Synergic analysis of radio ducting anomalies and atmospheric aerosols’ concentration over Nigeria

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Abstract. The study investigates the influence of the three atmospheric aerosols viz dust particles (DST), ammonium nitrate (NH\(_4\)NO\(_3\)), and sulphate (SO\(_4\)) on the radio ducting anomalous propagation over thirteen selected locations and their respective regions in Nigeria. Radio duct was computed from temperature, relative humidity, and pressure datasets obtained from the ERA5 database of the European Centre for Medium-Range Weather Forecasts (ECMWF). Also, dust, ammonium nitrate (NH\(_4\)NO\(_3\)), and sulphate (SO\(_4\)) aerosol emissions were obtained from the Representative Concentration Pathway (RCP) 8.5 scenario database of the Integrated Assessment and Climate Modelling community. The data covered a period of seven years (2010 – 2016) across sixteen locations in Nigeria. The seasonal analysis of the ducting frequency of occurrence and that of mass concentration of the aerosols were performed. Beta weight analysis was carried out between atmospheric duct and aerosols. Analyses showed that ducting occurrences were relatively higher when the concentration of dust and SO\(_4\) aerosols were very low. Whereas there was no or low occurrence of ducting in the months with a high concentration of dust, SO\(_4\), and NH\(_4\)NO\(_3\) aerosols across studied locations. It can be concluded based on correlation analysis that aerosols have a greater influence on the atmospheric duct in the Coastal regions, followed by the Sahel region and then the Savannah region.

1. Introduction
Radio ducting is an irregular phenomena of electromagnetic propagation produced by variable air refraction, which affects radar and communication systems [1, 2]. They reflect an anomalous atmospheric condition. The ducts capture electromagnetic waves in a specific atmospheric layer and transport them with minimal propagation loss at an over-the-horizon distance, substantially increasing radar ranges [3]. The ducts, on the other hand, modify the propagation path of EM waves, resulting in radar holes [4] and lower radar detection capability. In the time division long term evolution network system (TD-LTE), it also produces long-distance co-channel interference, which has a substantial impact on the city's communication infrastructure [5]. [6] studied the relationship between the ducting refractive conditions and the latitudes in Nigeria. The study found that there was a strong positive correlation between the latitude of a location and ducting. Furthermore, in the study by [7], they observed that propagating signals in radio ducts are confined between the ducting layer and the surface, causing their power to also not travel isotropically into the atmosphere. As a result, these signals have lower trajectory losses and can pass over the horizon. On the other hand, atmospheric aerosols are particles ranging in sizes that are suspended in the atmosphere, they are usually created by nature and anthropogenic activities. They exert direct radiative forcing by scattering and absorbing solar radiation,
as well as indirect radiative forcing and impacting the hydrologic cycle by functioning as cloud condensation nuclei [8–10]. The scattering and absorption properties of the atmospheric aerosols played important roles when electromagnetic radiation attenuated and thus affected both the distribution of climatic components and the atmospheric refractive index. Also, the scattering and absorption by aerosols is capable of reducing beam of radio signals intensity incident on signal detectors in the free space optical (FSO) communication system through optical scintillation. The absorbing aerosols has great perturbation potential to alter the refractive index structure parameter and thereby exert influence on the performance of FSO communication systems [11].

Therefore, there is a need to investigate the effect and contribution of atmospheric aerosols on the ducting anomalous of radio signals. This study first evaluates the frequency of ducting and secondly deduces the mass concentration of dust, ammonium, and sulphate aerosols in some locations in Nigeria. Finally, the relationship between the occurrence of atmospheric ducting and aerosols is analyzed using statistical metrics.

2. Materials and Methods

Daily data of temperature, relative humidity, and pressure at the surface and 1000 hPa pressure level were obtained from the ERA5 database of the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 is the 5th generation ECMWF atmospheric reanalysis dataset covering global climate from 1950 to present. It provides estimate of several atmospheric, land and oceanic climate variables on different time series (hourly, daily and monthly). ERA5 datasets cover 30 km grid and 137 atmospheric pressure levels from the surface up to a height 80 km. Meanwhile, data of dust, ammonium (NH₄NO₃), and sulphate (SO₄) aerosol emissions were obtained from the representative concentration pathway (RCP) 8.5 scenario database of the Integrated Assessment and Climate Modelling community. The data covered a period of seven years (2010 – 2016) across sixteen locations in Nigeria. The sixteen locations were further divided into three climatic regions of Nigeria namely Sahel, Savannah, and Coastal regions as shown in Figure 1.

![Figure 1: A Map of Nigeria Showing Studied locations](image)

The surface and 1000 hPa pressure level refractivity (N) were evaluated using:

\[
N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}
\]
where $P$ is the atmospheric pressure (hPa), $T$ is the temperature (K), $e$ is the water vapour which can be obtained according to [6] using

$$e = \frac{6112H}{100} \exp \left( \frac{17.50t}{t + 240.97} \right)$$

(2)

where $H$ is relative humidity (%) and $t$ is the temperature (°C). Refractivity gradient, $G$, is calculated from:

$$G = \frac{N_s - N_{1000}}{h_s - h_{1000}}$$

(3)

where $h_s$ and $h_{1000}$ represent surface height and altitude pressure level of 1000 hPa respectively. The refractivity conditions for ducting anomalous propagation is $G < -157$. Under this condition, radar microwaves may be trapped and travel within the duct layers like a waveguide. This may lead to signal enhancement near and beyond the radio horizon [12]. Standardized beta weight ($\beta$) for each of the aerosols (dust, ammonium (NH$_4$NO$_3$), and sulphate (SO$_4$) aerosol emissions) was computed to ascertain their contribution to atmospheric ducting according to [13] using

$$\beta_i = \frac{n}{n - 1} \sum_{i=1}^{n} \frac{D_i - \bar{D}}{A_i - \bar{A}}$$

(4)

where $A_i$ represent each of the aerosols, $\bar{A}$ is their mean value, $D_i$ is the frequency of ducting, $\bar{D}$ is the mean value of frequency of ducting and $n$ is the number of observations. $\beta_1$ is the beta weights of between dust aerosol and radio ducting occurrence, $\beta_2$ is the beta weights of between SO$_4$ aerosol and radio ducting occurrence, and $\beta_3$ is the beta weights of between NH$_4$NO$_3$ aerosol and radio ducting occurrence. $\epsilon_1$, $\epsilon_2$, and $\epsilon_3$ are their respective standard errors. The value of $\beta$ show the total effect of the predictor variables, so the absolute top-ranked variable is theoretically the one with the greatest total effect [14, 15]. The overall synergy between the atmospheric aerosols and radio ducting anomalies was evaluated using the correlation analysis – the correlation coefficient (R) and correlation of determination ($R^2$).

3. Results and Discussion

Figure 2 – 4 (a-d) shows the monthly variations of frequency of radio ducting occurrence and three aerosol emissions (dust, SO$_4$, and NH$_4$NO$_3$) over some locations in Sahel, Savannah, and Coastal regions over Nigeria. The radio duct was observed to be prominent in Geidam in July (Fig. 2a), Yola in August (Fig. 3a), and Lagos in October (Fig. 4a) in the Sahel, Savannah, and Coastal regions respectively. There was no occurrence of ducting in January, February, and December in the Sahel region and only in December in the Savannah region. Also, it was observed that ducting has the highest frequency of occurrence in the Coastal region, followed by the Savannah region and the least occurrence in the Sahel region. That is the frequency of occurrence of ducting decreases with increasing latitude across Nigeria.

Comparative analysis between radio duct and aerosols revealed that ducting occurrences were relatively higher when dust and SO$_4$ aerosols were very low (Figure 2 – 4, a-c). Whereas there was no or low occurrence of ducting in the months with a high concentration of dust, SO$_4$, and NH$_4$NO$_3$ aerosols respectively across studied locations. Aerosols particles have varying sizes whose microphysical quantities are wavelength dependent derived from the complex refractive index and size distribution through Mie theory. These have made them capable of absorbing other smaller particles on its path such as radio signals propagating from the communication systems. This may be the reason why radio ducting has lower occurrences where there are higher concentrations of aerosols and vice-versa in agreement with [11].

Statistically from Table 1, the effect of aerosol emissions on the radio duct was further investigated using beta weight ($\beta$) and correlation analyses. Beta weight analyses showed that dust aerosol’s
concentration have the greatest attenuating effect on the radio ducting in Gashua, Maiduguri, and Sokoto in the Sahel region; Akure, Ilorin and Jos in the Savannah region; and only Port-Harcourt in the Coastal Region. Meanwhile, concentration of NH$_4$NO$_3$ aerosol has the greatest effect on the radio duct in Geidam and Kano in the Sahel region; Yola in the Savannah region; and only Lagos and Warri in the Coastal Region. Concentration of SO$_4$ aerosol only affects the radio duct in Abuja in the Savannah region. The correlation analyses showed that atmospheric aerosols have a strong relationship with radio ducting anomalies having correlation coefficient (R) values of 0.707 in the Sahel region, 0.689 in the Savannah region, and 0.814 in the Coastal region. Similarly, going with values of the coefficient of determination (R$^2$), aerosols contributed 50.10% to radio ducting in the Sahel region, 47.40% to radio ducting in the Savannah region and 66.30% to radio ducting in the Coastal region.

Figure 2: Monthly Variation of Ducting Occurrence and Aerosol Mass Concentration over Sahel Region in Nigeria
Figure 3: Monthly Variation of Ducting Occurrence and Aerosol Mass Concentration over Savannah Region in Nigeria

Figure 4: Monthly Variation of Ducting Occurrence and Aerosol Mass Concentration over Coastal Region in Nigeria
Table 1: Relationship between Ducting Occurrence and Aerosol Mass Concentration over Some Locations and their Regions in Nigeria

| Station | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\varepsilon_1$ | $\varepsilon_2$ | $\varepsilon_3$ | $R$ | $R^2$ | $\varepsilon$ |
|---------|-----------|-----------|-----------|----------------|----------------|----------------|-----|-----|--------------|
| Gashua  | -0.814    | -0.030    | -0.043    | 0.257          | 0.189          | 0.258          | 0.846   | 0.716   | 1.446 |
| Geidam  | 0.136     | 0.055     | -0.700    | 0.540          | 0.455          | 0.674          | 0.571   | 0.326   | 3.130 |
| Kano    | -0.034    | 0.338     | -0.453    | 0.491          | 0.329          | 0.492          | 0.486   | 0.237   | 0.855 |
| Maiduguri | -0.493    | -0.027    | -0.117    | 0.411          | 0.288          | 0.411          | 0.586   | 0.343   | 2.309 |
| Sokoto  | -0.553    | 0.188     | -0.262    | 0.477          | 0.282          | 0.461          | 0.772   | 0.513   | 2.230 |
| Sahel   | -0.581    | 0.071     | -0.187    | 0.399          | 0.288          | 0.418          | 0.707   | 0.501   | 1.803 |
| Akure   | 0.933     | -0.195    | -0.892    | 0.666          | 0.349          | 0.717          | 0.539   | 0.290   | 3.303 |
| Ilorin  | 0.992     | -0.043    | -0.910    | 0.574          | 0.360          | 0.639          | 0.576   | 0.332   | 2.584 |
| Jos     | 0.489     | -0.387    | -0.143    | 0.501          | 0.384          | 0.527          | 0.428   | 0.184   | 0.633 |
| Abuja   | -0.426    | -0.602    | 0.492     | 0.632          | 0.583          | 0.847          | 0.405   | 0.164   | 1.617 |
| Yola    | -0.154    | -0.145    | -0.487    | 0.444          | 0.533          | 0.655          | 0.689   | 0.475   | 3.081 |
| Savannah| 0.747     | -0.062    | -0.989    | 0.612          | 0.507          | 0.786          | 0.689   | 0.474   | 1.236 |
| Lagos   | 1.183     | 0.077     | -1.625    | 0.432          | 0.280          | 0.508          | 0.837   | 0.701   | 5.041 |
| Port-Harcourt | 0.492 | -0.125 | -0.414 | 0.371 | 0.381 | 0.432 | 0.477 | 0.228 | 3.776 |
| Warri   | 0.560     | 0.547     | -0.987    | 0.342          | 0.511          | 0.561          | 0.582   | 0.339   | 3.481 |
| Coastal | 0.844     | 0.841     | -1.857    | 0.316          | 0.544          | 0.646          | 0.814   | 0.663   | 3.036 |

4. Conclusion

The synergy between radio ducting and atmospheric aerosol (dust, SO$_4$, and NH$_4$NO$_3$) concentrations was investigated over some selected locations across the Sahel, Savannah, and Coastal regions in Nigeria. Analyses showed that radio ducting anomalies are prevalent in the wet months than in the dry months in a year. Regionally, based on the beta weight values, dust aerosols were observed to have a greater influence on the radio ducting in the Sahel region; dust and NH$_4$NO$_3$ aerosols have a strong influence on ducting in the Savannah regions; and dust, SO$_4$, and NH$_4$NO$_3$ have a significant influence on ducting in the Coastal region. Also, the combination of aerosols in the atmosphere has a strong relationship with radio signal ducting considering the results of correlation analysis with strongest effect in the Coastal region where aerosol contributed 66.30% to radio ducting anomalies. Few departures were discernible in Kano (Sahel region), Jos and Abuja (Savannah region), and Port-Harcourt (Coastal region) where the correlation values were less 0.50 threshold value. Finally, it can be inferred that atmospheric aerosols among other factors contributed to occurrences of ducting anomalous in the radio signals propagation especially in the Coastal region in Nigeria.

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