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Vegetation Loss Measurements at 9.6, 28.8, 57.6, and 96.1 GHz Through a Conifer Orchard in Washington State

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Vegetation Loss Measurements at 9.6, 28.8, 57.6, and 96.1 GHz Through a Conifer Orchard in Washington State

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Propagation measurements were made in the Olympic National Forest of Washington state during October 1987 to examine millimeter-wave signal propagation through conifer vegetation. Linearly polarized continuous-wave signals at 9.6, 28.8, 57.6, and 96.1 GHz were used to evaluate attenuation, depolarization, and backscattering from conifer trees. Azimuth and elevation scans were conducted for various transmitter heights and path lengths. Results from the measurements are presented and compared with data gathered from similar measurements taken through deciduous vegetation.

Key words: attenuation; backscatter; depolarization; millimeter-wave; propagation; vegetation

1. INTRODUCTION

In 1982, the Institute for Telecommunication Sciences (ITS) conducted a measurement program to determine the propagation characteristics of millimeter-wave signals through deciduous vegetation. These measurements, at 9.6, 28.8, and 57.6 GHz, emphasized the determination of received signal properties as a function of foliage depth in order to support the development of a model for predicting link performance. Results of these measurements indicate that the received signal levels are highly dependent on the relative position and pointing of the antennas in the orchard (Schwering et al., 1988; Violette et al., 1983). A significant difference in signal loss between foliated and defoliated states of the orchard is also apparent. As an extension of this work, ITS conducted similar measurements in 1987 to study the propagation of millimeter-wave signals through conifer vegetation.

These conifer propagation measurements were made in late October and early November 1987 at a U.S. Forest Service seed orchard in the Olympic National Forest of Washington State. This location was chosen for its uniform tree sizes and densities, which provided a controlled measurement environment. Most of the measurements were made

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through Douglas fir trees because of the abundance of these trees in the seed orchard. However, a few measurements were also made through both ponderosa pine and yellow pine trees. The millimeter-wave equipment used in the 1982 deciduous propagation measurements was modified to include a channel operating at 96.1 GHz to enhance the measurement capabilities of the system. Measurements were thus made using linearly polarized continuous-wave (cw) signals at 9.6, 28.8, 57.6, and 96.1 GHz.

The results of these measurements are presented in this report. Measurements were made on several paths, varying in length from 55 to 177 m. The data gathered on one representative path are presented in detail including azimuthal and elevation scans of the receiving antennas for both copolarized and cross-polarized signals. Data from all of the paths are then combined to produce plots of propagation loss versus foliage depth. Data from depolarization and backscatter measurements as well as transmitter height scans are also presented.

2. EXPERIMENT DESCRIPTION

Selecting a suitable location for the conifer propagation measurements involved several considerations. An examination of naturally forested areas revealed a nonuniform foliage density, which was difficult to describe in terms of depth. Naturally forested areas also exhibited a variety of tree types and significant undergrowth. For the purposes of these measurements, a stand of uniformly planted trees, all of the same type and approximate size and free from underbrush, was sought. Measurements conducted in such a uniform stand of trees would provide propagation data as a function of the trees of interest and not of other vegetation.

The location selected, based on these criteria, was the U. S. Forest Service's Dennie Ahl Seed Orchard in Washington State's Olympic National Forest. A map showing the location of the seed orchard appears in Figure 1. This orchard is comprised of uniformly planted conifer trees of nearly identical size and shape. An aerial photograph of the orchard is shown in Figure 2. The section of the orchard in the upper right-hand corner of the photograph was used for the propagation measurements. The uniformity of tree size and density is evident from this view of the orchard. (The photo was actually taken 5 years before the measurements were made; therefore, the trees were larger when the measurements were made than they appear in the photograph.)

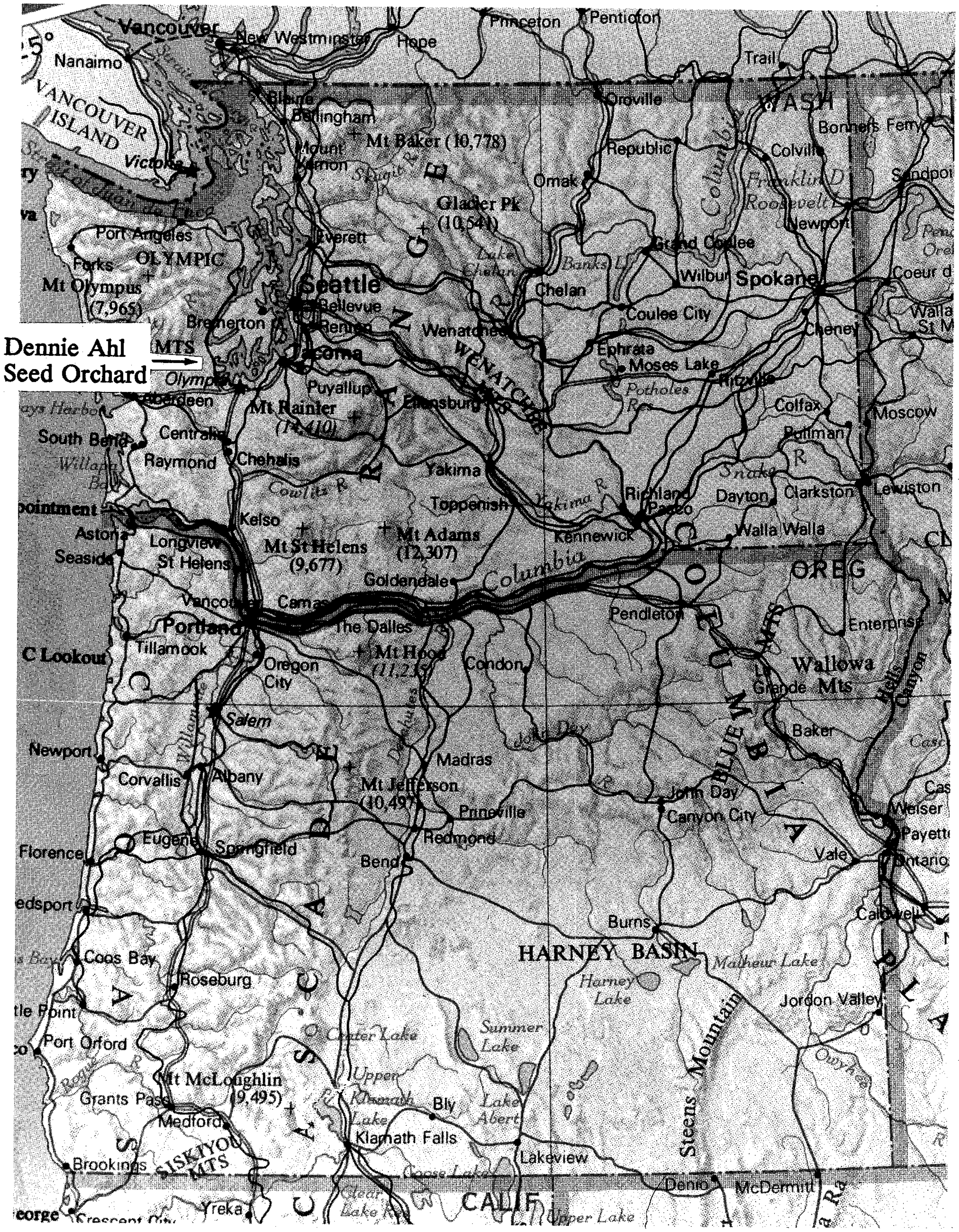

Figure 1. Map illustrating location of Dennie Ahl Seed Orchard.

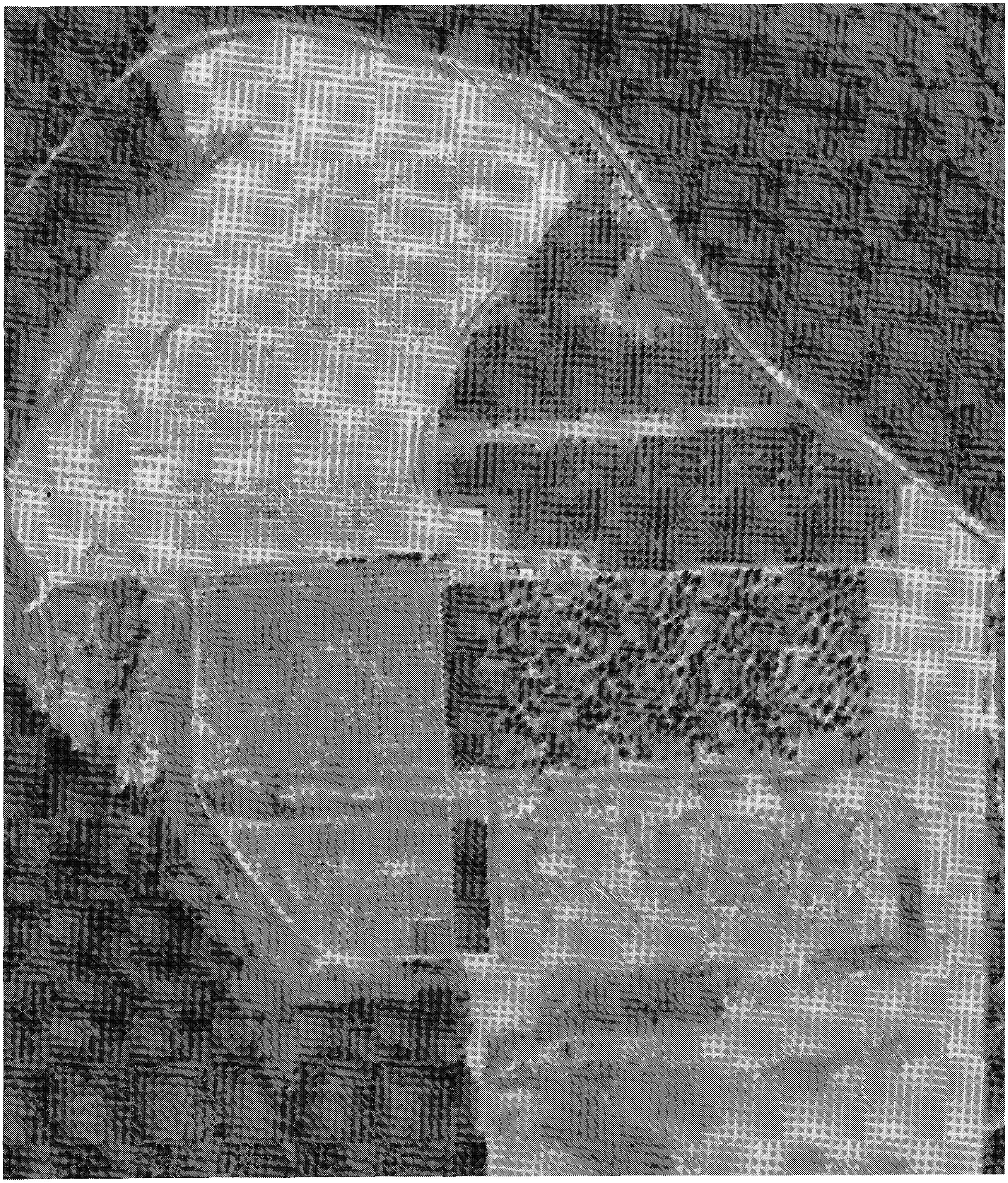

Figure 2. Aerial photograph of Dennie Ahl Seed Orchard.

Most of the trees in the Dennie Ahl Seed Orchard are of the Douglas fir variety; therefore, most of the propagation measurements were conducted in stands of Douglas firs. However, a few measurements were made in the presence of ponderosa pine and white pine trees. The terrain in the seed orchard is generally flat, although there is a slight slope to it (less than 3 degrees). All the measurements were made on the most level ground available.

The Douglas fir trees in the orchard were planted in a grid pattern, with a spacing of approximately 6.1 m between trees. The trees are the same age and are thus quite uniform in size and density. The Douglas fir trees are roughly 10 to 12 m high and 5 to 6 m wide at their broadest point. The initial branching occurs at about the 1.5- to 2-m height with significant branching at the 3- to 5-m level, leaving mainly trunks below the 1.5-m level. Trees typical of the Douglas firs in the orchard are shown in Figure 3. The needles on the Douglas fir trees are roughly 2 to 4 cm in length and cover all of the limbs and branches. The Douglas fir branch shown in Figure 4 is typical of those found in the orchard.

Measurements were taken on seven different paths within the Douglas fir orchard as well as one path each with ponderosa pine and white pine trees. These paths varied in length from 55 to 177 m and contained from 1 to 14 trees. An unobstructed path was also used for equipment calibration. The transmitter and receiver were carefully positioned on each path to provide the desired geometry. On each of the seven paths obscured by Douglas fir trees, a comprehensive set of measurements was taken. These data sets include azimuth and elevation angle scans by the receiver terminal at transmitter heights of 1, 3, and 5 m. These scans were conducted for copolarized received signals and then for cross-polarized received signals using an orthomode transducer and separate scans. Depolarization levels were calculated from the difference between the co- and cross-polarized signals. Transmitter height scans were also conducted on selected paths, as were backscatter measurements.

The link configurations used to obtain these data are represented pictorially in Figure 5. Representative signal traces are also shown in this figure. A description of each configuration follows:

- Azimuthal angle scans

  In this configuration the transmitter and receiver are set at fixed locations and the receiver antennas are scanned in the azimuth plane. Calibration runs were performed in this mode.

Figure 3. Photograph of typical Douglas fir trees in the orchard.

Figure 4. Close-up photograph of typical Douglas fir branch.

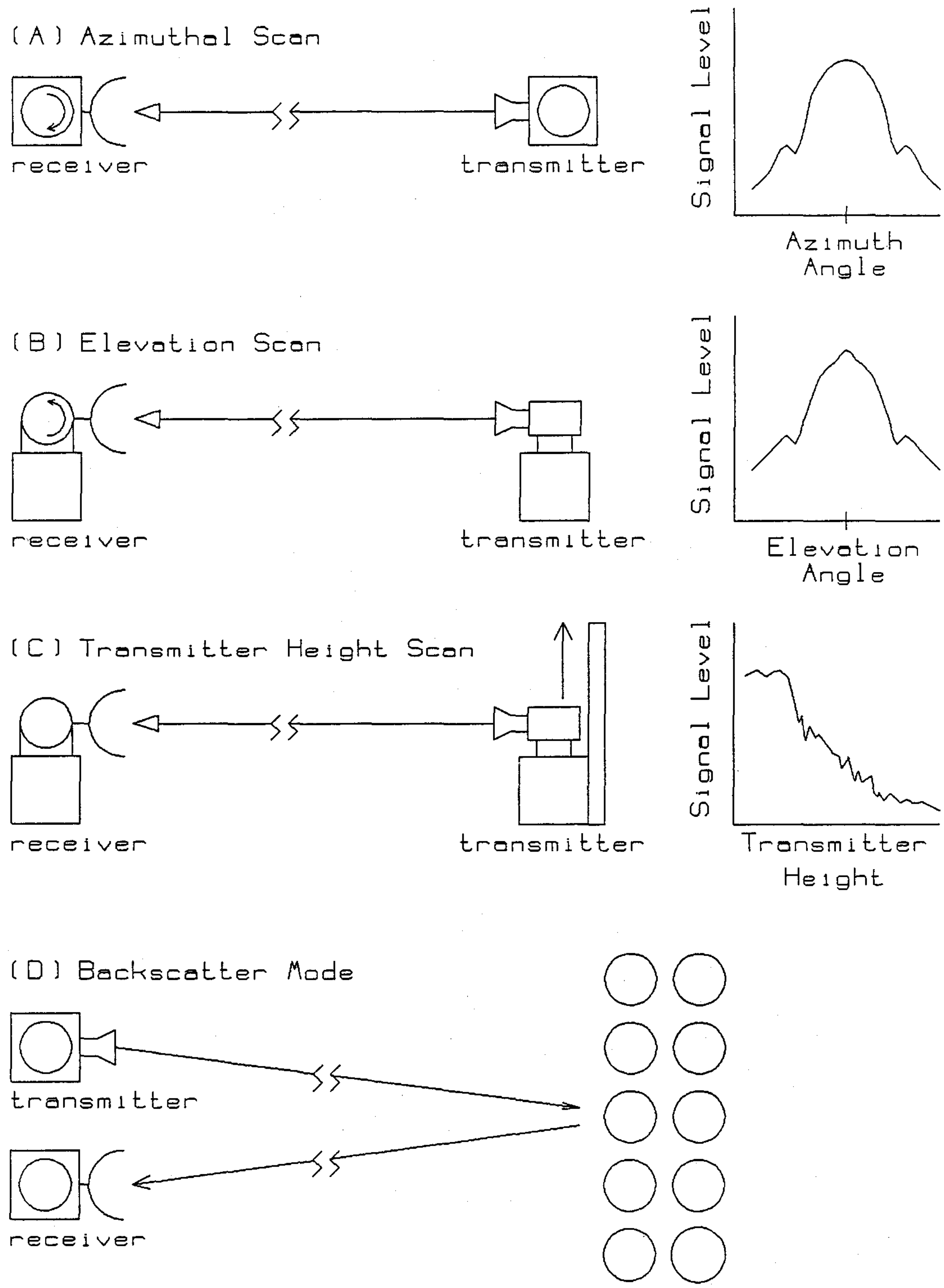

Figure 5. Test link operating configurations.

- Elevation angle scans

  The transmitter and receiver are set at fixed locations and the receiver antennas are scanned in the elevation plane. Calibration runs were also performed in this mode.
- Transmitter height scans

  The transmitter and receiver are set at a fixed distance and the transmitter is moved vertically over a 5-m height range. The vertical travel is small compared to the path length. The receiver antennas are fixed.
- Backscatter mode

  The transmitter and receiver are set side by side in an open field facing the conifer orchard such that the direction of propagation is roughly perpendicular to the edge of the orchard. Both azimuthal and elevation angle scans were conducted in the backscatter mode.

The transmitter and receiver locations were carefully noted on each path to facilitate an accurate representation of the paths on the orchard layout diagram. This diagram, shown in Figure 6, illustrates the locations of the transmitter and receiver relative to the orchard and the adjacent open fields. (A similar diagram for paths 8 and 9 appears in Figure 7.) Table 1 summarizes the various measurement paths, including a transmitter and receiver designation listed under the path number for each path. The transmitter and receiver locations corresponding to these designations are represented in Figure 6. The path length indicated is the distance in meters between the transmitter and receiver antennas and is never totally populated with trees in these measurements. Early in the measurement process it became apparent that on every path (except for the calibration path) the peak signal level did not occur at boresight antenna pointing, but at an antenna position of up to 7 degrees off boresight in the elevation plane. This variation in the receiver antenna position for peak signal is the result of some propagation mechanism present in the orchard. This mechanism may result from re-radiation of the electromagnetic energy by the needles of the trees or perhaps from a ground reflection mode underneath the branches. Due to this phenomenon, measurements were made in both peak signal and boresight antenna pointing modes.

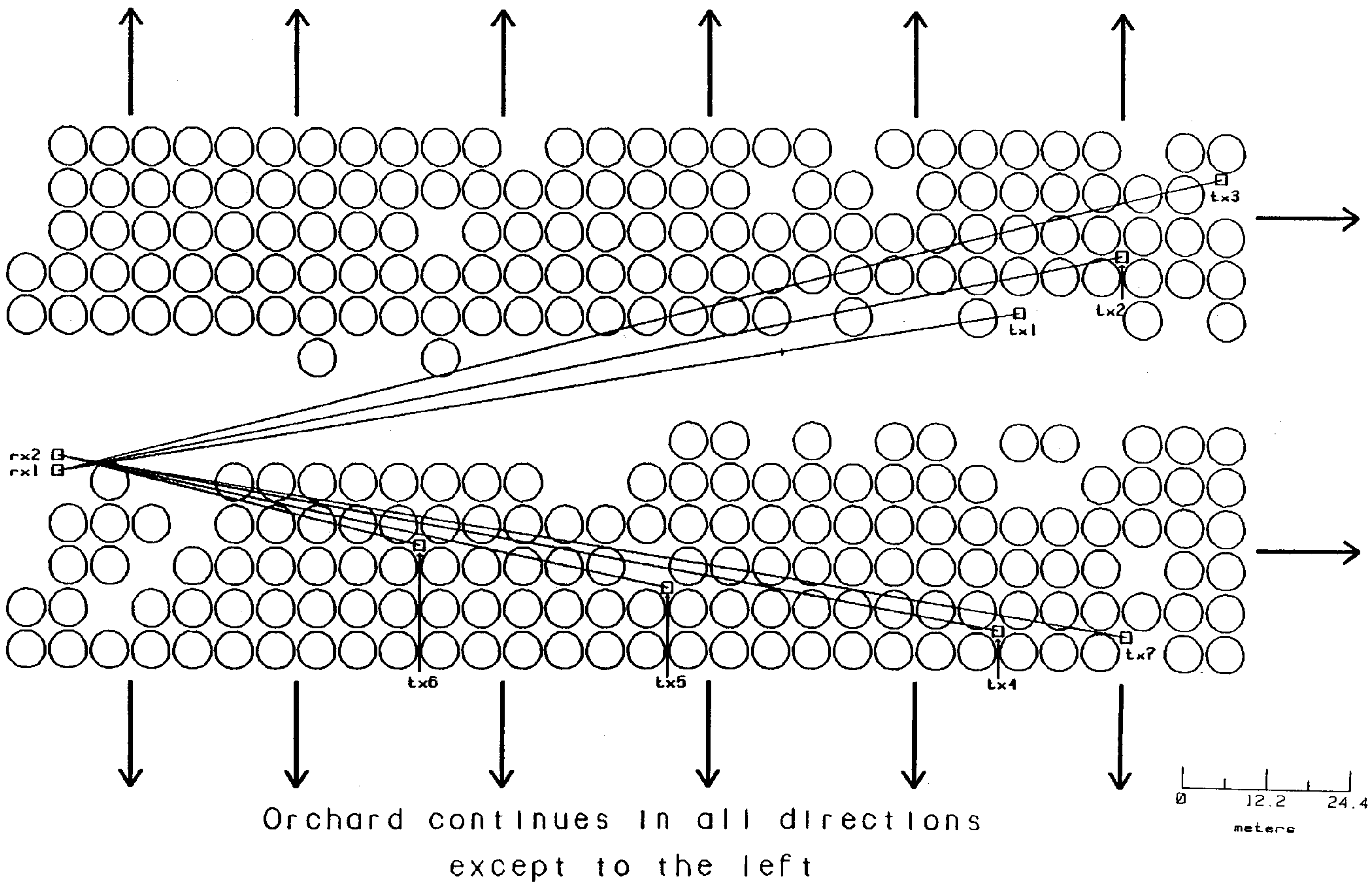

Figure 6. Diagram of orchard layout (paths 1 through 7).

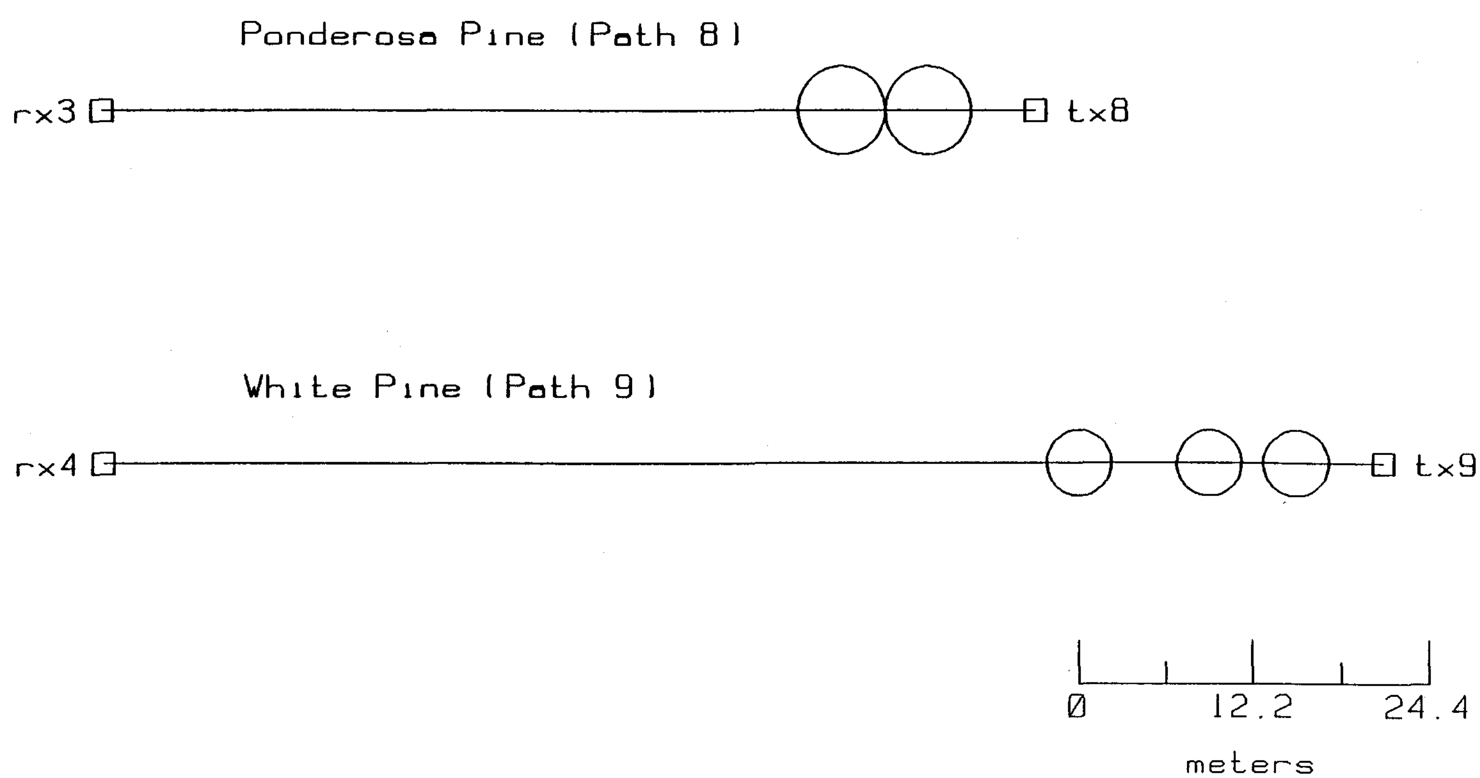

Figure 7. Diagram of orchard layout (paths 8 and 9).

Path Number	Path Length (meters)	Foliage Depth (meters)	Equivalent # of trees	Tree Type
1 tx1-rx1	143	5.33	1.0	Douglas fir
2 tx2-rx1	160	29.7	5.6	Douglas fir
3 tx3-rx1	177	61.0	11.4	Douglas fir
4 tx4-rx2	142	64.8	12.2	Douglas fir
5 tx5-rx2	92	40.4	7.6	Douglas fir
6 tx6-rx2	55	24.4	4.6	Douglas fir
7 tx7-rx2	160	77.7	14.6	Douglas fir
8 tx8-rx3	65	12.0	2.0	Ponderosa pine
9 tx9-rx4	89	11.5	3.0	White pine

3. EQUIPMENT DESCRIPTION

The electronic equipment used to make the propagation measurements was housed in two vehicles that could be positioned in the orchard independently. The transmitter antennas and radio frequency (rf) electronics were mounted directly to an elevator tower, which allowed for continuously variable height adjustments. This tower was rigidly attached to a truck and was thus easily moved to any clearing in the orchard. The receiver antennas and rf electronics were mounted on a pedestal on the back of a van. This van also housed the intermediate frequency (IF) sections of the receivers and the data acquisition computer.

The computer also controlled the antenna pedestal, permitting the receiver antennas to be scanned in either the azimuth or elevation plane.

All of the transmitter and receiver electronics were protected from the elements and housed in thermostatically controlled, electrically shielded boxes. (A constant enclosure temperature is necessary to minimize amplitude and frequency drift of the rf electronics.)

A block diagram of the transmitters appears in Figure 8. In order to maintain phase coherency among the transmitted signals, a single 100 MHz temperature compensated crystal oscillator (TCXO) was used as a reference for all of the transmitters. All four of the channels operated simultaneously and each transmitted an unmodulated continuous-wave signal.

The 9.6-GHz signal was generated from the 100-MHz reference by means of a phase-locked, cavity-tuned X96 multiplier. This multiplier fed a 19-dB-gain horn antenna with 20 mW of rf power at 9.6 GHz. An identical X96 multiplier followed by a varactor tripler produced a 2-mW, 28.8-GHz signal from the 100-MHz reference. The tripler output was used to injection lock a Gunn-type source through a high-isolation ferrite circulator. The Gunn source output (85 mW at 28.8 GHz) fed a 6-dB directional coupler that split the signal into two ports. A 24.5-dB gain horn antenna was fed by 20 mW of the 28.8-GHz signal from the coupler. The remaining power from the coupler (60 mW) drove a varactor doubler (The coupling process resulted in the loss of 5 mW.) The doubler output of 12 mW at 57.6 GHz was fed to a 25.5-dB-gain horn antenna.

The 96.1-GHz transmitter used the 100-MHz TCXO signal as a reference for a phase-locked Gunn oscillator. The 25-mW output of the 96.1-GHz transmitter fed a 27-dB gain horn antenna. All of the channels used compact, low-gain horn antennas to enhance maneuverability of the transmitter terminal in the orchard and because the short path lengths did not require larger, high-gain antennas. All signals were transmitted using vertical linear polarization. The transmitter characteristics are summarized in Table 2.

Table 2. Summary of Transmitter Characteristics

FREQUENCY	POWER OUTPUT (to antenna)	ANTENNA GAIN	ANTENNA BEAMWIDTH
9.6 GHz	20 mW	19.0 dB	20.0 deg
28.8 GHz	20 mW	24.5 dB	10.7 deg
57.6 GHz	12 mW	25.5 dB	9.5 deg
96.1 GHz	25 mW	27.0 dB	8.0 deg

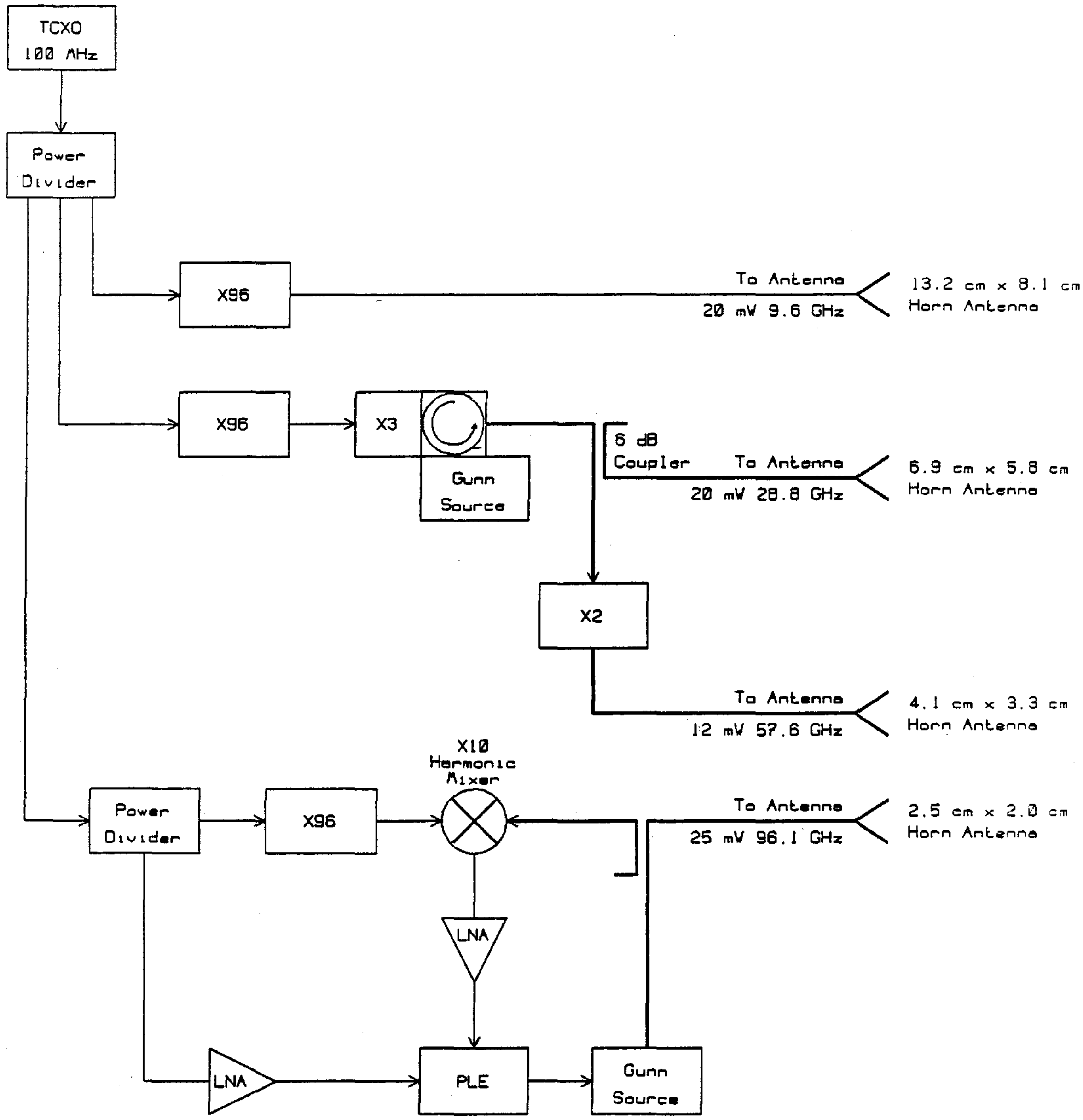

Figure 8. Block diagram of transmitter equipment.

A block diagram of the receivers appears in Figure 9. The incoming signals were intercepted by high gain parabolic dish antennas and then fed to low-noise down-converters. The receiving antennas were mounted on a 1.2-m square plate. Although they were located as close together as was practical, the antennas were separated by as much as 1 m. This fact introduced minor variations in the paths seen by any pair of antennas and should be kept in mind when examining the data. All local oscillator (LO) signals used in the down-conversion process were derived from a 99.9479-MHz, voltage-controlled crystal oscillator (VCXO), which was phase-locked to the received 9.6 GHz signal. The multiplier configurations used to generate the LO signals for the down-converters were the same as those used in their respective transmitters.

The 99.9479-MHz VCXO reference fed an X96 multiplier to generate a 9.595-GHz LO signal. This LO signal was mixed with the 9.6 GHz rf signal to produce a 5-MHz intermediate frequency (IF) for the 9.6-GHz channel. The IF's for the 28.8-, 57.6-, and 96.1-GHz channels, being proportional to the 5-MHz IF of the 9.6-GHz channel, were 15, 30, and 50.0521 MHz, respectively. The IF s, after passing through low-noise preamplifiers, were fed into narrow-band crystal filters and then to ac-to-dc logarithmic amplifiers (log-amps). The log-amps converted the IF signals to dc voltages that are logarithmically proportional to the received rf signal amplitudes. The log-amps have an 80-dB dynamic range with a linearity of +/- 0.5 dB. The 28.8-, 57.6-, and 96.1-GHz receiving antennas were configured with orthomode transducers (OMT's) and manual waveguide switches, allowing the reception of either vertical or horizontal linear polarizations by the receivers. The measured polarization isolation of the OMT s and other receiver characteristics are summarized in Table 3.

Table 3. Summary of Receiver Characteristics

FREQUENCY	GAIN	BEAMWIDTH	ANTENNA POLARIZATION ISOLATION	RECEIVER NOISE FIGURE	RECEIVER SENSITIVITY
9.6 GHz	27.5 dB	7.5 deg	N/A	7.5 dB	-130 dBm
28.8 GHz	46.6 dB	0.84 deg	35 dB	5.5 dB	-130 dBm
57.6 GHz	49.1 dB	0.63 deg	20 dB	6.0 dB	-130 dBm
96.1 GHz	49.3 dB	0.75 deg	30 dB	6.5 dB	-108 dBm

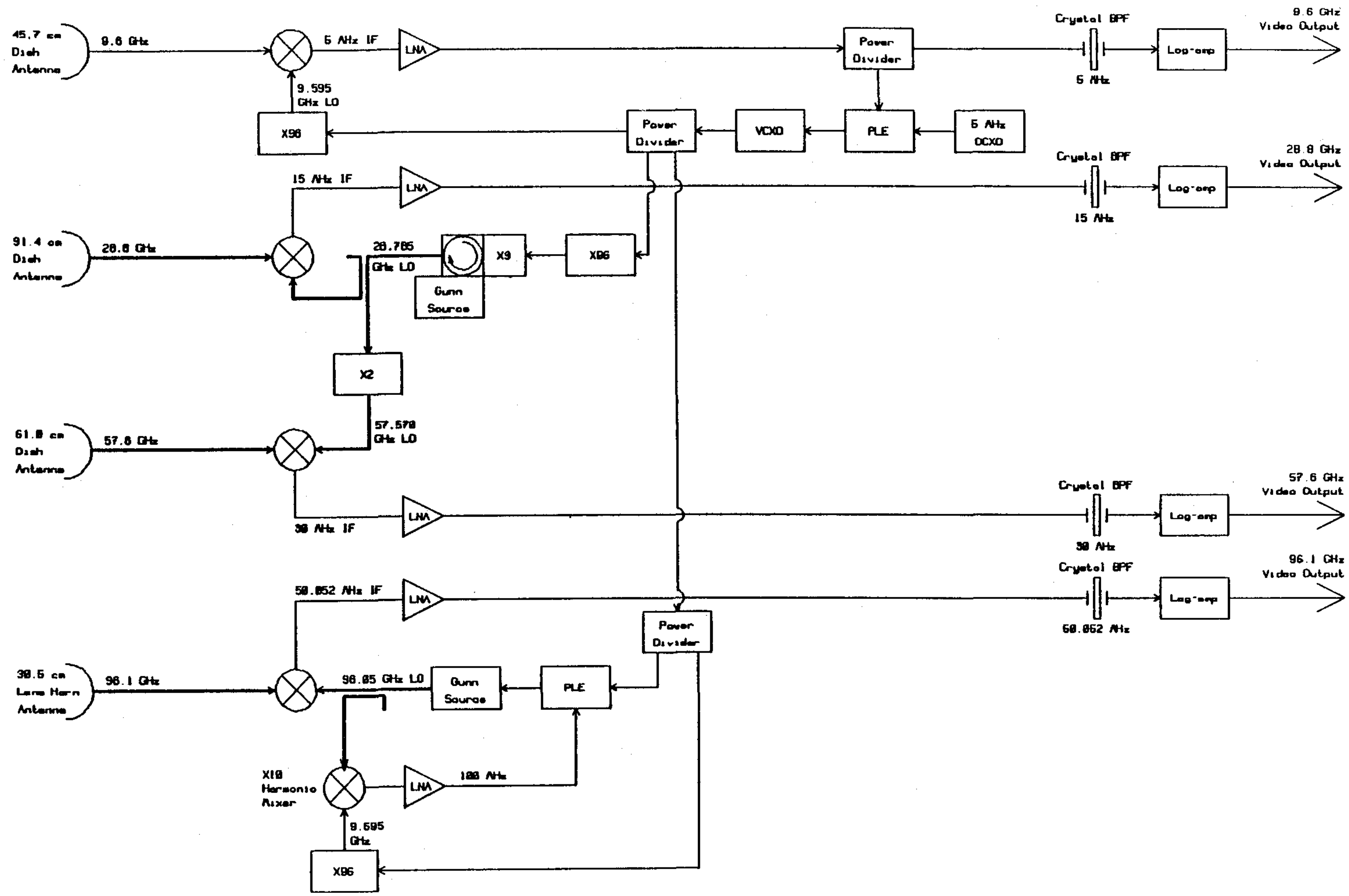

Figure 9. Block diagram of receiver equipment.

The data acquisition and antenna pedestal control functions were carried out on a microcomputer. The computer utilized an analog-to-digital (A/D) converter operating at 100 Hz to sample data during the experiment.

4. DATA ANALYSIS

A complete set of measurements was taken on each of the nine paths used in the measurements. In the analysis of the data, a representative path was chosen for which detailed data are presented. Combined data from all paths are then presented in the form of propagation loss versus foliage depth plots for both peak signal and boresight pointing. Depolarization, height scan, and backscatter data are then discussed. All of the data presented in these plots have been adjusted for free-space loss and gaseous absorption such that the signal loss presented is all attributable to the presence of vegetation on the path.

4.1 Calibration Scans

The millimeter-wave equipment was calibrated on a 174-meter unobstructed path in an open field. An azimuthal scan taken on this calibration path is shown in Figure 10. These plots show received signal level versus azimuth angle for all four frequencies. As in all of the scans presented, the boresight pointing angle is at 0 degrees azimuth and 90 degrees elevation. In this report, elevation angle is referenced to the ground; i.e., a 0 degree elevation angle corresponds to pointing "straight down," a 90 degree elevation angle corresponds to horizontal pointing, and a 180 degree elevation angle corresponds to zenith pointing. The signal levels are normalized to 0 dB at the center (0 degrees) of the -15 degree to +15 degree scan. In addition to supplying a system calibration, these data provide a reference azimuth antenna pattern at each frequency. To produce these patterns, the transmit and receive antennas are first aligned on path for maximum signal and the receive antenna is then scanned in the azimuth plane while its elevation angle remains at 90 degrees.

Figure 11 shows the results of an elevation scan taken on the calibration path. Received signal level versus elevation angle is plotted for all four frequencies. In this figure, the signal levels are also normalized to 0 dB at the center (90 degrees) of the 80- to 100-degree scan. These patterns are generated by first aligning the transmit and receive

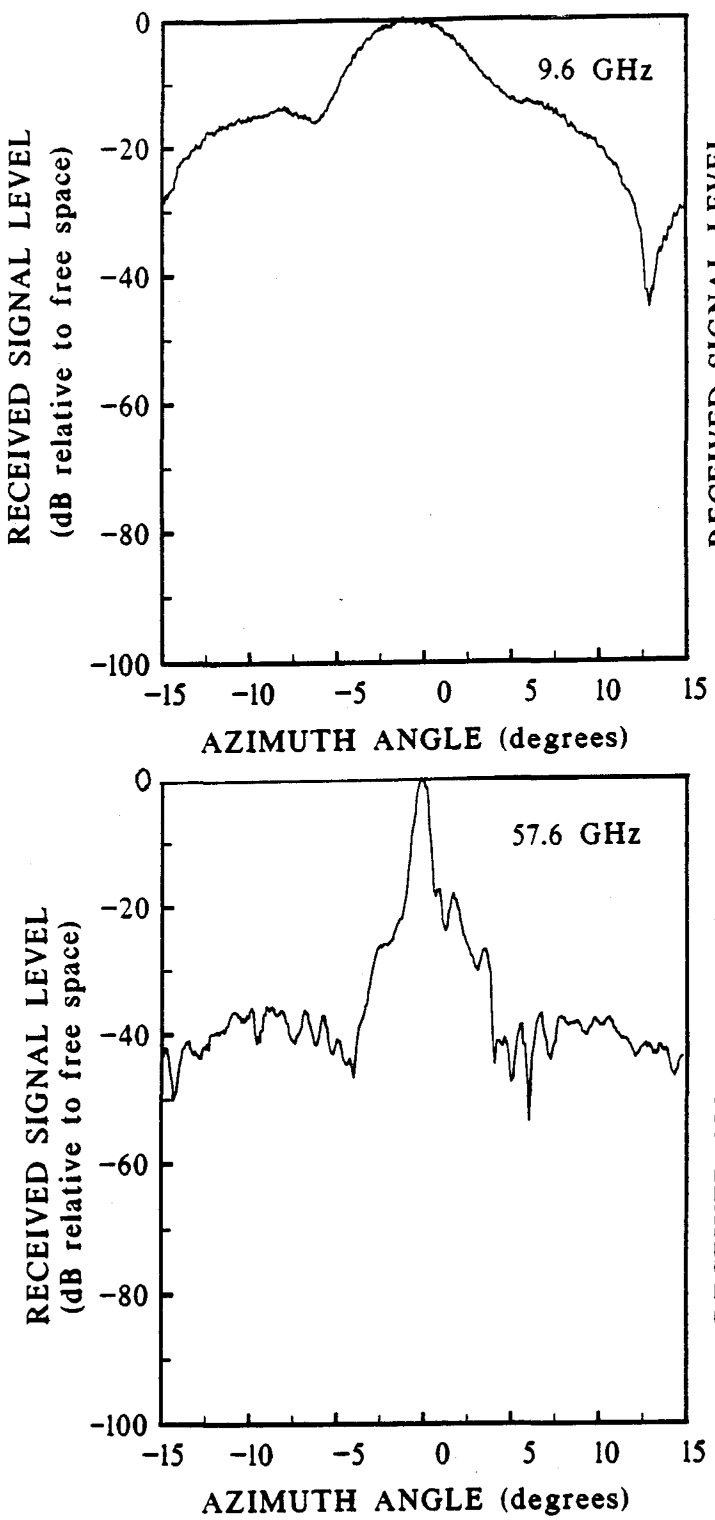

Figure 10. Azimuthal scan of RSL from calibration path.

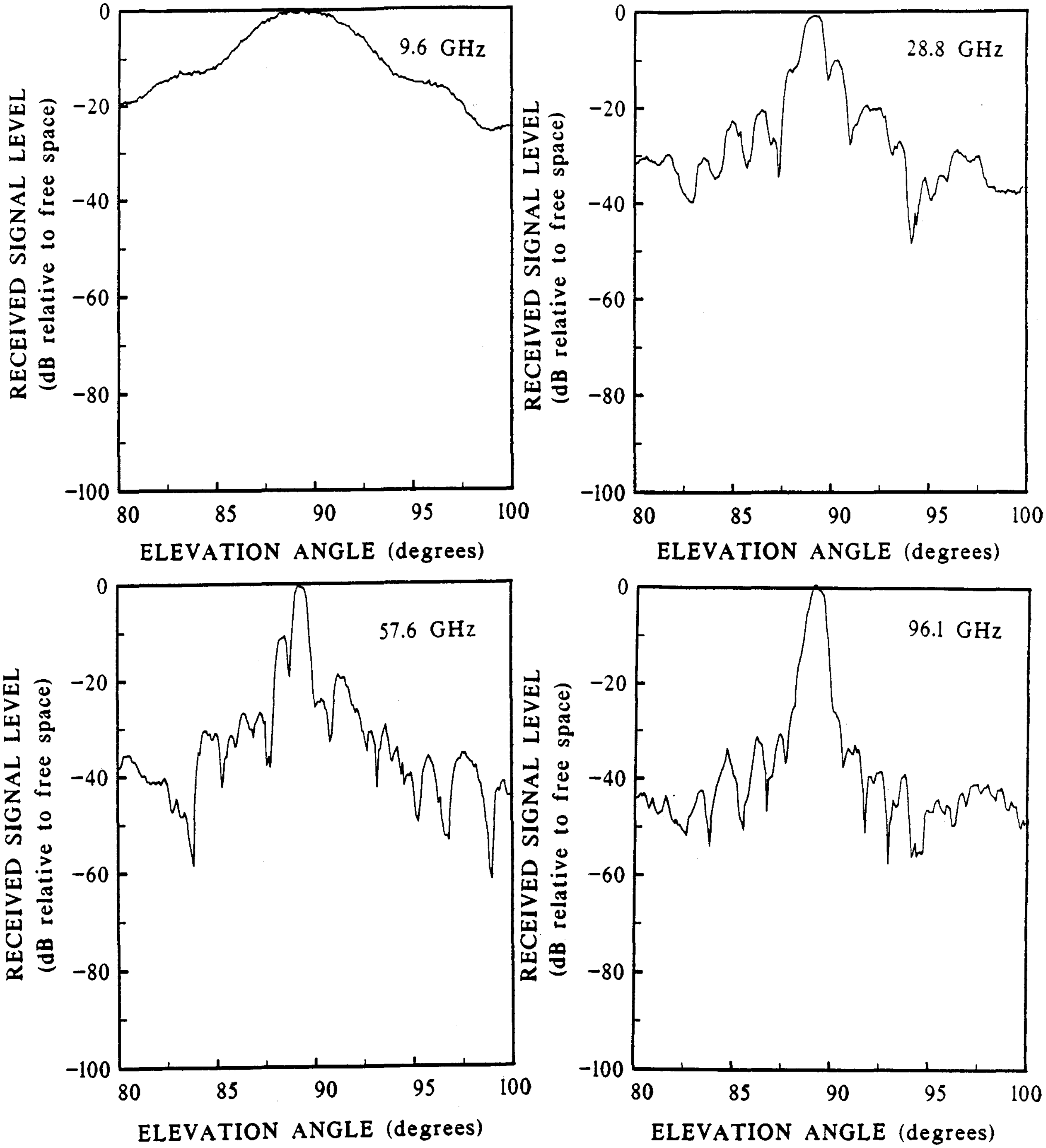

Figure 11. Elevation scan of RSL from calibration path.

antennas for maximum signal and then scanning the receive antennas in the elevation plane while the azimuth angle remains at 0 degrees. In plots of elevation scans, elevation angles of 80 degrees, 90 degrees, and 100 degrees correspond to below horizontal, horizontal, and above horizontal pointing, respectively.

4.2 Representative Path Data

The data from measurements on path 4 (a 143-m path with a foliage depth of 64.8 m) are presented in detail in Figures 12 through 17. These data include azimuthal and elevation scans of both copolarized and cross-polarized received signal levels (RSL's) at 9.6, 28.8, 57.6, and 96.1 GHz. Plots of actual vegetation loss (with the free-space antenna pattern subtracted out) were also generated for the copolarized scans. All of these data were taken at a transmitter height of 3 m.

4.2.1 Copolarized Scans

Figure 12 shows the results of an azimuthal scan of the copolarized received signal levels on path 4. Received signal level is plotted as a function of azimuth angle for all four frequencies. The data in these plots generally have the same shape as in the calibration (see Figure 10) scans except that the levels are lower due to the attenuative effect of the vegetation. The maximum signal levels occur near the center of the azimuthal scan (as would be expected)--except in the 96.1-GHz data. The peak 96.1-GHz signal is off center most likely because of a variation of the foliage density on the path for the 96.1-GHz antennas. This variation in peak signal location in the azimuthal plane is evident in the data from other paths and at all frequencies as well (except at 9.6 GHz, where the wider receiver antenna beamwidth makes this channel less sensitive to slight changes in peak signal pointing). This variation results from: (1) the fact that the antenna pairs at each frequency see slightly different paths due to the antenna locations, and (2) the foliage density varies throughout the orchard. No consistent pattern of peak signal location in the azimuthal plane is evident from path to path; the peak signal, although it may occur to either side of center, usually occurs very near the boresight angle (0 degrees).

In Figure 13 the results of an elevation scan of the copolarized received signal levels are plotted. Here the maximum signal level for the 9.6-GHz channel occurs in the center of the elevation scan, but for the other channels, it occurs at a slightly lower angle (85 to 88 degrees). This shift in the location of the peak signal is evident in the data from all

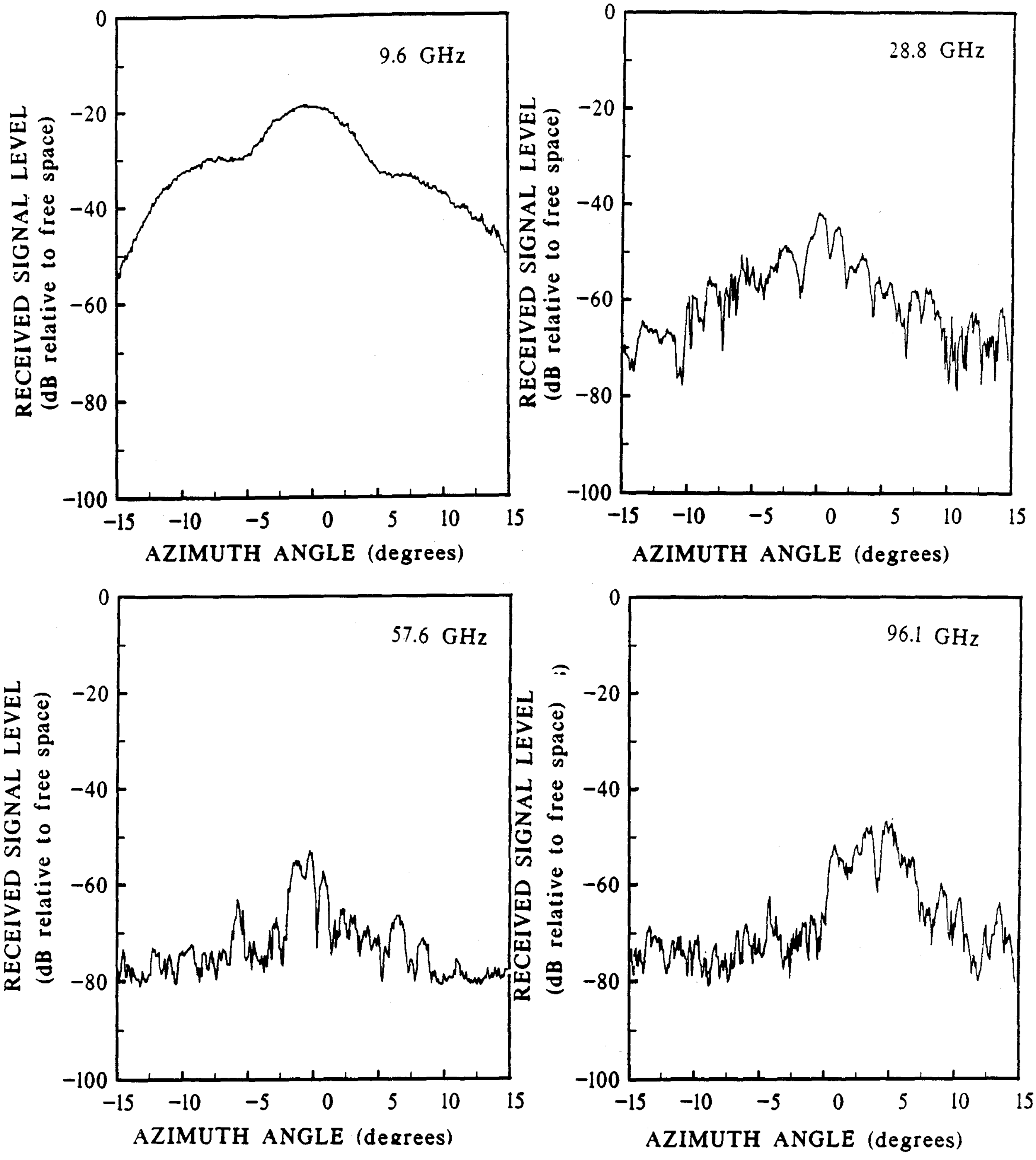

Figure 12. Copolarized azimuthal scan of RSL from path 4.

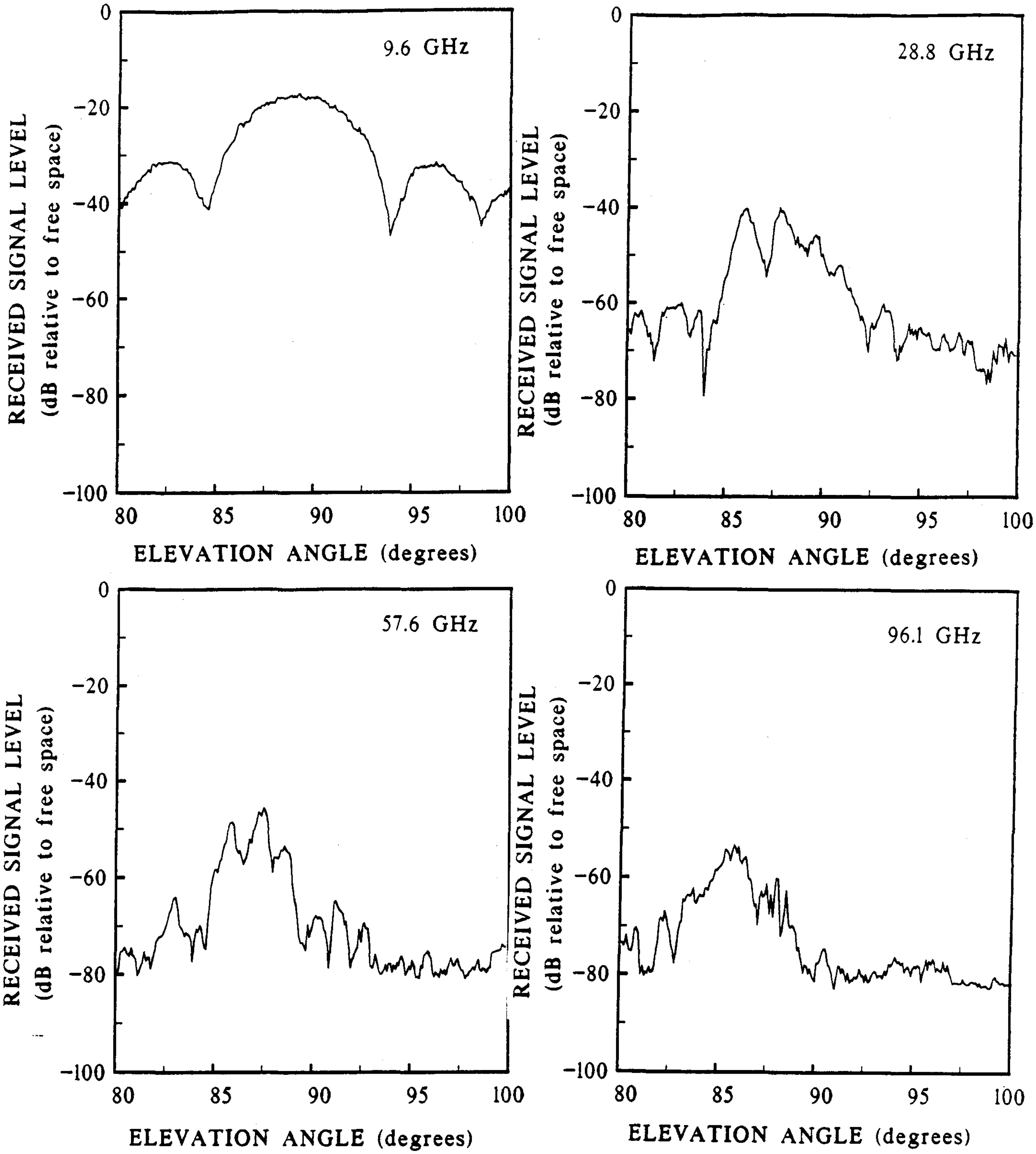

Figure 13. Copolarized elevation scan of RSL from path 4.

paths within the orchard and is probably due to the combined effects of a relatively unobstructed ground reflection and an obstructed direct path component. The lack of obstructions below the 1.5- to 2-m height in the orchard provides an opportunity for such a ground reflection mechanism. This effect is not seen in the 9.6-GHz data because of the relatively wide (4.6 degree) beamwidth of the 9.6-GHz receiver antenna.

4.2.2 Cross-Polarized Scans

In Figure 14, data from an azimuthal scan of the cross-polarized received signal levels are presented. To receive the cross-polarized signals, the receive antennas were switched to a horizontal polarization mode while the transmit antennas remained in a vertical polarization mode. The 9.6-GHz receiver antenna was not capable of receiving horizontally polarized signals; therefore, no cross-polarized data is available at 9.6 GHz. Theoretically the cross-polarized scans should have the same pattern as the copolarized scans, but they should be weaker by the amount of the polarization isolation of the system. The presence of a stronger cross-polarized signal indicates that some depolarization is occurring on the path. The cross-polarized received signal levels in these plots generally have characteristics similar to those of the corresponding copolarized data in Figure 12 except that the levels are lower, as would be expected. However, the levels are not as low as the measured polarization isolation values (which are tabulated in Figure 2) would dictate. Thus, some depolarization has been induced by the orchard. The depolarization data for all paths is summarized in the depolarization versus foliage depth plots that appear in Figure 22.

Data from an elevation scan of the cross-polarized received signal levels are shown in Figure 15. Again, the received signals in these plots generally have characteristics similar to those of the corresponding copolarized data in Figure 13, except that the levels are lower. As in the azimuthal scan, the levels are not as low as the polarization isolation values would dictate. The orchard, therefore, has a depolarization effect on the elevation scan data as well. The fact that the shape of the plots in Figures 14 and 15 are very similar to those in Figures 12 and 13 indicates that the depolarization effect is largely independent of antenna pointing.

4.2.3 Copolarized Scans of Path Loss Relative to Calibration Path Loss

In order to further characterize propagation through the conifer orchard, plots of the difference between the received copolarized signal levels (from Figures 12 and 13) and the

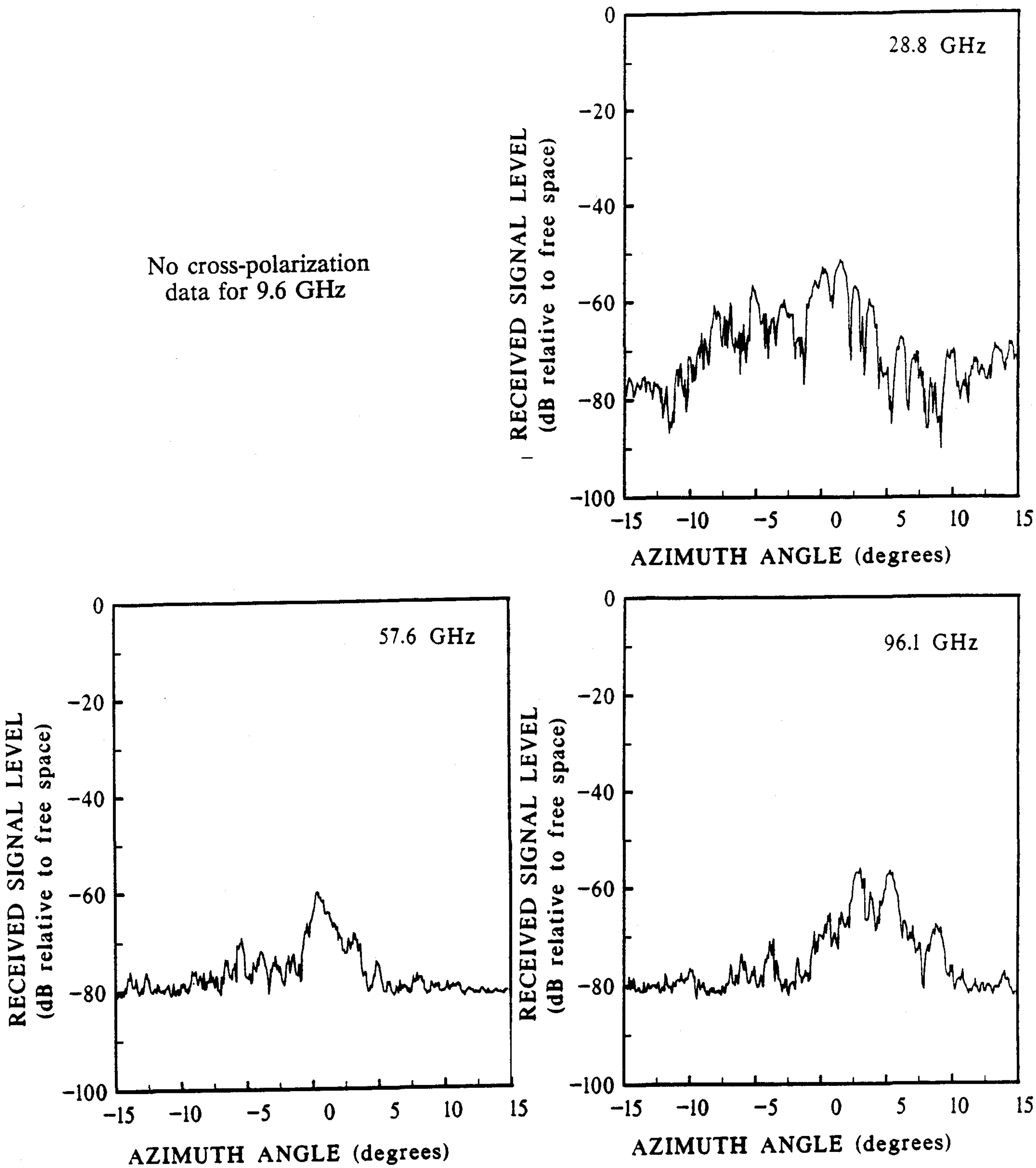

Figure 14. Cross-polarized azimuthal scan of RSL from path 4.

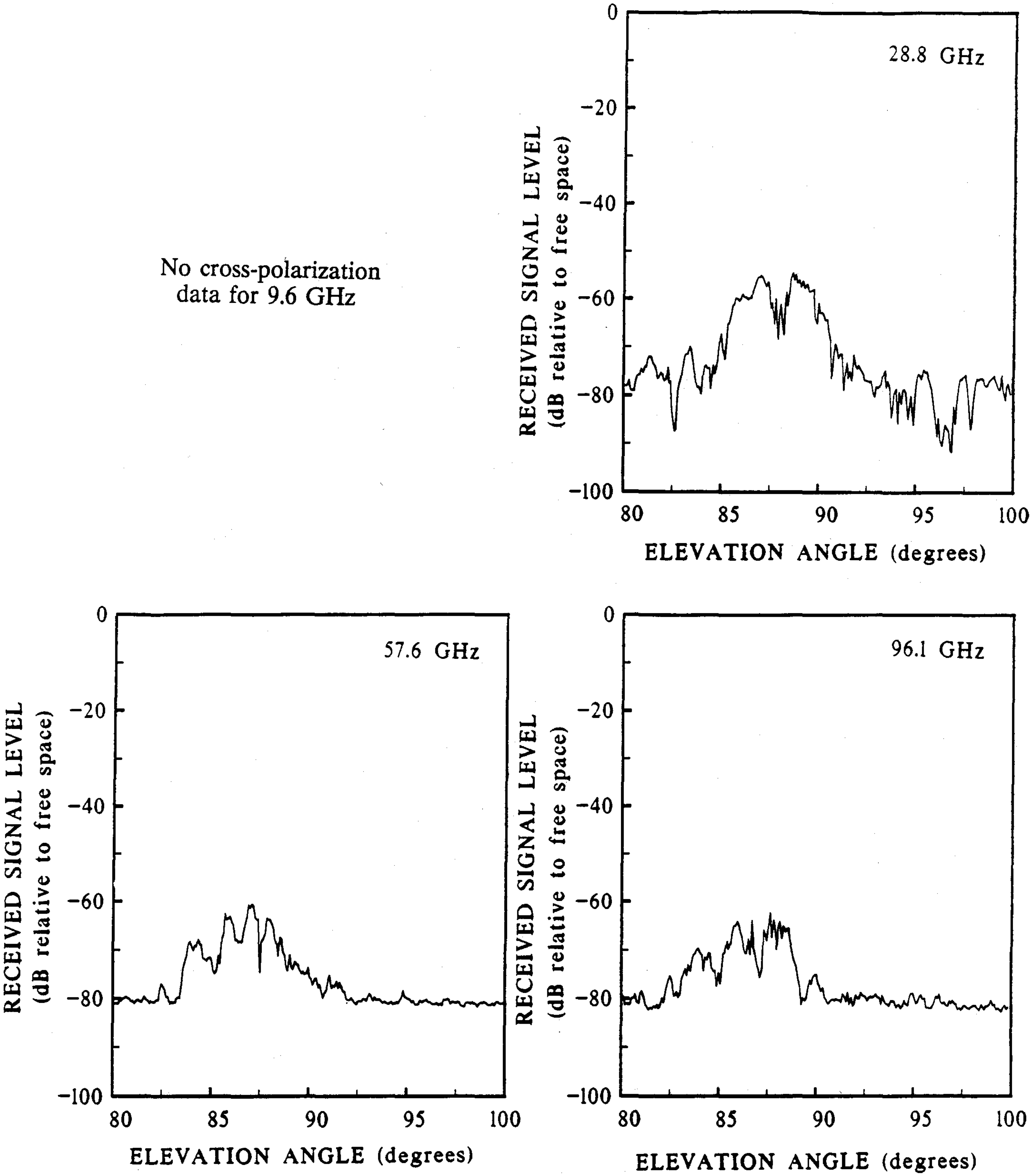

Figure 15. Cross-polarized elevation scan of RSL from path 4.

calibration path data (from Figures 10 and 11) were generated. These plots appear in Figures 16 and 17 for azimuthal and elevation scans, respectively. In these plots, the propagation loss through the orchard can be seen with the effect of the antenna patterns removed. If the orchard had acted as a perfect absorber with an attenuation of A dB, these plots would appear as a straight horizontal line with a propagation loss of A dB for all azimuth and elevation angles. A deviation from this constant propagation loss value is a result of the combined absorption, reradiation, and reflection mechanisms present in the orchard.

A significant variation in received signal level is evident in the plots from both azimuthal and elevation scans. This variation is smallest in the 9.6-GHz data; once again, this is probably due to the relatively wide antenna beamwidth at this frequency. The variation in RSL is greater at higher frequencies. A prominent feature in all of the plots (except at 9.6 GHz) is a substantial drop in the boresight signal level relative to the RSL at other pointing angles. These data indicate that the vegetation causes the received signal to lose much of its directivity in both the azimuth and elevation planes.

4.3 Summary of Data From All Paths

Data from all of the paths have been summarized in the form of propagation loss versus foliage depth plots. These plots, shown in Figures 18 through 21, permit an analysis of the dependence of vegetation loss on the tree depth, on frequency, and on the height of the transmitter terminal. Each of these figures includes a plot for each of the four frequencies (9.6, 28.8, 57.6, and 96.1 GHz). In each plot, propagation loss is plotted against foliage depth for various paths. Data are plotted for each of three transmitter heights (1, 3, and 5 m) on each path except in Figure 18, for which there is no 1-m height data available. Figures 18 and 19 contain data from paths 4, 5, 6, and 7. Figure 20 contains data from paths 1, 2, and 3. Figure 21 contains data from paths 8 and 9, the paths containing ponderosa and white pines. The data in Figures 19 and 20 have not been combined because of the difference in terrain between the two sets of paths represented by these figures. Figure 6 shows that paths 1, 2, and 3 are on one side of the orchard while paths 4, 5, 6, and 7 are on the other side. The terrain on the two sides of the orchard is sufficiently different that the data from the two sets of paths should not be combined, even though they contain the same type of trees.

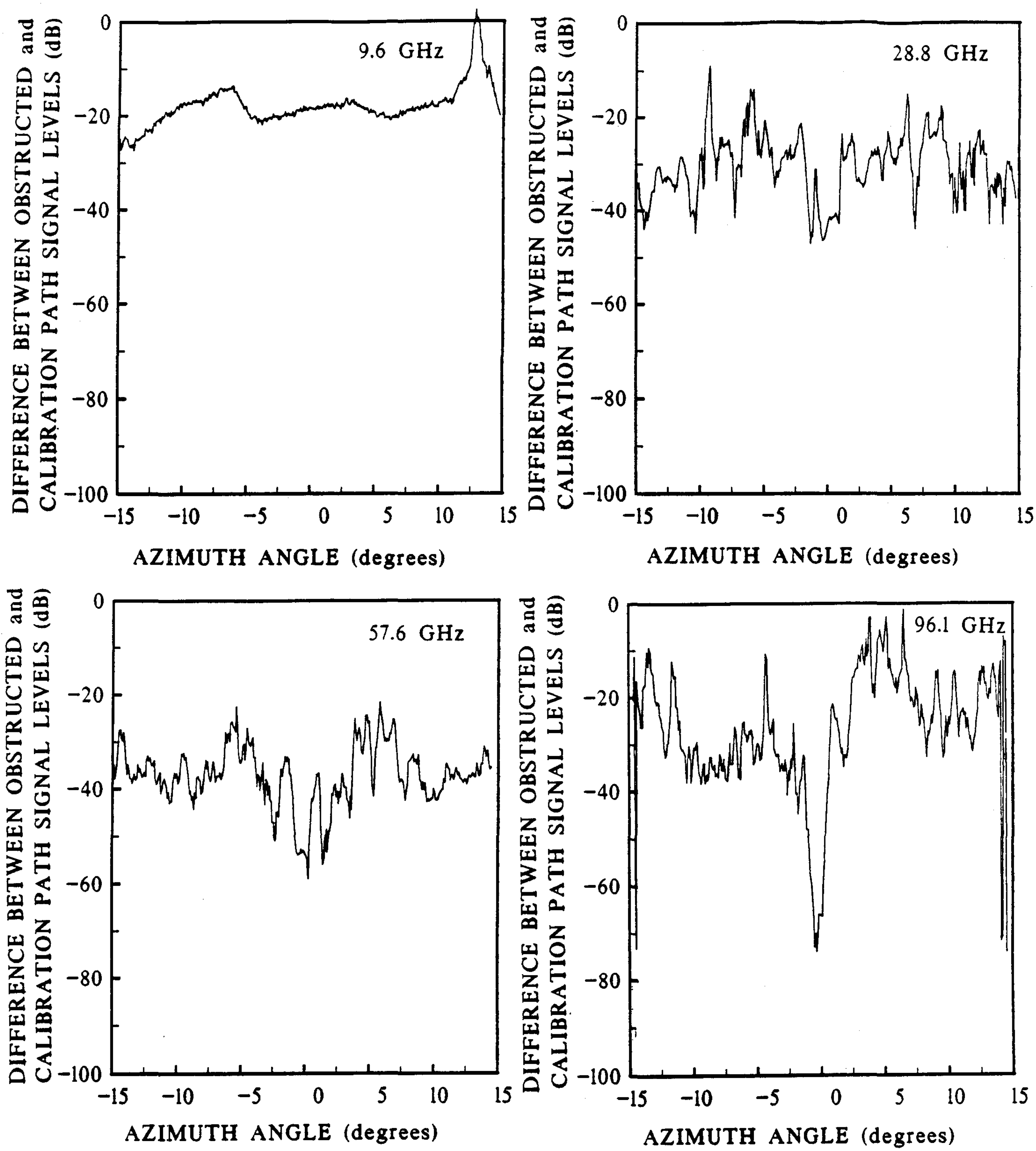

Figure 16. Copolarized azimuthal scan of RSL from path 4 relative to calibration path.

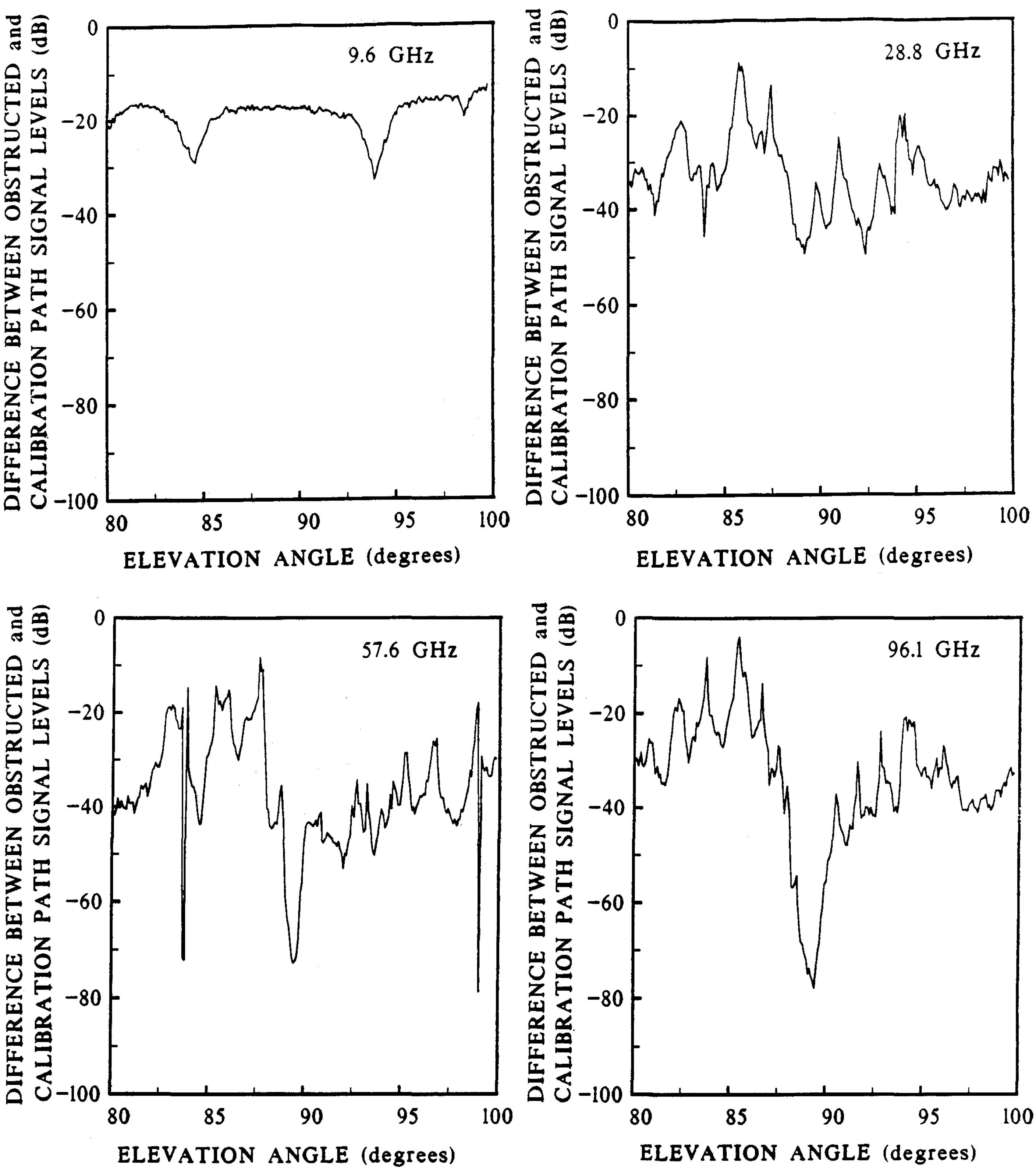

Figure 17. Copolarized elevation scan of RSL from path 4 relative to calibration path.

In reports from previous measurements, signal loss was plotted against the number of trees on the path. Since many trees only partially obstruct a given path, a preferred method is to plot signal loss versus foliage depth. The foliage depth figure used in these plots is an estimation of the actual amount of conifer foliage on the boresight path between the transmitter and receiver antennas. Foliage depth is calculated by tracing the direct path between the transmitter and receiver terminals on the orchard layout diagram and then summing the portions of the trees that are intercepted by the path. Foliage depth can be expressed as an equivalent number of whole trees through division by the average tree width (5.33 m). Both of these measures are tabulated for all paths in Table 1.

As is the case with the plots from the representative path, the free-space loss and signal loss due to atmospheric absorption has been taken into account for so that only the signal loss due to the path obstruction (the conifer trees) is indicated in Figures 18 through 21.

4.3.1 Vegetation Loss Versus Foliage Depth--Boresight Pointing on Paths 4, 5, 6, and 7

In Figure 18, copolarized propagation loss is plotted versus foliage depth. These measurements were made with the antennas aligned for boresight pointing in both azimuth and elevation planes. This alignment provides the best measure of signal loss due to foliage on the path with a minimal contribution from ground-reflected signals. The data are from 3- and 5-m transmitter heights (no 1-m data are available on these paths) on four different paths--paths 4, 5, 6, and 7. The individual signal loss values are indicated with a square (3-m height) or triangle (5-m height) and the average values for each set are connected by lines. (There is a set of data points for each path length/transmitter height combination because several measurements were made for each combination to verify repeatability of the measurements.)

Several observations can be made from the plots in Figure 18. First, the signal loss at each tree depth and transmitter height are consistently higher with increased frequency. Also of interest is the relationship between signal loss and foliage depth for a given frequency and transmitter height. The signal level drops off rapidly after the first several trees, but then drops off much more slowly as the tree depth is increased. It is believed that this change in attenuation rate (decibels per meter of foliage) occurs when the dominant propagation mode changes from a strongly attenuated direct path mode to a multiple-scatter mode. This multiple-scatter mode results from the combined effects of the large number of scattering objects (conifer needles and branches) on the electromagnetic

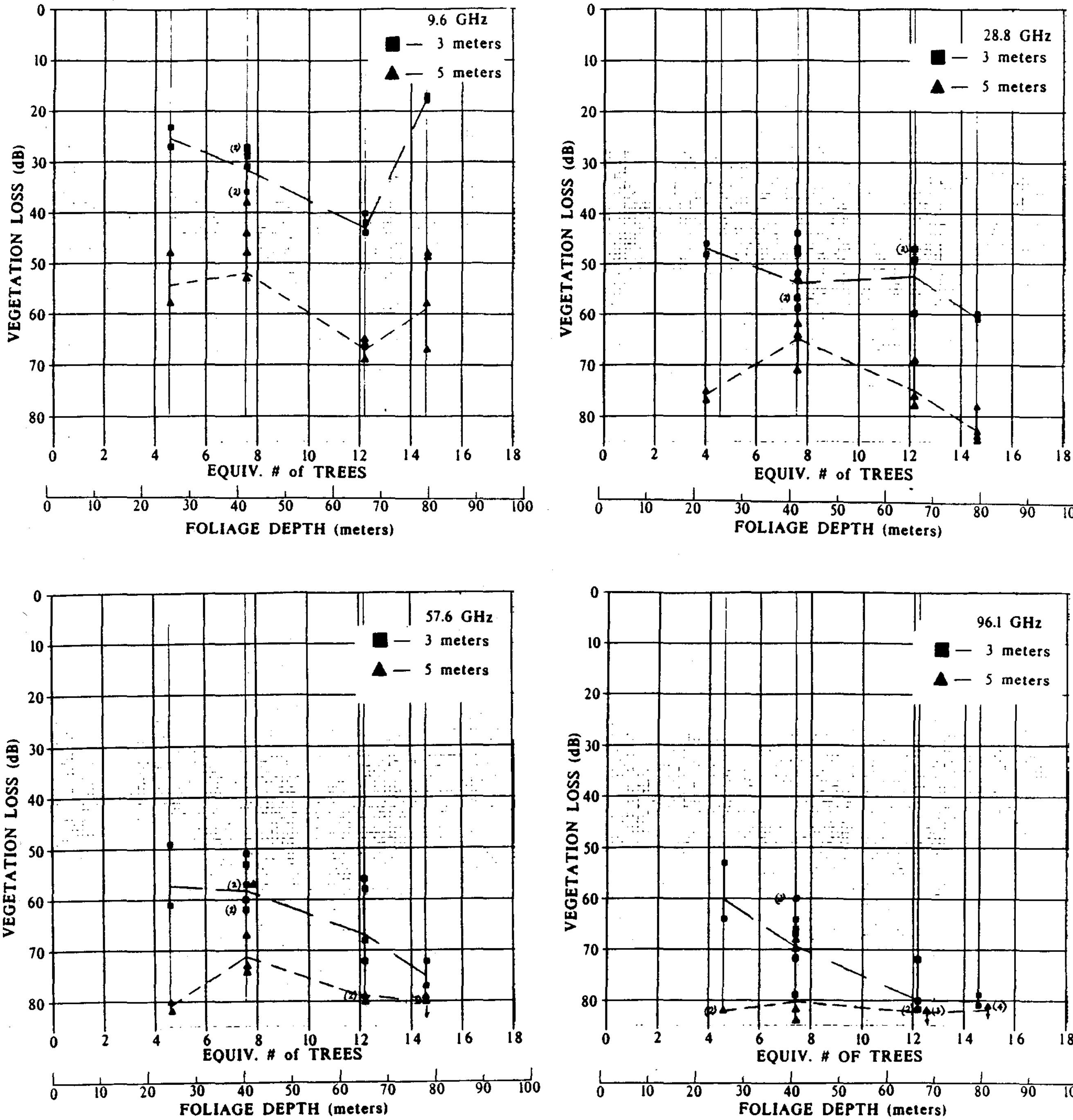

Figure 18. Vegetation loss as a function of foliage depth from boresight pointing data on paths 4, 5, 6, and 7.

energy incident upon them. This pattern is present at all frequencies and transmitter heights, although it is more pronounced at the higher frequencies.

Signal loss is also consistently higher (by 10 to 20 dB) at the 5-m height than at the 3-m height. This height dependence is presumably due to the greater foliage density at the 5-m height, which would be expected to result in a higher attenuation rate.

4.3.2 Vegetation Loss Versus Foliage Depth--Peak Signal Pointing on Paths 4, 5, 6, and 7

The plots in Figure 19, like those in Figure 18, present copolarized propagation loss as a function of foliage depth. The data displayed in Figure 19, however, are taken from scans in a peak signal rather than a boresight pointing mode. These data are also from paths 4, 5, 6, and 7 and represent transmitter heights of 1, 3, and 5 m. Again the average values for each data set are connected by lines. Peak signal pointing conditions are those in which the received signal levels are maximized. In these measurements, the peak signal pointing usually occurred at the boresight (0 degrees) azimuth angle and at an elevation angle of 1 to 7 degrees below the boresight elevation angle.

The data in Figure 19 show similar characteristics to those in Figure 18. These plots indicate that by switching to peak signal (nonboresight) pointing, the received signal level can be as much as 20 dB stronger than with boresight pointing at the same location. This effect appears to be dependent on tree depth, being most prominent at a depth of 4 trees and tapering off such that it is no longer apparent beyond a depth of 12 trees.

These data also follow the relationship between signal loss and transmitter height seen in Figure 18 in which more loss is seen at greater transmitter heights. This relationship is supported by the addition of data from a 1-m transmitter height. As much as 30 dB difference in received signal level is evident between the 1-m and 3-m transmitter heights. Again, this observation can possibly be explained by the variation of foliage density with height. At the 1-m height, there are practically no branches on the trees; only the trunks are present.

4.3.3 Vegetation Loss Versus Foliage Depth - Peak Signal Pointing on Paths 1, 2, and 3

Copolarized propagation loss data gathered on paths 1, 2, and 3 are presented in Figure 20 as a function of foliage depth. These plots are similar to those in Figure 19, except that they are from different paths over differently shaped terrain. Only one set of

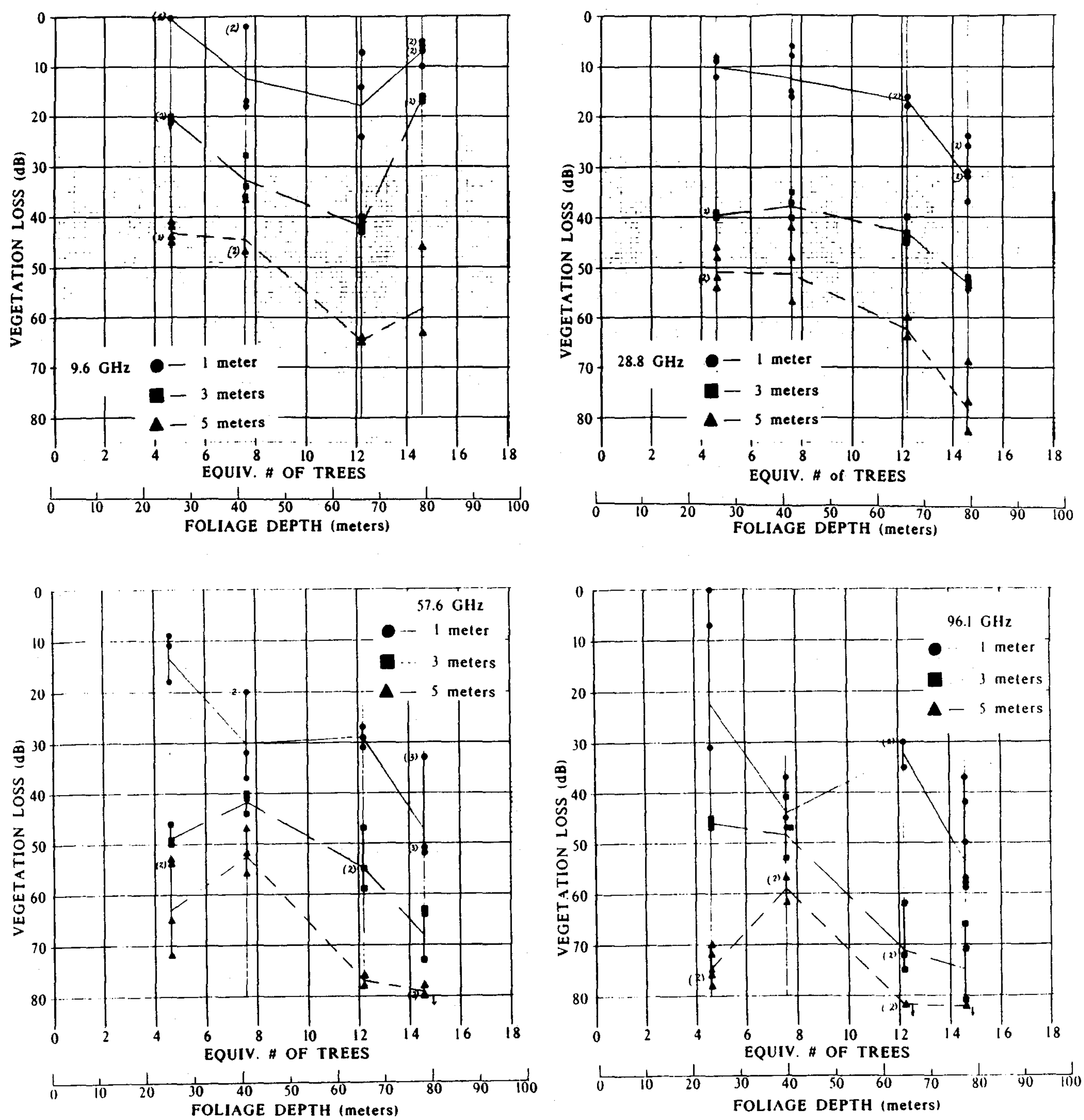

Figure 19. Vegetation loss as a function of foliage depth from peak signal pointing data on paths 4, 5, 6, and 7.

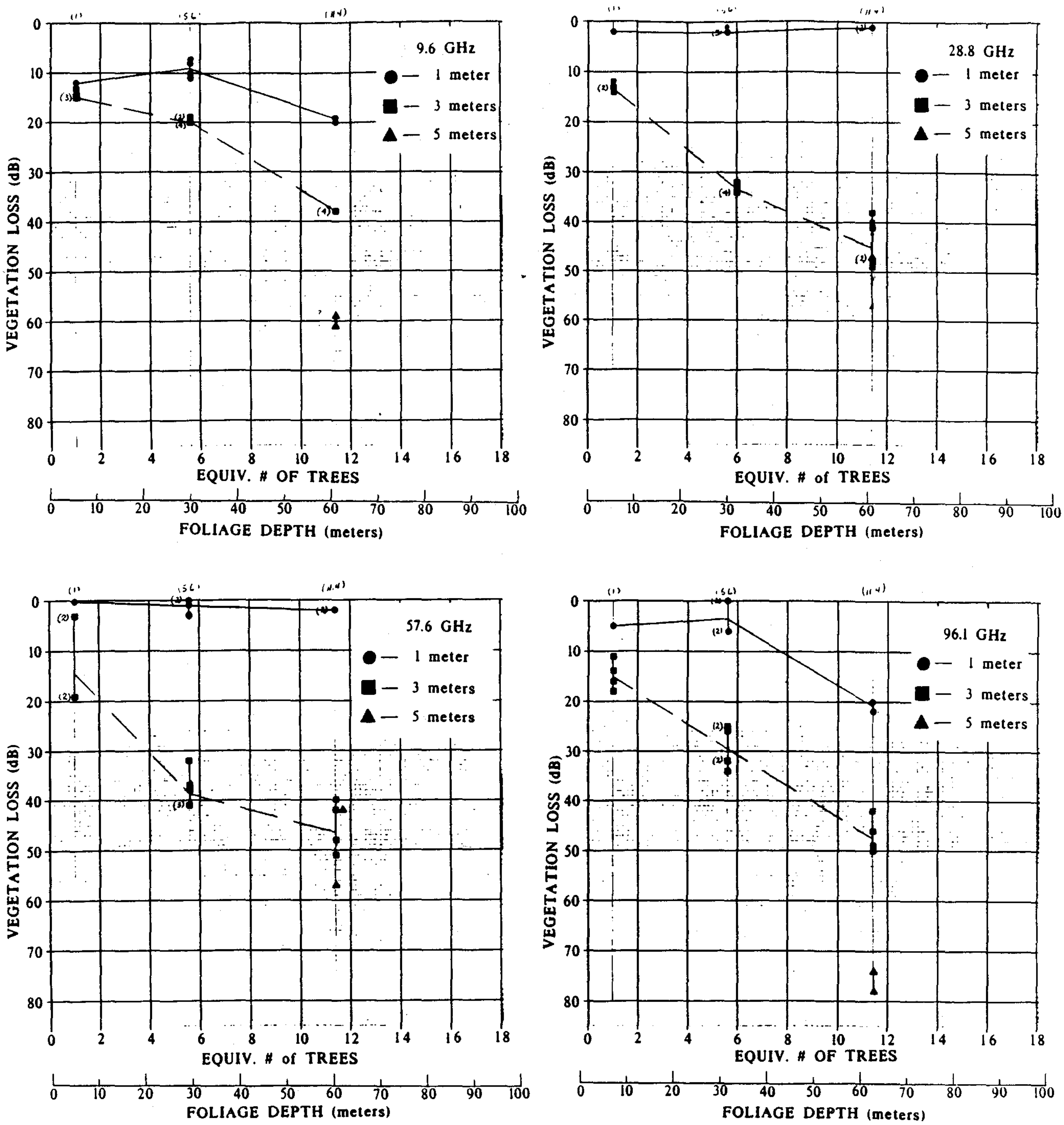

Figure 20. Vegetation loss as a function of foliage depth from peak signal pointing data on paths 1, 2, and 3.

measurements (from path 3) is available at the 5-m transmitter height. Average values for each data set are connected by lines. These plots, like those in Figure 19, present data corresponding to peak signal antenna pointing. The data indicate increasing signal loss as the transmitter height is varied from 1 to 5 m, as is the case in Figures 18 and 19. However, the signal loss at any given tree depth and transmitter height is smaller than for the same point in Figure 19. The difference in signal loss becomes more pronounced as frequency increases. This variation is most likely due to the difference in the topography between the two sets of paths represented in Figures 19 and 20.

The two sets of paths differ in two ways: First, the open space between the receiving antennas and the edge of the orchard was only about 6 m on paths 4, 5, 6, and 7 while it varied from about 107 to 168 m on paths 1, 2, and 3. Although free-space loss is taken into account in the data presented, the greater distance between the van and the edge of the orchard on paths 1, 2, and 3 could have an effect on the received signal levels. Second, the shape of the terrain is different on the two sets of paths. The receiver van is at a low point in the terrain on both sets of paths. The transmitter terminal on paths 4, 5, 6, and 7 was located on a slight uphill, level grade, resulting in a propagation path roughly parallel with the ground. The transmitter terminal on path 1 was located across noninclined level ground from the receiver and was essentially located outside of the orchard. Thus, the data gathered on path 1 show the effect of one tree on the signals without much contribution from the orchard. On paths 2 and 3, the transmitter terminal was located on or just over the crest of a very slight hill. The propagation paths on paths 2 and 3 thus intercept some of the trees at a lower height than on paths 4, 5, 6, and 7. The results of this terrain variation are most evident in the 1-m height data where signal loss is consistently lower on paths 1, 2, and 3.

4.3.4 Vegetation Loss Versus Foliage Depth - Peak Signal Pointing on Paths 8 and 9

The data gathered on paths 8 (ponderosa pine, two trees) and 9 (white pine, three trees) are summarized in the plots in Figure 21. In these plots, copolarized propagation loss is plotted against foliage depth for transmitter heights of 1, 3, and 5 m. These data also correspond to peak antenna pointing. It is not appropriate to connect the average values from the two paths because of the difference in tree type. The trees on these paths

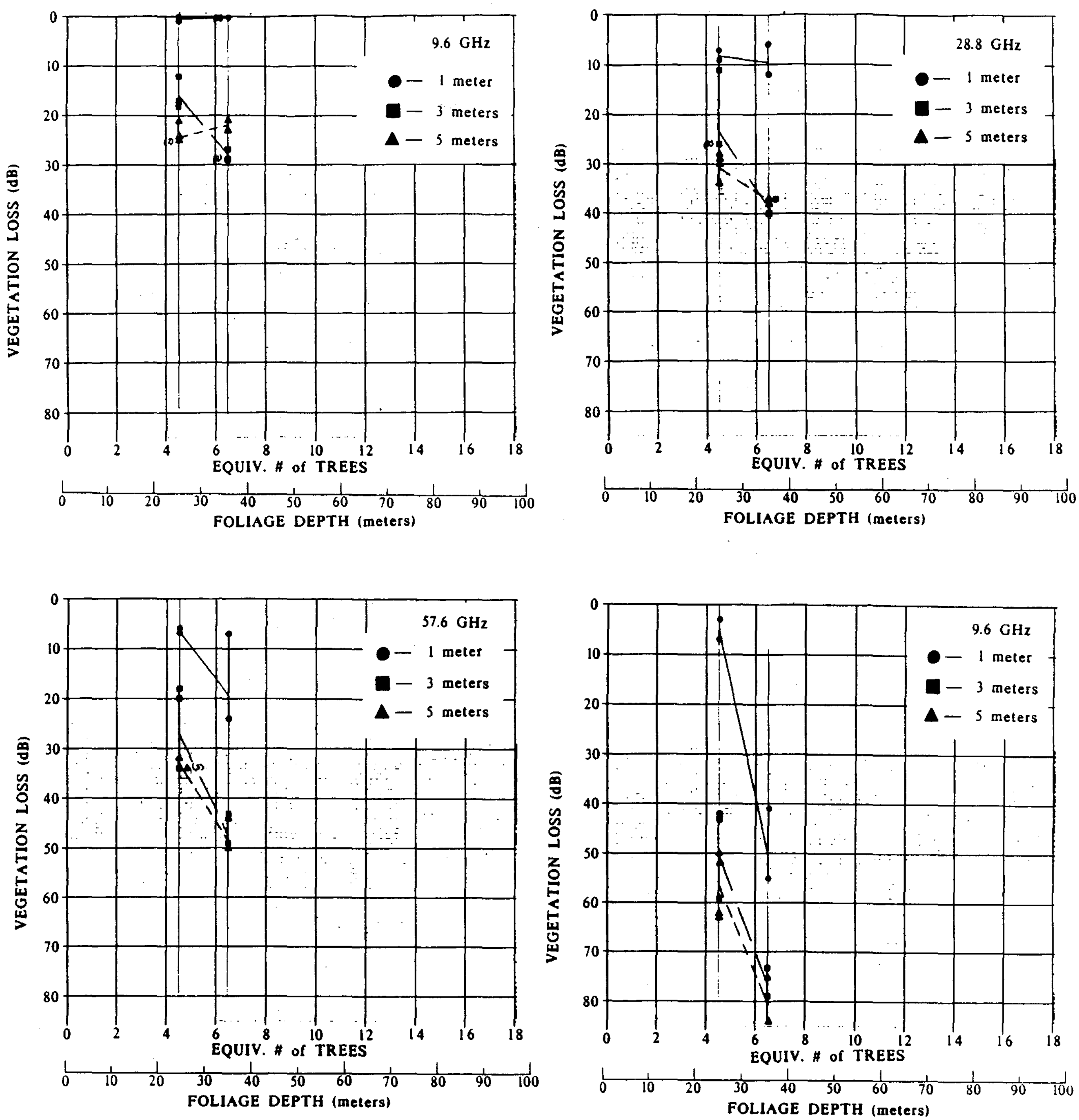

Figure 21. Vegetation loss as a function of foliage depth from peak signal pointing data on paths 8 and 9.

were the only trees in the orchard that weren't of the Douglas fir variety; therefore, data were only taken on two non-Douglas fir paths.

These data show the same dependence of signal loss on transmitter height and frequency seen in Figures 18 through 20--that is, increasing signal loss with increasing transmitter height and increasing frequency. However, the signal loss for any given frequency, transmitter height, and tree depth is generally lower in these data from paths 8 and 9 than in the data from other paths. This difference in loss is likely due to the location of the trees on the path (see Figure 6) than to the different tree types. Since the ponderosa pine and white pine trees were essentially in an open field, the effect of the orchard is not seen in the data gathered on these paths.

4.4 Other Data

4.4.1 Depolarization Versus Foliage Depth

One effect of the conifer vegetation is to cause a depolarization of the transmitted signals. Depolarization, as discussed in this report, refers to an increase in the received cross-polarized signal (vertically transmitted and horizontally received, or VH) relative to the received copolarized signal (vertically transmitted and vertically received, or VV). Depolarization can also be thought of as an decrease in the cross-polarization discrimination (XPD).

Plots of the difference between the VH and VV signals versus foliage depth were generated from data gathered on paths obscured with Douglas fir trees (paths 1 through 7). These plots, shown in Figure 22, contain depolarization data for the 28.8-, 57.6-, and 96.1-GHz links. (No depolarization data are available at 9.6 GHz.) These measurements are limited by the polarization isolation of each channel--that is to say that a cross-polarized signal that is weaker than the copolarized signal by more than the polarization isolation can not be detected. The measured polarization isolation for the 28.8-, 57.6-, and 96.1-GHz receivers is 35 dB, 20 dB, and 30 dB, respectively. In these plots, a value of (VH-VV) greater than the polarization isolation corresponds to a depolarization.

The data from all three frequencies show a definite increase in depolarization as the tree depth is increased. At depths of 10 to 15 trees, the cross-polarized signal becomes as little as 2 dB weaker than the copolarized signal. This depolarization effect is more pronounced at the higher frequencies.

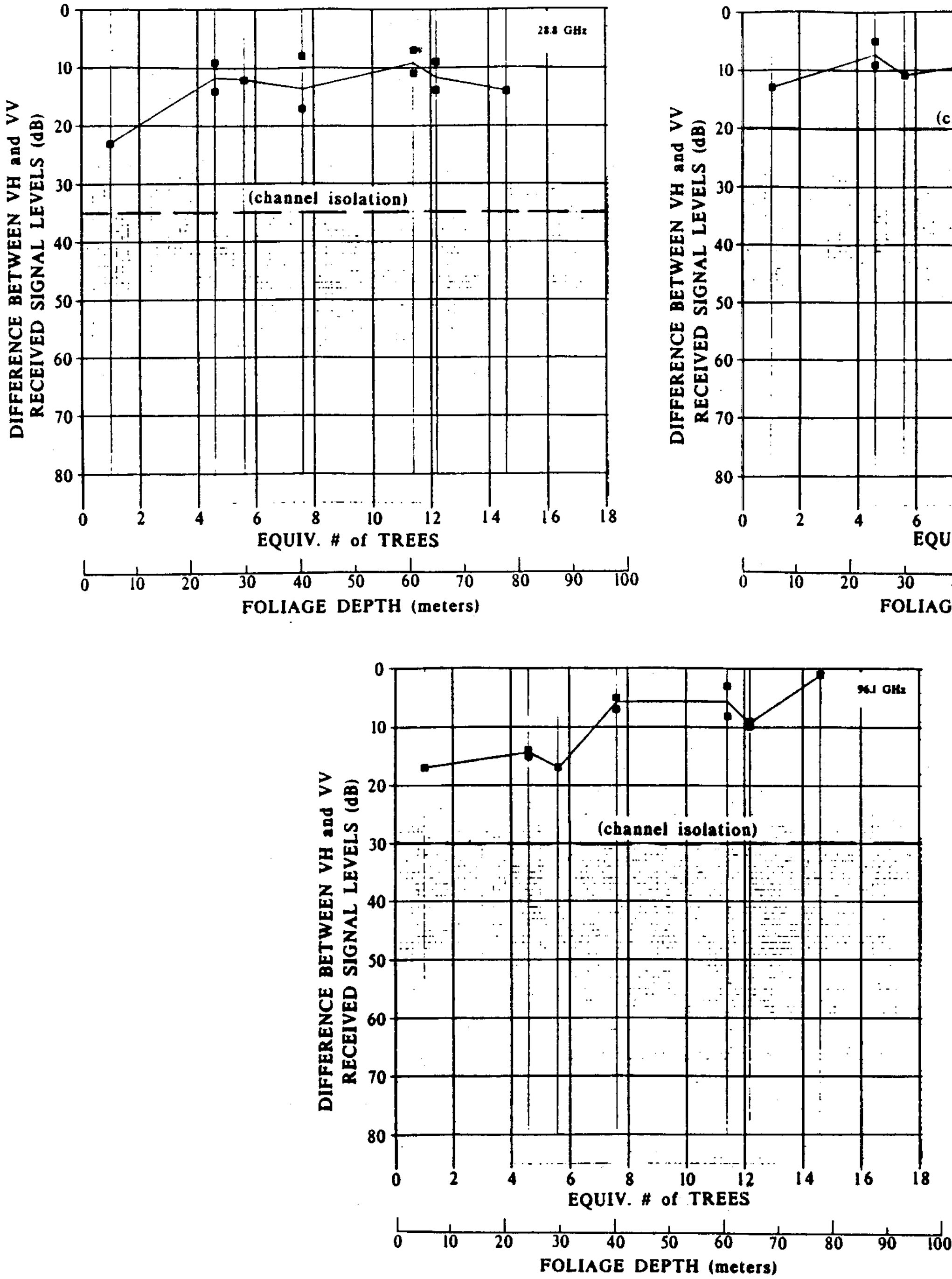

Figure 22. Difference between cross-polarized and copolarized signals as a function of foliage depth.

4.4.2 Copolarized Loss Versus Foliage Depth--Boresight Pointing Comparison of Douglas Fir and Pecan Measurements

The propagation loss data gathered in these conifer (Douglas fir) measurements are compared with similar data from the 1982 deciduous (pecan) measurements in Figure 23. The data are compared as a function of foliage depth at various transmitter heights, for frequencies of 9.6, 28.8, and 57.6 GHz (no data were taken at 96.1 GHz in the deciduous measurements). All of the data points represent average values. The results of the 1982 deciduous measurements are summarized in some detail in the appendix .

In general, propagation through the deciduous orchard (in its foliated state) resulted in less loss than propagation through the conifer orchard for any given combination of frequency, transmitter height and foliage depth. Signals were detectable much deeper into the orchard in the case of the deciduous trees. Possible reasons for this include (1) the fact that the conifer vegetation appeared to be much more dense than the deciduous vegetation and (2) the water content is believed to be significantly higher in the conifer branches and needles--which would result in greater absorption by the conifer vegetation.

4.4.3 Received Signal Level Versus Height Scans

Measurements of propagation loss were also made as the transmitter antenna height was varied on selected paths. Data from these measurements are presented in Figures 24 and 25. In these figures, received signal levels are plotted as a function of transmitter antenna height for frequencies of 9.6, 28.8, 57.6, and 96.1 GHz. The data in Figures 24 and 25 were taken on path 2 (length = 160 m, foliage depth = 29.7 m) and path 3 (length = 177 m, foliage depth = 61 m), respectively. These plots show that the RSL decreases as the transmitter height is increased, particularly above the 2-m level--the level at which branching begins. As the transmitters are raised into the denser areas of vegetation, the signal loss increases, as would be expected. Another important observation from these plots is the sizable variation in signal level that occurs with small changes in transmitter height; variations of up to 25 dB in RSL are evident with an 0.2 m change in transmitter height.

4.4.4 Copolarized Scans in Backscatter Mode

Another configuration used in the conifer measurement effort involved a backscatter mode. In this mode, the transmitter and receiver, set in an open field, are both pointed toward the edge of the Douglas fir orchard. The signal scattered off the orchard and back

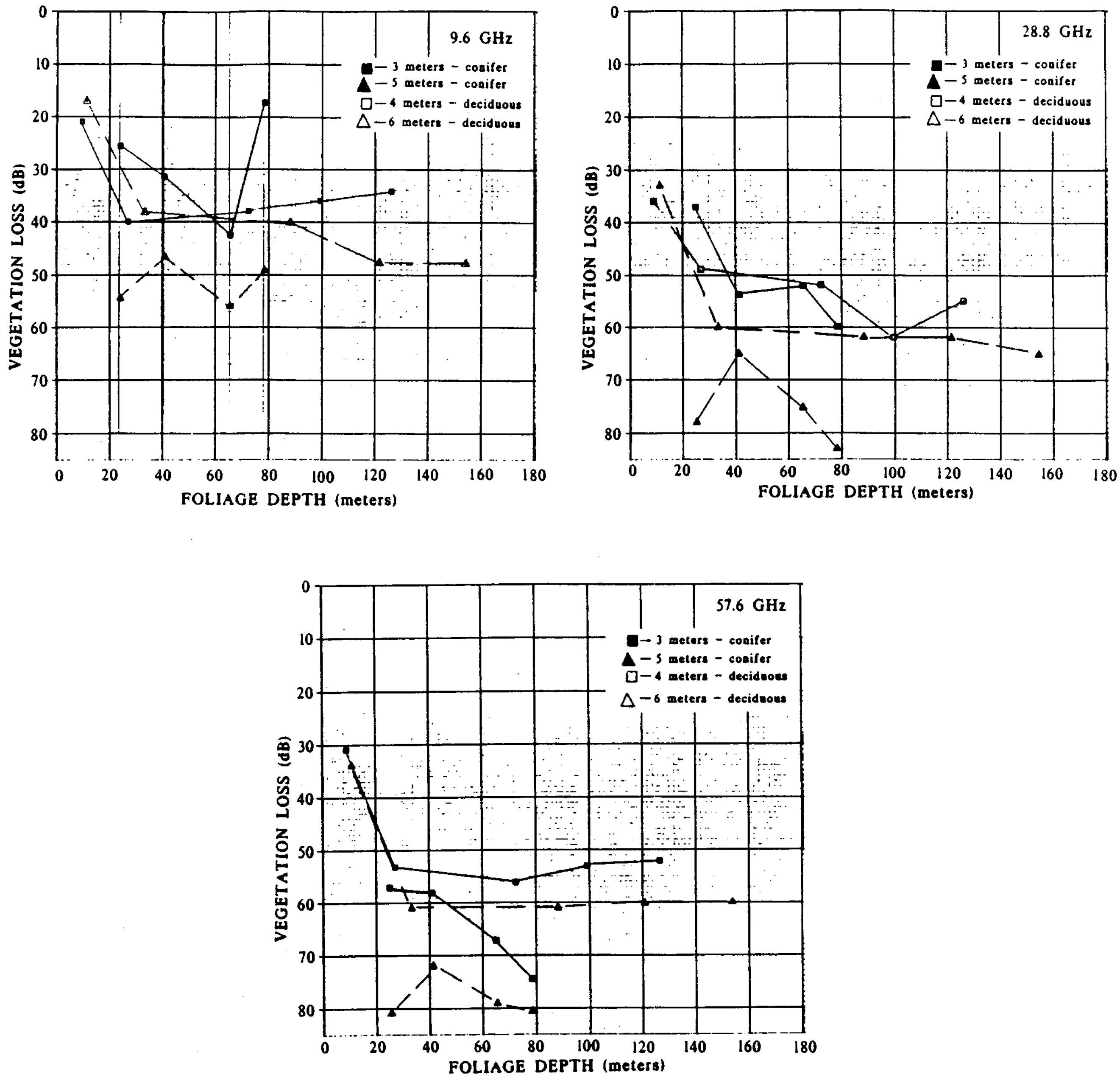

Figure 23. Comparison of vegetation loss data from conifer and deciduous vegetation as a function of foliage depth.

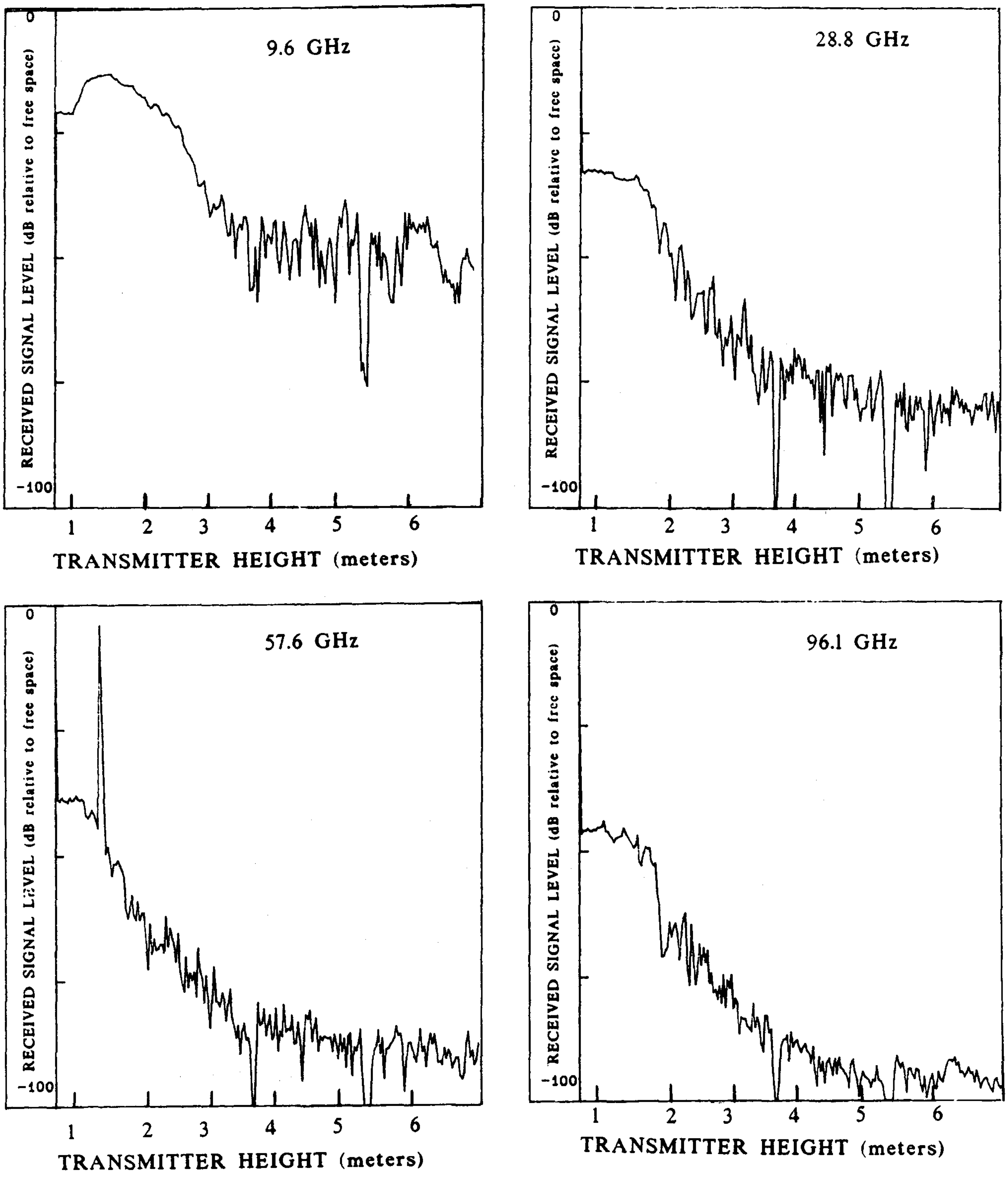

Figure 24. RSL as a function of transmitter height on path 2.

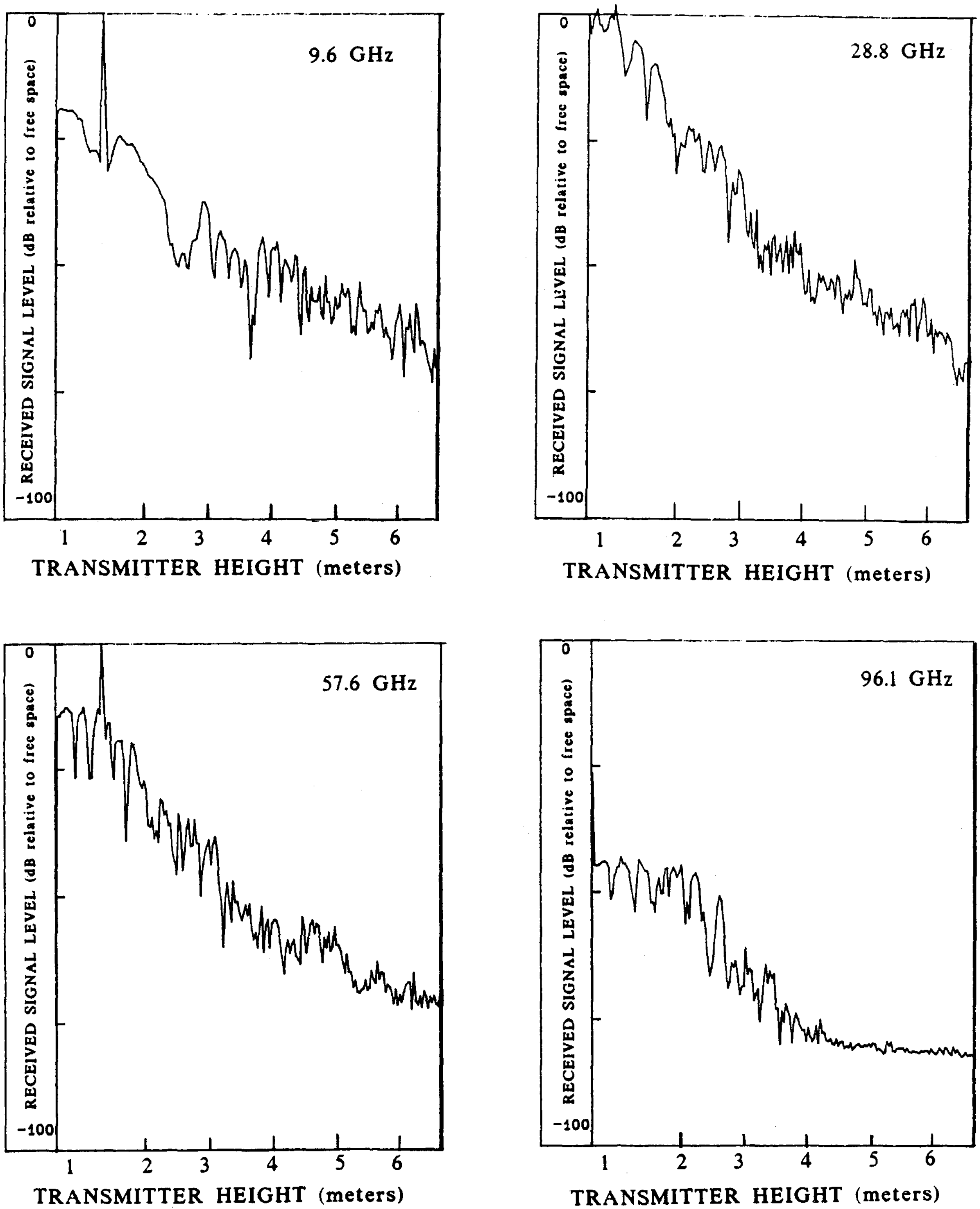

Figure 25. RSL as a function of transmitter height on path 3.

toward the transmitter/receiver terminal is measured. Azimuthal and elevation scans were made in the backscatter configuration, and measurements were made at all four frequencies. The path used for the backscatter measurements was a 75-m folded path (37.5 m one way) and all data were taken at a 1-m transmitter height.

Data gathered during an azimuthal scan in backscatter mode are shown in Figure 26 in the form of received signal level versus azimuth angle plots. (The elevation angle was fixed at 90 degrees (horizontal) while the azimuth angle was varied from -15 to 15 degrees.) In Figure 27, data from an elevation scan are shown in plots of received signal level versus elevation angle. (The azimuth angle was fixed at 0 degrees while the elevation angle was varied from 80 to 105 degrees.) The 0-dB reference level in these plots refers to the boresight signal level that would be present over an equivalent (75-m) unobstructed line-of-sight (LOS) path.

If the backscattering mechanism of the orchard had acted as a perfect reflector, the plots in Figures 26 and 27 would have the same shape as the calibration scan plots in Figures 10 and 11 but would be lower in level by the effective loss of the reflector. The shape of these plots, however, shows very little resemblance to that of the calibration antenna patterns. The received backscattered signals therefore appear to be fairly insensitive to receiver antenna pointing.

In Figure 28, data from another azimuthal scan is shown. This scan is similar to the one shown in Figure 26 except that the elevation angle was set at 5 degrees above horizontal. These plots are similar to those in Figure 26 except that the signal peaks are more defined. These signal peaks correspond to the spacing of tree rows at the edge of the orchard. These peaks are particularly evident in the 96.1-GHz data. The peaks are more prominent in the scans taken at the higher elevation angle (Figure 28) because the spaces between rows of trees are wider near the tops of the trees.

One characteristic that is shared by all of the plots in Figures 26 and 28 is a slowly decreasing signal level from left to right in the azimuthal plane. This phenomenon is the result of sidelobe coupling of the transmitter and receiver antennas. These antennas were isolated as well as possible, but some signal still leaked through to the receiver antennas. Since the transmitters were located to the left of the receivers, this coupling is greatest on the left side of the azimuthal scans.

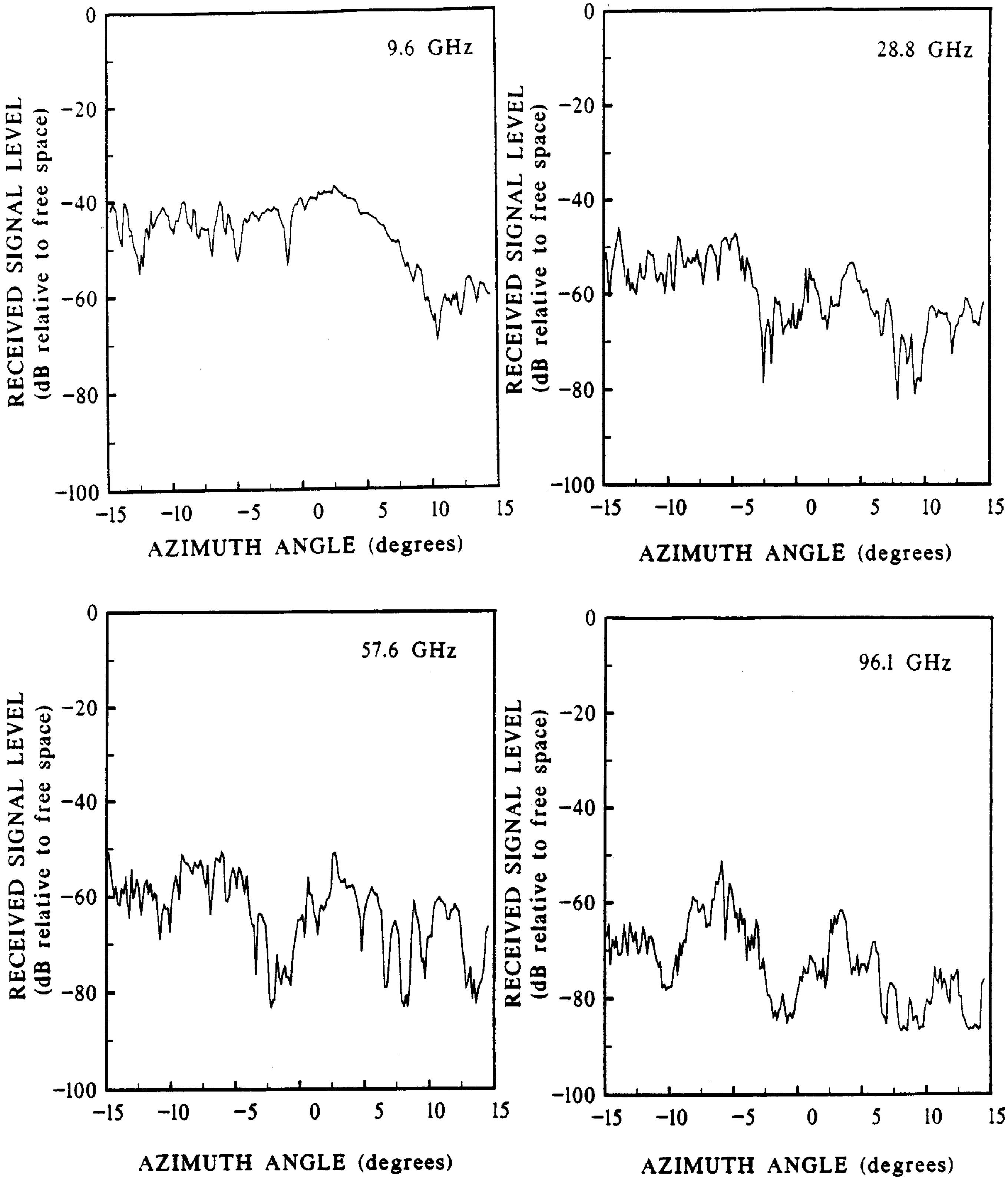

Figure 26. Azimuthal scan of RSL from backscatter measurements at an elevation angle of 90 degrees.

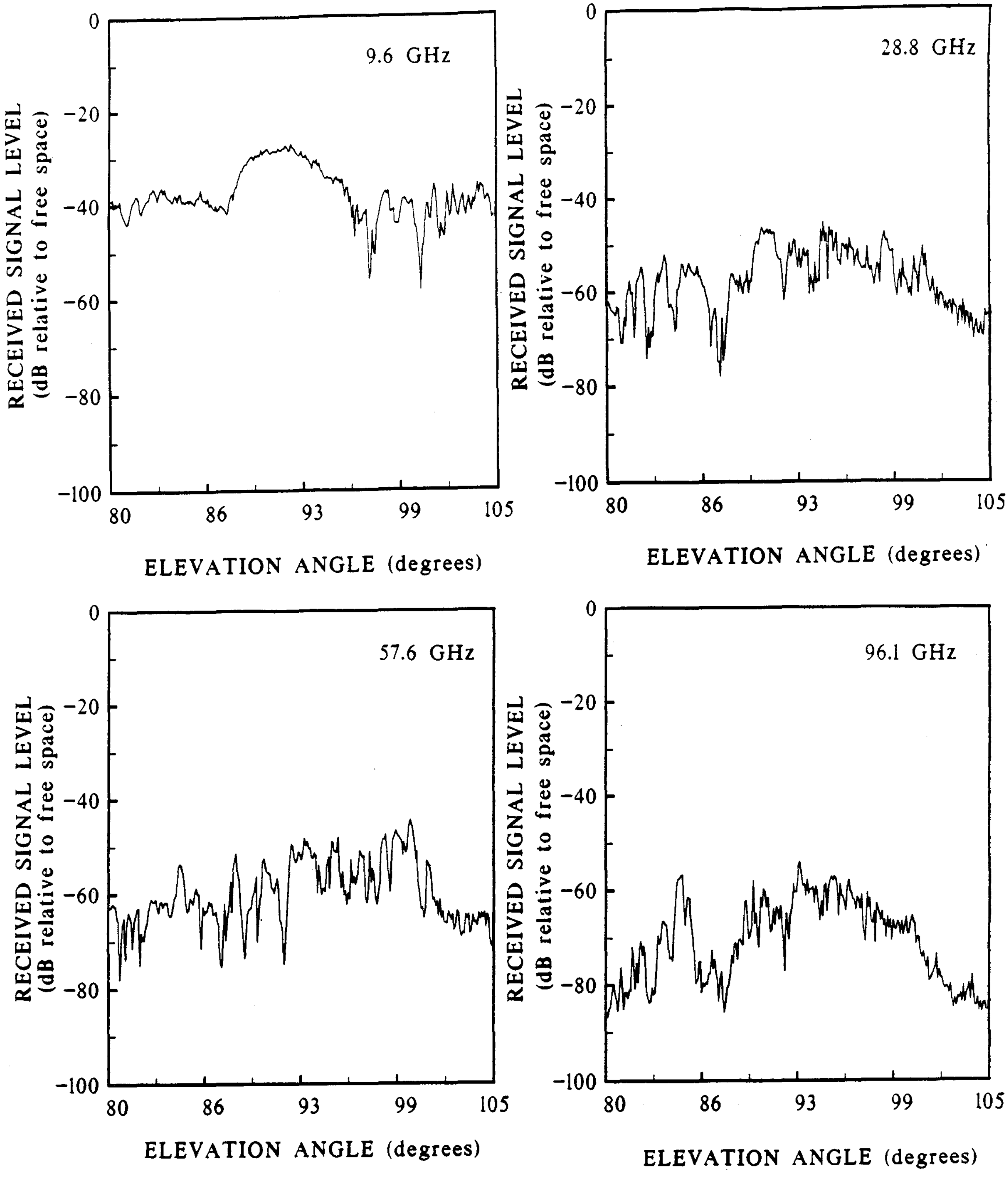

Figure 27. Elevation scan of RSL from backscatter measurements.

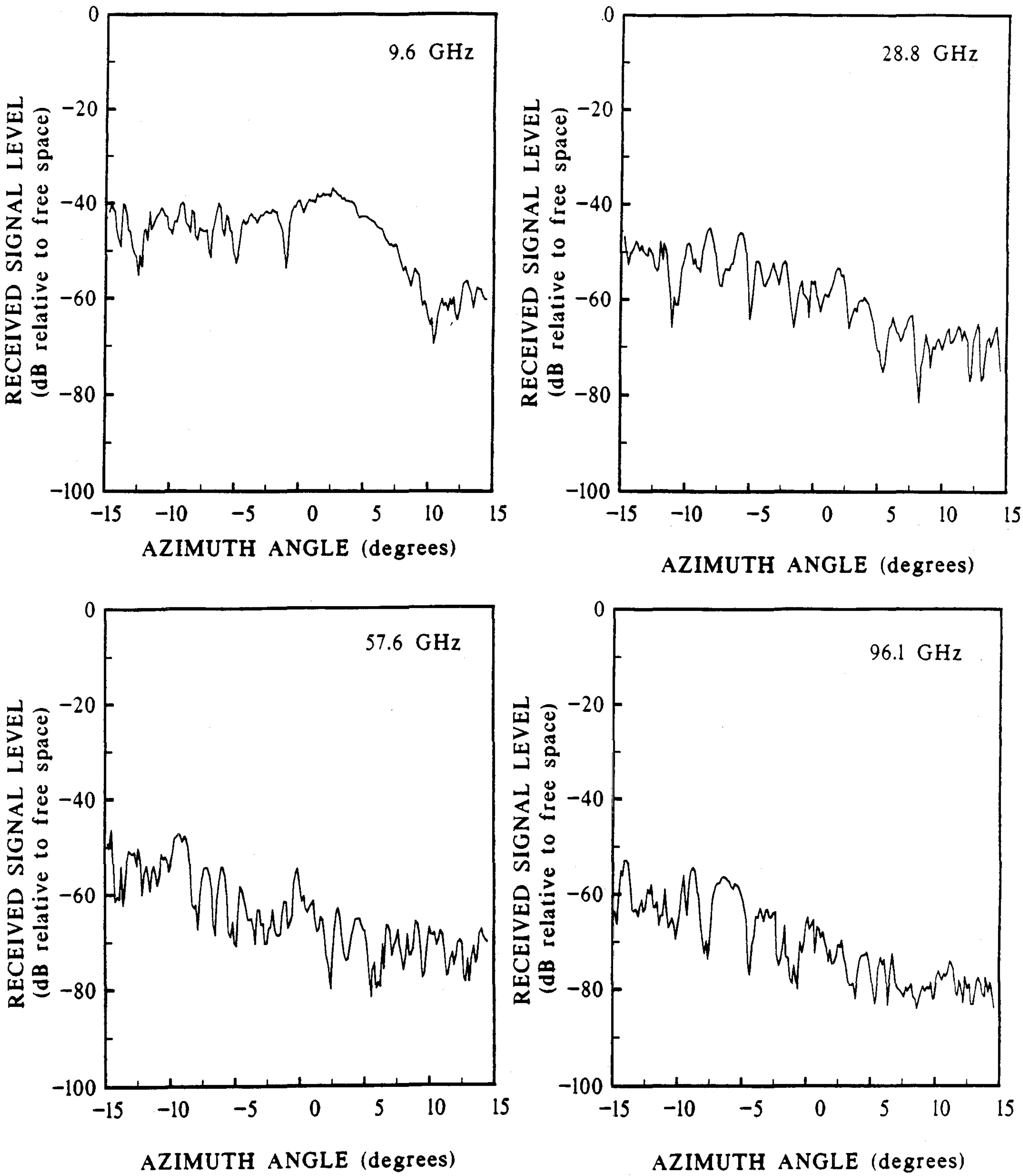

Figure 28. Azimuthal scan of RSL from backscatter measurements at an elevation angle of 95 degrees.

5. SUMMARY

Measurements were made at 9.6, 28.8, 57.6, and 96.1 GHz to characterize propagation through conifer vegetation. The measurements were conducted in a seed orchard because of the uniform density of conifer trees present. Analysis of the received signal data reveals several characteristics attributable to the presence of the conifer vegetation on the path.

The conifer vegetation produced significant attenuation in the received signal. For example, the 96.1-GHz signal was attenuated by 80 dB at a foliage depth of 78 m. The amount of attenuation on a given path generally increased with increasing frequency but not in a proportional manner, i.e., higher frequencies were attenuated less than the increase in frequency from lower frequencies.

The relationship between attenuation and foliage depth appears to be nonlinear. Attenuation due to the vegetation (or vegetation loss) increases rapidly through the first several trees (approximately 25 m of foliage depth) but then increases much more slowly (or even decreases) as the tree depth is increased. This relationship is apparent at all four frequencies, although it is more pronounced at the higher frequencies. The shape of the vegetation loss curve as a function of foliage depth is interpreted as an initial loss rate due to the high attenuation of the direct path mode and, beyond the first several trees, a low-loss rate due to a multiple scatter mode.

The data show a considerable variation in received signal level with small changes (fractions of a meter) in the position of either the transmitter or receiver antennas. As foliage depth increases, the signal loses greater portions of its directional and polarization identity. The changes in these signal properties are likely accompanied by a time delay distortion effect. On nearly all of the measurement paths the peak signal was found to occur at an elevation angle of 3 to 7 degrees below horizontal. This phenomenon is attributed to a ground reflection mechanism resulting from the lack of foliage below the 1.5-m height.

The results of these measurements are qualitatively similar to those from measurements made through deciduous trees in an earlier study. Attenuation, depolarization and directivity loss effects were observed through both types of trees, but the attenuative effects were significantly greater with the conifer trees.

A more detailed analysis of millimeter-wave propagation through vegetation could be conducted through the use of ITS's nanosecond resolution impulse response probe. A fully polarimetric, frequency-swept millimeter-wave probe with full phase measurement capability would also provide insightful data. ITS hopes to develop such a probe in the near future.

6. ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance and cooperation of Richard Chavez, who was instrumental in setting up the equipment and conducting the measurements; Robert DeBolt, who was responsible for the computer programming and data reduction associated with the measurements; and the U. S. Forest Service personnel at the Dennie Ahl Seed Orchard and in the Hood Canal Ranger District who assisted in selecting the site.

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Violette, E.J., R.H. Espeland, and F. Schwering (1983), Vegetation loss measurements at 9.6, 28.8, and 57.6 GHz through a pecan orchard in Texas, U. S. Army CECOM Research and Development Technical Report CECOM-83-2.

APPENDIX: VEGETATION LOSS MEASUREMENTS AT 9.6, 28.8, AND 57.6 GHz THROUGH A PECAN ORCHARD IN TEXAS

1. INTRODUCTION

A measurement program was conducted in 1981 to determine the effects on millimeter-wave signals propagated along paths obscured with deciduous and conifer trees. The objective of the project was to obtain information on signal loss as well as spatial, polarization, and scattering characteristics for propagation through a variety of foliage and atmospheric conditions at 9.6, 28.8, and 57.6 GHz. Results of this work are reported in U.S. Army Report CECOM-81-CS020-F entitled, "SHF-EHF Propagation through Vegetation on Colorado East Slope." [1] The principal results of the 1981 work included a measure of signal loss through vegetation as a function of tree depth, height above ground, foliage (leaves and no leaves for deciduous), antenna polarization, vertical and horizontal terminal displacement, and frequency.

In 1982, the vegetation studies for the U.S. Army continued with emphasis on determining signal properties as a function of foliage depth in order to support the development of a model for predicting link performance. In forested areas, the density of foliage was found to be nonuniform and difficult to describe in terms of depth. An evenly planted orchard permits a controlled measurement removing the density variable. Because of the tree size, foliage density, and humid climate, a pecan orchard near Wichita Falls, Texas, was selected as best suited to the measurement requirements.

The material in this appendix summarizes the measurements made at the pecan orchard in April 1982, before the trees were in foliage and in August 1982, when the trees were completely in leaf. The data includes measurements over path lengths from approximately 0.1 to 0.9 km with 1 to 35 trees on a path. Most of the measurements were made with the terminals carefully positioned such that a row of trees was directly in the transmitter-receiver path. A sequence of measurements was made for an increasing number of trees in path, starting with one tree. The transmitter and receiver locations were carefully noted, to allow a replication of measurements in the foliated state. For each path, azimuthal and elevation scans were made at terminal heights of 1, 4, and 6 meters. Other measurement variables included antenna polarization and the transmitter antenna horizontal and vertical position.

The measurement link operated at three coherent frequencies: 9.6, 28.8, and 57.6 GHz. Beamwidths of the transmitting antennas were 10° at all frequencies. Receiver beamwidths were 4.8° at the 9.6 GHz frequency and 1.2° at 28.8 and 57.6 GHz. A 60 dB dynamic range limited by the last IF amplifier stage and a minimum sensitivity of -100 dBm were available at all frequencies.

2. MEASUREMENTS

The segment of the Chitwood Pecan Orchard near Wichita Falls, Texas, used for these tests was a well-established and well-groomed stand of trees. These trees were planted in a square grid with a tree spacing of approximately 13 meters and had at that time attained heights of 8 to 10 meters. The maximum span of branches reached 10 to 13 meters, filling the space between rows in many areas. The initial branching occurred at the 1.5 to 2.0 meter height showing significant branching at the 4 and 6 meters levels, leaving mainly trunks at the 1 meter level. When the trees were in leaf, the weight of the new growth of twigs and nuts caused the branches to droop, such that some foliage extended down to the 1 meter level. The leaves of the pecan tree grow in clusters of 10 to 12 leaves on each twig. The leaves are arranged on the twig in balanced symmetry and range in size from 5 cm long and 2 cm wide near the branch to 20 cm long and 5 cm wide at the end of the twig. In April, during the time of the defoliated measurements, a grain crop planted as a temporary ground cover had attained a height of 10 to 15 cm, providing a uniform clean-looking ground plane from of weeds and underbrush. The pictures on the left side of Figure A.1 were taken of the grove in early April. The first picture (a) shows the uniform planting of the trees. In picture (b), the receiver is located with one tree on path. In picture (c), the scene includes the receiver van looking toward the transmitter with several trees on path. The unit on the tripod provides the 9.6 GHz phase-locked signal. An arrow points to the transmitter site.

In August, the trees were in full leaf and the nuts had grown to nearly full size. The ground-cover had been turned under leaving essentially no foliage on the ground. However,

Figure A.1 Photographs of the pecan orchard. Photographs a, b, and c were taken in April when the trees were free of leaves. Photographs d, e, and f were taken in August when the trees were in full leaf.

at the base of some trees, areas with diameters of 2 to 3 meters were missed, leaving a .5 meter stand of weeds. The pictures on the right side of Figure A.1 were taken in the middle of August. Picture (d) shows the full leaf condition of the orchard and picture (e) shows the van behind one tree, nearly hidden by leaves. The view in picture (f) is taken; from the side showing the van and mast. The receiver is at a 6 meter height. The undergrowth around some of the trees can be seen in this picture.

The results of the vegetation loss measurements conducted in 1982 are reported in U.S. Army Report CECOM-83-2 entitled, "Vegetation Loss Measurements at 91.6, 28.8, and 57.6 GHz through a pecan orchard in Texas," [2]. Whereas, the measurements are extensively analyzed and discussed in CECOM-83-2, only summary material are presented in this appendix.

2.1 Loss versus Tree Depth

The emphasis of this study was placed on determining signal properties as a function of the number of trees on path. Data sets were recorded with 1, 3, 8, 11, 14, 20, 23, and 35 trees obstructing the path. The data used in this section to determine vegetation loss as a function of tree depth are taken from the combined azimuthal and elevation scans where the terminals were carefully positioned at trunk level on a lone that passed through the center of the tree row. Each recorded value is adjusted to compare to the free space level that would have occurred without path obstructions. In other words, the signal reduction due to path length and atmospheric absorption was removed so that only the loss due to the path obstruction (trees) is indicated. Values recorded for this purpose are the highest measured received signal level that occurred on either the azimuthal or elevation scan. There was concern that the maximum signal might not have occurred within the horizontal-vertical slice take across the 0° intercept. Tests were conducted incrementing one axis by ±1 or 2° and repeating the scan for the other axis. This process was repeated for several tree depths particularly if a null occurred for the zero scans that passed through the 0° intercepts.

The average value plots of Figures A.2, A.3, and A.4 permit an analysis of vegetation loss dependence on the number of trees, on frequency, and on height of the terminals. At the 1 meter height, Figure A.2, the loss was more or less a linear function of the number

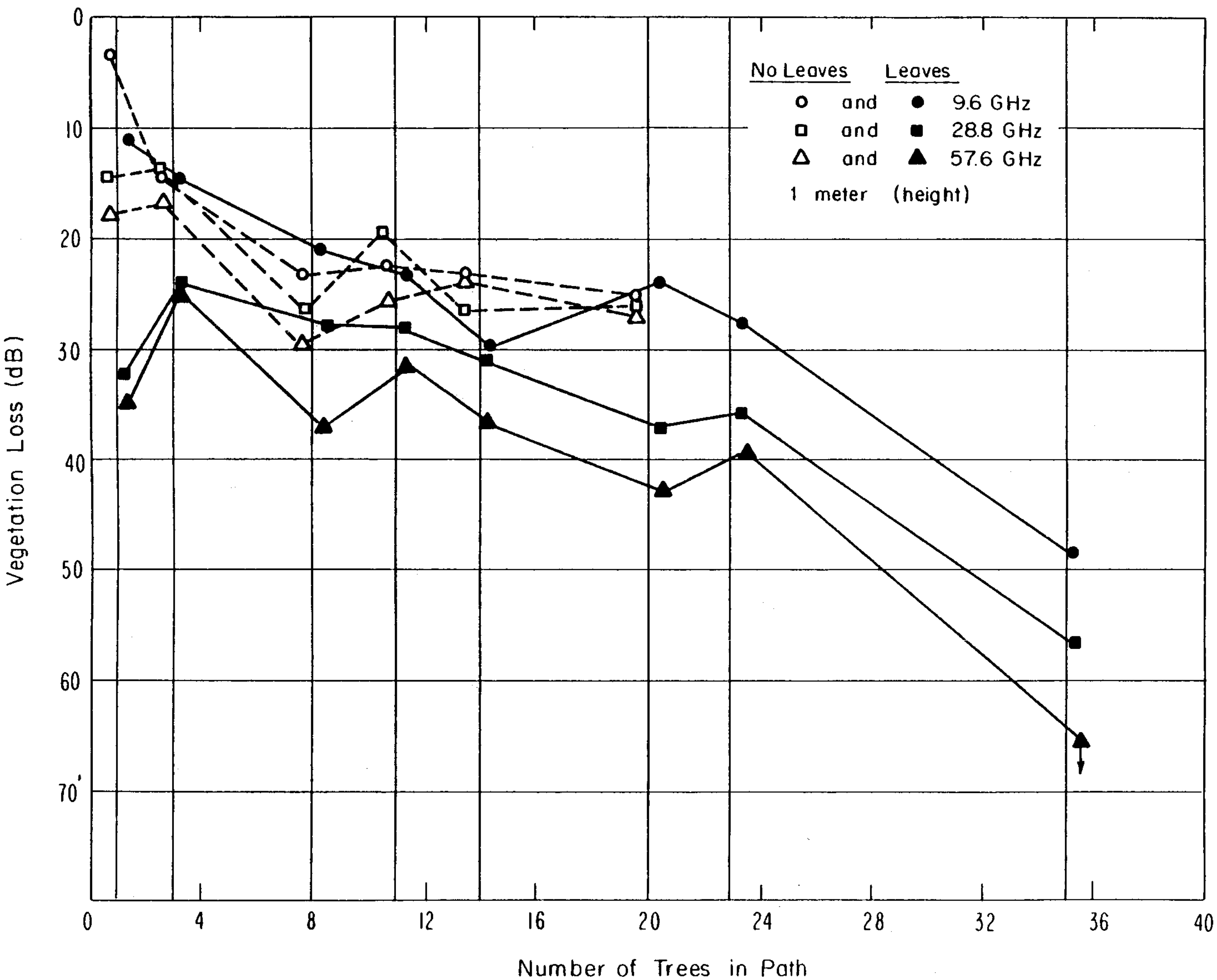

Figure A.2 Average values of vegetation loss as a function of the number of trees on path for 9.6, 28.8, and 57.6 GHz at 1 meter.

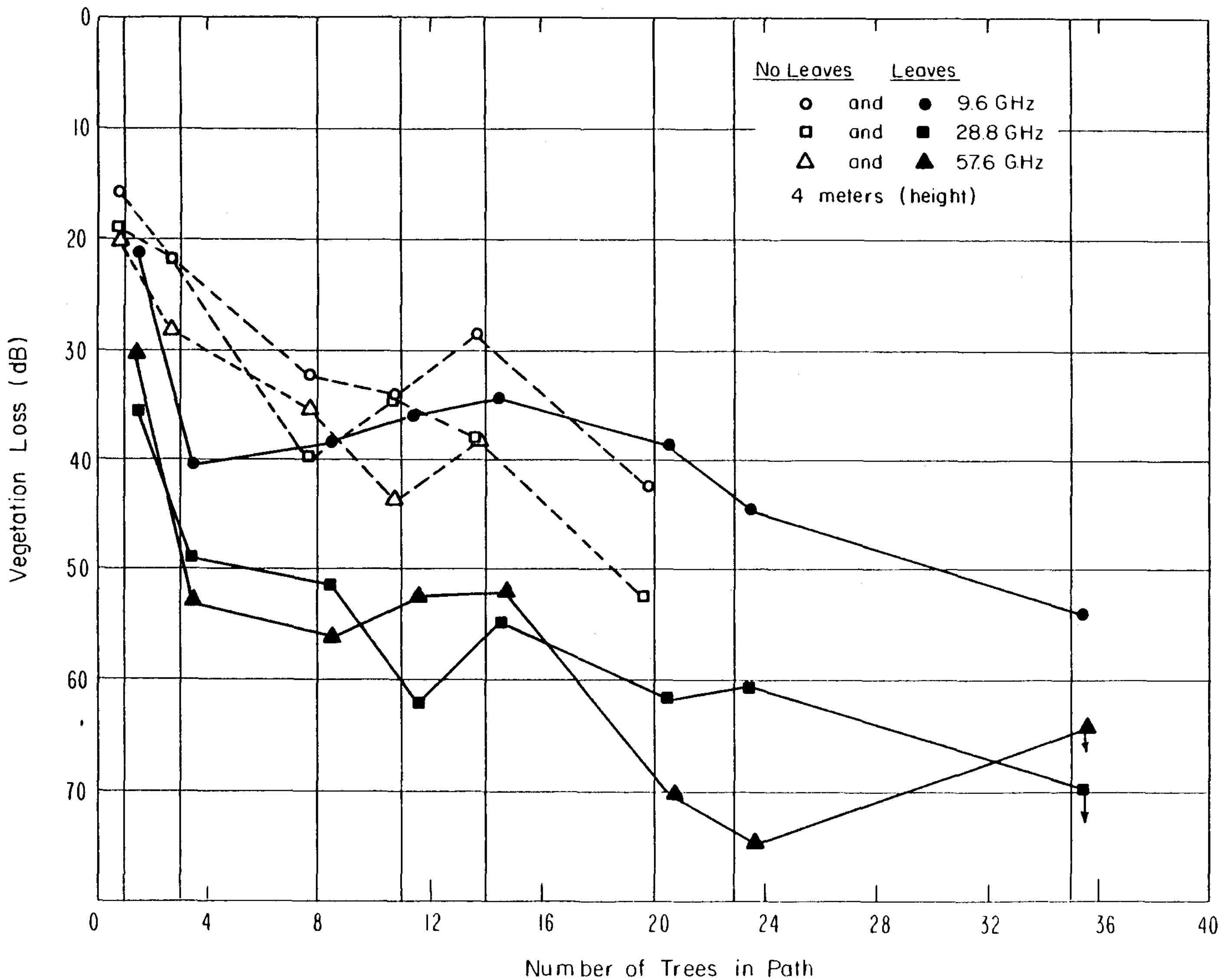

Figure A.3 Average values of vegetation loss as a function of the number of trees in path for 9.6, 28.8, and 57.6 GHz at 4 meters.

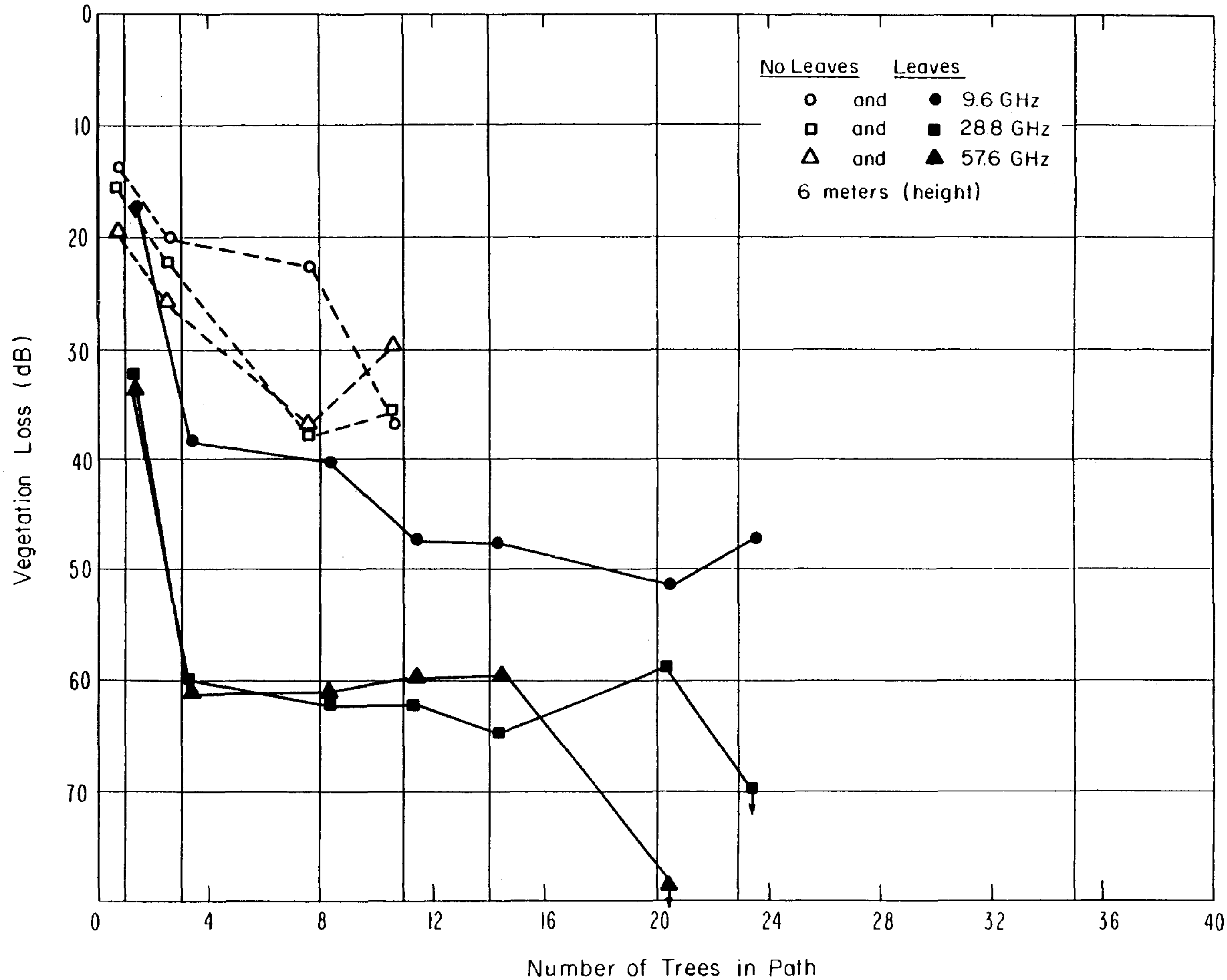

Figure A.4 Average values of vegetation loss as a function of the number of trees in path for 9.6, 28.8, and 57.6 GHz at 6 meters.

of trees except for some of the points taken for 1 tree on the path. At 28.8 and 57.6 GHz a higher loss occurred for 1 tree than for 3 trees which was not the case for the 9.6 GHz. The loss for 1 tree is sensitive to the position of the antenna relative to the center of the trunk since the antennas could not be absolutely co-located. The centers of the two higher frequency antennas lie in nearly the same vertical plane, seeing the obstruction somewhat differently than the 9.6 GHz receiving antenna. Also, the 9.6 GHz antenna beamwidth in 5°, about 4 time that of the upper two frequencies, and is large compared to the angle subtended by the trunks as seen by the receiver. The losses at each tree depth are consistently higher with increased frequency. The presence of leaves in the vicinity of the 1 meter height and some tall grass would be expected to produce a greater loss for the two upper frequencies.

The propagation mode for theses signals must be primarily diffraction scattering from the trunks, since little signal would pass through the 40 to 50 centimeter diameter trunks. Because of the variations in trunk size and positions relative to the antenna beam, the geometry is quite complex. Antenna scans plotted in the next section show that the maximum signal arrives from the direction of one or the other edge of the trunk nearest the receiver.

In the data at the 4 meter height, Figure A.3, an abrupt break in the plot of vegetation loss versus number of trees can be seen. In the case of no leaves, the break occurs after the 8 tree point. For the measurements with the trees in leaf, the break in the curve is very pronounced after 3 trees. Is assumed that this break occurs when the dominant propagation mode changes from the strongly attenuated direct path mode (coherent component) to the multiple scatter mode (incoherent component).

With no leaves, the small twigs and branches absorb the electromagnetic waves at a low rate, so that multiple diffraction does not become the dominant mode of propagation until after several trees. Therefore, it is multiple diffraction from the large number of scattering objects that define the lower loss propagation mode. With leaves, there is a much higher attenuation per unit volume so the transition takes place with fewer trees in the path but at a much grater loss.

Without leaves, there was not a consistent dependence of loss with frequency, but with leaves the higher two frequencies showed much higher losses than 9.6 GHz. The loss at 28.8 and 57.6 GHz appeared to very nearly the same.

In Figure A.4, the data at the 6 meter height show very similar loss characteristics as a function of number of trees as the 4 meter height data, except that the span of the trees at this height was somewhat greater producing greater losses. The 28.8 and 57.6 GHz data has the break in the curve at 8 trees for the no-leaves state; however, only one additional point at 11 trees was measured so the trend cannot be confirmed beyond this number. With leaves, the break in the curve at 3 trees is even more abrupt than at the 4 meter height. Again the 28.8 and 57.6 GHz data show about the same loss, considerable more than at 9.6 GHz.

Table A.1 is included to provide an indication of the order of magnitude of the difference between leaf and no leaf conditions at the three heights and frequencies for which measurements were made. These values are averages for all paths where comparative measurements were made regardless of the number of trees on path. The Table tends to highlight the effect of the presence of leaves. The most significant observation is the spread in loss between 9.6 GHz and the upper frequencies and the closeness of the 28.8 and 57.6 GHz values.

Table A.1. Vegetation Loss (dB) as a Differential Value Between Trees in Leaf and Trees Without Leaves

Height	Frequency (GHz)		
(m)	9.6	28.8	57.6
1	2.8	10.1	12.6
4	8.9	22.6	22.7
6	14.3	29.1	29.6

2.2 Loss versus Foliage Depth

Selected data from the previous section are presented in this section not as a function of the number of trees on the path, but as a function of depth of foliage. Only data measured when the trees were in leaf is included. The data for the 4 and 6 meter heights are presented in Figures A.5, A.6, and A.7 for 9.6, 28.8, and 57.6 GHz, respectively. The 1 meter height data was not included because of the nonuniform foliage at that height. To convert from trees on path to the depth of foliage in meters, an estimate)based on measurement of number of trees) was made of average depth per tree at the 4 meter and 6 meter heights. Nine meters per tree was used for the 4 meter height and 11 meters per tree was used for the 6 meter height. The vegetation losses measured at 4 meters are less (on average) than the vegetation losses at 6 meters. This difference might be attributable to the branch structure and/or the leaf population per meter at these heights. Or the difference may be due to a miscalculation of the average depth of foliage per tree along the actual path, or a combination of these.

Curves showing predicted values in these figures come from a modified exponential decay model described in "An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Trees," Report No. ESD TR-812-101. [3] The most significant difference between the measured and predicted data is the point at which the slope changes. The predicted curve is straight and steep to a depth of 14 meters. From 14 meters to 400 meters, the slope is still steep but the roll-off is exponential. As can be seen in the figures, the measured data has a steep slope to about 30 meters and then has a considerable more shallow slope to the extent of measurements. The lack of uniform data samples in the 20 to 80 meter range prohibits a more precise statement concerning the break in the curve using the measured data.

2.3 Azimuth and Elevation Angle Scans

Because of the propagation mode that occurred when diffraction scattering appeared to be dominant, the directional properties of the arriving signals are most interesting. A series os azimuth and elevation angle scans ere recorded for all three frequencies, the three terminal heights, and both leaves and no leaves states at tree depths of 1, 3, 8, and 11 trees; showing that the angle of arrival varies with tree depth. Only the results from the 4 meter height are shown here. Figure A.8 shows antenna scans with no leaves and Figure A.9 shows antenna scans with leaves. An unobstructed reference scan is superimposed (the light trace) on each of the data scans in these figures. The reference antenna patterns used were

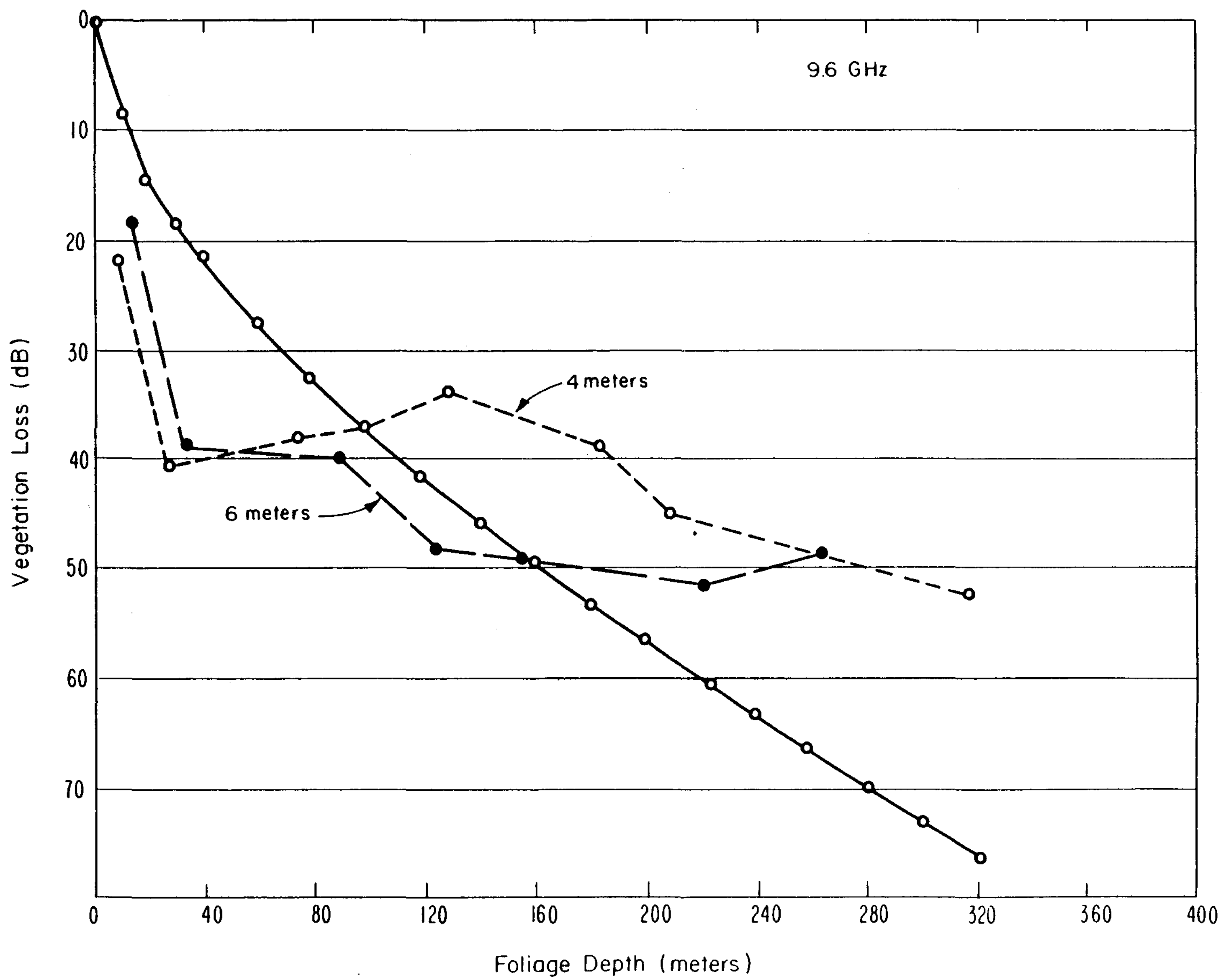

Figure A.5 Measured and predicted values of vegetation loss as a function of foliage depth for 9.6 GHz.

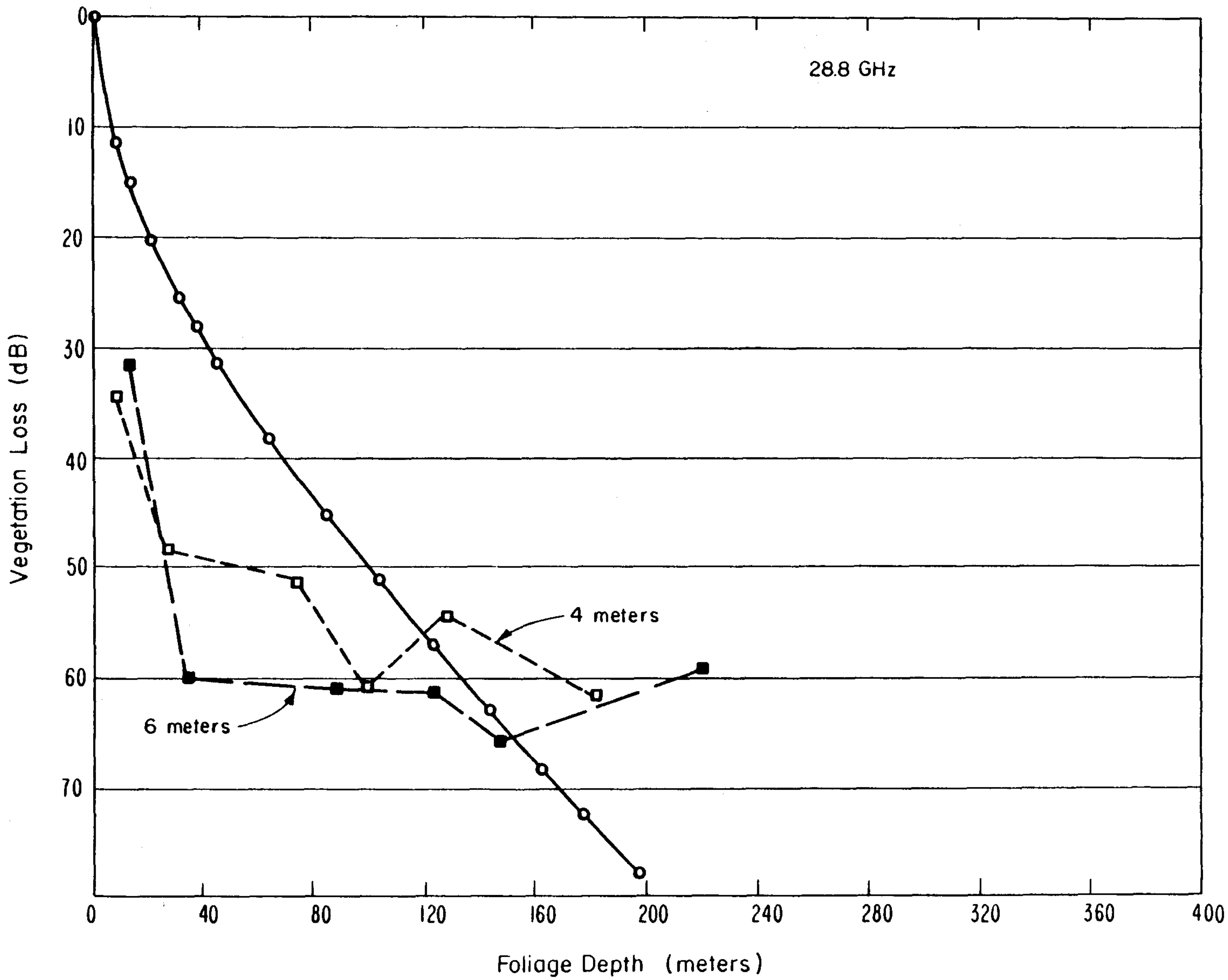

Figure A.6 Measured and predicted values of vegetation loss as a function of foliage depth for 28.8 GHz.

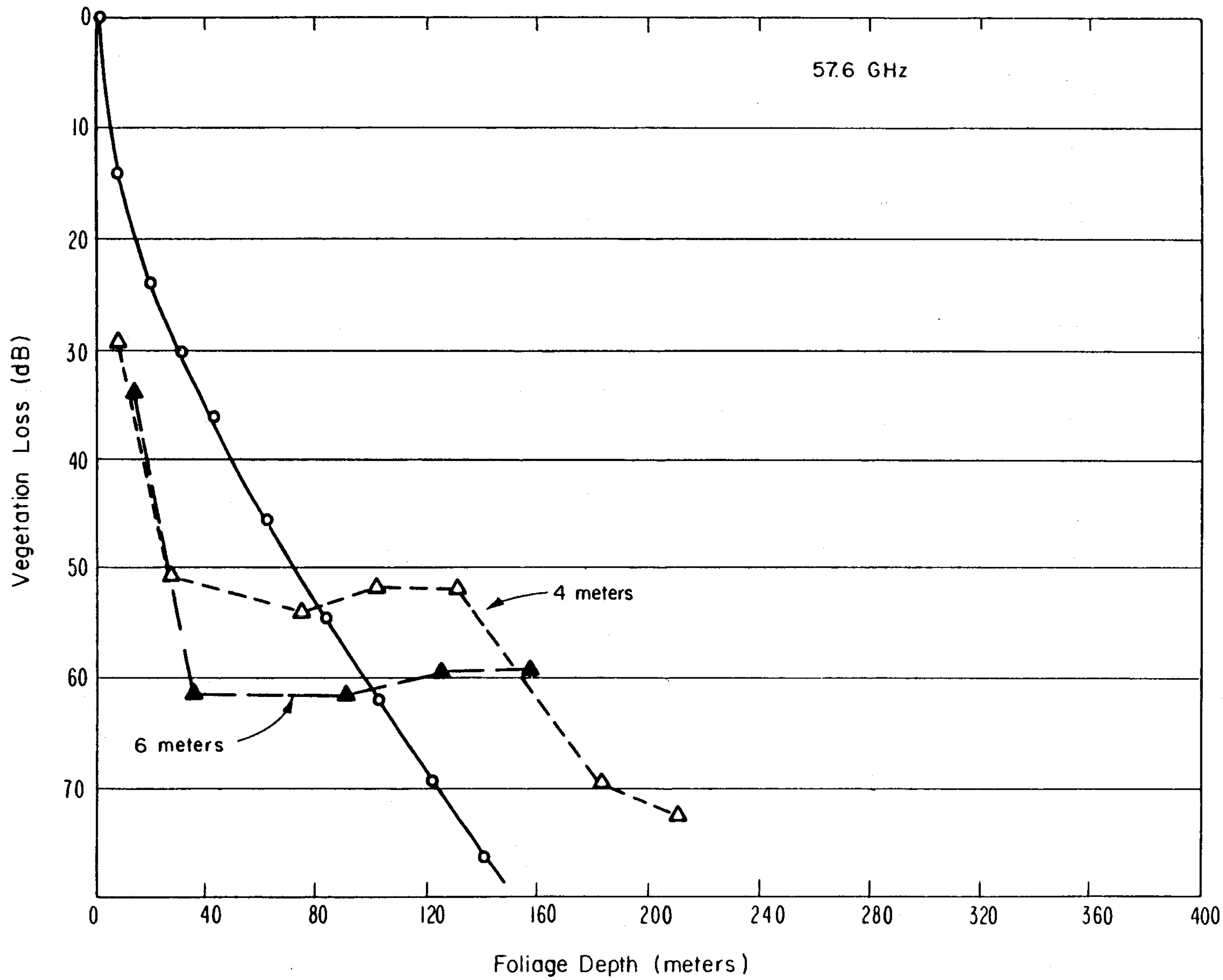

Figure A.7 Measured and predicted values of vegetation loss as a function of foliage depth for 57.6 GHz.

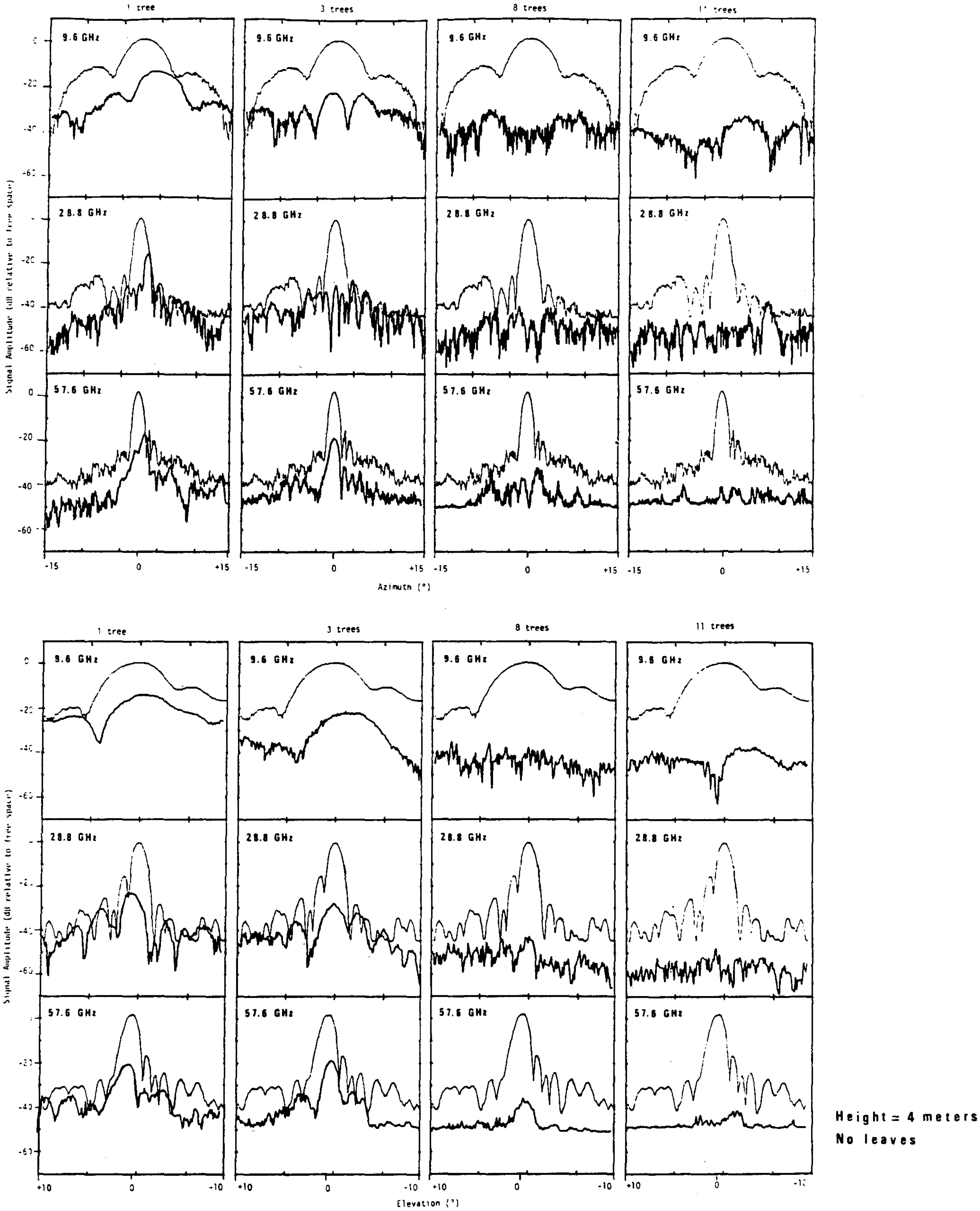

Figure A.8 Azimuthal and elevation angle scans at the 4 meter height for 1, 3, 8, and 11 trees without leaves. The reference scans are at 1 meter along an unobstructed 300 meter path.

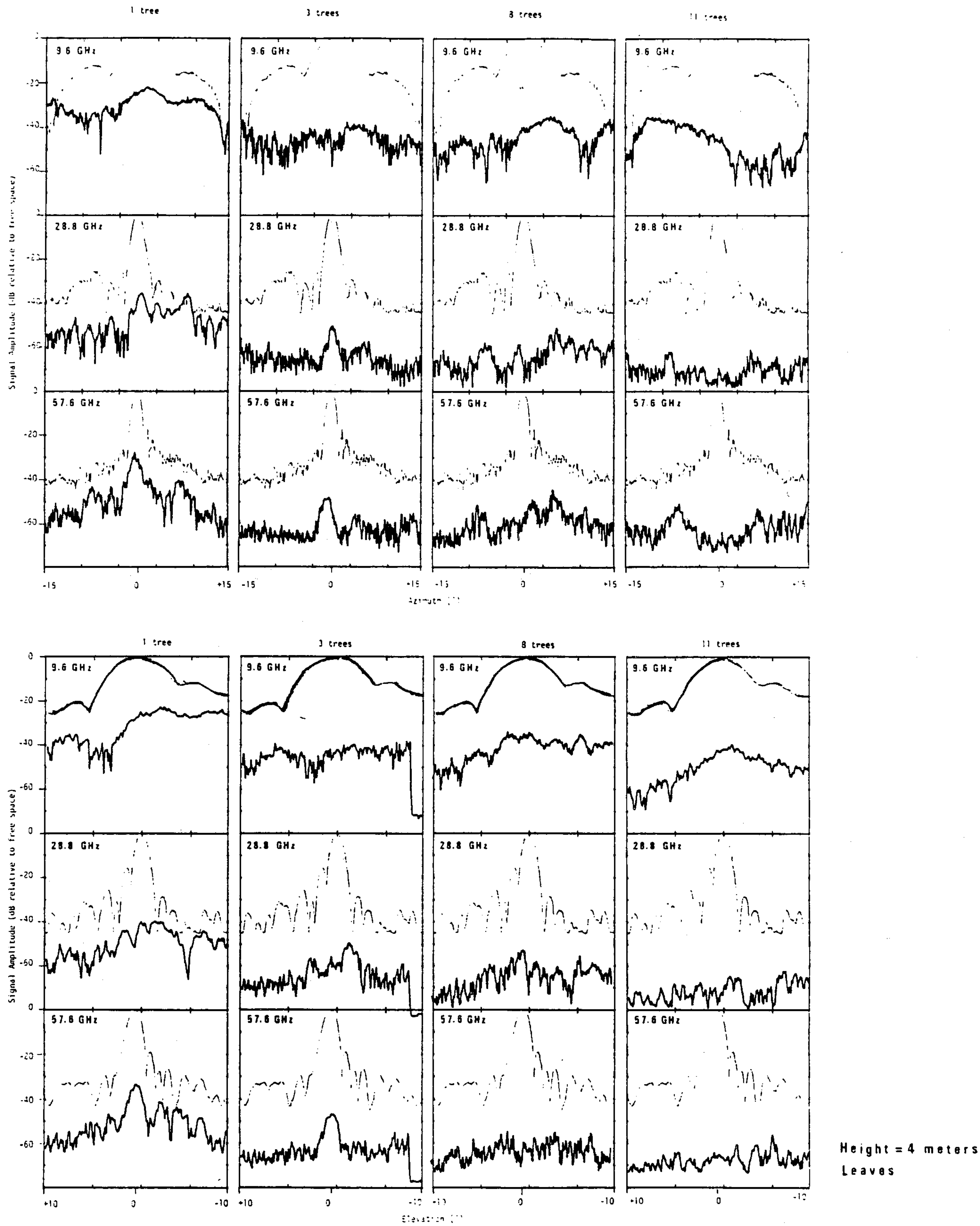

Figure A.9 Azimuthal and elevation angle scans at the 4 meter height for 1, 3, 8, and 11 trees with leaves. The reference scan are at 1 meter along an unobstructed 300 meter path.

with VV polarization, take on a 300 meter path at a 1 meter height. The height over ground for unobstructed antenna patterns affects the elevation plots slightly as the ground reflection produces a multipath signal. [1]

Azimuth and elevation angle scans at the 4 meter height without leaves, Figure A.8, show a gradual loss of signal directivity, with increasing tree depth and at the 11 tree depth, the signal level is nearly flat over all scans. For the foliated state at 4 meters, Figure A.9, the flattening out of the signal level occurs at the 8 tree depth. This suggests that the energy is scattered nearly equally from the entire tree. At the 4 meter level, the receiving antenna is generally 2 to 4 meters from the branches, but 12 to 14 meters from the trunk of the last tree on the path. The ±15° azimuth scans illuminate nearly the full width of the tree except for some branches that may be partially obscured at the extreme outer edge. The elevation scan at ±10° almost illuminates the highest branches of the closest tree to the receiving antenna at the 4 meter height and passes through many layers of branches before intersecting the ground at the -10° pointing. This estimate of the pointing geometry is included to point out that no over-the-top or down-the-row mode of propagation was detected.

3. CONCLUSIONS

Measurements at 9.6, 28.8, and 57.6 GHz were made to describe vegetation loss. A well-established, uniformly planted pecan orchard was chosen because the density of foliage was very constant with distance. At tree trunk height (1 meter with no underbrush) and at branch heights with trees in defoliated state (early spring), the vegetation loss curve takes on a decreasing, nearly linear shape as a function of number of trees. In contrast, at branch height (4 and 6 meters) in a foliated state, the curve makes an abrupt break at a foliage depth of about 30 meters. For the first 30 meters of foliage depth, the increase in vegetation loss in nearly linear at a rate of 1.3 to 2.0 dB per meter, depending on frequency, and beyond 30 meters, the curve decreases at an exponential rate that averages only 0.05 dB loss per meter. The shape of the vegetation loss curve as a function of foliage depth is interpreted as an initial loss rate due to the high attenuation of the direct path mode, and beyond 30 meters, a low loss rate due to the multiple scatter mode. These data also show a clear trend for increased losses with increased frequency but not in a directional proportional relationship, i.e., higher frequencies were attenuated less than the ratio of the increase in frequency. These ratios of vegetation losses versus frequency appear to be related to the wavelength of the propagated wave compared to the scale size of the leaves and branches obstructing the path. This relationship cannot be determined from measurements at the three frequencies used, but there may be little increase in loss above foliage dependent frequency as suggested by the data.

4. REFERENCES

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[2] E.J. Violette, R.H. Espeland, and F. Schwering (1983), "Vegetation loses measurements at 9.6, 28.8, and 57.6 GHz through a pecan orchard in Texas," CECOM-83-2, U.S. Army Communications-Electronics Command, Ft. Monmouth, NY 07703.

[3] M.A. Weissberger (1981), "An initial critical summary of models for predicting the attenuation of radio waves by trees," ESD-TR-81-101, Department of Defense, Electromagnetic Compatibility Analysis Center, Annapolis, MD 21402.

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Propagation measurements were made in the Olympic National Forest of Washington state during October 1987 to examine millimeter-wave signal propagation through conifer vegetation. Linearly polarized continuous-wave signals at 9.6, 28.8, 57.6, and 96.1 GHz were used to evaluate attenuation, depolarization, and backscattering from conifer trees. Azimuth and elevation scans were conducted for various transmitter heights and path lengths. Results from the measurements are presented and compared with data gathered from similar measurements taken through deciduous vegetation.

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