University of Toronto

Faculty of Applied Science and Engineering

ECE422H1 Radio and Microwave Wireless Systems

Lab 3: Plane-Earth Reflection and Diffraction

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2 Experimental Setup for Both Experiments

After calibrating the network analyzers, determine the frequency at which the dipoles are operating by measuring the input reflection coefficient of one of the dipoles, and setting the marker to report measurements at this frequency.

Figure 1: Frequency of operation & input reflection coefficient of the half-wave dipole

Theoretical

$$f = 900 \text{ MHz}$$

$$\lambda = \frac{3 * 10^8}{900 * 10^6} = 33\, cm$$

$$\lambda/2 = 16.6 \text{ cm}$$

Our Measurement

$$f = 865.526 \text{ MHz}$$

$$\lambda = \frac{3 * 10^8}{866 * 10^6} \approx 34\, cm$$

$$\lambda/2 = 17 \text{ cm}$$

Hence, we determine the antenna spacing to be 17 cm.

3 Multipath Measurements

2. Determine the far-field distance of each antenna and place them at a starting distance from each other corresponding to the sum of the far field distances of the two antennas.

$$Far\ field\ distance:\ d \geq \frac{2 * D^2}{\lambda}$$

We measure the diameter of the antenna to be D = 51 cm.

$$d \geq \frac{2 * (0.51)^2}{(0.34)}$$

$$\text{d} \geq 1.53\, m$$

Table 1: S_{21} (dB) measurements with respect to increased distance (m)

Distance (m)	S21(dB)
3.06	-27.9
3.36	-30.5
3.66	-31.9
3.96	-30.9
4.26	-32.1
4.56	-33.2
4.86	-34.9
5.16	-36.8
5.46	-39.5
5.76	-40
6.06	-37
6.36	-41.5
6.66	-39
6.96	-40.5
7.26	-38
7.56	-38.5

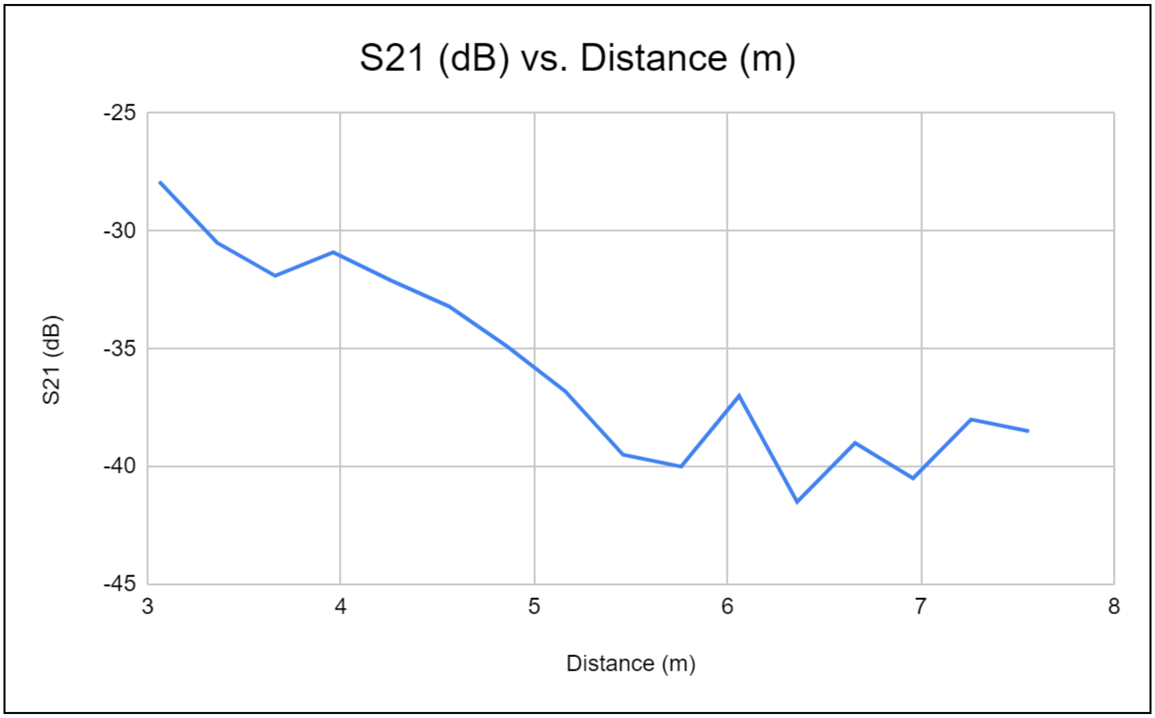

Figure 2: Experimental S21(dB) values as a function of distance (m)

1. Compare the measured signal strength with the theoretical signal strength from plane-earth reflection. How does the data compare to the theoretical path loss as a function of distance compared to that predicted by plane-earth reflection theory?

$$Wr = G_r * EIRP * \left(\frac{\lambda}{4\pi D}\right)^2 * 4sin^2\left(\frac{2\pi h_1 h_2}{\lambda D}\right)$$

We measure the height of the antennas to be $h_1 = h_2 = 135\ cm$

Therefore, gain due to plane-earth reflection is $4sin^2\left(\frac{3.645\pi}{0.34D}\right) = 4sin^2\left(\frac{10.72\pi}{D}\right)$

We know λ=34cm. From there we can find "S21" relative to Wr/Wt being = -27.9dB when plane earth reflection is neglected. This gives a proportional Gr*Gt of around 7.05. Thus, all other S21 can be relatively calculated with PER taken into account.

Table 2: S_{21} (dB) calculated with respect to increased distance (m)

Distance (m)	S21(dB)
3.06	-21.9
3.36	-27.4
3.66	-37.2
3.96	-26.2
4.26	-24.8
4.56	-26.3
4.86	-30.2
5.16	-38.4
5.46	-46.6
5.76	-35.1
6.06	-31.5
6.36	-29.9
6.66	-29.2
6.96	-29.1
7.26	-29.4
7.56	-30.0

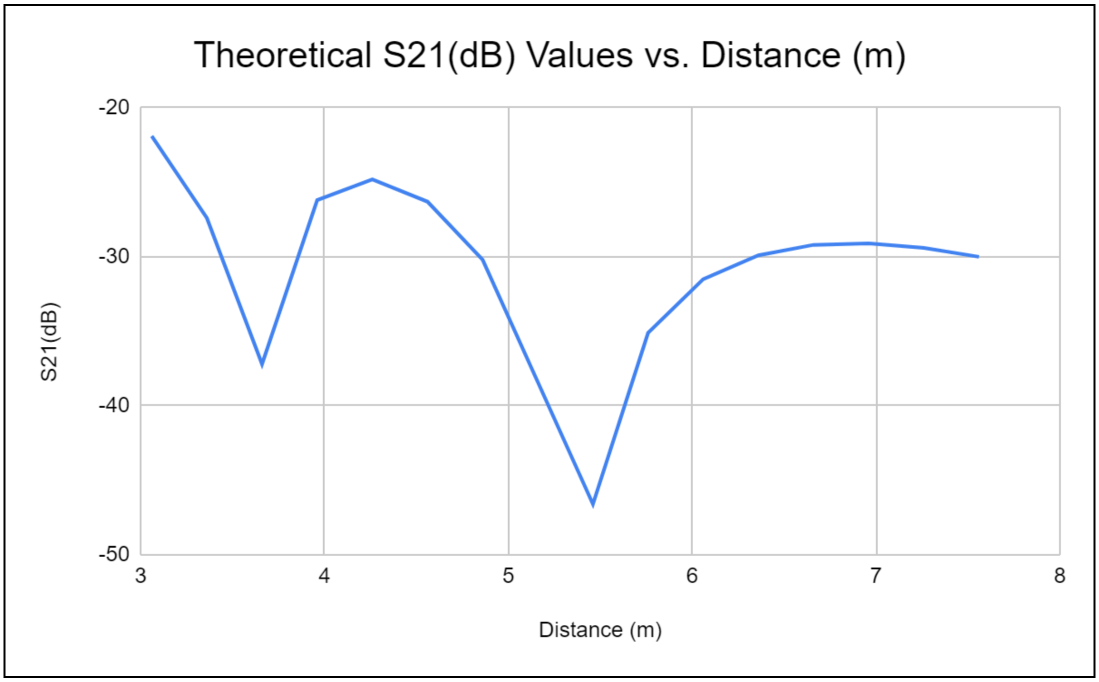

Figure 3: Theoretical S21(dB) values as a function of distance (m)

In general, the theoretical S21 values are greater than the recorded values, with lower minimas. The nulls are observed to be sharper in the theoretical plot than in the experimental one but the null location shifts after 6 m away from the transmitter.

2. You will likely not get an exact match between theory and measurements, especially with regard to null locations. Explain possible sources of error, and in particular, elaborate upon assumptions made in the plane-earth theory development that may have been violated in this experiment.

A source of error could be that in an ideal case, D is much greater than h. In our experiment, this was not the case. This could lead to a reduced plane-earth term and decreased loss compared to reality.

The presence of other objects, such as tables and other antennas in the lab environment could have introduced multipath interference that is not accounted for in the theoretical model. These additional reflections and diffractions can alter the propagation characteristics and lead to deviations from expected null locations. In addition, the theoretical plane-earth reflection model assumes a perfect ground surface to achieve grazing incidence. Imperfections in the ground plane, such as surface roughness and ground conductivity could have led to deviations as well.

3. We have seen for links in free space, that power falls off as 1/R2 , whereas in plane-earth reflection, for large TX-RX separation distances, the power rolls of as 1/R4. In real multipath propagation scenarios, the power falls of as 1/Rn , where n is a path loss coefficient between 2 and 4. Given this fact, try fitting your path loss data to the following formula for the path loss in dB.

$$PL\ [\text{dB}] = PL(d_0)\ [\text{dB}] + 10n \log_{10}\left(\frac{d}{d_0}\right)$$

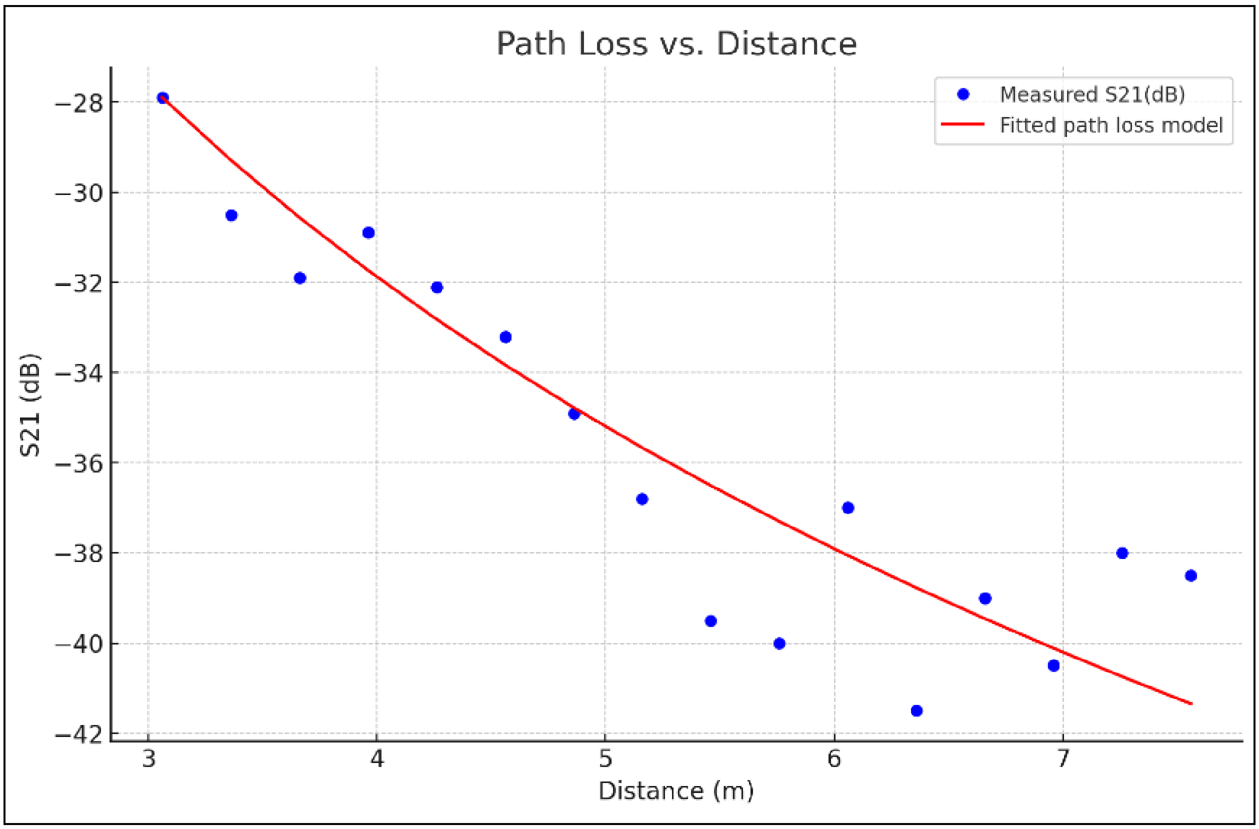

Figure 4: Path loss data and fitted path loss curve

The fitting of the path loss data to our experimental model resulted in a path loss exponent (n) of approximately 3.42. Since this value is between 2 and 4, it aligns with our expectation. Actual path loss behavior is consistent with the expectation that it decays faster than the free space but not as fast as the large distance plane-earth reflection scenario.

4. Would you expect the fading to be better or worse if an antenna having more directivity was used? In particular, if the beamwidth is narrowed in the E-plane, what effect would this have on the reception of the plane-earth reflection and consequent fading process?

$$\frac{P_r}{P_t} = G_r * G_t * \left(\frac{\lambda}{4\pi D}\right)^2 * 4sin^2\left(\frac{2\pi h_1 h_2}{\pi D}\right)$$

Narrowing the beamwidth in the E-plane would result in a more focused transmission and reception pattern, increasing the directivity of the antenna. Therefore the gain from plane-earth reflection would be expected to increase. As a result, reflected signal strength would be enhanced whereas the impact of the multipath interference from other directions such as the E-plane is reduced. Since the reception of the plane-earth reflection is improved, the fading effects would be reduced, resulting in higher reception quality and reduced fading effects.

4 Diffraction Measurements

Record the distance between the two antennas.

d1 = d2 = 153 cm = 1.53 cm

D = d1 + d2 = 306 cm = 3.06 m

Height of metallic sheet = 93.5 cm = 0.935 m

Table 3: S_{21} (dB) measurements versus height of the obstacle with respect to the LOS path

Height (cm)	S21(dB)
No obstruction (-Infinity)	-29
-6.5	-33
-5.5	-34.6
0.5	-32.7
5.5	-33
10.5	-34
15.5	-40
20.5	-44
25.5	-48
30.5	-47.2
35.5	-42
40.5	-41

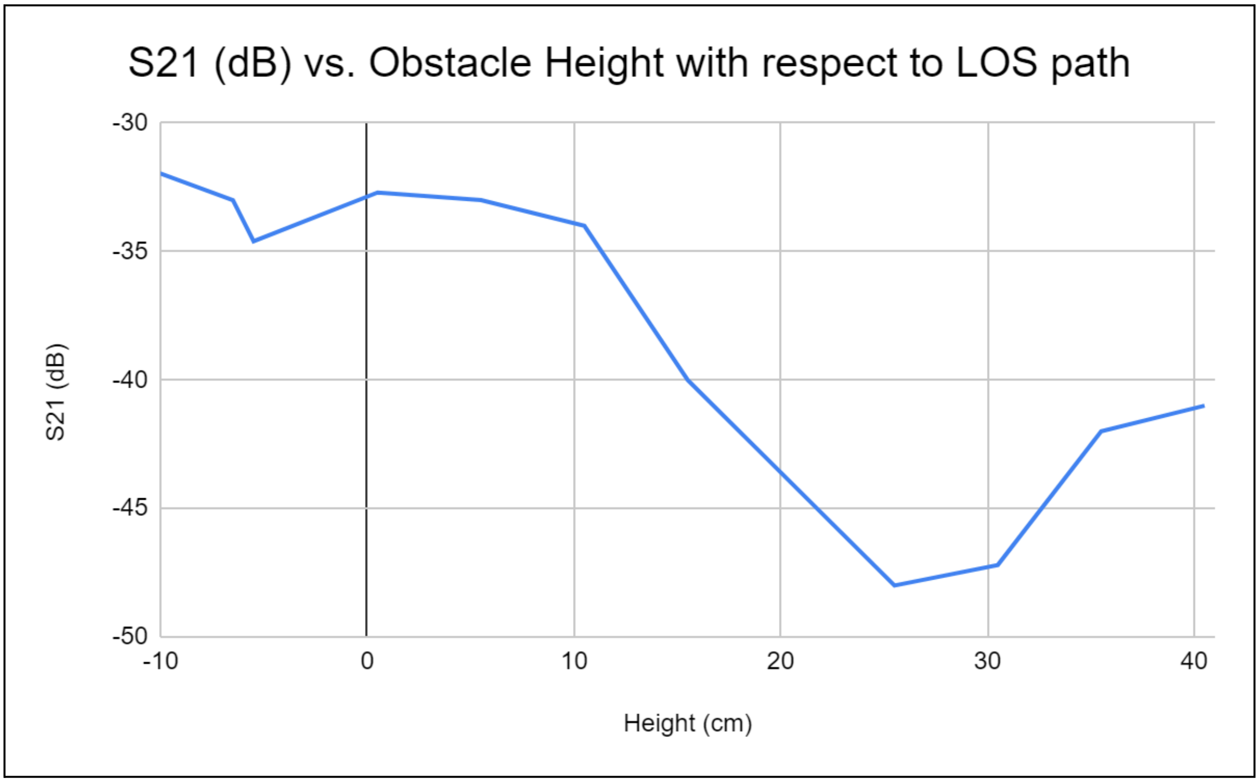

Figure 5: Experimental S21(dB) values as a function of obstacle height (cm) with respect to LOS path

1. Compare the theoretical path loss to the actual path loss you actually obtained (similar to the plane-earth experiment). Comment on differences and possible reasons for discrepancies.

Calculating the Fresnel-Kirchoff coefficient using:

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

where λ = 33 cm theoretically.

Using the Fresnel-Kirchoff coefficient, we can find the theoretical diffraction gain using the Lee approximation for the following ranges:

$$g_{diff}(\mathrm{dB}) = \begin{cases} 0 & v \le -1 \\ 20\log(0.5 - 0.62v) & -1 \le v \le 0 \\ 20\log(0.5\exp(-0.95v)) & 0 \le v \le 1 \\ 20\log(0.4 - \sqrt{0.1184 - (0.38 - 0.1v)^2} & 1 \le v \le 2.4 \\ 20\log\left(\frac{0.225}{v}\right) & v > 2.4 \end{cases}$$

To find the experimental diffraction gain, we use the non-obstructed setup as a reference where S_{21} = -29 dB.

Table 4: Comparison table for theoretical path loss using Lee approximation versus actual path loss using experimental diffraction gain in dB with respect to various obstacle heights

Height (cm)	Fresnel-Kirchoff coefficient, v	Theoretical Lee Approximation for Diffraction Gain g_d	Experimental Diffraction Gain (dB)
No obstruction (-Infinity)	v << -1	0	0
-6.5	-0.183	-4.24	-2.6
-5.5	-0.155	-4.5	-4
0.5	0.014	-6.14	-3
5.5	0.155	-7.3	-4.2
10.5	0.296	-8.46	-5.3
15.5	0.436	-9.62	-7
20.5	0.577	-10.78	-8.9
25.5	0.718	-11.94	-11.6
30.5	0.858	-13.1	-12.1
35.5	0.999	-14.27	-9.1
40.5	1.14	-14.81	-13.6

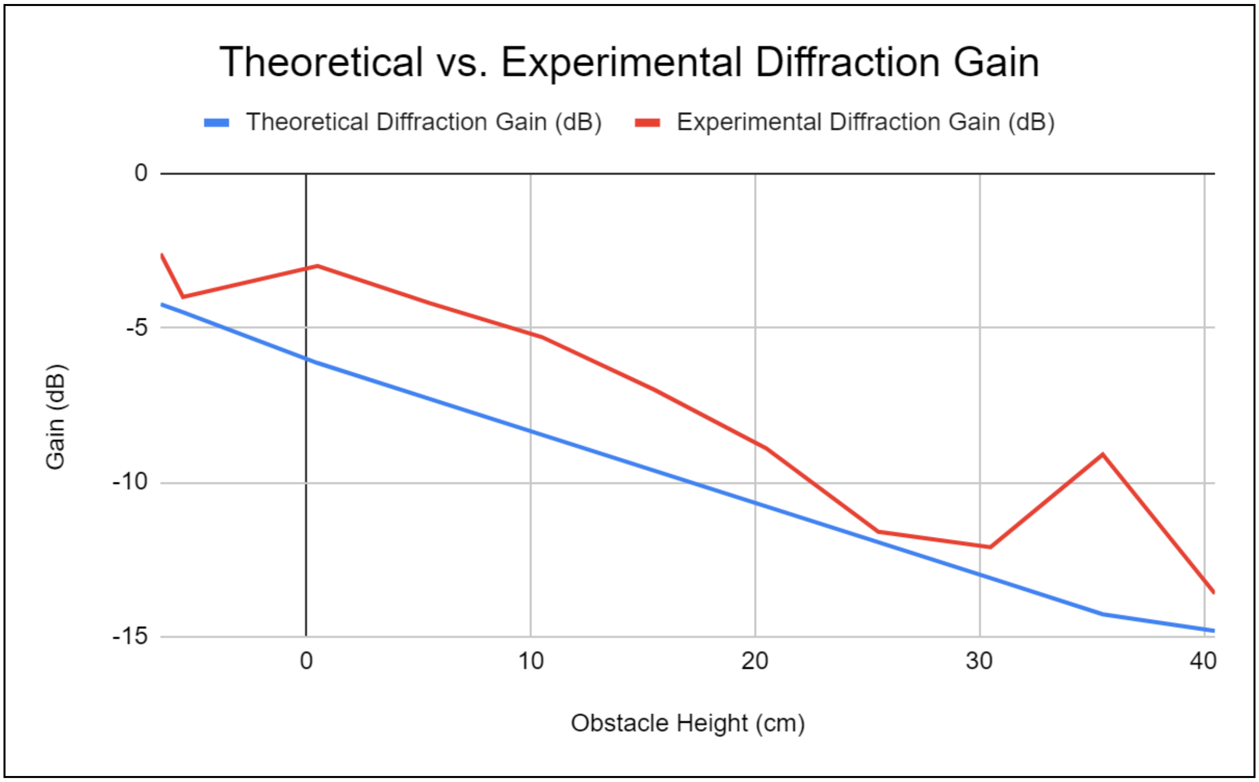

Figure 6: Theoretical path loss using Lee approximation plotted against actual path loss using experimental diffraction gain in dB with respect to various obstacle heights

Comparing the theoretical path loss to the actual path loss presented in Table 4, we observe that they are quite consistent with each other. From *Figure 6,* we can clearly observe that the experimental values are higher than the theoretical values estimated using the Lee approximation.

A potential cause for discrepancies could be experimental setup and measurement errors. The setup is necessarily a scaled-down version of a real life transmission scenario, so the geometry of our problem is exaggerated and the ratio between the distance between the antennas and the obstacles relative to their height is non-negligible. We should keep in mind the Lee approximation merely an estimation and not a perfect model, which may not capture all aspects of diffraction accurately especially in very close distances to the obstacle's edges.

2. The finite width of the screen is obviously a problem when comparing to theoretical calculations which assume an infinitely wide screen. Explain how using an array as we have done relaxes this constraint.

Using the array relaxes this constraint because the beam is primarily formed in the H-plane, towards the screen. Using multiple elements increases the directivity of the array and reduces the amount of power that will be outside the finite width of the screen.

3. Explain if, based on your measurements, that the rule of thumb that "diffraction can be neglected provided the first Fresnel Zone is not blocked", was valid based on your measurements.

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

$$F_1 = \sqrt{\frac{(1)(0.34)(1.53)(1.53)}{3.06}} = 0.51\, m$$

The radius of the first Fresnel zone is calculated to be 51 cm. Since it is recommended to leave 60% of the first Fresnel zone clear in general, the diffraction can be neglected when h = $0.6F_1$ = 30.6 cm.

From Table 4, we can observe that both theoretical and experimental gains are 0 dB with respect to the measured S21 value of -29 dB when no obstacle was present in Table 3. From Table 4, we can observe that at negative clearance heights -6.5 cm and -5.5 cm, the diffraction losses were measured to be -2.6 dB and -4 dB respectively, which are nearly small enough to be neglected. As the height is increased, we start to observe more significant losses. At h = 25.5 cm, we observe a loss of -11.6 dB which is greater than -10 dB. This aligns with our expectation that diffraction loss is negligible until around 30.6 cm.

Therefore, we can conclude that the rule of thumb that "diffraction can be neglected provided the first Fresnel Zone is not blocked" is valid based on our measurements.

4. Explain why we can ignore the effects of plane-earth reflection effects in most diffraction scenarios.

In most diffraction scenarios we ignore the effects of plane-earth reflection due to the fact that the diffracted ray incident from the ground or image plane is often occluded owing to the angle of incidence by which it approaches the receiver relative to the obstacle. Thus, the majority of the power that becomes diffracted and then reaches the receiver belongs to the LOS path.