Impact of Refractivity Gradient and Effective Earth's Radius Factor on Radio Signal Propagation at 100 m under Clear Air in Ibadan, South Western, Nigeria

Aremu Olaosebikan Akanni[1]*, Olayiwola, Olanike Grace[1],
Mufutau Jelili Adekunle[2], Anie Nicholas Oliseloke[2]
[1]Physics Department, The Polytechnic,
P.M.B 22, UI Post Office, Ibadan, Nigeria
[2]Physics unit, General Studies Department, Federal School of Surveying,
P.M.B. 1024, Oyo, Nigeria

Abstract. Radio refractivity gradient and effective earth's radius factor are very significant parameters in planning radio communication links. The refractivity gradient statistics for the lowest 100 m in the troposphere are used to determine the probability of occurrence of anomalous propagation condition known as ducting. In this work, twelve months data of primary radio climatic parameters were obtained using high resolution radiosonde data. A radiosonde is an airborne weather station equipped with a radio transmitter. This transmitter measures meteorological parameters with a given frequency rate at various heights. International telecommunication union (ITU) recommendation models were used in obtaining refractivity gradient, G and effective earth radius factor over Ibadan, Nigeria. The results obtained show that the average radio refractivity, N, was higher during the rainy season (382.7 N-unit) due to the rise in the atmospheric moisture content in the region, it was lower during the dry season (365.8 N-unit) and the value of N also decreases with height. At 100 m, the mean radio refractivity gradient and the average effective earth's radius obtained were -41.9167 Nunit/km and 1.43 respectively. Since the value of effective earth's factor obtained is greater than the global standard value (1.333), the implications of the result are that propagation in this geographic region is mostly super-refractive. It is suggested that the mean refractivity gradient should be used to plan wireless links on short time basis while the average effective earth's radius factor 1.43 should be used to plan long-time wireless communication in this understudy environment.

Key words: Effective earth's radius, Radio signal, Refractivity gradient, Super-refractivity, Troposphere

Introduction

The atmosphere is mainly characterized by temperature, pressure, humidity, and vapor pressure. These parameters affect the propagation of electromagnetic waves in the lower part of the atmosphere (troposphere). To quantify this effect, an index named the radio refractive index, n is used (Grabner & Kvicera, 2003; Zilinskas et al., 2012; Igwe & Adimula, 2009). Thus, the knowledge of the structure of the index *n* is very important for the design of the communication links. For a radio link/propagation design, some parameters such as the effective earth radius factor, k, and the point refractivity gradient, G, must be set carefully so as to optimize its performance. Both the effective earth's radius factor, which is directly related to the refractivity gradient, need to be determine correctly (ITU-R, 2005). Commonly, the k-factor is set as a standard value of $^4/_3$, and estimated values of G are provided by ITU tables for different geographical locations wherever reliable local data are not available (ITU-R, 2003a). This experimental work seeks to study the effects of refractivity gradient and the effect of earth's radius factor on signal strength over Ibadan using primary radio climatic variables during twelve months. It should be noted that, for any locations where atmospheric data were

* Corresponding Author

not available, k-factor value of 1.333 is taken as a standard value and estimated value of point radio refractivity as provided by International telecommunication union (ITU) can be used (Aboualmal et al., 2015).

Theoretical Background

Radio Refractivity (N)

The radio refractivity, N, is related to the refractive index, n of air as (ITU-R, 2003b)

$$N = (n - 1) \times 10^6 \quad (1)$$

In terms of meteorological parameters, the ITU recommended the radio refractivity, N, as (Hall, 1989)

$$N = 77.6\left(\frac{P}{T}\right) + 3.732(10^5)\left(\frac{e}{T^2}\right) \quad (2)$$

where P is the atmospheric pressure (hpa), T is the absolute temperature and e is the atmospheric water vapour.

The water vapor pressure, e, is obtained from the relative humidity, H, and temperature, T, by (Hall, 1989; Afullo, Motsoela, & Molotsi, 1999)

$$e = H\left(\frac{6.1121\exp\left(\frac{17.502T}{T+240.97}\right)}{100}\right) \quad (3)$$

The radio refractivity decreases exponentially in the troposphere with height given as (Afullo, Motsoela, & Molotsi, 1999)

$$N = N_s \exp\left(\frac{h}{H}\right) \quad (4)$$

where N is the refractivity at the height h (km) above the level where the refractivity is N_s and H is the applicable scale height.

Refractivity Gradient (G)

A refracted wave is associated with gradient of the refraction index which depends on atmospheric temperature and pressure (Afullo & Odedina, 2006; Procopio et al., 1993; Brockel et al., 1993). The bending of propagated waves takes place due to the varying index of refraction. The gradient of the refraction index (n) changes with atmospheric temperature and moisture content. The bending of rays away from the earth occurs when refractivity index gradient increases with height.

The refractivity gradient is obtained by differentiating equation (4) with respect to h as shown in equation (5)

$$\frac{dN}{dh} = \frac{-N_s}{H}\exp\left(\frac{-h}{H}\right) \quad (5)$$

The point refractivity gradient, dN/dh was obtained using (Bean & Dutton, 1968)

$$G = \frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} \quad (6)$$

where h_1 is the ground level while h_2 is the height at which the measurement took place. N_1 is the refractivity at the ground level, N_2 is the refractivity at the reference height. In this work, the reference heights considered were (100, 200, 300 and 400 m). The vertical gradient of refractivity in the lower layer of the atmosphere is an important parameter in estimating path clearance and propagation effects such as such sub-refraction, super-refraction and tropospheric ducting (Bean & Dutton, 1968).

For sub-refraction $\frac{dN}{dh} > -40$, the refractivity N increases with height and in this case, the radio wave moves away from the earth's surface and the line of sight, the range of propagation decreases accordingly (ITU-R, 2012; Freeman, 2007).

For super-refraction, $\frac{dN}{dh} < -40$. During this condition, radio waves are bent downward towards the earth. The degree of bending depends upon the strength of the super-refractive condition. On reaching the earth's surface and being reflected from it, the waves can skip large distances thereby giving abnormally large ranges beyond the line of sight due to multiple reflections (Pupala, 2005).

For tropospheric ducting, $\frac{dN}{dh} < -157$. During the tropospheric ducting, the waves bend downwards with a curvature greater than that of the earth.

Effective Earth's Radius

The effective earth's radius is the radius of a hypothetical spherical Earth, without atmosphere, for which propagation paths follow straight lines, the heights and ground distances being the same as for the actual Earth in an atmosphere with a constant vertical gradient of refractivity. It used to characterize refractive conditions as normal refraction or standard atmosphere, sub-refraction super-refraction and ducting, it is given as (Pupala, 2005)

$$k = \frac{1}{\left[1+\frac{\left(\frac{dN}{dh}\right)}{157}\right]} \tag{7}$$

The value of dN/dh around the earth's surface is approximately -40 N-units/km, which will give a k-factor of 1.333; this is referred to as normal refraction or standard atmosphere. Here, radio signals are transmitted along a straight line path on the earth's surface and go into space unhindered. If $1.333 > k > 0$, we will have sub-refraction; which indicates that the radio waves propagate abnormally away from the earth's surface. But when $\infty > k > 1.333$ super-refraction occurs and this signifies that the radio wave signals spread irregularly towards the earth's surface. Hence, extending the radio horizon and increasing path clearance thereby giving irregularly huge ranges above the line of view as a result of several reflections. But, if $-\infty < k < 0$ there will ducting and this will make the radio waves to bend downwards with a curvature bigger than the earth's own. The radio signals can become trapped between a layer in the lower atmosphere and the surface duct which is the earth's or sea's surface or between two layers in the lower atmosphere which is the elevated duct. In this wave guide-like propagation, very lofty radio signal strengths can be obtained at a very long range which is far above the line of view (Adediji, Ajewole, & Falodun, 2011).

Methodology

The estimations of refractivity gradient and effective earth's radius factor is based on the values of the twelve months meteorological parameters (temperature, relative humidity and atmospheric pressure). The meteorological parameters were obtained from radiosonde in Ibadan, South western, Nigeria in the year 2020. A radiosonde is an airborne weather station equipped with a radio transmitter, this transmitter measures meteorological parameters at given frequency rate and height and the measured parameters were saved for further processing.

In this work, the following steps were used to estimate the secondary radio parameters:

i) Daily variations of signal strength was carried out using a developed VHF transmitter capable of transmitting audio signal between 87.7 MHz and 108 MHz. a hand-held spectrum analyzer was used to captured the signal strength at various distance.

ii) Radio refractivity at ground level was determine using equation (2)

iii) Refractivity gradient, G, at altitudes 100, 200, 300 and 400 m was determined using equation (6)

iv) Computation of the effective earth's radius factor was done using equation (7).

Results and Discussion

Seasonal Variation of Radio Refractivity

Figure 1 shows the variation pattern of average radio refractivity for all months of the year 2020. The results obtained shows that, generally, the average radio refractivity values were higher during the rainy season which could be attributed to high values of relative humidity in the troposphere while the average monthly radio refractivity was low during the dry season which could be attributed to high temperature values and low values of relative humidity. Figure 2 shows the mean daily radio refractivity for the months of February and July which represents dry and wet seasons. It was noticed that the values of daily refractivity was higher in the morning and at night due to high relative humidity and low temperature while it was lower in the afternoon due to low relative humidity and high temperature. The minimum average radio refractivity value (365.2 N-units) was obtained in the month of February (dry season) while the maximum value of 383 N-units was obtained for the monthly refractivity in July (rainy season).

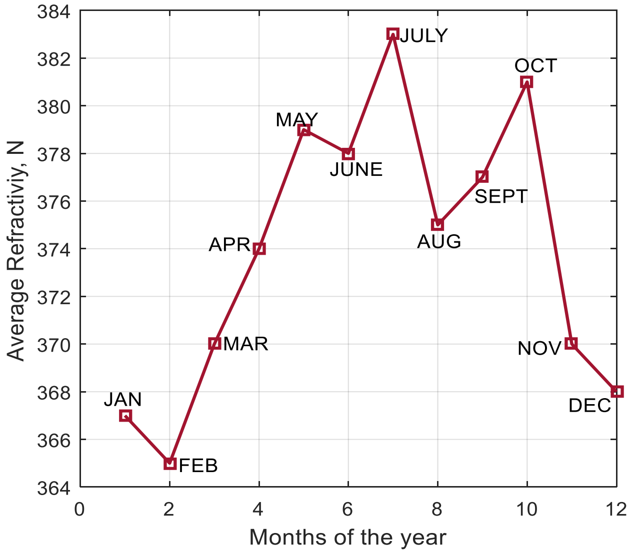

Figure 1. Seasonal variation of radio refractivity

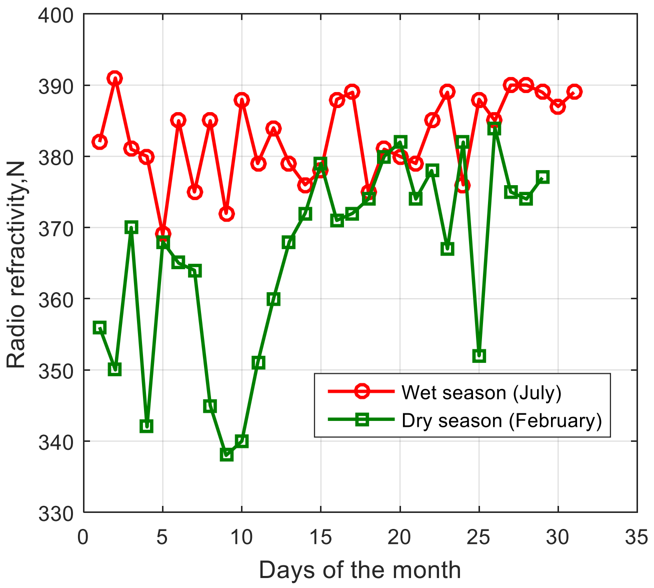

Figure 2. Daily radio refractivity for dry and wet season

Daily Variation of Signal Strength

It was clearly shown that propagation of radio signal on the surface of the earth is affected by radio refractivity. At different points when the radio refractivity was low most especially in the morning and at night due to increase in relative humidity in the atmosphere, the signal strengths was observed high and at the points when N was high (most especially during the day when temperature is higher), there was an decrease in signal strengths. Hence, the higher the radio refractivity, the lower the signal strength. The correlation coefficient between the signal strength and radio refractivity (N) was found to be -0.8775. This shows that as radio refractivity increase, the measured signal strength decreases. This work ascertained the inverse proportionality or anti-phase relationship which exists between radio refractivity and radio signal propagation

Figure 3 shows the average VHF signal strengths measured against the time of the day for the months of July and February which represents rainy and dry season respectively. High signal strengths was noticed during the rainy season compared with dry season which might be as a result of high moisture content in the atmosphere in rainy season than in dry season. It was found that the measured signal strength increases with decrease in temperature and vice versa (inverse relations). Opposite scenario was experienced in the case of relative humidity because the measured signal strength increases with increase in relative humidity (direct relations). This observation was also collaborated by the correlation analysis between the signal strength and the temperature and relative humidity accordingly. The coefficient of correlation between the signal strength and temperature is -0.7236, while that between the signal strength and relative humidity is 0.8210. This shows that both have effects on signal strength but temperature has more effect than relative humidity. The variation of these primary weather parameters which leads to changes of radio refractivity might results in fluctuations of radio frequency signals such as Radio broadcasting as well as GSM signal transmissions. It may cause transmitted radio signal not to reach the supposed horizon further leading to fading or transmitting beyond the horizon.

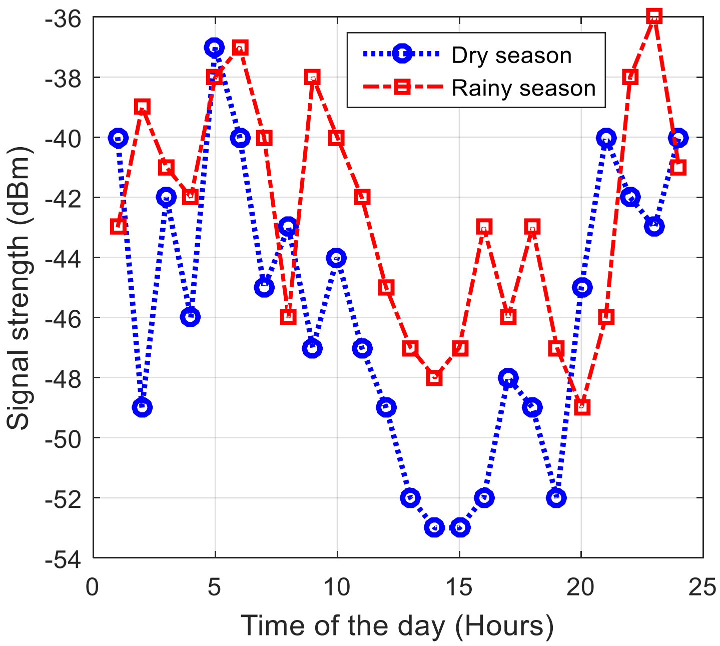

Figure 3. Daily variation of signal strengths for dry and rainy seasons

Seasonal Variations of Radio Refractivity Gradient

The results obtained shows that, the average radio refractivity gradient, G, was higher during the rainy season (April–October), this is due to the rise in atmospheric moisture content in the region. During the months of January, February, November and December when the dry air was intense, the values of observed refractivity gradient falls sharply. Figure 4 depicts the variation of radio refractivity gradient against the months of the year at 100 m above sea level, the average value of G obtained for the year was -41.91 Nunit/km. The implications of the result is that propagation in this geographic region is mostly super-refractive, which implies that the electromagnetic waves are bent downward towards the earth. The degree of bending is a function of the strength of the super-refractive condition. As the refractivity gradient continues to decrease, the wave path's curve approach the radius of curvature of the earth. Super-refraction occurs when the bending of the trajectory of propagating radio wave bends toward the ground surface is greater than its bending in case of normal positive refraction.

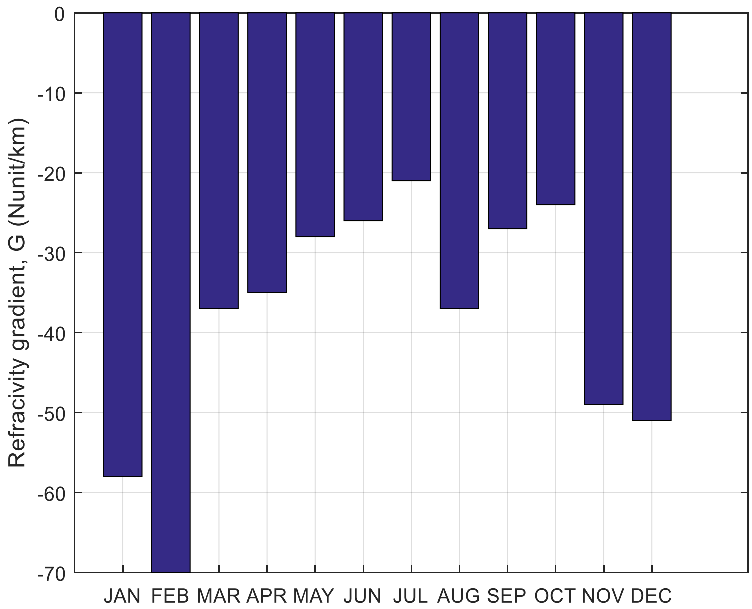

Figure 4. Seasonal variation of point refractivity gradient at the altitude of 100 m

Seasonal Variation of K-Factor at Different Altitudes

Figure 5 depicts the effective earth's radius against the months of the year. It was noted that k-factor increase with increasing in vertical heights and the mean values are within the range 1.43 to 1.61 for 100 m to 400 m altitude above sea level. At 100 m as shown in Figure 5, the average k-factor obtained for the year was 1.43 and the implication of the result is that, propagation in this geographical region is mostly super-refractive. Super refraction results from such meteorological conditions as a rise in temperature with increasing height (temperature inversion) or a marked decrease in total moisture content in the air, either of which caused a reduction in the dielectric constant gradient with height. Under these situations, the k-factor increases resulting in an effective flattening of equivalent earth's curvature. One of the conditions which caused this type of abnormal refraction is the passage of warm air over a cool body of water and water evaporation can cause an increase in moisture content and a decrease in temperature near the surface producing a temperature inversion. However, if is not only the temperature inversion itself which causes the abnormal bending of the microwave beam. The large increase in water vapour content and hence, the dielectric constant near the surface further increases this effect.

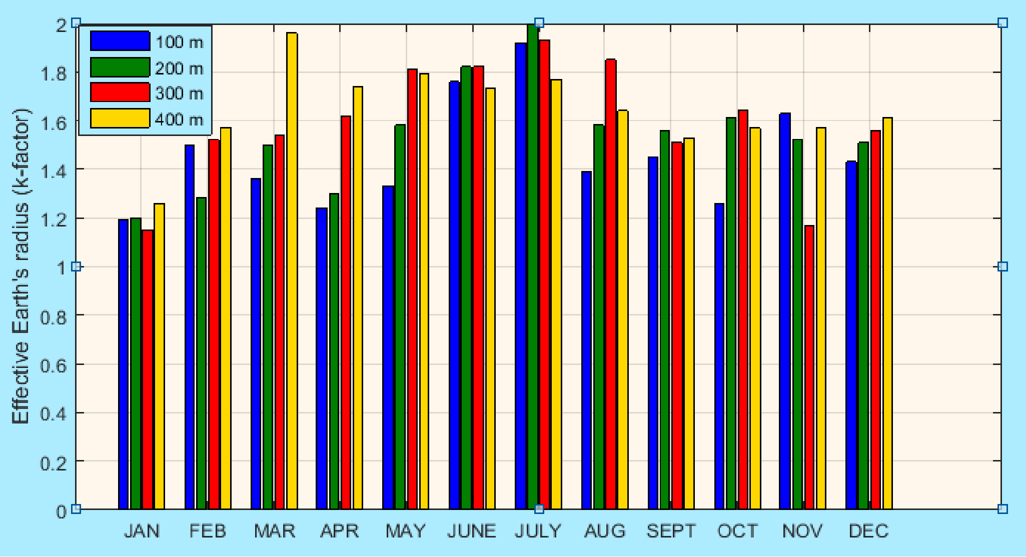

Figure 5. Seasonal variation of effective earth's radius factor at different altitudes

Figure 6 shows the Seasonal variation of effective earth's radius factor at the altitude of 100 m. The results show that this altitude, the k-factor values increase during the rainy season with the peak value of 1.91 obtained in the month of July. The lowest value was obtained in the month of January with average value of 1.20. From this work, the mean annual value of k-factor in this study area is 1.43. This implies that, the propagation in this geographical region is mostly super-refractive.

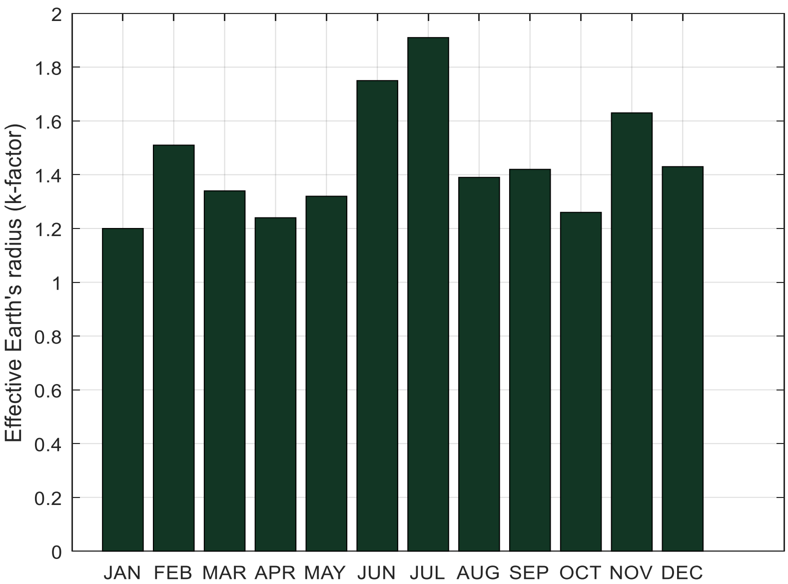

Figure 6. Seasonal variation of effective earth's radius factor at the altitude of 100 m

Conclusion

The obtained values of the radio refractivity gradient and effective earth's radius factor in this study shows that these parameters are function of meteorological data, particularly the temperature, atmospheric pressure and relative humidity. Thus, the estimation of the radio refractivity, refractivity gradient and earth's radius factor has to be based on local geographical and meteorological data as confirmed by other researchers. The work revealed that, the average radio refractivity, N, was higher during the rainy season due to the rise in the atmospheric moisture content in the region and this increases the VHF signal strengths compared to dry season. It was also discovered that the value of N and G decreases with height. At 100 m, the mean refractivity gradient and effective earth's radius factor obtained from this study area under investigation are -41.9107 Nunit/km and 1.43 respectively. Since the refractivity gradient statistics for the lowest 100 m in the troposphere are used to determine the probability of occurrence of anomalous propagation condition known as ducting. Hence, the implications of the result is that, the propagation in this geographic region is mostly super-refractive. It is suggested that, the mean refractivity gradient should be used to plan wireless links on short time basis while the average effective earth's radius factor 1.43 should be used to plan long-time wireless communication in this region understudy.

References

Aboualmal, A., Abd-Alhameed, R.A., Jones, S.M., & Al-Ahamad, H. (2015). New Methodology for predicting vertical atmosphere profile and propagating parameters in sub-tropical Arabam Gulf region. *Antennas and Propagations, IEEE Transaction, 63*(9), 4057-4068.

Adediji, A.T., Ajewole, M.O., & Falodun, S.E. (2011). Distribution of Radio Refractivity Gradient and Effective Earth Radius Factor (k-factor) over Akure, South Western Nigeria. *Journal for Atmospheric and Solar-Terrestrial Physics, 73*(2011), 2300.

Afullo, T. J., Motsoela, T., & Molotsi, D.F. (1999). Refractivity gradient and k-factor in Botswana. *Radio Africa, 73,* 107-110.

Afullo, T.J. & Odedina, P. K. (2006). On the K-factor distribution and diffraction fading for South Africa. *South African Institute of Electrical Engineers Journal, 97*(2), 172-181.

Bean, B. R., Dutton, E.J. (1968). *Radio Meterology National Bureau of Standards Monograph*. 92. US. Government printing office, Washington, pp. 9-13.

Brockel, K.H., Inserra, J.R., Loso, F.G., Major, P.A., Procopio, V.J., Chaney, K.D., Locher, R.J., Vigants, A., Barnett, W.T., & Riehl, M. (1993). Tactical Line-ofsight path reliability: Propagation climate factors. *Proc. of Military Communication Conference, IEEE, 2*, pp. 614-618, 11-14, Boston, MA.

Freeman, R.L. (2007). *Radio system design for telecommunications* (3rd ed.). New York: Wiley-Interscience, John Wiley & Sons Inc.

Grabner, M. & Kvicera, V. (2003). Introduction to Project of Refractive Index Measurement in Prague. *Antennas and Propagation, ICAP, Twelfth International Conference, 2, No. 491,* 784-787.

Hall, M.P.M. (1989). Effect of the troposphere on radio communication. *IEEE Electromagnetic Wave Series,* pp. 105-116, Peter Peregrinus Ltd, United Kingdom.

Igwe, K.C. & Adimula, I.A. (2009). Variations of surface radio refractivity and radio refractive index gradients in the sub-Sahel. *Nigerian Journal of Space Research, 6,* 135-144.

ITU-R. (2003a). Recommendation ITU-R P.453-9, "The radio refractive index: its formula and refractivity data," International Telecommunication Union.

ITU-R. (2003b). "The radio refractive index, its formula and refractivity data", pp. 453-459. International Telecommunication Union Recommendation.

ITU-R. (2005). Recommendation ITU-R P.452-12, "Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz," International Telecommunication Union.

ITU-R. (2012). ITU-R rec. F.746-10, "Radio-frequency arrangements for fixed service systems."

Procopio, V.J., Brockel, K.H., Inserra, J.R., Loso, F.G., Major, P.A., Chaney, K.D., Locher, R.J., Vigants, A., Riehl, M., & Barnett, W.T. (1993). Tactical Line-of-sight radio propagation reliability. *Proc. of Military Communication Conference, IEEE, 2*, pp. 609-613, 11-14, Boston, MA.

Pupala, R.N. (2005). *Introduction to Wireless Electromagnetic Channels and Large Scale Fading*. Department of Electrical Engineering, Rutgers University, Piscataway, NJ 08854.

Zilinskas, M., Tamosiunaite, M., Tamosiuniene, M., Valma, E., & Tamosiunas, S. (2012). Gradient of Radio Refractivity in Troposphere. *Progress in Electromagnetics Research Symposium Proceedings*, Moscow, Russia, pp. 603-607.