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Deduction of the Radio Wave Propagation Condition at Low Altitude from Self-measured Meteorological Data for Ekpoma Area, Nigeria

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Abstract

Refractivity indices (RI) such as the surface refractivity (SR), the refractivity gradient (RG), and the effective earth radius factor (k-factor) are valuable components for predicting the local radio wave propagation (LRWP) conditions in the troposphere. Hence, in this study, the estimation and analysis of the RI (SR, the RG, and k-factor) from the measured m weather/meteorological variables (WV); air temperature (T) , relative humidity (RH), and atmospheric pressure which was reduced to mean sea level pressure (MSLP) in the Ekpoma area of Edo State, Nigeria, which is located within Latitude 6.74° N and Longitude 6.14° E for a period of twelve months (January to December, 2022), so as to infer the radio propagation conditions using a self-designed weather/meteorological monitoring device (WMD), were investigated. The WMD was positioned at a low altitude (height level) of 50 m above sea level at a low-rise building located within the area so as to measure the needed WV. The results show that the SR and the k-factor values were generally higher during the months with high RH (rainy periods) compared to those of the months with lower relative humidity (dry periods), while the RG, values were higher in the dry periods compared to the rainy periods. The average values of the RI for the period under consideration are 355.58 N-units, -61.58 N-units/km, and 1.51 for the SR, the RG, and k-factor respectively. Thus, it is inferentially concluded that the LRWP condition for the Ekpoma is mostly super-refractive.

1.0. Introduction

Due to their evident impact on radio wave communication connections in the atmosphere, weather/meteorological variables (WV) are useful components in predictions of refractivity distributions/refractivity indices (RI) and the anomalous or aberrant radio wave propagation (LRWP) conditions of the atmosphere [1, 2]. Accessing these WV will undoubtedly contribute to improved LRWP conditions, which will enable cellular network service providers and the designers of navigation and radar systems to improve the quality of their services [1, 3, 4, 5, 6].
With the intention of dealing with issues that arise due to the anomalous or aberrant LRWP and unexpected route loss that influence the operation of these systems, refractivity distribution analyses are crucial in cellular networks, navigation, and surveillance systems [1, 3]. Radar may even entirely miss its intended location as a result of these unpredictable radio wave propagations' severe impacts, which can even result in an entire disruption of communication between transmitters and receivers [1, 3, 7].

The deviation of the LRWP caused by variations in the distribution of refractivity must thus be taken into account by the management of radio communication systems [1, 8]. Since weather/meteorological conditions have an impact on LRWP, the transmission medium must be taken into account in order to have a higher quality signal from the radio communication network [1, 3, 9].

The haphazard variations in the surface refractivity (SR) and vertical refractivity are what cause the attitude and phase scintillations, absorption, scattering of radio wave network signals, and other numerous multifaceted processes that take place in the lower layers of the atmosphere (troposphere), which can lead to transmission signals being lost and co-channel interference [1, 3, 10]. Due to the prevalence of high-intensity humid rains, the effect of interference caused by refractive variations in the atmosphere's lower layers is substantially stronger in humid climate regions than in moderate climate regions [1, 3, 9]. Broadcasting services for frequencies greater than 30 MHz are now planned using certain standard formats for referencing the International Telecommunications Union recommendation (ITU-R).

The observations conducted in most parts of the world with temperate climates, such as Europe, Asia, and North America, provided the most widely used LRWP curves and equations [1, 3]. Due to the dearth of reliable data from these places and the fact that the climate of sub-Saharan Africa differs from that of these mild climate zones, these curves and formulas can nevertheless be utilized to develop LRWP services in the sub-continent [1, 3, 11, 12, 13, 14]. Ultra-high frequency (UHF), very high frequency (VHF), and super-high frequency (SHF) radio transmissions all have different qualities, which are all influenced by the radio refractive index [5, 6].

The SR and vertical refractivity measurements are mostly required to identify a radio channel's properties. For the prediction of some propagation effects, the SR in N-units is more crucial than the elevated refractivity [1, 3]. The most important explanation of the likelihood of a refractivity-related influence required for LRWP prediction techniques is provided by local coverage, refractivity gradient (RG) in N-units/km, and other statistics of refractivity [9, 14, 8].

It is worth noting that WV are also very important for agricultural purposes [15, 16, 17, 18, 19, 20, 21], as well as other atmospheric purposes [1, 3]. Albeit, in this study, the measurement results of air temperature (T), relative humidity (RH), and atmospheric pressure (P) were made at a low altitude (height level) of 50 m above sea level at a low-rise building located within the Ekpoma area of Edo State, Nigeria, utilizing a set of self-implemented, cost-effective portable weather/meteorological monitoring device (WMD) for a period of twelve months (January to December, 2022). The measured WV were used to derive and analyze the RI, such as SR (N-units), RG (N-units/km), and the effective earth radius factor (*k*-factor), which are vital in describing the LRWP as recommended by the ITU-R. Though there have been comparable studies done in some other places, such as Ukhurebor and Azi [1]; Ukhurebor and Nwankwo [3]; Falodun and Ajewole [22]; Adediji et al. [9], etc.

However, the implications and rationale for consideration of this study is due to the fact that, from the best of what can be gathered from the literature that is at present accessible, this study is one of the most recent studies on the deviation of the LRWP conditions of the lower layers of the atmosphere (troposphere), specifically in the Ekpoma area. This study is also distinctive and unique due to the fact that self-measured weather/meteorological data was utilized.

2. Theoretical Background on the Formulations on Radio Propagation Conditions

The different layers of the atmosphere and its permittivity have been shown to cause the electromagnetic waves that are passing through it to bend; otherwise, if the atmosphere were homogeneous, the opposing effects of the air's spatially distributed refractive index (n) would have prevented this from happening [1, 3, 14, 22, 23, 24, 25]. The mathematical relationship between the relative permittivity ($\mathcal{E}r$) and the n of the atmosphere is given as:

$$n^2 = \varepsilon_r \quad (1)$$

Since, n ≈ 1 and the variations are microscopic. A suitable parameter that could be utilized when modelling the variation of the atmospheric n is what is known as the SR of the atmosphere (N-units) [1, 3, 9, 8], which can be expressed mathematically as [1, 2, 3, 9]:

$$N = (n-1)\times 10^6 \quad (2)$$

N may be theoretically linked to WV including T, P, and vapor pressure (e) by Eqn. (3):

$$N = \frac{77.60}{T}\left(P + 4810\frac{e}{T}\right) \quad (3)$$

Hence, N can be expressed theoretically by Eqn. (4) [11, 12, 13];

$$N = 77.60\frac{P}{T} + \left(3.73\times 10^5\frac{e}{T^2}\right) \quad (4)$$

The dry component (Nd) and the wet portion (Nw) of the lower atmosphere's refractivity may both be identified. Approximately 70% of the total amount of refractivity in the lower atmosphere comes from the Nd. The density of the gas molecules directly affects this Nd, which also varies depending on the distribution. It is typically stable and may be computed with an accuracy of around 20% given the measured T and P by Eqn. (5) [1, 2, 3, 9]:

$$N_d = 77.60\frac{P}{T} \quad (5)$$

Where P is in mbars and T is Kelvin (K) [1, 2, 3, 9].

While the Nw, which is a result of the polar nature of water molecules and contributes to the major alteration in the SR in the lower atmosphere, can be estimated using Eqn. (6) [1, 2, 3, 9]:

$$N_w = 3.73\times 10^5\frac{e}{T^2} \quad (6)$$

Where e (the partial pressure of water vapor) is in mbars and defined mathematically as [1, 2, 3, 9]:

$$e = \frac{RH}{100}\times e_s \quad (7)$$

Where RH is in % and saturated vapour pressure (es) which is the is in mbars and expressed mathematically as [1, 2, 3, 9]:

$$e_s = 6.11\times 10^{\frac{17.27(T-273.15)}{T-35.85}} \quad (8)$$

If the height or altitude of a ray above the earth's surface (h), the radius of the ray curvature or the refractive index gradient (r), and the vertical gradient of refractive index (dN/dh) are known, the horizontal angle of the path (θ) to a given point can be expressed mathematically as follows [1, 2, 3, 9]:

$$\frac{1}{r} = \frac{1}{N}\left(\frac{\partial N}{\partial h}\right)\cos\theta \quad (9)$$

As stated by Brussaard and Watson [26], r could be linked to the relative earth radius (R) in terms of the refractive index gradient by Eqn. (10):

$$\frac{r}{R} = k \quad (10)$$

The k, which is also known as the *k*-factor, could now be stated mathematically by Eqn. (11) [1, 2, 3, 9]:

$$k = \frac{1}{1 + R\left(\frac{\partial N}{\partial h}\right)} \quad (11)$$

Therefore, Eqn. (11) may now be expressed in terms of refractivity (N) since R ≈ 6370 km as Eqn. (12) [1, 2, 3, 9]:

$$k \approx \frac{\dfrac{1}{1+\left(\dfrac{\partial N}{\partial h}\right)}}{157} \tag{12}$$

Depending on the situation, the *k*-factor could potentially be utilized for categorizing the refractive conditions as sub-refraction, super-refraction, ducting, normal refraction, or standard atmosphere [1, 2, 3, 25, 9].

Around the earth's surface, dN/dh ≈ --39 N-units/km and k ≈ 1.33; this is referred to as normal refraction or standard atmosphere. Here, radio signals are transmitted along a straight-line path on the earth's surface and go into space unhindered.

If 1.33 > k > 0, we would have sub-refraction, which signifies that the radio waves propagate abnormally away from the earth's surface. But when we have super-refraction, this indicates that the radio wave signals spread irregularly towards the earth's surface, thereby extending the radio horizon and increasing path clearance, thereby giving irregularly huge ranges above the line of view as a result of multiple reflections.

However, if ∞ > k > 1.33 there would be ducting, this could cause the radio waves to bend downward with a curvature greater than the earth's own. The radio signals can become trapped between a layer in the lower atmosphere and the surface duct, which is the earth's or sea's surface, or between two layers in the lower atmosphere, which is the elevated duct. In this waveguide-like propagation, very high radio signal strengths could be obtained at a very long range, which is far above the line of view [1, 2, 3, 25, 9].

2. Materials and Methods

The measurements of the WV utilized for this study were done at a low altitude (height level) of 50 m above sea level at a low-rise building located within Ekpoma area, which is located within Latitude 6.74° N and Longitude 6.14° E of the Greenwich Meridian (see Figure 1), utilizing a set of self-implemented, cost-effective portable WMD that measure T, P, RH, and light intensity.

The WMD was designed in such a way that it can be used remotely, and the readings are displayed on the user-friendly LCD display in numerical digital values for T (ºC), P (mbar), RH (%), and light intensity (lux), which can also be sent to a computer via the programmed micro-SD card or/and through the serial port (the Arduino SD card module). The user has the option of choosing how often the WV will be logged, measured, recorded, stored, and displayed. The acquired WV are analyzed, and the LCD displays the values. In addition, the WV for each day were saved on the micro-SD card in Excel format on a separate file, with each file having a file name that corresponds to the date and time when the WV were acquired. The users also have the option to stop the WV acquisition process at any time by interrupting the routine. Details of the design and implementation of the WMD, including its validity, are contained in Ukhurebor *et al.* [27].

Figure 1. Map of Ekpoma area of Edo State, Nigeria

The P readings from the source were reduced to the mean sea level pressure (MSLP) so as to make the readings of different sources comparable by cancelling out altitude-dependent differences. The reduction to the mean sea level was performed on all P readings based on information about the P, height or altitude (h), and T data obtained. Eqn. (13) was used for the reduction to the mean sea level [28];

$$P_{(mslp)} = P \times \left[1 - \frac{0.0065 \times h}{T + 0.0065 \times h \times 273.15}\right]^{-5.257} \quad (13a)$$

$$= 0.03414 \times \frac{Ph}{(273.15 + T)} \quad (13b)$$

3. Results and Discussions

3.1. Measurement of the WV

The fixed measuring method was utilized for the measurements of the various WV at a low altitude (height level) of 50 m above sea level at a low-rise building located within Ekpoma for continuous measurements from January to December 2022. As stated earlier, the WMD measures four WV. The average daily measurements for 2022 of each of the measured WV, while the average monthly measured WV are contained in Table 1.

Table 1. Average measured WV for 2022

Month	T (ºC)	RH (%)	MSLP (mbars)
January	27.70	43.20	1010.64
February	31.30	48.70	1012.42
March	29.60	69.20	1013.38
April	28.80	85.70	1013.18
May	27.90	92.60	1011.64
June	25.80	93.90	1012.49
July	24.50	95.80	1013.66
August	26.10	79.10	1013.41
September	25.00	78.90	1014.80
October	25.20	69.40	1012.26
November	27.30	68.70	1010.10
December	26.00	58.80	1009.38
Average	25.00	73.67	1012.28

3.2. The LRWP condition

The prediction or deduction of the local wave propagation condition was done procedurally by estimating the RI, that is, SR or atmospheric refractivity, RG and *k*-factor, from the measured WV using Eqn. (1) to (13) accordingly. The monthly average estimated SR, RG, and *k*-factor for January to December 2022 are shown in Table 2.

Table 2. Monthly average estimated RI for 2022

Months	SR (N-units)	RG (N-units/km)	*k*-factor
January	317.00	-191.00	1.26
February	317.00	-29.00	1.40
March	363.00	-66.00	1.60
April	361.00	-41.00	1.50
May	359.00	-31.00	1.40
June	371.00	-65.00	1.58
July	373.00	-71.00	1.62
August	359.00	-73.00	1.78
September	365.00	-69.00	1.50
October	364.00	-31.00	1.54
November	361.00	-21.00	1.50
December	357.00	-51.00	1.42
Average	355.58	-61.58	1.51

3.2.1. The SR

The estimated SR values for the months (January to December, 2022) range from 317.00 N-units to 373.00 N-units, with an average value of 355.58 N-units. These estimated SR results agree very well with the results of Adediji et al. [9] and Falodun and Ajewole [22], where they obtained the average SR values of 366.00 N-units and 369.00 N-units for Akure, Nigeria, respectively. Also, results agree very well with the results of Ukhurebor and Azi [1] and Ukhurebor and Nwankwo [3] where they obtained the average RI for Auchi area, Nigeria. Both results are in conformity with the results of Bean and Dutton [29], where they obtained an annual average value of SR for subtropical savannah of 350.00–400.00 N-units with an annual range of 30.00–60.00 N-units.

In Figure 2, the SR monthly variations for January to December 2022 that were obtained from the monthly records are shown. It was observed that the values are higher during the months of April to October, which happen to be periods of much rainfall and are induced by very high RH values. While the values were lower in the months of November and December as well as January to March, which happen to be the dry periods when rainfall is limited and induced by very low RH.

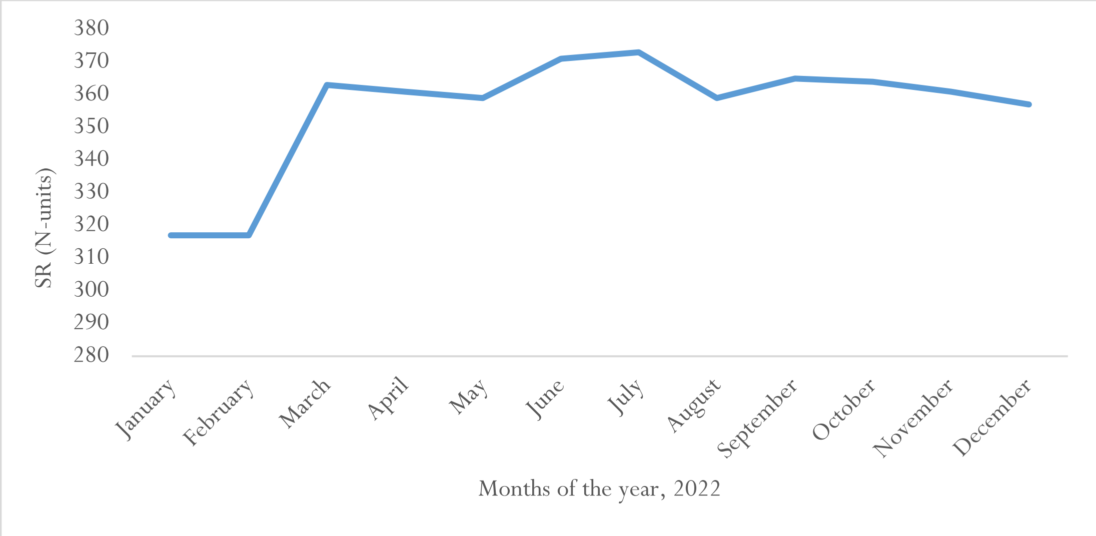

Figure 2. Monthly variations of SR for 2022

3.2.2. The RG

In Figure 3, the RG values for January to December 2022 on a monthly basis, which were obtained from the estimation of the average monthly statistical distribution of the SR at 50 m height above sea level, are shown. A critical view at the figure showed that the months with less rainfall have higher RG values (lower RH) compared to the ones with much rainfall (higher RH), and this makes the figure exhibit an undulating display. It was observed that the values were higher in the months of November and December, as well as in January to March, which happen to be the dry periods when rainfall is limited (lower RH), and dropped gradually during the months of April to October, which happen to be the periods of much rainfall (higher RH). The obtained RG values for the months (January to December, 2022) range from -191.00 N-units/km to -21.00 N-units/km, with an average value of -61.58 N-units/km. This result is again in conformity with the results of Adediji et al. [9]; Falodun and Ajewole [22]; Ukhurebor and Azi [1]; Ukhurebor and Nwankwo [3].

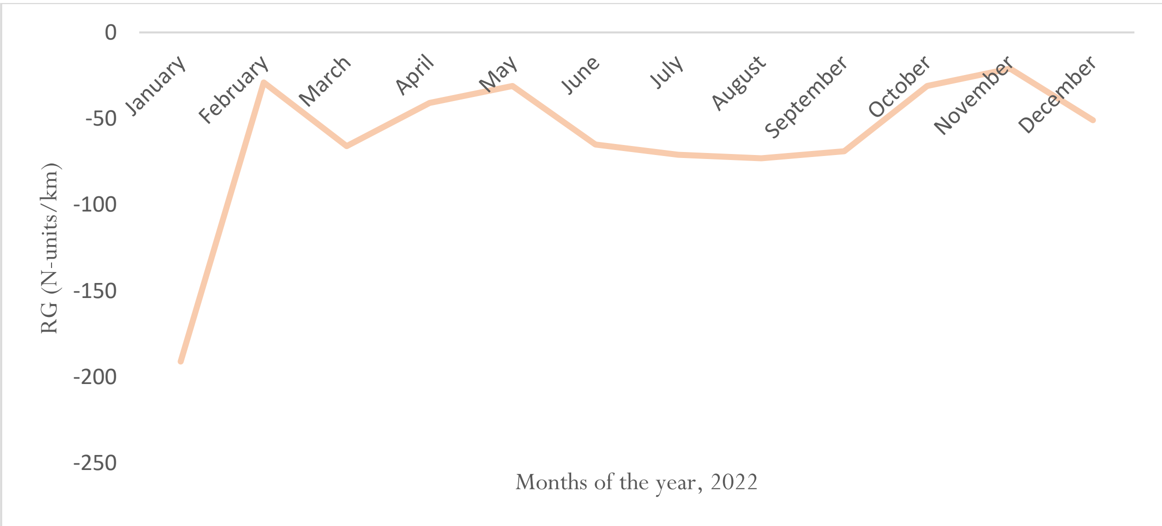

Figure 3. Monthly variations of RG for 2022

3.2.3. The *k*-factor

In Figure 4, the *k*-factor for January to December 2022 on a monthly basis, which was estimated from the monthly records of the measured WV, is shown. Censoriously view at the figure revealed that the months with much rainfall that is the months with higher RH (April to October) have higher values compared to the ones with lesser rainfall that is the months with lower RH (November and December, as well as January to March). The values range from 1.40 to 1.78 during the months with much rainfall (higher RH), while the values for the months with less rainfall (lower RH) range from 1.26 to 1.60. The average value of the *k*-factor obtained was 1.51. This result again agrees very well with the results of Adediji et al. [9]; Falodun and Ajewole [22]; Ukhurebor and Azi [1]; Ukhurebor and Nwankwo [3].

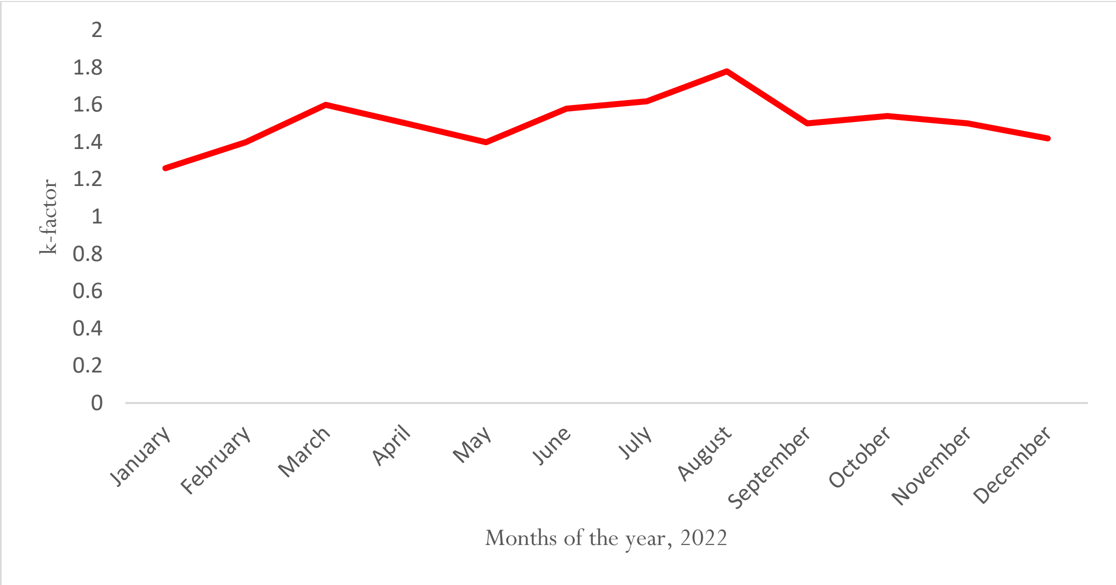

Figure 4. Monthly variations of *k*-factor for 2022

The results reveal that the SR and the *k*-factor values were generally higher during the rainy seasons (higher RH) compared to the dry seasons (lower RH), while the RG values were higher in the dry seasons (lower RH) compared to the rainy seasons (higher RH).

The measured T, RH, and P were having an influence (at different rates) on the estimated SR, RG, and *k*-factor all through the months in 2022; this again affirmed the fact that WV have a substantial influence on RI as reported by Adediji et al. [9]; Falodun and Ajewole [22]; Ukhurebor and Azi [1]; Ukhurebor and Nwankwo [3].

The average values of the SR, RG, and *k*-factor are 355.58 N-units, -61.58 N-units/km, and 1.51, respectively. Thus, we can inferentially conclude that the LRWP condition for the Ekpoma area is predominantly super-refractive since This signifies that the radio wave signals spread irregularly towards the earth's surface $\infty > k > 1.33$, hence extending the radio horizon and increasing path clearance, thereby giving irregularly huge ranges above the line of view as a result of multiple reflections.

3.3. Summarized findings

The summarized major findings from this study for the twelve-month period (January to December, 2022) are:

- The SR and the *k*-factor values were generally higher during the months with high relative humidity (rainy periods) compared to the months with lower RH (dry periods), while the RG values were generally higher in the months with lower RH (dry periods) compared to the months with high RH (rainy periods).

- The average values of the SR, the RG, and *k*-factor are 355.58 N-units, -61.58 N-units/km, and 1.51, respectively.
- Deductively, the LRWP condition for the Ekpoma is mostly super-refractive.

4. Conclusion

The measurements of T, RH, and P were made at a low altitude (height level) of 50 m above sea level at a low-rise building located within the Ekpoma area using a set of self-implemented, cost-effective portable WMD for a period of twelve months (January to December, 2022), respectively, so as to ascertain and analyse the RI (SR, the RG, and *k*-factor) in order to derive the LRWP conditions in the lower layers of the atmosphere (troposphere) for the area.
From the results of this study, it was deductively concluded that the LRWP condition for the Ekpoma area, Nigeria is mostly super-refractive. Furthermore, it is suggested that more measurements be carried out over a long period of time at different locations in the area so as to acquire more comprehensive results.

List of abbreviations

Words	Abbreviations
Atmospheric pressure	P
Effective earth radius factor	*k*-factor
Local radio wave propagation	LRWP
Mean sea level pressure	MSLP
Refractivity gradient	RG
Refractivity indices	RI
Relative humidity	RH
Surface refractivity	SR
Temperature	T
Weather/meteorological monitoring device	WMD
Weather/meteorological variables	WV

Data Availability

Complete data produced or investigated during this work were involved in this submitted article.

Conflicts of Interest

There is no conflict whatsoever to declare.

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Authors’ contribution

All authors contributed significantly to this research study. Ukhurebor, K.E: Conceptualization, Investigation, Methodology, Analysis, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing. Abanihi, V.K., Oisamoje, V, Aliu, D: Analysis, Validation, Writing - review & editing.

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