Analysis of Variation in the Vertical Profile Of Radio Refractivity Gradient and its impact on the Effective Earth Radius Factor

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***Abstract*— In this paper, a study on the variation of radio refractivity gradient with altitude along with its impact on effective earth radius factor (K-factor) was presented. The study specifically evaluated the estimation error that will occur when K-factor is evaluated using refractivity gradient at altitude that is less than 1 Km. The study was performed using Nigerian Meteorological Agency (NIMET) empirical vertical profile data of radioclimatic parameters for Cross River state. The data was for the twelve months of 2013 and covers altitude of over five (5) kilometers. Refractivity gradient was computed with respect to surface level refractivity and refractivity at selected altitude of 50 m, 65 m, 100 m, 150 m, 200 m, 500 m and 1000 m. Ideally, 1 Km is the conventional altitude for refractivity gradient used for computing K-factor. Hence, the refractivity gradients and hence K-factors computed at altitudes lower than 1 Km were compared with the value at altitude of 1 Km. The estimation percentage errors were computed for each of the twelve months and for the annual average values. The results showed that a maximum of 4.7 % estimation percentage error was observed for the annual average refractivity gradient while that of K-factor was 2.6 % maximum annual average estimation percentage error. With respect to the months, a maximum estimation percentage error of 11.76 % was observed in the month of September for the refractivity gradient while a maximum estimation percentage error of -8.92 % was recorded for K-factor in the same month of September. Based on the maximum annual estimation error foe K-factor which is less than 5%, it can be said that using refractivity gradient for altitude less than 100 m is acceptable for computing effective earth radius factor (k- factor).**

Keywords*— *Effective Earth Radius, K-factor, Radioclimatic factor, Diffraction, Diffraction Loss

I. INTRODUCTION

Wireless network designers are generally concerned with the atmospheric conditions through which the radio signal will propagate. Depending on the atmospheric condition the radio signal can be reflected, refracted, scattered or even be absorbed [1,2,3,4]. Particularly, radio signal path can bend towards the earth or away from the earth due to variations in the refractivity with altitude [5,6,7,8,9,10]. Generally, refractivity gradient is used to represent the variation of atmospheric refractivity with altitude. Importantly, atmospheric refractivity gradient is essential for computing other secondary radio climatic parameters such as effective earth radius factor (K-factor) and geoclimatic factor which is used in computing multipath fading [11,12,13,14]. In line-of-sight (LOS) communication link, the K-factor is used to determine the earth bulge and hence the LOS clearance height, the antenna mast height for ensuring clear LOS and also for computing diffraction loss due to LOS obstruction.

In order to compute geoclimatic factor, the point refractivity gradient, dN1 computed at altitude of 65 m above the ground is used [15,16,17,18,19]. On the other hand, for the K-factor computation, refractivity gradient at altitude of 1 Km above the ground is recommended [17,19, 20,21,22]. However, is rare to have vertical profile data of meteorological parameters with altitude up to 1 Km. as such, most wireless network designers and researchers resort to vertical profile data of meteorological parameters for altitude of about 100 m to 200 m above the ground. Refractivity gradient in the lower 100 m above ground is usually useful for studying atmospheric duct or trapping conditions. In this paper, the focus is to estimate the error that will emanate from using such low altitude refractivity gradient in computing the effective earth radius factor. The study is based on radiosonde vertical profile data of primary radioclimatic parameters, namely; atmospheric temperature, pressure and relative humidity. The data covers altitude of over 5 . The study seeks to estimate the error that may emanate from such approximation and to check wether the error is within acceptable range.

II. METHODOLOGY

Radiosonde vertical profile data of primary radioclimatic parameters (namely, temperature, pressure, and relative humidity) were obtained from Nigerian Meteorological Agency (NIMET) for cross River state for the year 2013. The data contained the altitude along with the values of the temperature, pressure, and relative humidity for the given altitude. The data extends beyond the altitude of 5 Km from the ground. However, the focus in this paper is the vertical profile data for the first 1 Km from the ground. Because vertical profile data for such altitude as 1 Km is rare most published works resorted to vertical profile data collected at altitudes of 50 m, 100 m 150 m and 200 m from the ground. In this case, the data collection equipment is mounted on high rising antenna masts at the designated heights of 50 m, 100 m 150 m and 200 m.

In this paper, the refractivity, refractivity gradient and effective earth radius factor (K-factor) computed for the designated heights of 50 m, 100 m 150 m and 200 m , 500 m and 1000 m are extracted from the entire dataset results. The refractivity gradient and K-factor at height of 1000 m are taken as the reference or actual value and them the estimation percentage error is computed for each of the other heights designated heights of 50 m, 100 m 150 m ,200 m and 500 m. Such computation are performed for meteorological dataset of each of the twelve months in 2013. Again, the yearly or annual average values of refractivity gradient and K-factor are determined and the estimation percentage error is also computed for the annual average values.

Generally, refractivity index, N is computed as follows [10, 23,24,25,26,27]:

$$N = 77.6\left(\frac{P}{T} + 4810\left(\frac{e}{T^2}\right)\right) \quad (1)$$

where T is the absolute temperature in Kelvin

p is the atmospheric pressure in hPa

e is the water vapour pressure

The water vapour pressure is given as:

$$e = 6.112\left(\frac{H}{100}\right) \exp\left(\frac{17.5(t)}{t + 240.97}\right) \quad (2)$$

Where H is the relative humidity in %

t is the atmospheric temperature (Celsius)

Refractivity gradient is determined as

$$\frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} = 77.6\left(\frac{1}{T}\left(\frac{dP}{dh}\right) + \left(\frac{4810}{T^2}\right)\left(\frac{de}{dh}\right)\right) \quad (3)$$

Here N_2 and N_1 are the radio refractivity at different heights, h_2 and h_1 are the heights at different pressure levels. In most cases h_1 is the ground or surface level height denoted as h_s and N_2 is is the surface level refractivity index denoted s N_s, then

$$\frac{dN}{dh} = \frac{N_2 - N_s}{h_2 - h_s} \quad (4)$$

In this paper, the data used showed that the ground level height , $h_s = 0$, so,

$$\frac{dN}{dh} = \frac{N_2 - N_s}{h_2} \quad (5)$$

The variation in refractivity with height cause radio waves path to be bent as the wave pass through the atmosphere. In order to simplify analysis, researchers represent the waves as if they travel in straight lines then compensation is done by assuming an imaginary earth radius, otherwise referred to as effective earth radius, r_e. If r_o is the true earth radius, then the effective earth radius factor (K-factor) is given as [28,29,30,31];

$$K = \frac{r_e}{r_o} = 1 + r_o\left(\frac{dN}{dh}\right) \quad (6)$$

The effective earth radius factor (K-factor) can be determined from refractivity gradient, dN/dh as follows;

$$K = \frac{1}{1 + \left(\frac{\frac{dN}{dh}}{157}\right)} \quad (7)$$

III. RESULTS AND DISCUSSIONS

The Cross River state radiosonde vertical profile data for the radioclimatic parameters (temperature , pressure and relative humidity are given in Table 1 for the months of February, June and November, 2013. In the study, the data for the twelve months were used. However Table 1 gives data on only three months as listed in the Table. Also, although the complete data extends beyond altitude of 5 Km , only data for the first 1 Km are considered.

Generally, in many cases , radiosonde does not give the parameter values at the expected altitude. In some publications spatial interpolation can be used to get the missing data at the required altitudes. In this paper, suitable models are fitted to the computed refractivity and the model is used to determine the refractivity values at those required altitudes.

The computed refractivity index and refractivity gradient for the selected three months February, June and November are given in Table 2, Table3 and Table 4 respectively. Figure 1 shows the graph of refractivity index versus altitude along with the model to estimate the refractivity at any altitude ,h for the month of February and the model is given as;

$$N_{(February)} = N = 370.795598\left(e^{(-0.000186h)}\right) = N_{s(February)}\left(e^{(-0.000186h)}\right) \quad (8)$$

The model for February has RMSE of 0.00000035 (N-Units) and Maximum Absolute Percentage Error of 0.00000054 %.

The graph of refractivity index versus altitude along with the model for June and November are given in Figure 2 and Figure 3 respective and the and model performances are as follows;

$$N_{(June)} = N = \mathbf{376.934929}\left(e^{(\mathbf{-0.000147h})}\right) = N_{s(June)}\left(e^{(\mathbf{-0.000147h})}\right) \quad (9)$$

For June RMSE = **0.00015524** (N-Units) and Maximum Absolute Percentage Error = **0.00000079** %

$$N_{(November)} = N = \mathbf{382.6194489}\left(e^{(\mathbf{-0.0001402h})}\right) = N_{s(November)}\left(e^{(\mathbf{-0.0001402h})}\right) \quad (10)$$

For November RMSE = 0.00000838 (N-Units) and Maximum Absolute Percentage Error = 0.00001181 %

Table 1 The radiosonde vertical profile data for temperature , pressure and relative humidity for the months of February, June and November, 2013

	DATA FOR THE MONTH OF FEBRUARY 2013				DATA FOR THE MONTH OF JUNE 2013				DATA FOR THE MONTH OF NOVEMBER 2013			
S/N	**Altitude [m]**	**P [hPa]**	**T [C]**	**H [%]**	**Altitude [m]**	**P [hPa]**	**T [C]**	**H [%]**	**Altitude [m]**	**P [hPa]**	**T [C]**	**H [%]**
1	0.0	1014.2	31.9	58.0	0.0	1016.9	25.8	90.0	0.0	1015.0	31.7	65.0
2	47.7	1009.0	30.2	61.0	44.3	1011.8	28.9	81.2	0.4	1015.0	30.1	64.1
3	91.6	1003.9	29.7	64.0	88.7	1006.8	25.9	80.5	9.6	1010.7	29.5	65.8
4	138.3	998.8	29.2	66.4	133.0	1001.8	24.9	82.3	59.2	1003.2	28.9	67.5
5	185.1	993.8	28.8	67.1	177.4	996.3	24.2	84.0	141.8	995.8	28.3	69.2
6	228.8	988.8	28.3	67.7	221.7	990.7	23.7	85.8	224.3	988.4	27.7	70.9
7	271.0	984.1	28.0	68.4	266.0	985.1	23.1	87.5	305.4	981.0	27.1	72.7
8	308.1	979.6	27.6	69.4	322.1	979.6	22.6	87.9	381.8	973.2	26.4	74.4
9	348.6	975.2	27.2	70.5	380.2	975.1	22.0	87.8	455.0	965.5	25.7	76.1
10	431.8	966.4	26.4	72.5	427.5	969.2	21.9	87.7	522.6	957.9	25.0	77.8
11	473.6	961.8	26.0	73.6	475.3	963.5	21.9	87.6	589.5	950.3	24.3	79.2
12	519.9	956.8	25.5	75.2	525.7	958.1	22.0	87.3	653.9	943.0	23.8	79.8
13	567.6	951.5	25.1	76.8	573.3	952.8	22.2	86.8	715.3	936.5	23.4	80.4
14	667.1	940.9	24.1	79.9	623.9	947.1	21.9	86.3	773.9	930.4	23.0	81.0
15	718.3	935.6	23.7	81.4	677.3	941.5	21.5	85.8	832.8	924.2	22.6	81.6
16	770.1	930.1	23.2	82.5	729.8	935.8	21.1	85.3	885.8	918.1	22.3	81.9
17	820.8	924.7	22.7	83.6	781.2	930.1	20.6	85.1	934.1	911.8	21.9	81.3
18	872.1	919.2	22.2	84.7	835.5	924.4	20.3	85.0	1001.1	905.5	21.5	80.7
19	925.3	913.4	21.7	85.8	889.3	918.8	20.3	84.8	1070.9	899.3	21.1	80.2
20	981.5	907.6	21.2	86.8	941.3	913.5	20.3	84.7	1130.2	893.1	20.8	79.6
21	1037.8	901.9	20.7	87.7	991.3	908.2	19.9	84.5	1188.8	887.0	20.5	79.1
22	1090.3	896.5	20.2	88.7	1040.9	902.9	19.5	84.8	1247.4	881.1	20.2	78.9

Table 2 The computed refractivity index and refractivity gradient for the selected three months February, June and November

	FEBRUARY			**JUNE**			**NOVEMBER**		
S/N	**Altitude [m]**	**N (N - Units)**	**dN/dh (N – Units /Km)**	**Altitude [m]**	**N (N - Units)**	**dN/dh (N – Units /Km)**	**Altitude [m]**	**N (N - Units)**	**dN/dh (N – Units /Km)**
1	0.0	368	0.0	0.0	389	0.0	0.0	380	0.0
2	47.7	364	-77.6	44.3	392	77.9	0.4	371	- 24180.6
3	91.6	366	-23.5	88.7	374	- 172.5	9.6	370	-1119.3
4	138.3	366	-13.1	133.0	370	-	59.2	368	-215.0

						143.7			
5	185.1	364	-20.8	177.4	367	-122.6	141.8	366	-104.2
6	228.8	361	-28.7	221.7	365	-105.5	224.3	364	-75.6
7	271.0	360	-29.8	266.0	363	-96.5	305.4	361	-62.3
8	308.1	358	-31.1	322.1	360	-90.0	381.8	359	-57.3
9	348.6	357	-31.3	380.2	356	-86.9	455.0	356	-54.5
10	391.4	356	-31.7	427.5	354	-82.3	522.6	353	-53.0
11	431.8	354	-32.3	475.3	352	-77.4	589.5	349	-52.8
12	473.6	353	-32.5	525.7	351	-72.5	653.9	346	-52.8
13	519.9	351	-32.3	573.3	350	-68.3	715.3	343	-52.1
14	567.6	350	-31.4	623.9	346	-68.2	773.9	341	-51.5
15	616.5	349	-31.7	677.3	342	-68.4	832.8	338	-51.1
16	667.1	347	-31.7	729.8	339	-68.6	885.8	335	-50.9
17	718.3	346	-31.3	781.2	335	-68.9	934.1	331	-52.6
18	770.1	343	-32.3	835.5	332	-67.8	1001.1	327	-53.0
19	820.8	341	-33.1	889.3	330	-65.6	1070.9	324	-53.1
20	872.1	338	-33.9	941.3	329	-63.6	1130.2	320	-53.3
21	925.3	336	-34.7	991.3	326	-63.6	1188.8	317	-53.5
22	981.5	333	-35.3	1040.9	323	-63.1	1247.4	314	-53.3
23	1037.8	331	-36.0	1092.8	321	-62.4	1299.0	312	-52.9

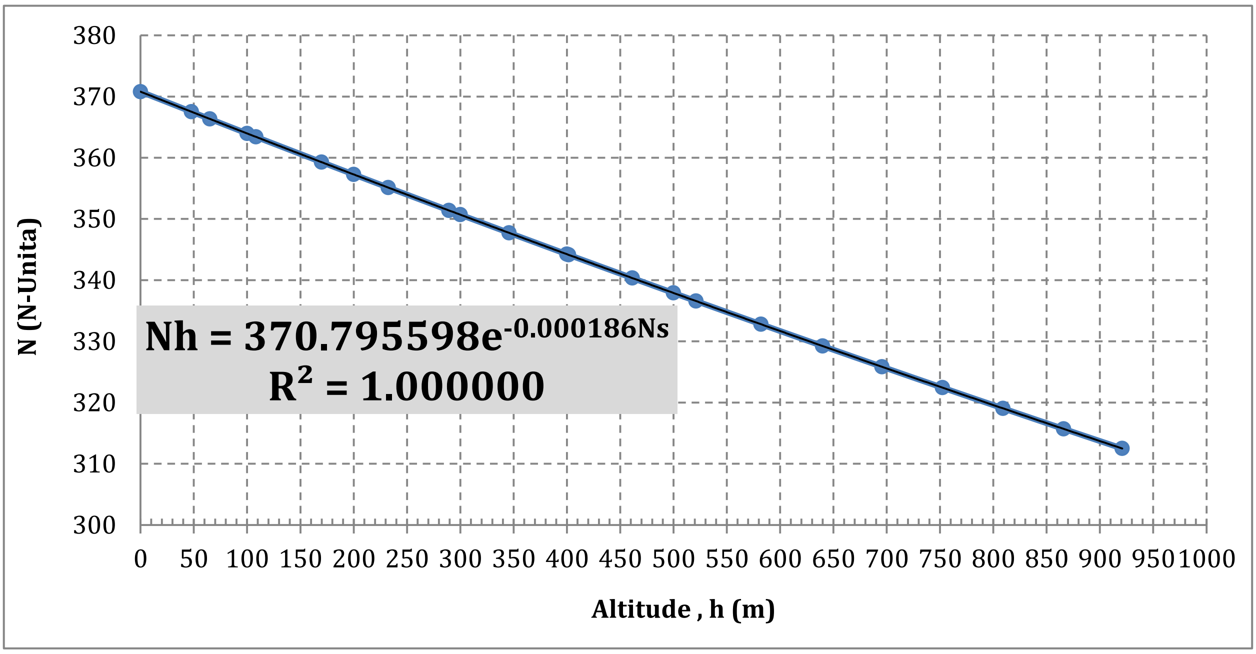

Figure 1 The graph of refractivity index versus altitude along with the model to estimate the refractivity at any altitude ,h for the month of February

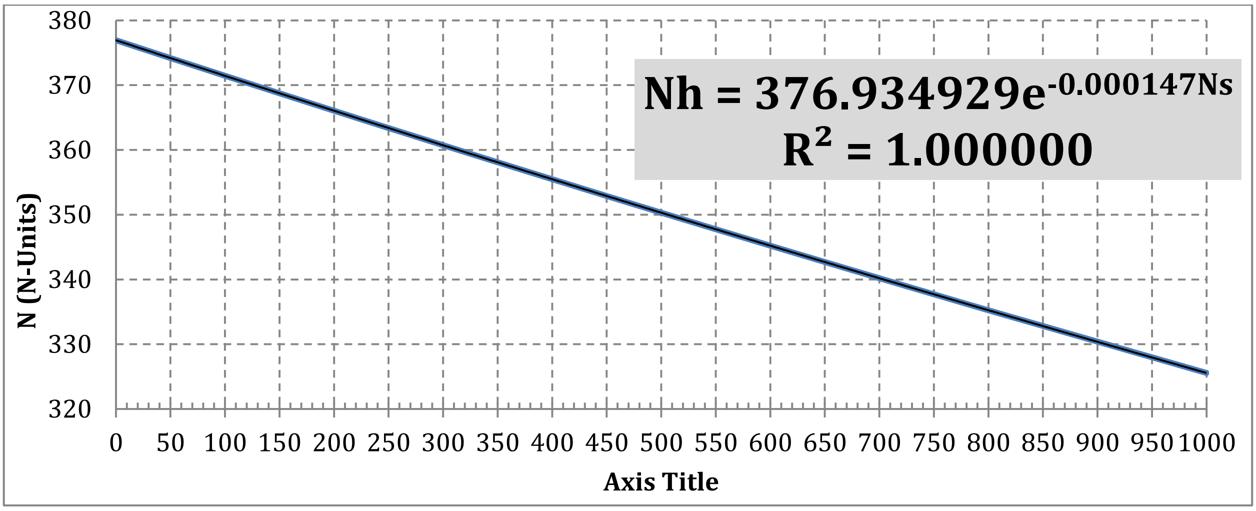

Figure 2 The graph of refractivity index along with the model to estimate the refractivity at any

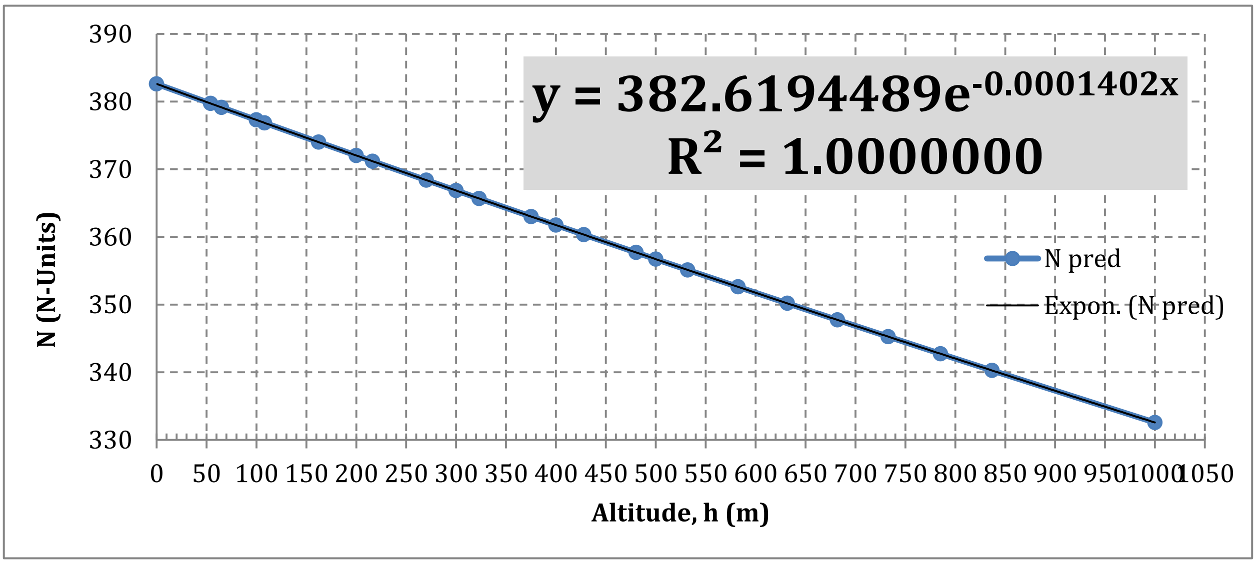

Figure 3 The graph of refractivity index along with the model to estimate the refractivity at any altitude ,h for the month of November

Since the radiosonde data missing for some of the selected altitudes, 50 m, 100 m, 150 m, 200 m , 500 m and 1000 m, the models such are the ones shown in Equations 8,9 and 10 were developed for each of the months considered and the refractivity are then determined at each of the required altitudes for each of the months. Afterwards, the refractivity gradients were computed along with the K-factor. Table 3 shows the refractivity gradients and K-factors at the selected 7 altitudes for the three months of February , June and November along with the percentage errors for the refractivity gradient and K-Factor. The month of February has maximum estimation percentage error of 11% when the refractivity gradient at 50 m is compared to that at 1000 m. Also, the K-factor estimation percentage error for the month of February is about 8.5 % %. Accordingly, among the three months presented in Table 3, the month of February had the highest estimation percentage errors for refractivity gradient and K-factor.

The refractivity gradients for the entire twelve months for the selected 7 altitudes are given in Table 4. Furthermore, Table 5 shows the annual average refractivity gradient and annual average k-factor for the selected 7 altitudes along with the estimation percentage errors. While the absolute estimation percentage error can be as high as 4.7 % for the refractivity gradient, the K-factor has a maximum absolute value of about 2.6 %. In essence, for the case study data, a maximum of 2.6 % error in the k-factor may exist if the refractivity gradient at 50 m altitude is used for computing K-factor instead of using the refractivity gradient at 1000 m altitude. In view of this result, it may be acceptable to use refractivity gradients at lower altitudes (h < 100 m) for computing k-factor without incurring much error in the final result.

Table 3 The refractivity gradients and K-factors at the selected 7 altitudes for the three months of February , June and November along with the percentage errors

February , 2013						
Altitude, h [m]	**dN/dz**	dN/dz Estimated	dN/dz Percentage error, dNe%	K Factor Estimated	K -Factor Actual	K -Factor Percentage error, Ke%
50	**-70.08**	-62.71	-11.75	1.81	1.67	-8.48
65	**-69.95**	-62.71	-11.55	1.80	1.67	-8.32
100	**-69.65**	-62.71	-11.07	1.80	1.67	-7.94
150	**-69.42**	-62.71	-10.70	1.79	1.67	-7.66
200	**-68.99**	-62.71	-10.01	1.78	1.67	-7.14
500	**-66.49**	-62.71	-6.03	1.73	1.67	-4.18
1000	**-62.71**	-62.71	0.00	1.67	1.67	0.00
June , 2 103						
50	**-52.99**	-51.73	-2.44	1.51	1.49	-1.21
65	**-52.98**	-51.73	-2.41	1.51	1.49	-1.20
100	**-52.94**	-51.73	-2.34	1.51	1.49	-1.16
150	**-53.16**	-51.73	-2.76	1.51	1.49	-1.38
200	**-53.07**	-51.73	-2.59	1.51	1.49	-1.29
500	**-52.56**	-51.73	-1.60	1.50	1.49	-0.79
1000	**-51.73**	-51.73	0.00	1.49	1.49	0.00
November, 2013						
50	**-51.04**	-50.45	-1.17	1.48	1.47	-0.56
65	**-51.03**	-50.45	-1.15	1.48	1.47	-0.55
100	**-51.02**	-50.45	-1.13	1.48	1.47	-0.54
150	**-51.28**	-50.45	-1.65	1.49	1.47	-0.79
200	**-51.23**	-50.45	-1.55	1.48	1.47	-0.74
500	**-50.93**	-50.45	-0.95	1.48	1.47	-0.45
1000	**-50.45**	-50.45	0.00	1.47	1.47	0.00

Table 4 The refractivity gradients for the entire twelve months for the selected 7 altitudes

	dN/dh	dN/dh	dN/dh	dN/dh	dN/dh	dN/dh
Altitude, h [m]	Jan	Feb	March	April	May	Jun
50	-52.7	-70.1	-48.2	-59.7	-56.8	-53.0
65	-52.8	-70.0	-48.2	-59.6	-56.8	-53.0
100	-52.9	-69.6	-48.2	-59.6	-56.6	-52.9
150	-53.4	-69.4	-48.4	-59.8	-56.7	-53.2
200	-53.5	-69.0	-48.3	-59.7	-56.5	-53.1
500	-53.8	-66.5	-47.8	-58.9	-55.4	-52.6

1000	-54.4	-62.7	-47.0	-57.6	-53.6	-51.7
	dN/dh	dN/dh	dN/dh	dN/dh	dN/dh	dN/dh
Altitude, h [m]	JUL	AUG	SEP	OCT	NOV	DEC
50	-60.8	-56.8	-72.0	-79.2	-51.0	-37.3
65	-60.7	-56.8	-71.9	-79.1	-51.0	-37.4
100	-60.6	-56.7	-71.6	-78.8	-51.0	-37.6
150	-60.6	-56.8	-71.4	-78.8	-51.3	-37.6
200	-60.3	-56.6	-70.9	-78.3	-51.2	-37.9
500	-59.0	-55.7	-68.4	-75.6	-50.9	-39.7
1000	-57.0	-54.2	-64.5	-71.4	-50.4	-41.9

Table 5 The Annual Average refractivity gradients and Annual Average K-Factor for the selected 7 altitudes along with the estimation percentage error

Altitude, h [m]	Annual Average Estimated dN/dh	Percentage error, e% for the Annual Average Estimated dN/dh	Annual Average Estimated K-Factor	Percentage error, e% for the Annual Average Estimated K-Factor
50	-58.13055594	-4.704164473	1.587952694	-2.64156
65	-58.09476181	-4.639692443	1.587378008	-2.60442
100	-58.01183364	-4.490323075	1.586048169	-2.51846
150	-58.09914452	-4.647586534	1.587448351	-2.60896
200	-57.94353902	-4.367311494	1.584954666	-2.44778
500	-57.01412862	-2.693266976	1.570221851	-1.49548
1000	-55.51885757	0	1.547085461	0

IV CONCLUSION

Computation of refractivity, refractivity gradient and K-factor for altitudes from ground or surface level where height is taken as zero (0 m) to an altitude of about 1000 m above the ground. The computations were based on vertical profile data obtained using twelve months radiosonde equipment in Cross River state. Models were developed for the vertical profile refractivity as a function of surface level refractivity and altitude. The model was developed for each of the twelve months and the models were used to determine the refractivity at the required altitudes of 50 m, 100 m, 150 m, 200 m, 500 m and 1000 m. Refractivity gradients and k-factor were computed for the selected altitudes and the estimation percentage error was computed . the result showed that for the given study site, a maximum of about 2.6 % can be incurred by using refractivity gradient at lower altitude to compute K-factor rather than the recommended refractivity at 1000 m altitude. In view of the result, the lower altitude refractivity gradient can be used without incurring much error in the final result. However, this result may not be generalized to every other site since the variation of refractivity with altitude is not the same for every site.

REFERENCES

1. Intini, A. L. (2014). *Performance of wireless networks in highly reflective rooms with variable absorption* (Doctoral dissertation, Monterey, California: Naval Postgraduate School).
2. Karagianni, E. A., Mitropoulos, A. P., Latif, I., Kavousanos-Kavousanakis, A., Koukos, J., & Fafalios, M. E. (2014). Atmospheric effects on EM propagation and weather effects on the performance of a dual band antenna for WLAN communications. *J Nav Sci Technol Part B: Electr Eng Comput Sci*, *5*, B-29.
3. Mason, S. P. (2010). *Atmospheric effects on radio frequency (RF) wave propagation in a humid, near-surface environment*. Naval Postgraduate School Monterey Ca.
4. Sim, C. Y. D. (2002). *The propagation of VHF and UHF radio waves over sea paths* (Doctoral dissertation, University of Leicester).
5. Kingsley, E. U., & Samuel, O. A. (2018). Review of Methodology to Obtain Parameters for Radio Wave Propagation at Low Altitudes from Meteorological

Data: New Results for Auchi Area in Edo State, Nigeria. *Journal of King Saud University-Science*.
6. Akpootu, D. O., & Iliyasu, M. I. (2017). Estimation of Troposgeric Radio Refractivity and its Variation with Meteorological Parameters over Ikeja Nigeria. *Journal of Geography, Environment and Earth Science International*, *10*(1), 1-12.
7. Falodun, S. (2015). Quantitative Studies of Vertical Structure of Radio Refractive Index in a Coastal Area of Nigeria. *Journal of Sustainable Technology*, *6*(2).
8. Usman, A. U., Okereke, O. U., & Omizegba, E. E. (2015). Instantaneous GSM signal strength variation with weather and environmental factors. *American Journal of Engineering Research*, *4*(3), 104-115.
9. Mufti, N. (2012). *Investigation into the Effects of the Troposphere on VHF and UHF Radio Propagation and Interference between Co-Frequency Fixed Links* (Doctoral dissertation, University of Leicester).
10. Adediji, A. T., & Ajewole, M. O. (2008). Vertical Profile of Radio Refractivity Gradient in Akure South-West Nigeria. *Progress In Electromagnetics Research*, *4*, 157-168.
11. Rundstedt, K. (2014). *Measurements and Channel Modelling of Microwave Line-of-Sight MIMO Links* (Doctoral dissertation, Master's thesis, Chalmers University of Technology, Sweden).
12. Asiyo, M. O. (2013). *Characterization and Modelling of Effects of Clear Air on Multipath Fading in Terrestrial Links* (Doctoral dissertation, University of KwaZulu-Natal, Durban).
13. Asiyo, M. O., & Afullo, T. J. (2012, September). Tropospheric Propagation Mechanisms Influencing Multipath Fading Based on Local Measurements. In *Proc. of Southern Africa Telecommunication Networks and Applications Conference, Fancourt, George, South Africa*.
14. Abu-Almal, A., & Al-Ansari, K. (2010). Calculation of effective earth radius and point refractivity gradient in UAE. *International Journal of Antennas and Propagation*, *2010*.
15. Ugwu, E. B. I., Umeh, M. C., & Ugonabo, O. J. (2015). Microwave propagation attenuation due to earths atmosphere at very high frequency (VHF) and ultra-high frequency (UHF) bands in Nsukka under a clear air condition. *International Journal of Physical Sciences*, *10*(11), 359-363.
16. Göktaş, P. (2015). *Analysis and implementation of prediction models for the design of fixed terrestrial point-to-point systems* (Doctoral dissertation, bilkent university).
17. Bettouche, Y., Agba, B. L., & Kouki, A. B. (2014, August). Geoclimatic factor and point refractivity evaluation in Quebec-Canada. In *General Assembly and Scientific Symposium (URSI GASS), 2014 XXXIth URSI* (pp. 1-4). IEEE.
18. Asiyo, M. O., & Afullo, T. J. O. (2013). Statistical estimation of fade depth and outage probability due to multipath propagation in Southern Africa. *Progress In Electromagnetics Research*, *46*, 251-274.
19. Abu-Almal, A., & Al-Ansari, K. (2010). Calculation of effective earth radius and point refractivity gradient in UAE. *International Journal of Antennas and Propagation*, *2010*.
20. Doerry, A. W. (2013). Earth curvature and atmospheric refraction effects on radar signal propagation. *Sandia Report SAND2012-10690*.
21. Goldhirsh, J., & Dockery, G. D. (2001). K factor statistics for subrefraction in the mid-Atlantic coast of the United States. *Radio Science*, *36*(6), 1425-1437.
22. Robertshaw, G. (1986). Effective earth radius for refraction of radio waves at altitudes above 1 km. *IEEE transactions on antennas and propagation*, *34*(9), 1099-1105.
23. Saleem, M. U. (2016). Statistical investigation and mapping of monthly modified refractivity gradient over Pakistan at the 700 hectopascal level. *Open Journal of Antennas and Propagation*, *4*(02), 46.
24. Louf, V., Pujol, O., & Sauvageot, H. (2016). The Seasonal and Diurnal Cycles of Refractivity and Anomalous Propagation in the Sahelian Area from Microwave Radiometric Profiling. *Journal of Atmospheric and Oceanic Technology*, *33*(10), 2095-2112.
25. Falodun, S. E., & Okeke, P. N. (2013). Radiowave propagation measurements in Nigeria (preliminary reports). *Theoretical and applied climatology*, *113*(1-2), 127-135.
26. Holleman, I., & Huuskonen, A. (2013). Analytical formulas for refraction of radiowaves from exoatmospheric sources. *Radio Science*, *48*(3), 226-231.
27. Hulley, G. C., & Pavlis, E. C. (2007). A ray-tracing technique for improving Satellite Laser Ranging atmospheric delay corrections, including the effects of horizontal refractivity gradients. *Journal of Geophysical Research: Solid Earth*, *112*(B6).
28. Etokebe, I. J., Udofia, K. M., & Ezenugu, I. A. (2016). Determination of Atmospheric Effective Earth Radius Factor (k-factor) Under Clear Air in Lagos, Nigeria. *Mathematical and Software Engineering*, *2*(1), 30-34.
29. Nyete, A. M., & Afullo, T. J. O. (2013). Seasonal distribution modeling and mapping of the effective earth radius factor for microwave link design in South Africa. *Progress In Electromagnetics Research*, *51*, 1-32.
30. Chaudhary, N. K., Trivedi, D. K., & Gupta, R. (2011). The impact of k-factor on wireless link in Indian semi-desert terrain. *International Journal of Advanced Networking and Applications*, *2*(4).
31. Odedina, P. K., & Afullo, T. J. (2006). On the k-factor distribution and diffraction fading for Southern Africa. *SAIEE Africa Research Journal*, *97*(2).