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INVESTIGATION OF NON-STANDARD REFRACTION IN A COASTAL AREA OF NIGERIA USING RADIOSONDE DATA

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ABSTRACT
Radio meteorological data obtained by *radiosonde* measurements in Lagos (3.35^0E, 6.06^0N) were used to calculate the refractivity, N at different altitudes as well as at the ground surface, in order to derive the refractivity gradient. The values were computed to a height of about 12km being the highest level for which complete *radiosonde* data were available. The refractivity profile were plotted versus altitude for all the data analysed. The observed refractivity distribution is more nearly an exponential function of height than a linear function as assumed by the 4/3 earth atmosphere. It was also observed that the N-values decrease with altitude from the earth surface. Other parameters, such as the k-factor and the values of the gradient exceeded for given percentages of the time were also derived. The analysis of the results have shown that most of the values of the refractivity gradient for this coastal area are larger than the standard (normal) value of -40 N-units/km and therefore the propagation conditions are super-refractive. The shapes of the curves have confirmed the exponential dependence of refractivity on height, irrespective of the season.
Keywords: *Radiosonde* data, non-standard refraction, refractivity gradient.

INTRODUCTION

The standard atmospheric model used in propagation studies is the one where index of refraction decreases linearly with height, and the decreasing value of refraction causes the radio-wave rays to curve downward. The effect is accounted for by increasing the effective earth's radius by a factor of 4/3 and then assuming that there is no ray curvature for propagation over this larger earth.

However, the standard atmospheric model does not always apply. In certain parts of the world, it often turns out that the index of refraction will have a rate of decrease with height over a short distance that is sufficient to cause the rays to be refracted back to the surface of the earth. These rays are then reflected and refracted back again in such a manner that the field is trapped or guided in a thin layer of the atmosphere near the earth. This phenomenon is known as trapping, or ducting. The confined field will propagate over long distances with much less attenuation than for free-space propagation because of the guiding action. In order to obtain trapping the rays must propagate in a nearly horizontal direction and thus, in order to satisfy the conditions for guiding within the duct, the wavelength has to be relatively small. Consequently, ducting occurs primarily for frequencies above several hundred megahertz (UHF and microwave bands). The formation of ducts is due primarily to the water vapour content of the atmosphere, since this has a stronger influence on the index of refraction than temperature gradients do. For this reason, ducts are most often form over large bodies of water such as in the trade-wind belt of the oceans. Ducting over land surfaces is much less common.

RELEVANT THEORY

The value of radio refractivity on the earth's surface and in particular its vertical gradient most essentially within the first kilometre height, are important parameters influencing the behaviour of radio waves in the troposphere. For practical work in radio meteorological studies, the refractivity is calculated by equation 1 (Smith and Weintraub, 1953).

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

Where *P* is the dry atmospheric pressure, *e* the water vapour pressure (both in millibars), and *T*, the absolute temperature, in Kelvin.

By differentiating the refractivity equation (1), we can obtain an expression for the refractivity gradient as:

$$\frac{dN}{dh} = 77.6\left[\frac{1}{T}\frac{dP}{dh} - \frac{1}{T^{2}}\left(P + \frac{9620}{T^{3}}\right)\frac{dT}{dh} + \frac{4810}{T^{2}}\frac{de}{dh}\right] \quad (2)$$

A very useful parameter for predicting the course of a radio wave propagating in the troposphere is the refractivity gradient. The mean refractivity in the first km height ΔN is a very important parameter in radio communication studies; its value represents approximately the vertical structure of the tropospheric radio refractivity and determines ray bending, fluctuation in the angle of arrival, tropospheric ducting and defocusing among other things.

By substituting average gradient of pressure and water vapour at ground level for temperate latitudes in equation (2) we obtain

$$\frac{dN}{dh} = -4 \times 10^{-2} \ \ m^{-1} = -40 \ N/km \quad (3)$$

The curved path of the radio wave refracted in an atmosphere with such gradient is equivalent to a straight line path on an imaginary earth with a radius 4/3 times true earth radius.

The special case when the ray curvature is the same as the earth's curvature occurs when

$$\frac{dN}{dh} = \frac{1}{a} = -157 \ \ N/km \quad (4)$$

On average conditions, N decreases by about 40 N-units per km in the lowest km of the troposphere. However, the troposphere is a variable medium and quite significant deviations do occur. Over a given height range refractivity profiles can be designated sub-refractive, normal, super-refractive, and ducting as listed below:

$$\frac{dN}{dh} > -40 \qquad subrefraction \quad (5a)$$

$$\frac{dN}{dh} = -40 \qquad normal \quad (5b)$$

$$\frac{dN}{dh} < -40 \qquad super-refraction \quad (5c)$$

$$\frac{dN}{dh} < -157 \qquad ducting \quad (5d)$$

Under sub-refractive conditions, rays will be bent towards the earth less rapidly than in normal conditions whilst in super-refractive conditions rays are bent towards the earth more rapidly than in normal conditions. In ducting conditions, rays are bent towards the earth more rapidly than the earth's curvature over the height range in which dN/dh is less than -157. During ducting, abnormally large ranges beyond the line-of-sight are possible with only modest transmitter powers.

For a ray that propagate along a path parallel to the earth's surface, i.e at constant height, the gradient of the index of refraction is given by

$$\frac{dn}{dz} = -\frac{n}{a+z} \approx -\frac{1}{a} \quad (6)$$

where *a* is the earth's radius and *z* is the height above earth's surface. The average value of the index of refraction gradient for the standard atmosphere is smaller than this value and is given by

$$\frac{dn}{dz} = -\frac{1}{a_e} \quad (7)$$

where

$$a_e = 4a/3 \quad (8)$$

for the standard atmosphere, the ray curves downward, and its height above the earth's surface is the same as that which a ray propagating along a straight line would have relative to an earth with an effective radius a_e integrating equation (3) gives

$$n(z) = n(0) - z/a \quad (9)$$

i.e

$$n = n_s - z/a \quad (10)$$

while for the standard atmosphere

$$n = n_s - z/a_e \quad (11)$$

with non-standard refractive conditions, the index of refraction may decrease with height less rapidly or more rapidly than according to the standard atmosphere (equation 11).

When the decrease is more rapid, the ray will curve downward at a greater rate and hence propagate to a greater distance without getting too far away from the earth's surface. For this reason, the refraction is referred to as super-refraction for this case. When the index of refraction decreases less rapidly, there is less downward curvature, and we have sub-standard refraction. The curvature of the ray path is usually expressed by a *k-factor* which is a scaling factor assumed to be constant for a particular path. For a given climatic region, the *k-factor* can be calculated using equation (Bean and Dutton, 1968):

$$k = [1 + a(dN/dh) \times 10^{-6}]^{-1} \quad (12)$$

METHODOLOGY

Source and Scope of Data

The basic data employed for this study were radio meteorological data obtained by *radiosonde* measurements in Lagos, Nigeria. The data cover the two main seasons of the year, the rainy and dry seasons. The meteorological data which were extracted from the recorded charts include the pressure, *P(mb)*; the temperature, $t(^0C)$; and the relative humidity, *RH(%)*. The records cover every day of the months selected and the recordings were made at 1200hr local time of each day.

The values of *RH* were converted to water vapour pressure, *e*, by using equation (13) (CCIR, 1986):

$$e = \frac{RH}{100} e_s \quad (13a)$$

$$e_s = ae^{\left(\frac{bt}{t+c}\right)} \quad (13b)$$

$$a = 6.1121; \; b = 17.502; \quad c = 240.97;$$

e_s *= saturation vapour pressure (hpa) at the temp* t^0C.

A typical data of the upper air used for the analysis is shown in Table 1. The refractivity is calculated using equation (1), and the data analysis are done using the necessary empirical equations for determining the onset of super-refraction and ducting as indicated in equation (5). Refractivity values were computed to a height of about 12km being the highest level for which complete *radiosonde* data were available. The refractivity values were plotted versus altitude for all the data analysed. Other parameters, such as the k-factor was derived for the coastal area of Lagos. The statistical analysis of the results was also carried out and the values of the gradient exceeded for given percentages of the time were also derived plotted from which the probability of occurrence of each the propagation phenomena could be read.

RESULTS AND DISCUSSION

The data used for the study were from measurements of meteorological parameters made by *radiosonde* of upper air. The data cover selected months in 1990, 1991, 2013 and 2014. The measurement covered both the main seasons (rainy and dry seasons) in the coastal area of Lagos. The measurements were taken at 12:00 noon each day at different altitudes up to a height of about 12km. Using these data, the refractivity modulus was calculated for both the ground surface (N_s) and at different altitudes. A typical result is shown in Table 2.

The height versus N curves were plotted and typical profiles are shown in Figure 1. The figure displays some cases of super-refraction, sub-refraction, and ducting conditions. For the standard atmosphere the N-profile is a straight line with constant positive slope. However, when the slope is less, we have sub-standard condition, while a greater slope indicates super-refraction. An inversion in the profile indicates the presence of a surface duct or elevated duct. Examples are found in the curves for 9th January, 10th January, 2nd February, 2014. It is important to note that these dates fall into the dry season.

Cumulative probability distribution curves were also drawn for the refractivity gradients calculated for all the data analysed. The curve is shown in Figure 2 and deductions from the graph are presented in Table 3.

The k-factor was derived for the coastal area of Nigeria based on the results obtained from this study. The monthly average values are presented in Table 4. The mean value of ΔN for all the data sets was computed for the station and equation (9) was then used to calculate the k value with earth's radius, *a=6370 km*; the average value obtained was 1.66.

Table 1: Upper air temperature, height and winds for December 2013.
At Oshodi - 19 metres @ 1200GMT.
LAT: 6^0 32'N: LONG: 3^0 20'E

			AIR PRESSURE P = 925 HPA			AIR PRESSURE P = 850 HPA				
Day	Ht.	DBT	DPT	RH		Ht.	DBT	DPT	RH	WIND
	GPM	˚C	˚C	%	WIND	GPM	˚C	˚C	%	
1	830	22.8	20.2	85	24004	1558	17.4	14.2	82	4502
2	831	23	19.5	81	4505	1561	18.8	14.5	77	7010
3	841	22	19.5	86	23004	1570	20.6	9.6	48	3511
4	843	23.2	19.2	79	7502	1573	19.2	13.2	67	1512
5	829	22.4	19.4	84	25509	1556	17	14.2	84	2504
6	826	22.8	19.9	84	24008	1554	18.8	14.6	76	22504
7	826	23.4	18.4	74	3002	1555	18.8	14.9	78	3502
8	822	22.4	18.6	79	27005	1550	18.6	14.6	78	8509
9	827	22	18.4	80	/	1556	19.4	11.4	60	/
10	831	22.8	19.4	81	19503	1560	18.8	12.8	70	1508
11	832	21.8	19.1	84	30507	1561	18	14	78	4508
12	/	/	/	/	/	/	/	/	/	/
13	/	25.2	20.5	76	/	/	21	15.9	73	/
14	839	21.6	18.3	82	12007	1566	17.8	5.8	46	9012
15	823	21.4	15.4	71	5509	1549	17.4	10.4	64	/
16	820	24.2	10.2	42	11006	1558	17.8	4.8	41	10006
17	836	26.8	9.8	34	22014	1578	25.2	5.2	28	21510
18	826	23.4	6.4	32	9009	1556	18.2	4.2	39	8010
19	833	26	13	44	11005	1568	21.2	6.2	37	/
20	827	22	17	74	28504	1556	19.2	7.2	44	13005
21	823	18.2	8.2	52	7009	1540	14.4	5.4	53	9509
22	825	23	18.9	78	34002	1554	19.6	6.6	43	6511
23	830	23.4	19	81	26001	1557	19.8	4.8	38	7506
24	828	22.6	18.7	79	28005	1554	15.4	9.4	67	1006
25	836	23.2	19.8	81	35003	1566	20	10	52	5513
26	838	31.4	25.4	70	34001	1583	20.8	10.8	55	4014
27	826	23.2	22.1	94	23003	1554	17.4	16.7	97	7506
28	821	22.6	20.3	87	22507	1550	18.8	17.3	90	30501
29	832	22.4	20	87	26503	1562	19.2	17.1	88	7006
30	837	23.2	19.4	79	26503	1567	18.8	14	74	4505
31	829	23.8	19.8	78	34001	1559	18.2	14.9	81	6507

Ht = Height above ground surface, DBT = Dry Bulb temperature, RH = Relative Humidity

Table 2: Refractivity values calculated at different altitudes for 4th January, 2014.

Altitude (m)	Temperature (^{0}C)	Relative Humidity (%)	Pressure (mb)	Refractivity (N-units)
0.0	31.24	66.8	1028	384.7149
832.0	22.6	72.0	925	326.9289
1563.0	20.6	23.0	850	248.6765
3207.0	10.4	53.0	700	222.5948
5930.0	-6.1	35.0	500	152.3978
9750.0	-30.7	18.0	300	96.56237
12490.0	-52.5	14.0	200	70.38771

Table 2B: Surface Refractivity values (N_s) calculated January, 2014.

Date	N_s	Date	N_s	Date	N_s
1	388.34	12	379.99	23	376.94
2	386.60	13	380.91	24	382.27
3	381.36	14	384.43	25	385.41
4	378.91	15	385.17	26	388.39
5	377.66	16	393.65	27	389.25
6	373.23	17	386.42	28	326.23
7	381.05	18	392.41	29	314.92
8	370.40	19	373.81	30	322.56
9	371.36	20	379.60	31	328.01
10	383.35	21	374.31		
11	367.38	22	379.01		

Table 3: Occurrence probabilities of Non-standard refraction in Lagos.

Probability of occurrence of sub-refraction	12.6%
Probability of occurrence of super-refraction	87.1%
Probability of occurrence of Ducting	0.3%

Table 4 : Average monthly *k-factor* values derived for the coastal area of Nigeria.

MONTHS	k-factor
JAN	1.286061
FEB	1.685774
MAR	1.618204
APR	1.761863
MAY	1.916812
JUN	1.837375
JUL	1.697177
AUG	1.573672
SEPT	1.605314
OCT	1.594026

NOV	1.632874
DEC	1.82146

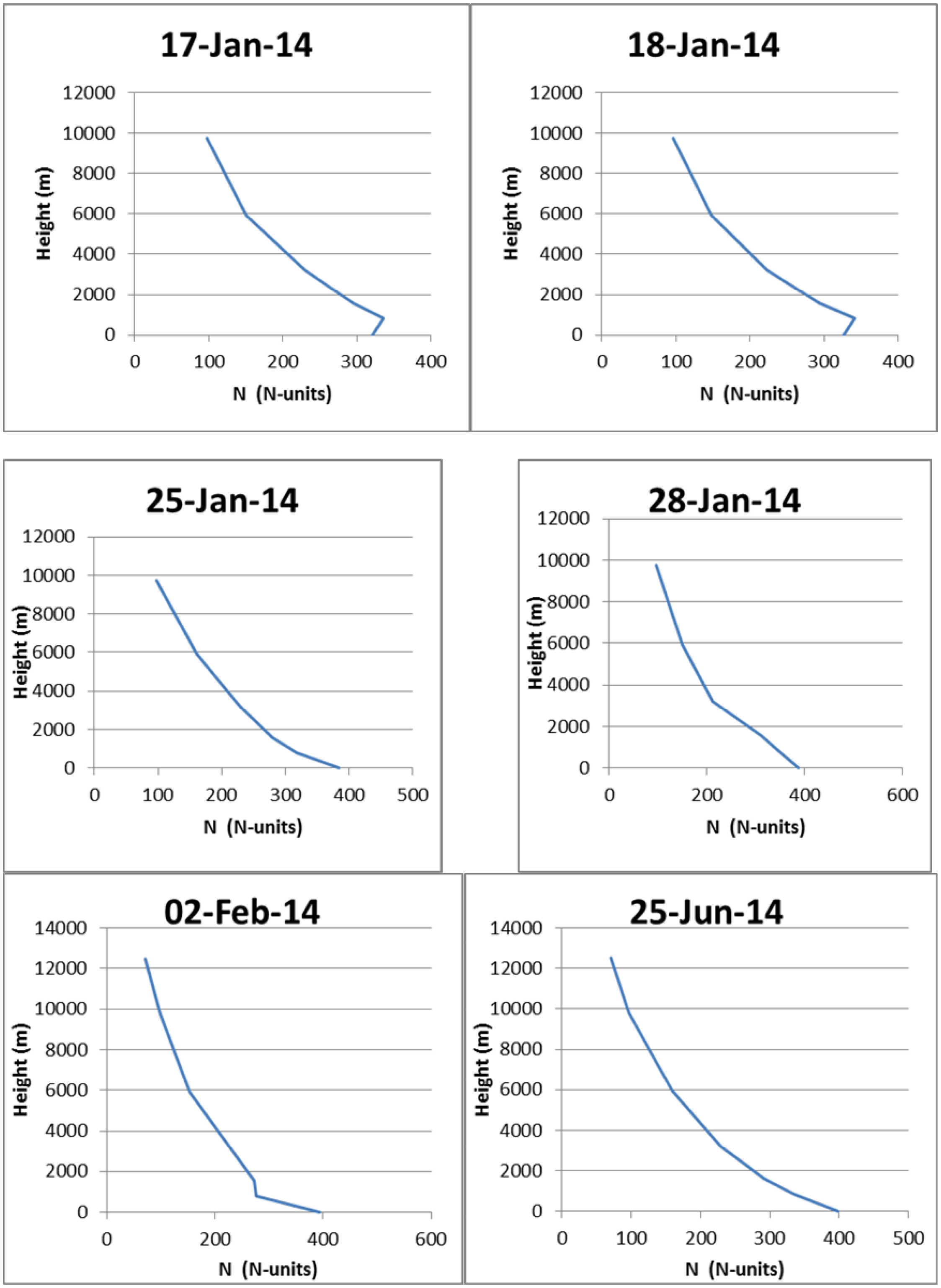

Figure 1: Typical Midday Refractivity profiles for Lagos.

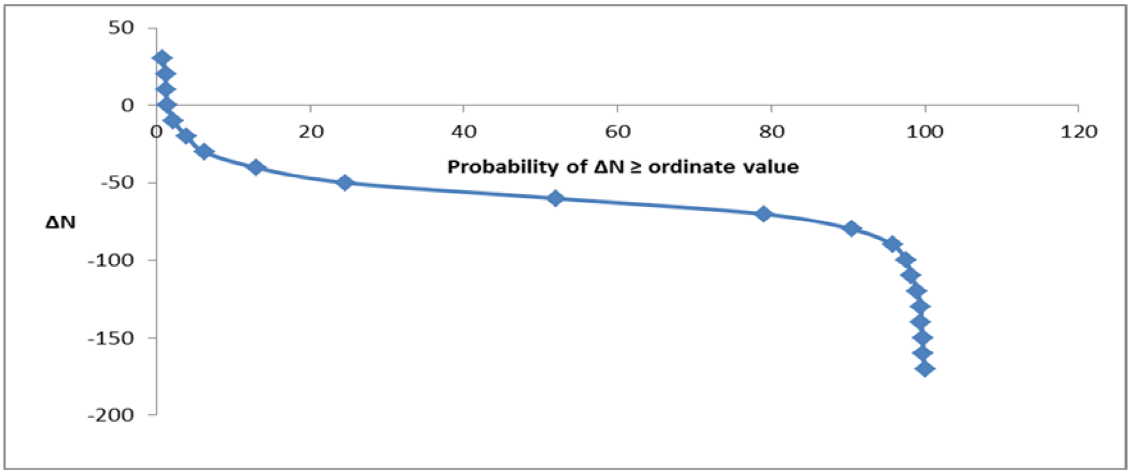

Figure 2: Cumulative Probability Distribution curve for the refractivity- gradients.

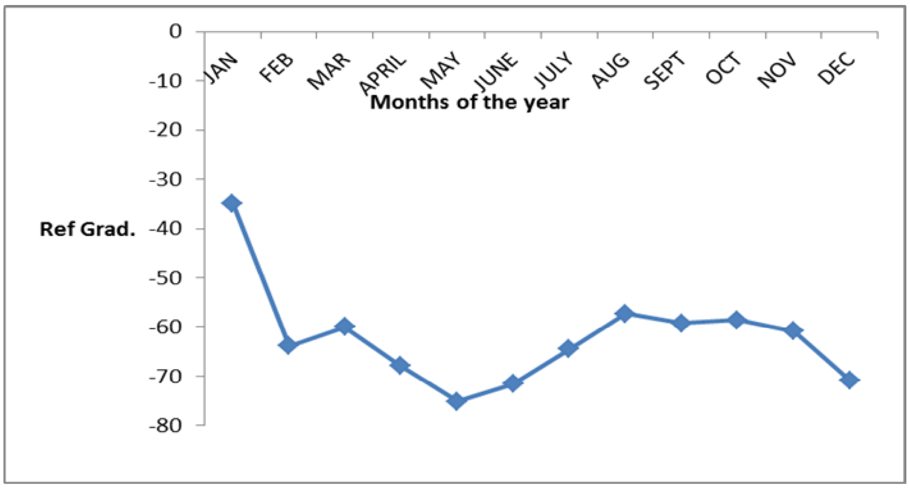

Figure 3: Seasonal variation of Refractivity Gradient.

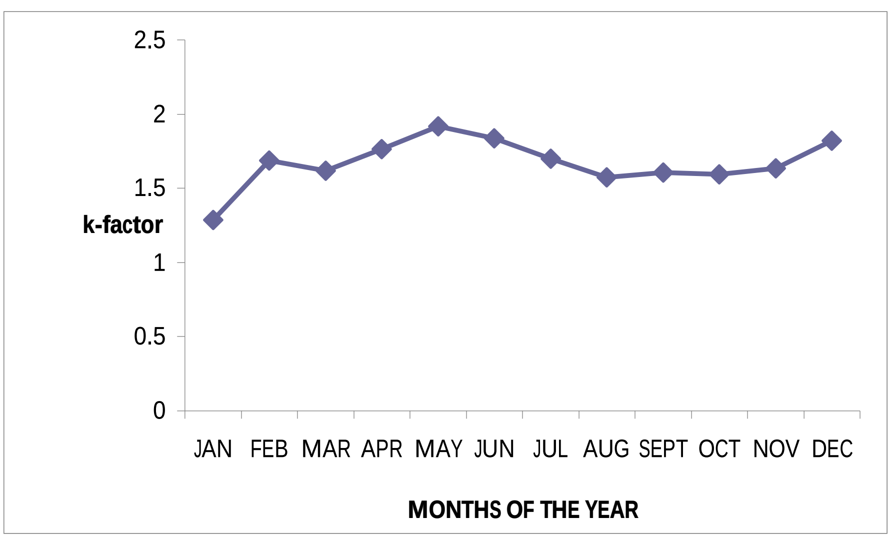

Figure 4: Seasonal variation of the *k-factor* for Lagos, Nigeria.

Seasonal Variation of Refractivity.

The surface meteorological data of temperature, relative humidity, and pressure were used to calculate the surface refractivity N_s. The surface refractivity values were calculated for the two main seasons (rainy and dry seasons) in Lagos.

The climate in Lagos is tropical and is governed by the movement of the inter-tropical discontinuity, a zone where warm, moist air from the Atlantic converges with hot, dry and often dust-laden air from the Sahara, known locally as the harmattan. Lagos like many of the cities in southern Nigeria is in particular under the influence of a large quantity of moisture laden tropical maritime air resulting from the continuous migration of the inter-tropical discontinuity with the sun. The ITD reaches its maximum northward position in July or August and its maximum southward extent in January (Ojo, 1977). In January, its position is approximately 6^0N and all regions north of it will be under the influence of the tropical continental flow resulting in dry season conditions in west Africa (Willoughby, 2002). The inland stations fall under the tropical continental influence during this period. The conditions are such that the water vapour pressures are lower especially at the ground surface. These are responsible for lower values of N_s during this period. However, because of the location of Lagos at the coastal region, there is no marked difference between the wet and rainy seasons which is responsible for the low range of values recorded for this station.

The results obtained show that the coastal station of Lagos displays all-the-year round high values of N_s in the range of 370 to 414 N-units for most of the time, yielding a range of about 44 N-units (see Table 4.2B). The N_s values are generally high during the rainy season while the values fall to the lowest around January, during the harmattan period (270-310 N-units). The high values of N can be associated with the periods of high air humidity observed in Lagos especially during wet season (i.e. March to October). The dry season on the other hand is characterised with dust-laden wind which blows off-shore from the Sahara desert. The effect of the dry, dust-laden wind on radio-wave propagation is more at the surface layer than at higher altitudes. Harmattan could encourage stable stratification of the troposphere which may result in refractivity layering (Falodun and Ajewole, 2006). The results obtained for the surface refractivity are in good agreement with the result of the climatological variations of surface radio refractivity in Nigeria by Kolawole (1980). The high values of N_s recorded in Lagos could be explained by the fact that the wet-term and dry-term have considerable high values as a result of which the total N_s value is high. Furthermore, there is lack of marked seasonal climatic variation, this makes the annual range of N_s to be small as evident in the result (range of N_s = 44 N-units).

The refractivity, N, were plotted versus altitude for all the data analysed. The observed refractivity distribution is more nearly an exponential function of height than a linear function as assumed by the *4/3* earth atmosphere. One might expect the refractivity to decrease exponentially with height since the first term of the refractivity equation involving *P/T*, comprises at least 68% of the total N value, and is proportional to air density, a well- known exponential function of height (Bean *et al*., 1968).

The shapes of the vertical refractivity profiles shown in Figure 4.1 are in conformity with the exponential dependence of N on height reported by other workers (e.g. Bean, 1953; Lane, 1961; Akiyama, 1971; Kolawole, 1980). There is not much difference between the N-vertical profiles for the samples considered for the station because the climate of this region do not have marked seasonal changes especially with reference to humidity. However, some remarkable features could be seen in the profiles for January 16,9,17, 18 (2014); and also February 2, and march 6. As observed for some of the days listed, there is an inversion in the profile structure which suggested the presence of ducts. A ground – based duct is one in which the gradient of N is sufficient to reflect a ray to the same curvature as that of the earth, since ray curvature is given by the gradient of the refractive index: $dn/dh \leq -1/a = -157$ *N-units.*

Typical temperature and humidity conditions are associated with ground-based ducts within each climate. For example, at temperate latitudes, such as Nigeria, ducts arise from typical radiation inversion conditions of increasing temperature and decreasing relative humidity with height. Tropical ducts appear to be due to slight decreases of both temperature and humidity with height at temperature near 25^0C (Hall, 1979). This condition is more prevalent in the morning or late evening and night hours. The low percentage of occurrence of ducting (0.3%) recorded in this study could be attributed to the hour of the day when the *radiosonde* data were collected. Non-the-less, the fact that ducting event is recorded at this hour of the day shows that abnormal propagation of radio-wave can be observed during this hour of day.

The vertical gradient of the refractive modulus in the first km atmospheric layer was calculated on the basis of the mean monthly statistical distributions of N_1 (at 1km) and N_s. Seasonal trend of the vertical gradient of the refractive modulus (Fig 3) shows that the monthly variation has a form of the curve with some minima points with the first corresponding to the end the dry season around February; and the second, the onset of the rainy season around May. The more negative value observed in the month of December could be associated with the peak of the harmattan in this period.

The most common parameters are $g_{0.1}$, the gradient averaged over the first 100m, or g_1 the gradient averaged over the first kilometre of the atmosphere. Whereas $g_{0.1}$ is the most appropriate for studies concerning line-of-sight propagation, g_1 on the other hand, is more adapted to studies relative to ground–to-aircraft or ground-to-satellite propagation as well as to trans-horizon propagation. Other parameters such as the values of the gradient exceeded for given percentages of the time were also derived and results are tabulated in Table 3. The gradient g_1 was evaluated between the earth's surface and height of 1km. Most of the values of g_1 for this coastal area are larger (more negative) than -40 N-units/km, the value of the standard atmosphere.

Therefore the propagation conditions are super-refractive, that is, the path loss is smaller than in the standard atmosphere. The probability of occurrence of super-refraction was found to be 87.1%, while that of sub-refraction was 12.9% (Table 4). An increase of humidity with height was noticed within the first km height in many of the cases analysed. The occurrence of super-refraction, which is very frequent at the station could be attributed to this increase.

The effective-earth-radius factor was calculated based on the data analysed for this study and the average value was found to be 1.66. The k-factor was calculated to be 1.70 for the rainy season while the value was 1.606 for the dry season months. These results agree with previous works done on k-factors in this tropical region. For example, Kolawole and Owonubi (1984) found that equatorial climatic region has a k-factor value of 1.52 which is greater than that of the tropical continental region of 1.43. Their analysis was based on radiosonde ascents made once a day at 12:00hr local time. In another study coducted by Falodun *et al.* (2000), the effective-earth-radius factors for the coastal and savannah regions of Nigeria were found to be 1.62 and 1.59 respectively.

This analysis is based on *radiosonde* data obtained from *radiosonde* ascents made once a day at 12:00hr LT. It is pertinent to note that abnormal or non-standard refraction which may have appeared during the early morning and late night hours may have been missed.

Furthermore, the *radiosonde* data used for the study have limitation with regard to the accuracy with which refractivity gradient can be estimated. They only give average gradients over a height range and can therefore miss very thin and intense ducting layers. Apart from this, they are usually collected once or twice a day at given times and can therefore lead to a statistical description which may not adequately reflect daily variations (Bean and Dutton,1968).

Implications of the Results

For proper understanding of the influence of the measured refractivity profiles on wave propagation, the losses measured on the same days have to be considered as a function of local time. The losses depend in general on the variation of the refractivity along the radio path. The occurrence of propagation phenomena such as sub-refraction, super-refraction and ducting, which is due to the variation of the radio refractivity may be responsible for the reduction or enhancement in signal level compared with the values in the standard atmosphere. The enhanced field strength is associated with increased refractivity gradient variation above that of the normal condition and this can create interference with signals from distant systems. Conversely, less rapidly changing refractivity gradient than the normal condition implies low variation in the field strength. The interference (sometimes resulting in an outage) from distant stations often experienced in this locality can thus be partly explained in terms of this anomalous propagations associated with this area. For example, the super-refraction of radio waves may be responsible for signals often received from distant radio/television stations in Lagos during dry (harmattan) season. Interference of signals is also observed when these signals superimpose on the existing locally transmitted signal that shares the same frequency. However, the planning of optimized broadcasting services requires that interference with other radio services sharing the same frequency band, occurs for a small percentage of the time (e.g 5%) ITU-R, 2004. The expected outage period (in terms of super-refraction and ducting occurrence only) for Lagos, based on this study, is however, higher than this required minimum.

SUMMARY AND CONCLUSIONS

The refractivity values at Lagos, a coastal area of Nigeria, shows that the propagation conditions are super-refractive especially during the raining season.

1. The shapes of the refractivity profile curve have confirmed the exponential dependence of refractivity on height, irrespective of the season of the year.
2. It was observed that for this coastal station, the shape of the vertical N-profiles are quite similar throughout the heights considered.
3. For the refractivity gradient averaged over the first kilometre of the atmosphere, the probability of occurrence of super-refractivity was found to be 87.1% while the probability of occurrence of sub-refraction and ducting were found to be 12.9% and 0.3% respectively.
4. The refractivity in the coastal area of Lagos has all-the-time high N-values between 370 and 414 N-units.
5. The effective-earth-radius factor for the coastal area was found to be 1.66. Therefore, the value of $k = 4/3$ used for design purposes for temperate latitude is inadequate for the coastal area of Nigeria.

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