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ANALYSIS OF THE EFFECT OF VARIATIONS IN REFRACTIVITY GRADIENT ON LINE OF SIGHT PERCENTAGE CLEARANCE AND SINGLE KNIFE EDGE DIFFRACTION LOSS

Eduediuyai, Dan[1]
Enyenihi, Johnson[2+]
Idorenyin Markson[3]

[1]*Department of Computer Engineering Federal Polytechnic Ukana, Akwa Ibom State, Nigeria*
[2]*Department of Electrical/Electronic Engineering, Akwa Ibom State University Mkpat Enin, Akwa Ibom State, Nigeria*
Email: gentlejayy@yahoo.com
[3]*Department of Mechanical Engineering, University of Uyo, Akwa Ibom, Nigeria*

(+ Corresponding author)

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ABSTRACT

In this paper, analysis of the effect of variations in refractivity gradient on line of sight percentage clearance and single knife edge diffraction loss is presented. Relevant, mathematical expressions and approaches for the analyses are presented. Sample path profile data of terrestrial line of sight (LOS) microwave communication links operating at C-band 5.5 GHz frequency and Ku-band 11 GHz frequency with 15 Km path length are used in the study to demonstrate the application of the ideas presented in this paper. The results showed that the critical point of minimum LOS percentage clearance occurred at a distance of 8.89 Km from the transmitter. Based on the results regression models were derived for relating the refractivity gradient to the effective earth K-factor, earth bulge, LOS percentage clearance and single knife edge LOS percentage clearance. The implication of the result is that, given that for any location the refractivity gradient varies with the primary atmospheric parameters like temperature, pressure and relative humidity, the amount of diffraction loss posed to the signal in the atmosphere will be varying at different rates depending on the prevailing values of the atmospheric parameters upon which refractivity gradient depends. Also, apart from the reference refractivity gradient of 39.25 N units/km, different frequencies will experience different amount of diffraction loss. The specific impact of the refractivity gradient on different frequencies depends on whether the prevailing refractivity gradient is above or below the reference refractivity gradient of 39.25 N units/km.

Contribution/Originality: This study is one of very few studies which have investigated the effect of variations in refractivity gradient on line of sight percentage clearance and single knife edge diffraction loss. The ideas presented can easily be used to study the effect of variations in atmospheric parameters on wireless signal quality.

1. INTRODUCTION

Microwave communications systems are line of sight (LOS) communication which requires that the transmitter and receiver antennas are aligned in a clear line of sight without obstruction (Alsharekh *et al.*, 2016; Kakkar and Sah, 2017; Ren *et al.*, 2017; Shrestha and Choi, 2017; Yoo *et al.*, 2017; Chen *et al.*, 2018; Jones *et al.*, 2018; Navarro, 2018). However, in reality, there are obstructions along the signal path. These obstructions cause diffraction loss depending on the extent to which the obstructions block the line of sight between the transmitter and the receiver (Abdulrasool *et al.*, 2017; Loo, 2017; Wang *et al.*, 2017; Raghavan *et al.*, 2018).

In practice, the clearance between the LOS and the highest point of the obstruction is represented in percentage called the LOS percentage clearance. The LOS percentage clearance is the percentage of the clearance height to the radius of the first Fresnel zone at the location of the obstruction. Usually, 60 % LOS percentage clearance of the first Fresnel zone is recommended (Ali, 2007; Saha, 2017; Shamsan, 2018). However, other factors can cause the obstruction to violate this recommendation after the link has been deployed.

Among other things, the clearance height between the LOS and the obstruction apex depends on a number of the parameters which includes; the frequency of the signal, the distance of the signal from the transmitter, the earth bulge, the elevation profile of the path and the actual height of the obstruction. The earth bulge depends on effective earth radius factor which is a function of the refractivity gradient of the atmosphere (Gunashekar, 2006; Abu-Almal and Al-Ansari, 2010; Ippolito and Ippolito, 2017). As such, even the other parameters are kept constant; the earth bulge can still be affected by changes in the atmospheric refractivity gradient.

Furthermore, the clearance height or the LOS percentage clearance is used to determine the amount of diffraction loss that an obstruction in the signal path will present to the signal. As such, anything that will affect the LOS percentage clearance will equally affect the diffraction loss. Consequently, given that the atmosphere is dynamic, the changes in the atmospheric conditions will continuously cause changes in the LOS percentage clearance and the attendant diffraction loss. As such, in this paper, the focus is to present mathematical models that can be used to determine the LOS percentage clearance and the diffraction loss for LOS microwave communication systems. Sample numerical example is used to demonstrate the application of the ideas presented in this paper.

2. MATHEMATICAL EXPRESSION FOR LOS PERCENTAGE CLEARANCE AS A FUNCTION OF REFRACTIVITY GRADIENT

In the determination of earth bulge the effective earth radius K-factor is usually needed, and K is related to refractive index gradient, Δ as follows Nnadi *et al.* (2017); Nwokonko *et al.* (2017); Wali *et al.* (2017):

$$k = \frac{157}{157 + \Delta} \qquad (1)$$

The radio refractivity gradient, Δ is given as Nnadi *et al.* (2017); Nwokonko *et al.* (2017); Wali *et al.* (2017).

$$\Delta = \frac{dN}{dh} = \frac{\mathrm{N_2 - N_1}}{\mathrm{h_2 - h_1}} \qquad (2)$$

Where $\mathrm{N_1}$ is refractivity at height $\mathrm{h_1}$ and $\mathrm{N_2}$ is refractivity at height, $\mathrm{h_2}$. The earth bulge, $\mathrm{h_{eb(j)}}$ at point j is given as Nnadi *et al.* (2017); Nwokonko *et al.* (2017); Wali *et al.* (2017).

$$H_{eb(x)} = \frac{(\mathrm{d_{tj(j)}})(\mathrm{d_{rj(j)}})}{12.75\left(\frac{157}{157+\Delta}\right)} = \left(\frac{(\mathrm{d_{tj(j)}})(\mathrm{d_{rj(j)}})(157+\Delta)}{2001.75}\right) \qquad (3)$$

Now consider a line of sight (LOS) wireless communication link elevation data set with N elevation points , each with elevation $\mathrm{h_{el(j)}}$ and distance from the transmitter $\mathrm{d_{tj(j)}}$. Also, the link has path length d, so, $\mathrm{d_{rj(j)}}$ the distance from the receiver to point j is given as;

$$\mathrm{d_{rj(j)}} = d - \mathrm{d_{tj(j)}} \text{ where } j = 1,2,3,\ldots,N \qquad (4)$$

If the required LOS percentage clearance is $\mathrm{P_c}(\%)$ and the radius of curvature of first Fresnel zone at j is $\mathrm{r}_{fz(j)}$, then Jude *et al.* (2016); Akkasli (2009).

$$\mathrm{r}_{fz(j)} = \sqrt{\frac{\left(\lambda(\mathrm{d_{tj(j)}})(\mathrm{d_{rj(j)}})\right)}{\left((\mathrm{d_{tj(j)}})+(\mathrm{d_{rj(j)}})\right)}} \qquad (5)$$

Let $\mathrm{h_{pc(j)}}$ be the required LOS clearance height for the specified percentage clearance, $\mathrm{P_c}$ then Jude *et al.* (2016); Akkasli (2009).

$$h_{pc(j)} = \left(\frac{P_c}{100}\right)\left(r_{fz(j)}\right) = \left(\frac{P_c}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(j)}\right)\left(d_{rj(j)}\right)\right)}{\left(\left(d_{tj(j)}\right)+\left(d_{rj(j)}\right)\right)}} \qquad (6)$$

In other to guarantee the required LOS clearance, the height of the obstruction tip, denoted as $h_{obt(j)}$ is given as;

$$h_{obt(j)} = h_{el(j)} + h_{ob(j)} + h_{eb(j)} + \left(\frac{P_c}{100}\right)\left(\sqrt{\frac{\left(\lambda\left(d_{tj(j)}\right)\left(d_{rj(j)}\right)\right)}{\left(\left(d_{tj(j)}\right)+\left(d_{rj(j)}\right)\right)}}\right) \qquad (7)$$

$$h_{obt(j)} = h_{el(j)} + h_{ob(j)} + \left(\frac{\left(d_{tj(j)}\right)\left(d_{rj(j)}\right)(157+\Delta)}{2001.75}\right) + \left(\frac{P_c}{100}\right)\left(\sqrt{\frac{\left(\lambda\left(d_{tj(j)}\right)\left(d_{rj(j)}\right)\right)}{\left(\left(d_{tj(j)}\right)+\left(d_{rj(j)}\right)\right)}}\right) \qquad (8)$$

So, the line of sight height is the maximum of $h_{obt(j)}$ at design time. If the location of the maximum of $h_{obt(j)}$ is at jmx, then,

$$h_{obt(jmx)} = h_{el(jmx)} + h_{ob(jmx)} + \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta)}{2001.75}\right) + \left(\frac{P_c}{100}\right)\left(\sqrt{\frac{\left(\lambda\left(d_{tj(j)}\right)\left(d_{rj(j)}\right)\right)}{\left(\left(d_{tj(j)}\right)+\left(d_{rj(j)}\right)\right)}}\right) \qquad (9)$$

Let Δ_1 be the value of the refractivity gradient at the design time and Δ_2 be the value of the refractivity gradient at any given time during operation of the communication link. Then, at design time the percentage clearance is denoted as P_{c1} and during operation time it is denoted as P_{c2}, hence;

$$h_{obt(jmx)} = h_{el(jmx)} + h_{ob(jmx)} + \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_1)}{2001.75}\right) + \left(\frac{P_{c1}}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}} \qquad (10)$$

$$h_{obt(jmx)} = h_{el(jmx)} + h_{ob(jmx)} + \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_2)}{2001.75}\right) + \left(\frac{P_{c2}}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}} \qquad (11)$$

$$h_{obt(jmx)} - \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_1)}{2001.75}\right) - \left(\frac{P_{c1}}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}} = h_{el(jmx)} + h_{ob(jmx)} \qquad (12)$$

$$h_{obt(jmx)} - \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_2)}{2001.75}\right) - \left(\frac{P_{c2}}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}} = h_{el(jmx)} + h_{ob(jmx)} \qquad (13)$$

$$\left(\frac{P_{c2}-P_{c1}}{100}\right)\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}} = \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_1)}{2001.75}\right) - \left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(157+\Delta_2)}{2001.75}\right) \qquad (14)$$

$$P_{c_2} - P_{c_1} = \frac{100}{\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}}}\left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(\Delta_1-\Delta_2)}{2001.75}\right) \qquad (15)$$

$$P_{c_2} = P_{c_1} + 100\left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(\Delta_1-\Delta_2)}{2001.75}\right)\left(\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}}\right)^{-1} \qquad (16)$$

$$P_{c_2}(\%) = P_{c_1}(\%) + \frac{100}{r_{fz(j)}}\left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(\Delta_1-\Delta_2)}{2001.75}\right) \quad (17)$$

3. DETERMINATION OF DIFFRACTION LOSS AS A FUNCTION OF REFRACTIVITY GRADIENT

Knife edge diffraction parameter (V) is determined as follows (Akkasli, 2009):

$$\mathbf{V} = \frac{P_c}{100}\left(\sqrt{2}\right) = 0.01414(P_c) \quad (18)$$

$$\mathbf{V} = 0.01414\left(P_{c_1} + 100\left(\frac{\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)(\Delta_1-\Delta_2)}{2001.75}\right)\left(\sqrt{\frac{\left(\lambda\left(d_{tj(jmx)}\right)\left(d_{rj(jmx)}\right)\right)}{\left(\left(d_{tj(jmx)}\right)+\left(d_{rj(jmx)}\right)\right)}}\right)^{-1}\right) \quad (19)$$

The knife edge diffraction loss can be determined using the Lee knife edge diffraction loss model given as:

$$\left.\begin{array}{ll} G_d(dB) = 0 & \text{for } V < -1 \\ G_d(dB) = 20\log(0.5 - 0.62\,V) & \text{for } -1 \le V \le 0 \\ G_d(dB) = 20\log\left(0.5\exp(-0.95V)\right) & \text{for } 0 \le V \le 1 \\ G_d(dB) = 20\log\left(0.4 - \sqrt{0.1184 - (0.38 - 0.1V)^2}\right) & \text{for } 1 \le V \le 2.4 \\ G_d(dB) = 20\log\left(\frac{0.225}{V}\right) & \text{for } V > 2.4 \end{array}\right\} \quad (20)$$

4. RESULTS AND DISCUSSION

Sample path profile data of terrestrial microwave communication link with 15 Km path length is used in the study to demonstrate the application of the models presented in this paper. The elevation profile plot of the path is shown in Figure 1. The link was studied at two microwave frequencies, namely, 5.5 GHz C-band frequency and 11 GHz Ku-band frequency. In the link, uniform 10 m obstruction height is assumed along with 60% LOS clearance for the first Fresnel zone. According to the path profile analysis result, the distance from the transmitter to the point of minimum LOS percentage clearance is 8.89Km for both frequencies.

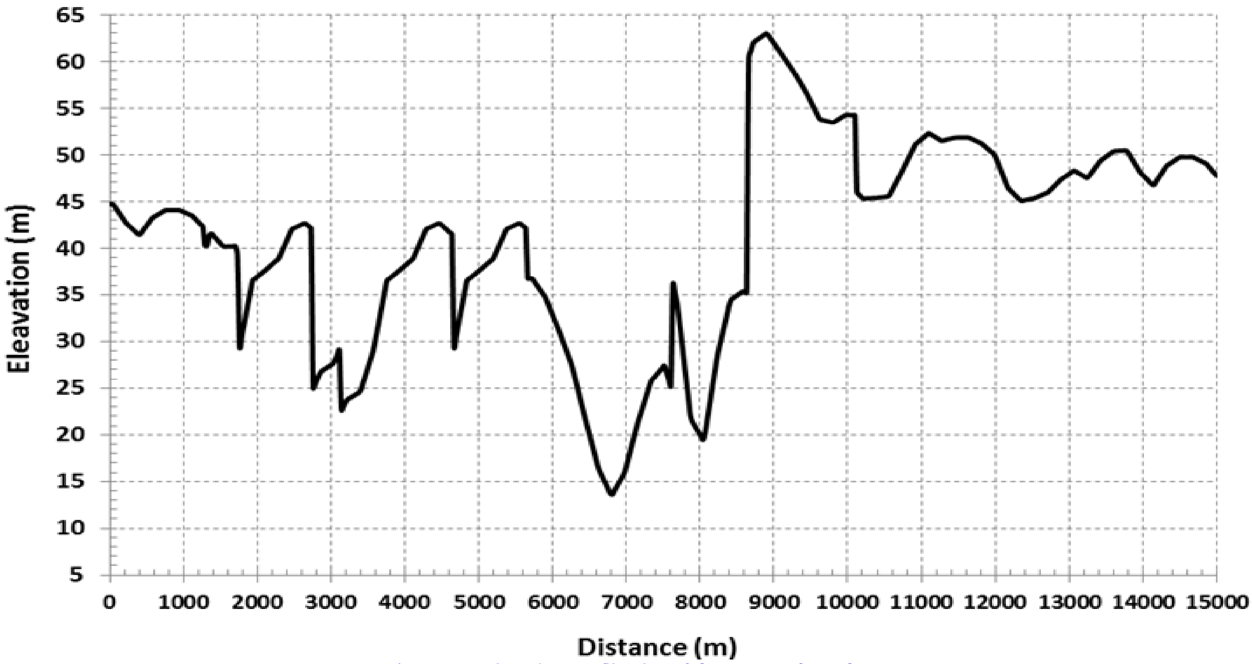

Figure-1. Elevation profile plot of the case study path.

The effective earth radius factor (k-Factor), earth bulge, LOS percentage clearance , diffraction loss parameter and single knife edge diffraction loss G(dB) computed at C-band microwave frequency of 5.5 GHz and refractivity gradient range of 96 to -120 N-units are shown in Table 1. Similar results for the Ku-band microwave frequency of 11 GHz are shown in Table 2. The radius of the first Fresnel zone at the point of minimum LOS percentage clearance is 14.05 m at 5.5 GHz and it is 9.94 m at 11 GHz.

Table-1. The effective earth radius factor (k-Factor), earth bulge, LOS percentage clearance , diffraction loss parameter and single knife edge diffraction loss G(dB) is computed at Ku-band microwave frequency of 5.5 GHz and refractivity gradient range of 96 to -120 N-units.

Operating Refractivity Gradient (N units/km)	Effective Earth Radius Factor (k-Factor)	Earth Bulge, in m	LOS percentage clearance (%)	Diffraction Loss Parameter, V	Single Knife Edge Diffraction Loss G(dB) in dB
96.00	0.62	6.86	33.89	0.48	-9.98
72.00	0.69	6.21	38.52	0.54	-10.52
48.00	0.77	5.56	43.16	0.61	-11.06
24.00	0.87	4.91	47.79	0.68	-11.60
0.00	1.00	4.26	52.42	0.74	-12.14
-24.00	1.18	3.61	57.06	0.81	-12.68
-39.25	1.33	3.19	60.00	0.85	-13.02
-48.00	1.44	2.96	61.69	0.87	-13.22
-72.00	1.85	2.31	66.32	0.94	-13.76
-96.00	2.57	1.65	70.96	1.00	-14.00
-120.00	4.24	1.00	75.59	1.07	-14.39

Table-2. The effective earth radius factor (k-Factor), earth bulge, LOS percentage clearance , diffraction loss parameter and single knife edge diffraction loss G(dB) computed at Ku-band microwave frequency of 11 GHz and refractivity gradient range of 96 to -120 N-units.

Operating Refractivity Gradient (N units/km)	Effective Earth Radius Factor (k-Factor)	Earth Bulge, in m	LOS percentage clearance (%)	Diffraction Loss Parameter, V	Single Knife Edge Diffraction Loss G(dB) in dB
96.00	0.62	6.86	23.07	0.33	-8.71
72.00	0.69	6.21	29.63	0.42	-9.48
48.00	0.77	5.56	36.18	0.51	-10.24
24.00	0.87	4.91	42.73	0.60	-11.01
0.00	1.00	4.26	49.28	0.70	-11.77
-24.00	1.18	3.61	55.84	0.79	-12.54
-39.25	1.33	3.19	60.00	0.85	-13.02
-48.00	1.44	2.96	62.39	0.88	-13.30
-72.00	1.85	2.31	68.94	0.97	-14.07
-96.00	2.57	1.65	75.49	1.07	-14.39
-120.00	4.24	1.00	82.05	1.16	-14.93

The plot of effective earth radius factor (k-factor) and earth bulge, in m versus operating refractivity gradient (N units/km) at 5.5 GHz and at 11 GHz are shown in Figure 2. The regression equation fitted to the plots are given in Equations 21 and 22;

$$h_{eb(jmx)} = 0.0271(\Delta) + 4.2582 \qquad (21)$$

$$k = 0.910437147\left(e^{-0.011998689020(\Delta)}\right) \qquad (22)$$

According to Equation 21, the earth bulge increases linearly with refractivity gradient whereas in Equation 22, the k-factor decreases exponentially with respect to the refractivity gradient . In any case, although in all the refractivity gradient values considered the k-factor and earth bulge are the same for both frequencies, the same is not true for the variation of LOS percentage clearance and diffraction loss.

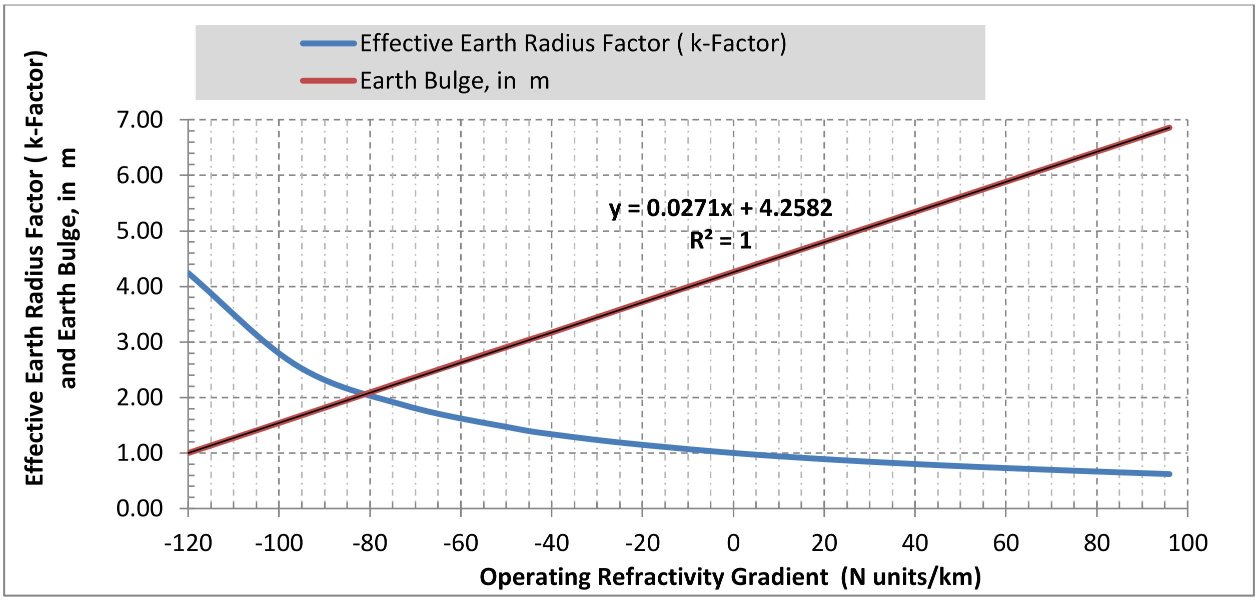

Figure-2. Plot of Effective Earth Radius Factor (k-Factor) and Earth Bulge, in m versus Operating Refractivity Gradient (N units/km) at 5.5 GHz and at 11 GHz.

The plot of the LOS percentage clearance (%) versus refractivity gradient (N units/km) at 5.5 GHz and at 11 GHz are shown in Figure 3. For the 5.5 GHz , the LOS percentage clearance is related to refractivity gradient as follows;

$$P_{c(5.5\ GHz)}\ \% = -0.1930601427(\Delta) + 52.42319748 \qquad (23)$$

For the 11 GHz , the LOS percentage clearance is related to refractivity gradient as follows;

$$P_{c(11\ GHz)}\ \% = -0.2730252843(\Delta) + 49.28370213 \qquad (24)$$

Based on the equations and Figure 2, the LOS percentage clearance decreases linearly with refractivity gradient. As the refractivity gradient increases the LOS percentage clearance decreases but the rate of decrease is faster for higher frequency. Also, for both frequencies, the LOS percentage clearance is the same at the reference refractivity gradient of -39.25 N units/km which is equivalent to the reference k-factor of 1.33 or 4/3.

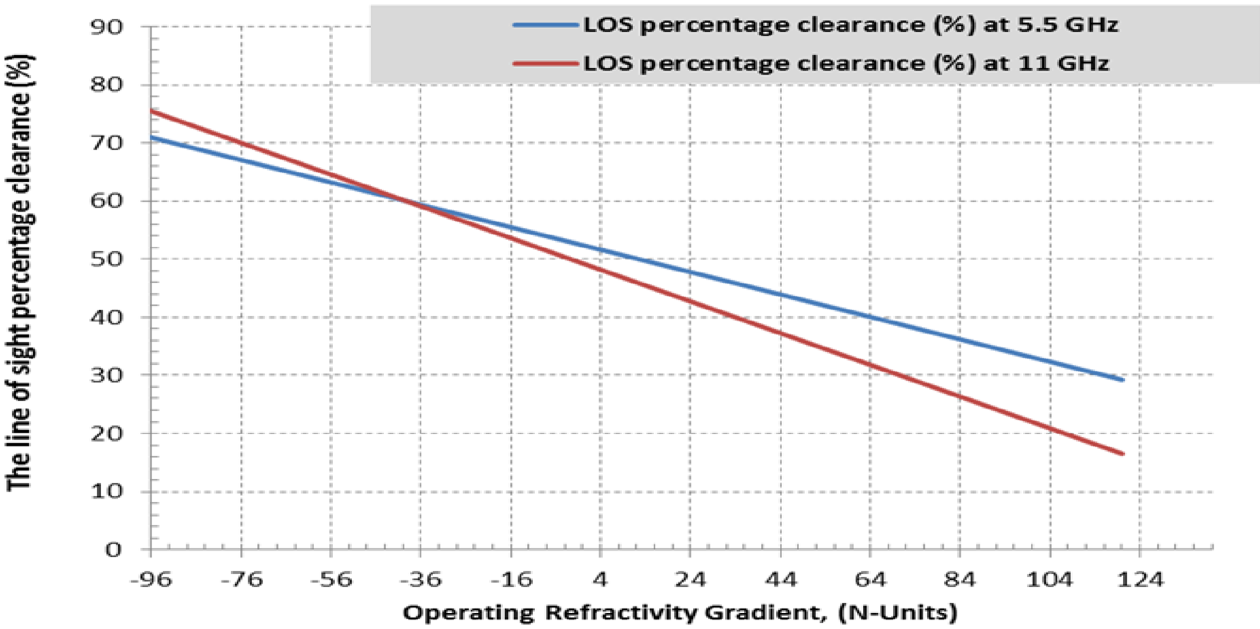

Figure-3. Plot of the LOS Percentage clearance (%) versus refractivity gradient (N units/km) at 5.5 GHz and at 11 GHz.

The plot of the single knife edge diffraction versus refractivity gradient (N units/km) at 5.5 GHz and at 11 GHz are shown in Figure 4. For the 5.5 GHz , the single knife edge diffraction is related to refractivity gradient as follows;

$$G_{d(5.5\,GHz)}(dB) = 0.02100566711\,(\Delta) - 12.09316795 \qquad (25)$$

For the 11 GHz , the single knife edge diffraction is related to refractivity gradient as follows;

$$G_{d(11\,GHz)}(dB) = 0.02966814925(\Delta) - 11.70321337 \qquad (26)$$

Based on the equations and Figure 3, the single knife edge diffraction increases linearly with refractivity gradient. As the refractivity gradient increases the single knife edge diffraction increases but the rate of increase is faster for higher frequency. Also, for both frequencies, the single knife edge diffraction is the same at the reference refractivity gradient of -39.25 N units/km which is equivalent to the reference k-factor of 1.33 or 4/3.

In any case, because it is a loss factor the more negative the value of the diffraction loss in dB the higher the value of the loss. As such, the interpretation of equations 25 and 26 as well as Figure 4 is that for refractivity gradient lower than the reference refractivity gradient of -39.25 N units/km the higher the frequency the greater is the absolute value of diffraction loss that will be experienced for any given refractivity gradient less than 39.25 N units/km. On the other hand , the lower the frequency the greater is the absolute value of diffraction loss that will be experienced for any given refractivity gradient above 39.25 N units/km.

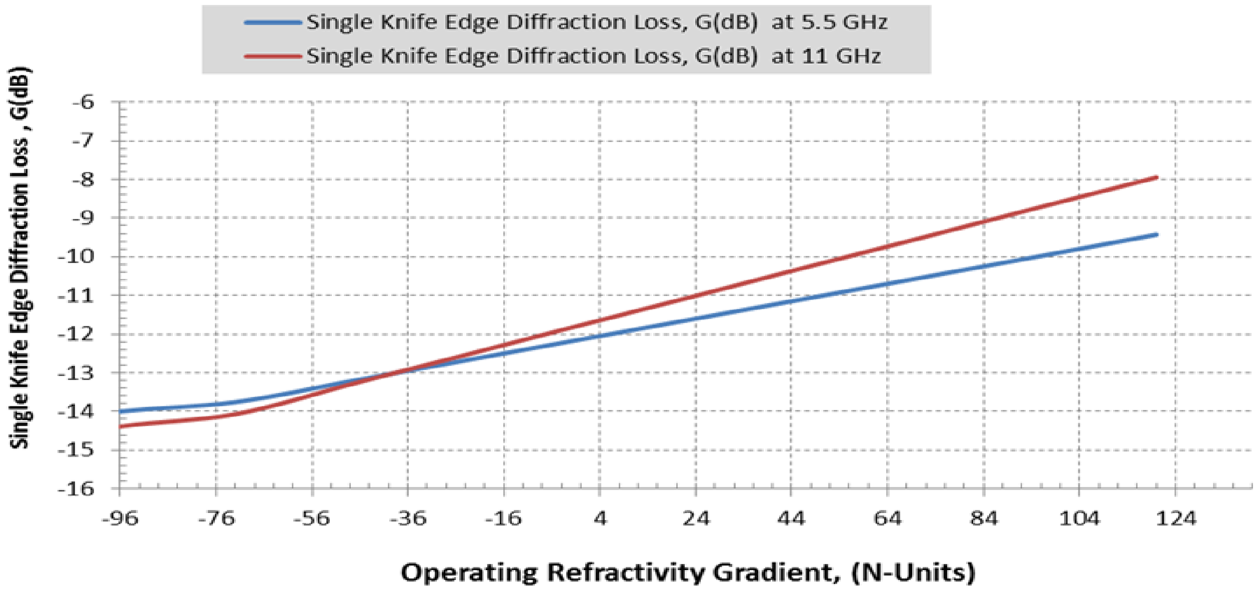

Figure-4. Plot of the single knife edge diffraction loss versus refractivity gradient (N units/km) at 5.5 GHz and at 11 GHz.

The implication of the result is that, given that for any location the refractivity gradient varies with the primary atmospheric parameters like temperature, pressure and relative humidity, the amount of diffraction loss posed to the signal in the atmosphere will be varying at different rates depending on the prevailing values of the atmospheric parameters upon which refractivity gradient depends. Also, apart from the reference refractivity gradient of 39.25 N units/km different frequencies will experience a different amount of diffraction loss. The specific impact of the refractivity gradient on different frequencies depends on whether the prevailing refractivity gradient is above or below the reference refractivity gradient of 39.25 N units/km.

5. CONCLUSIONS

Mathematical expressions and approaches for analyzing the impact of refractivity gradient on line of sight percentage clearance and diffraction loss presented. The study showed that the changes in the vertical profile of atmospheric temperature, pressure and relative humidity affect the value of refractivity gradient which in turn affect effective earth radius factor, the earth bulge , the line of sight percentage clearance and diffraction loss. Apart from the effective earth radius factor which is exponentially related to the refractivity gradient, all the other parameters listed are linearly related to refractivity gradient. Particularly, the earth bulge increases linearly with refractivity gradient, the line of sight percentage clearance decreases linearly with refractivity gradient and single knife edge diffraction increases linearly with refractivity gradient. For any given refractivity gradient, the line of sight percentage clearance decreases faster for higher frequency. Also, for any refractivity gradient greater than reference refractivity gradient of 39.25 N units/km the absolute value of the knife edge diffraction loss is higher for lower frequency. In all, the variations in the atmospheric condition can change the refractivity gradient and hence increase or decrease the line of sight percentage clearance and the attendant diffraction loss. This paper has effectively presented the mathematical models to understand and estimate the impact of the variations in the atmospheric parameters on the redioclimatic parameters and diffraction loss.

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