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VERTICAL PROFILE OF RADIO REFRACTIVITY GRADIENT IN AKURE SOUTH-WEST NIGERIA

A. T. Adediji and M. O. Ajewole

Department of Physics
Federal University of Technology
Akure, Ondo State

Abstract—In the planning and design of microwave communication links, the structure of the radio refractive index in the lower part of the atmospheric boundary layer is very important. In this work, measurements of atmospheric pressure, temperature and relative humidity were made in Akure (7.15°N, 5.12°E), South Western Nigeria. Wireless weather stations (Integrated Sensor Suite, ISS) were‘positioned at five different height levels beginning from the ground surface and at intervals of 50 m from the ground to a height of 200 m (0, 50, 100, 150 and 200 m) on a 220 m Nigeria Television Authority TV tower at Iju in Akure North Local Government area of Ondo State. The measurement of the atmospheric variables was made every 30 minutes everyday. The study utilized the data for the first year of measurement (January–December 2007) to compute the radio refractivity and its refractivity gradient in Akure. From these parameters, the vertical distributions of radio refractivity are then determined. The results obtained show that the propagation conditions have varying degree of occurrence with sub-refractive conditions observed to be prevalent between January–July while Super-refraction and Ducting were observed mostly between August–December.

1. INTRODUCTION

Multipath effects arise due to large scale variations in atmospheric radio refractive index, such as horizontal layers with very different refractivity [4]. This effect becomes noticeable, when the same signal takes different paths to its target and the rays arriving at different times thereby interfering with each other during propagation through the troposphere. The consequence of this large scale variation in the atmospheric refractive index is that radiowaves propagating through the atmosphere becomes progressively curved towards the earth. Thus, the range of the radiowaves is determined by the height dependence of the refractivity. Therefore, the refractivity of the atmosphere will not only affect the curvature of the ray path but will also provide some insight into the fading of radio waves through the troposphere.

Most of the previous work done on this subject in Nigeria are based on surface refractivity while refractivity gradients were based on extrapolated data from radiosonde measurements, examples includes; [2 7, 9, 10], and so on. Recently however, [3] carried out experimental studies on this subject at the surface and at 100 m altitude. Though the study presented some interesting results, it however lacked the necessary spatial resolution to observe the small scale changes in the vertical distribution of radio refractivity and propagation effects over Akure.

The information on radiosonde measurements also lacks the spatial and temporal resolutions which are necessary for the measurement of small-scale variations particularly in the lower atmosphere [8]. Furthermore, it is generally recognized that radiosonde measurement do not have a sufficiently high degree of accuracy to be completely acceptable for use in observing changes in the degree of stratification of the very lowest layers of the atmosphere [5]. In this study, sensors are positioned at the ground level for the measurement of the surface weather parameters (atmospheric pressure, temperature and relative humidity) and at altitudes of 50, 100, 150 and 200 m respectively from which the radio refractivity and refractivity gradient are determined.

2. THEORY

Radio-wave propagation is determined by changes in the refractive index of air in the troposphere. Because it is very close to unity (about 1.0003), the refractive index of air is measured by a quantity called the **radio refractivity N**, which is related to refractive index, n as (ITU-R, 2003):

$$n = 1 + N \times 10^6 \tag{1}$$

In terms of measured meteorological quantities, the refractivity N, can be expressed as:

$$N = 77.6\frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{2}$$

where: $p =$ atmospheric pressure (hPa), $e =$ water vapour pressure (hPa) and $T =$ absolute temperature (K).

Equation (2) may be used for radio frequencies up to 100 GHz [1]. The error associated with the use of this expression is less than 0.5% (ITU-R, 2003).

The water vapour pressure e is usually calculated from the relative humidity, and saturated water vapour, using the expression:

$$e = H \times \frac{6.1121 \exp\left(\dfrac{17.502t}{t + 240.97}\right)}{100} \tag{3}$$

where: $H =$ relative humidity (%), $t =$ temperature in degree Celsius (°C) and $e_s =$ saturation vapour pressure (hPa) at the temperature t (°C).

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 sub-refraction, super-refraction, or ducting according to the following criteria:

- Sub-refraction: $\dfrac{\partial N}{\partial z} > -40$.

Refractivity N increases with height and in this case (sub-refraction), the radio wave moves away from the earth's surface and the line of sight range and the range of propagation decrease accordingly.

- Super-refraction: $\dfrac{\partial N}{\partial z} < -40$.

During super-refractive conditions, electromagnetic waves are bent downward towards the earth. The degree of bending depends upon the strength of the super-refractive condition. The radius of curvature of the ray path is smaller than the earth's radius and the rays leaving the transmitting aerial at small angles of elevation will undergo total internal reflection in the troposphere and it will return to the earth at some distance from the transmitter. 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.

- Ducting: $\dfrac{\partial N}{\partial z} < -157$,

During ducting phenomenon, the waves bend downwards with a curvature greater than that of the earth. Radio energy bent downwards can become trapped between a boundary or layer in the troposphere and the surface of the earth or sea (surface duct) or between two boundaries in the troposphere (elevated duct). In this wave guide-like propagation, very high signal strengths can be obtained at very long range (far beyond line-of-sight) and the signal strength may exceed its free-space value.

3. LOCATION AND INSTRUMENTATION SET UP

The site of the study is located at the old premises of the Nigerian Television Authority (NTA) at Iju in Akure North local government area of Ondo state. It is about 17 km by road away from the city of Akure, about 26 km by road from the campus of the Federal University of Technology, Akure (FUTA) and about 11.5 km on line of sight from Akure with coordinates, (7.15°N, 5.12°E) (Fig. 3). The instrument for this measurement is the Davis 6162 Wireless Vantage Pro2 equipped with the Integrated Sensor Suite (ISS) (Fig. 1), a solar panel (with an alternative battery source) and the wireless console. The console is connected to a computer, through which the stored data are downloaded. The ISS houses the sensors for pressure, temperature, relative humidity, UV index and dose, solar radiation among others and the sensor interface module (SIM). The SIM contains electronics that measure and store values of weather variables for transmission to the console via radio. The fixed measuring method by a high tower is employed for the measurement with the ISSs positioned on the ground surface and at different heights (50 m, 100 m, 150 m and 200 m) on the tower (Fig. 2) for continuous measurement of the atmospheric pressure, air temperature and relative humidity. The TV tower carrying the ISS is 220 m high. The measurement covers 24 hours each day beginning from 00 hours local time (LT) and for a time interval of 30 minutes. The data is then transmitted by wireless radio connection to the data

Figure 1. The Integrated Sensor Suit (ISS) on site at Iju.

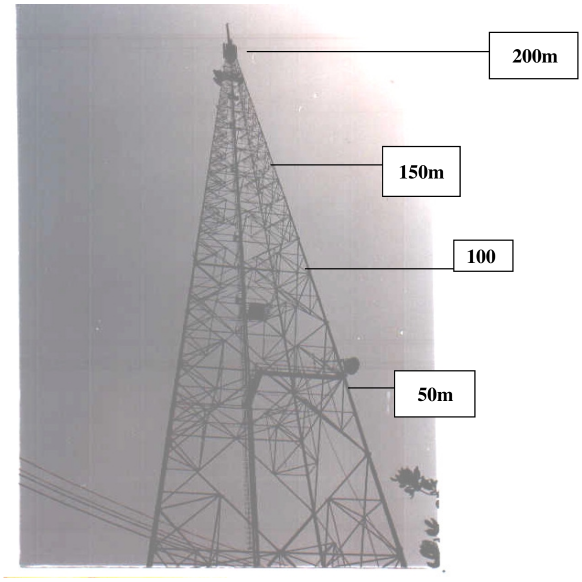


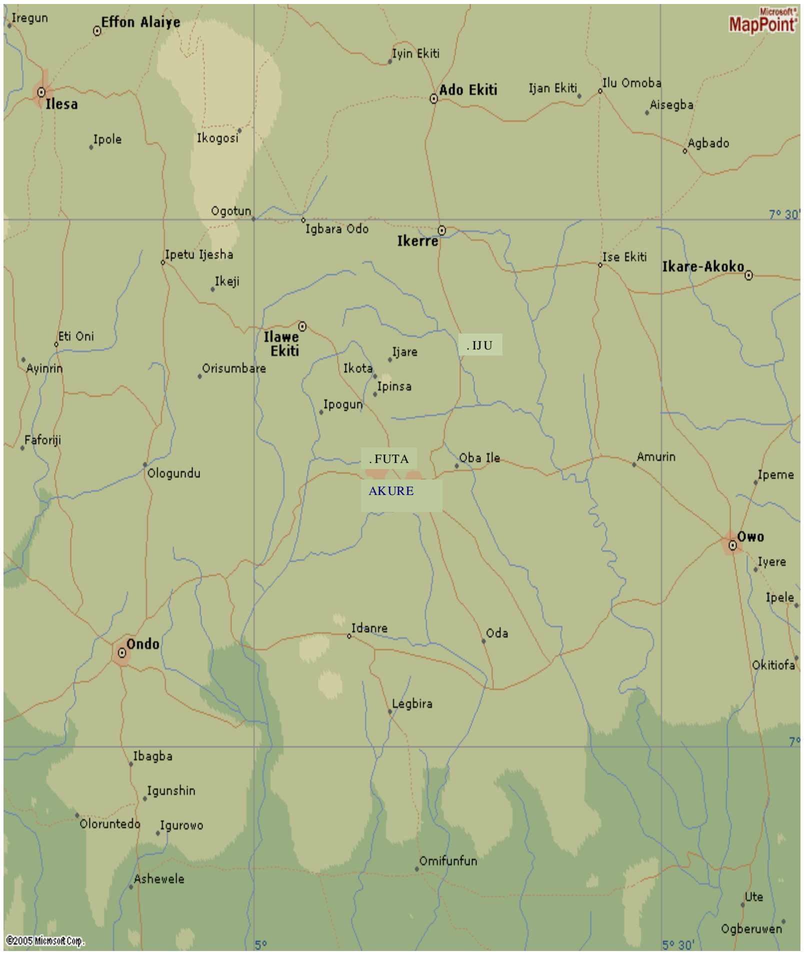
Figure 2. Communication Mast showing the positions of the ISS's.

logger attached to the console which is located in-door on the ground. The data are then copied to the computer laptop for analysis. The error margin of the ISS device for temperature, pressure and relative humidity are ±0.1°C, ±0.5 hpa and ±2% respectively.

4. RESULTS AND DISCUSSION

Data used for this work were from in-situ measurements of meteorological parameters made from (January–December 2007). The measurement covered both climatic seasons (dry season and wet season) occurring in Akure every year. The dry period is usually from November to March while the wet season months are usually from April to October every year. The Akure climate is basically tropical; it is a zone where warm, moist air from the Atlantic converges with hot, dry and often dust-laden air from Sahara called the 'harmattan'.

The measured relative humidity was converted to water vapour pressure, e (hpa) by using Equation (3). The data were used to compute the refractivity using Equation (2). From the calculated values of the refractivities, refractivity gradient at 50 m, 100 m, 150 m and 200 m are then determined. Result obtained for the average monthly records is presented in Fig. 4. The values were observed to



Scale: - 1cm = 9km

Figure 3. Map of the experimental site in Ondo State.

be generally high during the rainy season (April–October). The high values are due to high air humidity (very close to 100%) observed in this part of the globe during this period when the city of Akure is under the influence of a large quantity of moisture laden tropical maritime air resulting from continuous migration of inter-tropical discontinuity with the sun.

Generally, when the dry and dust-laden north-west winds become dominant in December, the dry harmattan season sets in, resulting

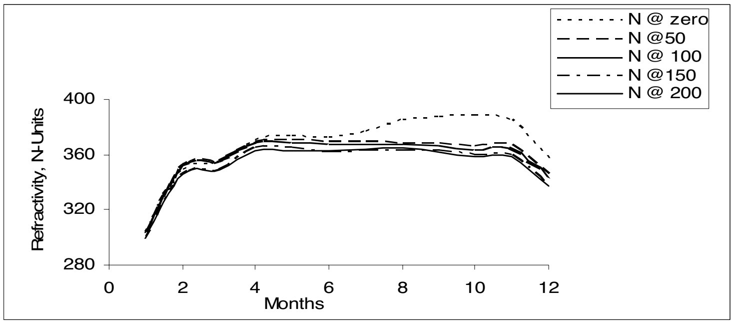


Figure 4. Variation of monthly mean value of refractivity from January to December 2007 at the different height levels in Akure.

in low values of refractivity as observed in January–February window. The slight decrease in refractivity in the March–April window is mostly due to the high temperatures associated with the commencement of the rainy season in April. Fig. 5 shows the vertical gradient of refractivity calculated on the basis of the mean monthly statistical distribution of refractivities at each of the levels. It shows that the monthly variation peaks around February corresponding to the end of the harmattan season characterised often with very cool nights and morning times and very dry day time. The values drop gradually between April–June and drastically between July and October corresponding to the period of rainy season. In Figs. 4 and 5, there observed a large difference in the values of refractivity and refractivity gradients at zero (ground surface) and other levels from September to December. This can be associated with ground heat flux and the change of seasons which occurs in association with the meridional movement of the Inter-Tropical Discontinuity (ITD) which demarcates at the surface, the warm and moist (maritime) south-westerly trade winds from the warm and dry (continental) north-easterly winds leading to high temperature at the surface. There are however some observed days during the dry harmattan season of intensive temperature inversion especially in the morning hours. Typical example is shown in Table 1 for 50–200 m altitude. Here, it is observed that at 00:30–09:00 hours, temperature increases with increasing height. This may be caused by advection processes, cooling of the earth's surface through radiation and compression of air masses. Fig. 6 shows the variation of refractivity with height from the ground surface to 200 m altitude calculated on the basis of the monthly mean of refractivity. It shows that refractivity decreases with increasing altitude. At the height interval of 50–100 m and 150–200 m, the refractivity profile is quite steep while it is gentle at

Table 1. Typical day of observed temperature inversion at 50 m–200 m levels.

Date	Time	50 m			100 m			150 m			200 m		
		Tem p.	Hum.	Press.	Temp.	Hum.	Press.	Temp.	Hum.	Press.	Temp.	Hum.	Press.
01/01/2007	00:30	23	34	976.7	23.3	33	983.2	23.6	28	984.5	23.7	28	992.1
01/01/2007	01:00	23.1	33	976.4	23.3	33	982.8	23.8	28	984.3	23.7	27	991.7
01/01/2007	01:30	22.9	33	976.2	23	33	982.6	23.2	28	984	23.3	28	991.5
01/01/2007	02:00	22.9	33	975.8	23.1	33	982.3	23.4	28	983.8	23.3	27	991.1
01/01/2007	02:30	22.6	34	975.6	22.8	33	982	23.1	29	983.3	23.2	27	990.9
01/01/2007	03:00	22.7	32	975.4	22.8	32	981.9	23.1	27	983.3	22.9	28	990.8
01/01/2007	03:30	22.6	32	975.4	22.8	32	981.8	22.9	28	983.2	22.9	28	990.5
01/01/2007	04:00	22.5	32	975.1	22.8	31	981.5	23.1	27	982.9	22.9	27	990.5
01/01/2007	04:30	22.2	34	975.3	22.8	31	981.6	22.9	27	983.1	22.9	27	990.5
01/01/2007	05:00	21.2	37	975.6	22.1	33	982	22.4	28	983.3	22.4	28	990.9
01/01/2007	05:30	20.9	37	975.6	21.6	34	982.1	21.8	28	983.5	21.8	28	991.1
01/01/2007	06:00	20.7	37	976.2	21.2	34	982.6	21.2	30	984.1	21.2	30	991.6
01/01/2007	06:30	20.7	35	976.3	20.8	33	982.6	20.7	28	984.2	20.7	28	991.6
01/01/2007	07:00	19.8	39	976.6	20.5	36	983	20.7	30	984.5	20.7	30	992
01/01/2007	07:30	19.6	39	976.5	20.1	36	983	20.4	29	984.5	20.5	29	992
01/01/2007	08:00	19.1	40	977	19.7	35	983.4	20.3	28	984.9	20.2	28	992.3
01/01/2007	08:30	19.6	39	977.4	20.3	33	983.9	20.4	28	985.4	20.4	29	992.8
01/01/2007	09:00	20.3	37	977.4	20.4	33	983.9	21.1	28	985.5	20.8	27	992.8
01/01/2007	09:30	21.1	35	977.5	21	34	983.9	21.3	28	985.5	20.9	28	992.8
01/01/2007	10:00	22.4	31	977.3	22.1	29	983.8	21.7	25	985.4	21.8	28	992.8
01/01/2007	10:30	23.3	27	977.2	22.7	27	983.7	22.4	28	985.2	22.2	27	992.7
01/01/2007	11:00	23.7	30	977	23.1	32	983.5	22.9	28	985	22.7	28	992.5
01/01/2007	11:30	24.2	31	976.7	23.7	32	983.2	23.6	27	984.7	23.3	27	992.2
01/01/2007	12:00	25.4	29	976.3	25	31	982.8	24.6	27	984.4	24.6	28	991.7
01/01/2007	12:30	26.1	27	975.8	25.6	28	982.1	25.4	25	983.7	25.3	25	991.1
01/01/2007	13:00	27.1	23	975.2	26.4	24	981.7	26.1	21	983.2	25.9	21	990.6
01/01/2007	13:30	27.6	22	974.6	27.2	23	981	27.1	20	982.4	26.7	20	990
01/01/2007	14:00	28.1	22	974.1	27.6	23	980.5	27.6	20	982	27.2	20	989.4
01/01/2007	14:30	28.6	22	973.6	27.9	23	979.9	27.8	20	981.3	27.6	20	988.9
01/01/2007	15:00	28.9	21	973.2	28.4	22	979.6	28.3	20	980.9	27.9	19	988.4
01/01/2007	15:30	29.1	22	973	28.7	23	979.4	28.7	19	980.7	28.4	19	988.3
01/01/2007	16:00	29.3	21	972.9	28.9	22	979.3	28.7	19	980.7	28.5	19	988.2

other levels. Figs. 7–9 show the monthly statistics of the occurrence of propagation conditions (Sub-refraction, Super-refraction and ducting) over the one year period of this study. The statistics shows that the propagation conditions have varying degree of occurrence with sub-refractive conditions prevalent at all the levels from January to May. Super-refractive conditions are prevalent at the altitudes of 150 m and 200 m from June to December while ducting at 50 m, 100 m and 150 m from the month of August to December. During the months when sub-refractive conditions are present, stations around Akure will have reduced radio horizon and are also open to severe interference from distant stations due to the combined effect of super-refraction and ducting. This effect may lead to frequent signal outage from the stations. When super-refraction and ducting are prevalent, very high radio signal strengths can be obtained at very long range (far beyond line-of-sight) and the signal strength may exceed its free-space value.

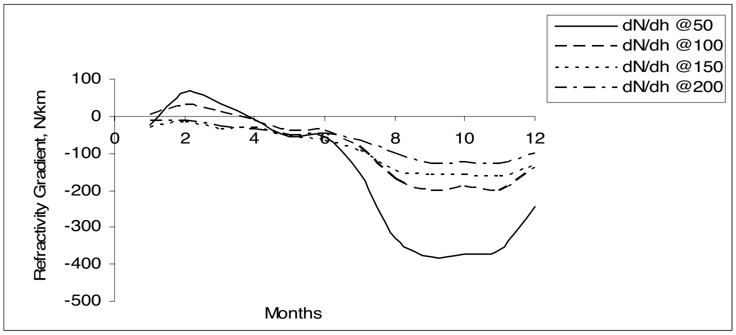


Figure 5. Variation of monthly mean value of refractivity gradient from January to December 2007 at the different height levels in Akure.

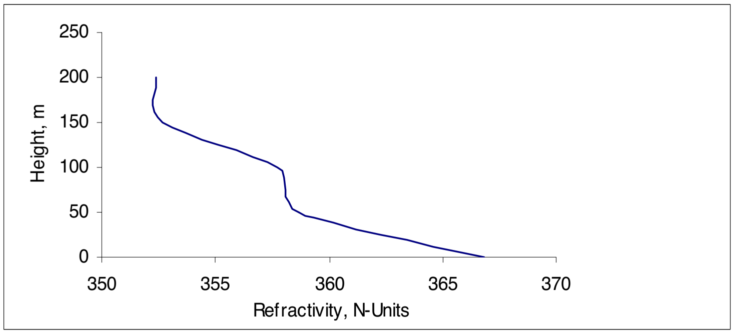


Figure 6. Variation of refractivity with height.

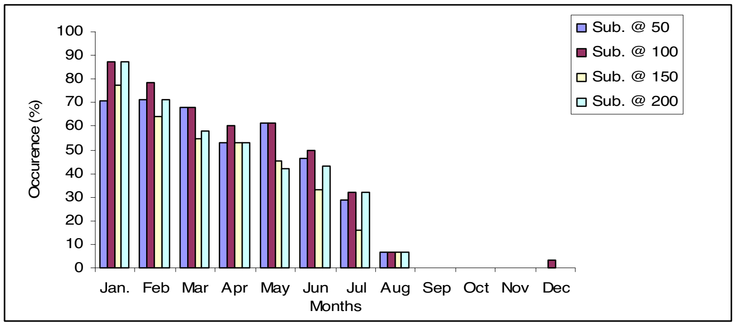


Figure 7. Summary of occurence of sub-refractive conditions at all the levels.

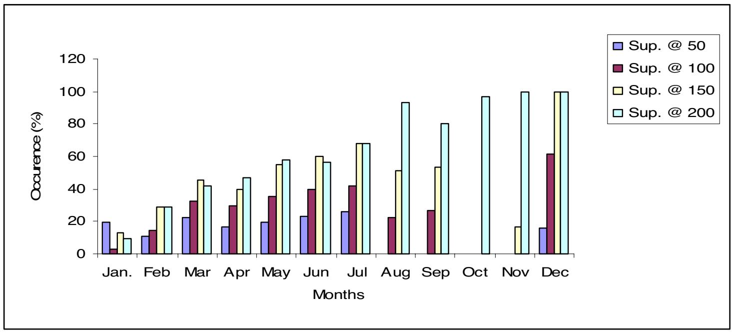


Figure 8. Summary of occurence of super-refraction conditions at all the levels.

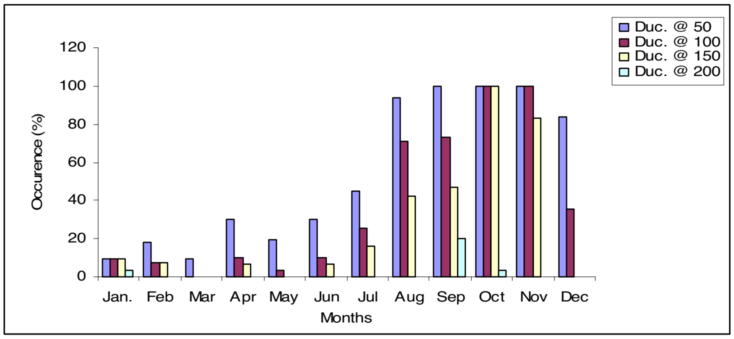


Figure 9. Summary of occurence of ducting conditions at all the levels.

5. SUMMARY AND CONCLUSION

This study reveals that the refractivity is generally high during the rainy reason (March–October) at all the levels. During the months of December and January, when the dry harmattan was intense, the values of observed refractivity fall sharply. Propagation conditions have varying degree of occurrence with sub-refractive conditions prevalent at all the levels from the month of January to May, super-refractive conditions are prevalent at 150 m and 200 m levels from June to December and ducting conditions are observed at 50 m, 100 m and 150 m from August to December.

This study is intended to have a database for the prediction of microwave communication impairment in the South-West sub-region of West Africa; however, the measurement is continuing.

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REFERENCES

1. Babin, S. M., G. S. Young, and J. A. Carton, "A new model of the oceanic evaporation duct," *Journal of Applied Meteorology*, Vol. 36, 193–204, 1997.
2. Falodun, S. E. and L. B. Kolawole, "Studies of super-refractivity and ducting of radiowaves in Nigeria," *Nigeria journal of Pure and Applied Physics*, Vol. 1, 5–10, 2000.
3. Falodun, S. E. and M. O. Ajewole, "Radio refractive index in the lowest 100 m layer of the troposphere in Akure, South Western Nigeria," *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 68, 236–243, 2006.
4. Grabner, M. and V. Kvicera, "Clear-air propagation modelling using parabolic equation method," *Radio Engineering*, Vol. 12, No. 4, 50–54, 2003.
5. Hajj, G. A., E. R. Kursinski, L. J. Romans, W. I. Bertiger, and S. S. Leroy, "A technical description of atmospheric sounding by GPS occultation," *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 64, 451–469, 2002.
6. ITU-R, *The Refractive Index: Its Formula and Refractivity Data*, 453-9, 2003.
7. Kolawole, L. B., "Statistics of radio refractivity and atmospheric attenuation in tropical climates," *Proceedings of the URSI Commission F Symposium*, 69–75, Belgium, 1983.
8. Lowry, A. R., C. Rocken, and S. V. Sokolovskiy, "Vertical profiling of atmospheric refractivity from ground-based GPS," *Radio Science*, Vol. 37, No. 3, 13-1–13-10, 2002.
9. Oyinloye, J. O., "The troposphere in tropical and sub-tropical latitudes," *Handbook on Radio Propagation for Tropical and Sub-Tropical Countries*, 77–79, URSI Committee on Developing Countries, 1987.

10. Willoughby, A. A., T. O. Aro, and I. E. Owolabi, "Seasonal variations of radio refractivity gradients in Nigeria," *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 64, 417–425, 2002.