Inter Jour. of Scientific Research
Vol.1, No.1 (2011) 43-54

SEASONAL VARIATION OF COASTAL REFRACTIVITY GRADIENTS IN A TROPICAL ENVIRONMENT

O. D. Oyedum, S. O. Ibrahim, J. O. Eichie, K. C. Igwe and M. Abiodun

Department of Physics
Federal University of Technology
Minna, Nigeria

ABSTRACT

Variation of radio refractivity in the troposphere is an important factor for predicting the behavior of electromagnetic wave propagation as well as performance of terrestrial communication systems. This effect can be quite pronounced in coastal areas especially in the Tropics. This paper presents results of analysis radiosonde data obtained from Lagos (a southern Nigeria city on the Atlantic coast of West Africa) between 1991 and 1993. The effort is to determine the variability of vertical refractivity gradients at various height ranges within the first kilometer above the surface. The result shows that high prevalence of isolated strong ducting events due to severe refractivity gradients occur in clear-air conditions while more moderate ducting, or even subrefractive, gradients also occur during the wet season. Variability of surface temperature and refractivity gradients are highest in wet season, and the monthly means of surface refractivity and vertical refractivity gradients are generally poorly correlated. Observed propagation conditions and their seasonality have considerable impacts on terrestrial radio applications.

1. Introduction

Variation of refractive index of air is an important factor of interest concerning many applications of propagation of radio waves in the lower atmosphere, especially at microwave frequencies under clear-air ducting conditions. The propagation path and intensity of terrestrial microwave communications and radar transmissions can be substantially affected by changes in the vertical refractivity profiles in the troposphere. Large-scale variation of refractive index with height, and the extent to which it changes with time, are useful parameters for assessing the propagation characteristics of the troposphere which may vary greatly, depending on the type of air mass (Gossard, 1977). Lateral and vertical temporal variations of refractive index over time scales of minutes to hours can be used with appropriate propagation methods such as the parabolic equation method to predict diurnal signal level variations, especially in modeling terrestrial link performance as a function of time. Variations in vertical refractivity gradients change the propagation conditions to non-standard conditions such as subrefraction, superrefraction or ducting, each of which has serious implications with regard to signal loss, signal enhancement, anomalous propagation as well as variations in angle of arrival at the receiver (Valtr and Pechac, 2005). Less negative (or less severe) refractivity gradients increase the height of potential obstacles as well as the earth's bulge on a line-of-sight (LOS) path, thereby increasing possibility of obstruction of the link.

Keywords: Radio Refractivity, Refractivity Gradient, Propagation, Duct.

Changes in effective obstacle height (including hills) due to changes in refractivity gradients, and hence effective earth's radius factor *k*, may produce significant fading beyond a LOS path. Thus, knowledge of variability of vertical refractive index gradient and *k* enables determination of path-averaged *k* required to minimize subrefractive diffraction to ensure good Fresnel zone clearance on such LOS paths (Oyedum, 2008). Anomalous propagation may cause adverse interference at transhorizon distances, thereby limiting frequency re-use. Reflections from stratified atmospheric layers cause multipath fading on line-of-sight paths as well as interference on transhorizon paths, especially at frequencies below about 1 GHz, while effects of ducting dominate at higher frequencies. Superrefraction of a radar beam for weather surveillance produces more bending towards the ground surface than expected for standard conditions, thereby intensifying the problem of ground clutter echoes in such applications as automated quantitative precipitation estimates (Bech et al, 2002). Studies of radar propagation conditions are often carried out to determine the prevailing propagation conditions, particularly in coastal areas which are potentially prone to such anomalous propagation.

There is evidence, in some climates, of negative correlation between transmission loss and mean refractive index in the first kilometer of height (ΔN), except where the annual range of the parameter is relatively small. ΔN is particularly useful in predicting performance of tropospheric radio links. Studies have shown that there is good correlation between ΔN and surface refractivity N_s, especially in temperate climates (Bean and Dutton, 1968), while Oyedum and Gambo (1994) show that significant correlation between N_s and field strength of transhorizon VHF signals in a tropical environment. World maps giving values of ΔN at various locations have also been prepared, although the values shown may well be exceeded in particular seasons or months, especially in mountainous or coastal regions where the charts are not suitable (Hall, 1979; Bech, et al, 2002). Knowledge of variability of vertical refractivity gradient dN/dZ from the surface up to specific height ranges in a region is desirable for planning communication links for which such height ranges are particularly relevant (Hall, 1996). Thus, variability of surface refractivity gradients is generally important for terrestrial transmissions, while variability of refractivity gradients in the 0-100m height range is important for short paths with low terminal heights; larger height intervals like 0-1000m are relevant to more distant paths such as transhorizon paths or slant paths. Implementation of various propagation models also require information on dN/dZ variability within certain height ranges in the region concerned.

ITU-R Recommendation *P*.530-6 for prediction of terrestrial LOS link reliability when degraded by clear-air effects requires the parameter P_L which represents the percentage of time that average refractivity gradient in the lowest 100m of the atmosphere is less than –100N/km for the worst month (Hall, 1996). ITU-R Recommendation *P*.453-8 also provides charts indicating values of refractive index gradient not exceeded for given time percentages during an average year in the first 65 m height of the atmosphere (Sizun, 2005).

2. Coastal Environments And Atmospheric Ducts

Good design of modern communication and radar systems involves assessment of the system performance based on ability to predict variation of the received signal level in the troposphere due to changes in refractivity and terrain, especially in coastal regions where the two factors often combine to induce formation of surface-layer evaporation ducts as well as elevated ducts, which are common features of coastal areas. Transitions from land to sea can cause strong horizontal temperature and humidity gradients which may combine with the associated local circulations such as land and sea breeze systems to induce subrefractive, superrefractive or ducting conditions over relatively short distances in coastal regions (Kulessa et al, 2007). A good account of the influence of marine layer boundary dynamics on coastal refractivity profiles is given by Haack and Burk (2001). Coastal circulations generally have significant influence on propagation conditions around the coast. While compression and shallowing of marine boundary layer is favourable to surface-based ducting, lifting due to orographic blocking or local convergence may sufficiently weaken the temperature and moisture gradients to induce subrefraction. Signal enhancement occurs if both ends of a communication link are situated within the ducting layer; multipath interference may occur if both terminals are below or above the ducting layer; while defocusing or beam blockage may result when the terminals are on either side of the ducting layer.

Surface-based ducts and elevated ducts (Figure 1) result from temperature inversion, sharp decrease in vertical gradient of humidity or a combination of the two.

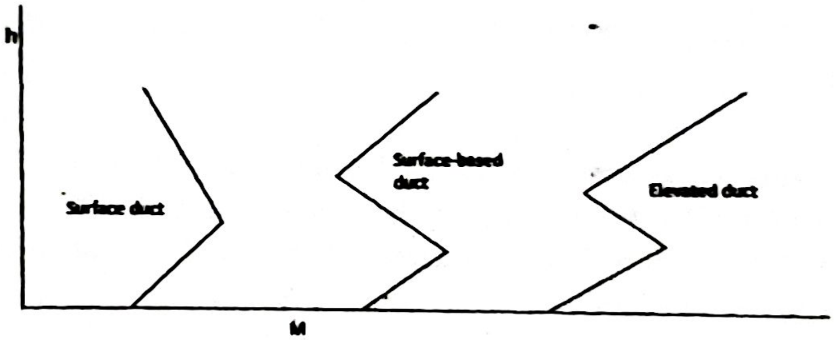


Figure 1: Typical Profiles Of Modified Refractive Index *M* With Height *h* Showing Surface Duct, Surface-Based Duct And Elevated Duct

Temperature inversion may be caused by evaporation, advection, night-time ground cooling by radiation, and subsidence of air; it occurs in stable atmospheric condition, causing a good amount of water vapour to be trapped below the inversion layer. Temperature inversion causes subrefraction if accompanied by condensation and resultant reduction in water vapour pressure (typical of high humidity areas); otherwise it results in superrefraction or ducting due to resultant steeper humidity gradients. Coupling into the duct depends on the angle of incidence at the duct layer boundary, the duct width, the refractivity gradient within the duct and the frequency of the radio wave.

Subsidence of drier air associated with anticyclonic motion results in warming of the air mass due to adiabatic compression, making the air parcel above warmer than that below. The resulting temperature inversion has a stabilizing role on the atmosphere and gives rise to elevated subsidence ducts. Elevated duct is associated with rapid decrease of refractive index with height and occurs if the value of modified refractive index M at the top of the ducting layer is greater than the value at some height below the layer. Subsidence ducts can persist for substantial time durations with lateral spread of many hundreds of kilometers; typically they occur between 1 and 2 kilometres of altitude, which is too high for coupling from low elevation base stations. However, they still have potential for causing pockets of anomalous propagation and 'radio holes' at given distances from the transmitter; and even relatively modest ducts can produce substantial regions of signal depletion and beam distortion with considerable implications for performance of communication systems such as airborne radar system detection capability. Whereas significant signal enhancement requires strong gradients, radio holes may result from relatively modest ducts or less severe non-ducting changes in refractivity gradients (Hermann et al, 2002). Elevated ducts can cause multipath fades on point to point microwave links, especially over flat terrain in coastal areas.

Surface-based evaporation ducts occur over large water surfaces like oceans when the refractivity value at the top of the ducting layer is less than the value at the surface, and are more or less persistent. They can be as low as 1-2 m high, higher than 10-15 m over warm seas, but generally less than 30 m for advection duct. They can substantially affect VHF/UHF and microwaves above 3 GHz (Gerstoft et al, 2000), especially sea-to-shore transmissions. Surface ducts are more common and generally of much greater practical importance, and wideband applications at microwave ranges are particularly susceptible to perturbations of the duct strength (Sirkova, 1998).

3. Methodology

Daily record of radiosonde data collected at 12.00 GMT from the Nigerian Meteorological Station in Lagos between 1991 and 1993 were used for the study. Lagos (06°27′N, 03°24′E) is in southwestern Nigeria, located in the Bight of Benin end of the Gulf of Guinea on the Atlantic coast of West Africa (Figure 2).

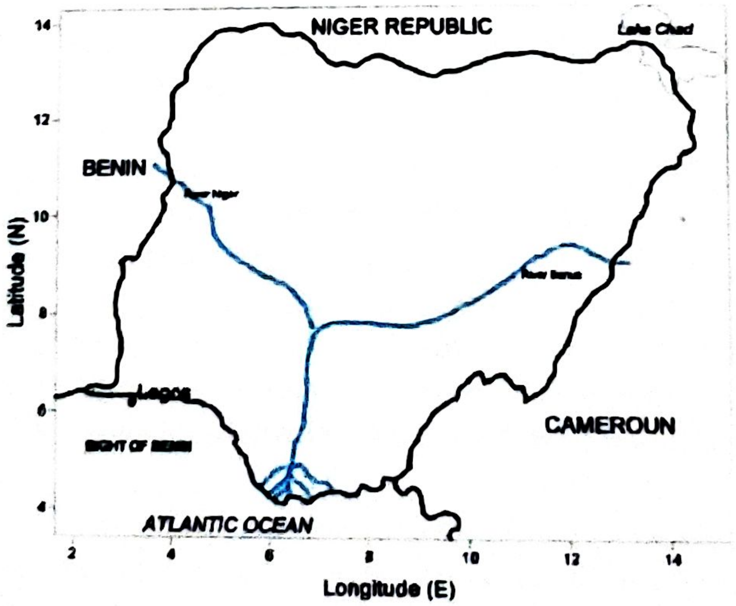


Figure 2: Map Of Nigeria Showing Location Of Lagos On The Atlantic Coast

The Radiosonde data (air temperature, pressure and dew point temperature) were used to compute radio refractivity N values at various heights, using the relation (Bean and Dutton, 1968):

$$N = 77.6/T\,(P + 4810e/T) \tag{1}$$

T is the air temperature (K), P is the atmospheric pressure (hPa) and e is the water vapour pressure (hPa).

The water vapour pressure may be obtained from (Hermann et al, 2002):

$$e = 6.1078 \times 10^{\{AT_d/(B+T_d)\}} \tag{2}$$

where T_d (°C) is the dew point temperature, $A = 7.5$ and $B = 237.3$

The modified refractive index M at a height h (km) and refractivity N is given by $M = N + 157h$. Using (1) and typical Midlatitude values ($P = 1000$hPa, $T = 273$K and $e = 15$hPa), it can be shown that variability of N relatively depends on the meteorological variables of P, e and T as

$$\delta N = 0.26\delta P + 4.3\delta e - 1.4\delta T \tag{3}$$

Thus, changes in refractivity gradient largely depend on changes in humidity and temperature gradients. The effect of pressure change is further reduced by the fact that it does not last, as winds quickly restore equilibrium. Atmospheric refractive bending depends most on humidity; but it may also be severely influenced by vertical temperature gradient, especially in a marine environment where it may have good correlation with air-sea temperature difference (Seiffer and Stein, 2005). These effects are higher in tropical maritime environments where slight changes in T may cause much greater changes in e and hence the refractivity N.

Values of N were computed for the surface level and at higher levels (up to 1000 m) where values of T, P and e are available. The refractivity gradient dN/dZ was obtained for surface level and subsequently for the height ranges 0-100 m, 0-200 m, 0-300 m..., 0-900 m and 0-1000 m. The surface gradients were derived between the surface and the next available level (usually < 100 m) while dN/dZ for 100m level was derived between surface and highest available level in the range 0-100 m. The same procedure was adopted for dN/dZ in subsequent height ranges. Daily values of refractivity gradients for the various ranges were determined for each of the twelve calendar months and statistically analysed. The relative prevalence of ducting (dN/dZ <–157N/km) and superrefraction (dN/dZ <– 100 N/km) was also explored.

4. Results

4.1 Refractivity Gradients At Various Height Ranges

As expected, least (more negative) refractivity gradients occur at the surface while less negative gradients occur at 100 m and higher ranges. The profiles show a clear seasonal trend: Least gradients for each range are more in dry season months (November-April) while the highest gradients occur in the wet season (May-August). This seasonal trend is particularly visible at surface level for each of the twelve calendar months. Figure 3a shows the profiles for the month of December which represents a typical dry season month in Nigeria. Very severe ducting gradients (<–600 N/km) are observed at surface level during the season. Figure 3b shows the profiles for the month of July, representing a typical rainy season month in Lagos. The Figure shows that during the month the least gradient is about –340 N/km, with isolated traces of extreme subrefraction gradients (up to about +40 N/km) even at surface level. The Figures show that throughout the year surface gradients are generally characterized by ducting and superrefraction. At other levels the relative prevalence of ducting and superrefraction is as presented in Figure 3c; the Figure shows that, whereas ducting approaches 70% at the 100 m height interval and remains perceptible up to 500m, prevalence of superrefraction (dN/dZ ≤ –100 N/km) is above 90% at 100 m level and remains perceptible up to 1000 m level.

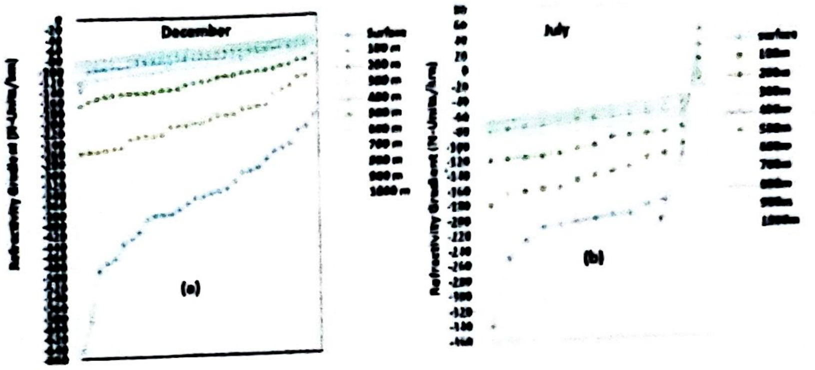
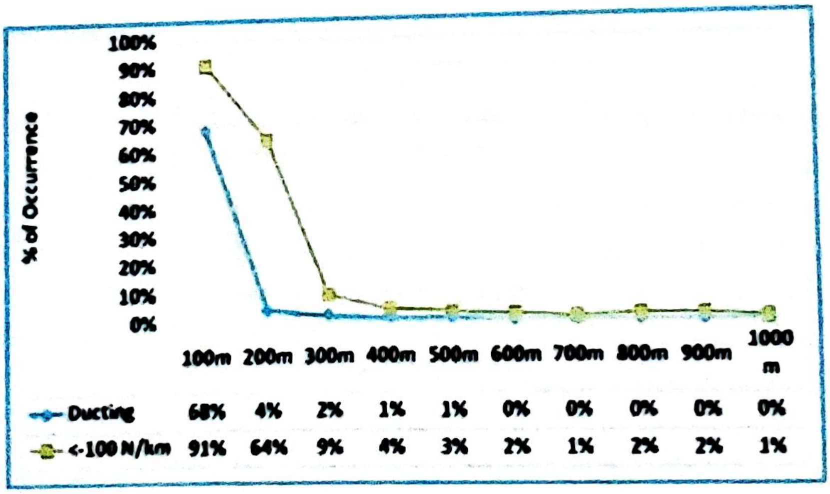


Figure 3(a,b) : Refractivity Gradients In Lagos For (a) Dry Season Month And (b) Wet Season Month



	100m	200m	300m	400m	500m	600m	700m	800m	900m	1000 m
Ducting	68%	4%	2%	1%	1%	0%	0%	0%	0%	0%
<-100 N/km	91%	64%	9%	4%	3%	2%	1%	2%	2%	1%

Figure 3c: Relative Prevalence Of Ducting And Superrefraction Between 100m And 1000m Height Ranges In Lagos

4.2 Surface Refractivity Gradients

Refractivity gradients at surface level show high prevalence of ducting and superrefraction, except in the month of July which represents the peak of the rainy season (Figure 4a).

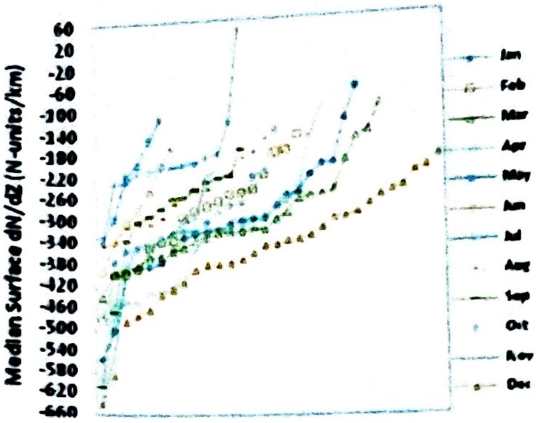


Figure 4a: Surface Refractivity Gradients Ranges

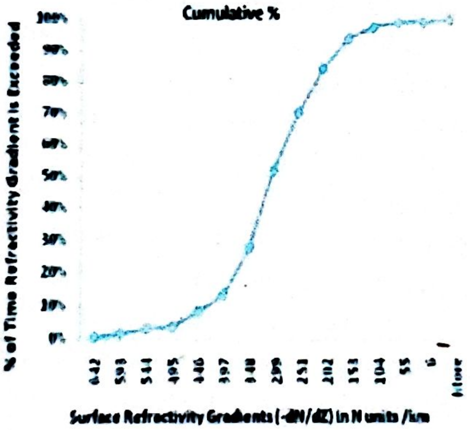


Figure 4b: Cumulative Distribution Of Surface Refractivity Gradients

The most negative gradients occur in dry season months, especially between September and December. The cumulative distribution of surface refractivity gradients (Figure 4b) shows that severe ducting gradients less than –640 N/km can occur for about 1% of the time, while ducting gradients less than –202 N/km appear for about 85% of the time. The Figure also reveals that superrefraction (≤ –100 N/km) prevails for about 98% of the time at surface level.

4.3 Monthly Medians Of dN/dZ

The annual variation of monthly refractivity gradient medians for the various height ranges considered shows a clearer picture of the seasonal pattern (Figure 5a). Minimum values (more negative median gradients) occur in dry season months (November-March) while less negative gradients occur in the rainy season months (May-September), especially at surface level, as well as in the 100m and 200m ranges.

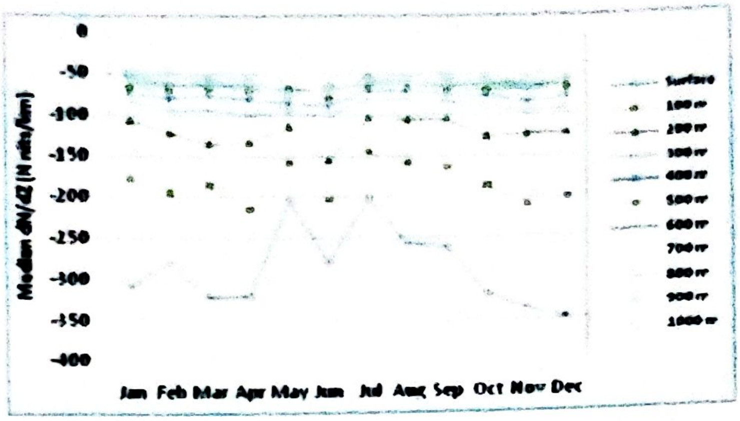


Figure 5a: Monthly Medians Of Refractivity Gradients

The median wet season minimum occurs in the month of June which also represents the seasonal variability maximum (based on range of values within the first kilometer of height), while the months of May and July maintain the annual variability minimum. The month of December represents the median annual minima as well as maximum annual variability. At surface level, median refractivity gradients are as low as –349 N/km in dry season, and as high as –202 N/km in wet season. However, the seasonal trend observed at lower levels is slightly reversed at higher levels such that value of median ΔN is as low as –74 N/km in wet season and as high as –46 N/km in dry season. Figure 5a also shows that variability of the refractivity gradients is maximum in dry season and minimum in rainy season. Variability of the median gradients is further explored for the annual ranges in each height range considered. Figure 5b, shows that annual range of variation of dN/dZ is widest at surface level, but decreases steadily up to 600 m after which there is a slight increase up to the highest level considered. Consequently, monthly averages of ΔN are in the range –50 N/km (in dry season) to –85 N/km (in rainy season) which shows a slight disparity with the ITU-R value of between –50 N/km and –60 N/km for the region (ITU, 1997).

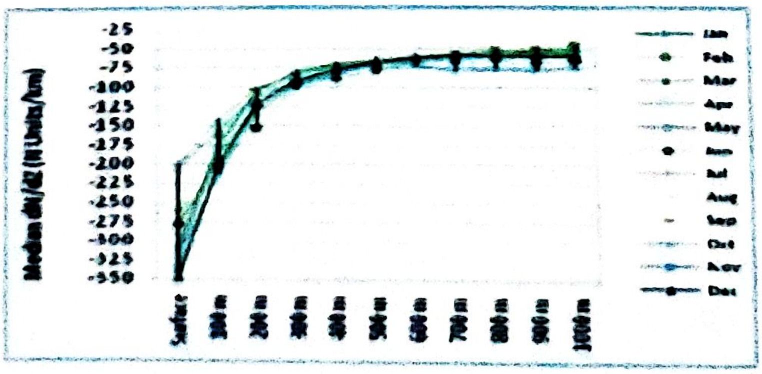


Figure 5b: Range Of Refractivity Gradients In Different Height Ranges

The relationship between monthly averages of ΔN and surface refractivity N_s (Figure 6) was also found to have a poor correlation coefficient of 0.144, as may be expected in coastal environments especially in the tropics.

5. Summary And Discussion

In the city of Lagos, which is located on the Atlantic coast of West Africa, refractivity gradients at different height ranges within the first 1000 km reflect a high prevalence of superrefraction and ducting, with considerable seasonality.

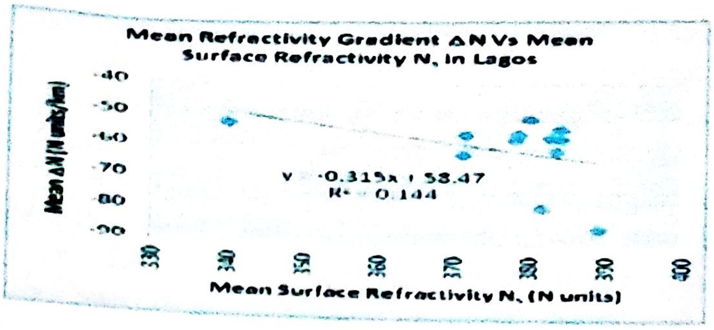


Figure 6: Vertical Refractivity Gradient ΔN Vs Surface Refractivity N_s

Generally, the wet and dry seasons in Nigeria are governed by the N-S migration of the semi-permanent low pressure zone across West Africa which is known as the Inter Tropical Discontinuity (ITD). Refractivity gradients become increasingly less negative between January and August when the ITD slowly migrates northward, and become increasingly more negative between September and December when the ITD makes a southward and faster migration. The ITD also represents a division between two major wind regimes over Nigeria: On the southern side is the southwesterly trade which brings warm and moisture-laden air over the country, while on the northern side is the northeasterly trade which brings cold and dry air, sometimes laden with dust haze from the Sahara desert; local differences may however occur due to local conditions. The surface position of the ITD is closest to Lagos in January after which it reaches the farthest northern position in eight months around August. High tropical surface temperatures prevail, with maximum values in February-April while minimum values occur in July-September (Figure 7). By July the whole country is at the peak of rainy season. Turbulent convection is common due to prevailing high surface temperatures and high humidities.

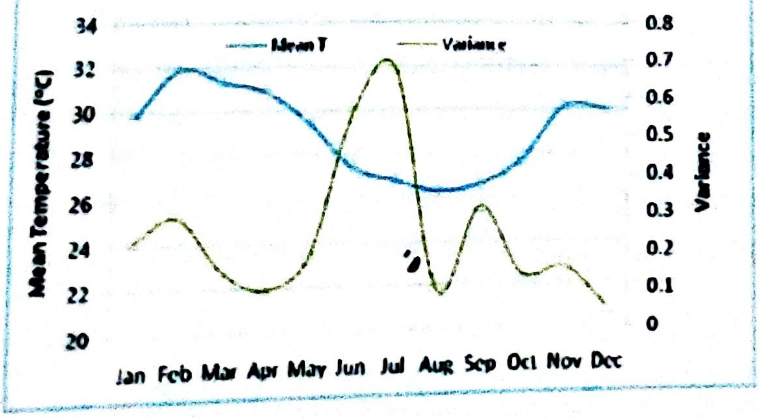


Figure 7: Annual Variability Of Surface Temperature In Lagos

Figure 7 also shows that convective destabilization seems to peak in July which has maximum variance of surface temperature and relatively mildest refractivity gradients in the year (Figure 3b). However, by August substantial degree of stabilization may result from the impacts of cooling by rainfall in preceding months, upwelling of the Atlantic and the cool Benguela and Canary currents, as well as the shielding effect of the tall cumulus clouds (Trewartha, 1966; Ilesanmi, 1972; Nieuwolt, 1982). Obasi (1964) shows that the flux over Lagos is high in July/August with predominantly divergent moisture transport. Divergence of the marine boundary layer around Lagos may result from impact of the upwelling on the trades (Brooks and Mirrlees, 1932) or fanning out of the coastal Marine Boundary Layer (Haack and Burk, 2001), as the southwesterly trades approach Lagos in the Bight of Benin. By September the ITD begins its southward migration, at faster pace than the northward movement and reaches the most southern position in December-January. Although such low level divergence can significantly contribute to the superrefraction and ducting in Lagos, the pronounced temperature inversion at the southern extreme of the ITD (Ojo, 1977) appears to be a major factor, with maximum impact on Lagos in December when it is closest and least impact in July when it is farthest.

The intensity and duration of the observed gradients are indicative of the high prevalence of anomalous propagation expected in the region. Terrestrial and low altitude communication links are substantially vulnerable to the negative effects of ducting and superrefraction, and applications such as radar precipitation estimates and processing procedures assuming standard propagation conditions must be made with caution (Bech et al, 2002). In particular, beam blockage between terminals at different altitudes as well as link extension beyond the normal limits, would be constantly expected in and around the Lagos area. Based on the seasonal trend of the refractivity gradients, the effects of superrefraction and ducting on communication links is more in dry season months within the lower height ranges, but this trend is reversed at higher height ranges. Although the diurnal trend was not investigated due to lack of data, significant diurnal variability of refractivity gradients is also expected in view of the maritime tropical nature of the climate. Recent report from Lagos reveals that signal reception by a ground-based console from a weather monitoring sensor located at a higher altitude fails sometimes, especially between midnight and early morning hours even though the instrument's battery is in perfect condition (Najib, 2009). Oyedum (2004) also reported high level of ducting and superrefraction in Lagos, with minimum ductable frequencies in the range 120 MHz - 320 MHz. Thus, the occurrence of duct-induced communication link breakdown such as between an airborne aircraft and the ground control terminal in Lagos environment cannot be ruled out. Diurnal and seasonal variations of refractivity gradients will also be associated with disparities in the height estimation of radar echoes. The severity of the observed refractive index gradients (<–600 N/km) in Lagos, especially in dry season, indicates preponderance of clear-air ducting conditions and certainly evokes a lot of interest to be further explored. This will be the subject of a subsequent report.

6. Acknowledgement

The authors are indebted to the Nigerian Meteorological Services for making available the radiosonde data used in the study.

REFERENCES

1. Bean, B. R. and Dutton, E. J. : Radio Meteorology. Dover Publications Inc., New York, (1968), 1-22.
2. Brooks, C. F. P. and Mirrlees, S. T. A. : A Study Of The Atmospheric Circulation Over Tropical Africa, Great Britain Meteor Office, Geophys. Mem., No. 55, (1932), 13.
3. Gossard, E. E. : Refractive Index Variance And Its Height Distribution In Different Air Masses, Rad. Sci., 12, (1977), 89-105.
4. Bech, J., Codina, B., Lorente, J. and Bebbington, D. : Monthly And Daily Variations Of Radar Anomalous Propagation Conditions: How "Normal" Is Normal Propagation? Proceedings Of ERAD (2002), (2002), 35-39.
5. Gerstoft, P., Gingras, D. F., Rogers, L. T. and Hodgkiss, W. S. : Estimation Of Radio Refractivity Structure Using Matched-Field Array Processing, IEEE Trans. On Antennas And Propagation, Vol. 48, (2000), 345-355.
6. Hall, M. P. M. : Effects Of The Troposphere On Radio Communications. IEEE, Peter Peregrines Ltd., London And New York, (1979), 202.
7. Hall, M. P. M., Craig, K. H. : Clear-Air Characteristics Of The Troposphere. In Hall et al (Eds): Propagation Of Radio Waves. IEEE London, (1996), 105-130.
8. Herman, J. A. A., Kulessa, A. S., Lucas, C., Vincent, R. A., Hacker, J. M. and C. M. Ewenz : Impact Of Elevated Atmospheric Structures Upon Radio Refractivity And Propagation, Workshop On The Applications Of Radio Science, Leura, NSW Australia, (February, 2002), 20-22. (www.ips.gov.au/IPS Hosted/NCRS/wars/wars2002/Proceedings/comm-f/Screen/hermann.pdf)
9. Haack, T. and Burk, S. D. : Summertime Marine Refractivity Conditions Along Coastal California, Journal Of Applied Meteorology, Vol. 40, (2001), 673-687.
10. Ilesanmi, O. O. : Aspects Of The Precipitation Climatology Of The July-August Rainfall Minimum Of Southern Nigeria, Journal Of Tropical Geography, 35, (1972), 55-57.
11. ITU-R P. 453-6 Recommendation 'The Radio Refractive Index: Its Formula And Refractivity Data', ITU-R P-Series, (1997).
12. ITU-R P. 453-8 Recommendation 'The Radio Refractive Index: Its Formula And Refractivity Data', ITU-R P-Series, (2001).
13. Kulessa, A. S., Ewenz, C. M., Leiff, W. and Salamon, S. : Coastal Environment Refractivity And Propagation Predictions Using Numerical Atmospheric Models, www.ursi. org/Proceedings/ProcGA02/papers/p2120.pdf
14. Nieuwolt, S. : Tropical Climatology-An Introduction To The Climates Of The Low Latitudes. John Wiley And Sons, New York, (1982), 197.

15. Najib, Y. : Personal Communication On Regular Link Failure Between An Elevated Transmitter And A Ground-Based Receiver Of A Weather Monitoring Station In Lagos, (2009).

16. Obasi, G. O. P. : Thermodynamic And Dynamic Transforms Over Ikeja. Proceedings Of The Symposium On Tropical Meteorology, Oshodi-Lagos, (August 1964), 1-18, 54-61.

17. Ojo, O. : The Climates Of West Africa. Heinemann, (1977), 61-84.

18. Oyedum, O. D. : Study Of Tropospheric Effects On Radio Propagation In Nigeria Using Radiosonde Data. Unpublished PhD Thesis, Department Of Physics, Federal University Of Technology, Minna, Nigeria, (2004).

19. Oyedum, O. D. : Climatic And Seasonal Variations Of Effective Earth-Radius-Factor And Scale Height In Three Meteorological Stations In West Africa. Nigerian Journal Of Physics, Vol. 20 (1), (2008), 102-110.

20. Sirkova, I. : A Clear-Air Propagation Prediction System: Evaporation Duct Application, Bulgarian Journal Of Physics, Vol. 25, Nos. 3-4, (1998), 181-187.

21. Sizun, H. : Radio Wave Propagation For Telecommunication Applications. Springer, (2005), 93-151.

22. Seiffer, D. and Stein, K. : Variations Of Apparent Target Position Due To Refraction (Results Of The VAMPIRA-Trial). ECPS 2005 Conference, (15-18 March, 2005), BREST, FRANCE, Proceedings Of SPIE (2005).

23. Trewartha, G. T. : The Earth's Problem Climates. Madison, University Of Wisconsin Press, (1966).

24. Valtr, P. and Pechac, P. : Novel Method Of Vertical Refractivity Profile Estimation Using Angle Of Arrival Spectra. In XXVIIIth General Assembly Of International Union Of Radio Science, New Delhi (India), (2005).