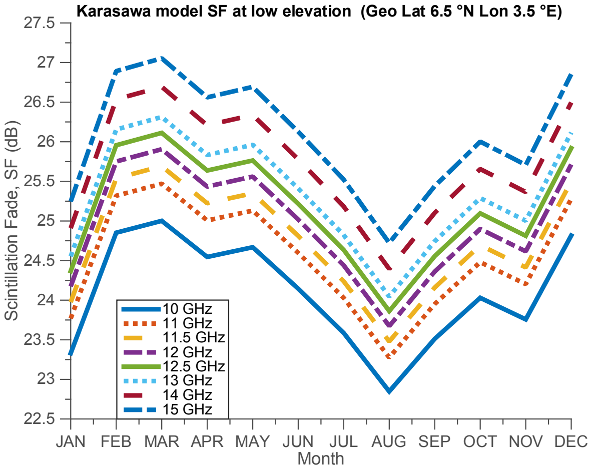

Figure 2. Karasawa scintillation fade depth in Lagos at θ = 5º

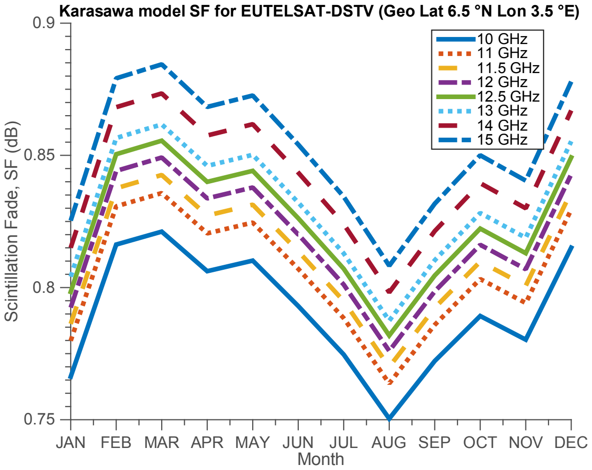

Figure 3. Karasawa Eutelsat fade depth in Lagos at θ = 51.4º

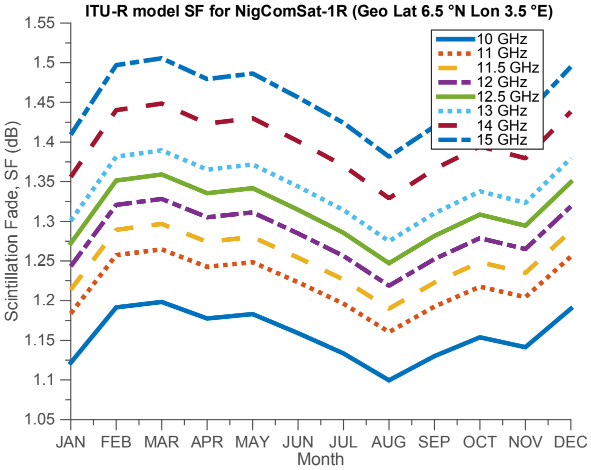

Figure 4. ITU-RNigComSat-1R fade depth in Lagos at θ = 44.2º

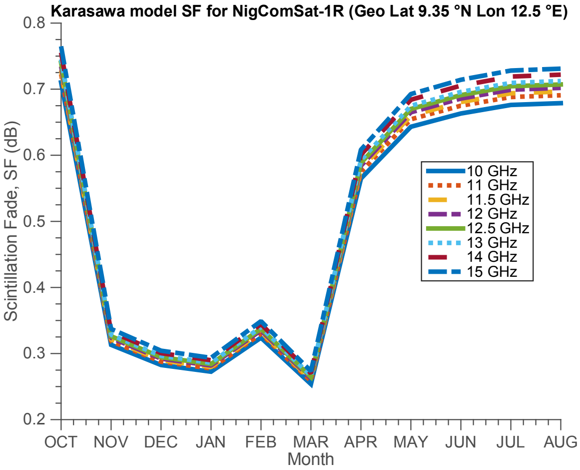

Figure 5. Karasawa NigComSat-1R fade depth in Yola at θ = 53.5º

Both Karasawa and ITU-R models in fig. 1-3 and fig. 4, respectively, agreed that the highest fade depth occurred in March while the lowest values were observed in August. The peak of the fade depth coincides with the spring equinox where the insolation peaks over the equatorial latitudes northward [29]. Hence highest scintillation occurrences were observed during increased solar activity during the equinoxes. It is clear from fig. 1 – 4 that scintillation fade increases with increasing signal frequency. The typical range of variability is 9% for both Karasawa and ITU-R models. Tropospheric scintillation varies across the latitudes [30].However, the highest values were obtained in the monsoon climate and the lowest values in the semi-arid climate, 1.51 dB and 0.22 dB, respectively.

In monsoon climate, at low elevation angle (5º), the scintillation intensity ranges between 22.85 dB − 27.05 dB and 13.58 dB − 18.72 dB for both Karasawa and ITU-R, respectively. However, with the antenna pointing to NigComSat-1R, the scintillation intensity ranges between 0.90 dB − 1.06 dB and 1.1 dB − 1.51 dB for both Karasawa and ITU-R, respectively. Similarly, the scintillation intensity ranges between 0.75 dB − 0.88 dB and 0.96 dB−1.31 dB for both Karasawa and ITU-R, respectively, with the antenna pointing to Eutelsat 36B.

B. Variance of Distribution over Yola (Geo. 9.35 ºN, 12.5 ºE)

The scintillation intensity observed in the warm semi-arid climate of Yola, typical of the southern Sahelian boundaries, showed that the standard deviation of signal variability due to scintillation fade for both Karasawa and ITU-R models in fig. 5-7 and fig. 8, respectively, agreed that the lowest fade depth occurs in March while peak periods were observed around August late monsoon period. The peak period coincides with the increased solar activity, in particular, the onset of the sun’s retreat after June solstice. Consequently, leading to autumn equinox with insolation peaking over the equatorial latitudes as the sun crosses southward [29].

The range of variability is □180% for Karasawa model and □158% for ITU-R model. In warm semi-arid climate, at low elevation angle (5º), the scintillation intensity ranges between 8.03 dB − 24.30 dB and 5.19 dB − 16.89 dB for both Karasawa and ITU-R models, respectively.

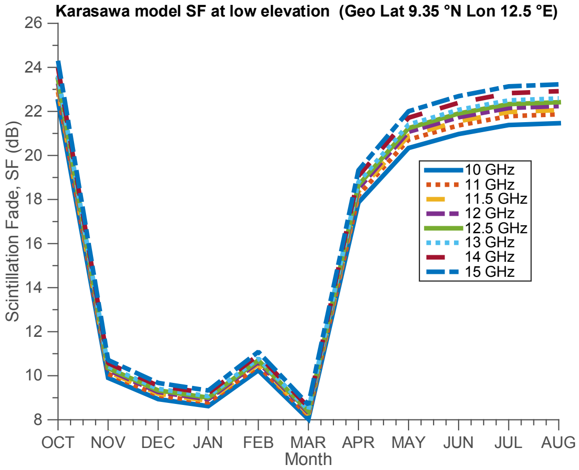

Figure 6. Karasawa fade depth in Yola at θ = 5º

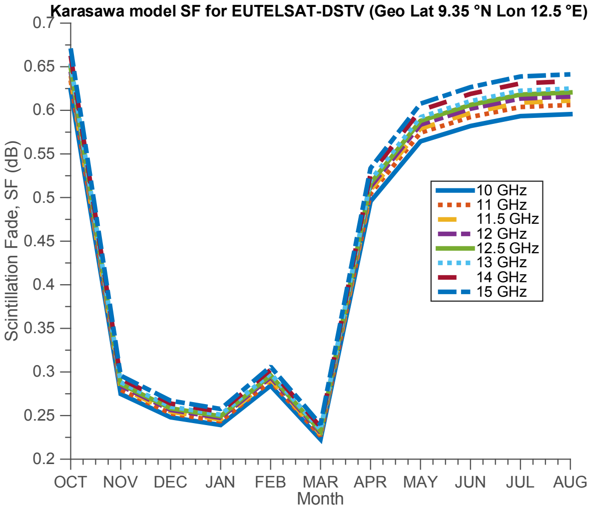

Figure 7. Karasawa Eutelsat-DSTV fade depth in Yola at $\theta = 60.5^{\circ}$

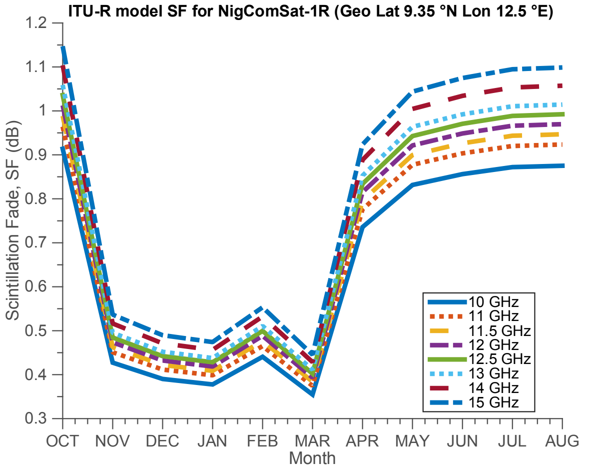

Figure 8. ITU-R NigComSat-1R fade depth in Yola at $\theta = 53.5^{\circ}$

However, with the antenna pointing to NigComSat-1R, the scintillation intensity ranges between 0.25 dB − 0.76 dB and 0.35 dB −1.45 dB for both Karasawa and ITU-R, respectively. Similarly, the scintillation intensity ranges between 0.22 dB − 0.67 dB and 0.32 dB − 1.04 dB for both Karasawa and ITU-R, respectively, with the antenna pointing to Eutelsat 36B.

C. Variability over Abuja (Geo. 8.99 ºN, 7.38 ºE)

The scintillation fade depth observed in Abuja showed cyclic variance of distribution. The scintillation intensity observed over the tropical savanna climate of Abuja, typical of the central Nigeria climate, showed that the standard deviation of signal variability due to scintillation fade depth for both Karasawa and ITU-R models in fig. 9-11 and fig. 12, respectively, agreed that the lowest fade depth occurred in March while the peak periods were observed around August. The peak period of the fade depth marks the onset of the sun's retreat. Consequently, leading to the autumn equinox where the insolation peaks over the equatorial latitudes as the sun crosses the equator southward [29], [30]. Variability ranges between□50%–54% for both ITU-R and Karasawa models.

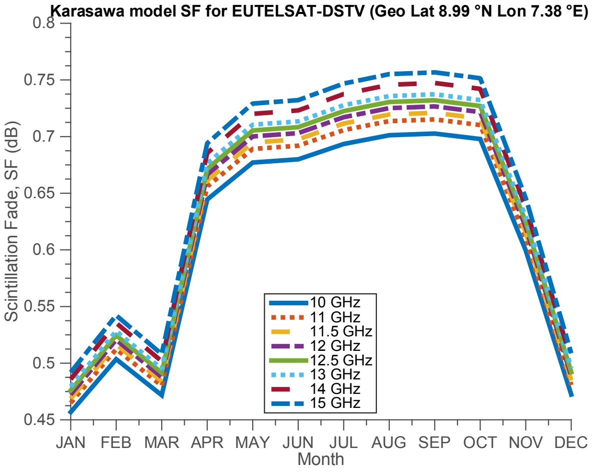

Figure 9. Karasawa Eutelsat-DSTV fade depth in Abuja at $\theta = 55.1^{\circ}$

At elevation of 5°, the scintillation intensity ranges between 15.0dB − 24.97dB and 9.14dB − 13.34dB forKarasawa and ITU-R, respectively. The low elevation scintillation fade depths are comparable to rain attenuation [31]-[32]. However, at 48.1° elevation pointing to NigComSat-1R, the scintillation intensity rangesbetween 0.5318 dB − 0.88 dB and 0.68 dB − 1.29 dB for Karasawa and ITU-R, respectively.Similarly, the scintillation intensity ranges between 0.46 dB − 0.76 dB and 0.61 dB − 1.14 dB for both Karasawa and ITU-R, respectively, with the antenna pointing to Eutelsat 36B.

V. CONCLUSION

The predicted scintillation amplitude deviations as a function of the monthly standard deviation of the signal log-amplitude showed strong dependence on the latitudes and the localclimates. The standard deviation of the log-amplitude is highest in the low latitudes and lowest at high latitudes.

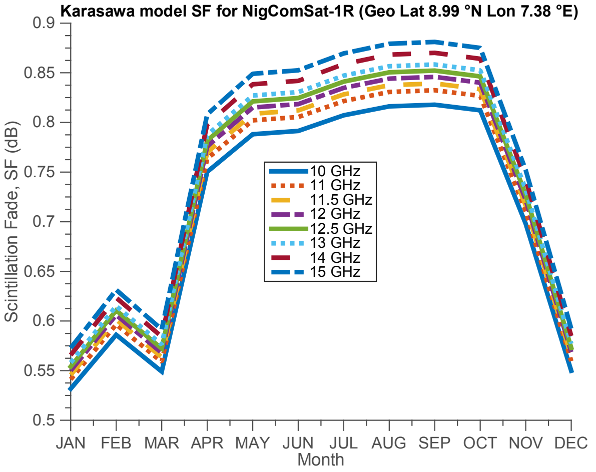

Figure 10. Karasawa NigComSat-1R fade depth in Abuja at θ = 48.1°

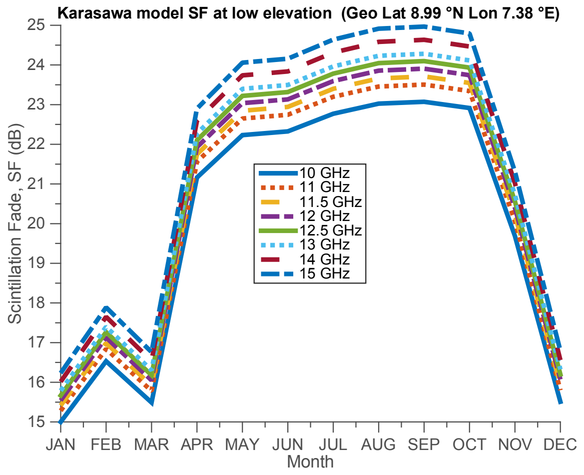

Figure 11. Karasawa fade depth in Abuja at θ = 5°

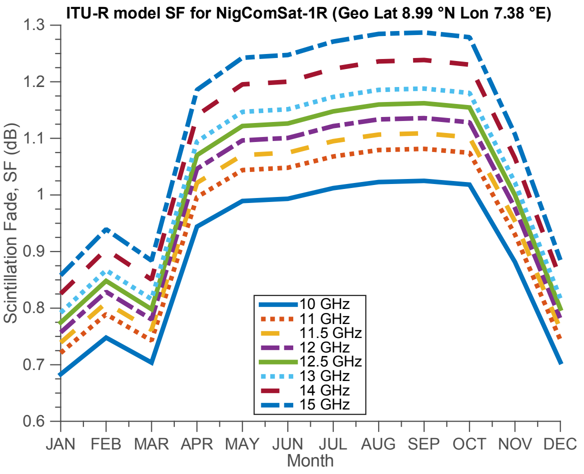

Figure 12. ITU-R NigComSat-1R fade depth in Abuja at θ = 48.1°

The long-term standard deviations predicted by the Karasawa model were considerably lower than that of ITU-R model forantennas pointing to NigComSat-1R and Eutelsat 36B. However, the reverse was the case at low elevation, where the monthly scintillation intensities predicted by Karasawa model were grater than those predicted by the ITU-R for both Ku band uplink and downlink at 0.01% time percentage exceededrequired for communication systems. In particular, higher values were obtained from both models at low elevation in comparison with rain attenuation and data retrieved from meteorological satellites. Scintillation intensity was highest in the monsoon climate with values of 1.31 dB, 1.51 dB and 18.72 dB using ITU-R model at 51.4°, 44.2° and 5° elevations to Eutelsat, NigComSat-1R and low elevation satellites, respectively.In the case of Karasawa model, 0.88 dB, 1.06 dB and 27.05 dB were obtained. In addition, the elevation angle of both satellites varies latitudinal, increasing from the low latitude upward.

In general, the variability of the scintillation intensity is greater using ITU-R model than in Karasawa model, with lower spread across the Ku band. In other words, ITU-R model is more sensitive to frequency than Karasawa model.

Considering the turbulent African equatorial climate regimes, it may be necessary to have in-situ scintillation instrument-cum-observatory in the Sahelian equatorial region and across Africa to improve and optimize existingmodelsfor effective performance of Earth-space links in Africa.

ACKNOWLEDGMENT

Thesupport ofProf. P. N. Okeke, Centre for Basic Space Science (CBSS), Nsukka, is acknowledged for access to data from the Tropospheric Data Acquisition Network (TRODAN).

REFERENCES

[1]. G.MaralandM.Bousquet,*SatelliteCommunicationsSystems:Systems, Techniques and Technology*, 5th ed., Z. Sun, Ed. Hoboken, United States: John Wiley and Sons Ltd, 2010.

[2]. T. Pratt, C. Bostian, and J. Allnutt, *Satellite Communications*, 2nd ed. New York: John Wiley and Sons, Inc., 2003.

[3]. W.L.StutlmanandD.Chakraborty,“The Olympus andactspropagation measurement campaigns in the U.S.” in *Conference publication: 14th Int. Comm. Satellite Systems Conf. and Exhibition held at Washington DC*, March 1992, pp. 1435–1439.

[4]. J. E. Allnut and D. V. Rogers, “Low-fade-margin systems: propagation considerations and implementation approaches,” in *6th International Conference on Antennas and Propagation (ICAP' 89)*, 1989, pp. 6–9.

[5]. L. J. Ippolito, *Satellite communications systems engineering: atmospheric effects, satellite link design, and system performance*. Sussex, U.K.: John Wiley & Sons, 2008.

[6]. D. C. Cox, H. W. Arnold, and H. H. Hoffman, “Observation of cloud- produced amplitude scintillation on 19- and 28-ghz earth-space paths,” *Radio Science*, vol. 17, no. 5, pp. 885–907, 1981.

[7]. Y. Karasawa and T. Matsudo, “Characteristics of fading on low-elevation angle earth-space paths with concurrent rain attenuation and scintillation,” *IEEE Trans. Ant. Prop.*, vol. 39, pp. 657–661, 1991.

[8]. R. A. Hinder, “Observations of atmospheric turbulence with a radio telescope,” *Nature*, vol. 225, pp. 614–617, 1970.

[9]. I. E. Otung and B. G. Evans, “Short term distribution of amplitudescintillation on a satellite link,” Elec. Lett., vol. 31, no. 16, pp. 1328–1329, 1995.

[10]. I. E. Otung and A. Savvaris, “Estimating tropospheric scintillation intensity on earth-space propagation paths,” *Elec. Let.*, vol. 42, no. 7, pp. 381–382, 2006.

[11]. Y. Jiao, J. J. Hall, and Y. T. Morton, “Automatic equatorial gps amplitude scintillation detection using a machine learning algorithm,” *IEEE Trans. Aerospace. Elec. Syst.*, vol. 53, no. 1, pp. 405–418,2017.

[12]. J. W. Strohbehn, “Line-of-sight wave propagation through the turbulent atmosphere,” *Proc. of the IEEE*, vol. 56, no. 8, pp. 1301–1318, 1968.

[13]. D. J. Fang, “4/6 GHz ionospheric scintillation measurements,” *AGARD Conf. Proc. 284 Prop. Effects in Space/Earth Paths*, vol. 33, pp. 1–12, 1980.

[14]. J. Haddon and E. Vilar, “Scattering induced microwave scintillations from clear-air and rain on earth-space paths and the influence of antenna aperture,” *IEEE Trans. AP*, vol. 34, pp. 646–651, 1986.

[15]. P. Brandt, G. Caniaux, B. Bourles, A. Lazar, M. Dengler, A. Fink,V. Hormann, H. Giordani, and F. Marin, “Equatorial upper-ocean dynamics and their interaction with the west african monsoon,” *Atmos. Sci. Lett.*, vol. 12, pp. 24–30, 2011.

[16]. G. D. Coetlogon, S. Janicot, and A. Lazar, “Intraseasonal variability of the ocean - atmosphere coupling in the Gulf of Guinea during boreal spring and summer,” *Q. J. R. Meteorol. Soc.*, vol. 136, pp. 426–441, 2010. [Online]. Available: https://doi.org/10.1002/qj.554

[17]. M. Vellinga, A. Arribas, and R. Graham, “Seasonal forecasts for regional onset of the west african monsoon,” *Clim. Dyn.*, vol. 40, pp. 3047–3070, 2010.

[18]. M. E. Gimonet, M. M. J. L. Van De Kamp, F. S. Marzano, C. Riva, and E. T. Salonen, *Cost Action 255: Radiowave Propagation Modelling for SatCom Services at Ku-Band and Above Final Report.* European Space Agency, 2002, ch. Scintillation/Dynamics of the signal, pp. 1–11.

[19]. G. Peetters, F. S. Marzano, G. d’Auria, C. Riva, and D. VanHoenacker-Janvier, “Evaluation of statistical models for clear-air scintillation pre- diction using olympus satellite measurements” *International Journal of Satellite Communications*, vol. 15, pp. 73–88, 1997.

[20]. J.K.Tervonen,M.M.J.L.VanDeKamp,andE.T.Salonen,“Prediction model for the diurnal behavior of the tropospheric scintillation variance,” *IEEE Trans. Ant. Prop.*, vol. 46, no. 9, pp. 1372–1378, 1998.

[21]. M. M. J. L. Van De Kamp, J. K. Tervonen, E. T. Salonen, and J. P. V. Poirares Baptista, “Improved models for long-term prediction of tropospheric scintillation on slant paths,” *IEEE Trans. Ant. Prop.*, vol. 47, no. 2, pp. 249–260, 1999.

[22]. Y. Karasawa, M. Yamada, and J. E. Allnut, “A new prediction method for tropospheric scintillation on earth-space paths,” *IEEE Trans. Ant. Prop.*, vol. 36, no. 11, pp. 1608–1614, 1988.

[23]. J. Mandeep and R. Zali, “Analysis and comparison model for measuring tropospheric scintillation intensity for Ku-band frequency in Malaysia,” *Earth Sciences Research Journal*, vol. 15, pp. 13 – 17, 2011

[24]. C. Y. Chen and M. J. Singh, “Comparison of tropospheric scintillation prediction models of the Indonesian climate,” *Earth, Planets and Space*, vol. 66, no. 1, p. 64, Jul 2014.

[25]. ITU-R P.453-12, “The radio refractive index; its formula and refractivity data,” ITU, Geneva, Switzerland, Tech. Rep., 2016.

[26]. R. A. Harris, “Cost action 255: Radiowave propagation modelling for satcom services at ku-band and above final report,” European Space Agency, Tech. Rep., 2002.

[27]. F. S. Marzano and G. d’Auria, “Model-based prediction of amplitude scintillation variance due to clear-air tropospheric turbulence on earth- satellite microwave links.” *IEEE Trans. Ant. Prop.*, vol. 46, no. 10, pp. 1506–1518, 1998.

[28]. ITU-R P.618-12, “Propagation data and prediction methods required for the design of earth-space telecommunication systems,” ITU, Geneva, Switzerland, Tech. Rep., 2015.

[29]. A. Akala, K. M. Groves, L. Amaeshi, R. Idolor, E. Okoro, C. Carrano, C. Bridgwood, P. Baki, F. Dujanga, and P. Doherty, “African Equatorial GPS Scintillations during the Minimum and Ascending Phases of Solar Cycle 24,” in *40th COSPAR Scientific Assembly*, ser. COSPAR Meeting, vol. 40, 2014.

[30]. T. V. Omotosho, S. A. Akinwumi, M. R. Usikalu, O. O. Ometan, and M. O. Adewusi, “Tropospheric scintillation and its impact on earth-spacesatellite communication in Nigeria,” in *2016 IEEE Radio and Antenna Days of the Indian Ocean (RADIO)*, Oct 2016, pp. 1–2.

[31]. Y. Abdulrahman, T. A. Rahman, R. M. Islam, B. J. Olufeagba and J. Chebil, “Comparison of measured rain attenuation in the 10.982-GHz band with predictions and sensitivity analysis,” *Int. J. Satell. Comm. Network*, vol. 33, pp. 185–195, 2015.

[32]. S. Shrestha, and D-Y. Choi, “Rain attenuation statistics over millimeter wave bands in South Korea,” J Atmos. Solar-Terrestrial Physics, Vol. 152–153, 2017, pp. 1-10