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MEASUREMENT OF ANTENNA GAIN WITH TRANSMITTING AND RECEIVING  
ANTENNAS ON A FINITE GROUND PLANE

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## 1.0 Introduction

The gain of an antenna is usually measured by placing a transmitting antenna in the far field of the antenna under test (AUT) and then comparing the power received by that antenna with that received by a reference antenna (RA), the gain of which has been calibrated, as is shown in Figure 1a. Rather than having a separate power source for the transmitter, it is convenient to utilize the two ports of a Hewlett-Packard 8510C Network Analyzer for the gain measurement, one for transmit, the other for receive, as is shown in Figure 1b. There are however some obstacles that arise when using this conventional approach, particularly if the AUT has low gain. The power transmitted by the HP8510C is only of the order of tenths of a watt. For our original experiment the transmitting antenna was about 30 feet from the receiver; in addition to the  $1/r^2$  loss for this distance, there is also the loss in the coaxial cables between the HP 8510C and the transmitter. The net result is that the received signal may be less than -45 dBm. We recently conducted an experiment in which we measured the gain of an electrically small antenna when the antenna was immersed in dielectric powders having different dielectric constants. [1]. The dielectric powder, for some cases, reduced the gain by an additional 8 dB so the received signal was lower than -50 dBm. Since the resonant frequency of the antenna also decreases as the dielectric constant increases, the transmitting and reference antennas have to also operate over a wide frequency band. The transmitting antenna that was originally used for this experiment was a broadband ridge horn shown in Figure 1c. It is a rather large antenna having a height and width of approximately 0.75 meter x 1 meter and barely covers the frequency band of interest.

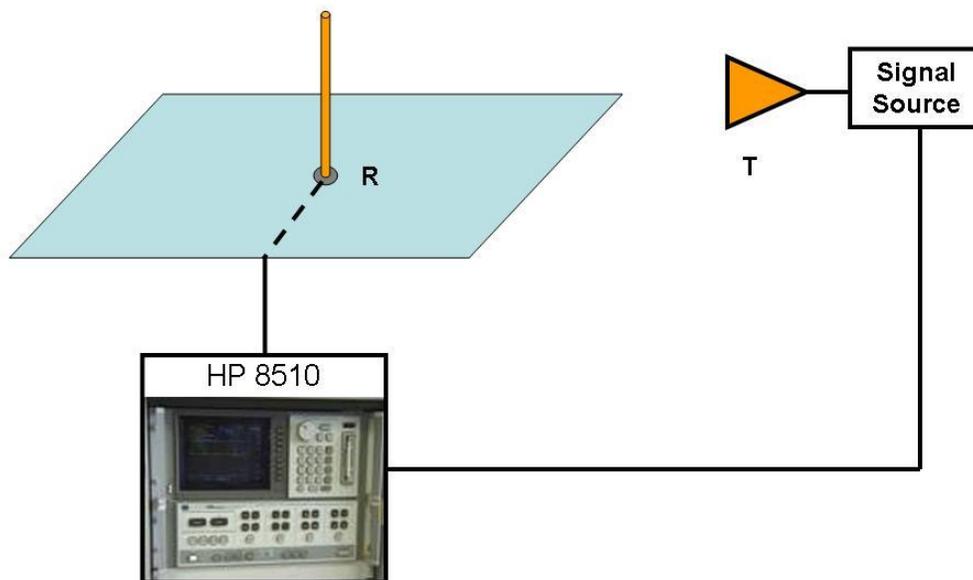
In order to overcome the above limitations we investigated an approach where the horn transmitting antenna is replaced by a resonant monopole which is mounted on the same ground plane as the AUT and RA, which is also a resonant monopole, as is shown in Figure 1d. The resonant frequency of each monopole can be easily changed by using a telescoping arrangement where a sliding rod is inserted in the monopole tube to adjust its height; thus it is very easy to make measurements at spot frequencies over a wide frequency band. Since the antennas are relatively close together, the power received by the AUT is high enough so that the transmit signal is significantly higher than for the conventional setup.

The edge reflections of the finite ground plane affect the gain measurement; however, if the AUT and RA are placed at the same exact location, the edge effects are assumed to be the same for both. If this is the case then why do we have to conduct this analysis? We thought that it would be important to investigate the magnitude and phase of the edge effects as a function of frequency and antenna separation.

We review the theory and then present simulations and measurements when both transmitting and receiving antennas are mounted on a 4-ft x 4-ft (1.22 m x 1.22 m) ground plane for the frequency range from 200 MHz to 1000 MHz. The resonant monopoles are spaced 30, 40, 50, 60 and 70 cm apart and the simulations are conducted using Ansoft's HFSS code. Finally, we compare experimental results for a 7-wire genetic antenna that was measured using a conventional gain approach with those that are obtained using the new method.



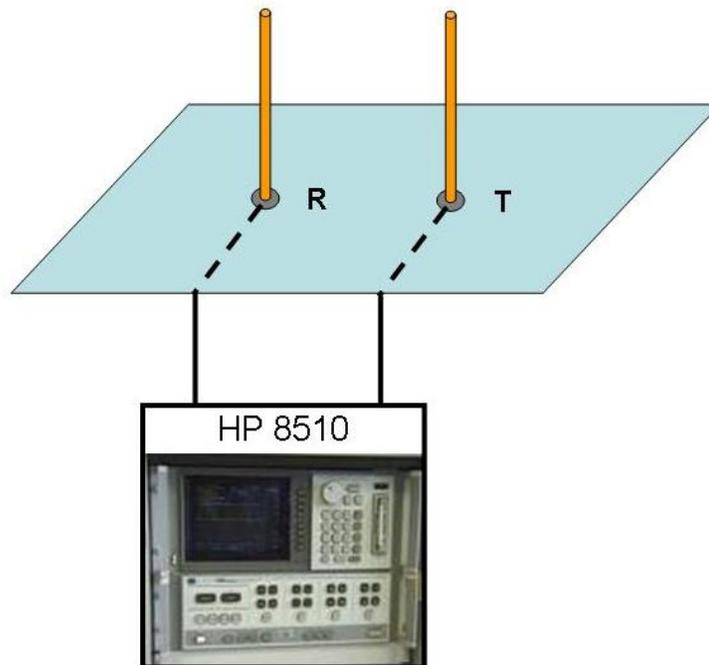
**Figure 1a: Conventional gain measurement**



**Figure 1b: Gain measurement using HP 8510 network analyzer. The 8510C network analyzer is used in conjunction with the 8517C S-parameter test set and the 83651A synthesized sweeper.**



**Figure 1c: Broadband ridge horn for transmitting**

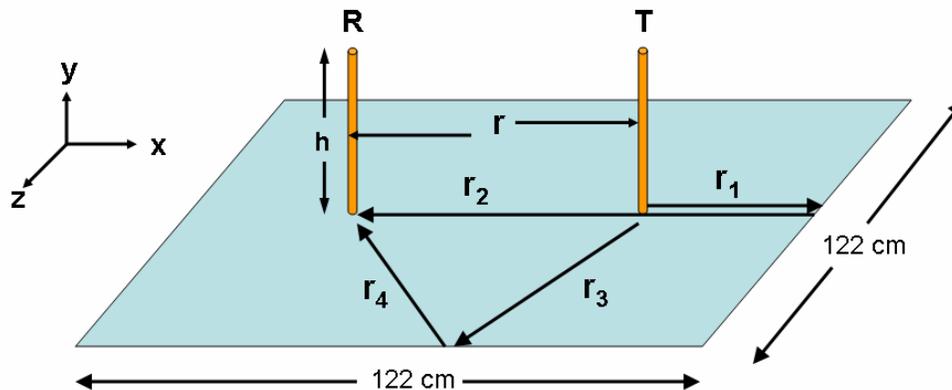


**Figure 1d: Transmit and receive antennas on same ground plane**

## 2.0 Approach

### 2.1 Theory

The edges of the ground plane produce reflections that affect both the input impedance and radiation pattern of the antennas. The effect on the input impedance for these separations is minimal. However the effect on the radiation pattern and gain can be significant; we will address the gain fluctuations produced by the edges. The monopole separations  $r$  were varied from 30 cm to 70 cm in 10 cm increments as is shown in Figure 2. The distance  $r_1$  from each monopole to its front or back edge ranged from 46 cm for a 30 cm separation to 26 cm for a 70 cm separation. The distance to the side edges, for the same separations, ranged from about 63 cm to 70 cm. The far field of two monopoles having a height of  $1/4\lambda$  is conservatively  $2r^2/\lambda$ . If we assume that the height of the monopole over a ground plane is equivalent to that of a dipole in free space, then  $r = 1/2\lambda$ , so the far field is about  $1/2\lambda$ . For the lowest frequency of 200 MHz, the electrical separation ranges from  $0.2\lambda$  at the closest separation of 30 cm to  $0.47\lambda$  for the furthest separation of 70 cm. Also for 200 MHz, the electrical distance of the monopole from the front or back edges is about  $0.31\lambda$  for a 30 cm separation and  $0.17\lambda$  for a 70 cm separation. For the side edges, the electrical distance,  $r_3$  or  $r_4$ , ranges from  $0.42\lambda$  to  $0.47\lambda$  for monopole separations of 30 cm and 70 cm respectively. Thus, it is for the longest wavelengths that the far field criterion becomes marginal.



**Figure 2: Geometry of transmit and receive antennas on same ground plane**

If the antennas are mounted over an infinite ground plane, the received power has a  $1/kr^2$  dependence. It is highest for the closest separation and decreases for increasing frequency. For the finite ground plane, the main reflections are from the centers of the front, back and side edges. These undergo a single reflection whereas all other rays undergo multiple reflections and are thus weaker. Using the Geometric Theory of Diffraction, we examine the amplitude and phase of the signals that have a single reflection off of the front, back and side

edges to the receiving antenna and compare this signal with that which would be received for the monopoles on an infinite ground plane.

## *2.2 Computations*

The computations were conducted primarily with Ansoft Corporation's HFSS 3D Electromagnetic Field Simulation, with Ansoft's Optimetrics software utilized for parameter sweeps. The main reason for using HFSS rather than the Numerical Electromagnetics Code (NEC) is that our future measurements will be made with an electrically small antenna immersed in a dielectric over a finite ground plane. Since NEC cannot be used to simulate an antenna in a finite dielectric, we used HFSS. Two copper resonant monopoles having a diameter of 1/16 inch (1.6 mm) were spaced at separations ranging from 30 cm to 70 cm while centered on the 1.22 x 1.22 meter perfectly electrical conducting (PEC) ground plane. The entire structure was enclosed in a radiation boundary air box. Each monopole was modeled with a 50  $\Omega$  lumped source at its base and the scattering matrix parameters between these two ports were computed. Simulations were performed at frequencies ranging from 200 MHz to 1000 MHz, with the monopoles set to resonance with a height slightly less than  $1/4 \lambda$  for each frequency. The Optimetrics code was used to parameter sweep the monopole separations. The resulting  $S$  parameters were exported into Matlab for comparisons and plotting. The monopoles were simulated at all of the aforementioned frequencies and separations.

## *2.3 Measurements*

The measurements were made with a Hewlett Packard 8510C Network Analyzer used in conjunction with an HP 8517B S-Parameter Test Set and a HP83651A 8360 Series Synthesized Sweeper for the same frequency range and monopole separations which were used for the theory and simulations. Since the measurements were made in an anechoic chamber, the effects of the surrounding environment were minimal. The 1.22 x 1.22 meter ground plane was mounted atop the HP8510C cabinet; thus the cables from the input and output ports to the antennas were very short. The transmitting and receiving monopoles were made of 3/32 inch (0.24 cm) diameter copper tubing with a 1/16 inch (0.16 cm) copper tubing insert. In this way the height of the monopole could be easily adjusted for resonance over the entire frequency band. The input VSWR for a resonant monopole driven from a 50  $\Omega$  coaxial line is typically less than 1.5 so the corresponding mismatch loss is less than 0.1 dB. The power received by monopole #2 from the transmitting monopole #1 was inferred from the transmission coefficient,  $S_{21}$ .

### 3.0 Results

#### 3.1. Theory

In Figure 2 we show a sketch of the two monopoles separated by the distance  $r$  mounted on the finite ground plane, along with the Cartesian coordinate system that was used in this analysis. Let us first consider the direct radiated field from the transmitting monopole #1 to the receiving monopole #2. The positions of the monopoles are symmetric about the center of the ground plane. The E-field travels a distance  $r$  along the ground plane from monopole #1 to #2. The next strongest fields will undergo a single reflection. These are a pair of fields, one which is reflected off the back edge of the ground plane and then to monopole #2 and the other that is reflected off the front edge and back to monopole #2. These fields each travel a distance of 122 cm. There is another pair of fields that reflect off of the center of each of the side edges. These travel a distance of  $2[(r/2)^2 + 61^2]^{1/2}$ . There will also be fields with multiple reflections from both the front, back and side edges of the ground plane; these will be weaker and are not included in this analysis. All of these reflected fields will interfere with the direct field both constructively and destructively. The power received by monopole #2 should have a quasi-sinusoidal variation superimposed on the power that would be received by monopole #2 if the monopoles were on an infinite ground plane.

The following analysis was taken from Ishimaru [2, pp. 402-403]. Referring to Figure 2, the E-field traveling along the ground plane from monopole #1 to monopole #2 is

$$E_y = \frac{E_0 e^{-jkr}}{kr} \quad (1)$$

where  $E_0$  is a normalization coefficient and  $k$  is the wave number.

The  $H_z$ -field from monopole #1 that is diffracted from the back edge to monopole #2 or from the front edge to monopole #2 is from Equations (13-59) and (13-60)

$$H_z^{fb} = \frac{E_0}{2} \frac{e^{-jkr_1}}{kr_1} D \left[ \frac{r_1}{r_2(r_1 + r_2)} \right]^{\frac{1}{2}} e^{-jkr_2} \quad (2)$$

with  $E_y^{fb} \propto -H_z^{fb}$

The diffracted field is based on the incident field and since the grazing incident field can be shown to be  $\frac{1}{2}$  of the total field,  $E_0$ , excited along the ground plane by the monopole, a factor of  $\frac{1}{2}$  multiplies  $E_0$  in equations (2) and (6), [3, pp. 811-813].

The diffraction coefficient  $D$  is given by

$$D(\theta_s, \theta_i) = -\frac{e^{-j(\pi/4)}}{2(2\pi k)^{1/2} \sin \beta_0} \left\{ \frac{1}{\cos \left[ \frac{(\theta_s - \theta_i)}{2} \right]} + \frac{1}{\cos \left[ \frac{(\theta_s + \theta_i)}{2} \right]} \right\} \quad (3)$$

For the front and back diffracted fields,  $\theta_i = \theta_s = 0$  and  $\sin \beta_0 = 1$ .

Therefore 
$$D = -\frac{e^{-j(\pi/4)}}{(2\pi k)^{1/2}} \quad (4)$$

and

$$E_y^{fb} = \frac{E_0}{2} \frac{e^{-jk r_1}}{k r_1} \frac{e^{-j(\pi/4)}}{(2\pi k)^{1/2}} \left[ \frac{r_1}{r_2(r_1 + r_2)} \right]^{\frac{1}{2}} e^{-jkr_2} \quad (5)$$

Likewise, the  $H_z^s$  - field diffracted from the side edges is

$$H_z^s = \frac{E_0}{2} \frac{e^{-jk r_3}}{k r_3} D \left[ \frac{r_3}{r_3(r_3 + r_4)} \right]^{\frac{1}{2}} e^{-jkr_4} \quad (6)$$

For the diffracted fields off the sides,  $\theta_i = \theta_s = 0$  and  $\sin \beta_0 = \frac{61}{\left[ (r/2)^2 + 61^2 \right]^{\frac{1}{2}}}$ .

Therefore

$$D = -\frac{e^{-j(\pi/4)}}{\left[ 2\pi k \right]^{\frac{1}{2}} \frac{61}{\left[ (r/2)^2 + 61^2 \right]^{\frac{1}{2}}}} \quad (7)$$

and

$$E_y^{fb} = \frac{E_0}{2} \frac{e^{-jk r_3}}{k r_3} \frac{e^{-j(\pi/4)}}{(2\pi k)^{1/2}} \frac{61}{\left[ (r/2)^2 + 61^2 \right]^{\frac{1}{2}}} \left[ \frac{r_3}{r_3(r_3 + r_4)} \right]^{\frac{1}{2}} e^{-jkr_4} \quad (8)$$

These fields were then normalized to the transmitted power from the Hewlett – Packard Model 8510C Network Analyzer to monopole #1, which was 0.16 watts, so that the theoretical, computational and experimental results could be compared. In Figures 3a-3e, it is seen that the theoretical received power undergoes the periodic behavior that should be produced by reflections from the edges. The differences between the received powers for the finite and infinite ground planes are seen to increase as the separation is increased and decrease slightly as the frequency is increased. The average deviation of these differences, for each of these plots, are shown in Table 1. We see that the difference is lowest for the smallest separation and then slightly higher for the larger separations. It should be mentioned that near field effects are not taken into account in this analysis.

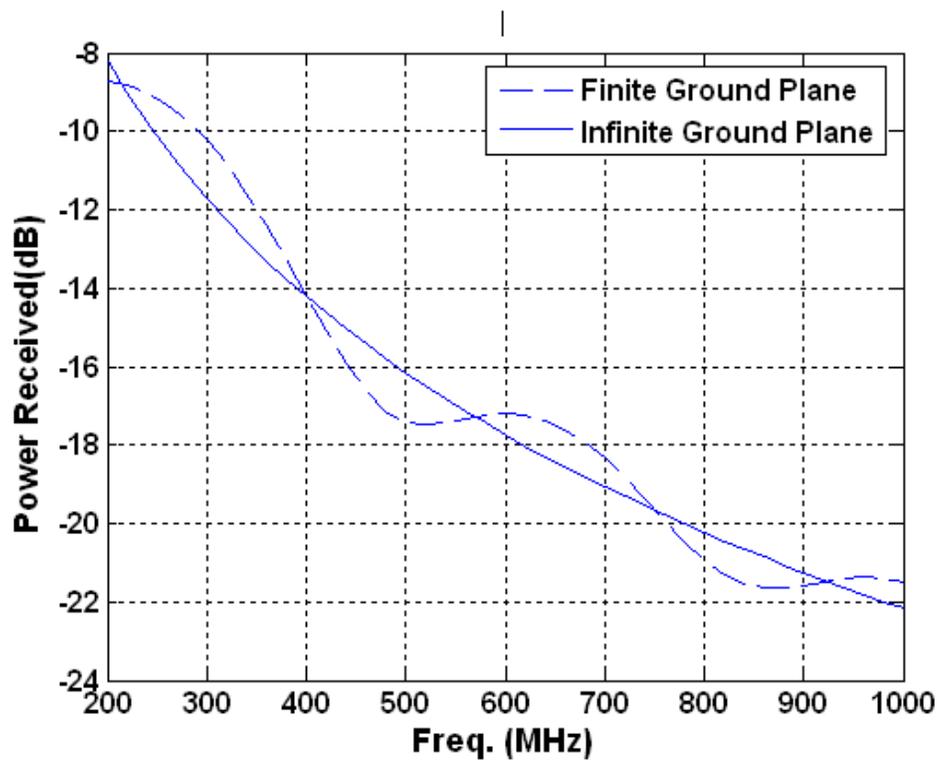


Figure 3a: Theoretical received power for finite and infinite ground planes,  $r = 30\text{cm}$

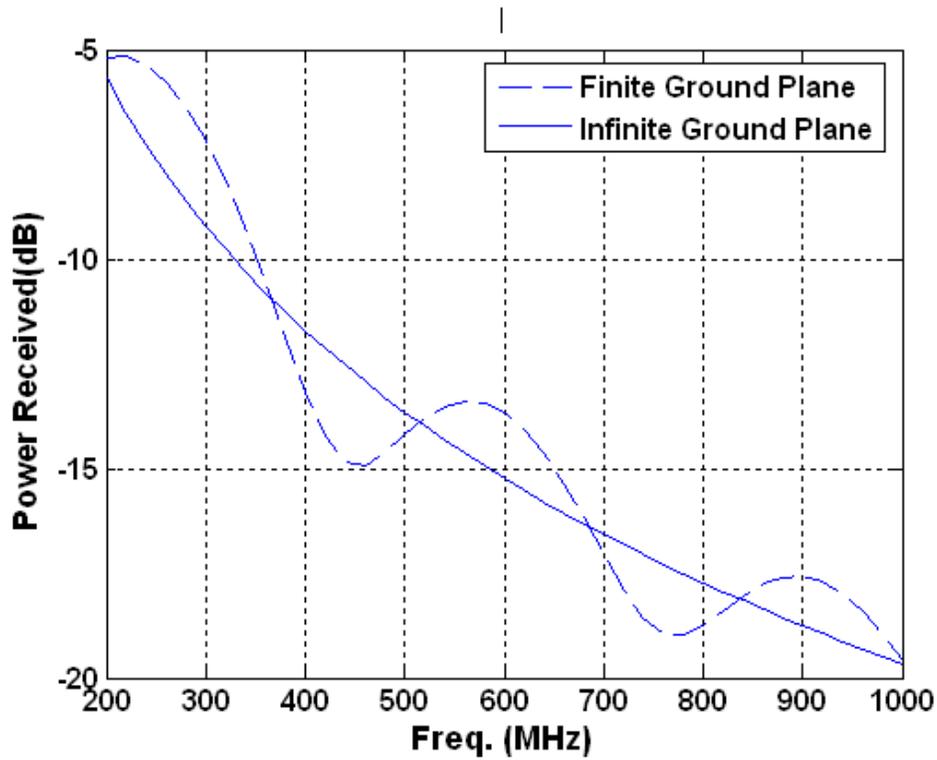


Figure 3b: Theoretical received power for finite and infinite ground planes,  $r = 40\text{cm}$

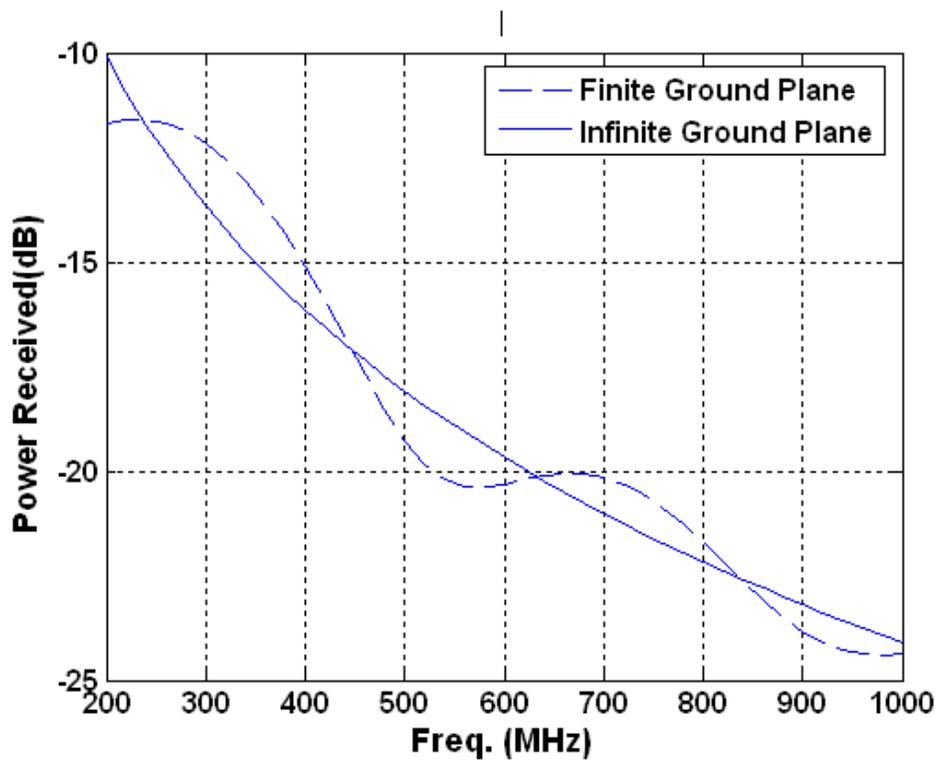


Figure 3c: Theoretical received power for finite and infinite ground planes,  $r = 50\text{cm}$

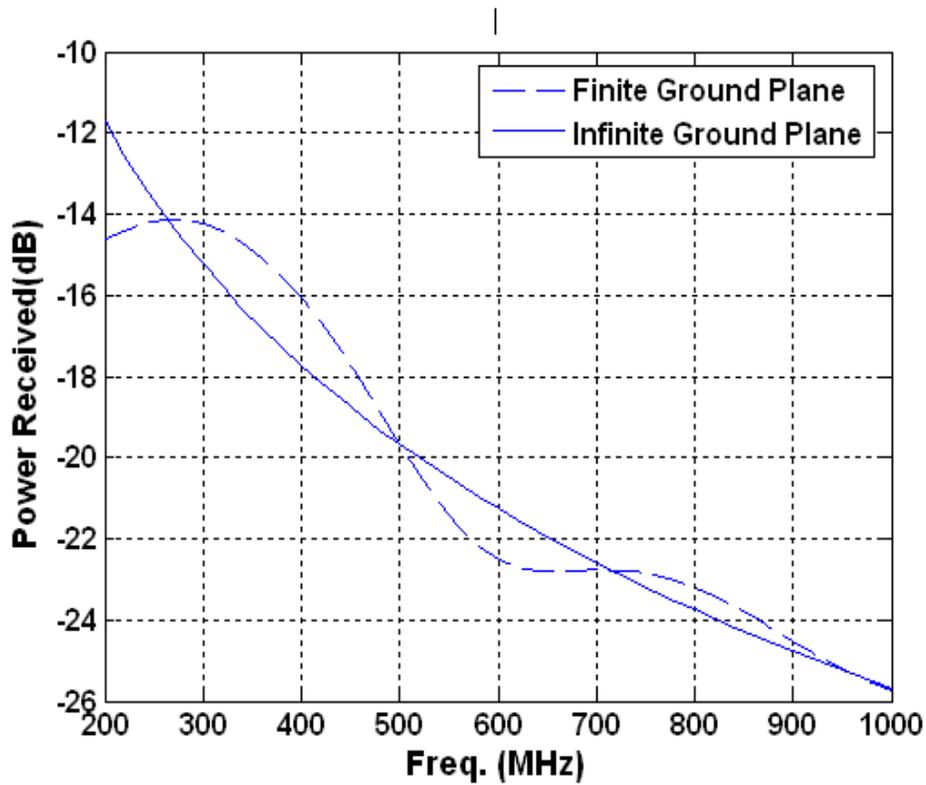


Figure 3d: Theoretical received power for finite and infinite ground planes,  $r = 60\text{cm}$

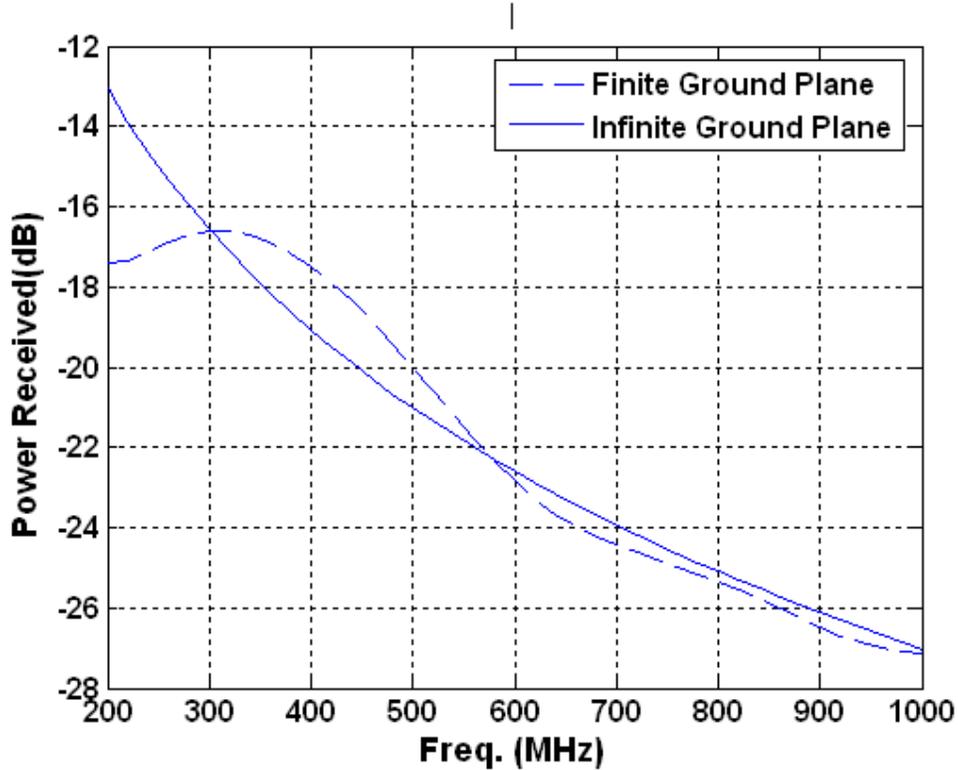


Figure 3e: Theoretical received power for finite and infinite ground planes,  $r = 70\text{cm}$

### 3.2 Computations

In Figures 4a–4e, we plot the computed power received from monopole #1 by monopole #2 along with the power calculated from theory. We note that these results have good agreement over most of the frequency range but that the agreement is poorer at the low frequencies. This is likely due to the fact that near field effects are taken into account in the simulation, but not in the theoretical analysis. The average deviation of the difference between theory and simulation is shown in Table 1 and we note the highest value occurs for the closest separation.

### 3.3 Measurements

The power that is transmitted from port #1 of the HP8510C to the transmitting monopole is 0.16 watts. As mentioned previously, the theoretical and simulated powers were then normalized to this power. In Figures 4a-4e we show the measured received power along with the theoretical and simulated powers. We note that over most of the frequency range the agreement is good. Once again the average deviations for the differences of the measurements and theory and measurements and simulations are shown in Table 1. We note that the average deviations are generally lower for the larger separations. Upon examining the actual data, we found that it was at the lowest frequencies at which the differences were greatest. This is likely due to the fact that the antennas are in the near field for these frequencies.

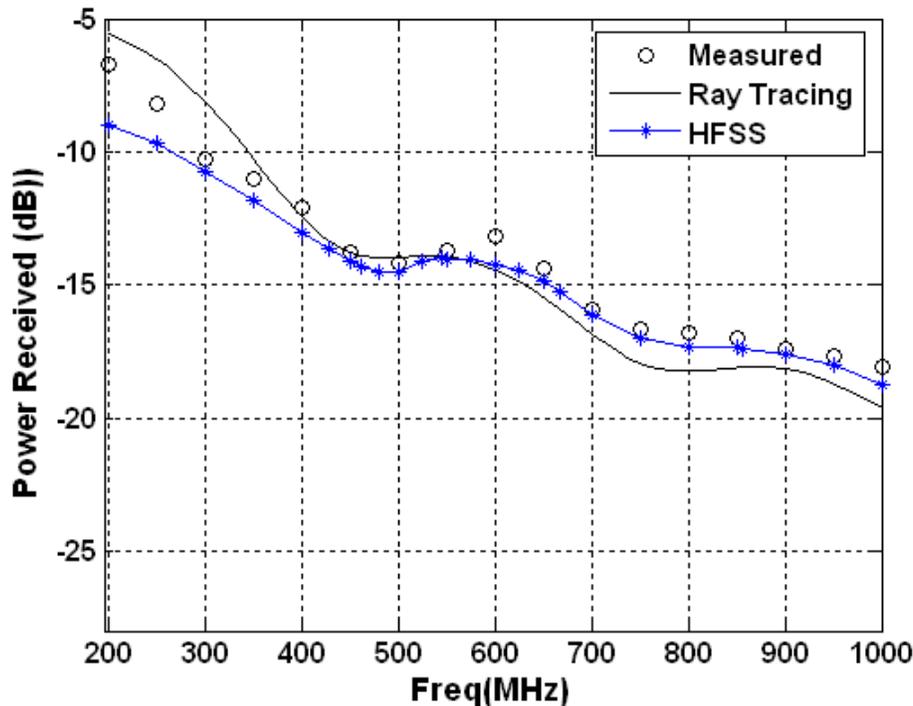


Figure 4a: Theoretical, computational and measured power received for  $r = 30$  cm

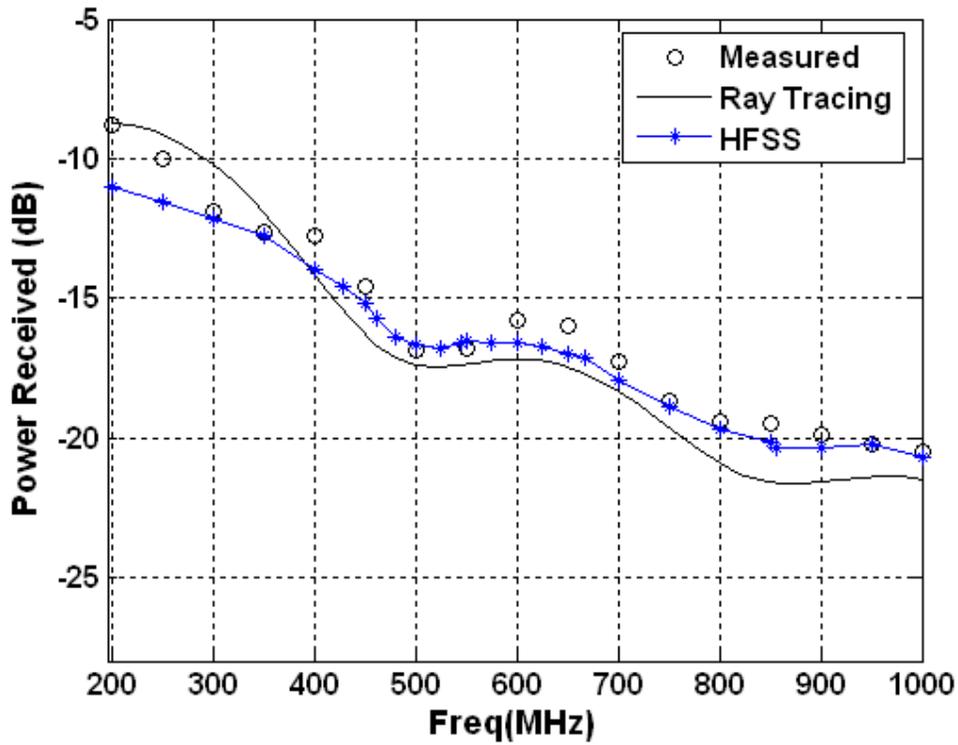


Figure 4b: Theoretical, computational and measured power received for r = 40 cm

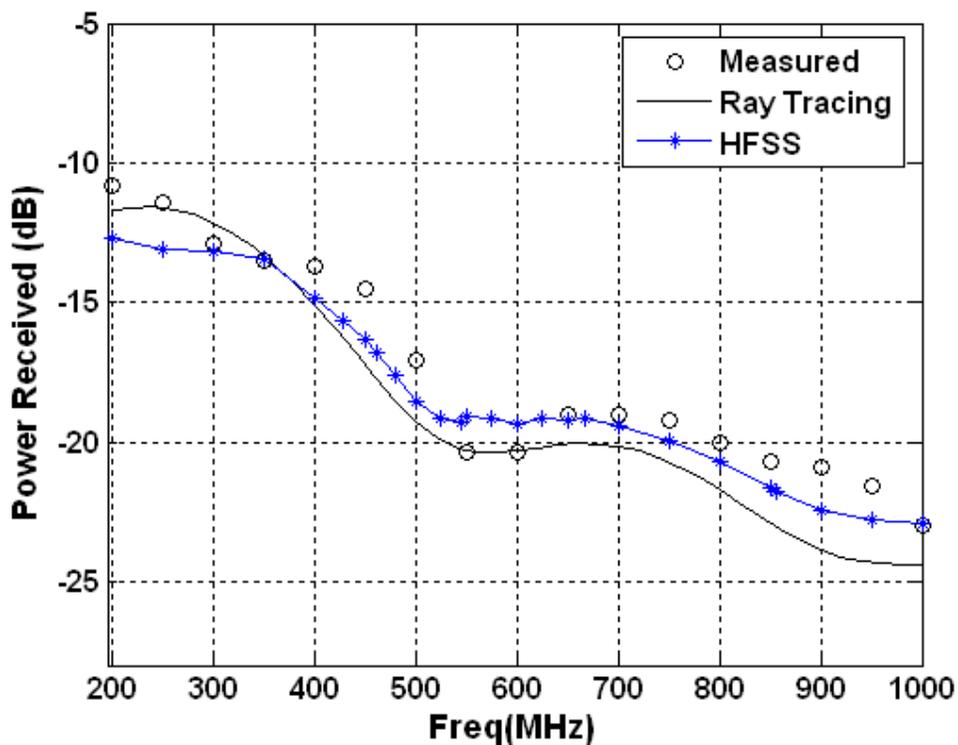


Figure 4c: Theoretical, computational and measured power received for r = 50 cm

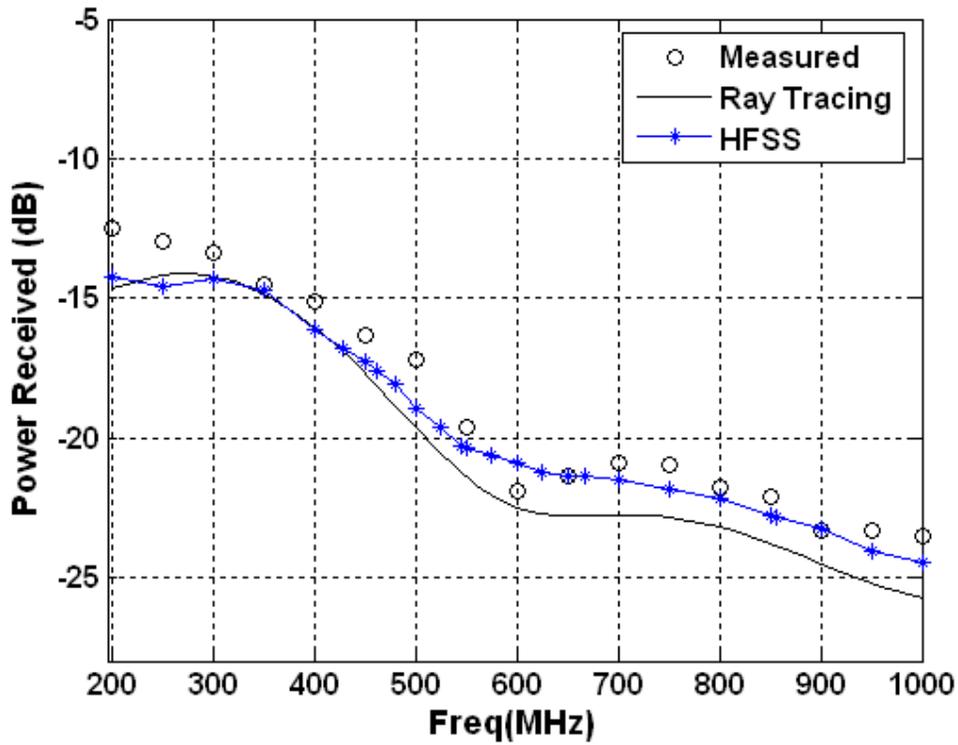


Figure 4d: Theoretical, computational and measured power received for r = 60 cm

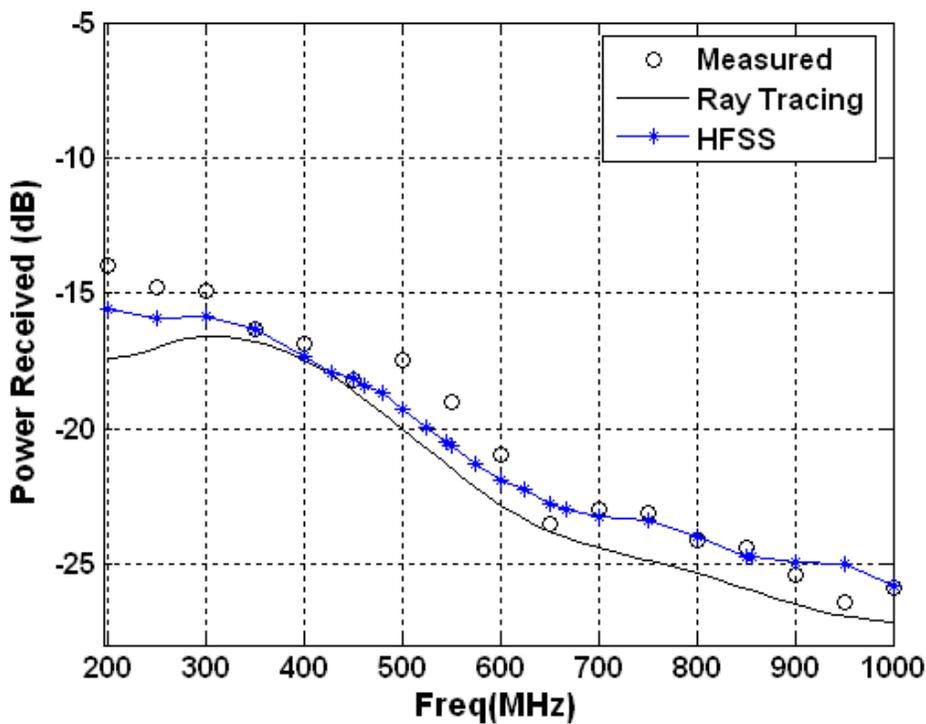
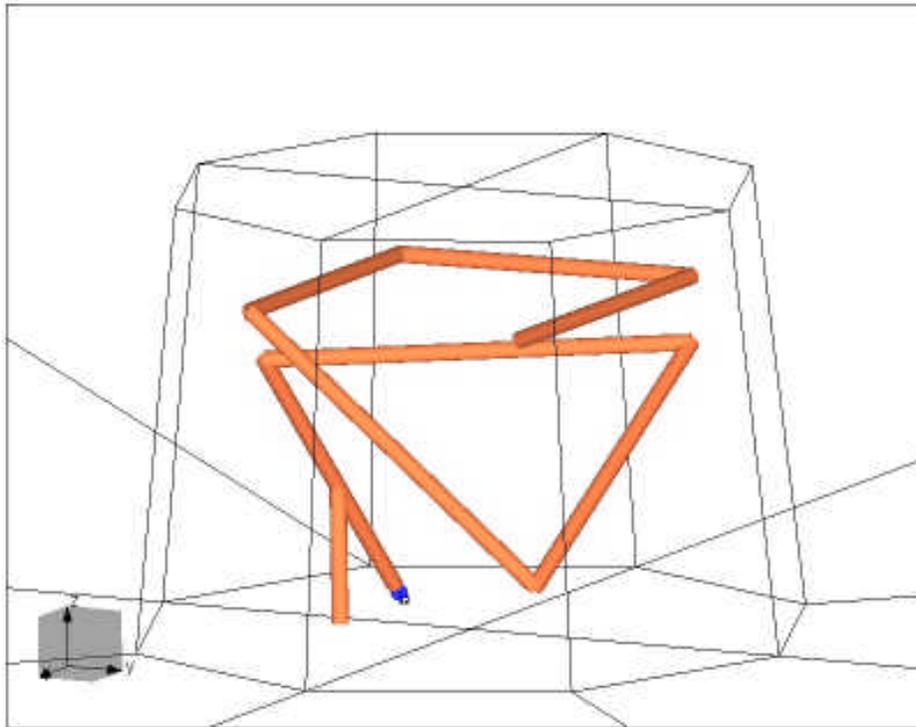


Figure 4e: Theoretical, computational and measured power received for r = 70 cm

Finally, we measured the gain of the electrically small 7-wire genetic antenna shown in Figure 5 using the new approach, and compared it with the gain of the same antenna that had been previously measured using the ridge horn antenna as a transmitter. With the ridge horn the received signal was about -45 dBm; with the monopole as a transmitter and on the same ground plane as the AUT and RA, the received signal was about -22 dBm, over 20 dB higher. More important, when the signal was -45 dBm, the fluctuations as a function of time were of the order of +/- 0.4 dB whereas they were only about +/- 0.2 dB when the signal was -22 dBm. The variability of the received signal for the reference monopole was about the same as for the AUT. Therefore the uncertainty of the gain measurement for the old approach was nearly 1.0 dB, whereas the uncertainty of the gain was less than 0.5 dB.

**Table 1: Average deviation of theory, simulations and measurements (dB)**

Separation ( cm )	30	40	50	60	70
Theory (Finite/Infinite)	0.55	0.70	0.80	0.77	0.79
Theory/Simulation	1.13	0.70	0.70	0.50	0.42
Theory/Measurements	0.92	0.80	0.90	0.50	0.71
Simulation/Measurements	1.28	0.45	0.70	0.48	0.65



**Figure 5: Electrically small 7-wire genetic antenna**

## 4.0 Conclusions

We have presented the theory, simulations and measurements of the power received by a monopole from a transmitting monopole when both are on a finite ground plane. Using the Geometrical Theory of Diffraction we examined the diffraction from the edges of the ground plane for five monopole separations. We showed that if we only consider the primary reflections from the center of the front, back and side edges of the ground plane, the theory, simulations and measurements almost always agree to within 1.0 dB. as is shown by the average deviation of the results shown in Table 1. The obstacles that arise when trying to measure the gain of a small antenna, immersed in a dielectric, and over a wide frequency band are removed when the HP 8510C Network Analyzer is used for transmitting and receiving and the large broadband ridge horn transmitter is replaced by a monopole antenna which is placed on the same ground plane as the antenna under test and reference monopole. We further show that the maximum edge effect is of the order of less than +/- 1.0 dB and that it is probably best to use a separation of at least 40 cm. between the transmit antenna and the AUT. Finally, we show that the fluctuations of the received signal are only about  $\frac{1}{2}$  as large for the new approach as they were from the old approach.

## References

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## List of Symbols, Abbreviations, and Acronyms

AUT	antenna under test
RA	a reference antenna