Communication in Physical Sciences, 2024, 11(4): 628-640

Statistical Characterization of Surface Duct Conditions and their Implications on Microwave Propagation Over Lagos, Nigeria

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Received: 04 April 2024/Accepted: 11 July 2024/Published: 23 July 2024

Abstract: *Surface ducts, and atmospheric layers that trap and guide radio waves can significantly impact microwave signal propagation. Consequently, in this study, we analyzed their statistical occurrence in Lagos, Nigeria, using five years (2018-2022) of meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 reanalysis. The investigation focused on how factors like temperature, humidity, and pressure influence radio refractivity and the formation of surface ducts at different heights (100 m and 300 m) and observation times (00:00 and 12:00 hours). The results reveal a higher prevalence of surface ducts at 100 meters, particularly during the dry season (November-March) and at noon (12:00 hour). This implies that microwave signals are more likely to be trapped and travel farther during these periods, potentially causing interference with distant communication systems. Our findings establish the importance of considering surface ducts when designing and deploying communication infrastructure in coastal regions like Lagos.*

Keywords: *Surface duct; microwave propagation; coastal region; ECMWF, ERA-5*

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1.0 Introduction

In meteorology and radio transmission, atmospheric ducting often referred to as atmospheric refraction or radio ducting is a phenomenon where electromagnetic waves bend as they pass through various levels of the Earth's atmosphere. The refractive index of air changes with height, temperature, and humidity, causing this bending (Adediji and Ajewole, 2008, 2010). Radio propagation, radar systems, and even optical views can all be significantly impacted by atmospheric ducting, which frequently results in longer signal wavelengths and surprising events. Due to the particular difficulties and traits that these areas present, radio wave propagation in Lagos, like in many other coastal areas across the world, is extremely important. Radio waves propagate differently in coastal areas due to a variety of circumstances, such as the existence of water bodies, meteorological conditions, and topographical features. Knowing these variables is essential for several applications, ncluding weather forecasting, communication, navigation, and disaster relief, particularly in a nation like Nigeria with a sizable Atlantic Ocean coastline (Adediji and Ogunjo, 2014; Adelakun et al., 2019; Adeniji et al., 2020) When a layer of air near the Earth's surface experiences a sudden change in humidity or temperature, it's referred to as "surface duct conditions" in meteorology. This makes a "duct" that can be used to steer and trap radio waves over great distances, which has a substantial impact on how these waves propagate.

Some literature has documented the impact of ducts on communication systems. For example, Liu et al. (2021) found that atmospheric ducting can significantly extend the range of radio signals by trapping and guiding them, and can subsequently create attenuation and open allowance for signals to travel much longer distances over the horizon. Yang et al. (2022) also conducted a study to investigate the potential of using evaporation ducts for wireless microwave transmission across the Taiwan Strait. The results they obtained indicated that the ducts was influenced by the Taiwan Strait Warm Current, which results in significantly higher evaporation intensity in this region compared to other southern and eastern coastal areas of China. The research focused on evaluating the effectiveness of this method for maritime communication. The study period covered January to December 2020 and observations were made between 9 and 14 hours. During this period, the height of the evaporation duct exceeded 10 meters over 90% of the time. They observed that high-quality transmission using BPSK modulation was successful in establishing 98.90% of the time between 12 and 13 hours with 89.89% of the signal-to-noise ratio (SNR) exceeding 90 dB. They concluded that utilizing the evaporation duct for wireless communication could provide substantial support for maritime applications across the Taiwan Strait. In their study, Ikharo et al. (2023) investigated the effects of tropospheric ducting on communication signals in the coastal regions of Abidjan, Douala, and Libreville, using Advanced Refractive Effects Prediction System (AREPS) to predict duct phenomena using radiosonde data from these regions. Their results led to the observation that the troposphere over Abidjan exhibited the highest presence of surface ducts, with 85.2% occurrences. In Douala, surface-based ducts were more prevalent, occurring 45.6% of the time. Libreville experienced elevated ducts 48.2% of the time. Specifically focusing on Abidjan, the study found that propagation loss increased with range but displayed a steady decay, indicating that the communication signal extended beyond the intended target.

In Nigeria, literature on the impacts of surface ducts on telecommunication systems in various locations is scanty. However, Afolabi et al. (2018) investigated the monthly classification of tropospheric refraction and duct height near sea level in Lagos State, Nigeria. Their study investigated the effects of evaporation ducting on millimetre electromagnetic waves over sea surfaces, which can result in path loss, poor line-of-sight, and sometimes complete signal loss due to refraction in shadow zones and signal noise. Data for the study were obtained from NIMET in Lagos State and were analysed using the P–J model technique to estimate evaporation duct height. They concluded that the evaporation ducting occurred only in a few months, with a mean duct height of 14.52 ± 0.52 meters and a standard deviation of 1.80 meters. This study provides valuable insights into the monthly variation of refraction types based on refractivity gradient in Lagos, a coastal region in Nigeria.

Ducting trends can vary over different locations within a city and could be influenced by season, indicating that periodic monitoring is necessary (Adediji et al., 2011, 2013). Lagos is the commercial Centre of Nigeria and is grossly surrounded by numerous communication systems, which signifies the significance of analysing information on surface ducting in the zone, especially as they affect communication systems. Therefore, the present study is aimed at investigating the influence of surface ducts on communication systems for five years.

1.1 Theoretical framework

In relation to the measured meteorological parameters such as temperature, atmospheric pressure, radio refractivity value can be calculated using the expression given below, to obtain the data point representing the seasonal variation for different levels and each location.

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

where N is the radio refractivity, p is the total atmospheric pressure (hpa), e is the water vapor pressure (hpa) and T is the absolute temperature (k). Radio refractivity of the lower atmosphere is divided into two compositions, which are shown in the below expressions.

$N_{dry} = \frac{77.6 P}{T}$ and $N_{wet} = 3.73x10^5 x \frac{e}{T^2}$ (2)

The two expressions above were used to compute the radio refractivity for dry and wet seasons respectively, which in turn is used to calculate the total radio refractivity for every measurement period. The average variation of each day was calculated from the recorded data. Hence, the vapor pressure was calculated as:

$$e = \frac{e_sH}{100} \quad (3)$$

where H is the relative humidity and e_s is the saturated vapour pressure which was evaluated based on equation (4) $e_s = 6.1121 x \exp\left(\frac{17.62T}{243.21+T}\right)$ (4)

The modified refractivity, *M* at a particular level is given by the sum of the radio refractivity and the product of the height at any given level as a constant of "157" with an expression: M = N + (157 x h)
(5)

The characteristics difference in modified refractivity denotes the difference in the modified refractivity of any two levels. It is simply the change in the modified refractivity; however it is denoted with ΔM and can be mathematically written as:

$\Delta M = M_2 - M_1$ (6)

2.0 Dataset and Analysis

The study location is Lagos, Nigeria, which is a part of the coastal region of the country. The city lies between latitude 6.5244°N and longitude 3.3792°E. Lagos State is a prominent state and the core financial city located in the southwestern part of Nigeria. Due to the state double rainfall pattern, which creates a wet land climate, the swamp forests of fresh water and mangrove swamp forests make up the majority of the vegetation in Lagos State. The two main climatic seasons in Lagos State are typically dry (November to March) and wet (April to October). It is the most populous and economically vibrant state in Nigeria. Lagos is the commercial and economic hub of Nigeria, playing a significant role in the country's socio-economic development. Lagos State is primarily known for its economic and commercial prominence, which houses the major communication companies. Hence, there is a need to create a platform for quality services that will meet customer-level agreements with the communication companies. Fig. 1 presents the map of Lagos State.

Fig 1: Lagos State Map (Afolabi et al., 2017)

The climate of Lagos is classified as a tropical climate that is controlled by the movement of the inter-tropical discontinuity, sometimes referred to as the Harmattan locally, which is the area where hot, dry and frequently dust-laden air from the Sahara and warm, moist air from the Atlantic meet. Like many other cities in southern Nigeria, Lagos is particularly impacted by a significant amount of humid tropical marine air that is brought about by the sun's constant migration of the inter-tropical discontinuity.

5-year (Jan 2018 to Dec 2022) data of air temperature, atmospheric pressure, relative humidity, and water vapor pressure were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis 5 (ERA-5) to deduce the surface duct conditions. The ECMWF created the extensive reanalysis dataset known as ERA-5. It provides high-resolution data in both time and space, which makes it useful for weather research and other scientific applications as well as climate studies. It offers hourly data, which makes it possible to analyze weather and climatic phenomena in great depth over time. The hourly data estimates at a horizontal resolution of 31 km and 137 vertical levels from the surface at 0.01 hPa (about 80 km). The dataset includes a wide range of observations from several sources and is subjected to stringent quality control (Labe, 2023).

3.0 Results and Discussion

3.1 Analysis of Surface Radio Refractivity

Figure 2 presents the results on the seasonal variation of radio refraction at two synopsis hours: 00:00 hour and 12:00 hour. It was observed during the dry season, which is between November and early March, that the radio refractivity is high at the surface both at 00:00 and 12:00 hours local time and low during the wet season, which is between late March and October. At the 100-metre heights, the refractivity was low during June, July, August, and September at the 00:00 hour local time, however, at the 12:00 hour local time, the refractivity was low during November, December, January, and February. This finding implies that the refractivity value does not significantly change between the dry and rainy seasons. This might be a result of the Atlantic Ocean, a sizable body of water, as present in Lagos, where it continuously raises the relative humidity, as corroborated in the work of Ayantunji and Okeke (2011), which claimed that the value of surface refractivity rises from the North-Desert region to the South-Coastal region. There is no discernible pattern to the fluctuations in refractivity at these sites, making them random. The value of refractivity in these regions does not seem to be affected by the decrease in precipitation. This is a result of the characteristics associated with the coastal location and the Atlantic Ocean's effect.

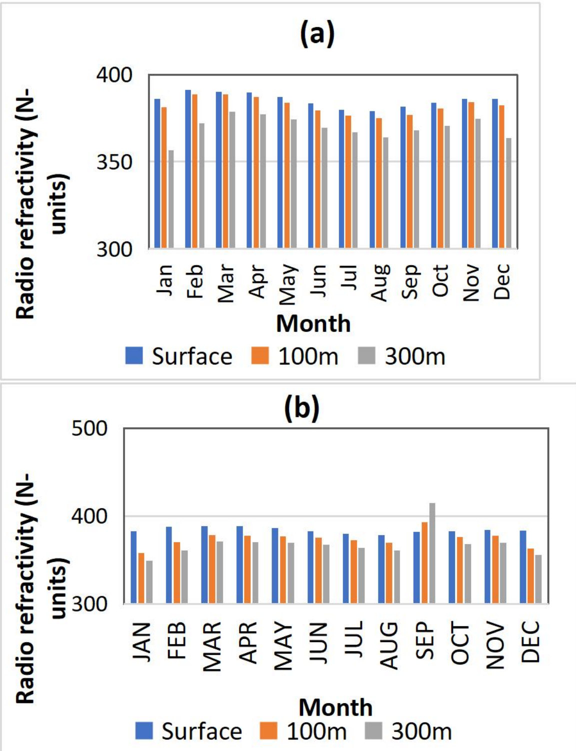

Fig 2: Average seasonal variation of radio refraction at the surface, 100 m and 300 m for (a) 00:00 hour and (b) 12:00 hour.

3.2 Seasonal analysis of the modified radio refractivity

Modified refractivity of Lagos at 00:00 hour and 12:00 hour at the surface, 100 m and 300 m heights are presented in Figure 3(a and b). A comparable trend of seasonal occurrences was observed at 300 m at the 00:00 hour and 12:00 hour local time, where there was extremely high modified radio refractivity, which can be due to temperature inversion. When the typical temperature drop that happens with height is inverted, an inversion occurs. Modified refractivity with height may rise in response to a substantial temperature inversion (Arya, 1988). Another reason can be the humidity gradient and pressure variation. Modified refractivity may also increase in response to steep variations in humidity with altitude. The refractive index of moist air varies from that of dry air, and abrupt changes in humidity can result in notable differences (Barry and Chorley, 2010). Modified refractivity can also be affected by notable pressure differences with height, although these are less frequent. Usually, this is connected to dynamic weather systems (Holton, 2004). At 100 m, the modified refractivity is also high at the 00:00 hour and 12:00 hour local time and low at the surface. The influence of variations in temperature, pressure, and humidity close to the earth's surface causes modified radio refractivity to be generally low at ground level. The modified refractivity is low during June, July, August, September, and December at 00:00 hour local time over 300 m height, while other months show extremely high conditions at that same height. At 12:00, the modified refractivity is low between December and February at all levels. As seasonal variations in atmospheric conditions occur throughout the year, the modified radio refractivity might fluctuate. Modified radio refractivity fluctuates due to several reasons, with certain periods experiencing comparatively low or high values, and the specific reasons for variations in modified refractivity may depend on regional and local climatic conditions.

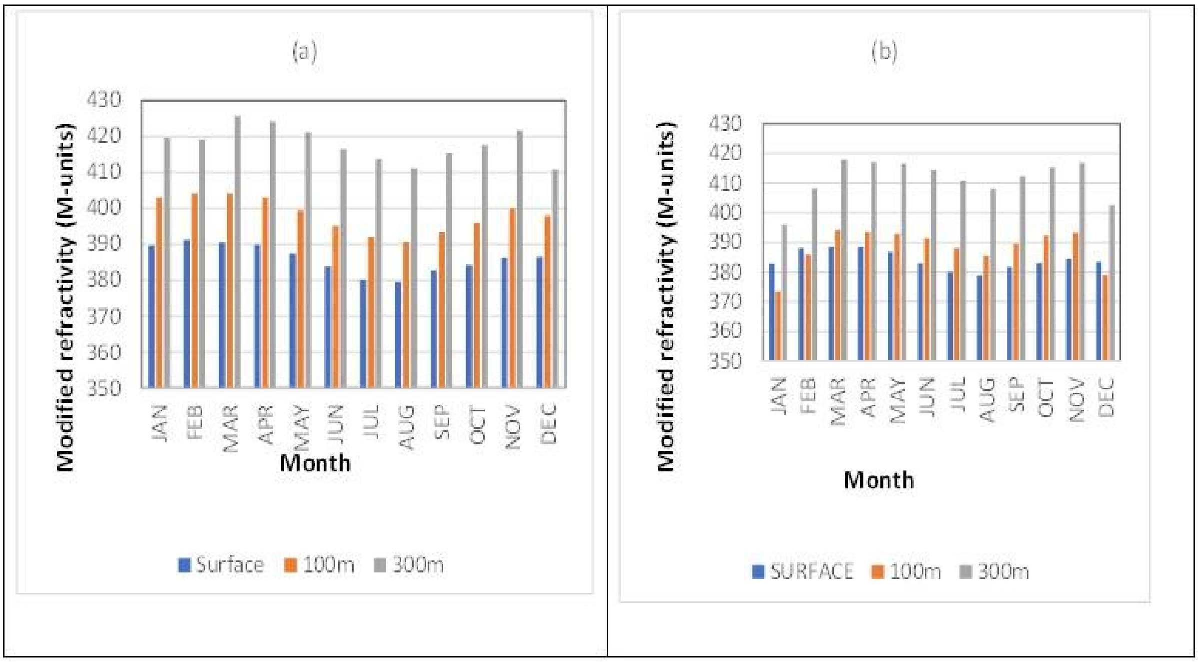

Fig 3: Average seasonal variation of modified refractivity in Lagos at the surface, (a) 100 m and 300 m at (b) 00:00 hour and 12:00 hour.

3.3 Refractivity Conditions

Upper-air measurements have been frequently used to evaluate ducting conditions in different parts of the world. One of the objectives of this research is to derive the statistics of ducting, super-refraction, normal/standard, and sub-refraction over Lagos. This has important implications for the reliability of radar and communication systems. The monthly average distribution of the duct, super refraction, normal, and sub refraction was discovered in all data and the data subset for 00:00 and 12:00 hours, which reflect night and day conditions, respectively (at the surface, 100 m and 300 m). When the change in refractivity gradient turns negative, ducting happens. In this instance, the electromagnetic signal is compelled to travel inside the ducting limits. But some electromagnetic energy leaks through the ducting layers' pliable boundaries (Craig and Hayton, 1995). The duct's strength has an impact on this. The stronger the duct, the more electromagnetic energy is contained. The atmosphere is known to have three different types of ducts, as noted by Brooks et al. (1999), Babin *et al*. (1997), and Babin (1995). These are surface ducts, surface-based ducts, and elevated ducts. The surface and surface-based ducts are bound by the earth at their lower boundaries. From the results in Lagos, it is observed that ducting occurs in January, February, June, and December. At 00:00 hour and 100 m height, there was high sub-refraction across the entire month. At 300 m of the 00:00 hour, there were high normal conditions throughout the years, and just one month showed sub-refraction. Ducting only occurs in January, February, and December. From Fig. 4, it is indicative that, there is no super-refraction in July, September, and November. All this may be due to a temperature inversion. The surface refractivity results seen from this research agree well with Kolawole's (1981) study of the climatological fluctuations of surface radio refractivity in Nigeria.

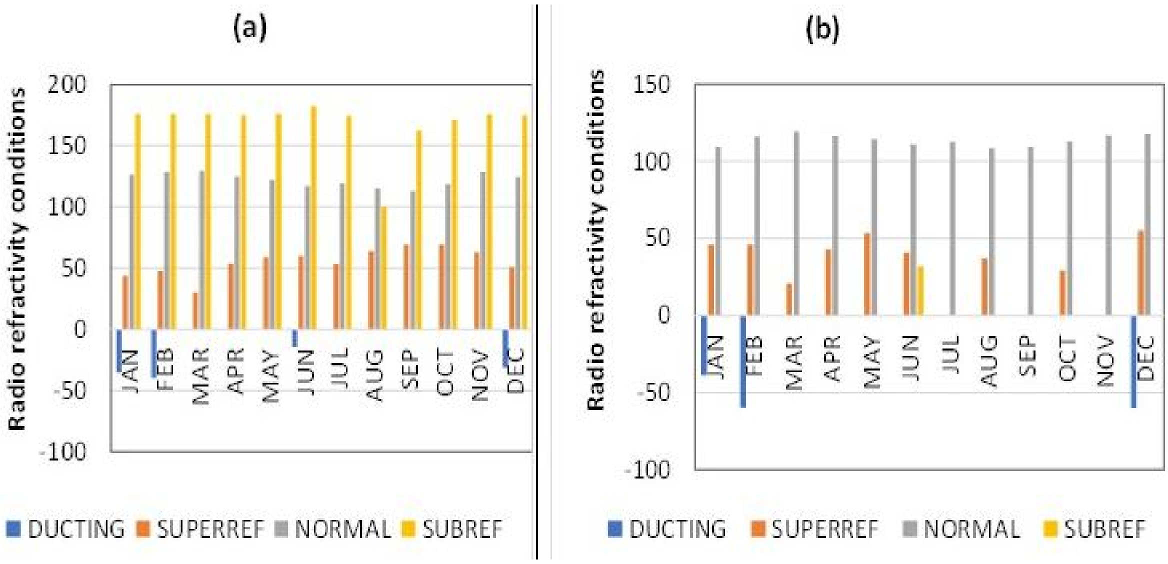

Fig 4: Refractivity conditions in Lagos at (a) 00:00 hour for 0-100m and (b) 00:00 hour for 0 -300 m

At the 100-metre height of 12:00 hour as presented in Fig. 5, ducting occurs throughout the year in Lagos, but higher occurrences were observed during January, February, and December. There was an absence of sub-refractivity in January, but high sub-refractive activity was observed in June, July, and November. At 300 m height and 12:00 a.m. local time, there was no sub-refractivity present in Lagos. The result is similar to that of the height of 300 m at 00:00 hour; expect that there was sub-refractivity in June at 00:00 hour local time. The presence of air mass in a high-pressure region is the main cause of ducting and super-refraction at the elevated layer. The air is compressed during descent, becoming normal and drying. Elevated ducts can obstruct ground-based communications and are mainly found above the clouds. This phenomenon is mostly responsible for the reported signal deterioration, fade-outs, and

anomalous range in the troposphere (Owolabi and Ajayi, 1976).
Radio waves pass through the atmosphere more directly when atmospheric ducting is not present. When certain weather conditions, such as temperature inversions, occur, the temperature rises with height rather than falling, resulting in a structure resembling a duct. Not all situations call for ducting since surface-reflected light can interfere with direct light, changing the lobe pattern, degrading the signal, and increasing background noise (Brooks *et al*. 1999). The way in which electromagnetic waves affect the ducting layer has a significant impact on how the ducts affect airborne or surface-based equipment on the field. The effect of the ducting layer during propagation will be less the steeper the angle (Richter & Hitney, 1980).

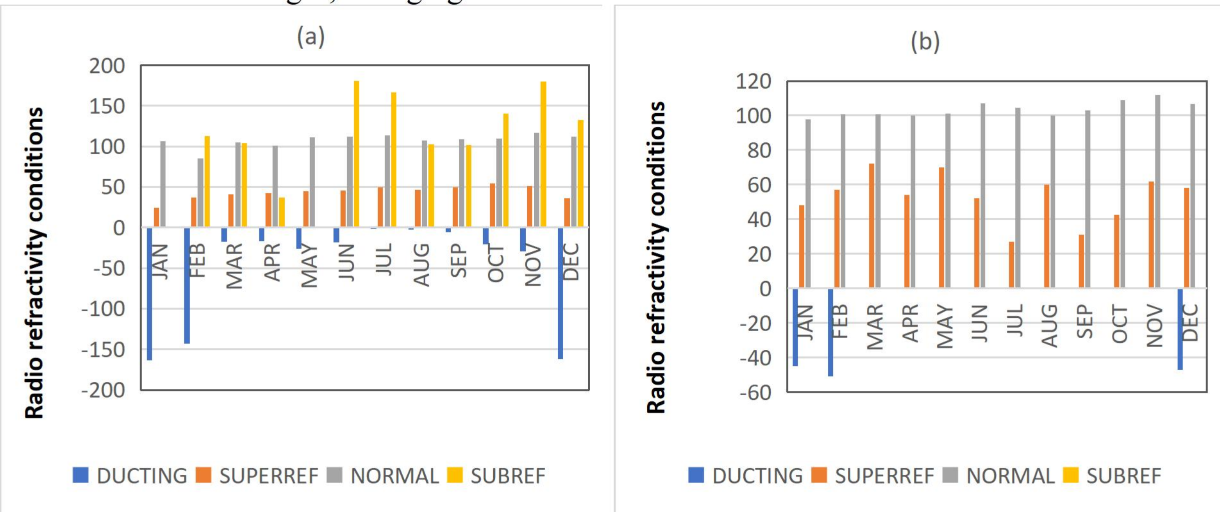

Fig 5: Refractivity conditions in Lagos at (a) 12:00 hour at 0 -100 m and at (b) 12:00 hour at 0-300 m

3.4 Percentage of Surface Duct

Variations in temperature and humidity guide or duct radio waves into a surface duct, a layer of the atmosphere. Temperature gradients and atmospheric stability have an impact on a surface duct. Audio signals are capable of travelling farther when they are propagated more effectively by a powerful surface duct. This occurs due to the possibility of waves becoming caught inside the duct and not being able to escape into the upper and lower layers of the water or the atmosphere. The percentage occurrences were obtained by dividing the total number of surface ducts for each month by the total number of days of the month in 5 years. Figure 6 presents the vertical profile of the percentage surface duct at the surface to 100 m height 00:00 hour and 12:00 am local time. It was observed that surface ducts occur more during the dry season at 100 m. Figure 6 also shows that the percentage of the surface duct is significant in January, February, and December with about 99%, 59% and 82% respectively. It is also observed that there is more occurrence of the surface duct at heights of 100 m with an average % value of about 99% than a t 300 m with an average % value of about 36% as presented in Figure 7. These may be due to temperature inversion, the presence of water vapour, and pressure near the earth's surface level.
The surface duct strength and thickness variations over time are shown in the results presented in this section. The median is proven to be more meaningful and accurate in expressing the physical features, while mean values include extreme occurrences. Although there are physical implications and comparisons for both values, results are represented using both means. At the 00:00 hour in Lagos for example, (Fig. 8a) there

was no duct thickness during the rainy season (April-October), except for June (about 6 m), and duct thickness occurred during the dry season (December – February) at the 100 m height. The mean duct thickness in January, February, June, and December is 33 m, 3 m, 4 m, and 9 m, respectively. February happens to be the month that the surface duct experiences the thickest level). The median duct thickness only occurs in January at 52 m. At 300 m of the 00:00 hour as presented in Figure 8b, duct thickness also occurs during the dry season of the year. The maximum mean duct thickness is in December, (21 m) and the minimum in February (7.8 m).

3.5 Surface duct thickness and surface duct strength

Median duct thickness occurs in December (30 m) and January (16 m). The duct strength nearly follows the same pattern, but is lower at 300 m than at 100 m as presented in Figure 9. The duct strength increases from January to March – within the dry season. The peak of the mean value of surface duct strength is found in February and December. In April to October, the surface ducts are weaker when compared with those in other wet months, the absolute median of the duct strength being smaller than 2 M-units.

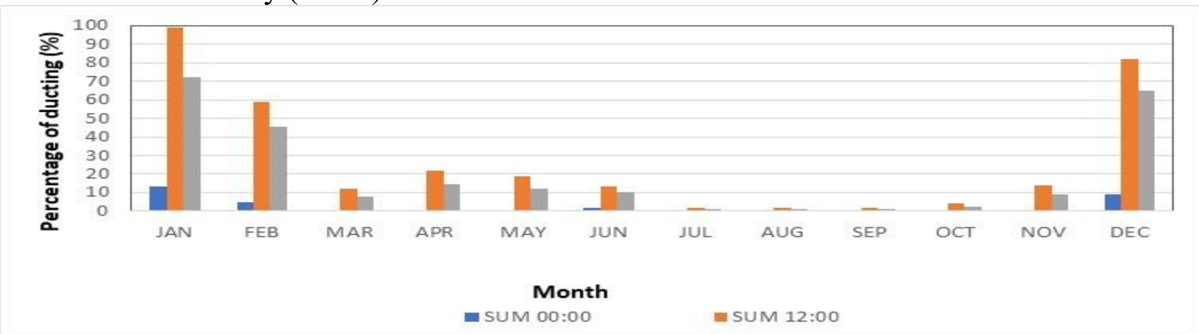

Fig 6: Vertical profile of the percentage surface duct at surface level to 100 m heights

Fig 7: Vertical profile of the percentage surface duct at surface level to 300 m heights

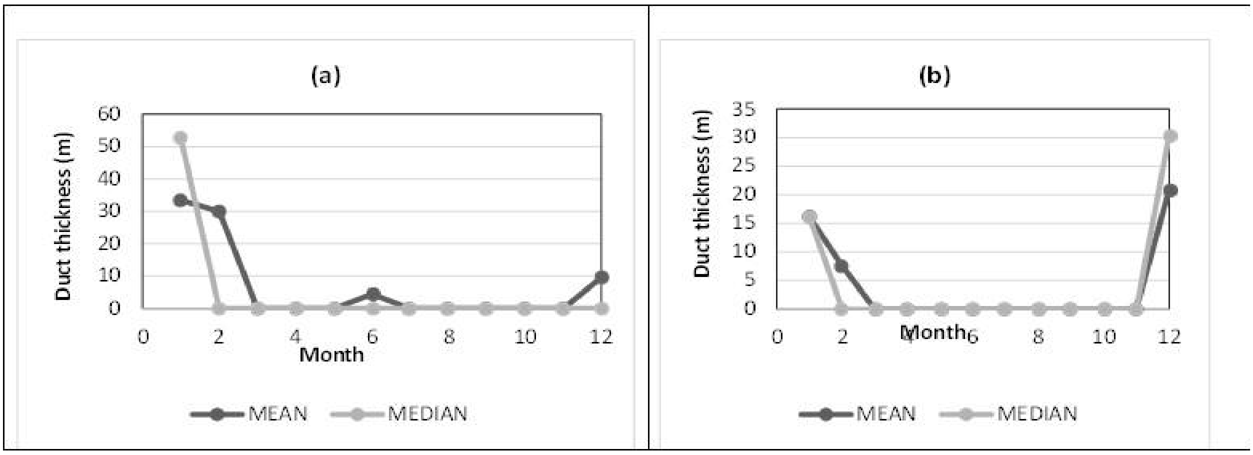

Fig. 8: Monthly variation of duct thickness at 00:00 hour over (a) 100 m heights and (b) 300 m heights

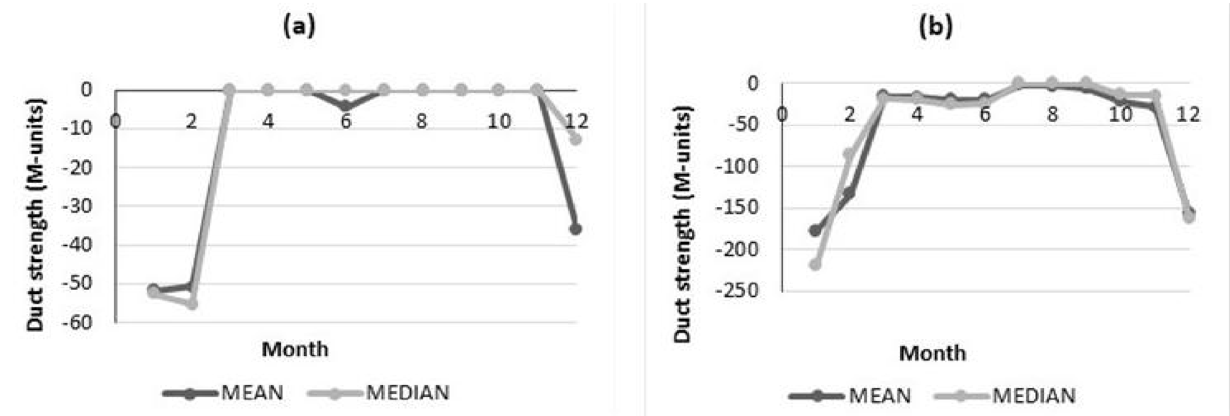

Fig. 9: Monthly variation of duct strength at 12:00 hour LT over (a) 100 m heights and (b) 300 m heights

At 12:00 a.m. in Lagos as presented in Figure 10 shows that the mean duct thickness occurs throughout the dry season, with an absence in March. The highest mean duct thickness was in December (105 m); the median duct thickness was also highest in December at 100 m height, but at 300 m height, the mean only occurs from December to February, with the highest in January (36 m) and the lowest in February (17 m). Median duct thickness only occurs in January and December.

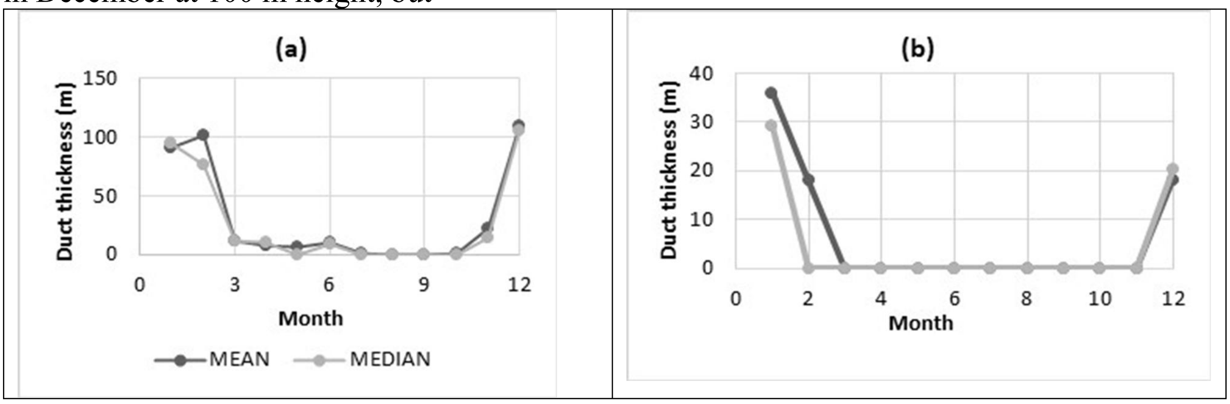

Fig. 10: Monthly variation of duct thickness at 12:00 hour LT over (a) 100 m heights and (b) 300 m heights

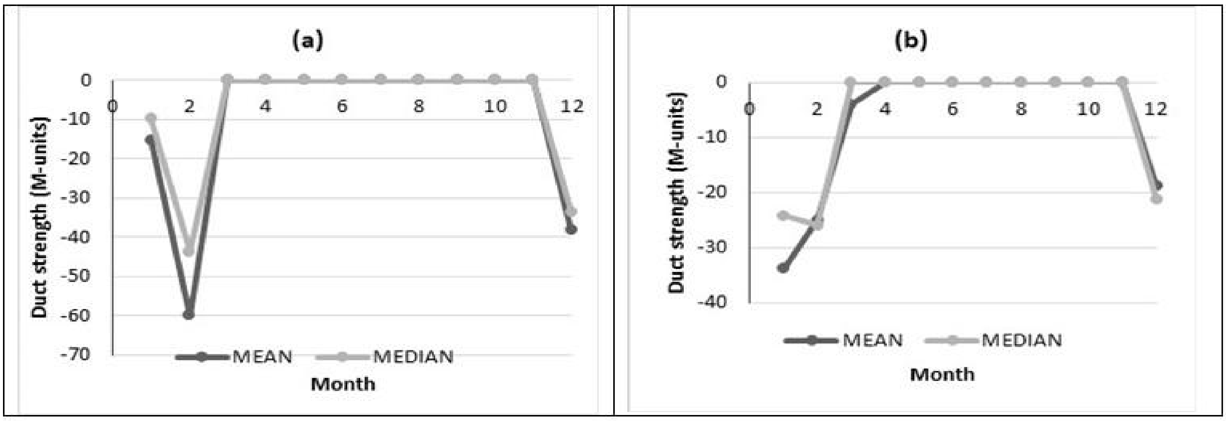

Fig 11: Monthly variation of duct strength at 12:00 hour LT over (a) 100 m heights and (b) 300 m heights

Surface duct strength at 12:00 hour both at 100 m and 300 m height, as presented in Figure 11, shows that the mean and median duct strength occur during the majority of the dry season. The peak mean and median at the 100-metre height were found in January. Duct strength was absent from March to November at the 100 m height, but at the 300 m height duct strength was absent from April to November based monthly mean.

4.0 Conclusion

This study investigated the occurrence of surface ducts and their influence on microwave propagation in Lagos, Nigeria. The analysis was based on five years of data (January 2018 to December 2022) on air temperature, atmospheric pressure, relative humidity, and water vapor pressure obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis 5 (ERA-5). The study looked at how these factors affect radio refractivity, modified radio refractivity, and ultimately the formation of surface ducts.

The findings from the studies indicated that ducting events were more frequent at 100 meters than 300 meters. The ducting frequently occurred at 12:00 hour compared to 00:00 hour. In the dry season, (November to March) witnessed a relatively higher percentage of surface ducts compared to the wet season (April to October). Peak occurrences of ducting were recorded in January, February, and December.

From the findings of the study, it can be stated that surface ducts are a prevalent phenomenon in Lagos, particularly during the dry season and at lower altitudes (100 meters). This has significant implications for microwave propagation, as signals can become trapped within the duct and travel over longer distances. This can potentially lead to interference with communication systems at far-off locations. The study highlights the importance of considering surface ducts when designing and deploying communication infrastructure in coastal regions like Lagos.

Given the above observation and conclusion, we hereby propose the following recommendations,

(i) The design of communication systems in Lagos should takes into consideration, the the expected impact of surface ducts, especially during the dry season (November to March) and at lower altitudes (around 100 meters).

(ii) The initiation of signal mitigating techniques to mimic interferences that could arise from microwave signals that can be trapped by surface ducts

(iii) Research should be conducted on the impacts of surface ducts on different communication frequencies and technologies.

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Compliance with Ethical Standards Declaration

Ethical Approval

Not Applicable

Competing interests

The authors declare that they have no known competing financial interests

Funding
The authors declared no external source of funding**.**

Availability of Data and Materials
Data would be made available on request**.**

Author Contributions

Olalekan Lawrence Ojo : initiated the methodology, carried out the analysis, participated in discussing the results, read the paper, and commented on it. Joseph Sunday Ojo participated in writing, reviewing and editing, the manuscript while Omotoyosi Omotayo Omoyele: participated in discussing the results, read the paper, and commented on it.