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Statistical Estimation of Effective Earth Radius Factor over Lagos using Radiosonde Data

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Abstract

The path followed by tropospheric radio waves between any two points on earth is largely influenced by atmospheric parameters which vary temporally and spatially. The effective earth radius factor (k-factor) is a function of these atmospheric parameters and it plays an important role in the design of wireless communication links operating in the Very High Frequency (VHF) and Ultra High Frequency (UHF) range. It defines a curved earth's surface without atmosphere, for which propagation pathis rectilinear. This study uses 2012-2014 radiosonde data of Relative humidity, Temperature and Pressure at first kilometer altitude in Oshodi (6^o 32'N, 3^o 21'E), Lagos, to estimate the effective earth radius factor for Lagos, a coastal region in southwestern Nigeria. An overall average value of 1.60±0.02 was obtained which is greater than the 4/3 recommended by ITU-R for this region.

Keywords: *Tropospheric radio waves, Refractivity gradient, k-factor, VHF, UHF, Rectilinear, ITU-R, Radiosonde*

1. Introduction

The process of sending information from one point to another without any physical link between these points is generally referred to as wireless communication. However, the information to be conveyed between these points must be correctly transformed into signals (electromagnetic waves) that are transportable through the space. The information is usually converted into radio waves which is a form of energy in the electromagnetic spectrum. Radio wave propagation is the sending out of electromagnetic energy from one point (transmitter) to another (receiver) and it is affected by changes in the refractive index gradient (i.e rate of change of radio refractivity N, with respect to altitude) of air in the troposphere [1]. When classifying the layers of the atmosphere based on temperature profile, the troposphere is the first layer of the atmosphere which extends from the earth's surface up to 9km at the earth's poles 17km at the equator. This is the layer that determines the Earth's weather conditions. It plays an important role in wireless communication especially at High Frequency (HF), Very High Frequency (VHF) and Ultra High Frequency (UHF) because it causes the bending of radio waves path.

When radio waves travel between two regions having different dielectric constants, there is always a change in direction of propagation of the waves. The reason for this change is as a result of changes in the speed of radio waves in the two regions; thus we define absolute refractive index of a medium as the ratio of the velocity of propagation of radio wave in a vacuum to its speed in the specified medium. However, the extent to which a radio signal will travel within a given medium is determined by some weather parameters which dictate the medium's refractive index. Temperature, pressure and humidity are the major atmospheric parameters that determine refractive index in the troposphere. The variations in the vertical profiles of the refractive index and its gradients and effective earth radius factor (k-factor) are responsible for the curvature in the trajectory of the radio waves in the troposphere. The numerical value of the index of refraction depends on the vertical distribution of atmospheric temperature, pressure and humidity [2].

When designing a radio link within the troposphere in a geographical location, it is important to first determine the local k-factor so that a propagated radio signal would not bend excessively towards or away from the earth. Excessive bending could lead to abnormal propagation such as sub-refraction, super-refraction and ducting. These are general conditions by which a radio signal leaving a transmitting antenna may not hit the receiving antenna or any intended target. Ducting is an abnormal form of refraction which occurs in the troposphere. Ducting occurrence is determined by the numeric value of radio refractivity gradient at a particular time in a given location. The formation of ducts is due primarily to the water vapour content of the atmosphere, since this has a stronger influence on the index of refraction (refractivity gradient) than temperature gradients do [3]. Under the atmospheric duct condition, anon-standard electromagnetic propagation can be observed, the performance of radar system and communication system can be affected, such as the maximum operation range, creation of radar holes where the radar is practically blind and strengthened sea surface clutter [4]. Ducts act like wave guide for RF energy.

This paper presents statistical estimation of effective earth radius factor obtained from the radiosonde archive data of the Nigeria Meteorological Agency (NiMet). The radio soundings were carried out at the NiMet Oshodi Meteorological Station with the aid of balloon-borne radiosonde instrument released from ground surface at 13:00 local time daily. The raw data contains atmospheric variables such as atmospheric pressure, temperature, and wind speed at various altitudes.

1.1 Theory of k-factor and effective earth radius (a_e)

Radio beam leaving the transmitter at the real earth surface of radius *R* describes a curved path. The relationship between the property of a radio signal incidence in the earth's atmosphere and the kind of refraction it experiences is described by the effective Earth radius factor k. The K-factor is a multiplying factor which helps to assume a hypothetical increased earth radius known as effective earth radius a_e such that propagation path can be rectilinear as definedin equation (1). Thus, it is an important parameter to be considered in the design of radio communication circuits in order to generate a standard atmospheric refraction. For a given climatic region, the k-factor can be calculated using equation (2)[5].

$$a_e = k \times R \tag{1}$$

$$k = \frac{157}{157 + \left(dN/dh\right)} \tag{2}$$

According to ITU-R 2003 recommendations, a standard tropospheric refraction is the one whose refractivity gradient dN/dh over the first few kilometers is -40 N-units/km. This corresponds to an effective earth radius of 4/3 for a standard tropospheric refraction. Tropospheric refractions with gradients less than or greater than this value are generally referred to as non-standard refractions. If the index of refraction varies rapidly with height such that refractivity gradient is greater than -40 N-units/km(i.e $4/3 > k > 0$), propagated radio signal may bend away from the earth and get lost in the atmosphere. Conversely, a Non-standard refraction in which the index of refraction decreases less rapidly with height such that refractivity gradient is less than -40 N-units/km (i.e $-\infty < k < 0$), is referred to as Super refraction. An extreme condition of super refraction is ducting which result in trapping of signals between two layers of the tropospherei.e elevation duct or trapping between the earth's surface and a layer in the troposphere i.e ground based duct. Thus, it is important to determine k-factor locally when designing radio links. Refractivity N is actually a scale up term used to express refractive index gradient n, of a medium and they are related as [6]:

$$N = (n-1) \times 10^6 \tag{3}$$

If refractivity N_1 is measured at an altitude h_1(km) and another value N_2 is obtained at a higher altitude h_2(km), then the refractivity gradient *dN/dh* is given by

$$\frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} \tag{4}$$

The refractivity gradients computed in this work is the statistical analysis of surface refractivityN_s and refractivity at first kilometer height N_1 in Lagos using the equations (5) and (6) respectively

$$\Delta N = N_1 - N_s \tag{5}$$

$$k = \frac{157}{157 + \Delta N} \tag{6}$$

The refractivity at various heights were computed using equation (7)

$$N = \frac{77.6P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{7}$$

2. Results and Analysis

2.1 Surface Refractivity and Refractivity at first km Height in Lagos

The weather condition in the coastal region of Nigeria in which the study area is one, is mostly categorized into raining and dry seasons. The rainy season lies between April and September while the dry season runs from November to March. The transition period between these seasons has no fixed date due to frequent rate of evapotranspiration on the Atlantic Ocean and land masses within this environment.

The seasonal variation of surface refractivity and refractivity at 1km follows closely the same trend for in Lagos. Figure 1shows the variation for 2014 which lies within the period understudied. Higher values of $N_s$were obtained as it is generally known that refractivity decreases with altitude. As the rainy season commences around March/April, high values of surface refractivity, N_s were noticed ranging from about 386 N-units in March to as high as 395 in May as shown in figure 4.18. The gradual rise in both N_s and N_1 are attributed to increase in water vapor reaching its highest value in the month of May which is associated with the rainy season. This observation correlates with the work of [7], where he concluded that Lagos has the maximum surface refractivity of 390 N-units during the raining season in

Nigeria. The peak observed in the month of May (395 N-units) is due to high values of water vapour pressure recorded in some days of this month. This increment is roughly maintained till around June, then followed by a steady fall till around August/September.

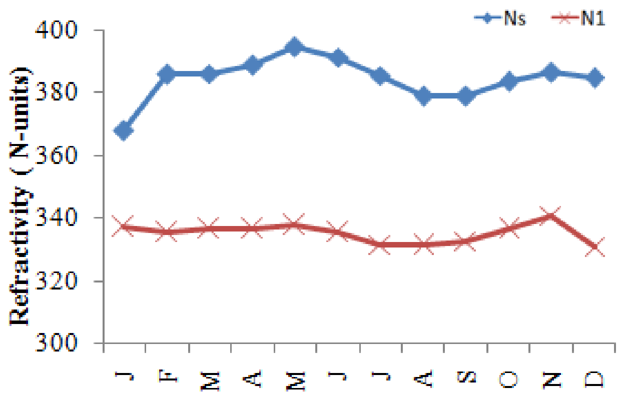

Fig. 1 Variation of N_s and N_1 in Lagos for 2014

Table 1: Vertical Profile of Radio Refractivity for 4th January, 2014

Altitude (m)	Temp (°C)	Humidity(%)	Pressure(hPa)	Vapour Pressure (hPa)	SaturationVapourPresure (hPa)	Refractivity (N-units)
0	31.24	66.83	1028	45.552	30.443	384.7
832	22.6	72	925	27.412	19.736	326.9
1000	21.5	61	875	25.634	15.636	297.6
1563	20.6	23	850	24.255	5.578	248.6
3207	10.4	53	700	12.608	6.682	222.5
5930	-6.1	35	500	3.8795	1.357	152.3
9750	-30.7	18	300	0.474	0.085	96.5
12490	-52.5	14	200	0.046	0.006	70.3

The fall in the values of surface refractivity in the month of August could be attributed to the famous August-break which is due to the movement of air masses to and from two climatic regions i.e the moist equatorial (monsoon) air originating from the Atlantic Ocean and the very dry tropical air originating from the sahara desert. These two air masses are separated by a quasi-static low pressure belt (called Inter Tropical Discontinuity, ITD), whose migration causes seasonal changes in the Tropical Continental region [8], [9].Although the refractivity at various altitude were computed as shown for a typical day in table 1, only the surface and first kilometer values were of interest in this work The gradients were calculated using equation (5).

2.2 Estimation of Effective Earth Radius Factor (k-factor)

As the variation of refractivity gradient depends solely on local weather parameters, so also the effective earth radius factor (k-factor) depends on refractivity gradient *dN/dh*. Tropospheric radio wave propagation is to a large extent influenced by the structure of the refractive index of the atmosphere and the refractive index is a function of pressure, temperature and water vapour pressure [10]. The relationship between k-factor and refractivity gradient is given by equation (2). Large negative value of refractivity gradient implies an increment in the effective earth radius factor and vice versa. Table 2 displays the calculated monthly mean values of k-factor for some months in 1990, 1991, 2013 and 2014. The k-factor is generally high during the rainy season with May having a maximum value of 1.83. As discussed earlier, it is obvious that the large negative values of refractivity gradient recorded in some days of May are responsible for this. Thus, it can be concluded that the k-factor is generally high during the rainy season. The minimum monthly mean value of k-factor was observed to be 1.27 in January which correspond to dry season The mean value for all months was calculated to be 1.60 ± 0.02 and hence, the value is greater than the ITU-R recommended value (k = $^4/_3$) for a standard atmospheric refraction indicating that super-refraction is the predominant type of refraction in this region. The implication of super refractive propagation is that radio wave paths are bent sufficiently downwards. This could prevent a propagated radio signal leaving a transmitting antenna from reaching its destination (receiving antenna) as the propagation paths curves excessively towards the earth. Parts of the signal will be absorbed by the ground especially on rainy days while other parts which may survive through ground reflection may even skip the receiving antenna as they propagate progressively. If k-factor is sufficiently high, the radio signal may get trapped between a layer of the atmosphere and the ground, a phenomenon known as ground-based duct and such signal will never hit its intended target.

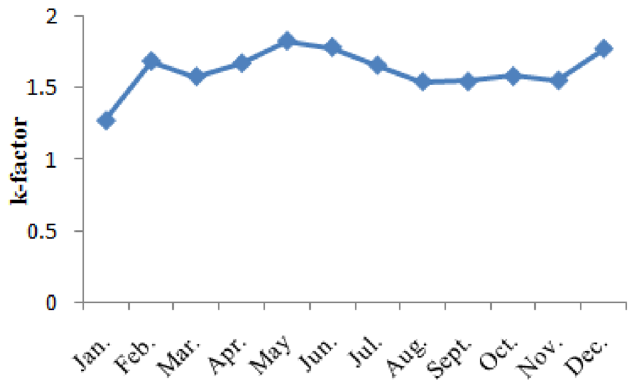

Figure 3: Monthly variation of k-factor in Lagos for the year 2014

The k-factor plays an important role in the design of wireless communication links operating in the VHF and UHF range. It defines an hypothetical spherical earth without atmosphere, for which propagation paths follow a straight lines, the heights and ground distances being the same as for the actual earth having atmosphere with a constant vertical gradient of refractivity [11]. From Table 2, the overall mean value of effective earth radius factor and refractivity gradient for the period under investigation are 1.60 and -58 N-units/km respectively. This value is approximately the same as the 1.62 obtained by [12] for this location. The result also agrees with the work of [13] where they found that the average value of the refractivity gradient and k-factor are -52.8 N/km and 1.51 respectively at height 200m in Akure.

Table 2: Monthly mean values of Surface Refractivity and its effects on the Effective Earth Radius

Months	Surface Refractivity (N-units)	Refractivity gradient (N-units/km)	K-factor	Effective Earth Radius (km)
Dec. 1990	383.20	-64.53	1.697803	10823.49
Jan. 1991	368.57	-51.05	1.481811	9446.54
Jun.1991	383.65	-54.79	1.536087	9792.55
Jul. 1991	374.64	-50.81	1.478459	9425.18
Sept. 2013	385.84	-59.20	1.605314	10233.87
Oct. 2013	387.78	-58.76	1.598038	10187.49
Nov. 2013	394.95	-58.68	1.596782	10179.49
Jan. 2014	365.06	-33.68	1.273055	8115.73
Feb. 2014	385.97	-63.87	1.685774	10746.81
Mar. 2014	386.10	-57.58	1.579155	10067.11
Apr. 2014	388.70	-63.04	1.670933	10652.20
May 2014	395.94	-71.04	1.826345	11642.95
Jun. 2014	393.57	-68.90	1.782105	11360.92
Jul. 2014	386.71	-62.27	1.657334	10565.50
Aug. 2014	379.11	-55.26	1.543145	9837.55
Sept. 2014	378.91	-55.33	1.544189	9844.21
Oct. 2014	383.55	-57.67	1.580595	10076.29
Nov. 2014	386.79	-55.81	1.551571	9891.26
Dec. 2014	387.73	-68.36	1.771286	11291.95
Mean	384.04	-58.45	1.603146	10220.06
Standard deviation	8.05	8.29	0.126	806.45

Conclusion

The result of this research work recommends 1.60 ± 0.02 as the k-factor value for an effective and reliable UHF/VHF radio wave propagation in Lagos, a coastal region in the south western Nigeria. This value disagrees with the ITU-R recommended value for normal radio wave propagation within the first kilometer height in the troposphere but conforms with the calculated and recommended values of some previous work on determination of k-factor in the coastal area of Nigeria.

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