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An *In-Situ* Investigation of Abnormal Propagation Conditions at Nsukka, Nigeria

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ABSTRACT: In commercial radio link planning, the statistical probability of occurrence of propagation events such as super-refraction, sub-refraction, and ducting are estimated for the link design of communication circuits. Since these phenomena vary for different propagation zones, it is important to determine the values for each locality. The basic data employed for this study were meteorological data of atmospheric pressure, temperature, and relative humidity obtained by *in-situ* measurements at Nsukka, *(7.4^{0}E, 6.9^{0}N)* Nigeria. Wireless meteorological sensors were positioned at the ground surface and at 100m altitude on a communication mast. The measurements were made every thirty minutes and round the clock for a period of two years (February 2007 to March 2009). Statistical distributions of the refractive index modulus, its vertical gradient, and the diurnal and seasonal variations of the refractivity modulus were determined from the measured data. The obtained results have been used to designate the refractivity profiles as sub-refraction, super-refraction, and ducting. The refractivity values at the station have shown that the surface layer is super-refractive most of the time with higher probability of occurrence of ducting during the rainy season. However, super-refractive conditions is predominant during the dry season. The results also show that the values of the refractive modulus at 100m altitude were higher in the morning and late evening hours while they show minima during the afternoon hours. The worst propagation condition (when possible signal outage due to propagation effects) is in the afternoon within the time window from 15:00 to 18:00 hrs when refractivity values are the lowest. Also deduced is the value of the effective-earth-radius factor, k, which is representative of south-eastern Nigeria.

Key words: Refractivity, k-factor, propagation zones, Refractive profile, Refractive modulus

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INTRODUCTION

A radio ray propagated through the earth's atmosphere encounters variations in the atmospheric refractivity index along its trajectory that causes the ray path to deviate from normal. Therefore, the refractivity of the atmosphere will affect not only the curvature of the ray path (expressed by the k-factor) but will also give some insight into the fading phenomenon. The effects of atmospheric refraction is more pronounced at radio frequencies than at the wavelength of visible light, and the result is that the radio waves can propagate beyond the optical horizon with no additional loss other than the free space distance loss.

Furthermore, unusual weather conditions can change the refractivity profile. For example, in super-refractive condition, rays bend more than normal and the radio horizon is extended, and in extreme the case, it leads to the phenomenon of ducting where the signal can propagate over large distances beyond the normal horizon. The consequence of this phenomenon is that occasional interference may be experienced from unexpected sources. A more serious concern is sub-refraction in which the bending of the rays is less than normal, thus shortening the radio horizon and reducing the clearance over obstacles along the path. This may lead to

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increased path loss and possibly an outage an outage of signal.

BACKGROUND THEORY OF RADIO REFRACTIVITY

Propagation of radio waves in the VHF, UHF and SHF bands are affected by meteorological conditions in the troposphere. The refractive index **n** of air depends on the atmospheric pressure **P** (in mb), the temperature **T** (in K), and the water vapour pressure**, e** (in mb) of the atmosphere (Hall, 1979). The radio refractivity **N** and the refractive modulus **M** for air, for frequencies up to 100 GHz, are given by the ITU-R formula [ITU-R, 1987] in equations (1) and (2).

$$N = 77.6\frac{P}{T} + 3.73\times 10^5\frac{e}{T^2} \quad (1)$$

$$M = (n-1)\times 10^6 + \frac{h}{R}\times 10^6 \quad (2)$$

where P is the atmospheric pressure, e is the water vapour pressure which can be calculated from the relative humidity and the saturation vapour pressure, using the relationship described in Rec. ITU- R.P. 453-9 (2004); and T is the absolute temperature. Also, h (km) is the height of atmospheric layer above the earth's surface and R (km) is the radius of the earth.

For VHF and UHF bands at standard conditions, the atmospheric property which is basic to radio ray tracing is the radio refractive index **n**. However, when evaluating refraction effects from the common meteorological variables, the refractivity **N** is normally used (Barclay, 2003).

In terms of the refractive index **n**, equation (1) can be expressed as

$$N = (n-1)\times 10^6 \quad (3)$$

For an ideal condition of the atmosphere, the atmosphere is uniformly stratified and the vertical gradient of the refractive index is assumed constant and defined by

$$k = \frac{1}{1+R\frac{dn}{dh}} = \frac{1}{1+R\frac{dN}{dh}10^{-6}} = \frac{10^6}{R\frac{dM}{dh}} \quad (4)$$

where k is the effective-earth-radius factor.

In temperate climates, the average variation of the refractive index near the ground is about -40N/km (ITU-R, 1987). Then, putting R=6370 km gives a value of **k=4/3**. It is therefore, common practice to use a 4/3 earth radius in the design of microwave communication links.

Furthermore, because of the convenience of the 4/3 effective-earth's-radius, it has been widely used in radio propagation work and the radar. However, the procedure has several limitations. It is only an average value and may not be used for purposes other than general computation. In addition, the assumption that **n** decreases linearly with height is in disagreement with the experimentally observed refractive index structure of the atmosphere (Bonkoungou and Low, 1993). It is therefore necessary to use data which is representative of a particular locality to estimate the appropriate values of **k** for a given region.

METHOD AND INSTRUMENTATION

The air temperature, the water vapour pressure, and the barometric pressure were measured simultaneously at the ground surface, and at a height of 100m above the ground surface. The fixed-measuring method using a high tower was adopted. The *'Integrated Sensor Suite' (ISS)* used for the measurements was positioned on a communication mast owned by NITEL and located within its premises in the heart of the town. The equipment is suitable for the measurement because of its *data logger* facility which allows the data to be logged in at regular time interval and stored in the logger. A set of the measuring equipment was also positioned at the ground surface to measure the surface values of these parameters. The data obtained were used to calculate the refractivity values and the mean gradient of M-profile for this range of propagation path, using equations (1) and (2).

The device used for the measurement is the *Davis 6162 wireless Vantage Pro Plus*, manufactured by Davis Instruments, Hayward, California, United States of America. It is equipped with the Integrated Sensor Suite (ISS), a solar panel (with an alternative battery power source) and wireless console, which provides the user interface, data display and analogue-to-digital conversion. The device uses the combination of fan-aspiration to minimize the effects of solar radiation induced temperature error. The ISS houses the external sensor array for measurements of pressure, temperature, relative humidity, UV index, solar radiation, rainfall rate among others. The console is connected to a computer through the data-logger from which the stored data are downloaded.

The frequency of transmission of the *ISS* varied between 868.0 and 868.6 MHz while the error margin of the *ISS* device for temperature, pressure, and relative humidity were ±0.1^{0}C, 0.5 hpa, and 2% respectively.

The basic data employed for the study were radio meteorological data obtained by *in-situ* measurements at a station located at Nsukka *(7.4^{0}E, 6.9^{0}N)* in Nigeria. The data cover the two main seasons of the years considered (i.e. the wet and dry seasons). The meteorological data used for the analysis include the atmospheric pressure P(mb), the temperature t (^{0}C), and the relative humidity R/H (%).The measurements were made every thirty minutes and round the clock for a period of two years (February 2007 to March 2009).

The measured parameters were used to calculate both the refractivity **N** and the refractivity modulus **M,** at the 100m height and at the ground surface, using equation (1) and equation (2) respectively. The refractivity gradients were calculated between the earth's surface and the 100m height.

RESULTS AND DISCUSSION

The results obtained show that the diurnal variation of the refractivity values at an altitude of 100m follow the same pattern for both dry and wet seasons. The maximum N-values are observed in morning and night hours while its minimum values are fixed between 3 pm to 6 pm (Figures 1and 2). The higher values obtained during the morning and night hours may be due to high values of the relative humidity recorded for these periods while the lower refractivity values in the afternoon can be attributed to the low relative humidity which resulted from high temperature associated with this period of the day. The figures also show that N-values are generally lower during the dry season than the values during the rainy season.

Large negative refractivity gradients were obtained for most of the refractivity profiles measured at the station as observed in figure 5. The values obtained revealed that the propagation conditions could be super refractive at any season of the year.

Cumulative probability curves were drawn for the refractivity gradients for the two seasons of the year, as shown in figures 3 and 4. Deductions from the curves are presented in Table 1. The results show that during the rainy season, the surface layer is super-refractive most of the time with the probability of occurrence of duct being 31% (Table 1). As stated in section 2.0 that by using the refractivity modulus model, a transition from a positive to negative gradient gives the evidence of the occurrence of a duct. Super-refraction may occur due to the large humidity lapse rate without any temperature inversion. On the other hand, ducting occurs on days when both the temperature and relative humidity decrease rapidly with height (Hughes, 1988). However, ducting observed in this study could be due to the lapse rate of vapour pressure with height among other factors.

The k-factors were also derived for the station for both the dry and the wet seasons. The mean values of the refractivity gradient □for all the data sets were computed for each of the seasons. Equation 4 was then used to calculate k-factor with R= 6370km.

It could be seen that the value for the rainy season is a little higher than the value for the dry season. But, in general, the values obtained for this station is higher than the value k=4/3 for the temperate climate.

The implication of these results are quite significant on the propagation conditions of microwave signals through the atmosphere in this locality. For example, in a super-refractive condition the path loss is smaller than in the standard atmosphere. Deductions from the cumulative probability curve shows that the occurrence of super- refraction is 80% in the rainy season. The high percentage of occurrence suggests that the worst month with respect to interference is likely to occur in the rainy season when N–values are relatively high. This observation agrees with the results reported by Falodun and Ajewole, (2006).

The probability of large variations due to anomalous propagation is very high in the rainy season owing to the fact that the atmospheric layers are formed above large, flat lakes which are filled only during the rainy season. This situation encourages high 'relative humidity' as a result of evaporation from the surface of the lakes (Grabner and Kvicera, 2003a & b).

As stated in section 2.0, an increase of temperature with height gives rise to super-refraction as does an increase of humidity with height. However, super refraction is most noticeable when both of these effects occur together. In normal atmosphere, temperature and humidity decrease with height since turbulence prevented any great changes in structure. However, there could be periods when the air becomes fairly calm and temperature inversions and humidity lapses could be built up and maintained. This type of situation was observed on the 1st of July, 2009 between 13hr and 20hr LT. This situation is favoured in Nsukka, partly, because of its location from the sea. The condition could build up strong humidity gradients as a result of which super-refractive layers could be formed and trapping of radio waves might follow. The large negative refractivity gradient (< -157) observed at this station confirms the presence of duct. Using the refractivity modulus mode, a transition from a positive to negative gradient gives the evidence of the occurrence of duct (Barclay, 2003). A negative M-gradient above the ground indicates a surface duct. The probability of occurrence of ducting at the surface layer was found to be 31% during the rainy season and 15% in the dry season. The meteorological phenomena involved in the formation of ducting layers are abnormal vertical structures of temperature and humidity, caused by processes such as subsidence, evaporation, advection or heating, and radiation cooling. These processes occur more during the rainy season than in the dry season and this could account for the higher probability of occurrence of ducting recorded during the rainy season. Furthermore, the stratification of the troposphere could result in refractivity layering with layers of different refractive index gradients. Such a layer with a refractivity gradient below -157 N-units/km immersed in a broader region having a smaller refractive index lapse rate is termed ducting layer. In the presence of such a layer, the radius of curvature of the wave trajectory becomes smaller than the radius of the earth, and as a consequence, waves propagating nearly horizontally could be trapped between two levels (the lower being the ground) (Hall, 1979).

Another abnormal phenomenon of interest is sub-refraction. A sub-refractive layer could be present during the day, especially at the time of maximum surface heating. The results have shown that the probability of occurrence of sub-refractivity is 20% in the rainy season while the probability reduces to 5% during the dry season. The presence of processes such as subsidence could be responsible for the low occurrence probability especially in the dry season. Furthermore, subsidence has a tendency to destroy sub-refractive layers and to intensify super-refractive layers. Although the effects of subsidence are generally observed at high levels, they are occasionally observed at lower levels, especially in the subtropics (Bean and Dutton, 1968). Conditions inimical to ducting are those which induce mixing of the lower atmosphere, where the processes of mechanical and convectively induced mixing are at work, the probability of the occurrence of ducting is vanishingly small. A consequence of sub-refraction on a nearly horizontal path is that the wave trajectory comes nearer to the ground. In extreme cases, if there is an obstacle (for instance a hill) along the link, the transmitted signal level can be severely reduced by diffraction resulting in obstruction fading. On the other hand, a large negative refractivity gradient causes ducting, the possible effects of which are prolonged space wave fade-outs, multi-path fading and excessive field strengths at distances many times the radio horizon. Super-refractive gradients are responsible for generally extended service horizon and could cause interference between widely separated radio circuits operating on the same frequency.

The k-factor derived for the station in Nsukka, Nigeria have shown that the ITU-R value of k=4/3 is not appropriate for this location where the value is 1.58. The value is in agreement with the results by Kolawole and Owonubi (1982). They found that the equatorial climatic region has a k-factor value of 1.52 which is greater than that of the tropical continental region of 1.43.

Table 1: Probability of occurrence of propagation phenomena

	Rainy season	Dry season
Probability of occurrence of Sub-refraction	20%	5%
Probability of occurrence of Super-refraction	80%	95%
Probability of occurrence of Ducting	31%	15%

Table 2: The k-factor values deduced for Nsukka

	Average refractivity gradient	k-factor
Rainy season	60.03	1.62
Dry season	57.05	1.53

Figure 1: Typical Diurnal Refractivity variation for February, 2008.

Table 3: Typical data (July 1st, 2008) used for the analysis

Measurements at 100m height						Measurements at ground surface			
Date	LocalTime	$T(^0C)$	RH%	P(mb)	N	$T(^0C)$	RH(%)	P(mb)	N_s
01/07/2008	12:00 AM	19.9	98	969.6	355.92	24.1	86	1014.0	373.98
01/07/2008	12:30 AM	20.1	97	969.1	355.69	23.9	87	1014.7	374.44
01/07/2008	1:00 AM	20.4	96	969.2	356.06	23.4	86	1014.7	370.78
01/07/2008	1:30 AM	20.6	96	968.7	356.85	23.4	86	1014.4	370.70
01/07/2008	2:00 AM	20.7	98	968.5	359.38	23.7	84	1014.1	369.57
01/07/2008	2:30 AM	21.0	98	968.1	360.73	24.5	81	1013.4	369.33
01/07/2008	3:00 AM	20.9	98	967.6	360.13	25.1	81	1012.9	372.06
01/07/2008	3:30 AM	20.8	98	966.6	359.36	25.3	80	1012.7	371.63
01/07/2008	4:00 AM	20.6	98	966.3	358.32	25.3	79	1012.3	370.18
01/07/2008	4:30 AM	20.4	98	965.5	357.16	25.6	78	1012.2	370.22
01/07/2008	5:00 AM	20.3	98	966.3	356.90	26.0	78	1011.8	372.04
01/07/2008	5:30 AM	20.4	97	966.4	356.36	25.9	77	1011.6	370.19
01/07/2008	6:00 AM	20.4	97	966.4	356.36	26.4	75	1011.1	369.52
01/07/2008	6:30 AM	20.6	95	966.6	355.24	26.4	75	1011.1	369.52
01/07/2008	7:00 AM	21.3	88	966.5	350.87	26.5	75	1010.9	369.95
01/07/2008	7:30 AM	21.7	84	966.9	348.28	25.9	80	1011.1	374.16
01/07/2008	8:00 AM	21.6	89	967.8	353.64	25.7	80	1011.1	373.17
01/07/2008	8:30 AM	20.9	94	968.2	356.00	25.5	80	1011.5	372.27
01/07/2008	9:00 AM	21.5	93	968.4	357.76	25.1	84	1011.7	375.77
01/07/2008	9:30 AM	22.2	91	968.3	358.8	24.3	88	1012.3	377.09
01/07/2008	10:00 AM	23.2	89	968.3	361.31	23.8	91	1012.3	378.31
01/07/2008	10:30 AM	23.7	87	968.5	361.37	23.4	92	1012.8	377.62
01/07/2008	11:00 AM	22.7	90	968.6	360.14	23.3	93	1013.1	378.40
01/07/2008	11:30 AM	22.3	91	968.4	359.32	23.3	93	1013.3	378.45
01/07/2008	12:00 PM	22.4	90	968.2	358.59	23.0	94	1013.5	378.16
01/07/2008	12:30 PM	22.9	87	967.6	357.28	22.9	94	1013.9	377.76
01/07/2008	1:00 PM	23.4	86	967.1	358.32	22.7	94	1013.7	376.68
01/07/2008	1:30 PM	23.9	85	966.9	359.43	22.4	95	1013.5	376.28
01/07/2008	2:00 PM	24.2	85	966.6	360.82	22.5	96	1013.0	377.82
01/07/2008	2:30 PM	24.4	85	966.4	361.76	22.6	96	1012.7	378.26
01/07/2008	3:00 PM	24.7	83	966.1	360.57	22.4	97	1012.8	378.42
01/07/2008	3:30 PM	25.3	81	965.8	360.79	22.2	97	1012.5	377.31
01/07/2008	4:00 PM	25.3	80	965.6	359.38	22.1	97	1012.4	376.77
01/07/2008	4:30 PM	26.1	77	965.4	359.08	22.0	97	1012.2	376.21
01/07/2008	5:00 PM	25.4	80	965.3	359.79	21.8	97	1012.3	375.23
01/07/2008	5:30 PM	25.1	82	965.3	361.01	21.7	97	1012.5	374.79
01/07/2008	6:00 PM	24.7	86	965.5	364.34	21.5	97	1012.2	373.72
01/07/2008	6:30 PM	24.5	86	965.5	363.32	21.4	97	1012.1	373.20
01/07/2008	7:00 PM	24.2	87	965.8	363.16	21.4	96	1011.9	372.05
01/07/2008	7:30 PM	23.9	89	966.3	364.30	21.3	96	1012.1	371.62
01/07/2008	8:00 PM	23.7	89	966.6	363.36	21.7	94	1012.0	371.31
01/07/2008	8:30 PM	23.7	89	966.9	363.44	21.9	94	1012.3	372.37
01/07/2008	9:00 PM	23.6	91	967.4	365.54	22.3	94	1012.5	374.36
01/07/2008	9:30 PM	23.4	89	967.4	362.06	22.7	94	1012.7	376.42
01/07/2008	10:00 PM	23.4	90	967.8	363.39	24.1	89	1012.7	377.45
01/07/2008	10:30 PM	23.3	93	968.1	366.62	24.5	87	1012.7	376.93
01/07/2008	11:00 PM	23.0	95	967.9	367.41	25.7	81	1012.7	374.97
01/07/2008	11:30 PM	22.8	95	967.8	366.33	26.4	81	1013.0	378.61

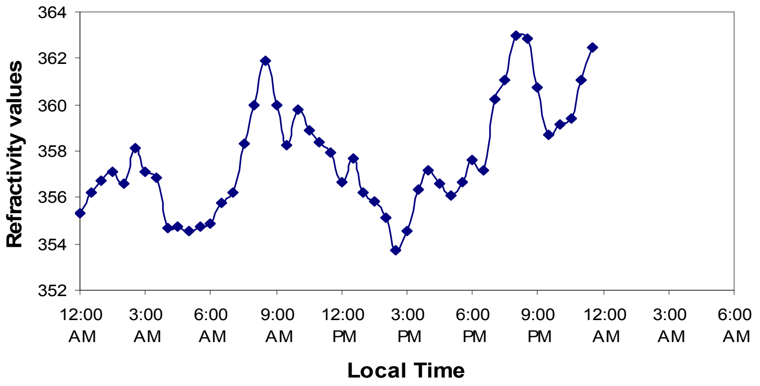

Figure 2: Typical Diurnal Refractivity variation for July, 2009.

Figure 3: Cumulative Distribution curve for Wet-condition.

Figure 4: Cumulative Distribution curve for Dry-condition.

Figure 5: Typical Refractivity Gradient (N-units/km) for December, 2007.

SUMMARY AND CONCLUSION

The refractivity gradient averaged over the 100m height of the atmosphere was studied at Nsukka, Nigeria, and the major findings of this study can be summarised as follows:

1. (1) The probability that the surface layer at Nsukka is super-refractive is 80% during the rainy season and 95% in the dry season.
2. (2) The probability of occurrence of sub-refraction is 20% in the rainy season and 5% during the dry season
3. (3) The probability of occurrence of ducting at the surface layer is 31% in the rainy season and 15% in the dry season
4. (4) The value of N are generally lower at the 100m height than at the ground surface during the two seasons of the year.
5. (5) The effective-earth-radius factor k for the locality was calculated to be 1.54.

Although these effects may not be sufficiently reliable for it to be utilized for commercial communication systems, it does account for some of the abnormally long-distance interference which has been observed in this locality at very high frequency (VHF).

Generally, the refractivity values obtained for the region between the surface and 100m height, have shown that the propagation conditions are super-refractive throughout the year. It is important to note that this report represents one of the recent efforts to acquire accurate refractivity values that reflects the variation of N at a particular locality; whereas most of the previous studies on the subject in Nigeria have been based on meteorological data obtained by radiosonde measurements.

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