ASSESSMENT OF TROPOSPHERIC DUCT CHARACTERISTICS AND THEIR IMPLICATIONS FOR MICROWAVE SIGNAL PROPAGATION OVER PORT HARCOURT, NIGERIA

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Abstract

Complexity and non-linear trend in the internal activities of the troposphere has been a great factor influencing the transmission and receiving of good quality signal globally. The formation of Duct is the most severe and deviation from the standard propagation conditions which occurs majorly in coastal and maritime areas. The tropospheric duct significantly affects the design and performance of communication system and can also enhance signal to travel beyond radio horizon which can lead to unexpected interference. Consequently, in this study, we focused on how factors like temperature, humidity, and pressure influence radio refractivity and the formation of tropospheric ducts at different heights (200 m and 300 m) in Port Harcourt, Nigeria, using ten years (2015-2024) of meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 reanalysis. The analysis of the result showed that modified refractivity remains consistently high throughout the year with the value above 330 N-unit at both altitudes

Keywords: Tropospheric Duct, Microwave propagation, Coastal region, Ducting

Introduction

Coastal and maritime regions host a substantial numbers of radio communication networks which are liable to experience anomalous propagation because radio signal frequently experience outages and distortions, consequently leading to serious degradation in the performance of dependant communication networks. This effect is partly ascribed to ducting, the phenomenon which constitutes the most severe case of anomalous propagation in radio communications (Ikharo *et al.,* 2015). 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, including weather forecasting, communication, navigation, and disaster relief, particularly in a nation like Nigeria with a sizable Atlantic Ocean coastline (Ojo *et al.,* 2024).

Some literatures have documented the implications of duct on communication systems. For example, Lee and Meng, (2011) worked on Analysis of ducting effects on Air-to Ground propagation channel over sea surface at C-band. In the study the measured propagation loss was used to estimate the possible signal enhancement due to ducting effect. The result obtained showed that evaporation ducts and elevated ducts over the sea surface are two important forms of ducting that can significantly improve over sea air-to-ground transmission and only elevated duct can influence radio wave propagation for flight path at higher airborne altitude. The probability of yearly occurrence of elevated duct is more than 10% of the time and an average height of 1km. Suleman *et al*., estimated refractivity gradient of the lower atmosphere using Integrated Sensor Suite which comprises of several sensors that measures basic weather parameters including rainfall, temperature, relative humidity. It was observed that the propagation condition in

Ogbomosho is mostly super-refractivity and it is high during rainy season, there is a decrease in value during dry months, but it has an intense value during dry harmattan.

Khan *et al.,* (2020) studied the effect of rising temperature on microwave communication in ducting environment over Northern Arabian sea. Data was collected from three different locations to observe the electromagnetic wave's effect on evaporation duct. The results show that rising temperature plays an important role in duct formation, thereby affecting microwave communication reliability over the sea. Duct occurs above 30 % in the summer month and less than 7 % in the spring, autumn and winter month. It is mainly due to an increase in temperature, especially in summer and autumn months, where humidity gradients play an essential role in creating a higher frequency of duct. Some effect of atmospheric ducts mentioned by Liu *et al.,* 2021 were channel modelling and propagation delay. Atmospheric duct can be exploited for wireless communication. Atmospheric duct enabled line of sight communication which has been considered as a promising technology in coastal and maritime area due to high availability of evaporation duct. The tapping region also plays an important role in both remote interference management and beyond the line of sight communication. Yang *et al.,* (2023), studied atmospheric ducts and their electromagnetic propagation characteristics in the North western South China Sea. data from seven automatic weather stations and five radio-sounding stations was used to statistically analyse the characteristics of the atmospheric ducts in the northwest region of the South China Sea (SCS). The performance and reliability of microwave communication systems are significantly influenced by atmospheric refractivity conditions within the lower troposphere. The absence of detailed assessment of duct characteristics in Port Harcourt therefore poses challenges to accurate microwave system design and performance predictions. The study aims to assess the tropospheric duct characteristics and their implications on microwave propagations.

Methodology

The study area is Port Harcourt City Local Government Area of Rivers State. It is a coastal area which is located in the southern part of Nigeria. Port Harcourt city lies within the Longitude 7°0'0" E and Latitude 4°46'30" N (Collins and Obafemi, 2019). The area which became Port Harcourt in 1912 was farmlands of Diobu and Rebisi communities in the study area. In 1956 crude oil was discovered in commercial quantities at Oloibiri, and Port Harcourt's economy became predominantly petroleum driven. The first shipment of Nigeria crude oil was exported through the city in 1958. The growth pole effect of the Nigerian petroleum industry, made Port Harcourt to further develop, with the aspect of modernization such as overpasses and city block. The study area has a tropical climate with a mean yearly temperature of 30 °C and yearly rainfall of 2000 mm (NIMET, 2018)

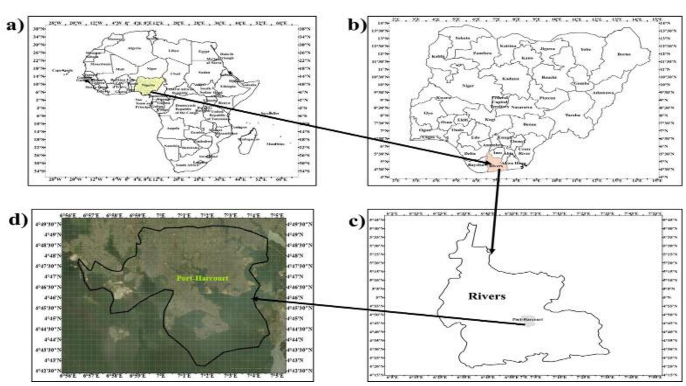

Fig 1: Map of Port Harcourt showing the study location

Ten years (2015-2024) meteorological parameters data of relative humidity, pressure and air temperature were obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) Re-analysis 5 (ERA-5) to deduce the tropospheric duct condition. The ECMCF created the extensive reanalysis dataset known as ERA-5, which 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 analyse the climatic and weather condition in great depth over time. Mapping, visualization and advance data analysis were done by Quantum Geographic Information System (QGIS) and Origin 8.5 Pro. The surface value of radio refractivity, N, and more importantly, its vertical gradients –particularly within the first kilometer above the earth's surface- are critical parameters governing radio wave propagation in the troposphere. Variations in these parameters significantly influence the bending, trapping, and overall transmission characteristics of electromagnetic waves. The estimation of radio refractivity is based on measured meteorological variables namely air temperature, atmospheric pressure, and water vapor pressure, applied through standard refractivity formulation. These parameters are utilized to generate data points that characterize the seasonal variability at different altitudinal levels of the study location. The mean N value for each year was calculated using the formula below (ITU-R 2015).

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

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 (kelvin).

Radio refractivity in the lower atmosphere can be classified into two primary components which are shown below

$$N_{dry} = \frac{77.6P}{T} \quad \text{and} \quad N_{wet} = 3.73 \times 10^5 \frac{e}{T^2} \qquad (2)$$

The two expressions were applied to determine the radio refractivity during the dry and wet seasons respectively, and the results were used to compute the total radio refractivity for each measurement period. For each day, average variation of refractivity was calculated using recorded data. Therefore, the vapour pressure, *e,* (hPa) was calculated using the saturated water vapour e_s (hPa) and relative humidity, using equations 3 and 4.

$$e = H \times \frac{e_s}{100} \qquad (3)$$

$$e = 6.1121 \times \exp\left(\frac{17.62T}{243.21 + T}\right) \qquad (4)$$

The modified refractivity, M, at a given atmospheric level is defined as the sum of the radio refractivity N, and the product of the height, h, at that level multiplied by a constant value of 0.157when the height is in meters.

$$M = N + (157 \times h) \qquad (5)$$

The characteristics difference in modified refractivity refers to the difference between the modified refractivity values measured at any two distinct atmospheric levels. It represents the change in modified refractivity (ΔM) between two heights in the atmosphere,

Results

Monthly Variation of Modified Refractivity

Figure 1 shows the monthly variation of modified refractivity at 200 m and 300 m heights. The results reveal that modified refractivity remains consistently high throughout the year, with values above 330 N-units at both altitudes. This stability indicates a refractive environment favourable for bending of radio waves and the occurrence of anomalous propagation phenomena such as super-refraction and ducting (Bean and Dutton, 1968; Turton *et al.*, 2014). A consistent observation is that modified refractivity at 300 m is slightly higher than at 200 m, suggesting a weak positive vertical gradient between these two levels. Such a gradient often results from stratification of temperature and humidity in the lower troposphere (Karimian *et al.*, 2014). Since refractivity increases with altitude in this range, electromagnetic waves propagating near 300 m may experience stronger bending effects than those near the surface. Seasonal variations are modest but discernible. During the warmer and more humid months (April–August), refractivity values peak slightly, reflecting enhanced atmospheric moisture and temperature gradients. In the cooler, drier months (October–December), values decrease marginally, consistent with reduced humidity and weaker thermal gradients. Nevertheless, the amplitude of this seasonal variability is small, highlighting the persistence of a humid, refractivity-favourable atmosphere throughout the year. This pattern aligns with studies conducted in other tropical and coastal environments, which also reported persistently high refractivity values due to abundant moisture (Reid *et al.*,1995; Adegoke and Adeyemi, 2017). From a propagation perspective, these findings imply that the region supports relatively stable anomalous propagation conditions year-round, with modest intensification during mid-year. Elevated refractivity at 300 m suggests that towers, elevated platforms, and airborne systems may experience more significant propagation anomalies compared to ground-level systems.

Monthly Duct Occurrence

The number of duct days per month over Port Harcourt is shown in Figure 3. The results indicate that ducts are present in all months, with frequencies ranging from 4 to 8 days per month. Peaks in duct occurrence are observed in January, April, May, and August, while minima occur in July, September, and November. This distribution strongly correlates with periods of enhanced refractivity values and sharp negative gradients, confirming that duct formation in this region is primarily controlled by moisture availability and temperature inversions. The relatively high duct frequency throughout the year underscores the persistent influence of coastal tropical meteorology on radio propagation conditions.

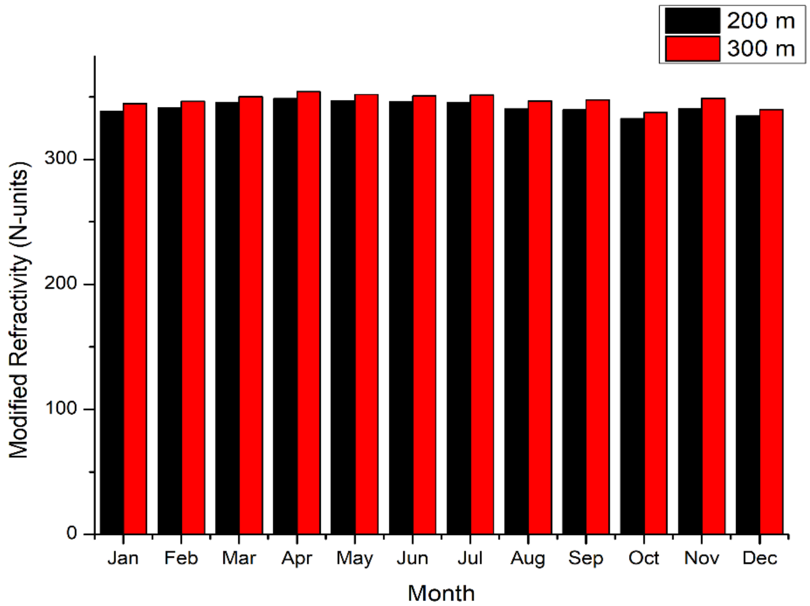

Figure2: Monthly variation of modified refractivity at heights of 200 m and 300 m.

Daily Vertical Gradients

The daily variation of vertical gradients is presented in Figure 2. The results highlight the highly dynamic nature of the atmospheric refractivity structure. Vertical gradients fluctuate frequently between positive and negative values, reflecting rapid changes in atmospheric stability and moisture distribution. Positive gradients correspond to normal refraction, where radio waves bend gradually toward the Earth's surface. Negative gradients, particularly those below –100 M/km, indicate super-refraction or ducting, conditions that can trap radio waves and guide them over long distances (Paulus, 1999; Willoughby *et al.*, 2016). The frequent occurrence of strong negative gradients suggests that the study region is highly susceptible to duct formation. Such conditions are common in humid and coastal environments where evaporation ducts and elevated ducts are sustained by temperature inversions and moisture stratification (Babin, 1996; Reid *et al.*, 1995). The variability of the gradient implies that propagation conditions can change rapidly, transitioning between normal and anomalous refraction. This has important implications for system reliability, as communication and radar networks in the region must account for sudden shifts in propagation behaviour.

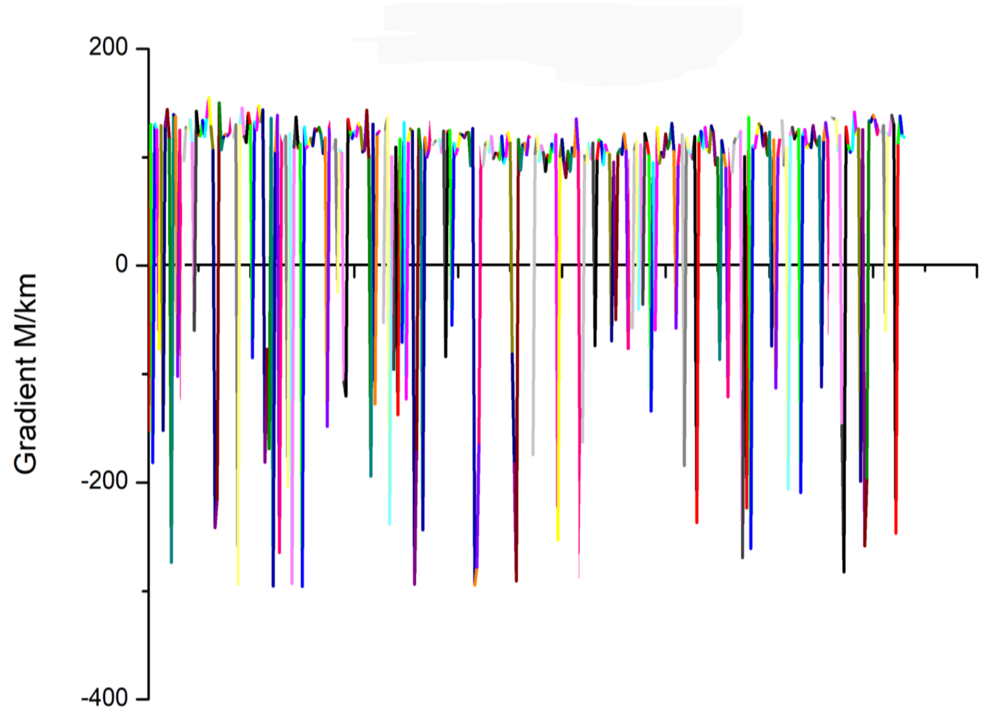

Figure 3: Daily variation of vertical gradients.

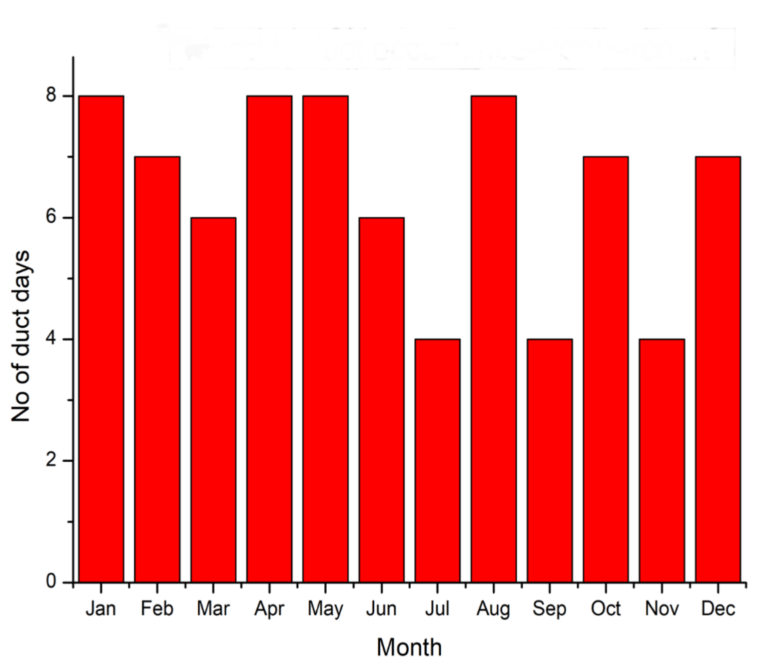

Figure 4: Monthly duct occurrence (number of duct days) over Port Harcourt

Statistical Occurrence of Ducts

The monthly percentage occurrence of atmospheric ducting over Port Harcourt is shown in Figure 4. The results revealed that ducting is a year-round phenomenon, though with significant seasonal variation. The percentage occurrence ranges from about 13 % to 27 %, with the highest values recorded in April (≈ 27 %), May (≈26 %), and January (≈25.6 %), while the lowest values occur in July (≈ 12.8 %) and September (≈13.4%). The elevated ducting percentages in the January–May period and again in August coincide with months characterized by higher surface humidity and stronger thermal stratification, which are conducive to the formation of surface-based and elevated ducts. This aligns with the findings of Tanko *et al.* (2022), who showed that coastal and rainforest regions in Nigeria exhibit the highest refractivity values, particularly during the wetter months. Similarly, Onuorah *et al.* (2022) observed that refractivity values in coastal environments remain persistently high, supporting frequent anomalous propagation conditions. In contrast, the reduced ducting percentages in July, September, and November correspond to the peak of the rainy season, when strong convective activity and vertical mixing disrupt the stability of the lower troposphere, thereby reducing duct formation. This behaviour is consistent with Omotoso and Olajide-Owoyomi (2025), who reported that convective rainfall periods in coastal Nigeria are associated with reduced refractivity gradients and a lower probability of ducting. The results confirm that Port Harcourt is a duct-prone environment, with ducting conditions prevailing for at least 20 % of the time in most months. This finding is consistent with recent results from Suleman *et al.* (2025), who reported frequent super-refractive and ducting conditions in south western Nigeria, with peak ducting probabilities occurring during early morning and wet season periods. The consistency of these results across different Nigerian stations underscores the reliability of refractivity-based analysis in characterizing ducting climatology. The results emphasize the need for system designers to integrate duct climatology into link budget estimations and interference management strategies.

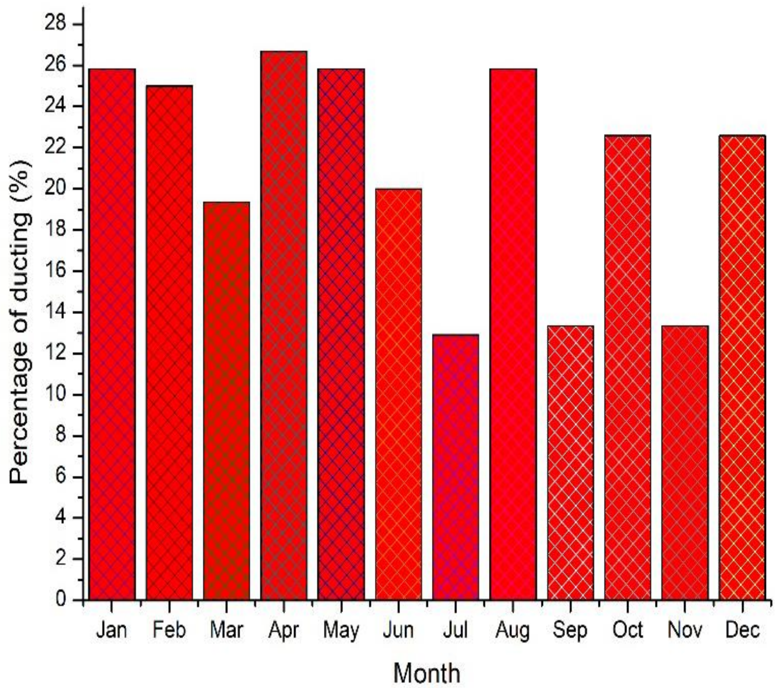

Figure 5: The monthly percentage occurrence of atmospheric ducting

Implications for Radio Propagation

The combined results demonstrate that Port Harcourt is a high-risk region for anomalous propagation. Elevated refractivity values, frequent negative gradients, and persistent ducting events create conditions that can significantly extend or distort the range of communication and radar systems. While ducts can improve signal coverage by extending line-of-sight ranges, they may also introduce challenges such as multipath fading, interference, and false target detection. These findings emphasize the need for adaptive communication strategies, frequency management, and the incorporation of ducting climatology into radar and navigation system design for operations in the region. The results also contribute to the broader understanding of tropical ducting behaviour, consistent with the findings of Willoughby *et al.* (2016), who noted the dominance of evaporation and surface ducts in humid coastal environments.

Conclusion

The modified refractivity at two different heights has been assessed and the corresponding vertical gradients and monthly occurrence of duct were analysed. The result of the variations of modified refractivity at 200 m and 300 m show higher values of modified refractivity, with the values at 300 m higher than those at 200 m, an indication that the refractivity of the region increases with altitude and radio waves may experience stronger bending at 300 m than at 200 m. The vertical gradient of the region fluctuates between positive and negative values due to rapid changes in atmospheric instability and moisture distribution. The frequent appearance of strong negative values duct formation which are common attributes of humid and coastal area. The monthly duct occurrence also shows that ducts present an all the months. The monthly percentage of duct occurrence over Port Harcourt from 12.8 % - 27 % which indicates that duct is an all-year occurrence.

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