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STUDIES OF SUPER-REFRACTIVITY AND DUCTING OF RADIOWAVES IN NIGERIA

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Abstract. Studies of tropospheric refraction of long and short wavelength radio signals have been carried out in the coastal and savannah areas of Nigeria using meteorological data collected by radiosondes in Lagos (3^0 45' E, 6^0 28' N) and Kano (8^0 30' E, 12^0 2'N). Daily mean values of the initial refractivity gradients, dN/dh, were computed for the two zones and the results obtained have been used to classify the refractivity profiles as sub-refractive, normal, super-refractive and ducting. The refraction of radiowaves in the lower atmosphere is considered to be normal whenever the refractivity gradient is –40N/km. Between about – 41N/km and –156.9N/km, the atmosphere is super-refractive and when the refractivity gradients become equal to, or more negative than –157N/km ducting occurs. The modified refractive index was also computed for the two zones. A negative gradient of M is a useful indicator as to the occurrence of ducting. The refractivity values obtained show that the propagation conditions are super-refractive at the coastal region, especially during the rainy season. At Oshodi, the surface layer is super-refractive 75% of the time with 38% probability of occurrence of ducting. The surface layer at Kano, on the other hand, is sub-refractive 88% of the time with the probability of occurrence of ducting being only 3.5%.

1. INTRODUCTION

At frequencies above 30MHz, the ionosphere does not normally reflect radio energy. On the other hand, the variability in the characteristics of the received fields is attributed to variation in the lower atmosphere and in particular to the radio refractive index. Hence, the refractive index of the troposphere is of major concern in the propagation of radio waves at these frequencies. The value of radio refractivity on the earth's surface and in particular its vertical gradients, most essentially within the first kilometer height are important parameters influencing the behaviour of radio waves in the troposphere.

The refraction of radio waves in the lower atmosphere is considered to be normal whenever the refractivity gradient is -40N/km. Between about –41N/km and –156.9N/km, the atmosphere is super-refractive and when the refractivity gradient becomes equal to, or more negative than –157N/km ducting occurs [1].

A consequence of super-refraction and ducting is the extension of the radio range, which sometimes leads to radio interference between neighbouring transmission links. On the other hand, sub-refraction produces greatly reduced radio horizon.

In the present study, daily mean values of the refractivity gradient have been used in the analysis of the daily occurrence of the phenomena of super-refraction and ducting.

The paper also discusses the temperature and relative humidity gradients responsible for occurrence of the phenomena.

2. RELEVANT THEORY

The radio refractive index, n, of an air parcel is given by:

$$n = \frac{c}{v} = \sqrt{\varepsilon\mu} \qquad (1)$$

where:

c: = speed of e-m wave in vacuum

v: = speed of e-m wave in air

ε = relative permitivity

μ: relative permeability

For most practical cases, $\mu = 1$. If the refractive index is regarded as a complex number, equation (1) can be written as [2]

$$n = \sqrt{\mu} = n - ik \qquad (2)$$

It is however usual to work with the refractivity N defined by:

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

N depends on the pressure P (mbar), the absolute temperature T (K) and the partial pressure of water vapour 'e' (mbar). For the purpose of practical work in radio meteorology, a form of the equation often employed for calculating refractivity is given as [1],

$$N = \frac{77.6p}{T} + \frac{3.73\times 10^5 e}{T^2} \qquad (4)$$

The first term of the equation is often called the dry term, while the second term, which is a function of vapour pressure, is referred to as the wet term. Another important parameter to be defined is the modified refractive index expressed as:

$$M = \left[(n-1) + \frac{h}{a}\times 10^6\right] = N + \frac{h}{a}\times 10^6 \qquad (5)$$

A negative gradient of M is a useful indicator as to the occurrence of ducting.

In the lower troposphere the radius of curvature of a ray path is decided by the lapse rate of refractive index with height according to the expression:

$$R = \frac{1}{-dn/dh} = -\frac{10^6}{dN/dh} \qquad (6)$$

The minus sign implies that the radius of curvature will be positive i.e. the propagation path will be convex only when the refractive index decreases with height. For tropospheric propagation, refractivity height gradient determines the path and this can be derived from equation (4) as:

$$\frac{dN}{dh} = 77.6\left[\frac{1}{T}\frac{dp}{dh} - \frac{1}{T^2}\left(p + 9620\frac{e}{T^3}\right)\frac{dT}{dh} + \frac{4810}{T^2}\frac{de}{dh}\right] \quad (7)$$

Under normal conditions, $\frac{dN}{dh} = -4\times10^{-2}$ m^{-1} = -40N/km. However, situation when the ray curvature is the same as the earth curvature occurs whenever $\frac{dN}{dh} = \frac{1}{a} = -157$ N/km.

N decreases by about 40N/km (M increases by about 117N/km) in average conditions at midlatitudes in the lower troposphere. If the lapse rate of N is less than 40N/km, the downward curvature of radio rays will decrease, sub-refraction occurs. On the other hand, if the lapse rate of N exceeds 40N/km, the ray curvature will increase, and super refraction occurs. When the lapse rate of N exceeds 157 i.e. dN/dh < -157 or equivalently dM/dh < 0, the rays are bent towards the earth more rapidly than the earth's curvature and ducting occurs [3].

3. MATERIALS AND METHOD

3.1 Sources and Scope of Data

The basic data employed for the study are meteorological data obtained by radiosonde measurement in Lagos (a coastal area) and Kano (a Savannah area) as shown in Table 1. The analysis is based on radiosonde data obtained from radiosonde ascents made once a day at 1200hr local time. The daily mean values of refractivity gradient, dN/dh, were computed for the two geographical zones. The results obtained were then used to classify the refractivity profiles as sub-refractive, super-refractive and ducting. Refractivity profiles figs.1 and 2, were plotted for each day and cumulative probability distribution curves, figs.3 and 4 were drawn from which the probability of occurrence was read for each phenomenon. The deductions from the cumulative probability curves were presented according to the seasons. The rainy season consists of the months of May, June, July and August while the dry season is made up of November, December, January and February. March, April, September and October are grouped as transition months between the two seasons.

Table 1: List of the months studied

Oshodi Station	Months
1966	March, June, July, December
1968	August, September, October, December
1969	January, Feb., March, April, August, September, October, Nov., December
1989	December
1990	Jan., Feb., March, April, May, September, October, November, December
1991	March, April, May, June
Kano Station	**Months**
1974	June, July, September
1989	May, September
1981	June, July, September, October
1985	January, June, July, Sept., October, November
1979	April, June, July, Sept., October, November
1980	January, May, June, July
1988	April, May, September
1990	January, May
1978	July, September
1983	July

4. RESULTS AND DISCUSSION

4.1 Super-refraction and ducting at the surface layer

For the purpose of this discussion, the surface layer would be considered as the layer between the earth surface and a vertical distance of 10m. Deduction from the cumulative probability curves tabulated on Table 2 shows that the probability of occurrence of super-refraction is 73% in the rainy season for the coastal region while a higher value of 78% was recorded for the dry season months of November to February. The probability of occurrence of ducting (surface ducts) is 24% during the rainy season and 33% in the dry season. Calculations of the refractivity N, and the modified refractivity M, were made using the meteorological data obtained by radiosonde. Typical values are shown in Tables and 4.

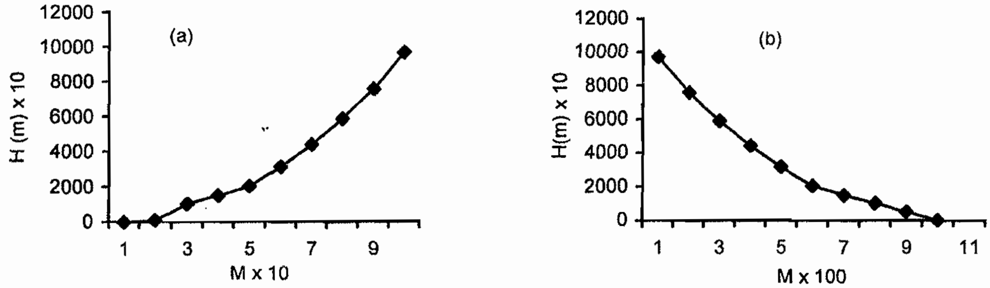

Fig.1: Typical vertical refractivity profile for oshodi

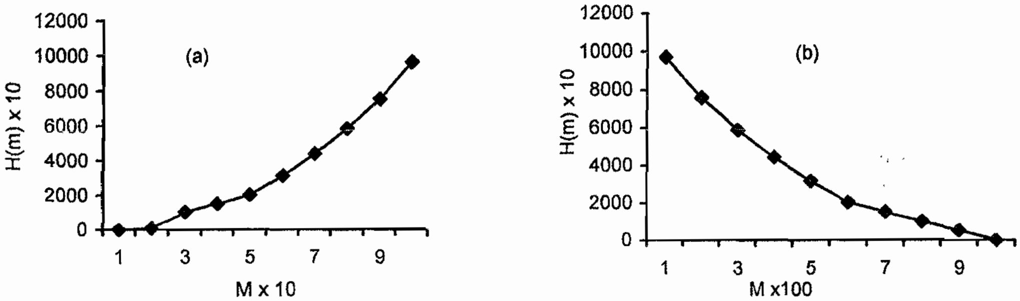

Fig.2: Typical vertical refractivity profile for Kano

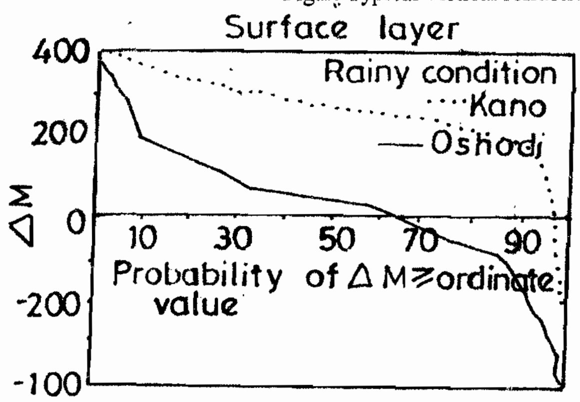

Fig.3: Cumulative probability distribution of ΔM for Oshodi

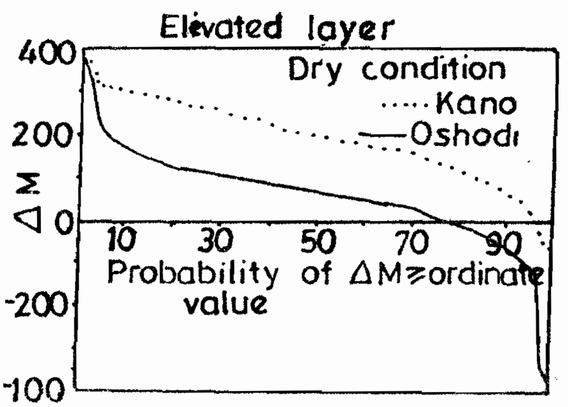

Fig.4: Cumulative probability distribution of ΔM for Kano

Table 2: Deductions from the cumulative probability curves for the surface layer

	Oshodi			Kano		
For the surface layer	Rainy	Transition	Dry	Rainy	Transition	Dry
Probability of occurrence of sub-refraction	27%	18%	95%	95%	-	81%
Probability of occurrence of super-refraction	73%	82%	78%	05%	-	19%
Probability of occurrence of ducting	24%	35%	33%	03%	-	04%

Previous studies have shown that African coasts are highly susceptible to both super-refractivity and ducting [4]. The sea breeze circulations responsible for the differential heating of the land and sea may cause warm air over land to become less dense and rise up giving way to cool moist air flowing in from the sea unto land. This exchange of the thermally different air is likely to produce ground-based temperature inversions associated with large humidity lapse rate resulting in the formation of super refractive layers. The formation of ducts is caused primarily by the water vapour content of the atmosphere since this has a stronger influence on the index of refraction

Table 3 Typical values of N and M computed using values of P, T, and e recorded in July 1978. Station of recording: Kano

Height (m)	Pressure, hpa	Rh/%	Temp./°C	N	M
9709	300	10.0	-13.60	96.71	1620.89
7598	400	3.0	-15.70	120.94	1313.72
5885	500	16.0	-8.70	149.48	1073.84
4447	600	28.0	1.30	178.95	877.07
3177	700	22.0	13.20	204.85	703.60
2050	800	37.0	20.10	249.69	571.51
1514	850	92.0	20.00	317.78	555.46
1020	900	76.0	23.80	329.43	489.55
520	950	48.0	30.07	325.45	407.09
0	1013	45.0	31.07	339.60	339.60
ΔM = 146.65					
ΔN = -10.34					

Table 4: Typical values of N and M computed using values of P, T, and e recorded in July 1978. Station of recording: Oshodi

Height (m)	Pressure, hpa	Rh/%	Temp./°C	N	M
0	1013	64.0	32.00	378.91	378.91
86	1000	64.0	30.00	365.64	379.15
1016	900	77.0	21.00	319.49	478.99
1508	850	66.0	18.00	286.14	522.87
2025	800	54.0	14.00	255.03	572.92
3142	700	43.0	8.00	214.88	708.12
4395	600	30.0	1.00	179.61	869.56
5852	500	29.0	-6.00	151.17	1069.86
7566	400	28.0	-16.00	123.52	1311.28
9657	300	28.0	-33.00	97.68	1613.69
ΔM = 96.36					
ΔN = -58.62					

than does temperature gradients. For this reason ducts commonly form over large bodies of water. A quiet atmosphere is also essential for ducting this makes the occurrence maximum in calm weather conditions over water or plains [5].

Also important for the formation of duct is a high humidity in the lower troposphere like the values recorded at Oshodi. The harmattan season in West Africa, which falls between about November to February, favours both super-refractivity and transhorizon propagation at VHF. The harmattan effect may be said to represent the effect of dust particle from the desert on tropospheric propagation [6]. During harmattan, Oshodi has high relative humidity and temperature inversion, which is very conducive for large lapse rate of refraction. This may be responsible for the higher probability of occurrence recorded during the dry season.

The occurrence probability of super-refraction in Kano is 19% in the dry season and 5% during the rainy season. This results show that Lagos has a higher probability of occurrence compared with Kano. It is also observed that the occurrence depends more on the season, which can be argued for Kano whose refractivity is characterized by marked seasonal changes. The lower probability of occurrence of super refraction estimated for Kano could be attributed to the weather condition. It is hot during daytime and when night falls the clear sky, which promotes intense heating during the day also, causes rapid radiation in the night. The increase in the probability of occurrence of both super-refraction and ducting during the dry season could be due to the effect of harmattan, which blows offshore from the Sahara desert and reach this region as a dry, dust-laden wind. The presence of harmattan could encourage stable stratification of the troposphere, which may result in refractivity layering.

It may be argued that super-refractivity and ducting conditions are minimal in the inland regions because of radiative heating, when temperatures become exceptionally high and relative humidity quite low. Also during the daytime hours, the atmospheric boundary layer is well mixed as a result of thermal convection. These processes are inimical to the stratification of the atmosphere and result in uniform vertical distribution of humidity and decrease of temperature with height, thus reducing the probability of occurrence of super-refractivity and ducting conditions [7].

Generally, the incidence of super-refraction and ducting in the dry season months of November to February exceeds the occurrence number observed in the rainy season from May to August. (For Oshodi, Lagos 33% and 24% during the dry and rainy season respectively). This is fairly in agreement with similar investigations carried out by [7] at three Nigerian radio-meteorological stations namely Lagos, Kano and Minna.

4.2 Super refraction and ducting at elevated layers

The elevated layer is considered as a height up to about 1000m above the earth surface. Table 5 shows the summary of the deductions from cumulative probability curve drawn for a 1km height layer. At this layer, the probability of occurrence of super-refraction is 98% in the rainy season and 90% during the dry season at Oshodi. The N-values computed for this layer are highest during the rainy season. The probability of layer 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 during the rainy season [5].

The occurrence of super-refraction and ducting at the elevated layer are caused principally by the subsidence of an air mass in a high-pressure area. As the air descends it is compressed and thus normal and dried. Elevated ducts occur mainly above the clouds and can interfere with ground-aircraft communications. The observed signal degradation, fadeouts and abnormal ranges observed in the troposphere are due largely to the occurrence of these phenomena [6].

At Kano, the probability of occurrence of sub-refraction is high at the elevated layer for both dry and rainy seasons. The value is however higher during the dry season. For super-refraction, the probability of occurrence at this layer was found to be 38% during the rainy season and 24% during the dry season. The atmospheric conditions that are inimical to the stratification of the atmosphere favours the formation of sub-refraction. These conditions are quite prevalent in the elevated layer of the Savannah region. Sub-refraction produces greatly reduced radio horizon.

Table 5: Deductions from the cumulative probability curves for the elevated layer

	Oshodi			Kano		
For the first km height	Rainy	Transition	Dry	Rainy	Transition	Dry
Probability of occurrence of sub-refraction	02%	02%	10%	62%	62%	76%
Probability of occurrence of super-refraction	98%	98%	90%	38%	38%	24%
Probability of occurrence of ducting	-	-	-	0.3%	-	-

5. CONCLUSION

It was observed among other things that an annual average of ground-based ducting occurrence probability is 28% at the coastal station of Oshodi, 33% occurrence in the dry season months of November to February and 24% in the rainy months of May to August. Super-refractive conditions also exist for about 7.5% of the time. At Kano, ducting occurs for 4% of the time and super-refraction for about 12% of the time. The probability of occurrence of sub-refraction is quite high at the elevated layer for both dry and rainy season.

It is to be borne in mind that the analysis is based on radiosonde data obtained from radiosonde ascents made once a day at 1200hr local time so that super-refractive and ducting gradients which may have appeared during the early morning and late night hours may have been missed.

At present, knowledge of duct is poor. This is due to the limitations of radiosonde data used. These data have limitation with regard to the accuracy with which refractivity gradients can be estimated. They only give average gradients over a height range and can therefore miss very thin and intense ducting layers. Despite the pervious work done so far on troposheric propagation what is readily available is surface refractivity. However the need still exists for the experimental determination of the refractivity gradient. The harmattan effect on tropospheric propagation also deserves more intensive and extensive investigation.

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