ARMY RESEARCH LABORATORY

Path-Loss Measurements in a Forested Environment at VHF

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Abstract

Designing a radar system capable of detecting objects concealed by foliage requires path-loss data and the development of path-loss prediction models. The challenge is to design a system with antenna elements of manageable size, while keeping foliage signal attenuation as small as possible. We took a series of measurements to characterize path loss in a mostly deciduous forest. Results show that the parameter values that give the least attenuation because of the intervening woods are the lowest frequencies and transmit horizontal, receive horizontal polarization (HH).

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1. Introduction

Quantitative knowledge of path loss due to foliage is essential for designing a radar system that can detect objects located in or near wooded areas, and for developing and validating path-loss prediction models. The Army Research Laboratory (ARL) is engaged in a research and development effort to design and demonstrate the feasibility of a phased-array system that could detect personnel and vehicles in woods. The frequency would require the antenna elements to be of manageable size, yet still provide optimum system performance by keeping foliage signal attenuation as small as possible.

We conducted a literature search that revealed that few data sets have been collected for the frequency range and antenna heights and distances of interest. The sparse data we found suggest that foliage attenuation increases with frequency [1–5]. This indicates that to ensure a high signal-to-noise ratio (SNR), the frequency of a system should be as low as practical. Yet, this might mean a physical antenna size impractical for a fielded system. Therefore, design trade-offs between attenuation and frequency, as well as polarization, will be required.

The dearth of path-loss data at the frequencies, polarizations, and antenna heights of interest prompted this investigation. ARL conducted a series of measurements in two phases to characterize the propagation path loss in a mostly deciduous forest. We were particularly interested in determining the attenuation due to the trees and vegetation along the propagation path as a function of transmission frequency, polarization, transmit and receive antenna heights, and range.

Measurements were taken in phases. Phase I measurements were taken from January to March and again in May 1999. Phase II measurements were made in September 1999, mainly to determine the attenuation due to 4700 m of trees and to add the 435-MHz measurements. Since the trees in this study are almost all deciduous, we took measurements both when the trees were bare and in full leaf. We compared the results to determine if leaf mass contributes significantly to path loss.

2. Methodology

Our objective was to determine how transmit and receive antenna height, polarization, frequency, and proximity to a tree line affect the propagation loss through a wooded area. To do this, we developed a test plan with several sets of experiments, listed in table 1.

2.1 Propagation Measurements

Propagation measurements determine the propagation loss for path lengths from 410 to 4700 m. The variables in our experiment were transmit and receiver antenna height, frequency, range, and polarization. Table 1 shows the frequencies used. We used transmitter heights of 7.6, 14, and 22 m. We chose these heights to get positions at approximately half the tree height, the tree height, and above the trees to determine the effect on propagation loss. We used receiver heights of 1, 2, 2.7, 3.6, and 5 m to simulate the height of personnel and vehicles. Our choice of frequency ranges was based on the penetration of forested areas demonstrated by these frequencies in the literature [1–5]. The specific frequencies chosen were based on the permission to use them in our test area. We made the propagation measurements at ranges of 410, 1000, 1930, and 4700 m. We chose only four ranges to give us enough data to extrapolate to other ranges while keeping to a manageable number of measurements. We chose the ranges based on access to specific positions in the woods. To study the polarization effects, we measured all linear polarizations: HH (transmit horizontal, receive horizontal), HV (transmit horizontal, receive vertical), VV (transmit vertical, receive vertical), and VH (transmit vertical, receive horizontal). We included propagation measurements in a relatively flat clearing and used these as a baseline to compare with theory as well as with the woods measurements. To determine the difference in propagation loss of a deciduous forest with and without foliage, we made measurements both in summer and winter. Tables 2 and 3 show the propagation measurements completed in phases I and II, respectively.

2.2 Multipath Measurements

We made multipath measurements to provide confidence in the data and to get an idea of how well our measurements of the clearing represented an ideal flat earth. We measured the path loss at a range of 410 m with the

Table 1. Measurement matrix.

Measurement	Location	Frequencies (MHz)	Season
Propagation	Clearing	145, 223, 910	Winter
Propagation	Wooded	145, 223, 910	Winter
Propagation	Wooded	145, 223, 300, 435, 910	Summer
Multipath	Clearing/wooded	145, 223, 300, 910	Summer
Tree-line proximity	Wooded	145, 223, 910	Winter
Tree-line proximity	Wooded	145, 223, 300, 435, 910	Summer
Statistical	Wooded	145, 223, 300, 910	Summer

Table 2. Phase I propagation measurements (all polarizations).

Frequency (MHz)	Transmit height (m)	Receive height (m)	Range (m)	Clearing	Woods	Summer	Winter
145, 223, 910	7.6, 14, 22	2.7, 3.6, 5	410, 1000, 1930	X	—	—	X
145, 223, 910	7.6, 14, 22	2.7, 3.6, 5	410, 967, 983, 1000, 1930	—	X	—	X
145, 223, 300, 910	7.6, 14, 22	2, 2.7, 4	410, 967, 983, 1000, 1930	—	X	X	—

Table 3. Phase II propagation measurements (all polarizations).

Frequency (MHz)	Transmit height (m)	Receive height (m)	Range (m)	Clearing	Woods	Late summer
145, 223, 300, 435, 910	7.6, 14, 22	1, 2.7	4230	X	—	X
145, 223, 435, 910	22	1, 2.7	1000	—	X	X
145, 223, 300, 435, 910	7.6, 14	1, 2.7	1930	—	X	X
145, 223, 300, 435, 910	7.6, 14, 22	1, 2.7	4700	—	X	X

receive antenna 2.7 m above the ground, varying the transmitter height from 6 to 21 m in 1-m steps. Figure 1 depicts this setup. We also used the multipath measurements to determine the effective combined gain of the antennas on their respective mounts. We compared this gain with both the manufacturer's antenna gain specifications and gain measurements made in an anechoic chamber.

2.3 Tree-Line Proximity Measurements

Tree-line proximity measurements are propagation data we took with the receiver placed in various positions in a clearing in the woods to study the effect of the tree line on the propagating signal. We used two different geometries, which are depicted in figure 2. The phase I measurement positions shown in figure 2 were made at ranges of 1000, 983, and 967 m. At 967 m, the receive antenna is up against the tree line, and at 1000 m, the receive antenna is 33 m from the tree line. Phase II measurements are shown as a "T"-shaped geometry where we made four measurements spaced 10 m apart parallel to the tree line at a range of 967 m (top of the "T"), and six measurements 10 m apart moving away from the transmitter. The measurement farthest from the transmitter was against the back edge of the clearing.

Figure 1. Multipath measurement setup.

$$\text{Theoretical propagation, } L_p = \frac{1}{\left[\left(2 \cdot \sin\left(2 \cdot \pi \cdot H_t \cdot \frac{H_r}{\lambda \cdot R}\right)\right)^2 \cdot \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2\right]}$$

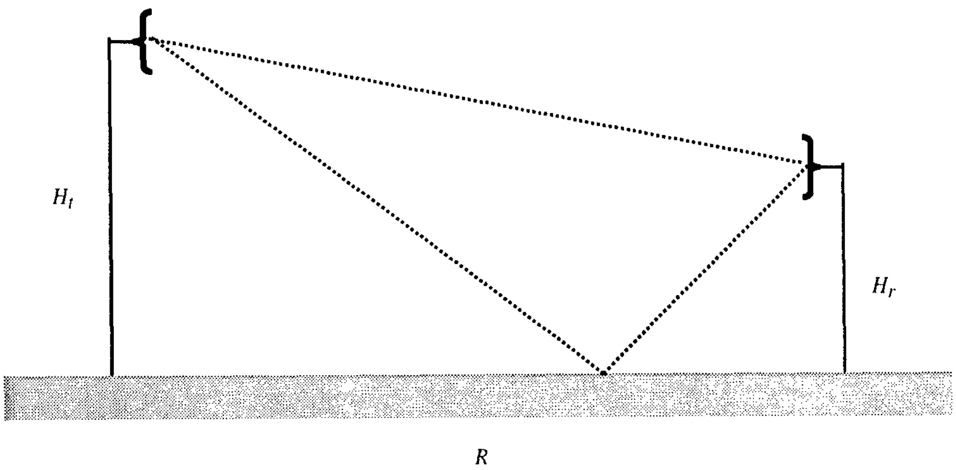
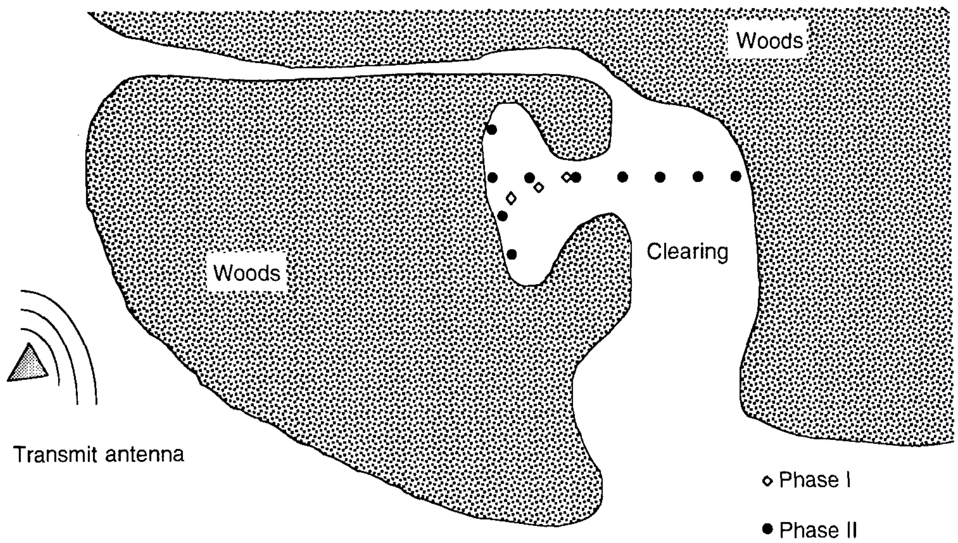


Figure 2. Tree-line proximity and statistical measurement area.



2.4 Statistical Measurements

We made 49 statistical measurements in a 7- by 7-m Cartesian grid to determine the variation that could be expected in the data in 1-m increments within this grid, which was located with its farthest side from the transmitter at 1000 m. This was the same location as the tree-line proximity measurements depicted in figure 2.

3. Experimental Setup and Measurements

We made propagation measurements of both wooded and cleared areas at Aberdeen Proving Ground, using a continuous wave (cw) transmit receive system. The maximum range measured was 4.7 km.

3.1 Instrumentation

The transmitter block diagram shown in figure 3 consists of a synthesized sweep oscillator, a 50-W amplifier, an antenna, a bidirectional coupler, and a spectrum analyzer. The bidirectional coupler and spectrum analyzer were used to monitor output power, frequency, and antenna voltage standing wave ratio (VSWR). A cw signal of about 5 W was transmitted at 145, 223, 300, 435, and 910 MHz. The receiver, shown in figure 4, consists of an antenna, a low-noise amplifier, and a spectrum analyzer and was used to measure received power. The transmit and receive antennas are identical log-periodic antennas with linear polarization and a 4- to 7-dB gain from 145 to 910 MHz. We used a crane boom to position the transmit antenna between 2.7 and 22 m high, as shown in figure 5. The receiver was housed in a truck with the receive antenna mounted on a fiberglass pole fastened to the bumper of the truck, as shown in figure 6. The fiberglass pole is adjustable and we set it to 2-, 2.7-, 3.6-, and 5-m heights during the measurements. For the Phase II measurements, we replaced the fiberglass pole with a photographer's tripod to get the 1-m receive height.

Figure 3. Simplified block diagram of transmitter.

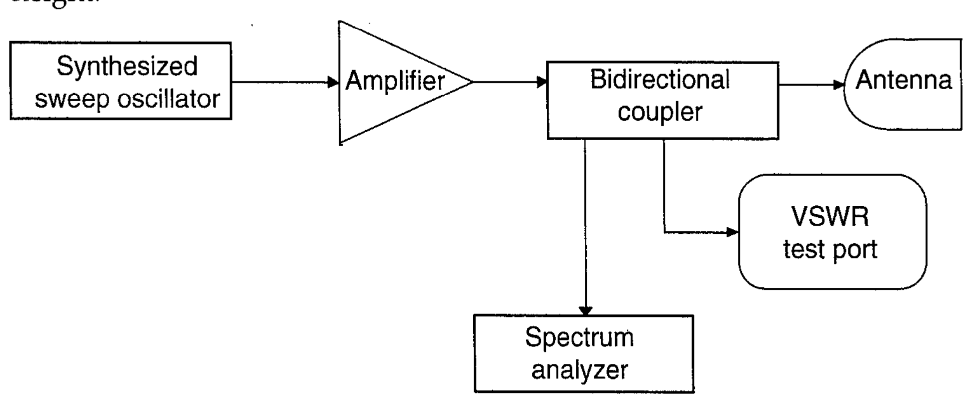


Figure 4. Simplified block diagram of receiver.

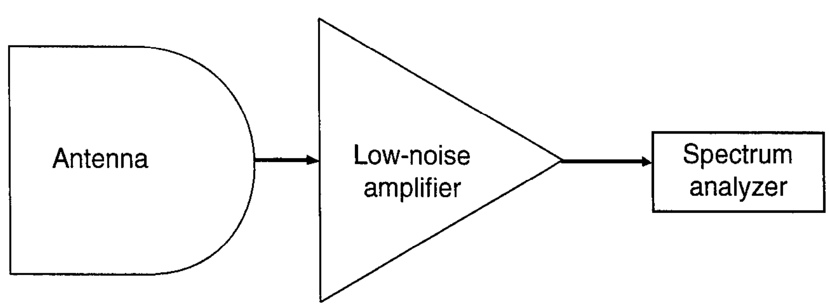
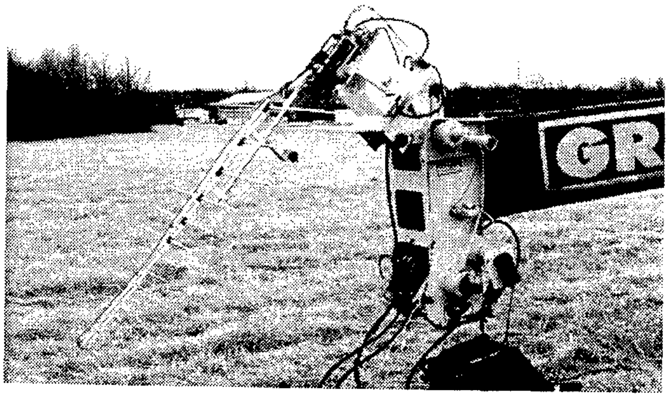


Figure 5. (a) Transmit antenna mounted to crane boom, (b) transmit antenna raised to 22 m.

(a)



(b)

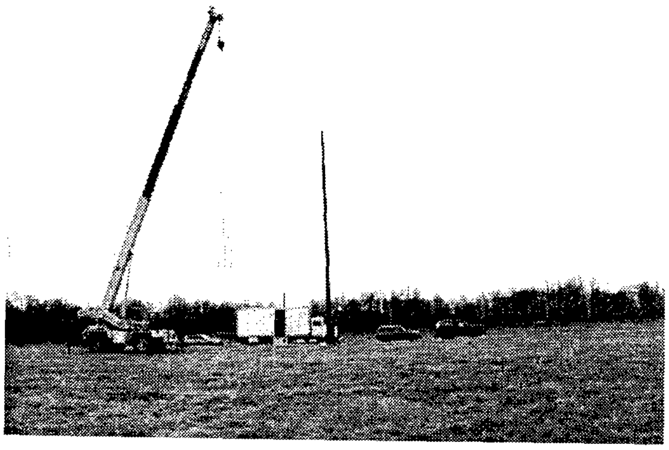
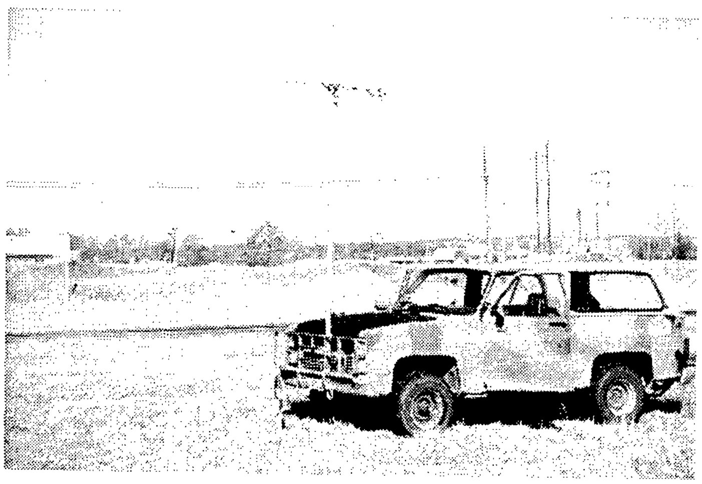


Figure 6. Mobile receive antenna station.



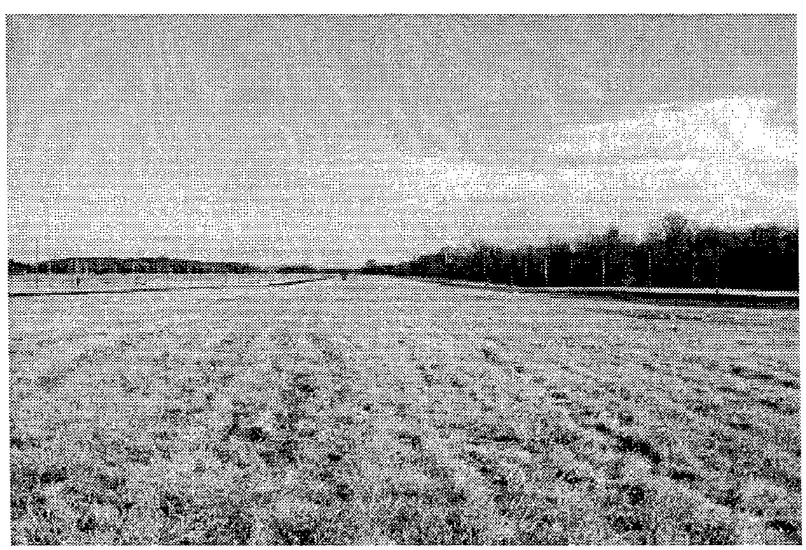
3.2 Measurement Procedures

We surveyed all positions of the transmit and receive antennas beforehand using the global positioning system (GPS). This allowed us to determine the ranges and positions of the equipment so that the experiments can be repeated at a later date. Appendix C gives the latitudes and longitudes. We determined the antenna heights using a tape measure. We did azimuthal alignment of the antennas before each measurement using compass headings derived from the GPS measurements. We aligned both receive and transmit antennas with 0° elevation relative to the horizon. We made all the measurements by recording both transmit and receive power.

3.3 Perryman Test Site

Figure 7 is a photograph of the propagation path area (the Perryman area of the Aberdeen Test Center (ATC)). The straight cleared area we used in the measurements is 5 km long. To the right of this area lies a wooded area cut through with dirt access roads. We used these access roads to set up the receive/truck antenna system for the wooded site propagation measurements. We chose the wooded sites to give path lengths of 410, 1000, 1930, and 4700 m through the woods. We positioned the transmitter at one end of this wooded area and left it in place while the receive/truck antenna system was moved to multiple locations. Figure 8 is a map of the area, with transmit and receive sites marked as follows: T1 and T2 are the transmit positions for the wooded and clearing measurements, respectively; R1, R2, R3, and R4 are receive positions for the wooded measurements at 410-, 1000-, 1930-, and 4700-m ranges, respectively; and R5, R6, R7, and R8 are receive positions for the clearing measurements at 410-, 1000-, 1930-, and 4230-m ranges, respectively. Note that the transmitter used for the wooded measurements (T1) is located 27 m from a patch of trees 20 m deep, followed by a clear area 40 m wide; the remaining propagation areas are wooded.

Figure 7. Test area at ATC Perryman.



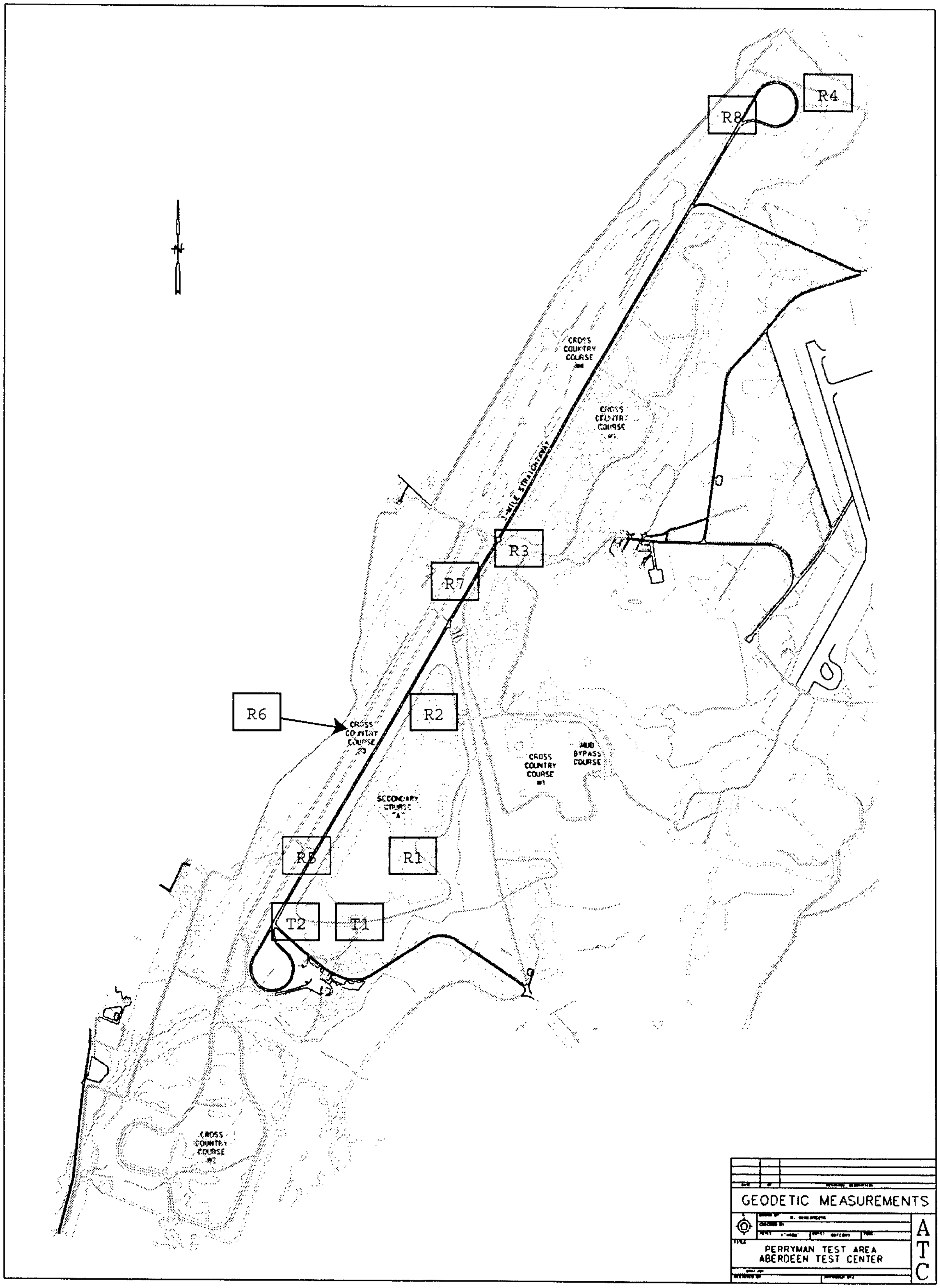


Figure 8. Perryman test site.

3.4 Calibrations

We measured the gain of the two identical log-periodic antennas used in the measurements described in section 2.1 in the field (the procedure was the same as that used for the multipath measurements, sect. 2.2). A separate measurement was made with an 8510 network analyzer system in an anechoic chamber and the results were compared to data on the manufacturer's specification sheet. All three of these measurements were within 2 dB of each other. We consider the field measurements the most reliable because they reflect the actual antenna mounts used in all the measurements. We then calculated the gain from the measured transmit and receive power using

$$G = \sqrt{\frac{P_R}{\left[2\sin\left(\frac{2\pi h_t h_r}{\lambda R}\right)\right]^2\left[\frac{\lambda}{4\pi R}\right]^2 P_T}}\ , \tag{1}$$

where

P_R = power received,
P_T = power transmitted,
h_r = power received,
h_t = power transmitted,
R = range, and
λ = wavelength.

This gain was used to determine propagation loss. We calibrated the transmit and receive chains, including all cables and connectors, using a vector network analyzer, both before and after the measurements, and noted no significant changes. We checked the transmit VSWR before and after changing the transmit antenna height to ensure there were no problems with the rf cabling to the transmit antenna.

4. Data Analysis

Propagation measurements for phase I consisted of 108 combinations of polarization, range, and transmit and receive antenna heights for each frequency in the clearing and 180 combinations in the woods. For phase II, there were 24 combinations in the clearing and 108 in the woods. The following sections present data for propagation loss versus antenna height, range, and frequency; average propagation loss versus range and frequency; and percent probabilities for obtaining specific propagation losses. All phase I and II data are tabulated in appendices A and B, respectively.

4.1 Multipath Data

In this section, we discuss the data for the measurements described in section 2.2. Figure 9 plots the transmission loss as a function of transmit antenna height for 145, 223, 300, 435, and 910 MHz, respectively. The receive antenna height was 2.7 m and the range was 410 m for all frequencies except 435 MHz, where the receive height was 3.6 m and the range was 200 m. The expected transmission loss in decibels over a flat earth is given by

$$\frac{P_R}{P_T} = 10 \log \left[2 \sin \left(\frac{2\pi h_t h_r}{\lambda R}\right)\right]^2 \left[\frac{\lambda}{4\pi R}\right]^2 , \tag{2}$$

where

P_R = power received,
P_T = power transmitted,
h_r = receive antenna height,
h_t = transmit antenna height,
R = range, and
λ = wavelength,

and is plotted in figure 9 for comparison [5]. The measurements agree well with the theory, as indicated by the similar slopes of the curves. Because of the geometry, only at 910 MHz do we see a peak in the transmission loss, and the 2-m displacement of the peak from theory is because we measured antenna heights relative to the ground at their location, and the ground was not level. Figure 10 plots the same data as figure 9 except that figure 10 is data for woods. Comparing figures 9 and 10, we conclude that woods adds attenuation, which essentially eliminates the large peaks caused by complete cancellation, as seen in the multipath results of figure 9(e) for 910 MHz. The multipath data is tabulated in appendix A, tables A-29 and A-30.

Figure 9. Comparison of measurements to theory for transmission loss over flat earth for a range of 410 m and a receive antenna height of 2.7 m for (a) 145, (b) 223, and (c) 300 MHz.

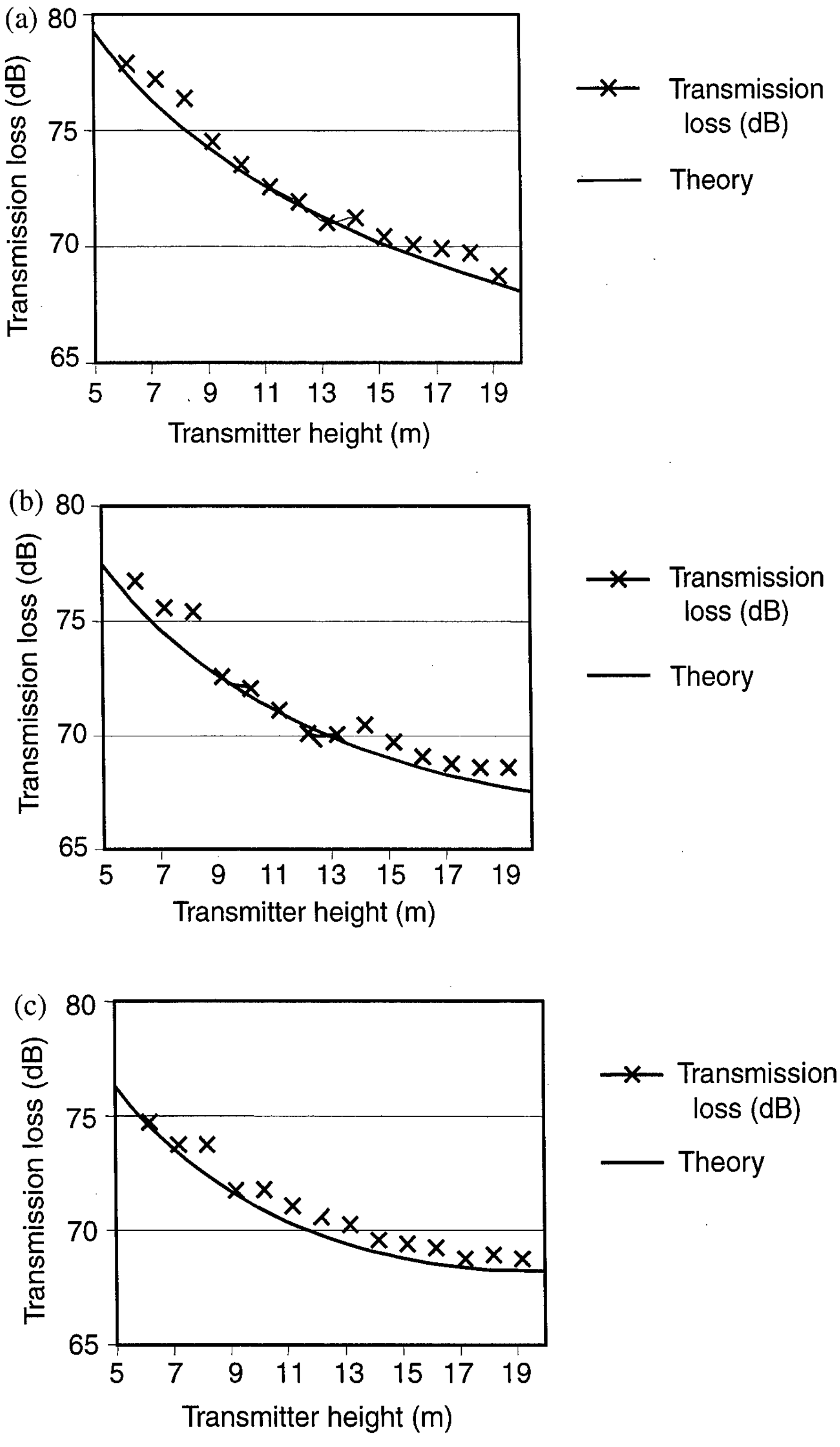


Figure 9 (cont'd). Comparison of measurements to theory for transmission loss over flat earth for a range of 410 m and a receive antenna height of 2.7 m for (d) 435 and (e) 910 MHz.

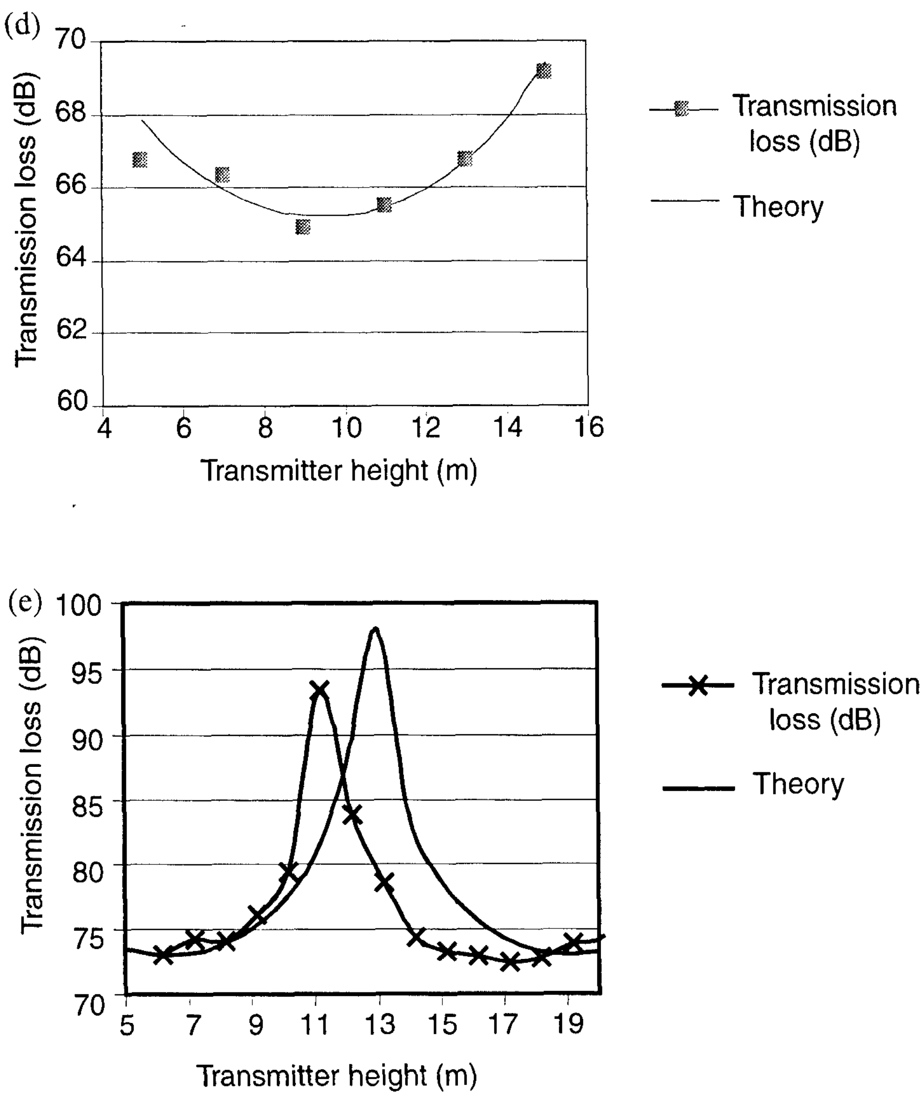
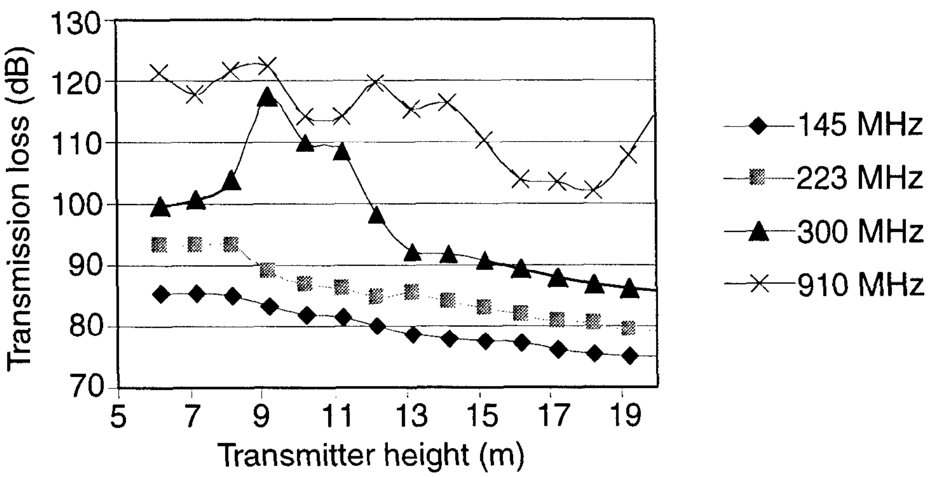


Figure 10. Transmission loss as a function of transmit antenna height at 145, 223, 300, and 910 MHz and a range of 410 m through woods in summer with a receive antenna height of 2.7 m.



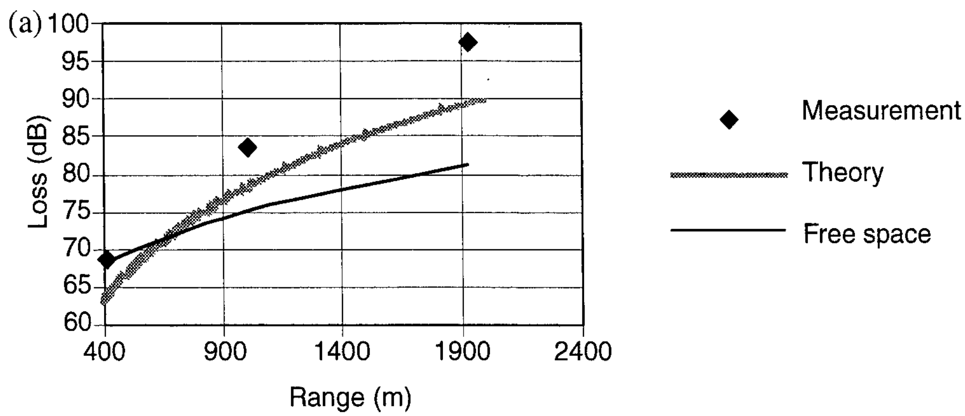
4.2 Propagation in Clearing

Figure 11 compares measured path loss in the cleared area depicted in figure 7 with free space loss, in decibels, given by

$$\frac{P_R}{P_T} = 10 \log \left(\frac{\lambda}{4\pi R}\right)^2 , \tag{3}$$

and with loss over the earth, in decibels, given by equation (2) (theory). Equation (2) assumes a flat, lossless, and perfectly reflecting ground. The measured data in figure 11 are for a transmit height of 22 m, a receive height of 5 m, and for HH polarization. Agreement within about 5 dB is obtained between theory and measurements. The difference between the theory for propagation over flat earth given by equation (2) and the measurements is because the measurements were made on an irregular lossy ground with obstacles on both sides.

Figure 11. Measured path loss, theoretical loss given by equation (2), and free space loss given by equation (3) versus range at (a) 145 and (b) 223 for transmit and receive heights of 22 and 5 m.



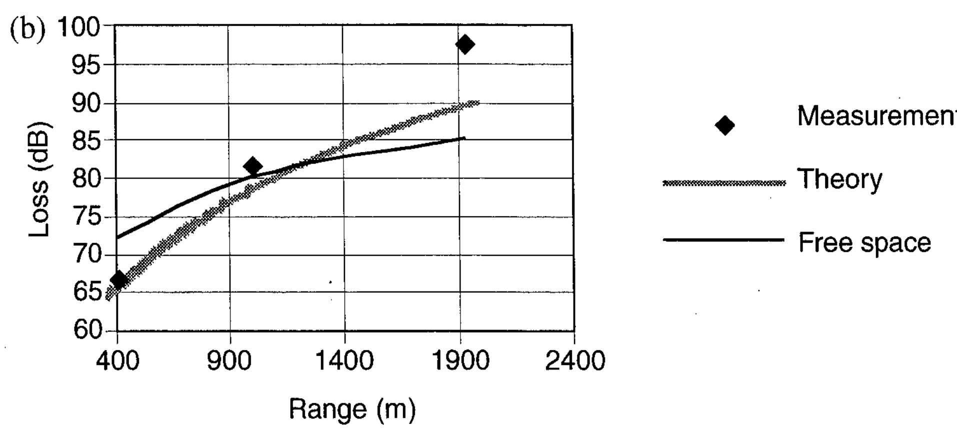
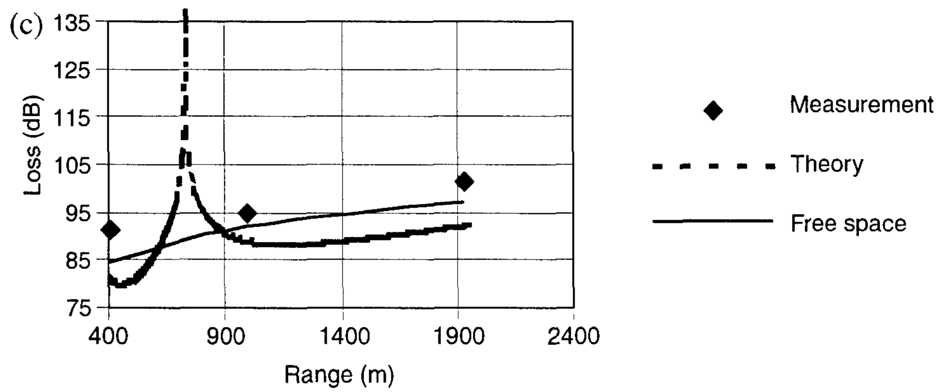


Figure 11 (cont'd). Measured path loss, theoretical loss given by equation (2), and free space loss given by equation (3) versus range at (c) 910 MHz for transmit and receive heights of 22 and 5 m.



4.3 HH Propagation Through Woods

In taking the HH polarization propagation data through woods both in winter and summer, we observed local fluctuations up to 20 dB. We avoided these large dips in receive power by minor repositioning of the receive antenna; it is important to note, however, that the multipath from the local trees and brush can cause such variations. After the data were inspected, it became apparent that they tended to agree with the theory given by equation (2), plus some fixed attenuation, and therefore allowed us to develop an analytical expression based on flat earth theory. This fixed attenuation is independent of range but varies with frequency. Tewari [1] also noticed this phenomenon at ranges above 400 m and attributed it to the characteristics of the lateral-wave mode, where the lateral waves encounter foliage only while traveling between the two antennas and the treetops. The rest of the time, the wave is traveling above the trees in open air. We modeled the added attenuation caused by woods by selecting a curve fit that performed well on average compared to all the data in wooded HH polarization data (see tables 2 and 3). The resultant expression for determining the propagation loss in decibels is given by

$$L_P = -10\log\left[\left(\frac{4\pi h_t h_r}{\lambda R}\right)^2\left(\frac{\lambda}{4\pi R}\right)^2\right] + 10\log\left(f^{5.4}\right) - 108\ , \tag{4}$$

where

h_r = receive antenna height,
h_t = transmit antenna height,
R = range,
λ = wavelength, and
f = frequency in megahertz.

The first part of equation (4) is based on equation (2), where the sine of the argument has been replaced with the argument. This approximation, $\sin x \approx x$, is valid where $x < \pi/4$. This will be true when d is much greater than $h_r \times h_t$, as in our ground-to-ground situation. The rest of equation (4) represents the added attenuation of woods. All the HH polarization propagation data taken through woods for all transmit and receive heights (see tables 2 and 3) are plotted in figure 12, along with data generated by the analytical model given by equation (4). The means are calculated from the loss in decibels and are plotted for comparison. The means of the data and model agree very well, but the scatter in the actual data tended to be larger. The data points having much greater loss than modeled at 145 and 223 MHz (see fig. 12(a) and (b)) were taken with the receive antenna 1 m from the ground. Table 4 shows the tabulated means

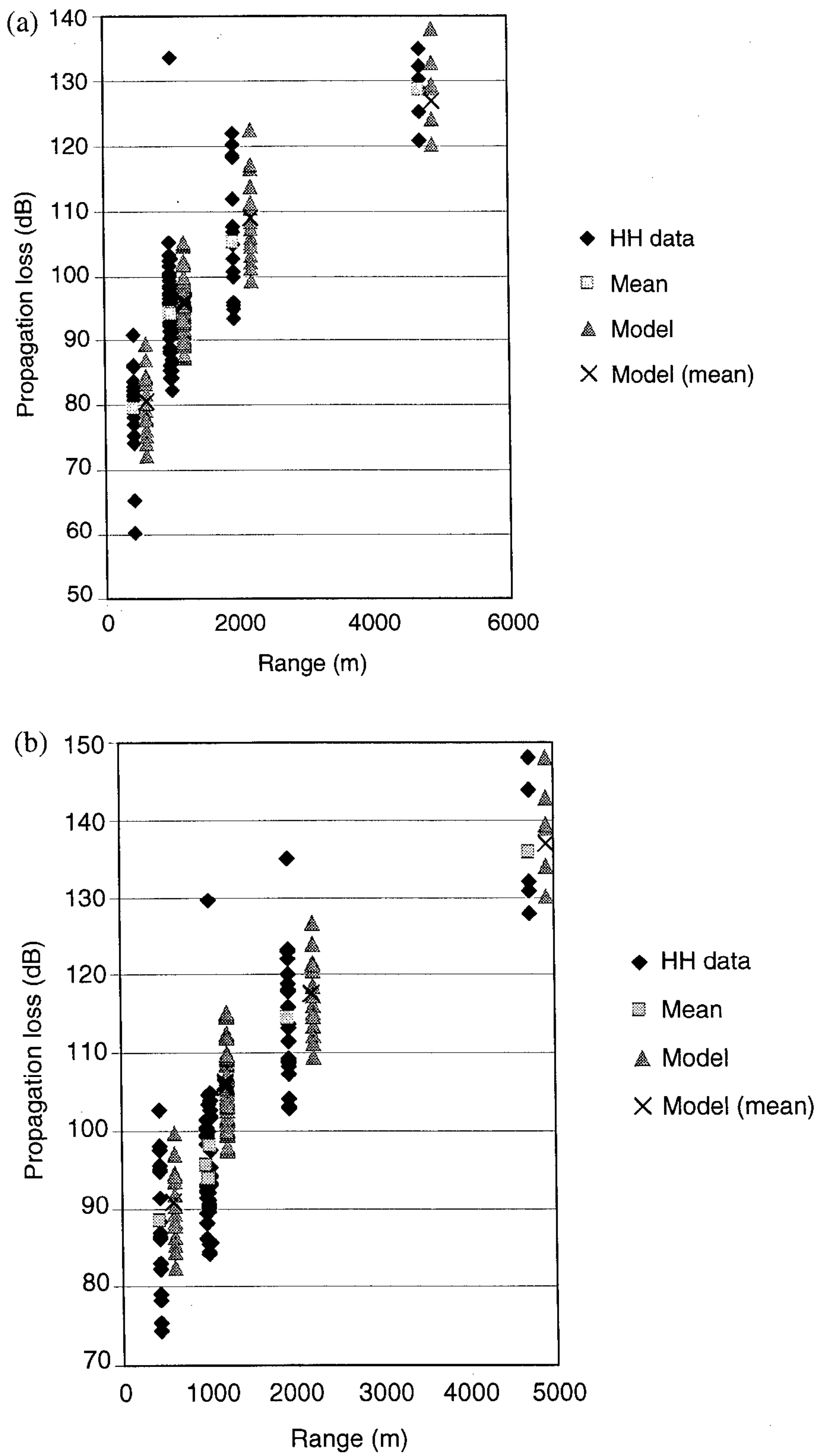
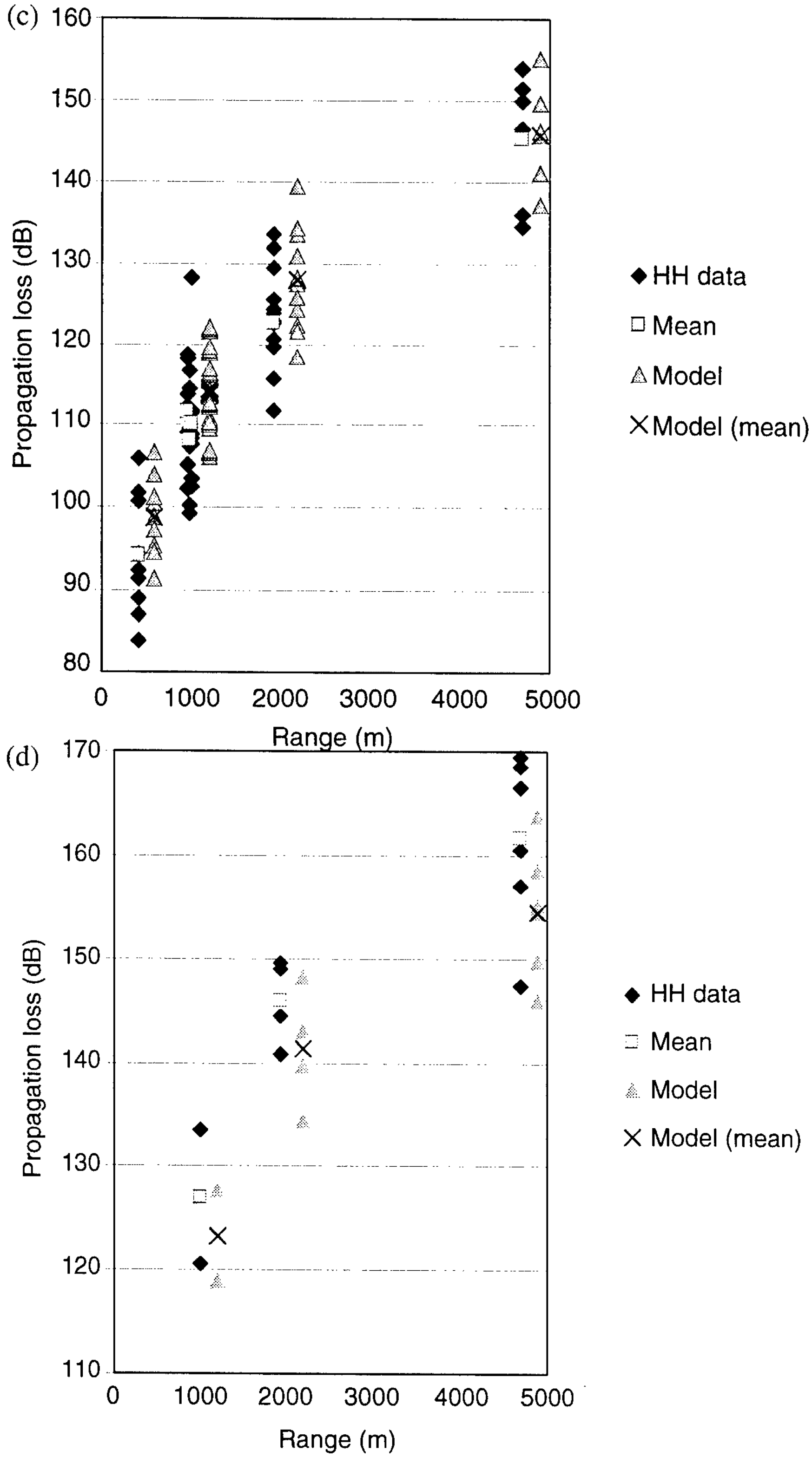


Figure 12. Scatter plots of propagation loss through woods versus range for HH polarization data in tables 2 and 3 compared to an analytical model at (a) 145 and (b) 223 MHz.

Figure 12 (cont'd). Scatter plots of propagation loss through woods versus range for HH polarization data in tables 2 and 3 compared to an analytical model at (c) 300 and (d) 435 MHz.



for the data shown in figure 12, along with the standard deviation in parentheses. The statistics were calculated from the values in decibels and are shown in decibels.

Figure 12 (cont'd). Scatter plots of propagation loss through woods versus range for HH polarization data in tables 2 and 3 compared to an analytical model at (e) 910 MHz.

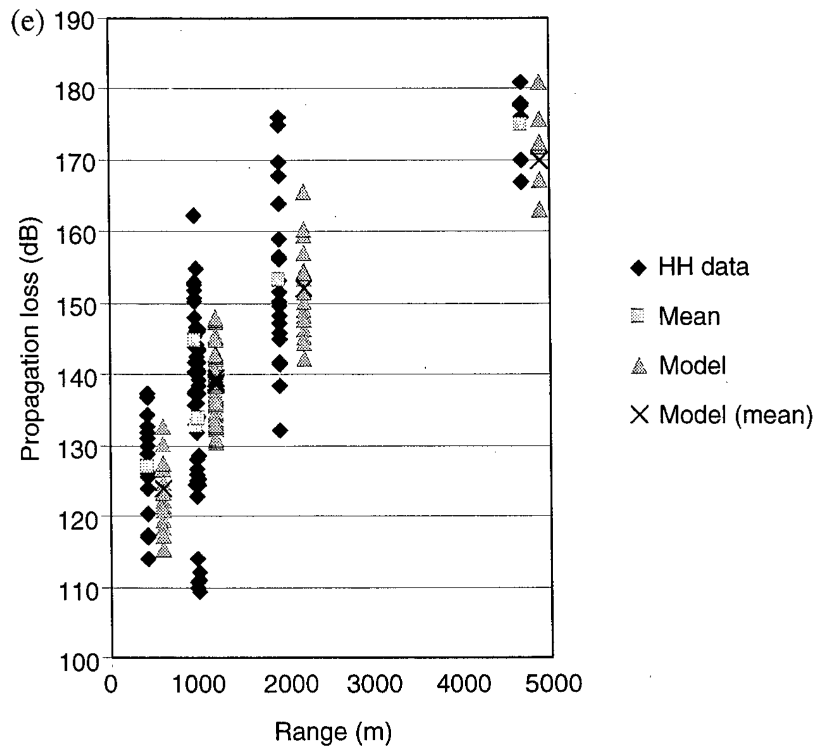


Table 4. Average propagation loss of woods.

Range (m)	Mean propagation loss (dB) and standard deviation				
	145 MHz	223 MHz	300 MHz	435 MHz	910 MHz
410	79.4 (7.4)	88.4 (8.4)	94.1 (7.3)	—	127.0 (7.3)
967	94.4 (4.6)	95.8 (5.1)	111.5 (5.4)	—	144.6 (8.9)
983	94.2 (6.3)	93.7 (6.4)	108.2 (5.6)	—	132.6 (13.1)
1000	94.0 (10.8)	97.9 (9.6)	110.0 (6.7)	127.1 (9.1)	133.8 (11.6)
1930	104.9 (8.7)	114.5 (7.8)	122.6 (6.9)	146.0 (4.1)	153.1 (11.8)
4700	128.7 (5.1)	135.8 (8.1)	145.4 (8.2)	161.6 (8.4)	174.9 (5.4)

Figure 13 shows the average propagation loss through woods (table 4) plotted as a function of range. Figure 14 plots the same data as a function of frequency. Figures 13 and 14 compare the measured average propagation loss with the model with the use of the same transmit and receive heights, frequency, and ranges. The data appear as data points whereas the results generated by the model are shown as curves. Figure 15 plots propagation loss data in decibels for selected antenna heights as a function of range (transmit height of 22 m and receive height of 2.7 m). The data in figure 15 compare loss over flat earth (theory) given by equation (2) in section 4.1 and the analytical model given in equation (4). The analytical expression models the data with good agreement and provides a convenient way to determine the propagation loss through wooded areas, given frequency, range, and transmit and receive height. The large scatter in the data (fig. 12) indicates that relatively small variations in transmit and receive positions can cause large changes in the propagation loss; therefore, it may be more useful in some applications to consider the propagation loss in terms of a probability distribution. Figure 16 plots the propagation loss data as a percent probability for specific frequencies. Figure 17 plots the propagation loss as a percent probability for 410-, 1000-, 1930-, and 4700-m ranges. Because of the large variations we observed during the project, we suggest that more measurements be made to obtain a better statistical distribution. This would allow specific plots for transmit and receive heights like those shown in figures 16 and 17.

Figure 13. Measured average propagation through woods versus range compared to an average generated by model in equation (4).

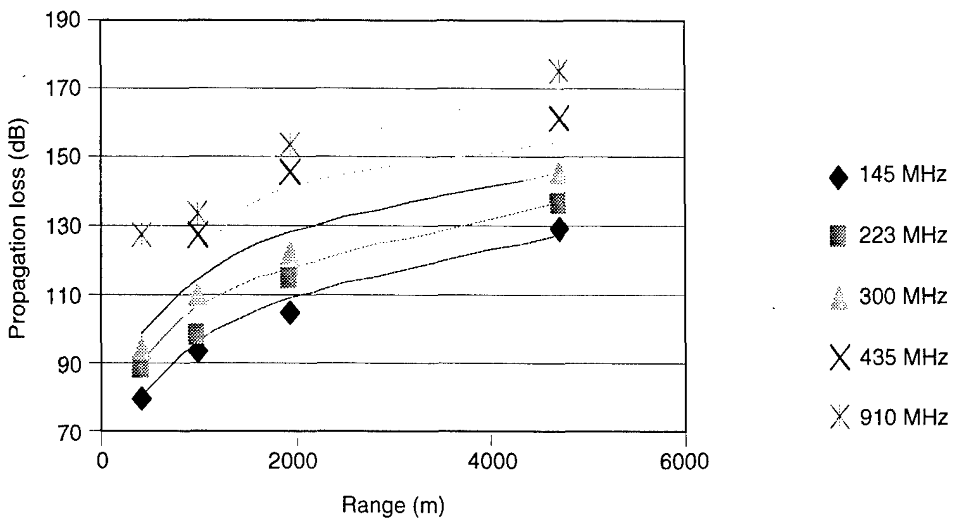


Figure 14. Measured average propagation loss through woods versus frequency range compared to an average generated by model in equation (4).

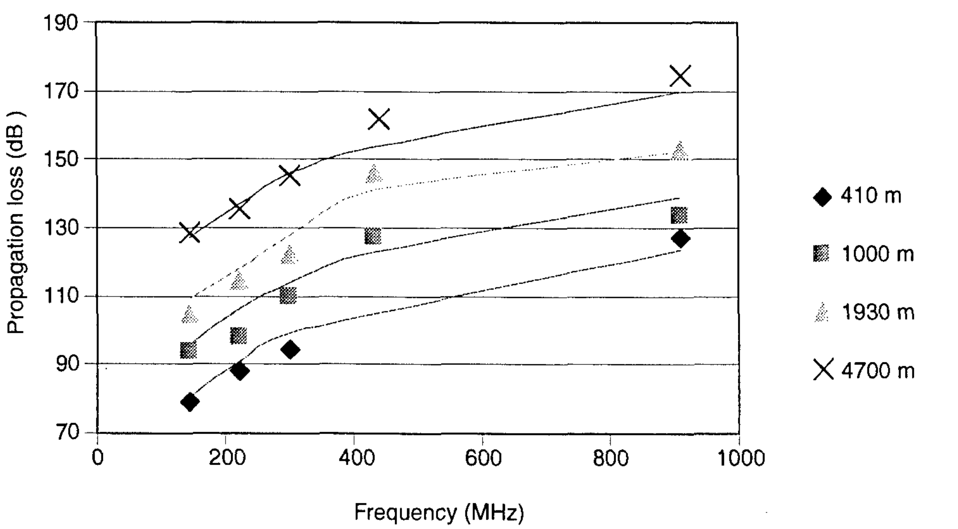


Figure 15. Comparison of measured propagation loss, loss over flat earth, and an analytical model for HH polarization in decibels plotted as a function of range for (a) 145, (b) 223, (c) 300 MHz.

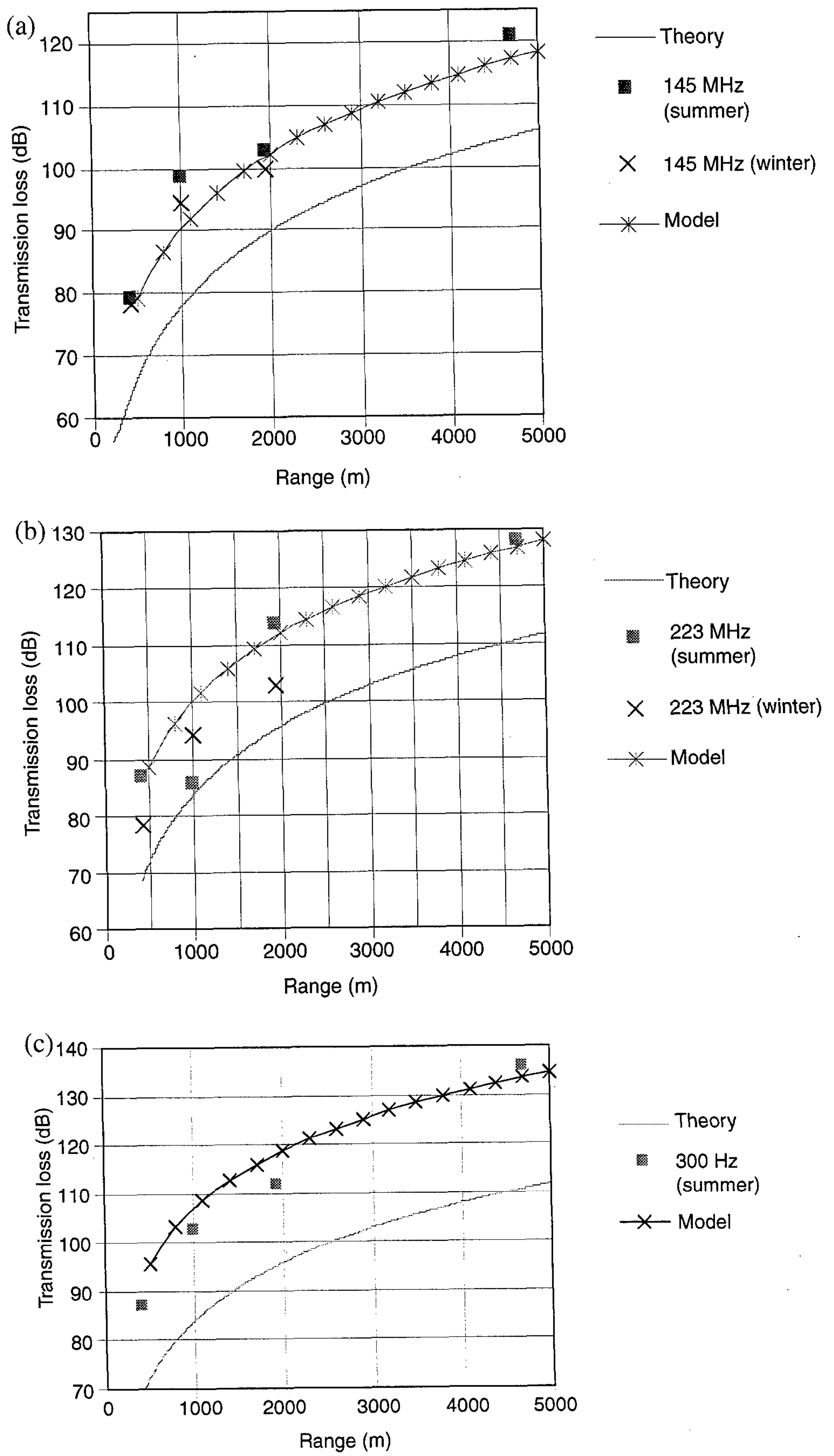
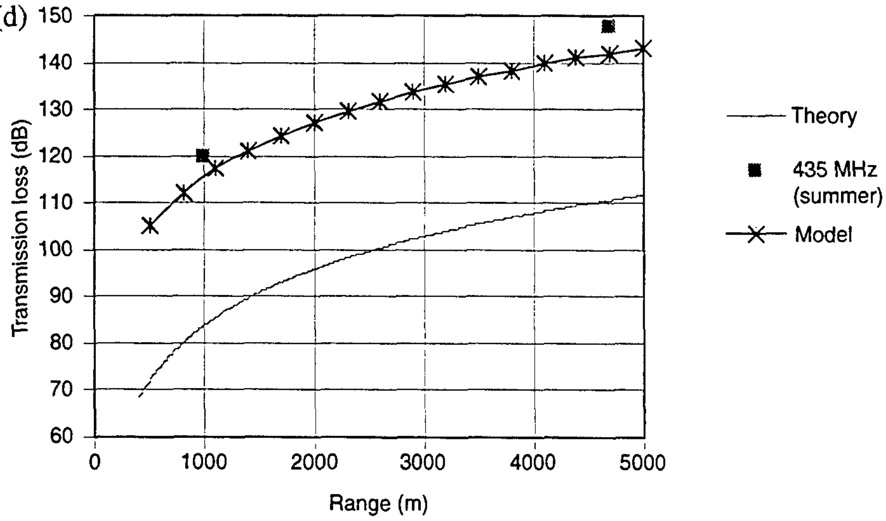


Figure 15 (cont'd). Comparison of measured propagation loss, loss over flat earth, and an analytical model for HH polarization in decibels plotted as a function of range for (d) 435 and (e) 910 MHz.

(d)



(e)

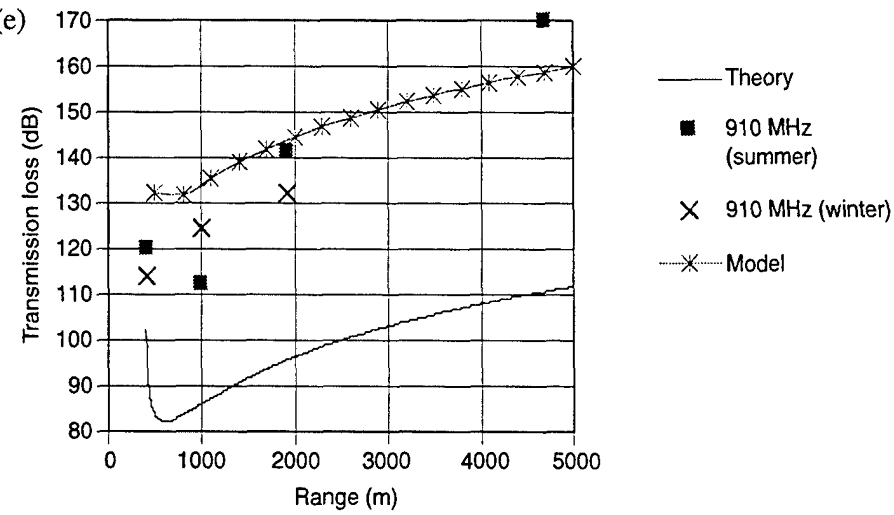
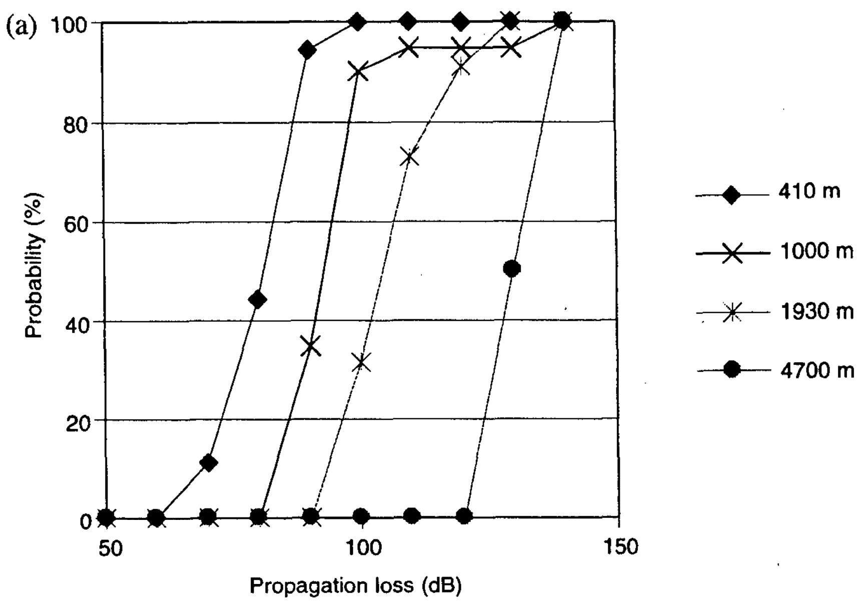


Figure 16. Percent probability versus propagation loss at (a) 145 and (b) 223 MHz.



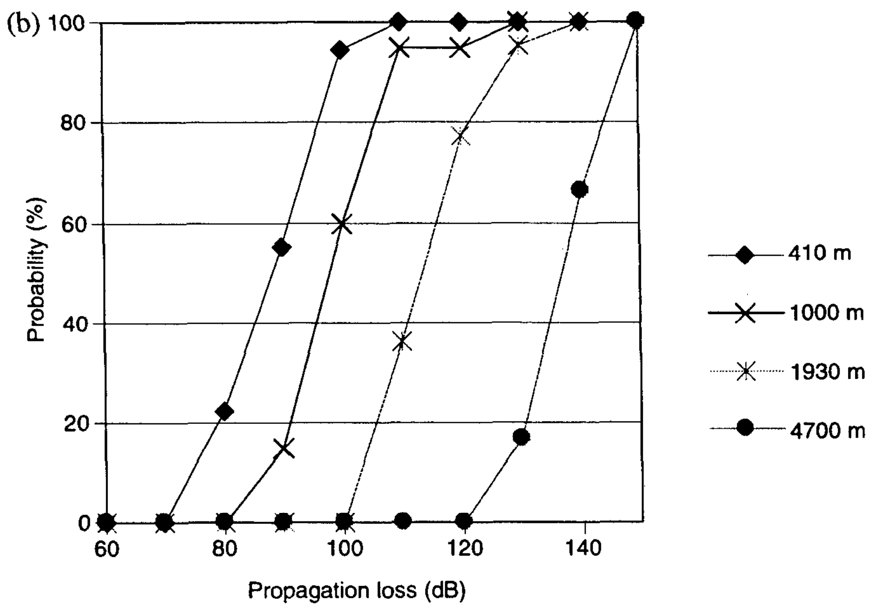
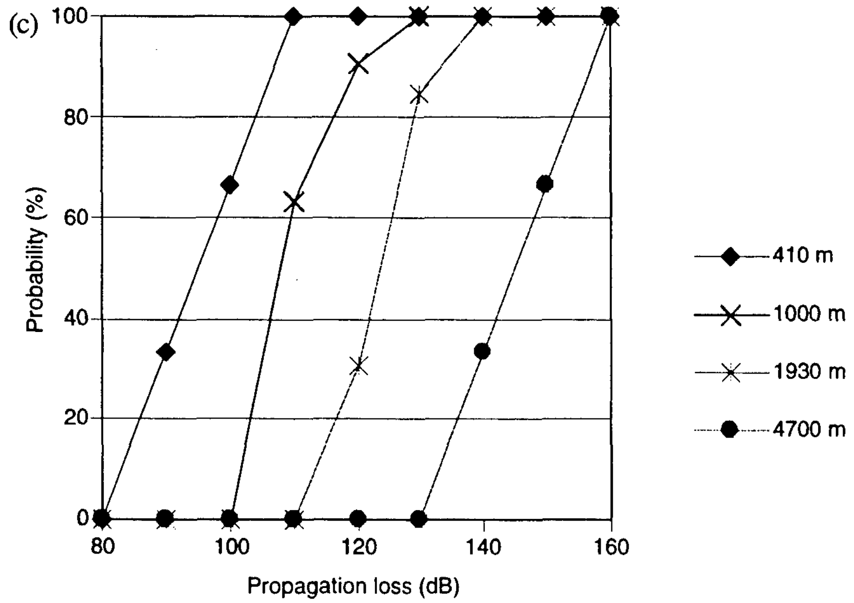


Figure 16 (cont'd). Percent probability versus propagation loss at (c) 300, and (d) 900 MHz.



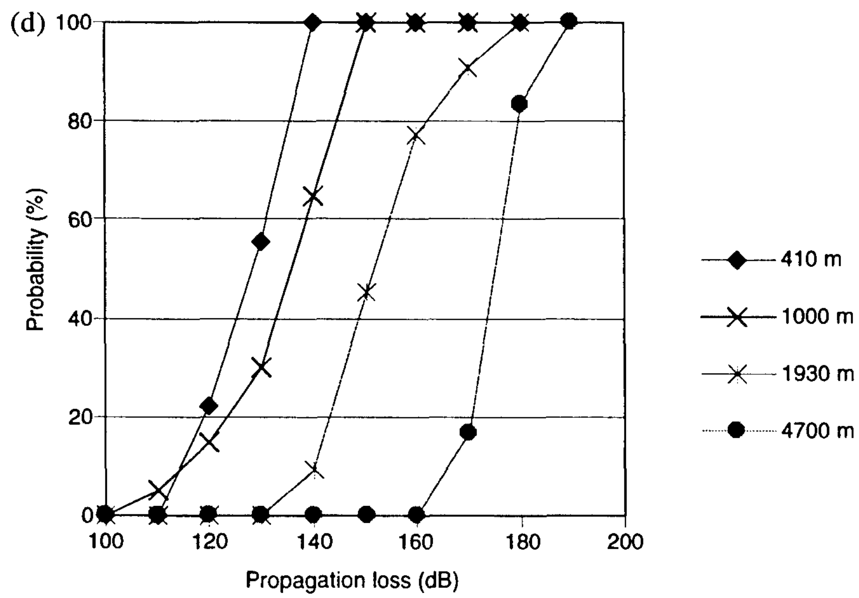


Figure 17. Percent probability versus propagation loss for (a) 410 and (b) 1000 m.

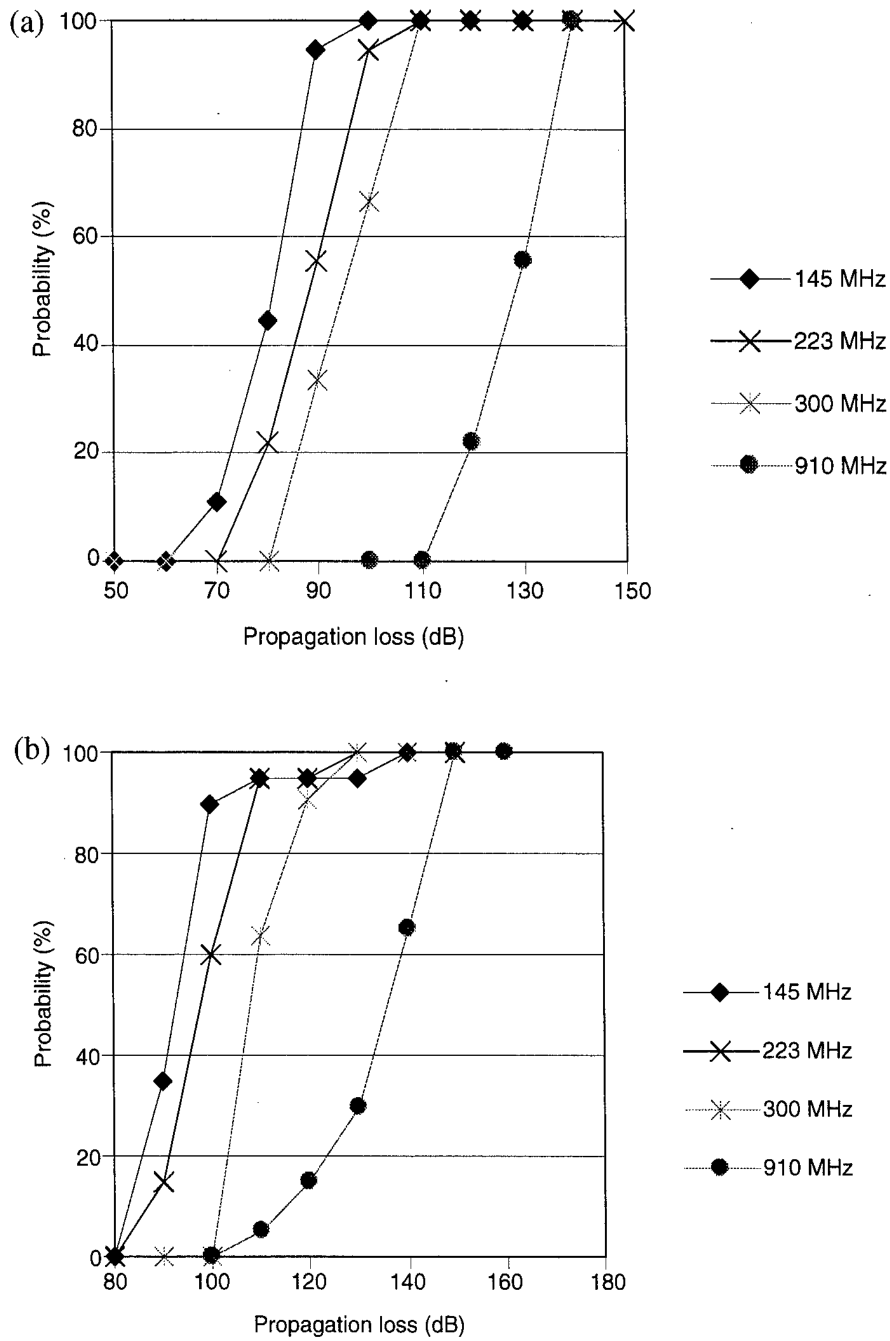
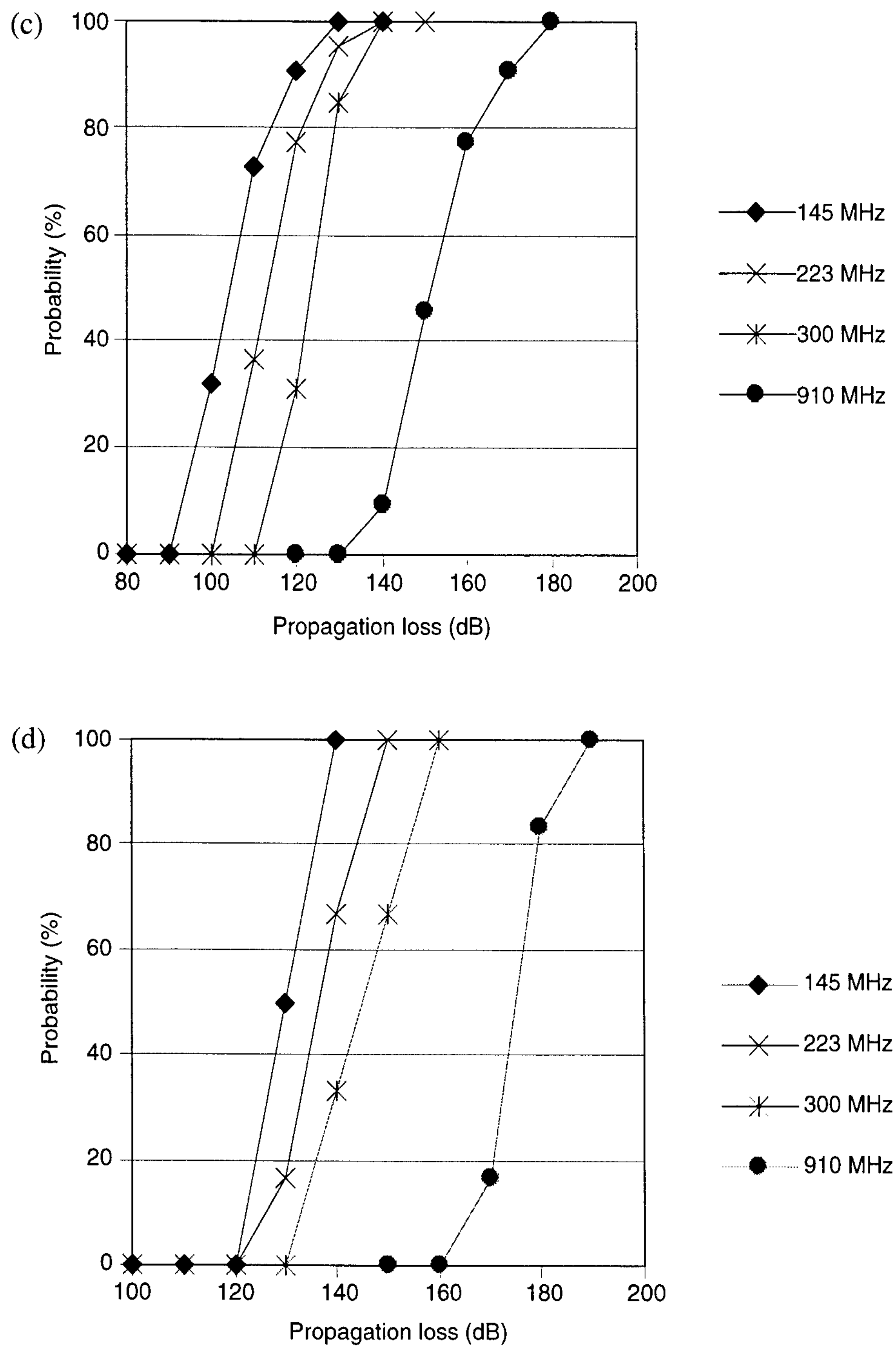


Figure 17 (cont'd). Percent probability versus propagation loss for (c) 1930 and (d) 4700 m.



4.3.1 *Frequency Effects*

Average propagation loss for woods increases with frequency as is shown by the data of table 4 plotted in figure 14. As the figure shows, the propagation loss increases approximately with frequency to the 5th power. This result dictates that the lowest possible frequency be used for the best penetration through woods.

4.3.2 *Polarization Effects*

With data taken in woods during both winter and summer, we used the data points for which polarization was the only variable to statistically determine which polarization resulted in the least propagation loss. Table 5 shows the percentage of time each polarization resulted in the least propagation loss (the percentages do not total 100 because two polarizations have the same loss). The number of data points in the table indicates the number of measurements used to calculate the percentages.

Clearly, HH polarization results in the least propagation loss through a wooded area. The lower frequencies increased the probability that HH would have the least propagation loss. The other parameters, range and transmit antenna height, do not appear to have a statistically significant relationship with the polarization that has the least propagation loss. In phase II, when the receive antenna was only 1 m from the ground, VV polarization showed the least propagation loss; however, with the antenna this close to the ground, the antenna's electrical properties are uncertain and therefore the propagation loss calculated at this antenna height is unreliable.

4.3.3 *Transmit Antenna Height*

We made transmission measurements at three transmitter heights, 7.6, 14, and 22 m, with the tops of the trees mostly between 14 and 22 m. Of 215 HH polarization transmission measurements through woods where transmit height was the only variable 82 percent of the time, a transmitter height of 75 ft, the highest position, resulted in the least transmission loss. The model developed in section 4.3 results in the least transmission loss for the highest transmit/receive product. Table 6 shows the probabilities of the least propagation loss as a function of transmitter height. The number of data points indicates the number of measurements used to calculate the percentages.

Table 5. Probability of least transmission loss by polarization.

	Probability of least transmission loss				
Polarization	145 MHz	223 MHz	300 MHz	435 MHz	910 MHz
HH	99.0%	92.2%	80.7%	50.0%	57.8%
VH	0.0%	0.0%	12.3%	16.7%	26.5%
VV	1.0%	5.9%	5.3%	42.0%	14.3%
HV	0.0%	2.9%	0.0%	8.3%	2.9%
No. of data points	102	102	57	12	102

Table 6. Probability of least transmission loss at HH polarization.

Transmitter height (m)	Probability of least transmission loss				
	145 MHz	223 MHz	300 MHz	435 MHz	910 MHz
22	42%	86%	100%	95%	97%
14	40%	6%	0%	5%	3%
7.6	17%	8%	0%	0%	0%
No. of data points	52	52	37	22	32

Table 7 shows the average propagation loss for multiple transmit heights and frequencies. The propagation loss decreases with increasing transmit height. Above 145 MHz, this propagation is given by

$$\left(\frac{1}{h_t}\right)^{1.3} \le P_L \le \left(\frac{1}{h_t}\right)^{2.5} .$$

On average, an increase from 25 to 46 ft (tree height) resulted in a decrease in attenuation of 1, 3, 3, and 5 dB for 145, 223, 300, and 910 MHz, respectively. At 145 MHz, the transmit height did not significantly affect the transmission loss, but at the higher frequencies, the higher transmit heights resulted in less transmission loss. In the model, the effects of transmit and receive height are independent of frequency.

4.3.4 *Receive Antenna Height*

We made propagation measurements at receive heights of 1, 2, 2.7, 3.6, and 5 m. For HH polarization, we made 105 measurements where receiver height (2.7 and 3.6 m) was the only variable. Table 8 shows the probability that a specific receiver height will result in the least transmission loss for these 105 measurements (the percentages do not total 100 because multiple polarizations have the same loss). The average propagation loss is also shown in parentheses. Table 9 shows the same data for 24 measurements where receive height was the only variable (1 and 2.7 m).

Neither the transmit height nor the presence or absence of leaves made a significant difference in the probabilities in tables 8 and 9. Generally, the higher the receiver, the less the propagation loss. The average

Table 7. Average propagation loss for HH polarization.

Transmitter height	Average propagation loss (dB)			
	145 MHz	223 MHz	300 MHz	910 MHz
22	95	94	107	129
14	94	101	114	143
7.6	95	104	117	148
No. of data points	32	32	17	32

Table 8. Probability of least transmission loss and average loss for HH polarization.

Receiver height (m)	Probability of least transmission loss and (average loss in dB)			
	145 MHz	223 MHz	300 MHz	910 MHz
2.7	17 % (93 dB)	27% (98 dB)	67% (107 dB)	37% (139 dB)
4	93% (91 dB)	80% (98 dB)	33% (110 dB)	67% (137 dB)
No. of data points	30	30	15	30

Table 9. Probability of least transmission loss and average loss for HH polarization.

Receiver height (m)	Probability of least transmission loss and (average loss in dB)			
	145 MHz	233 MHz	300 MHz	910 MHz
1	0% (129 dB)	17% (130 dB)	50% (138 dB)	67% (167 dB)
2.7	100% (118 dB)	83% (124 dB)	50% (134 dB)	50 % (165 dB)
No. of data points	6	6	6	6

transmission loss difference between 2.7 and 3.6 m was only 1.8 dB and it was 5.6 dB between 1 and 2.7 m.

4.3.5 *Summer Versus Winter Propagation Measurements*

We made measurements in both winter and summer to study the effect of leaves on propagation loss. Table 10 shows the average and standard deviation of the difference in decibels between the propagation loss with and without leaves for HH polarization. Positive averages indicate greater loss with leaves. All antenna heights and ranges were used in the averages. The leaves resulted in an average increase in attenuation of 8.9 and 6.2 dB for 145 and 223 MHz, respectively, and a 1.8-dB average decrease in attenuation at 910 MHz; this is probably insignificant at 910 MHz because of the 10-dB standard deviation. These results are the opposite of what we expected: we thought that the leaves would have less effect at lower frequencies and more at higher frequencies.

4.3.6 *Tree-Line Effects*

For the tree-line proximity measurements described in section 2.3, we made measurements at 1000, 983, and 967 m; at 967 m, the receive antenna was up against the tree line, and at 1000 m, the receive antenna was 33 m from the tree line. Little difference was evident in attenuation for the three antenna sites at 145 and 223 MHz. At 910 MHz, the data suggest that the farther the receive antenna is from the tree line, the lower the attenuation due to foliage, especially for lower receive heights. On average, there was 12 dB more loss at 910 MHz for 967 m than for 1000 m. We made the phase II measurements in a "T" shape with 10 m between measurement sights. We obtained similar results in this phase: at 910 MHz, there was about 10 dB more attenuation in the positions close to the wood line. No such trend was evident for the other frequencies.

4.3.7 *Statistics for a 7- by 7-m Grid Sample of Data*

Table 11 presents the statistical data (average and standard deviation) taken (as described in sect. 2.4) for 49 positions at 1000 m in woods spaced in 1-m increments in a 7- by 7-m grid. These measurements were made in the same location as the tree-line proximity measurements depicted in figure 2. We took data with a transmitter height of 14 m, a receiver height of 2.7 m, and HH polarization. The statistics in the table were calculated from the propagation loss in decibels. The results show a smaller standard deviation for lower frequencies. The average transmission loss ranged from 96 dB at 145 MHz to 145 dB at 910 MHz, with standard deviations from 1.2 to 4.3 dB. Transmission loss for the 49 positions is presented in appendix A, table A-28. Figure 18 plots the transmission loss at all positions in the "T" (see fig. 2) for a 22-m transmitter height and a 1-m receiver height. Of interest here is the 20 to 30 dB spread in the data, which is thought to be caused by the complex multipath and scattering caused by the woods. This spread again supports the earlier conclusion that this kind of data should be considered as probability distributions.

Table 10. Average difference and standard deviation between propagation loss with and without leaves.

Measure	Value at various frequencies		
	145 MHz	223 MHz	910 MHz
Average	8.9 dB	6.2 dB	–1.8 dB
Standard deviation	3.7 dB	6.8 dB	9.9 dB
No. of data points	45	45	45

Table 11. Average and standard deviation for 49 samples in woods.

Measure	Value at various frequencies			
	145 MHz	223MHz	300 MHz	910 MHz
Average	96 dB	103 dB	108 dB	145 dB
Standard deviation	1.2 dB	2.6 dB	2.5 dB	4.3 dB

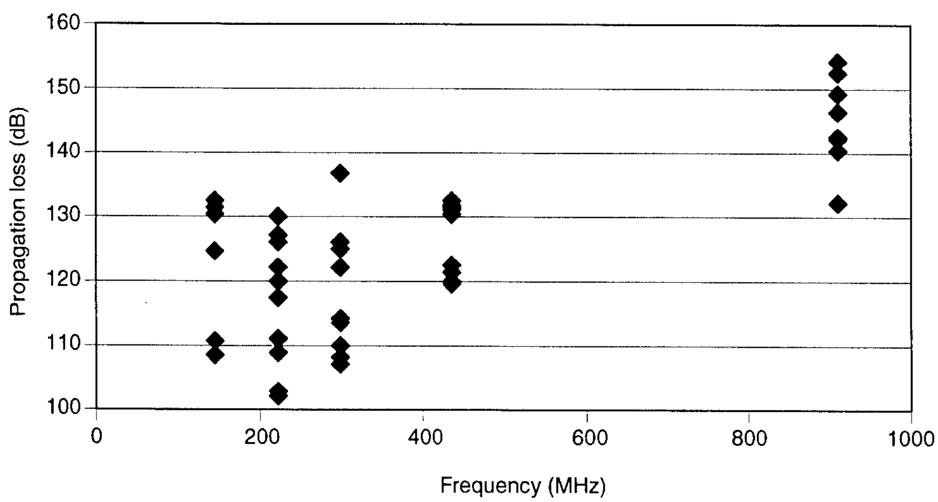


Figure 18. Scatter plot of propagation loss for a sample of data.

Conclusions

The measurements we made in the clearing area agreed with theory to within about 5 dB, and the deviations are largely because the clearing was not perfectly flat nor without obstacles. Because HH polarization clearly gave the best penetration through woods, all the following conclusions are based on HH polarization only. The propagation loss through woods tends to agree with the theory plus a fixed attenuation; therefore, we developed an analytical expression by adding an attenuation to the theory of loss over flat earth. The resultant expression for determining the propagation loss in decibels is given by

$$L_P = -\,10 \log\left[\left(\frac{4\pi h_t h_r}{\lambda R}\right)^2 \left(\frac{\lambda}{4\pi R}\right)^2\right] + 10 \log\left(f^{5.4}\right) - 108 \ , \qquad (4)$$

where

h_r = receive antenna height,
h_t = transmit antenna height,
R = range,
λ = wavelength, and
f = frequency in megahertz.

The first part of the above expression is the predicted path loss over flat earth [6]; the second part is the fixed attenuation caused by woods at a given frequency. This equation models the propagation loss through the moderately dense deciduous forest at Aberdeen Proving Ground in the state of Maryland, USA. The model showed good agreement with the measured data from 145 to 910 MHz and ranges from 500 to 5000 m. It is unknown how well it will work outside these parameters. The expression provides a convenient way to determine propagation loss through woods, given frequency, range, and transmit and receive height. Average propagation loss of the woods increases approximately to the 5th power with frequency as shown by the data of table 4 plotted in figure 14. Trees with leaves, as compared to trees without, resulted in an average increase in attenuation of 8.9 and 6.2 dB for 145 and 223 MHz, respectively. At 910 MHz, no significant difference was evident. The large differences in propagation through woods resulting from relatively small changes in antenna position (see figs. 12(a) to (e) and 18) indicate that it may be more useful to consider the propagation loss as a probability distribution as depicted in figures 16 and 17.

Appendix A.— Phase I Measurements

Table A-1.
Transmission loss (dB) measurements for 22-m transmitter height in clearing at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	74.8	88.8	103.3
2.7	VH	85.9	109.8	118.4
2.7	VV	81.1	93.6	108.4
2.7	HV	91.6	104.6	120.4
3.6	HH	69.8	85.6	99.4
3.6	VH	85.8	104.8	114.4
3.6	VV	75.9	89.6	102.4
3.6	HV	99.9	99.6	112.4
5	HH	68.8	83.6	97.4
5	VH	82.8	106.6	110.4
5	VV	75.9	88.6	99.4
5	HV	96.8	104.4	111.4

Table A-2.
Transmission loss (dB) measurements for 14-m transmitter height in clearing at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	76.1	93.1	105.1
2.7	VH	85.1	110.3	122.9
2.7	VV	81.27	96.1	103.9
2.7	HV	92.1	106.8	115.9
3.6	HH	73.1	89.1	102.9
3.6	VH	87.1	111.1	116.1
3.6	VV	79.9	93.1	102.8
3.6	HV	93.9	104.27	113.9
5	HH	71.6	86.1	100.1
5	VH	82.27	109.1	113.9
5	VV	77.9	92.9	99.9
5	HV	93.9	102.1	115.9

Table A-3.
Transmission loss (dB) measurements for 7.6-m transmitter height in clearing at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	77.6	97.4	110.4
2.7	VH	93.6	113.4	122.4
2.7	VV	84.6	95.4	108.4
2.7	HV	94.8	105.4	128.4
3.6	HH	77.6	93.4	107.4
3.6	VH	93.6	118.4	123.4
3.6	VV	80.6	94.4	107.4
3.6	HV	92.6	104.4	126.4
5	HH	75.6	91.4	104.4
5	VH	87.6	116.4	117.4
5	VV	80.6	94.4	106.4
5	HV	87.6	108.4	123.4

Table A-4. Transmission loss (dB) measurements for 22-m transmitter height in clearing at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	71.7	85.6	102.4
2.7	VH	83.7	99.6	113.4
2.7	VV	74.1	89.4	112.4
2.7	HV	89.9	99.4	116.4
3.6	HH	68.6	82.6	98.4
3.6	VH	101.8	102.6	112.4
3.6	VV	69.7	84.4	101.4
3.6	HV	95.7	99.4	119.4
5	HH	66.6	81.6	97.6
5	VH	92.7	96.4	110.4
5	VV	67.7	81.4	101.4
5	HV	99.7	99.4	113.4

Table A-5. Transmission loss (dB) measurements for 14-m transmitter height in clearing at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	75.1	86.2	104.9
2.7	VH	88.2	96.1	113.9
2.7	VV	73.4	93.1	105.9
2.7	HV	86.2	105.2	112.9
3.6	HH	72.2	85.1	100.9
3.6	VH	88.2	101.9	114.9
3.6	VV	73.2	87.2	101.7
3.6	HV	95.1	103.1	111.9
5	HH	70.2	82.1	97.9
5	VH	86.1	97.9	108.9
5	VV	71.2	83.9	100.9
5	HV	91.2	106.1	110.1

Table A-6. Transmission loss (dB) measurements for 7.6-m transmitter height in clearing at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	1000-m range	1930-m range
2.7	HH	75.7	89.7	107.6
2.7	VH	99.6	102.7	114.6
2.7	VV	79.9	89.7	115.6
2.7	HV	100.9	112.6	121.6
3.6	HH	76.6	88.7	103.6
3.6	VH	100.6	103.7	113.6
3.6	VV	75.9	90.6	111.6
3.6	HV	87.7	100.4	120.6
5	HH	73.1	85.7	101.4
5	VH	91.2	105.6	111.6
5	VV	73.7	87.6	105.6
5	HV	87.7	100.6	120.6

Table A-7. Transmission loss (dB) measurements for woods in winter, 22-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	78.2	94.8	94.6	94.6	99.9
2.7	VH	84.2	112.8	110.93	133.6	115.8
2.7	VV	78.2	100.9	104.9	105.1	112.1
2.7	HV	82.2	110	116.3	121.6	133.1
3.6	HH	60.2	93.8	92.6	90.6	100.8
3.6	VH	79.2	108.8	111.1	104.1	130.4
3.6	VV	73.2	99.9	102.8	103.1	134.3
3.6	HV	79.2	113.1	112.3	109.1	126.1
5	HH	65.2	92.9	89.1	86.6	100.8
5	VH	81.2	106.8	109.8	102.1	118.6
5	VV	73.2	96.8	100.8	101.1	111.8
5	HV	76.2	113.1	109.9	110.9	117

Table A-8. Transmission loss (dB) measurements for woods in winter, 14-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	78.27	90.27	88.4	87.1	94.8
2.7	VH	95.27	121.27	110.4	121.4	125.3
2.7	VV	91.27	105.27	113.4	110.4	116.3
2.7	HV	92.27	103.27	106.1	112.4	115.8
3.6	HH	75.27	88.27	85.4	84.4	94.8
3.6	VH	99.27	122.27	108.8	121.4	125.9
3.6	VV	92.1	101.1	109.4	107.4	122.3
3.6	HV	92.1	106.27	105.3	104.4	116.3
5	HH	74.27	86.27	84.3	82.4	94.8
5	VH	98.27	122.27	107.9	116.4	126.8
5	VV	90.27	101.27	105.4	108.4	118.3
5	HV	89.1	102.27	103.4	117.4	113.3

Table A-9. Transmission loss (dB) measurements for woods in winter, 7.6-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	83.6	91.4	92.3	88.6	96.3
2.7	VH	105.6	107.4	112.3	108.6	116.3
2.7	VV	93.93	108.4	117.4	110.4	118.4
2.7	HV	99.8	107.3	112.4	111.4	107.3
3.6	HH	81.6	90.4	88.3	86.6	95.3
3.6	VH	102.6	107.3	109.3	108.4	115.3
3.6	VV	92.8	107.4	116.4	112.4	117.3
3.6	HV	101.8	108.3	114.4	105.3	106.3
5	HH	80.8	88.4	86.3	85.4	96.1
5	VH	98.6	106.3	106.3	107.3	117.3
5	VV	92.8	106.4	111.3	112.3	117.3
5	HV	97.8	109.3	107.4	117.3	104.3

Table A-10. Transmission loss (dB) measurements for woods in winter, 22-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	78.4	89.4	90.7	94.23	103.1
2.7	VH	123.4	116.4	113.8	132.07	114.9
2.7	VV	89.4	103.4	101.1	107.57	125.9
2.7	HV	98.4	124.4	107.1	111.47	121.9
3.6	HH	75.4	86.1	90.07	93.07	102.9
3.6	VH	98.4	122.1	106.9	119.07	121.1
3.6	VV	91.4	100.4	99.07	117.57	121.7
3.6	HV	92.4	110.4	100.07	111.4	116.9
5	HH	74.4	88.1	89.7	93.07	104.2
5	VH	98.4	116.1	109.7	114.07	122.1
5	VV	89.4	96.4	98.7	110.9	115.7
5	HV	93.4	101.6	96.9	119.9	109.6

Table A-11. Transmission loss (dB) measurements for woods in winter, 14-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	86.1	92.9	92.1	97.4	109.23
2.7	VH	98.1	110.9	109.9	115.2	120.4
2.7	VV	92.1	108.1	104.1	123.1	121.4
2.7	HV	100.1	111.1	112.1	110.1	125.6
3.6	HH	83.1	92.1	92.2	95.2	107.2
3.6	VH	100.1	107.1	110.2	111.2	122.2
3.6	VV	93.9	104.1	102.1	107.9	130.6
3.6	HV	106.1	111.1	107.1	111.1	122.4
5	HH	79.1	93.1	94.1	94.1	108.2
5	VH	99.1	110.1	112.1	113.9	128.2
5	VV	93.1	104.1	104.1	105.2	118.4
5	HV	95.1	127.1	105.2	109.2	118.4

Table A-12. Transmission loss (dB) measurements for woods in winter, 7.6-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	97.4	92.4	93.1	97.6	109.1
2.7	VH	102.4	112.4	115.1	113.4	127.1
2.7	VV	94.9	114.2	110.1	115.4	141.2
2.7	HV	98.7	115.2	114.1	114.4	122.2
3.6	HH	95.1	91.4	91.2	93.4	135.1
3.6	VH	111.6	111.4	111.2	110.4	128.1
3.6	VV	93.73	111.4	108.1	114.4	130.4
3.6	HV	99.6	112.2	107.4	117.4	119.4
5	HH	91.4	92.4	90.4	93.4	111.4
5	VH	108.4	112.4	111.2	108.4	126.4
5	VV	94.6	110.2	111.4	118.4	123.1
5	HV	96.73	106.2	104.4	112.2	119.2

Table A-13. Transmission loss (dB) measurements for woods in winter, 22-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	113.9	140.4	131.9	124.4	132.2
2.7	VH	119.9	139.6	137.1	143.1	141.1
2.7	VV	112.9	130.9	142.9	140.4	139.1
2.7	HV	119.9	132.9	144.1	136.9	141.1
3.6	HH	116.9	137.4	125.9	128.4	145.9
3.6	VH	124.9	135.6	140.1	146.1	141.1
3.6	VV	116.9	132.9	129.9	131.9	139.6
3.6	HV	115.9	142.8	143.2	138.57	139.1
5	HH	116.9	124.4	122.9	125.2	141.4
5	VH	119.9	131.4	140.1	144.4	137.4
5	VV	123.9	135.9	129.9	131.9	137.7
5	HV	123.9	134.73	145.9	139.6	138.7

Table A-14. Transmission loss (dB) measurements for woods in winter, 14-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	131.7	145.57	154.9	137.23	144.9
2.7	VH	130.9	150.7	143.9	153.23	161.1
2.7	VV	132.1	149.9	142.9	152.23	146.2
2.7	HV	125.9	145.9	142.9	148.23	151.9
3.6	HH	130.9	150.7	141.9	146.23	148.4
3.6	VH	136.9	149.9	155.1	150.23	152.4
3.6	VV	121.9	149.9	141.1	142.23	149.2
3.6	HV	127.9	144.9	146.9	146.23	152.1
5	HH	129.9	137.7	135.9	143.4	147.2
5	VH	133.9	147.7	154.1	147.1	157.4
5	VV	125.9	152.1	148.1	135.9	150.9
5	HV	128.9	143.9	145.1	156.2	148.1

Table A-15. Transmission loss (dB) measurements for woods in winter, 7.6-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2.7	HH	128.9	152.6	146.6	141.7	150.23
2.7	VH	133.9	157.9	153.6	159.7	163.4
2.7	VV	129.4	154.4	150.6	147.7	161.23
2.7	HV	133.1	151.4	160.6	159.7	157.4
3.6	HH	132.7	162.4	142.4	143.7	156.23
3.6	VH	140.9	164.23	163.4	152.7	159.23
3.6	VV	120.1	153.4	144.4	145.6	162.1
3.6	HV	131.1	152.4	159.4	147.6	166.4
5	HH	136.9	145.4	140.4	140.7	153.23
5	VH	134.9	154.4	160.4	148.7	164.23
5	VV	125.1	150.4	150.6	147.7	161.1
5	HV	133.1	158.4	155.4	154.6	157.23

Table A-16. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	82.93	102.27	105.27	102.6	104.93
2	VH	98.93	130.27	127.43	114.6	129.77
2	VV	91.93	104.27	109.43	106.6	115.77
2	HV	97.93	112.27	125.43	121.4	121.77
2.7	HH	79.1	98.27	100.27	98.6	102.77
2.7	VH	93.93	116.43	122.27	110.6	123.77
2.7	VV	89.27	105.43	110.43	110.43	115.77
2.7	HV	95.27	114.27	119.43	124.43	117.77
4	HH	76.93	97.27	99.27	96.6	100.77
4	VH	92.93	117.43	118.27	112.6	128.77
4	VV	88.27	102.43	109.43	106.43	114.77
4	HV	94.27	114.27	117.43	126.43	121.77

Table A-17. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	86.27	100.43	101.6	98.6	111.93
2	VH	100.43	114.43	118.27	125.6	126.77
2	VV	93.43	107.43	113.27	113.6	122.77
2	HV	103.43	117.43	116.43	112.6	131.77
2.7	HH	82.27	98.43	96.43	93.6	107.77
2.7	VH	105.27	113.43	115.43	110.43	128.77
2.7	VV	94.43	108.43	117.43	112.6	120.77
2.7	HV	113.43	115.43	113.43	113.77	127.77
4	HH	81.67	96.43	95.43	91.6	106.77
4	VH	105.27	112.43	113.43	109.43	128.77
4	VV	92.43	108.43	113.43	108.6	120.77
4	HV	98.43	111.43	113.43	106.6	123.77

Table A-18. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	90.93	99.77	103.1	98.1	108.43
2	VH	103.93	117.77	119.93	120.77	124.6
2	VV	98.77	114.77	115.93	120.77	127.6
2	HV	103.77	116.77	115.93	110.77	123.77
2.7	HH	85.93	94.77	97.1	92.93	105.77
2.7	VH	109.77	118.77	115.93	117.77	122.6
2.7	VV	92.93	115.77	129.93	121.93	125.6
2.7	HV	99.93	112.77	112.93	119.93	132.77
4	HH	85.93	95.77	95.93	90.93	105.43
4	VH	114.77	116.77	113.93	113.77	121.6
4	VV	92.93	118.77	120.93	116.77	123.6
4	HV	98.93	108.77	97.93	107.77	135.6

Table A-19. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	86.4	101.4	84.4	85.6	108.7
2	VH	103.4	125.2	110.2	101.6	121.1
2	VV	89.4	109.2	91.4	99.6	115.1
2	HV	108.1	116.2	103.4	100.6	125.1
2.7	HH	86.9	100.4	85.4	85.7	113.7
2.7	VH	103.4	123.4	99.2	102.6	134.9
2.7	VV	90.4	111.2	88.4	93.6	119.1
2.7	HV	100.2	114.2	103.4	103.6	124.1
4	HH	82.2	99.4	84.2	85.6	117.9
4	VH	101.4	119.4	112.4	101.6	122.9
4	VV	99.4	110.4	86.4	100.6	127.1
4	HV	99.2	117.2	103.4	106.6	127.1

Table A-20. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	95.4	101.4	104.6	102.6	115.9
2	VH	98.4	123.4	125.4	123.6	122.9
2	VV	90.4	112.4	109.4	120.6	116.9
2	HV	106.4	123.4	123.6	117.6	125.9
2.7	HH	95.4	101.4	103.4	102.6	115.9
2.7	VH	100.4	128.4	120.4	121.6	121.9
2.7	VV	97.4	111.4	106.6	119.7	132.9
2.7	HV	109.4	113.6	120.6	120.7	125.9
4	HH	88.4	99.4	101.4	101.6	118.9
4	VH	101.4	117.4	121.4	118.7	128.9
4	VV	101.4	110.4	105.6	117.7	135.9
4	HV	106.4	111.4	115.6	119.7	125.9

Table A-21. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	94.9	100.1	99.9	104.9	118.1
2	VH	104.1	119.1	119.9	117.7	130.9
2	VV	94.9	120.1	114.9	126.9	119.9
2	HV	100.7	120.1	122.1	115.7	146.9
2.7	HH	97.9	99.1	99.9	103.9	120.1
2.7	VH	112.7	121.1	120.9	119.9	130.1
2.7	VV	98.9	118.1	116.9	119.7	132.9
2.7	HV	98.9	116.1	119.1	114.7	136.9
4	HH	102.7	98.1	99.9	101.9	123.1
4	VH	110.7	115.1	117.9	119.9	138.9
4	VV	99.9	118.1	112.9	119.9	137.9
4	HV	99.1	110.1	113.1	126.7	147.1

Table A-22. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	89.1	102.2	99.4	103.6	115.6
2	VH	96.1	121.2	119.2	113.6	134.9
2	VV	92.1	107.2	103.2	102.4	115.9
2	HV	107.1	117.2	116.4	124.4	126.9
2.7	HH	87.1	105.2	100.4	102.6	111.7
2.7	VH	96.1	119.2	116.2	111.6	131.9
2.7	VV	98.1	107.2	103.4	101.4	117.9
2.7	HV	108.1	120.2	114.4	125.4	126.9
4	HH	83.9	112.2	108.2	107.6	111.7
4	VH	94.9	115.2	127.2	112.6	127.7
4	VV	91.1	109.2	104.4	101.4	118.9
4	HV	103.1	117.2	118.4	121.4	126.9

Table A-23. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	94.4	109.2	107.6	107.6	122.7
2	VH	106.2	126.2	122.2	119.6	134.7
2	VV	102.2	113.2	112.4	114.4	128.7
2	HV	107.4	126.2	125.4	135.6	138.7
2.7	HH	92.4	112.2	107.4	107.6	120.7
2.7	VH	117.2	119.4	121.2	120.6	129.7
2.7	VV	104.2	119.2	109.4	110.6	128.7
2.7	HV	113.4	117.4	128.4	132.6	131.7
4	HH	91.4	118.2	114.4	111.6	119.6
4	VH	106.2	121.2	125.2	123.6	137.7
4	VV	98.4	122.4	111.4	110.6	119.7
4	HV	109.4	121.4	135.4	125.6	149.7

Table A-24. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	100.7	111.6	109.7	111.7	125.6
2	VH	112.9	122.7	121.9	120.7	145.6
2	VV	104.9	119.7	117.9	120.9	130.6
2	HV	104.7	131.6	130.7	119.7	147.6
2.7	HH	105.9	113.7	109.7	108.9	123.7
2.7	VH	112.6	123.7	119.9	120.9	142.6
2.7	VV	107.9	123.7	117.9	116.7	132.2
2.7	HV	114.7	123.6	129.7	122.7	142.6
4	HH	101.7	118.7	116.7	111.9	122.5
4	VH	124.7	124.7	123.9	125.9	135.6
4	VV	103.7	126.7	119.9	115.7	129.6
4	HV	106.2	119.6	128.9	123.7	138.6

Table A-25. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	117.4	132.9	113.9	109.4	138.4
2	VH	123.4	142.7	141.7	124.1	146.6
2	VV	119.6	140.7	119.9	117.9	145.9
2	HV	123.6	143.7	120.9	120.9	146.9
2.7	HH	120.2	141.7	109.9	112.2	141.4
2.7	VH	122.2	147.7	124.7	126.1	149.6
2.7	VV	123.6	136.9	115.9	115.9	140.9
2.7	HV	121.6	143.7	121.9	121.9	149.9
4	HH	125.4	135.7	110.7	111.1	141.6
4	VH	129.4	139.9	125.9	122.1	150.6
4	VV	122.6	131.7	115.9	114.9	140.9
4	HV	123.6	141.7	123.9	118.9	148.9

Table A-26. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m range	967-m range	983-m range	1000-m range	1930-m range
2	HH	130.9	143.9	127.9	137.4	149.7
2	VH	138.9	161.1	140.4	149.4	152.7
2	VV	121.9	148.1	136.6	154.4	160.6
2	HV	136.1	156.1	142.6	152.4	158.6
2.7	HH	131.9	150.1	124.9	138.4	156.6
2.7	VH	134.9	156.1	139.6	156.2	159.6
2.7	VV	126.9	149.1	137.7	140.4	149.6
2.7	HV	128.1	154.1	141.6	142.4	155.6
4	HH	123.9	150.1	126.6	137.2	151.7
4	VH	160.9	160.9	138.6	149.1	157.6
4	VV	148.1	146.1	133.7	140.4	145.6
4	HV	156.1	153.1	139.6	143.4	156.6

Table A-27. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	410-m Range	967-m range	983-m range	1000-m range	1930-m range
2	HH	137.2	151.9	146.2	140.2	174.9
2	VH	134.1	157.9	156.2	160.2	167.7
2	VV	129.2	151.9	155.2	159.2	170.9
2	HV	132.2	163.9	158.2	148.9	172.7
2.7	HH	134.2	152.9	144.2	139.2	163.9
2.7	VH	135.1	163.9	164.2	162.2	169.7
2.7	VV	130.4	152.9	161.2	156.1	164.9
2.7	HV	144.1	156.9	154.2	152.9	169.7
4	HH	126.1	147.9	140.2	139.2	167.7
4	VH	135.1	161.9	156.2	158.1	163.9
4	VV	126.2	151.9	156.2	142.9	160.7
4	HV	133.2	149.9	149.2	148.9	175.7

Table A-28. Statistical transmission loss data in decibels (as described in sect. 2.4).

96.1	96.1	96.1	95.1	95.1	93.93	96.1
96.27	96.1	96.1	96.1	96.1	95.1	96.1
98.27	96.1	96.1	97.1	97.1	96.93	96.1
98.27	97.1	97.1	97.1	97.1	96.93	96.93
98.27	96.1	97.1	96.1	96.1	95.93	95.93
96.1	96.1	97.1	95.1	95.1	95.93	95.93
96.1	96.1	95.1	96.1	94.04	96.1	93.93

Table A-29. Multipath measurements (dB) in clearing.

Transmit antenna height (m)	145 MHz	223 MHz	300 MHz	910 MHz
6.2	77.9	76.77	74.73	73.07
7.2	77.23	75.6	73.74	74.24
8.2	76.4	75.43	73.74	74.07
9.2	74.53	72.6	71.74	76.07
10.2	73.53	72.07	71.77	79.4
11.2	72.56	71.1	71.07	93.4
12.2	71.9	70.1	70.57	83.9
13.2	71.03	70.07	70.24	78.57
14.2	71.23	70.47	69.57	74.37
15.2	70.4	69.73	69.4	73.24
16.2	70.07	69.07	69.23	72.87
17.2	69.9	68.77	68.74	72.43
18.2	69.73	68.6	68.9	72.74
19.2	68.73	68.6	68.74	73.9
20.2	70.57	68.27	69.07	74.43
21.2	69.57	69.77	68.9	78.37

Table A-30. Multipath measurements (dB) in woods.

Transmit antenna height (m)	145 MHz	223 MHz	300 MHz	910 MHz
6.2	85.23	93.13	99.7	121.27
7.2	85.23	93.23	100.73	117.77
8.2	84.93	93.13	103.77	121.73
9.2	83.06	88.93	117.4	122.43
10.2	81.93	86.93	110.07	114.43
11.2	81.43	85.93	108.4	114.27
12.2	79.93	84.73	98.2	119.77
13.2	78.53	85.23	92.2	115.23
14.2	77.9	83.8	91.77	116.57
15.2	77.53	82.9	90.57	110.23
16.2	77.2	81.8	89.37	104.1
17.2	76.2	80.8	87.87	103.5
18.2	75.4	80.3	86.77	102.03
19.2	74.9	79.4	86.07	107.7
20.2	74.9	79.3	85.74	115.7
21.2	75.2	78.9	85.57	114.9

Appendix B.— Phase II Measurements

Table B-1. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1000-m range	4700-m range
1	HH	133.47	128.77
1	VH	146.47	138.97
1	VV	111.63	143.97
1	HV	127.47	144.97
2.7	HH	96.47	120.8
2.7	VH	107.47	141.13
2.7	VV	110.47	132.97
2.7	HV	130.63	128.13

Table B-2. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	121.97	135.13
1	VH	136.13	149.13
1	VV	126.13	143.13
1	HV	136.47	141.8
2.7	HH	118.47	130.3
2.7	VH	132.13	149.13
2.7	VV	124.47	147.47
2.7	HV	132.97	142.8

Table B-3. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 145 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	120.13	132.13
1	VH	135.97	148.13
1	VV	125.97	151.47
1	HV	137.97	143.47
2.7	HH	118.13	125.13
2.7	VH	132.3	138.13
2.7	VV	124.13	149.47
2.7	HV	132.97	138.13

Table B-4. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 223 MHz, for HH, VH, VV, and H.

Receiver height (m)	Polarization	1000-m range	4700-m range
1	HH	129.63	131.97
1	VH	137.63	137.97
1	VV	132.63	133.97
1	HV	117.47	139.97
2.7	HH	102.63	127.97
2.7	VH	113.97	132.97
2.7	VV	117.97	130.97
2.7	HV	105.97	133.97

Table B-5. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	118.13	131.97
1	VH	137.47	141.97
1	VV	130.3	142.97
1	HV	141.3	140.97
2.7	HH	113.3	130.97
2.7	VH	118.13	141.97
2.7	VV	115.47	134.97
2.7	HV	119.47	134.47

Table B-6. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 223 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	123.13	143.97
1	VH	140.13	145.63
1	VV	129.13	141.97
1	HV	128.13	152.63
2.7	HH	122.13	147.97
2.7	VH	137.13	147.63
2.7	VV	126.3	139.97
2.7	HV	126.97	145.97

Table B-7. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1000-m range	4700-m range
1	HH	128.13	134.64
1	VH	137.13	155.97
1	VV	114.13	144.97
1	HV	127.97	147.97
2.7	HH	108.47	136.13
2.7	VH	117.97	149.13
2.7	VV	109.13	141.97
2.7	HV	125.13	145.13

Table B-8. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	129.3	149.97
1	VH	140.3	158.13
1	VV	144.3	147.97
1	HV	133.3	155.97
2.7	HH	124.3	153.97
2.7	VH	137.3	163.97
2.7	VV	131.3	157.97
2.7	HV	137.3	154.97

Table B-9. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 300 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	131.97	151.47
1	VH	146.8	158.13
1	VV	143.47	150.47
1	HV	146.97	155.13
2.7	HH	133.63	146.47
2.7	VH	139.8	160.13
2.7	VV	154.8	155.47
2.7	HV	144.8	150.47

Table B-10. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 435 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1000-m range	4700-m range
1	HH	133.47	160.47
1	VH	146.47	155.47
1	VV	121.97	146.47
1	HV	137.8	151.47
2.7	HH	120.63	147.47
2.7	VH	135.47	153.63
2.7	VV	120.13	152.47
2.7	HV	138.13	156.47

Table B-11. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 435 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	148.97	168.47
1	VH	142.47	161.47
1	VV	145.47	157.47
1	HV	152.63	158.47
2.7	HH	140.8	156.97
2.7	VH	145.63	167.47
2.7	VV	133.63	154.97
2.7	HV	142.47	167.47

Table B-12. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 435 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	149.63	169.47
1	VH	161.63	165.47
1	VV	150.47	168.47
1	HV	152.97	165.47
2.7	HH	143.63	161.47
2.7	VH	155.63	169.47
2.7	VV	144.3	168.47
2.7	HV	144.437	166.47

Table B-13. Transmission loss (dB) measurements for woods in summer, 22-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1000-m range	4700-m range
1	HH	146.37	166.87
1	VH	154.37	165.87
1	VV	143.37	162.87
1	HV	150.37	169.87
2.7	HH	134.03	170.03
2.7	VH	151.53	163.03
2.7	VV	133.37	171.03
2.7	HV	143.37	160.87

Table B-14. Transmission loss (dB) measurements for woods in summer, 14-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	158.87	176.03
1	VH	165.53	170.87
1	VV	158.53	174.87
1	HV	162.87	173.87
2.7	HH	158.87	177.87
2.7	VH	162.87	175.87
2.7	VV	154.53	173.87
2.7	HV	165.53	171.87

Table B-15. Transmission loss (dB) measurements for woods in summer, 7.6-m transmitter height at 910 MHz, for HH, VH, VV, and HV.

Receiver height (m)	Polarization	1930-m range	4700-m range
1	HH	175.87	178.03
1	VH	173.7	179.87
1	VV	169.87	176.87
1	HV	170.87	183.83
2.7	HH	169.7	180.83
2.7	VH	170.87	186.87
2.7	VV	171.87	183.17
2.7	HV	171.87	180.83

Table B-16. Transmission loss (dB) for tree-line proximity measurements (described in sect. 2.3).

145 MHz

Receiver height (m)	Position	22-m transmitter height	14-m transmitter height	7.6-m transmitter height
1	A	110.63	133.63	132.97
1	B	110.63	128.47	129.13
1	C	110.63	126.47	134.13
1	D	108.63	133.67	133.13
1	1	130.47	132.47	129.69
1	2	131.47	130.47	130.63
1	3	131.47	128.13	125.63
1	4	132.47	123.13	127.63
1	5	124.47	126.13	133.13
1	6	131.53	131.63	130.47
2.7	A	101.63	126.47	124.13
2.7	B	98.63	125.47	136.13
2.7	C	99.47	118.97	129.13
2.7	D	103.47	118.47	122.47
2.7	1	122.47	118.63	121.97
2.7	2	120.47	121.47	121.47
2.7	3	127.47	120.47	122.47
2.7	4	122.47	113.63	119.47
2.7	5	118.47	113.63	123.3
2.7	6	117.47	118.13	123.13

223 MHz

Receiver height (m)	Position	22-m transmitter height	14-m transmitter height	7.6-m transmitter height
1	A	102.02	127.13	118.97
1	B	110.97	129.13	131.97
1	C	102.97	132.13	138.97
1	D	108.97	132.63	135.63
1	1	126.97	129.63	133.63
1	2	125.97	130.97	131.13
1	3	119.97	133.63	131.63
1	4	121.97	125.63	133.3
1	5	117.63	125.63	133.63
1	6	130.13	127.47	133.13
2.7	A	101.97	126.13	128.63
2.7	B	97.97	125.13	132.13
2.7	C	100.97	125.13	130.63
2.7	D	103.97	121.13	126.63
2.7	1	120.97	123.3	126.63
2.7	2	117.97	123.13	128.63
2.7	3	126.97	131.97	125.63
2.7	4	114.97	118.63	124.63
2.7	5	117.63	115.63	126.63
2.7	6	115.13	122.63	125.63

Table B-16 (cont'd). Transmission loss (dB) for tree-line proximity measurements (described in sect. 2.3).

300 MHz

Receiver height (m)	Position	22-m transmitter height	14-m transmitter height	7.6-m transmitter height
1	A	114.13	137.13	139.13
1	B	107.13	129.13	142.13
1	C	110.13	141.13	144.97
1	D	108.13	135.47	138.97
1	1	126.13	136.97	137.97
1	2	125.13	129.97	135.63
1	3	122.13	136.8	137.8
1	4	125.13	135.97	144.63
1	5	113.47	142.8	145.8
1	6	136.63	152.97	149.63
2.7	A	110.13	135.13	138.47
2.7	B	112.13	137.13	146.97
2.7	C	111.13	133.13	143.13
2.7	D	106.13	130.13	135.97
2.7	1	123.13	130.63	136.8
2.7	2	120.13	129.47	135.8
2.7	3	127.13	136.8	141.6
2.7	4	123.13	130.97	137.63
2.7	5	121.47	125.8	139.63
2.7	6	122.47	126.8	144.63

435 MHz

Receiver height (m)	Position	22-m transmitter height	14-m transmitter height	7.6-m transmitter height
1	A	122.47	141.47	150.13
1	B	121.47	136.47	161.13
1	C	120.13	139.47	150.13
1	D	119.47	144.13	150.13
1	1	130.47	137.13	146.13
1	2	130.97	134.13	143.13
1	3	132.47	138.13	154.13
1	4	131.47	135.13	150.13
1	5	122.63	139.13	150.97
1	6	131.63	134.97	152.13
2.7	A	120.47	142.47	149.13
2.7	B	126.47	162.47	157.97
2.7	C	121.97	144.47	158.13
2.7	D	123.63	142.47	154.13
2.7	1	131.47	135.13	155.13
2.7	2	128.47	138.13	145.97
2.7	3	151.47	137.47	155.13
2.7	4	140.13	143.13	151.13
2.7	5	134.63	136.13	151.13
2.7	6	127.63	143.13	160.13

Table B-16 (cont'd). Transmission loss (dB) for tree-line proximity measurements (described in sect. 2.3).

910 MHz

Receiver height (m)	Position	22-m transmitter height	14-m transmitter height	7.6-m transmitter height
1	A	140.37	155.03	174.03
1	B	146.37	167.53	174.83
1	C	142.37	155.53	173.53
1	D	140.37	161.53	177.83
1	1	154.37	172.53	178.67
1	2	152.37	156.03	169.17
1	3	149.37	158.37	172.53
1	4	146.37	155.53	169.03
1	5	132.03	148.53	174.83
1	6	142.03	150.03	170.37
2.7	A	144.37	164.03	172.03
2.7	B	145.37	163.87	183.33
2.7	C	141.37	156.53	172.37
2.7	D	151.37	164.37	165.03
2.7	1	159.37	164.53	173.03
2.7	2	144.37	151.53	183.17
2.7	3	147.7	149.53	174.37
2.7	4	161.37	158.87	173.03
2.7	5	139.03	146.53	166.33
2.7	6	143.03	160.53	164.87

Appendix C.—GPS Positions

Table C-1. Transmitter positions.

Location	Lat.	Long.
Woods	N 39° 26.691′	W 076° 12.022′
Clearing	N 39° 26.698′	W 076° 12.284′

Table C-2. Receiver positions.

Location and range (m)	Lat.	Long.
Woods 410	N 39° 26.886′	W 076° 11.868′
Woods 1000	N 39° 27.204′	W 076° 11.810′
Woods 1930	N 39° 27.653′	W 076° 11.520′
Woods 4700	N 39° 27.653′	W 076° 11.520′
Clearing 410	N 39° 26.893′	W 076° 12.145′
Clearing 1000	N 39° 27.152′	W 076° 11.917′
Clearing 1930	N 39° 27.604′	W 076° 11.623′
Clearing 4300	N 39° 28.757′	W 076° 10.770′

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Designing a radar system capable of detecting objects concealed by foliage requires path-loss data and the development of path-loss prediction models. The challenge is to design a system with antenna elements of manageable size, while keeping foliage signal attenuation as small as possible. We took a series of measurements to characterize path loss in a mostly deciduous forest. Results show that the parameter values that give the least attenuation because of the intervening woods are the lowest frequencies and transmit horizontal, receive horizontal polarization (HH).

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