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Software for Fresnel-Kirchoff Single Knife-Edge Diffraction Loss Model

Okoye O. Jude[1], Afolayan J. Jimoh[2], Akinloye Bolanle Eunice[3]

[1,2,3]Department of Electrical/Electronic and Computer Engineering,
University of Uyo, Uyo, Akwa Ibom State, Nigeria.

Abstract

In this paper, development of software for computing single knife-edge diffraction loss based on Fresnel-Kirchoff model and Lee's analytical approximation model is presented. The mathematical expressions and algorithm for the single knife edge diffraction loss software are presented. The input required by the software includes frequency, height of the transmitter and receiver antennas, height of obstruction, distance of the obstruction from the transmitter or receiver. The output includes diffraction loss, Fresnel diffraction parameter, path length and phase difference between the direct and diffracted paths, the number and radius of all Fresnel zones block by the obstruction. Moreover, the software is used to study the variation of diffraction parameter, diffraction loss and other link parameters with obstruction height. Results are presented in tables, graphs and also as a list of parameters and their values. Sample diffraction loss computation is conducted for a 9GHz microwave link with 25 m knife edge obstruction. At diffraction parameter of 5.4772255575 the corresponding diffraction loss is -27.72756218 dB. More importantly, at diffraction parameter of 0 (zero) the corresponding diffraction loss is -6.02 dB which is in agreement with the published works on single knife edge diffraction loss at diffraction parameter of 0 (zero).

Keywords: Diffraction Loss, Diffraction Parameter, Diffraction, Single knife Diffraction, Fresnel Zone, microwave Link, Line-Of-Sight Link

1 Introduction

Over the years, wireless communication has grown to be the dominant communication systems across the globe [1]. Accordingly, researchers and manufacturers are continuously inventing and improving on tools that can be used to advance the wireless communication technologies and their applications [2,3]. One of such tool is considered in this paper, namely, the software for computing diffraction loss of wireless communication links with single knife edge obstruction in the signal path.

Diffraction is the bending of radio waves around obstacles in the path of the waves, or as the radio waves pass through narrow openings [4,5]. Diffraction allows radio signals to propagate around the curved surface of the earth, beyond the horizon, and to propagate behind obstructions [4,6,7]. Diffraction results in a change of direction of path of the radio wave energy from the normal line-of-sight path. Diffraction enables radio signal to be receive around the edges of an obstacle. The ratio of the received signal power with and without the obstacle is referred to as the diffraction loss [8,9]. Diffraction loss is a function of frequency of operation and the path geometry. If the direct line-of-sight of a radio wave or wireless signal is obstructed by a single object, such as a mountain or building, the attenuation resulting from diffraction over such obstacle can be determined by considering the obstacle as a single knife-edge [10,11].

Single knife-edge diffraction model is used to predict diffraction losses caused by a single object such as a hill or mountain which lies in the path of the wireless signal [10,11]. Such, diffraction losses over isolated obstacles can be estimated using the Fresnel-Kirchoff knife-edge model [12,13]. Determination of diffraction loss is usually part of a larger network planning and design process that requires selection and fine-tuning of parameter values to suit a particular design specification. In other to facilitate the diffraction loss parameter selection and fine-tuning process, software tool is essential. In this paper, software that can be used to determine single knife edge diffraction loss and also perform parametric analysis on diffraction loss parameters is presented. Sample diffraction loss computation for a 9GHz microwave link is used to demonstrate the applicability of the software.

2 The Mathematics of the Fresnel-Kirchoff Model for Single Knife Edge Diffraction Loss

The Fresnel-Kirchoff model for single knife edge diffraction loss computation is explained using schematic diagram of a wireless communication link in Fig. 1. A simplified version of the link schematic diagram in Fig. 2 is obtained by subtracting the smaller of the two antenna heights in Fig. 1, from all other heights considered in the link. The communication link in Fig. 1 and Fig. 2 is for a wireless signal transmitted from the transmitter to the receiver with signal wavelength (λ) given as:

$$\lambda = \frac{c}{f} = c(T) \tag{1}$$

$$\therefore \mathrm{c} = \lambda(f) = \frac{\lambda}{T} \tag{2}$$

where: c is the speed of a radio wave ($c = 3\text{x}10^3 m/s$; λ is wavelength of a radio wave in m; f is frequency of a radio wave in Hz, and T is period of a radio wave in seconds.

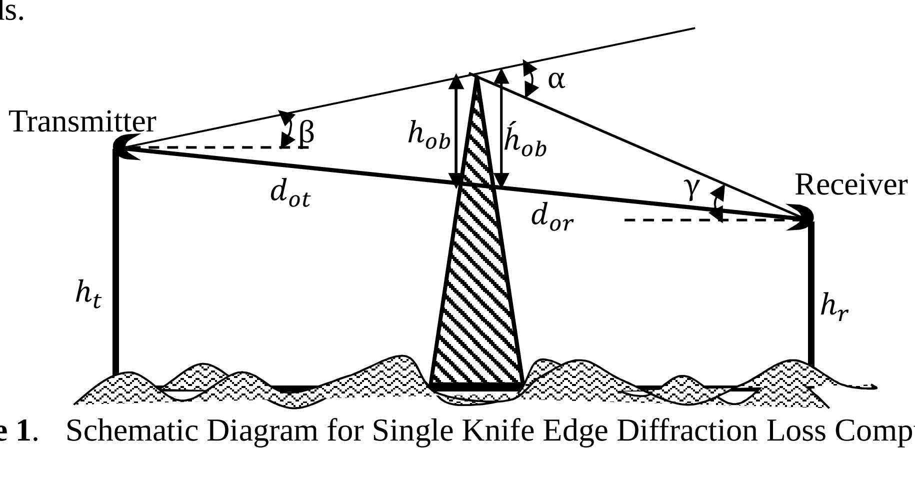

Figure 1. Schematic Diagram for Single Knife Edge Diffraction Loss Computation.

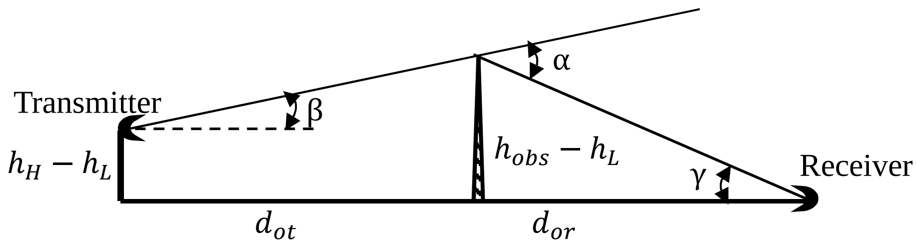

Figure 2. The Simplified Link Schematic Diagram for Diffraction Loss Computation

In Fig. 1 and Fig. 2, various link parameters are identified and defined as follows:

h_t is the height of the transmitter antenna

h_r is the height of the receiver antenna

h_L is the minimum antenna height between the transmitter and the receiver antennas, where

$$h_L = \min\text{imum}(h_r, h_t) \tag{3}$$

h_H is the maximum antenna height between the transmitter and the receiver antennas, where

$$h_H = \text{maximum}(h_r, h_t) \tag{4}$$

h_{obs} is the height of the impenetrable knife-edge obstruction from the ground.

h_{ob} is the height of the impenetrable knife-edge obstruction with respect to the straight line-of-sight path between the transmitter and the receiver. If h_{ob} is positive, it shows the obstruction height is above the line of sight. However, if h_{ob} is negative, it shows the obstruction height is below the line of sight.

$$h_{ob} = h_{obs} - h_L \tag{5}$$

d_{ot} is the distance of the obstruction from the transmitter

d_{or} is the distance of the obstruction from the receiver

If α and β are very small in Fig. 1 and Fig. 2 and also, if $(h_{ob})\approx \acute{h}_{ob}$ then, the excess path length (Δ) is the difference between the direct path and the diffracted path. Then, Δ is given as;

$$\Delta \approx \left(\frac{(h_{ob})^2}{2}\right)\left(\frac{(d_{ot}+d_{or})}{(d_{ot})(d_{or})}\right) \tag{6}$$

$$\alpha = \beta + \gamma \tag{7}$$

$$\alpha \approx h_{ob}\left(\frac{(d_{ot}+d_{or})}{(d_{ot})(d_{or})}\right) \tag{8}$$

Also, the Fresnel-Kirchoff diffraction parameter (V) is given as

$$V = h_{ob}\left(\sqrt{\frac{2(d_{ot}+d_{or})}{\lambda(d_{ot})(d_{or})}}\right) \tag{9}$$

$$V = \alpha\left(\sqrt{\frac{2(d_{ot})(d_{or})}{\lambda(d_{ot}+d_{or})}}\right) \tag{10}$$

where α is in radians.

The phase difference (ϕ) between the direct path and the diffracted path is given as:

$$\Phi = \left(\frac{2\pi}{\lambda}\right)\Delta = \left(\frac{2\pi}{\lambda}\right)\left(\left(\frac{(h_{ob})^2}{2}\right)\left(\frac{(d_{ot}+d_{or})}{(d_{ot})(d_{or})}\right)\right) = \left(\frac{\pi}{2}\right)V^2 \tag{11}$$

Hence, the phase difference (ϕ) depends on the height and position of the obstacle, as well as the transmitter and receiver locations.

Fresnel zones: Fresnel zones represent successive regions where secondary waves have a path length from the transmitter to the receiver which are $\frac{n(\lambda)}{2}$ greater than the total path length of a line-of-sight path. The radius of the n[th] Fresnel zone ($\mathbf{r}_{\boldsymbol{f(n)}}$) is given as [14]:

$$\mathbf{r}_{\boldsymbol{f(n)}} = \sqrt{\frac{n(\lambda(d_{ot})(d_{or}))}{(d_{ot}+d_{or})}}, \text{ for n =1,2,3,... and } d_{ot} \gg \mathbf{r}_{\boldsymbol{f(n)}} \; and \; d_{or} \gg \mathbf{r}_{\boldsymbol{f(n)}} \quad (12)$$

Graphical solution can be used to compute diffraction loss $\mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB})$ as a function of the diffraction parameter, V using the knife-edge diffraction loss graph of Fig. 3 [15,16]. Numerical solutions can also be used to compute diffraction loss $\mathrm{G}_d(dB)$ as a function of the diffraction parameter, V. Lee's approximation model for computing $\mathrm{G}_d(dB)$ with respect to V is given as follows [15,16].

$$\left\{\begin{array}{ll} \mathrm{G}_d(dB) = 0 & \text{for} \quad \mathrm{v} < -1 \\ \mathrm{G}_d(dB) = 20\log(0.5 - 0.62\mathrm{v}) & \text{for} \; -1 \leq \mathrm{v} \leq 0 \\ \mathrm{G}_d(dB) = 20\log\,(0.5\exp(-0.95\mathrm{v})\,) & \text{for} \; 0 \leq \mathrm{v} \leq 1 \\ \mathrm{G}_d(dB) = 20\log\left(0.4 - \sqrt{0.1184 - (0.38 - 0.1\mathrm{v})^2}\right) & \text{for} \; 1 \leq \mathrm{v} \leq 2.4 \\ \mathrm{G}_d(dB) = 20\log\left(\frac{0.225}{v}\right) & \text{for} \quad \mathrm{v} > 2.4 \end{array}\right\} \quad (13)$$

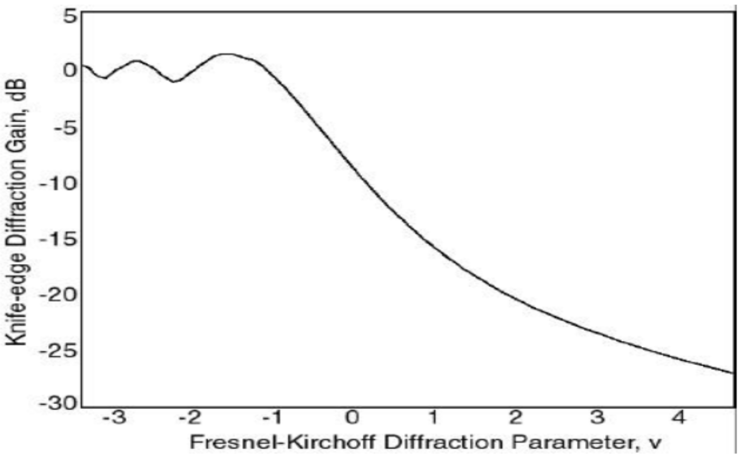

Figure 3: Knife-edge diffraction loss graphed as a function of the Fresnel-Kirchoff diffraction parameter [15,16].

3 Algorithm for Computing Single Knife-Edge Diffraction Loss.

The entire algorithm is given below.

Step 1 Input the following

- **(i)** f frequency of the radio wave in Hz.
- **(ii)** $\mathrm{h_t}$ is the height of the transmitter antenna (in meters) from the ground or sea level.
- **(iii)** h_r is the height of the receiver antenna (in meters) from the ground or sea level.
- **(iv)** h_{obs} is the height of the impenetrable knife-edge obstruction (in meters) from the ground or sea level.
- **(v)** d_{ot} distance of the obstruction from the transmitter (in meters).
- **(vi)** d_{or} distance of the obstruction from the receiver (in meters).

Step 2 Compute ʎ, the wavelength of a radio wave (in meters) as follows: $\lambda = \frac{c}{f}$.

Step 3 Compute h_L, the minimum antenna height between the transmitter and the receiver antennas (in meters), where $h_L = \min\text{imum}(h_r, h_t)$.

Step 4 Compute h_H, the maximum antenna height between the transmitter and the receiver antennas (in meters), where $h_H = \text{maximum}(h_r, h_t)$.

Step 5 Compute h_{ob}, the height of the knife-edge obstruction with respect to the straight line-of-sight path between the transmitter and the receiver, where $h_{ob} = h_{obs} - h_L$.

Step 6 Compute the Fresnel Diffraction Parameter, V as follows:

$$\text{v} = h_{ob}\left(\sqrt{\frac{2(d_{ot} + d_{or})}{\lambda(d_{ot})(d_{or})}}\right)$$

Step 7 Compute $\mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB})$ the diffraction loss as a function of the diffraction parameter V. Using Lee's numerical (approximation) solution method as follows:

$$\begin{Bmatrix} \mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB}) = 0 & \text{for} \quad \text{v} < -1 \\ \mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB}) = 20\log(0.5 - 0.62\text{v}) & \text{for} \; -1 \le \text{v} \le 0 \\ \mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB}) = 20\log\left(0.5\exp(-0.95\text{v})\right) & \text{for} \; 0 \le \text{v} \le 1 \\ \mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB}) = 20\log\left(0.4 - \sqrt{0.1184 - (0.38 - 0.1\text{v})^2}\right) & \text{for} \; 1 \le \text{v} \le 2.4 \\ \mathbf{G}_{\boldsymbol{d}}(\boldsymbol{dB}) = 20\log\left(\frac{0.225}{v}\right) & \text{for} \quad \text{v} > 2.4 \end{Bmatrix}$$

Step 8 Compute Δ, the path length difference between the direct and diffracted paths as follows:

$$\Delta \approx \left(\frac{(h_{ob})^2}{2}\right)\left(\frac{(d_{ot}+d_{or})}{(d_{ot})(d_{or})}\right) = \left(\frac{\lambda}{4}\right)\text{v}^2$$

Step 9 Find n, the Fresnel zone in which the tip of the obstruction lies . The excess path length (Δ) is also given in respect of n as $\Delta = \left(\frac{\text{n}\lambda}{2}\right)$, hence $\text{n} = \frac{2(\Delta)}{\lambda}$.

Step 10 Find n_{ob}, the Fresnel zones blocked by the obstruction. $n_{ob} = \lfloor \text{n} \rfloor$, where $\lfloor\ \rfloor$ means number truncated to the nearest lower integer. Hence, $n_{ob} = \left\lfloor \frac{2(\Delta)}{\lambda} \right\rfloor$. Therefore, the obstruction blocks the first n_{ob} Fresnel zones.

Step 11 Compute ϕ, the phase difference between the direct path and the diffracted path as follows; $\Phi = \left(\frac{2\pi}{\lambda}\right)\Delta = \left(\frac{\pi}{2}\right)\text{v}^2$.

Step 12 Compute $\mathbf{r}_{\boldsymbol{f(n)}}$, the radius (in meters) of the first n Fresnel zones the obstruction blocks fully or partially as follows; $\mathbf{r}_{\boldsymbol{f(n)}} = \sqrt{\frac{n(\lambda(d_{ot})(d_{or}))}{(d_{ot}+d_{or})}}$ where n=1,2,3,… n ; $d_{ot} >> \mathbf{r}_{\boldsymbol{f(n)}}$ *and* $d_{or} >> \mathbf{r}_{\boldsymbol{f(n)}}$.

The software is written in Visual Basic language and a sample single knife-edge diffraction loss is used to demonstrate the application of the software. The sample diffraction loss computation is for 9GHz microwave link with transmitter antenna height of 100 m, receiver antenna height of 90 m, obstruction with height of 25 m from the line of sight and with obstruction distance of 2500 m from both the transmitter and the receiver.

4 Results and Discussion

The results obtained from the sample run of the software is presented and discussed in this section. From Fig. 4, the Fresnel diffraction parameter (v) for the link is

5.4772255575 which correspond to diffraction loss of -27.72756218 dB. In addition, from Fig. 6, the path length difference is 0.25 and up to the 15th (that is, $n_{ob} = 15$, as shown in Fig. 6) Fresnel zones are completely blocked by the obstruction which is 115 metres high ($that\ is\ h_{ob} = 115$, as shown in Fig. 5) A where the radius of the 15th Fresnel zone is 25 m (that is, $r_{f(n)} = 47.13°$, as shown in Fig. 6). Also, in Fig. 6, the phase difference is 47.13° (that is, $\phi = 47.13°$, as shown in Fig. 6).

f	9000000000	Frequency of the radio wave in Hz
h_t	100	Height of the transmitter antenna (in meters)
h_r	90	Height of the receiver antenna (in meters)
h_{obs}	115	Height of the knife-edge obstruction (in meters)
d_{ot}	2500	Obstruction distance from the transmitter (in meters)
d_{or}	2500	Obstruction distance from the receiver (in meters)
	INPUT	

Figure 4. The Input Parameters For The Sample Diffraction Loss Computation

FRESNEL-KIRCHOFF SINGLE KNIFE-EDGE DIFFRACTION LOSS SOFTWARE		
λ	0.033333333	The wavelength of a radio wave (in meters) ; c =300,000,000m/s
h_L	90	Minimum antenna height b/w transmitter & receiver antennas (in meters)
h_H	100	Maximum antenna height b/w transmitter & receiver (in meters)
h_{ob}	25	Height of obstruction relative to LOS (in meters)
V	5.477225575	Fresnel Diffraction Parameter
$G_d(dB)$	-27.72756218	Diffraction loss (in dB)
	OUTPUT 1	

Figure 5. The First Output Screen for the Sample Diffraction Loss Computation

The results are also presented in table 1 which shows how the diffraction parameter and diffraction loss vary with the obstruction height. In the link, for obstruction height less equal to -5m, the diffraction parameter (v) is less or equal to -1.1 and the corresponding diffraction loss for such range of values of v by Lee's model is 0 dB. The various values diffraction loss and diffraction parameter are presented in table 1 and graph of Fig. 7 for obstruction height from -50 m to 50 m where the obstruction height is measured with respect to the line of sight between the transmitter and the receiver antennas.

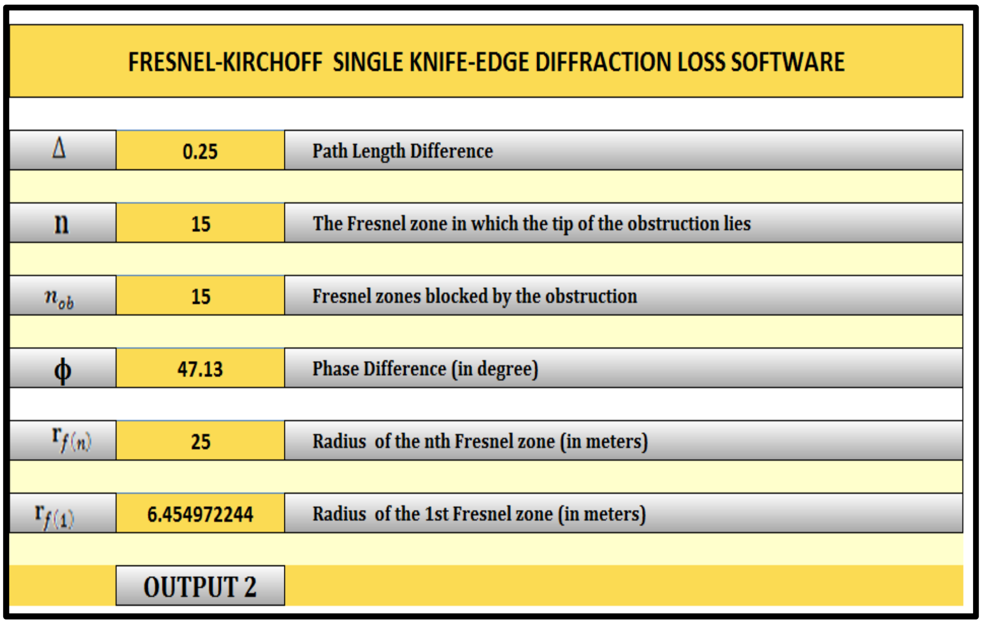

Figure 6. The Second Output Screen for the Sample Diffraction Loss Computation

Table 1. Variation of diffraction parameter, diffraction loss and other link parameters with obstruction height

	Height Of Obstruction (m)	Fresnel Diffraction Parameter	Diffraction Loss (dB)	Number of Fresnel Zones Affected	Radius Of The Highest Fresnel Zone Blocked (m)	Path Length Difference (m)	Phase Difference (°)
S/N	hob	V	G(dB)	n	rf(nob) (m)	Δ	φ (°)
1	-50	-10.95	0	60	50	1	188.52
2	-40	-8.76	0	38.4	39.79	0.64	120.65
3	-20	-4.38	0	9.6	19.36	0.16	30.16
4	-10	-2.19	0	2.4	9.13	0.04	7.54
5	-5	-1.1	0	0.6	0	0.01	1.89
6	0	0	-6.02	0	0	0	0
7	10	2.19	-20.37	2.4	9.13	0.04	7.54
8	20	4.38	-25.79	9.6	19.36	0.16	30.16
9	30	6.57	-29.31	21.6	29.58	0.36	67.87
10	50	10.95	-33.75	60	50	1	188.52

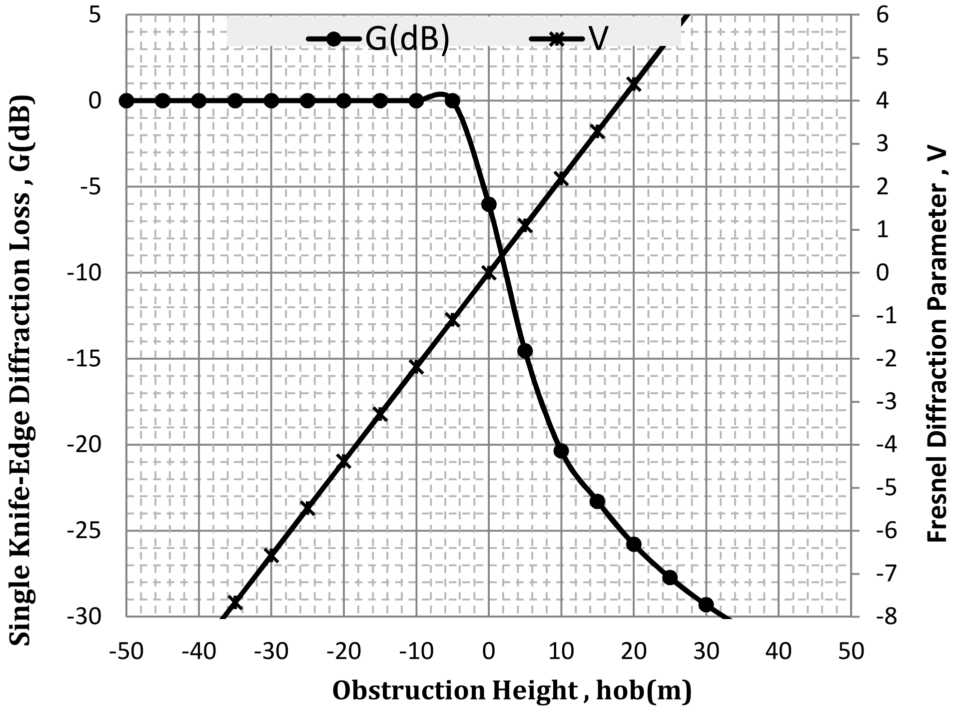

Figure 7. Diffraction Loss, G(dB) and Fresnel Diffraction Parameter Versus Obstruction Height, hob(m)

5 Conclusion

In this paper, mathematical expressions and algorithm for single knife edge diffraction loss software are presented. Sample application of the software in diffraction loss computation is presented; Also, the software is used to study the variation of diffraction parameter, diffraction loss and other link parameters with obstruction height.

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