

Initial Study of the Local Multipoint Distribution System Radio Channel

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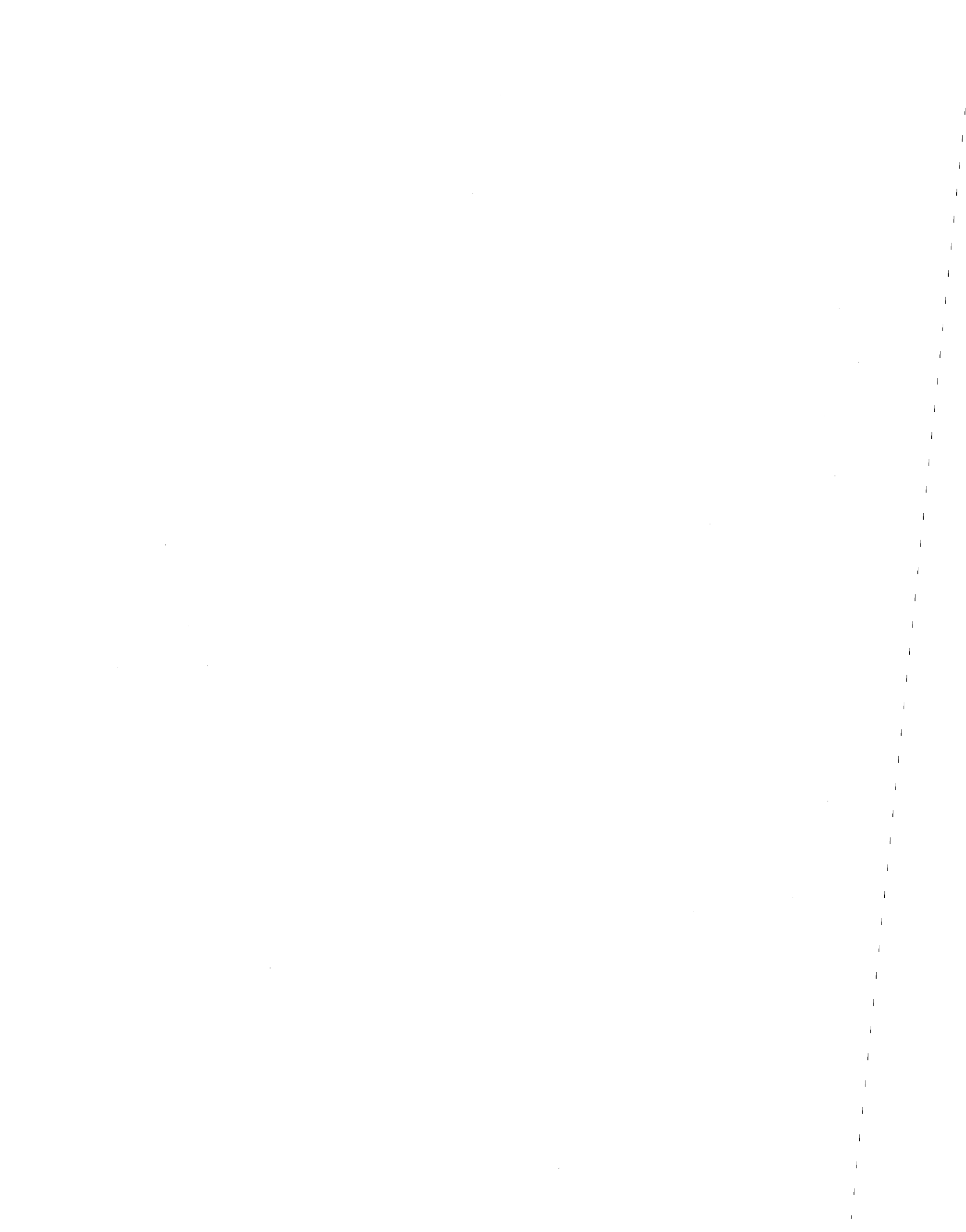
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INITIAL STUDY OF THE LOCAL MULTIPOINT DISTRIBUTION SYSTEM RADIO CHANNEL

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A broadband millimeter wave study was completed to characterize the radio channel for Local Multipoint Distribution Systems in Boulder, Colorado. The study determined characteristics for proposed 20-MHz channels centered at 30.3 GHz using two transmitter heights in a suburban environment. Distributions of delay spread, correlation bandwidth, frequency selective fading and scatter plots of signal loss are presented. The median signal loss for the 40-m transmitter height was 15 dB. Maximum delay spreads for this height were below 10 ns with a median value of less than 1 ns. Data was also collected to characterize a flat plate reflector proposed for use at 28.8 GHz. Cross cell interference and signal diffraction measurements were also made.

Key words: broadband, delay spread, local multipoint distribution system, radio channel

1. INTRODUCTION

A suite of measurements were made to characterize propagation representative of Local Multipoint Distribution System (LMDS) signals at 30.3 GHz. The study was designed to answer questions which could affect the economic viability of LMDS service. The primary emphasis was to complete a broadband area coverage study using two transmitter heights. This work characterized the delay spread and signal loss distributions for a random selection of single and multiple family dwellings. A second concern was the performance of passive repeaters, in particular their depolarization and loss characteristics at 28.8 GHz. Limited measurements were also made concerning signal diffraction over buildings and cross cell transmitter interference.

2. EQUIPMENT

The Institute for Telecommunication Sciences (ITS) used its 30.3-GHz wideband probe (WBP) for the experiments. Block diagrams of the transmitter and receiver as configured

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for the wideband LMDS measurements are given in Figures 1 and 2. The WBP uses a 28.8-GHz Gunn source mixed with a 1.5-GHz signal which has been bi-phase shift key (BPSK) modulated by a 500-Mb/s pseudo-random bit sequence. The spectrum of this signal has a null-to-null bandwidth of 1 GHz. The 30.3-GHz output is amplified using a solid state amplifier and a traveling wave tube (TWT) to a level of 1 W. The TWT was operated below its saturation level, which is between 10 and 20 W. Transmitter output was monitored using a power meter. The passive repeater study used the 28.8 GHz continuous wave (CW) transmitter and receiver sections of the WBP, configured as shown in Figures 3 and 4. The 28.8-GHz CW signal was amplified to 17.2 dBm.

Both wideband and narrowband signals were transmitted using a vertically polarized standard gain horn antenna. The horn has a 26-degree beam width and 15.2-dB gain at 30.3 GHz. Two standard gain horns were fabricated to match the receive antennas of proposed LMDS systems. The horns have an E-plane beam width of 5.5 degrees and were coupled to the receiver using a waveguide. Vertically and horizontally polarized signals could be routed to the broadband or narrowband receiver input using manual waveguide switches.

The 30.3-GHz wideband signal was downconverted and demodulated using a correlation receiver. The resulting channel impulse measurement was stored using a digital audio tape recorder (DAT). This data was then processed by computer. The 28.8-GHz narrowband signal was downconverted to 12.63 MHz and the received signal power was measured using a spectrum analyzer.

The WBP system was calibrated using a line-of-sight (LOS) path on the Department of Commerce (DOC) Boulder campus. The transmitter was located on the mesa on the west edge of the campus and the receiver was in the DOC south field. The calibration path length was surveyed and is 1.051 km. The narrowband system was calibrated using a short LOS path on the DOC south field.

3. MEASUREMENTS

3.1 Area Coverage Survey

Forty-five receiver sites in Boulder were surveyed using Williams Village, a 13-story apartment building complex as the transmitter site. Transmitter heights of 16 m and 40 m were selected to study transmitter height dependence in the area coverage statistics. Transmitter and receiver locations are shown on Figures 5, 6, and 7. Typical receiver locations consisted of one- and two-story single family homes and one- to three-story townhomes. At these locations, the recording van was parked curbside and the mast was raised 1 m above the house roof height. A video camera with a telephoto lens aligned with the antenna bore sight was used to determine the roof height. The

maximum antenna height was 8.5 m. Signal level was peaked by adjusting elevation and azimuth using a mast-mounted controller. A determination of line-of-sight [LOS versus obstructed line-of-sight (OLOS)] was then made using the video camera. Each station was recorded for 55 s using the short PN code (127 bits) and 120s using the long code (32767 bits). Since no delays beyond the 265-ns range of the short code were observed, only the short code data were processed.

3.2 Passive Repeater Study

Narrowband measurements were made on a short path using a 1.2 m² aluminum reflector. Geometry of the test is given in Figure 8. Both vertically and horizontally polarized signals were received using the 5.5-degree horn antennas. Signal strength was measured using a spectrum analyzer to monitor the 12.63-MHz IF of the 28.8-GHz receiver. The repeater loss was calculated using the following link equation [1]

$$L_{pr}(dB) = P_r - (P_t + G_t - G_r + G_{pr} - L_{fs}(r_1) - L_{fs}(r_2)) \quad (1)$$

where:

- L_{pr} = passive repeater loss
- P_r = received power
- P_t = transmit power
- L_{fs} = free space loss
- G_t = gain of transmit antenna
- G_r = gain of receive antenna
- G_{pr} = passive repeater gain = $20 \log 4\pi A/\lambda^2$
- A = area of repeater.

3.3 Diffraction Study

Four stations were recorded in the shadow zone of the 3100 Marine Street National Oceanographic and Atmospheric Administration (NOAA) site, a five story office building. Using transmitter and receiver heights, the NOAA building height and ground elevations from topographic maps, the diffraction angle was determined. Wideband excess path loss was then tabulated as a function of the diffraction angle. This diffraction angle is a deviation from the line-of-sight path that the signal must make to reach the receiver by bending over the top of the obstruction (Figure 9).

3.4 Interference Study

Wideband interference was studied by moving the transmitter to Table Mountain, 14.4 km north of Williams Village (Figure 5). A vertically polarized signal was transmitted directly south towards Williams Village. The receiver was positioned at several locations used in the Area Coverage Survey and scanned to determine received signal strength using both vertical and horizontal receive antennas.

4. DATA PROCESSING

The two channels of wideband data were digitally recorded and transferred to a micro computer for processing. Data were stored as a time series representing the cophase and quadphase baseband signals. At each of the 45 stations, which were occupied for both transmitter heights and sometimes several receiver mast heights, approximately 520 complex short code-word channel responses were recorded. This data was edited and a total of 103 recordings were selected for final processing. Several algorithms were used to reduce the channel response data to time and frequency domain parameters for each station. This produced a set of parameters for each of the 500-plus channel responses for each recording. These parameters are:

1. Excess Path Loss,
2. Delay Spread,
3. Correlation Bandwidth,
4. Frequency Selective Fading.

The average values of these parameters for each recording were then used to calculate distributions or scatter plots for each transmitter height. The algorithms for parameters 2 and 3 can be found in [2]. Only additional data processing and calibration methods will be discussed here.

5. CALIBRATION AND PROCESSING ALGORITHMS

Excess path loss was determined by comparing the received signal energy to the average received signal energy over the calibration path on the DOC campus. This path was line-of-sight with the transmitter located on the mesa to the west of campus and the receiver van stationed in the south field. The system was configured identically to the LMDS survey system. The transmit power was set to 1 W and monitored using a power meter. This meter was connected to the transmitter using a 20-dB coupler on the output waveguide before the antenna mounting flange. The only variable elements in the system were at the receiver. Here a variable gain IF amplifier and a variable attenuator were used. The settings of these components were recorded at each site and used to obtain differences in the system gain relative to the calibration path. Received energy

was calculated as in [1], as it is the integral of the power delay profile, and is referred to in the following as ΣP .

Using this convention, the excess path loss is calculated by

$$A = \Delta G - 20 \log (r / r_0) - 10 \log (\Sigma P / \Sigma P_0) \quad (2)$$

where

A	$=$	excess path loss
ΔG	$=$	$G - G_0$
G_0	$=$	system gain for calibration path
G	$=$	system gain
r_0	$=$	calibration path length
r	$=$	path length.

Frequency selective fading levels in proposed 20-MHz channels were calculated using the magnitude of the complex impulse spectrum. The primary concern was to normalize the received power spectrum by the spectrum of our system. This was done in order to obtain a flat power spectrum over the desired bandwidth. A development of the frequency selective fading algorithm follows.

We can express the received signal as

$$x(t) = \frac{\gamma}{2kr} h * p(t) \quad (3)$$

where $2kr$ (k the wave number, r the path length) provides the general "free space path loss", γ is a "receiver gain" which includes the receiving antenna and a factor to convert from "field strength" to A/D values, p is the (emulated) transmitted pulse and includes the transmitter power and antenna effects as well as the triangular shape, and finally, h is the impulse response of the radio channel except that the free space propagation effects have been removed. We assume that all the signals have been reduced to base band and, therefore, that x , h , and p are *complex* signals with real (cophase) and imaginary (quadphase) components.

In the frequency domain, we can write

$$X(f) = \frac{\gamma}{2kr} H(f) P(f) \quad (4)$$

where we use the convention that Fourier transforms are represented by their corresponding capital letters. What we really want to display is the function $H(f)$.

Calibration data from the DOC south field provides a propagation path that seemed very clean and free of obstructions or scatterers. Using the subscript 0 for this path, we can assume that the impulse response $h_0(t)$ is just the delta function, so that $H_0(f) = 1$ and

$$X_0(f) = \frac{\gamma_0}{2kr} P(f) . \quad (5)$$

This is nearly our final result, but we need to know more about the function $X_0(f)$.

We can suppose that the measured signal in the calibration run had the form

$$x_0(t) = x_1 (1 - |t|/\tau) \quad \text{for } |t| < \tau \quad (6)$$

and, therefore,

$$X_0(f) = x_1 \tau \text{sinc}^2(\pi f \tau) . \quad (7)$$

We know that τ is 2 ns. All that remains is to estimate the amplitude x_1 . One could look at the calibration run and measure an average peak value. But another way is to use an average "energy," which is also available from the calibration run, because then we would have

$$\|x(t)\|^2 = \int |x(t)|^2 dt = x_1^2 \frac{2}{3} \tau . \quad (8)$$

Such a computation shows an "energy" equal to 10.7 ns, therefore $x_1 = 2.83$.

To express these results in decibels, we would write

$$10 \log |H(f)|^2 = (G_o - G) + 20 \log(r/r_o) - 20 \log x_1 \tau + 10 \log \frac{|X(f)|^2}{\text{sinc}^4(\pi f \tau)} \quad (9)$$

and we would plot the negative of this as excess path loss. If we express τ in seconds, we find

$$20 \log x_1 \tau = 164.9 \text{ dB}$$

and we can include this as a constant to simplify the path loss expression.

In practice, it is not possible to extract the power spectrum over the entire 1-GHz bandwidth. As the power spectrum approaches its nulls, the available signal power drops below the noise spectrum. This effect is further complicated by the variable

signal-to-noise ratio of the data set. Since these effects cannot be avoided, we decided to use the spectrum between -100 and 100 MHz. Over this bandwidth, the spectrum was always above the noise floor and it was possible to normalize by $\text{sinc}^4(\pi f\tau)$. The normalized spectrum was then divided into ten 20-MHz channels and the average excess path loss and the *max-min* excess path loss or Δ excess path loss for each channel was calculated. For a typical station with 520 recorded impulses, 5200 average excess path loss, and Δ excess path loss numbers were calculated. This data is referred to as excess path loss per channel and Δ excess path loss per channel. Also tabulated were the average and median values of these data for each station. The averaged results are labeled average excess path loss per channel and average Δ excess path loss per channel and plotted as distributions for each transmitter height.

Because the transmitter was located behind glass in Williams Village and no glass was present on the calibration path, an additional calibration constant was needed for excess path loss data. Measurements showed that the 0.125-in tinted glass in the Towers added 3 dB of attenuation at 30.3 GHz. This constant was subtracted from excess path loss results.

6. RESULTS

6.1 Area Coverage Survey

A list of processed data grouped by transmitter height is given in Table 1. The list associates station number with data file name and lists the input parameters needed for data processing. It also gives the LOS and OLOS determinations for each station and receiver height. From this table, the station path length distribution can be determined. This distribution (Figure 10) has a median value of 4.5 km.

The data processing sequence is illustrated by a series of plots. First, a set of time series parameters for each station is calculated. Figures 11 through 13 show typical results for Station 26. Figure 11 shows the received power and excess path loss for the 514 impulse recordings with the transmitter on the 13th floor of Williams Village. Figure 12 is a similar plot for delay spread calculated using different threshold values. Figure 13 shows the received impulse dynamic range (DYR) and correlation bandwidth (CBW) results for this station. The DYR plot is the ratio of the peak of the impulse to the peak of the last 10 percent of its tail. These data are then used to calculate an average and standard deviation for each parameter.

Figure 14 shows some of the raw data for Station 26. Here the channel impulses with the minimum and maximum delay spreads are displayed. Figure 15 shows two real FFT's used for correlation bandwidth calculations. The frequency where magnitude drops below 0.5 was plotted as a time series in Figure 12.

The next set of graphs show typical results from frequency selective fading calculations. Figure 16 gives the magnitude of the complex power spectrum for the minimum delay spread impulse and also the normalized excess path loss for this impulse (Station 26, file u3p28). These frequency domain data are then separated into ten 20-MHz channels between -100 and 100 MHz. The average excess path loss and the Δ excess path loss are calculated for each channel. Figure 17 shows similar spectrum plots for Station 1 (u3p37). Distributions of these data for the ten channels are given in Figures 18, 19, 20, and 21. In order to make distributions for the two station groupings (13th floor transmitter versus 5th floor transmitter), averages, standard deviations, and median values were calculated for each distribution and tabulated by station; these results are listed in Tables 2 and 3. The delay spread calculations used 10 dB, 15 dB and noise plus 3 dB thresholds. Where the noise level is set to the peak signal for the last 10 percent of each impulse record. If the range between peak signal and the noise is less than the threshold plus 3 dB, that impulse is thrown out from the delay spread calculation.

Scatter plots of wideband excess path loss versus distance for the two transmitter heights are given in Figures 22 and 23. We see some higher losses, especially close in, for the lower transmitter height. Also, we see more stations with near zero excess path loss, at longer path lengths, for data collected using the 13th-floor transmitter site. Distributions for these two data sets are given in Figures 24, 25, 26, and 27. Here we see a median excess path loss of 18 dB and 15 dB, respectively, for the lower versus higher transmitter location. Distributions of average excess path loss per channel for the two cases show similar median values as compared to their wideband counterparts, but show slightly larger variance in the data sets. This is probably due to the averaging which was done over a smaller bandwidth (20 MHz) when the data was reduced to ten channels. These results are given in Figures 28, 29, 30, and 31.

The distributions of average Δ excess path loss per channel for the two transmitter heights are similar, with median values between 2 and 3 dB but with more outliers for the lower transmitter site. These data are shown in Figures 32, 33, 34, and 35. Distributions for average delay spread, Figures 36 through 39, indicate median values of less than 1 ns at both transmitter heights. This is at the resolving limit of our system and is partially due to the choice of a 10-dB threshold. For a 30-dB threshold, this limit is 0.8 ns; a 10-dB threshold raises this limit by truncating the base of the received pulse. The correlation BW results are also given using distributions. These distributions show a median value of 225 MHz for the lower transmitter and 250 MHz for the sites surveyed using the higher transmitter. These results are given in Figures 40 through 43.

6.2 Passive Repeater Study

Table 4 gives a summary of the measured passive repeater loss versus angle. We measured losses between 4 and 6 dB. These losses can be attributed to scattering off the tripod and surrounding buildings as well as the surface of the reflector which

was not perfectly flat. The 3-dB antenna pattern of the plate was measured at 0.2-degrees. This is consistent for a 1.2-m² reflector operating at 28.8 GHz [1]. This made aiming the reflector difficult. Antenna patterns for the repeater are shown in Figures 44 and 45. Cross polarization was measured by transmitting a vertical signal and measuring both vertical and horizontal polarizations at the receiver. Cross polarization varied between 16 and 24 dB and is shown versus angle in Figure 46.

6.3 Diffraction Study Results

The diffraction data are reported in Table 5. The stations selected were blocked from direct line of sight by the 3100 Marine Street NOAA building (Figure 6). By using the heights of the transmitter and receiver antennas, a diffraction angle was calculated. This angle is the deviation from LOS (from the transmitter to the top of the obstruction) that the transmitted signal must make to reach the receiver. Results indicate excess path losses of 35 dB to 9 dB for a range of angles from 5 to -0.46 degrees. A small negative angle indicates that there was a geometrical line of sight but that the radio signal was partially blocked. These results are compared to knife-edge diffractions calculated for the same angles [3]. The measured results do not have the smooth variation of the calculated ones. This may be due to additional obstructions on path, the non-ideal roof of the NOAA building, and uncertainty of elevations. In addition, there was an instrumentation shed on the NOAA roof which could have effected the signal diffraction.

6.4 Interference Study

A vertically polarized transmitter was pointed at Williams Village from a distance of 14.4 km. A direct signal was recorded at some locations but no reflected signals from Williams Village were measurable at the surveyed sites for either polarization. The surveyed sites are listed in Table 1.

7. CONCLUSIONS

7.1 Area Coverage Survey

Randomly selected single and multiple family dwellings in Boulder, CO, were surveyed to determine area coverage parameters for proposed LMDS channels. Signals were transmitted from two heights in Williams Village, 16 and 40 m, and received at an instrumentation van equipped with mast-mounted horn antennas. Radio path lengths for the survey varied between 1981 and 6927 m with a median value of 4.5 km. For each location, a time series of wideband 30.3-GHz signals was analyzed for excess path loss, delay spread, correlation bandwidth, and frequency selective fading.

The measured excess path losses were consistent with signals propagating over the tops of or through one to four trees without leaves [4]. The range of excess path losses varied from -6 dB to +32 dB. The median value for the 16-m transmitter height was 18 dB and for the 40-m height was 15 dB.

Multipath interference was minimal for the survey due to the directional receive antenna which had a beam width of 5.5 degrees. Using a 10-dB threshold, measured delay spreads were between 0.7 and 10 ns with a median value of less than 1 ns for both transmitter heights. Correlation bandwidth for these stations ranged between 11 and 471 MHz and 2 and 491 MHz for the upper and lower transmit heights, respectively. Median values for the two transmit heights were 250 and 225 MHz, respectively.

The complex spectrum of the signal was also analyzed to determine frequency selective fading for ten 20-MHz channels. The average excess path loss per channel for these data correlated with the wideband excess path loss results. However, the variance of this data set was 1 to 2 dB larger. This probably was due to the greater bandwidth over which the signals were averaged in the wideband case. The max-min (Δ) excess path loss per channel for all stations had a median value between 2 and 4 dB for both transmitter heights. This is consistent with the small delay spreads measured. The maximum average Δ excess path loss per channel for any station was 10 and 22 dB for the high and low transmitter sites, respectively.

7.2 Passive Repeater Study

Measurements of received power and cross-polarization effects were made for a range of angles between 3 and 109 degrees. Results indicate 16 to 24 dB cross polarization and 4 to 6 dB losses due to the non-ideal repeater and interference. The measured antenna pattern for the repeater was 0.2 degrees and this is consistent with theoretical results for a flat plate operating at 28.8 GHz. This made aiming the repeater difficult and would require surveying equipment and a skilled technician. It also makes it difficult to serve more than one or two households from each repeater location.

7.3 Diffraction Study Results

Four stations were measured in the shadow of the NOAA Marine Street facility. The diffraction angle for these sites varied between -0.03 and 3 degrees and excess path loss ranged between 9 and 35 dB.

7.4 Interference Study

An adjacent cell transmitter was set up to study possible cell-to-cell interference. No such effects were measurable using both vertically and horizontally polarized receive antennas aimed at Williams Village.

8. REFERENCES

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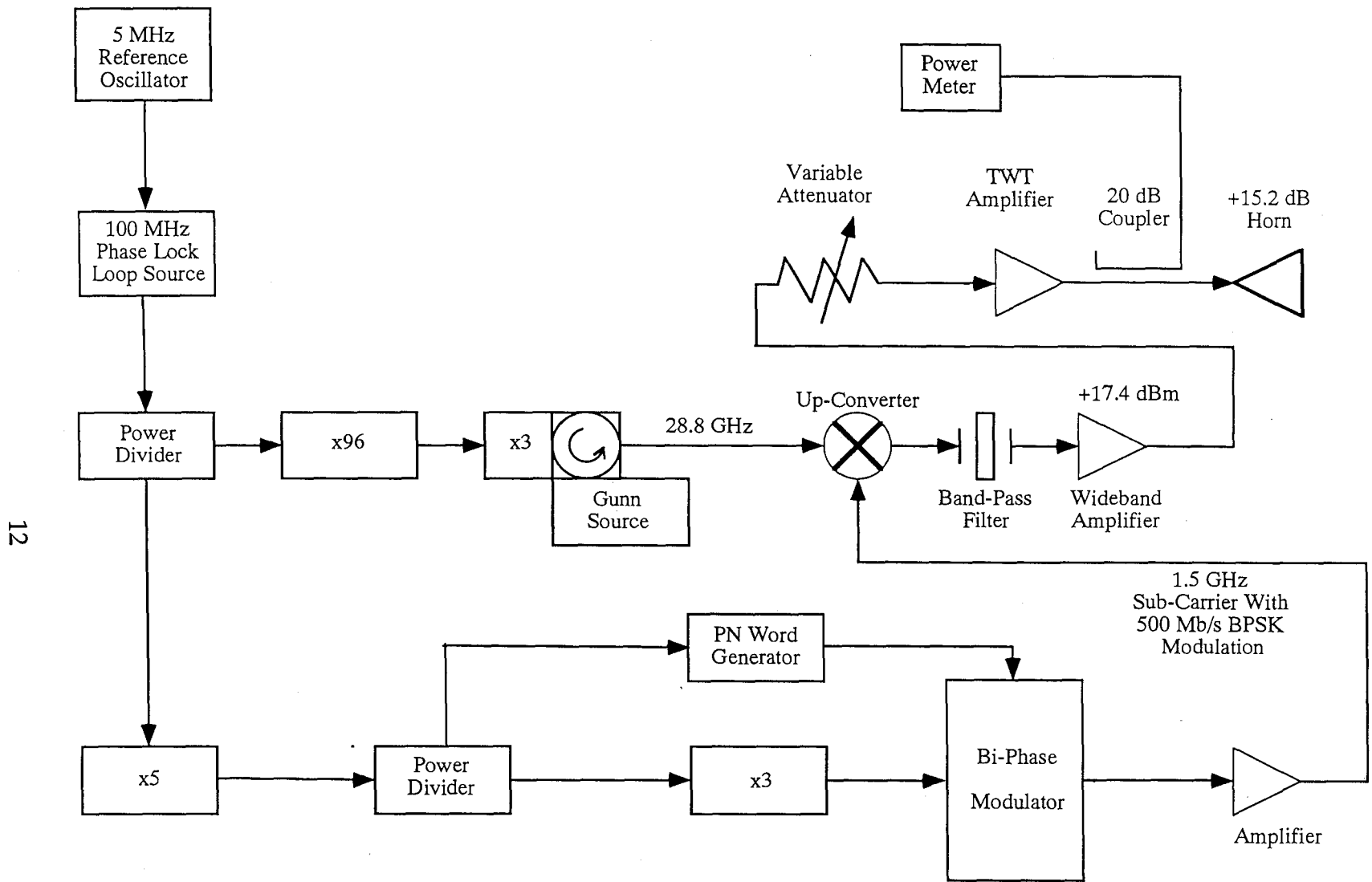


Figure 1. 30.3-GHz wideband transmitter.

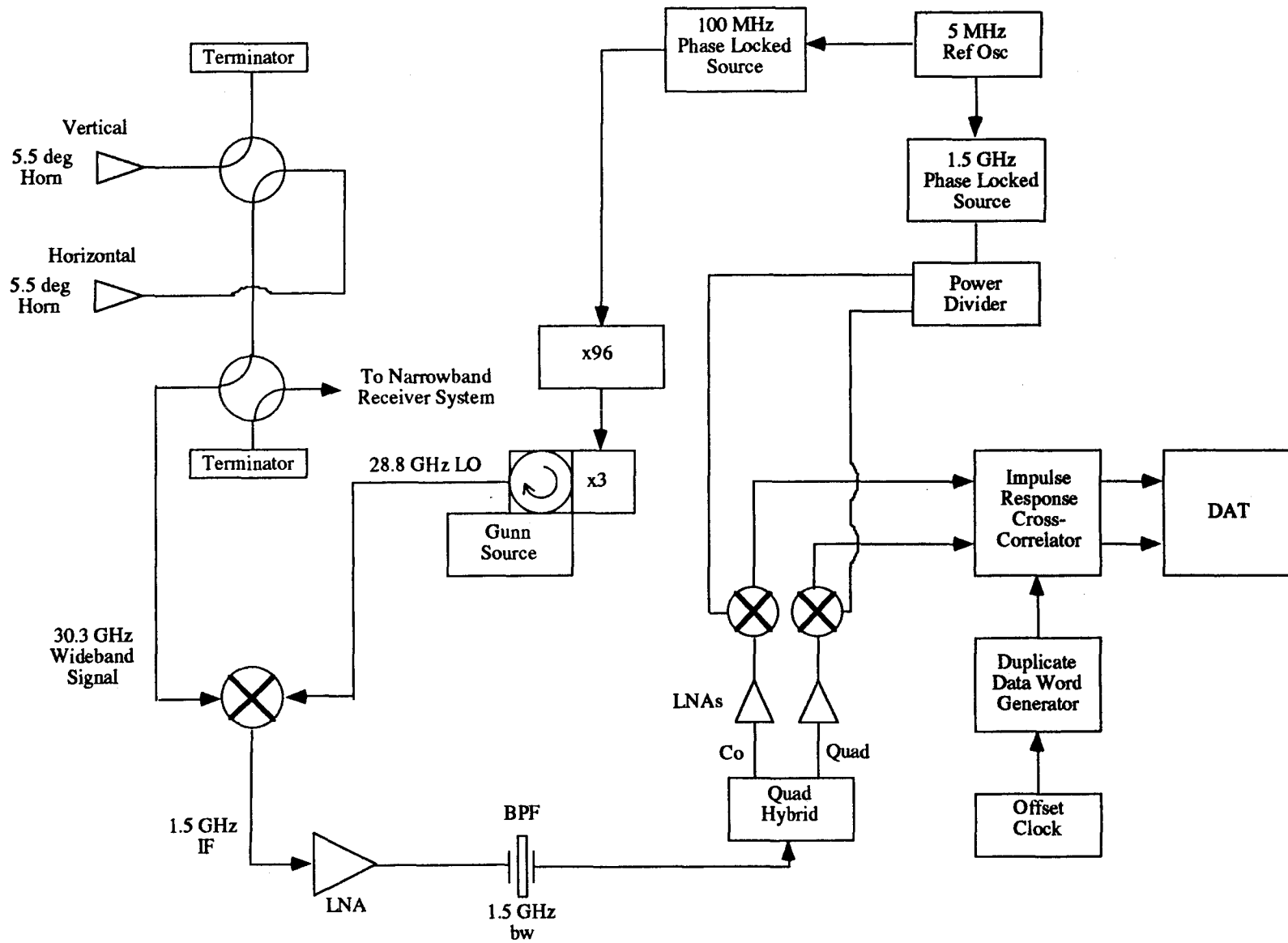


Figure 2. 30.3-GHz wideband receiver.

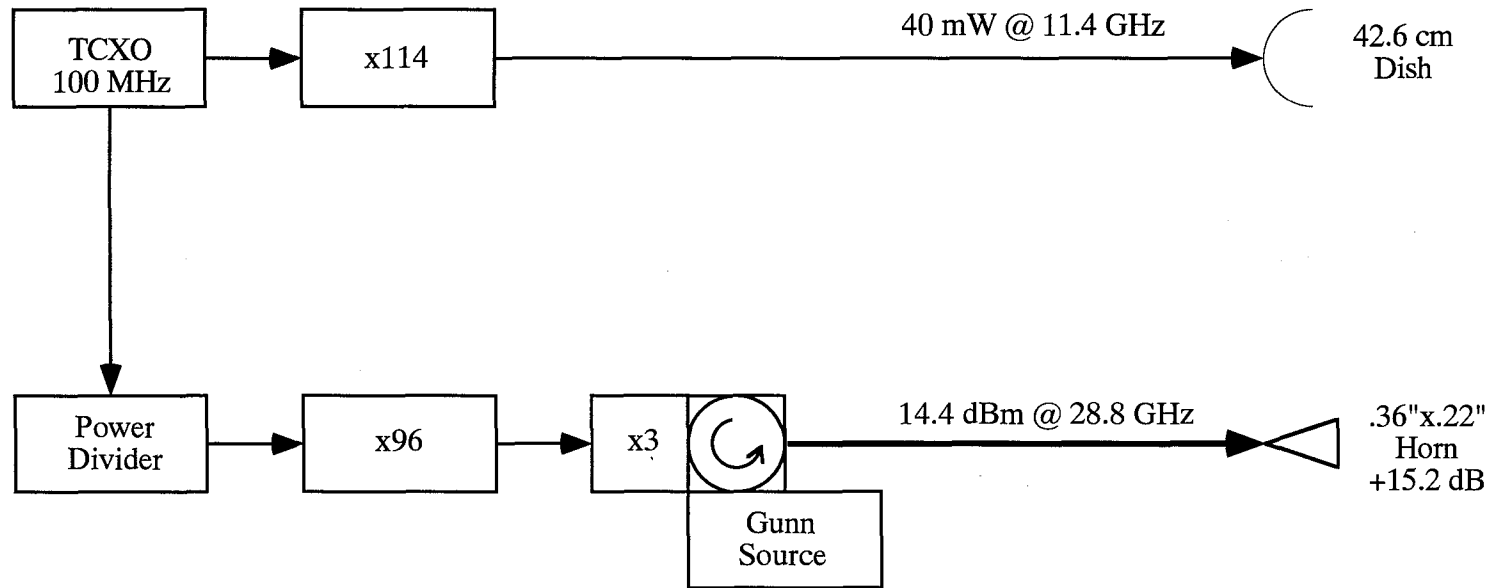


Figure 3. Transmitter, 28.8-GHz narrowband measurements.

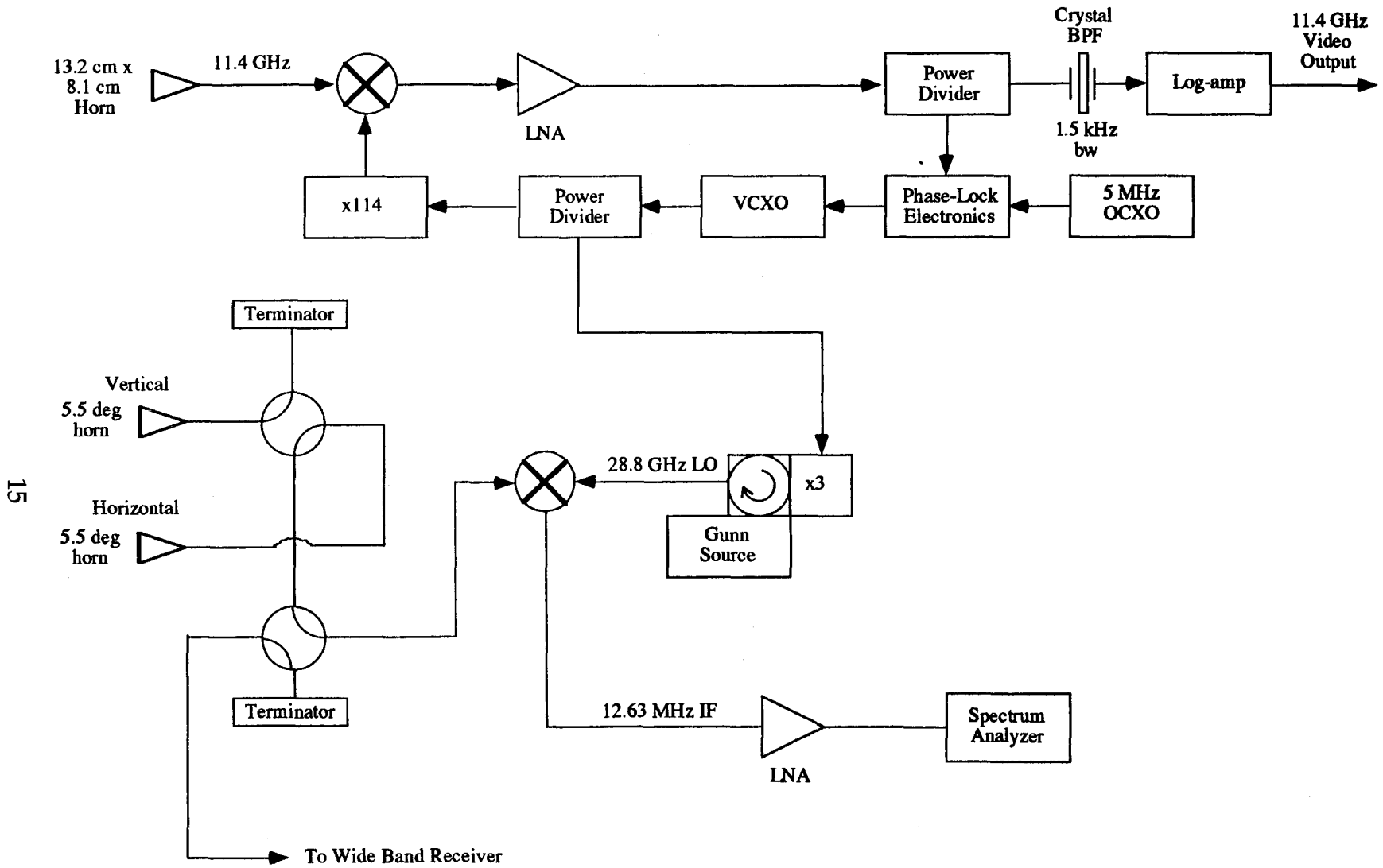
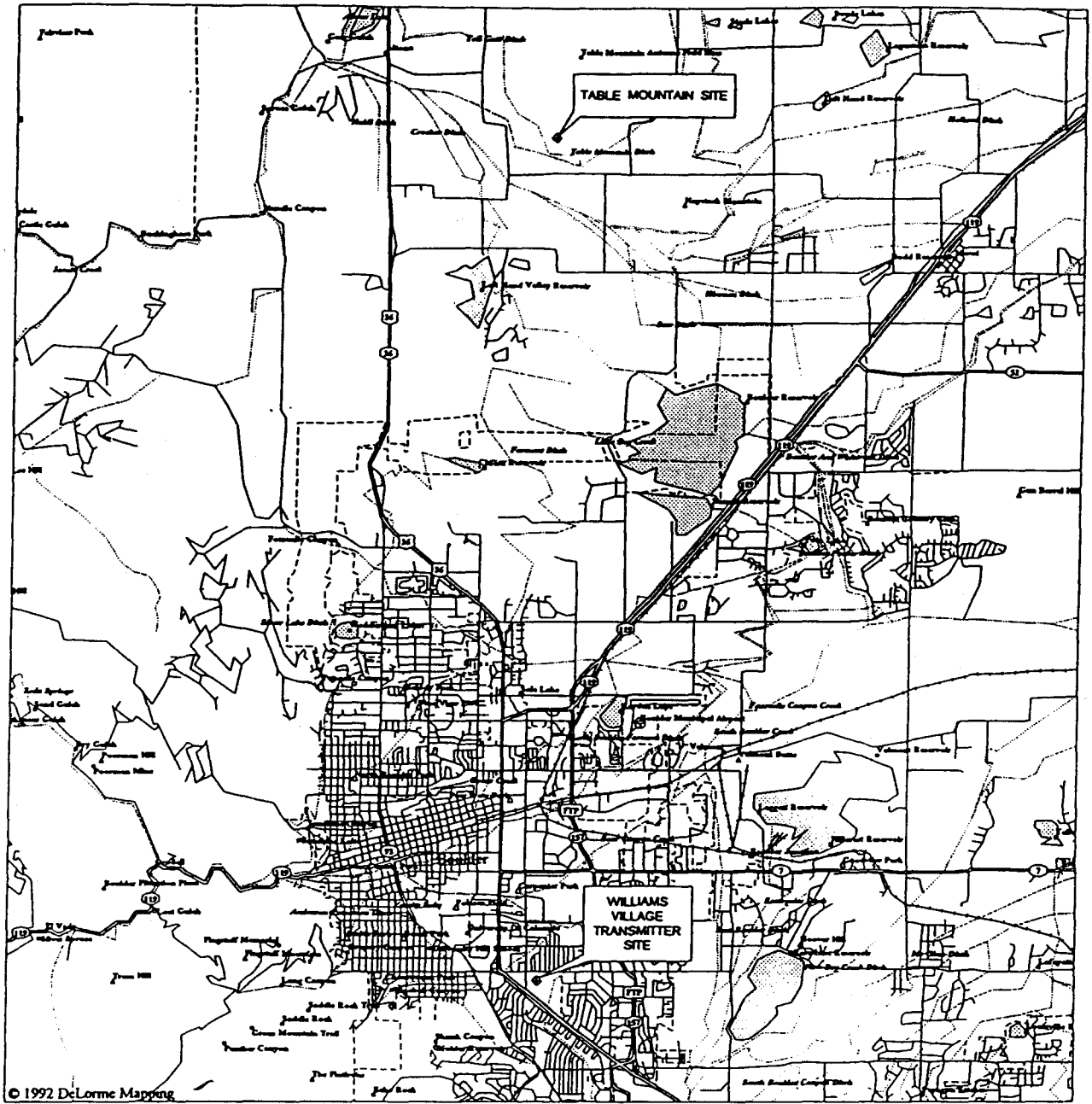


Figure 4. 28.8-GHz narrowband receiver.

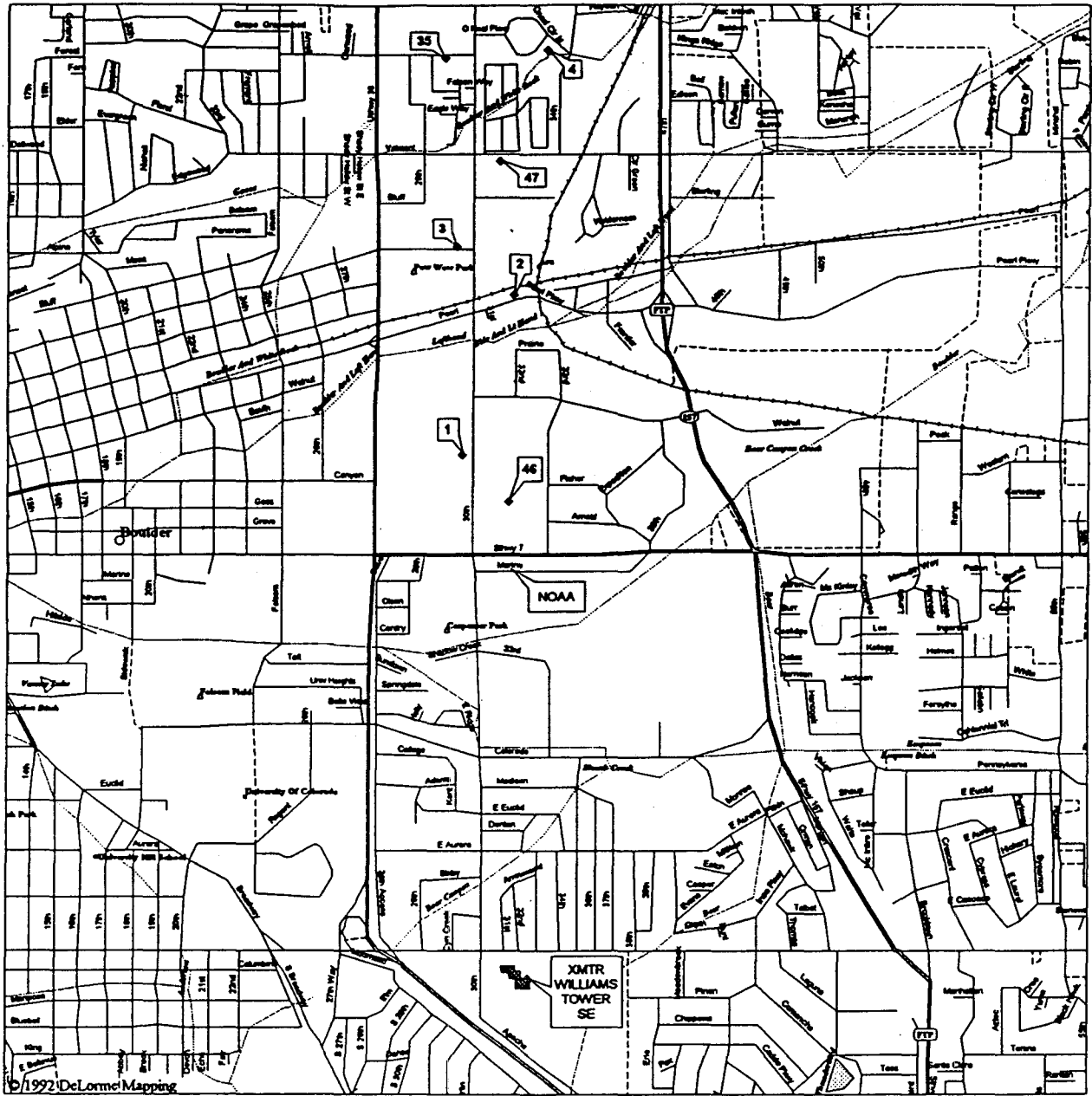


Scale 1:100,000 (at center)

2 Miles

2 KM

Figure 5. LMDS area coverage survey map, Boulder, CO.



Scale 1:25,000 (at center)

2000 Feet

500 Meters

Figure 6. LMDS area coverage survey, receiver station location map, south area.

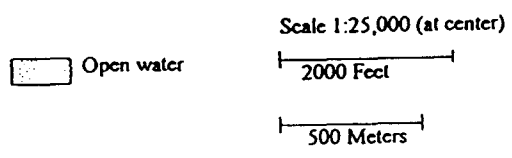
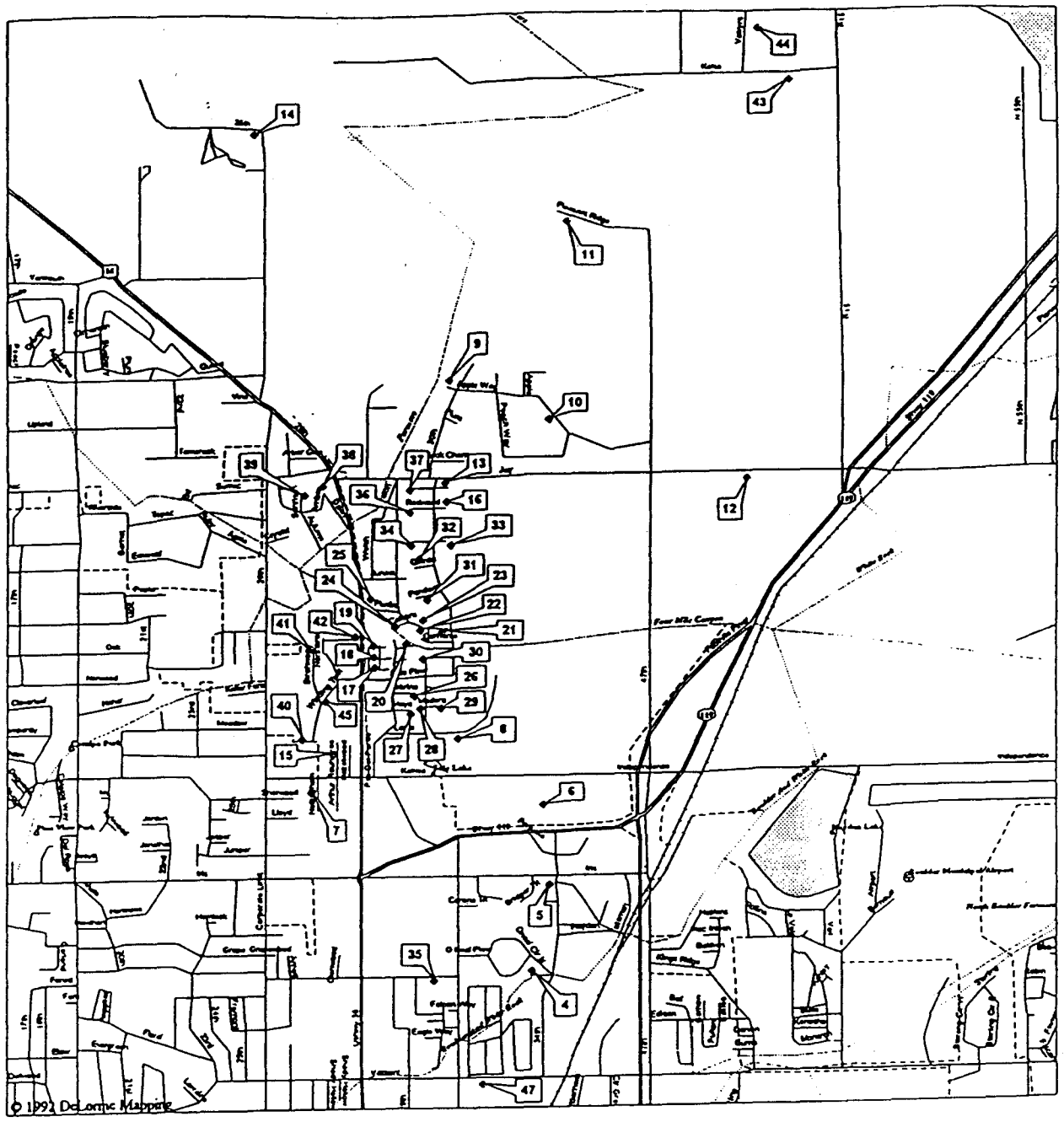


Figure 7. LMDS area coverage survey, receiver station location map, north area.

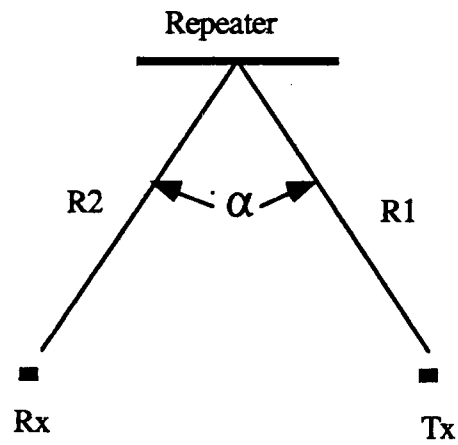


Figure 8. Passive repeater test geometry.

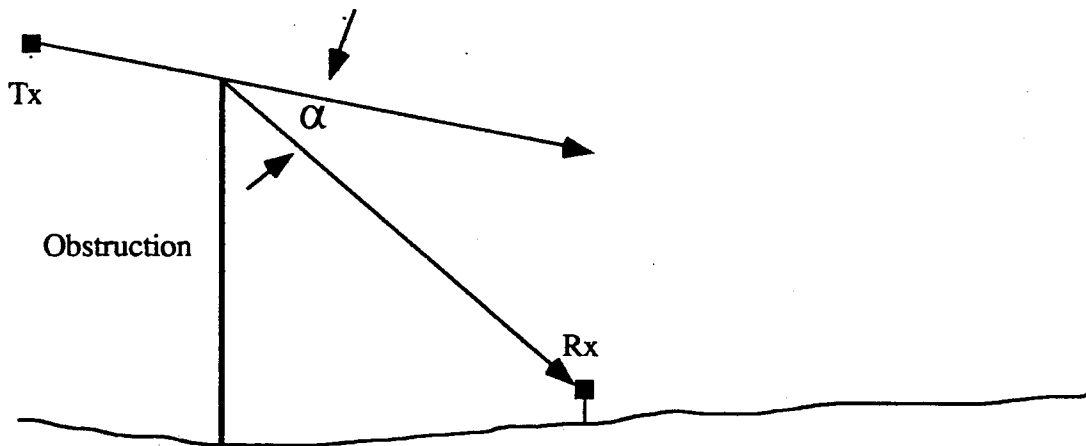


Figure 9. Diffraction study test geometry.

Table 1. 30.3 GHz Broadband Area Coverage Data

Calibration Files

Station	Date	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
DOC SF	12/11/92	1051	1			c4p4	s	19	35	-10.1	5.9
DOC SF	12/11/92	1051	1			c4p5	l	19	35	-10.1	5.9

Stations Grouped According to Transmitter Height

Transmitter Williams Towers 13th Floor

Station	Date	Rx H(m)	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
1	12/23/92	3.4	1981	1			u1p81	s	13	40	-10.1	16.9
2	12/23/92	3.4	2743			1	u1p84	s	6	40	-10.1	23.9
3	12/23/92	6.8	2819		1		u2p1	s	6	40	-0.6	33.4
4	12/23/92	3.4	3749		1		u2p3	s	0	40	-10.1	29.9
4	12/23/92	8.5	3749		1		u2p6	s	0	40	-5.6	34.4
5	12/23/92	3.4	4084			1	u2p15	s	0	40	4.4	44.4
6	12/23/92	3.4	4435	1			u2p16	s	13	40	-15.6	11.4
7	12/23/92	6.8	4252		1		u2p24	s	0	40	2.1	42.1
8	12/22/92	3.4	4627			1	u1p54	s	0	40	-10.1	29.9
9	12/22/92	6.8	5437			1	u1p61	s	0	40	4.4	44.4
10	12/22/92	6.8	5588			1	u1p64	s	0	40	4.4	44.4
11	12/22/92	6.8	6377			1	u1p66	s	0	40	2.1	42.1
12	12/22/92	3.4	5452			1	u1p68	s	0	40	-15.7	24.3
13	12/22/92	6.8	5351			1	u1p58	s	0	40	-3.1	36.9
14	12/22/92	3.4	6855	1			u1p70	s	0	40	-15.7	24.3
15	12/23/92	6.8	4431		1	1	u2p26	s	0	40	-7.9	32.1
16	12/22/92	6.8	5258			1	u1p56	s	0	40	-7.9	32.1
17	12/24/92	6.8	4707			1	u2p28	s	0	40	-3.1	36.9
18	12/24/92	6.8	4758			1	u2p30	s	0	40	-3.1	36.9
19	12/24/92	6.8	4798	1			u2p32	s	6	40	-15.7	18.3
20	12/24/92	6.8	4749			1	u2p34	s	0	40	-0.6	39.4
21	12/24/92	6.8	4873			1	u2p36	s	0	40	4.4	44.4
22	12/24/92	6.8	4873			1	u2p38	s	0	40	6.1	46.1
23	12/24/92	6.8	4946			1	u2p40	s	0	40	-5.6	34.4
24	12/24/92	6.8	4940			1	u2p44	s	0	40	-0.6	39.4
25	12/24/92	6.8	5004			1	u2p47	s	0	40	7.7	47.7
25	12/24/92	6.8	5004			1	u2p52	s	0	40	4.4	44.4
26	12/28/92	6.8	4495	1			u2p53	s	0	40	-10.1	29.9
27	12/28/92	6.8	4497	1			u2p55	s	0	40	-5.6	34.4
28	12/28/92	5.1	4497				u2p57	s	0	40	2.1	42.1
29	12/28/92	5.7	4489			1	u2p59	s	0	40	-0.6	39.4
30	12/28/92	6.0	4656				u2p61	s	0	40	-0.6	39.4
31	12/28/92	6.8	5033				u2p63	s	0	40	4.4	44.4
32	12/28/92	6.8	5105				u2p65	s	0	40	-0.6	39.4
33	12/28/92	5.7	5143	1			u2p67	s	0	40	-7.9	32.1
34	12/28/92	6.8	5174				u2p69	s	0	40	-5.6	34.4
35	12/23/92	8.5	3485			1	u1p79	s	0	40	-10.1	29.9
35	12/23/92	6.8	3485			1	u2p7	s	0	40	-0.6	39.4
35	12/23/92	8.5	3485	1			u2p10	s	0	40	-10.1	29.9
35-r	12/23/92	8.5	3485	1			u2p11	s	0	40	-10.1	29.9

Table 1. 30.3 GHz Broadband Area Coverage Data, (cont.)

Station	Date	Rx H(m)	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
36	12/28/92	6.0	5241		1		u2p73	s	0	40	6.1	46.1
37	12/28/92	6.0	5316		1		u2p77	s	0	40	6.1	46.1
38	12/28/92	6.8	5279		1		u2p81	s	0	40	6.1	46.1
39	12/28/92	6.8	5293				u2p79	s	0	40	-10.1	29.9
40	12/29/92	8.5	4570				u2p83	s	0	40	9.5	49.5
41	12/29/92	8.5	5134		1		u2p85	s	0	40	6.1	46.1
41	12/29/92	6.8	5134		1		u2p88	s	0	40	6.1	46.1
42	12/29/92	8.5	4844			1	u2p91	s	0	40	-0.6	39.4
42-n	12/29/92	7.7	4844			1	u2p89	s	0	40	-7.8	32.2
42-r	12/29/92	8.5	4844			1	u3p1	s	0	40	-0.6	39.4
43	12/29/92	6.8	6927		1		u3p3	s	0	40	7.7	47.7
43	12/29/92	8.5	6927		1		u3p5	s	0	40	7.7	47.7
44	12/29/92	8.5	7231				u3p7	s	0	40	12.3	52.3
45	12/22/92	6.8	4642		1		u1p72	s	0	40	-10.1	29.9

Transmitter Williams Towers 5th Floor

Station	Date	Rx H(m)	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
1	12/17/92	3.4	1981	1			u1p2	l	13	35	-10.1	11.9
1	12/31/92	3.4	1981	1			u3p37	s	13	40	-15.7	11.3
2	12/18/92	3.4	2743			1	u1p4	l	0	35	11.9	46.9
2	1/5/93	5.2	2743				u4p18	s	0	40	2.1	42.1
3	12/18/92	8.5	2819		1		u1p8	l	0	35	11.2	46.2
3	12/18/92	8.5	2819		1		u1p7	s	0	35	8.6	43.6
4	12/18/92	3.4	3749		1		u1p10	s	0	40	9.5	49.5
4	12/18/92	8.5	3749		1		u1p11	s	0	40	-0.6	39.4
5	12/18/92	8.5	4084		1		u1p14	s	0	40	-0.6	39.4
6	12/18/92	3.4	4435	1			u1p17	s	0	40	-10.1	29.9
7	12/18/92	8.5	4252		1		u1p20	s	0	40	12.3	52.3
8	12/18/92	3.4	4627		1		u1p22	s	0	40	2.1	42.1
8	12/21/92	3.4	4627		1		u1p25	s	0	40	-14.5	25.5
9	12/21/92	7.7	5437		1		u1p32	s	0	40	9.5	49.5
10	12/21/92	3.6	5588		1		u1p35	s	0	40	-5.6	34.4
11	12/21/92	3.4	6377		1		u1p38	s	0	40	-10.1	29.9
12	12/21/92	3.4	5452		1		u1p42	s	0	40	-5.6	34.4
13	12/21/92	6.8	5351		1		u1p46	s	0	40	2.1	42.1
14	12/21/92	3.4	6855	1			u1p44	s	0	40	-15.7	24.3
15	1/4/93	6.8	4431		1		u3p80	s	0	40	2.1	42.1
16	12/21/92	6.8	5258		1		u1p29	s	0	40	-10.1	29.9
17	12/30/92	6.8	4707		1		u3p8	s	0	40	-10.1	29.9
18	12/30/92	7.8	4758		1		u3p10	s	0	40	2.1	42.1
19	12/30/92	7.8	4798	1			u3p12	s	0	40	-10.1	29.9
20	12/30/92	6.8	4749		1		u3p14	s	0	40	2.1	42.1
21	12/30/92	6.8	4873		1		u3p16	s	0	40	-0.6	39.4
22	12/30/92	6.8	4873		1		u3p18	s	0	40	2.1	42.1
23	12/30/92	6.8	4946		1		u3p20	s	0	40	9.5	49.5
24	12/30/92	6.8	4940		1		u3p22	s	0	40	2.1	42.1
25	12/30/92	6.7	5004		1		u3p24	s	0	40	2.1	42.1
25	12/30/92	7.7	5004		1		u3p26	s	0	40	2.1	42.1

Table 1. 30.3 GHz Broadband Area Coverage Data, (cont.)

Station	Date	Rx H(m)	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
26	12/30/92	6.8	4495	1			u3p28	s	0	40	-5.6	34.4
27	12/30/92	6.0	4497	1			u3p30	s	0	40	2.1	42.1
28	12/30/92	6.0	4497				u3p32	s	0	40	4.4	44.4
29	12/30/92	6.0	4489		1		u3p35	s	0	40	3.0	43.0
30	12/31/92	6.8	4656				u3p42	s	0	40	2.1	42.1
31	12/31/92	6.8	5033				u3p45	s	0	40	-5.6	34.4
32	12/31/92	6.8	5105				u3p47	s	0	40	-7.8	32.2
33	12/31/92	6.0	5143				u3p50	s	0	40	2.1	42.1
34	12/31/92	6.8	5174				u3p53	s	0	40	6.1	46.1
35	12/21/92	8.5	3485		1		u1p51-n	s	0	40	10.5	50.5
35	12/21/92	8.5	3485		1		u1p52	s	0	40	-10.1	29.9
36	1/4/93	6.8	5241		1		u3p55	s	0	40	6.1	46.1
37	1/4/93	6.8	5316		1		u3p58	s	0	40	9.5	49.5
38	1/4/93	6.8	5279		1		u3p64	s	0	40	2.1	42.1
39	1/4/93	6.8	5293	1			u3p62	s	0	40	-7.4	32.6
40	1/4/93	6.8	4570				u3p66	s	0	40	-0.6	39.4
40	1/4/93	8.5	4570	1			u3p73	s	0	40	-15.7	24.3
41	1/4/93	6.8	5134		1		u3p74	s	0	40	0.5	40.5
42	1/4/93	8.5	4844			1	u3p78	s	0	40	-0.6	39.4
43	1/4/93	8.5	6927		1		u3p82	s	0	40	9.5	49.5
45	12/21/92	8.5	4642		1		u1p49	s	0	40	6.1	46.1
46	1/5/93	8.5	1808			1	u4p1	s	0	40	6.1	46.1
47	1/5/93	8.5	3080			1	u4p7	s	0	40	6.1	46.1
47	1/5/93	6.8	3080			1	u4p10	s	0	40	11.2	51.2
2-h	1/5/93	6.8	2743				u4p19	s	0	40	6.1	46.1

Transmitter Table Mountain												
Station	Date	Rx H(m)	Rx D(m)	LOS	OLOS (t)	OLOS (b)	File	Code	A(db)	G(db)	Rcl (dB)	RxG (dB)
1-hD	1/15/93	8.5	1981				u4p37	s	0	40	9.5	49.5
1-vD	1/15/93	8.5	1981				u4p36	s	0	40	9.5	49.5
1-vR	1/15/93	8.5	1981				u4p34	s	0	40	10.5	50.5
1-vWT	1/15/93	8.5	1981				u4p35	s	0	40	10.5	50.5
6-vD	1/15/93	8.5	4435				u4p32	s	0	40	9.5	49.5
6-vWT	1/15/93	8.5	4435				u4p31	s	0	40	9.5	49.5
8-hD	1/15/93	8.5	4627				u4p28	s	0	40	10.5	50.5
8-vD	1/15/93	8.5	4627				u4p30	s	0	40	-3.1	36.9
8-vWT	1/15/93	8.5	4627				u4p31	s	0	40	9.5	49.5
14-hD	1/15/93	6.8	6855				u4p27	s	0	40	-0.6	39.4
14-v	1/15/93	6.8	6855				u4p25	s	0	40	-7.9	32.1
14-vD	1/7/93	6.7	6855				u4p20	s	0	40	-10.1	29.9
14-vM	1/7/93	6.8	6855				u4p22	s	0	40	3.3	43.3
14-vWt	1/7/93	6.8	6855				u4p24	s	0	40	12.3	52.3

* Note - Transmitter Height = 40 m for Williams Village Towers 13th floor.
 Transmitter Height = 16 m for Williams Village Towers 5th floor.
 Transmitter Height = 1 m for Table Mountain
 t = trees
 b = building
 code : s = short, l = long

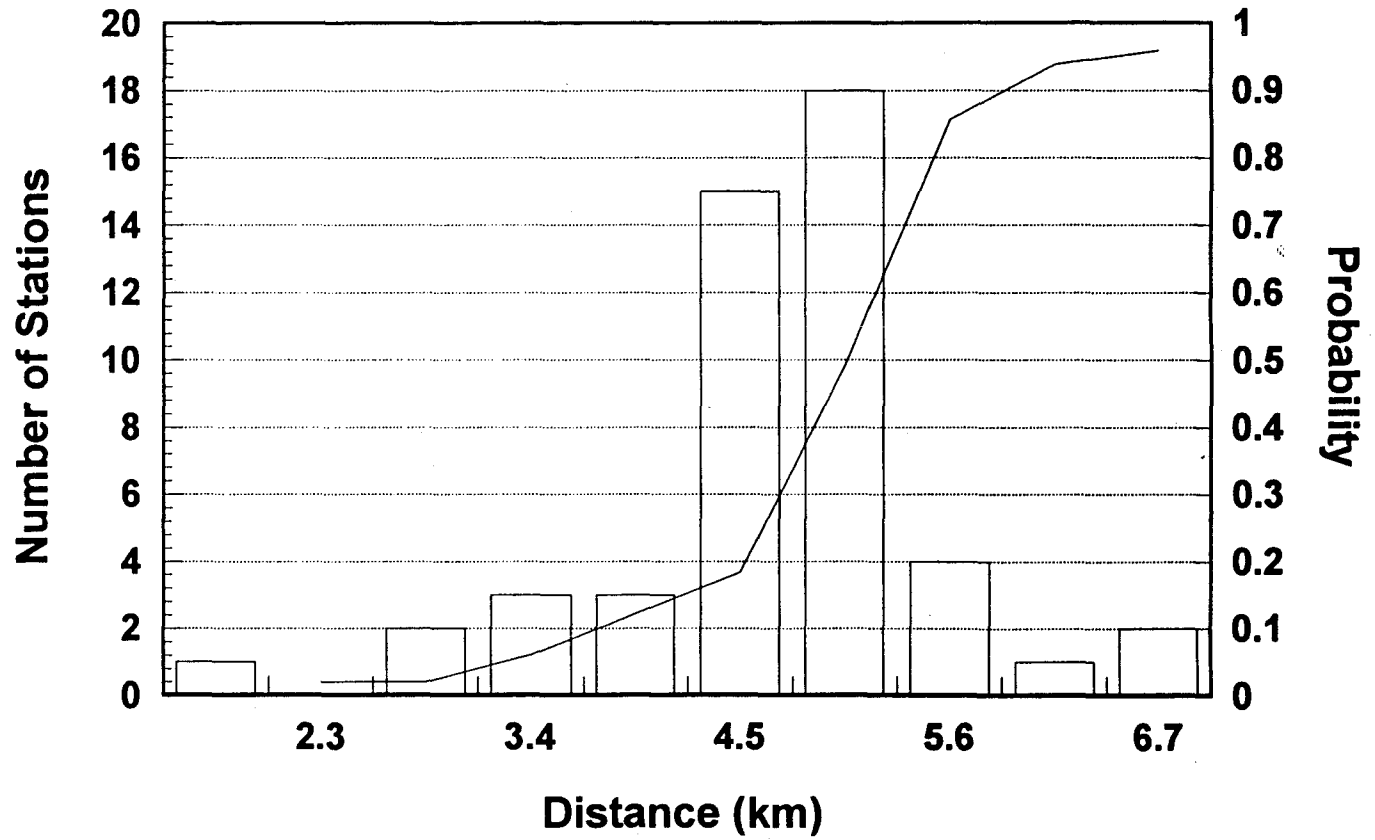


Figure 10. Receiver station path length histogram and cumulative distribution function.

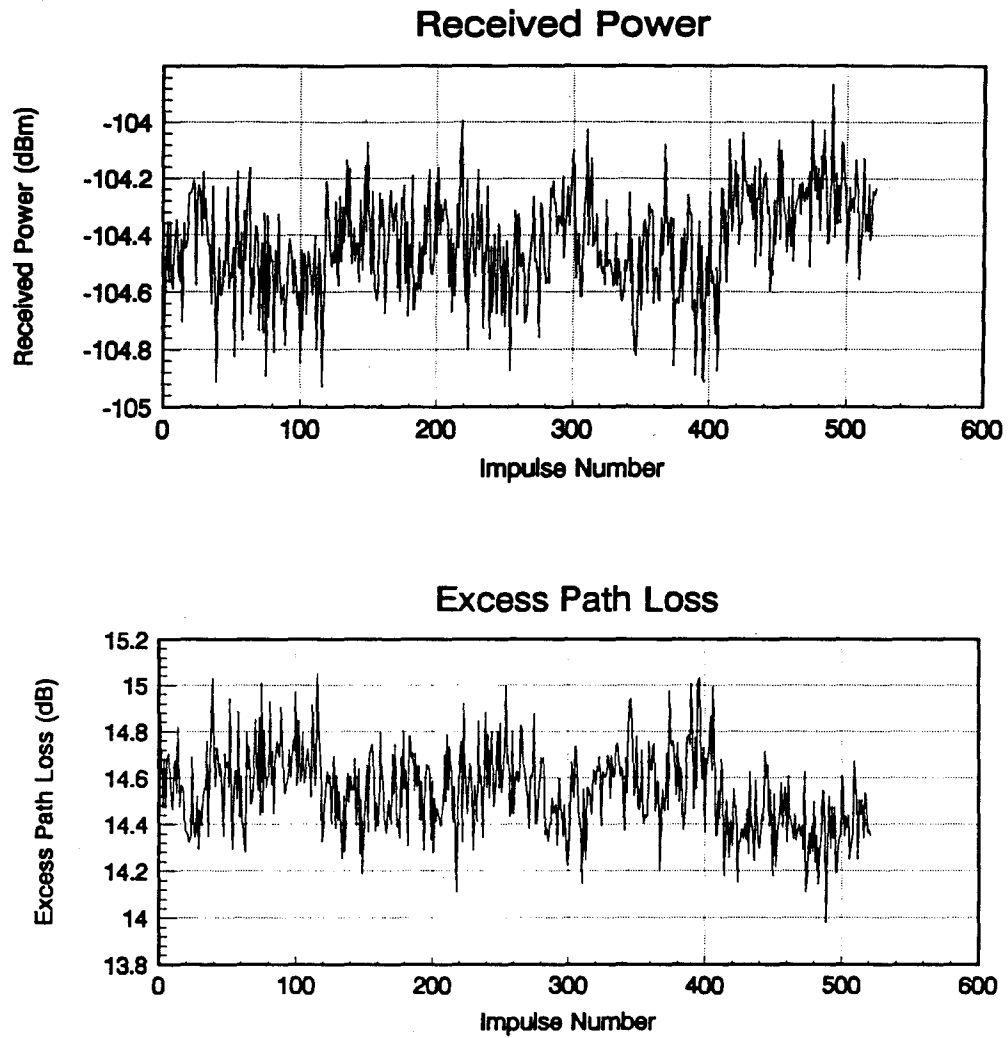


Figure 11. Station 26, recordings using 16-m transmitter, wideband data, time series plots: received power and excess path loss.

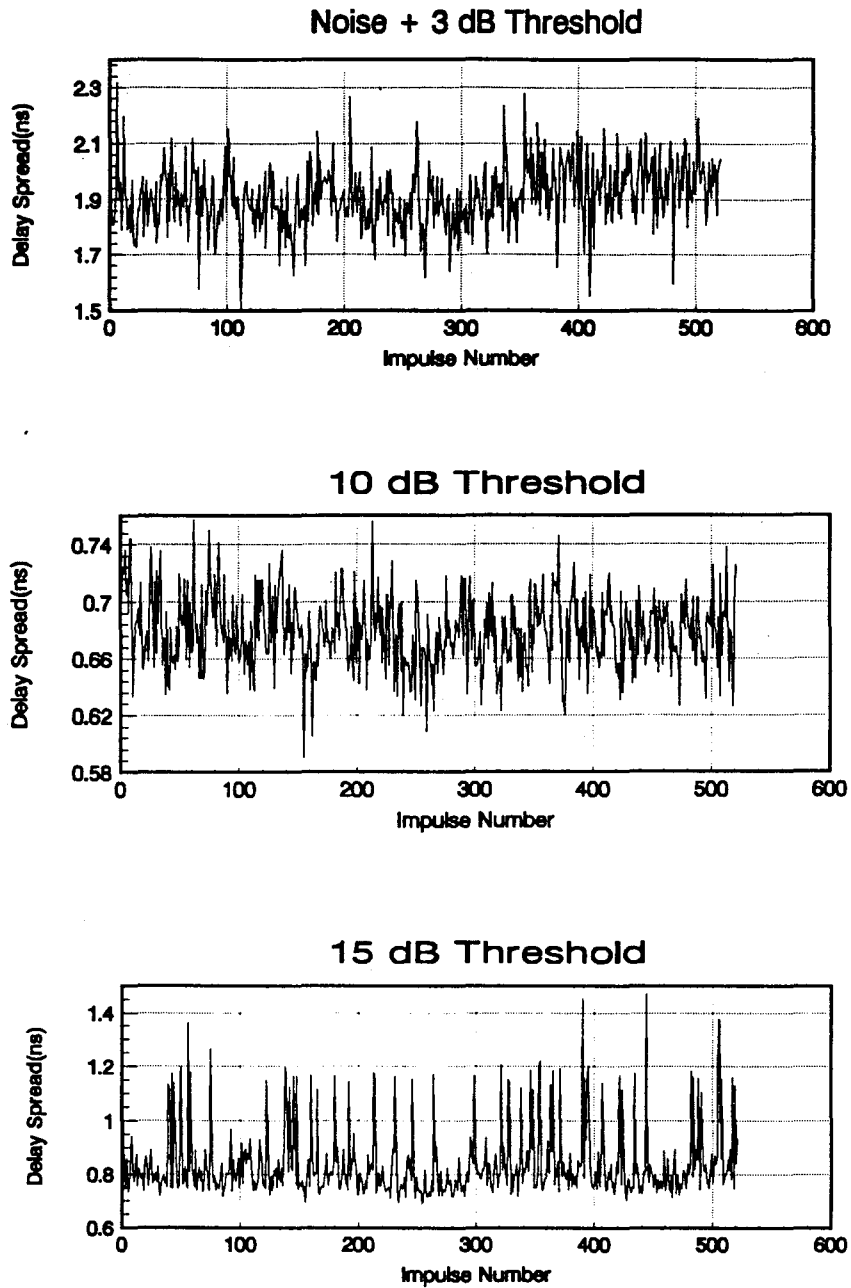


Figure 12. Station 26, recordings using 16-m transmitter, wideband data, time series plots: delay spread using three thresholds.

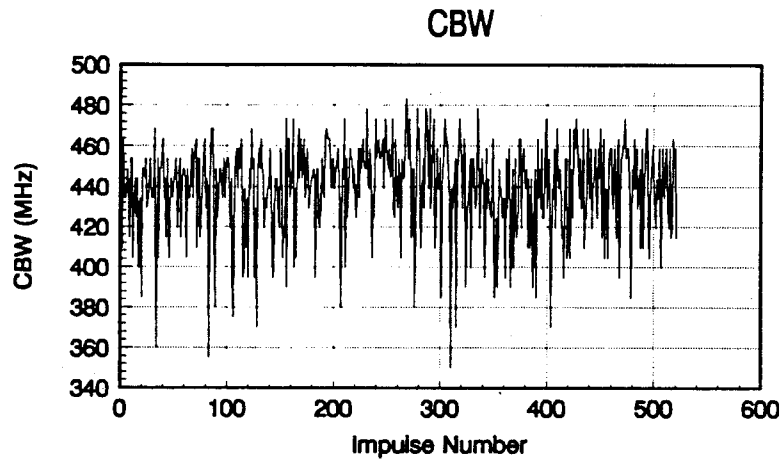
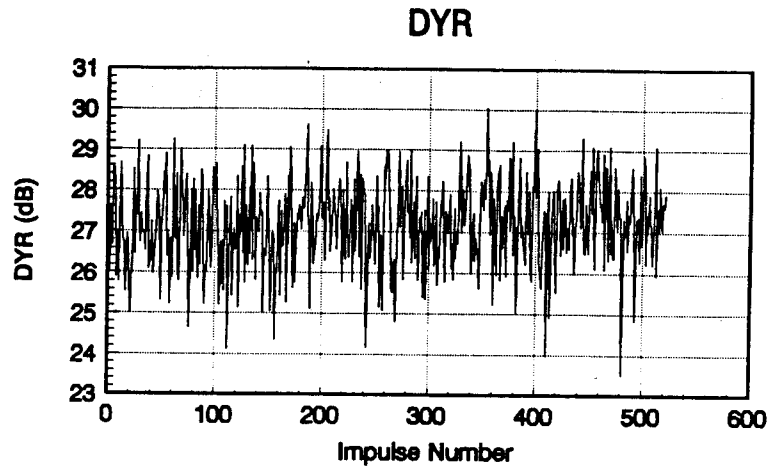


Figure 13. Station 26, recordings using 16-m transmitter, wideband data, time series plots: ratio of PDP peak amplitude to tail amplitude (DYR), and the correlation bandwidth of the PDP.

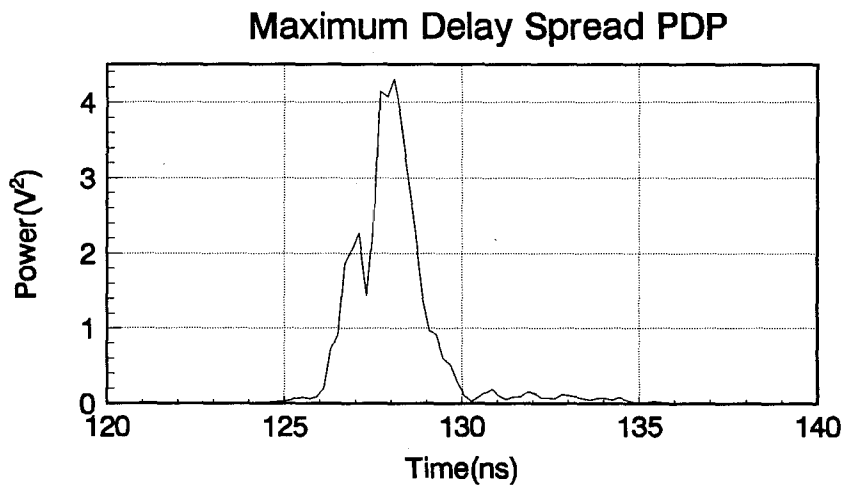
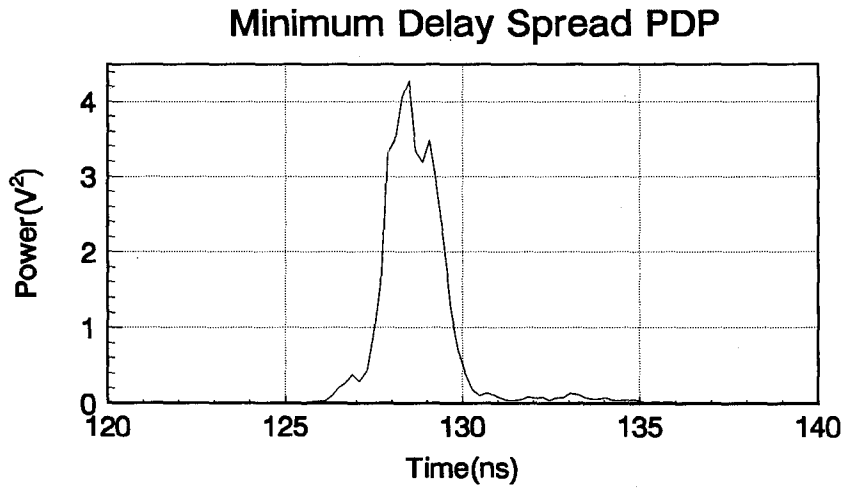


Figure 14. Station 26, recordings using 16-m transmitter: minimum delay spread PDP and maximum delay spread PDP.

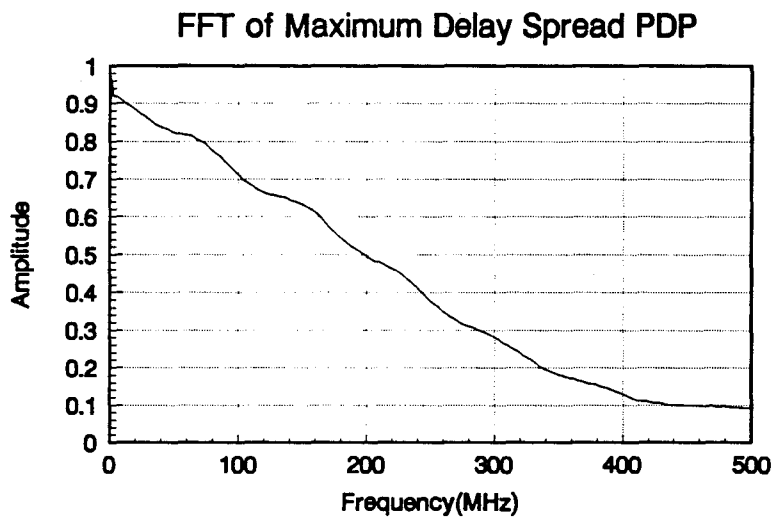
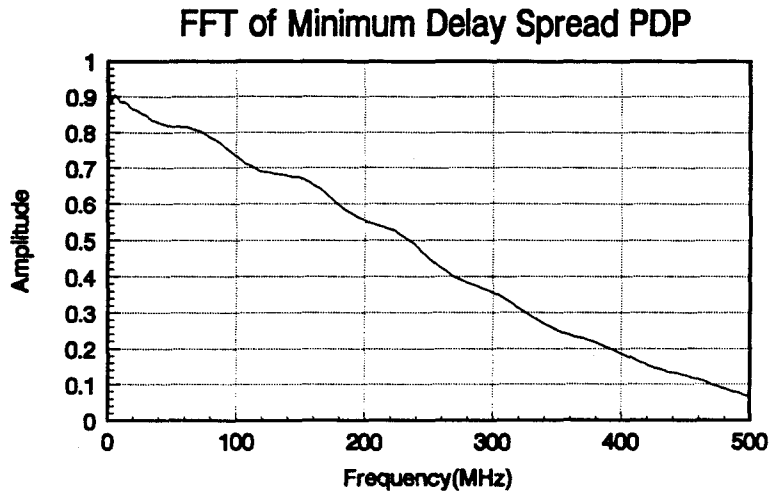


Figure 15. Station 26, recordings using 16-m transmitter: real FFT's used for correlation bandwidth calculations.

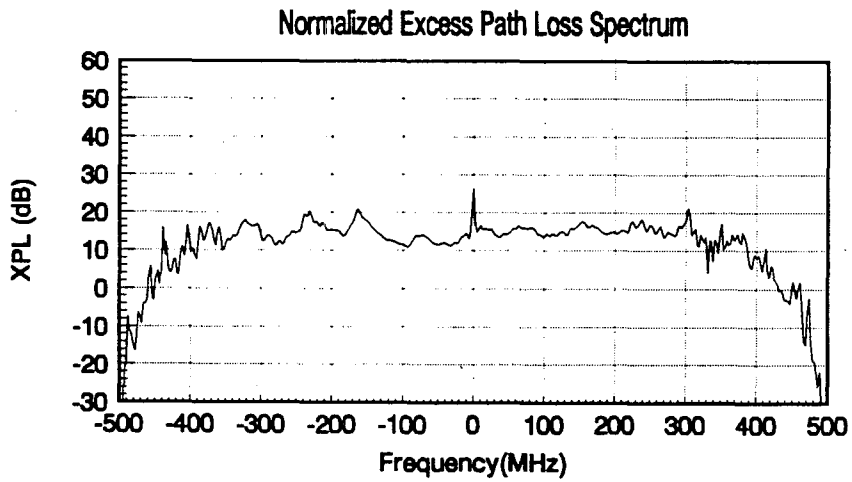
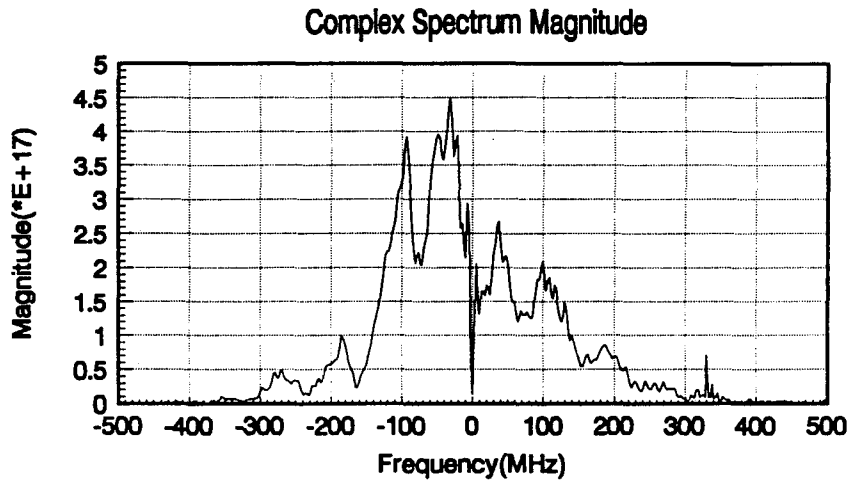


Figure 16. Station 26, 16-m transmitter: magnitude of complex FFT and normalized excess path loss spectrum.

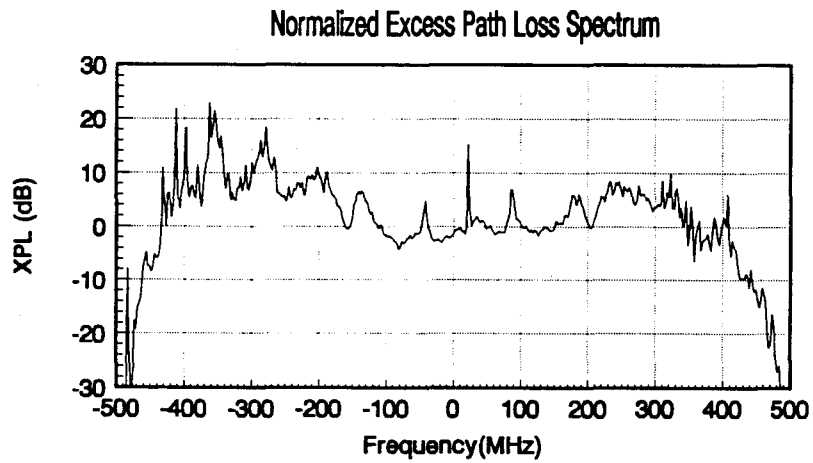
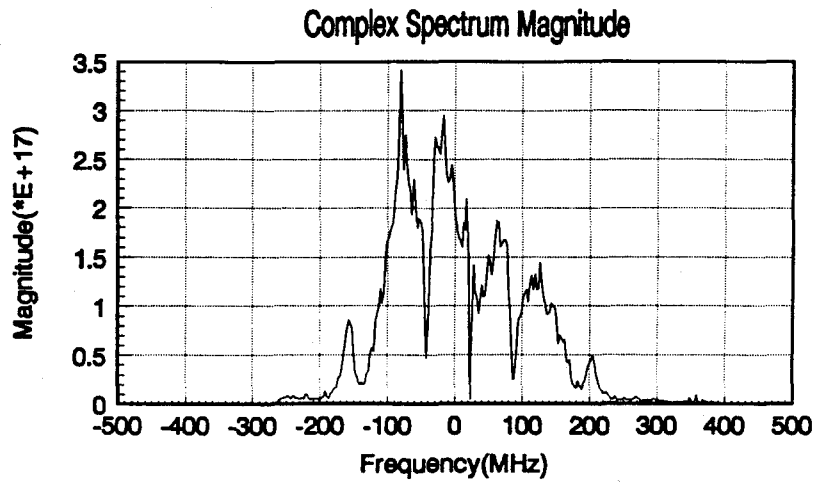


Figure 17. Station 1, 40-m transmitter: magnitude of complex FFT and normalized excess path loss spectrum.

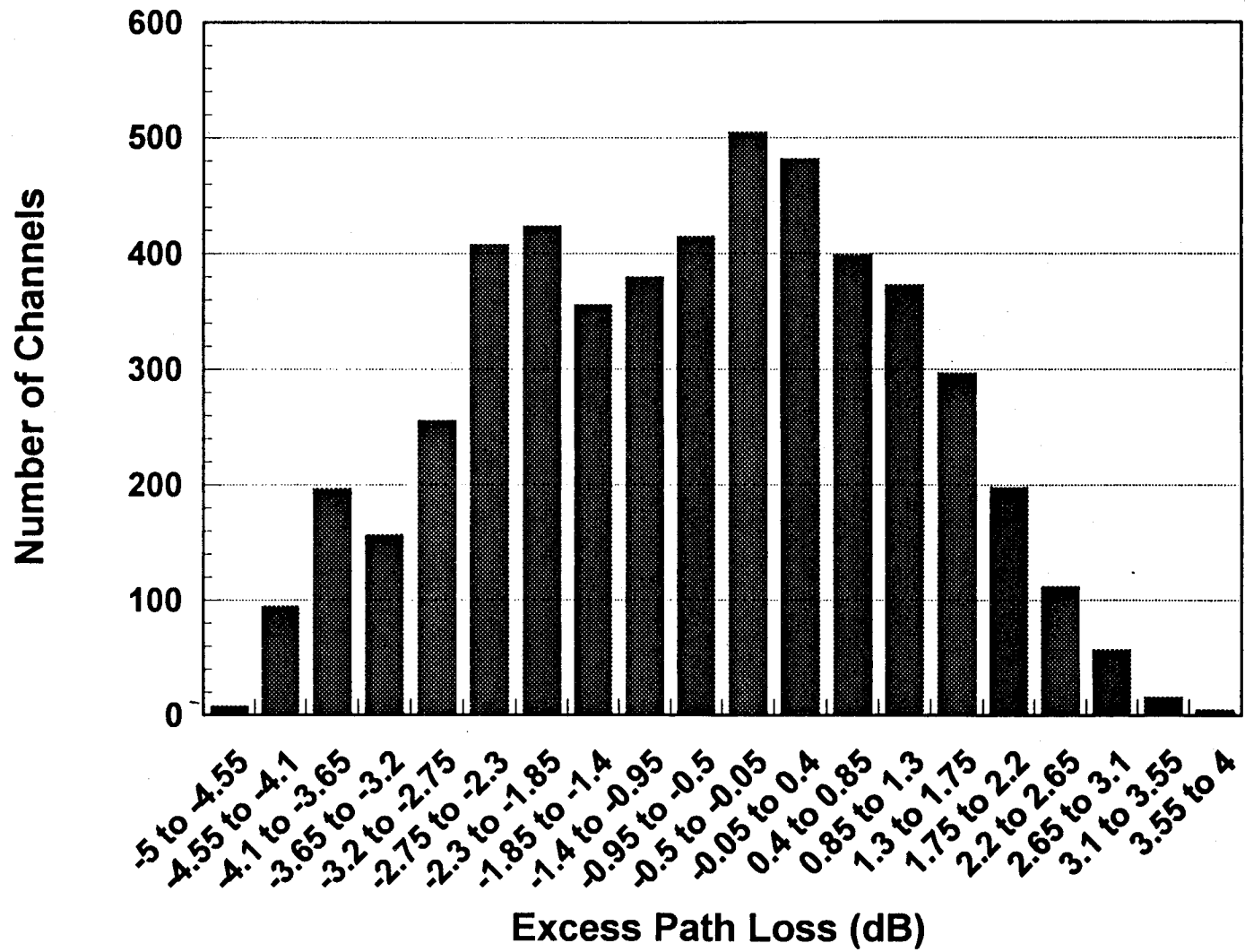


Figure 18. Station 1, 40-m transmitter: distribution of average excess path loss/channel.

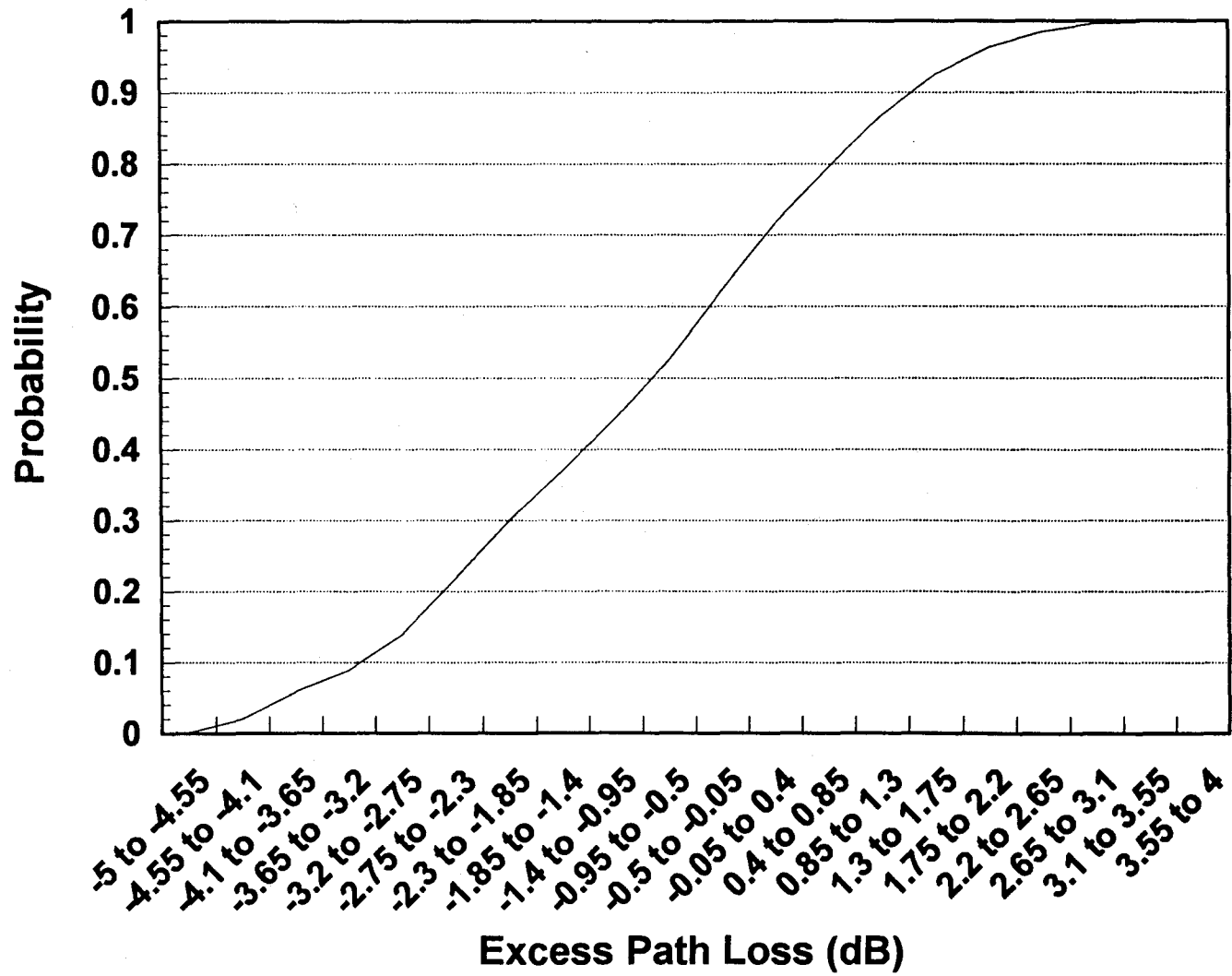


Figure 19. Station 1, 40-m transmitter: cumulative distribution of average excess path loss/channel.

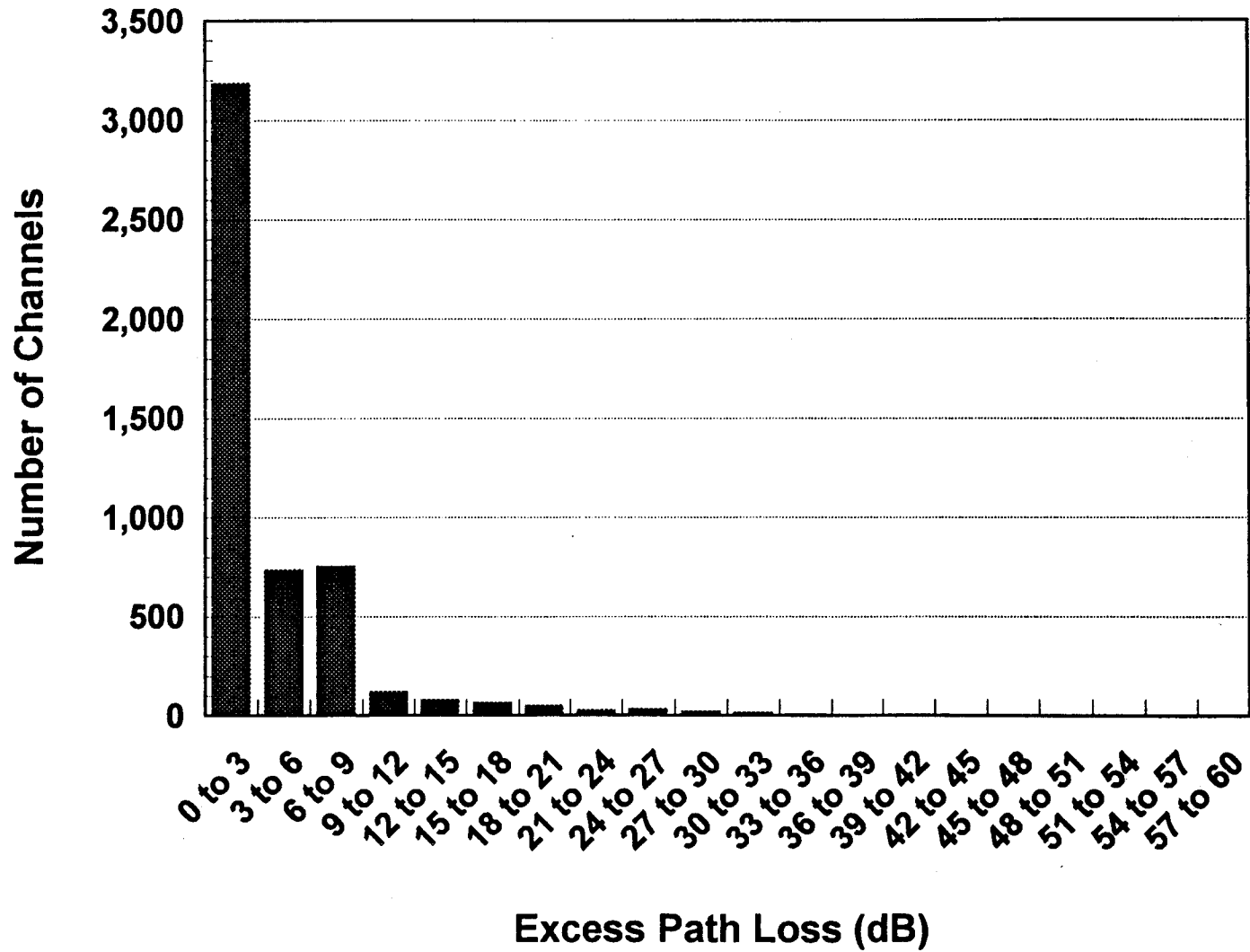


Figure 20. Station 1, 40-m transmitter: distribution of average Δ excess path loss/channel.

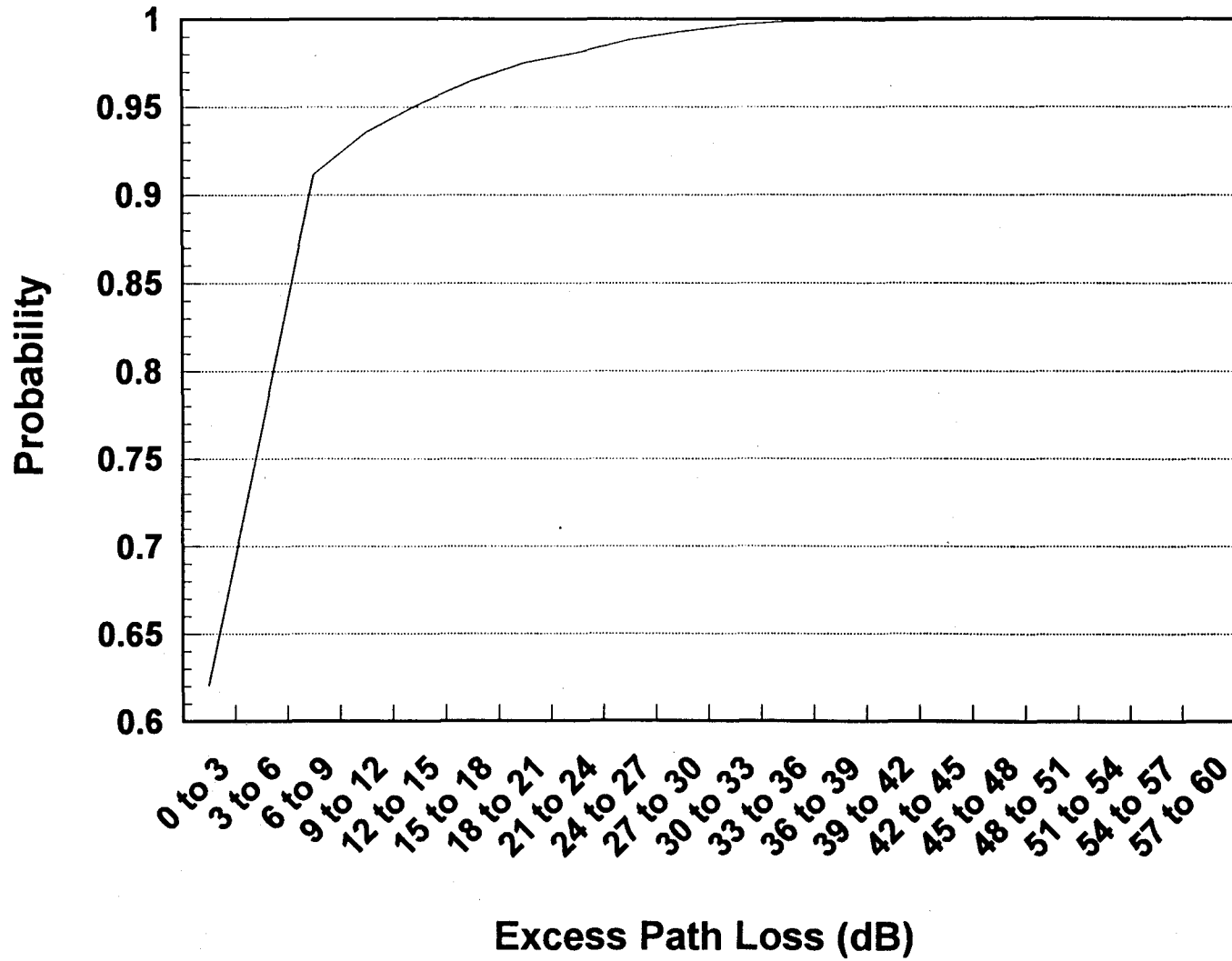


Figure 21. Station 1, 40-m transmitter: cumulative distribution of average Δ excess path loss/channel.

Table 2. Broadband LMDS Area Coverage Survey: Summary of Processed Data Using 40-m Transmitter Height.

Station	File	Dist (Km)	A (dB)	SA (dB)	D10 (ns)	SD10 (ns)	D15 (ns)	SD15 (ns)	Dm (ns)	SDm (ns)
1	u1p81	1.981	2.3	0.2	0.7	< .1	0.8	< .1	1.3	0.1
2	u1p84	2.743	7.1	0.0	0.7	< .1	0.7	< .1	3.4	0.9
3	u2p1	2.819	15.8	0.0	0.9	< .1	1.2	< .1	1.3	0.2
4	u2p3	3.749	14.0	0.2	0.8	< .1	0.9	< .1	1.0	< .1
4	u2p8	3.749	18.5	0.3	0.7	< .1	0.8	< .1	1.0	0.2
5	u2p15	4.084	22.2	0.4	1.6	0.1	1.8	0.2	1.9	0.3
6	u2p16	4.435	-6.6	0.2	0.7	< .1	0.8	< .1	1.4	< .1
7	u2p24	4.252	22.2	0.6	0.7	< .1	0.9	< .1	1.0	0.4
8	u1p54	4.627	10.1	1.8	0.8	1.3	1.0	1.8	1.8	1.8
9	u1p61	5.437	28.0	1.5	1.3	1.2	4.1	3.8	1.4	1.2
10	u1p64	5.588	21.1	1.5	1.1	0.1	2.1	0.5	2.0	0.6
11	u1p66	6.377	19.3	1.7	1.0	0.2	1.3	0.4	1.3	0.4
12	u1p68	5.452	0.7	0.2	0.7	< .1	1.0	< .1	1.7	< .1
13	u1p58	5.351	15.2	0.5	0.8	< .1	1.1	0.1	1.8	0.3
14	u1p70	6.855	0.0	0.3	0.7	< .1	0.7	< .1	1.6	0.1
15	u2p26	4.431	12.1	0.4	0.8	< .1	1.0	0.1	1.5	0.4
16	u1p56	5.258	10.1	1.4	0.7	0.2	1.2	1.3	2.1	1.4
17	u2p28	4.707	14.1	0.3	0.9	0.1	1.1	0.1	1.2	0.1
18	u2p30	4.758	18.6	0.4	0.8	< .1	0.9	< .1	1.0	0.3
19	u2p32	4.798	-3.0	0.2	0.8	< .1	0.9	0.1	1.7	0.4
20	u2p34	4.749	20.2	0.4	1.0	< .1	1.0	< .1	1.1	0.2
21	u2p36	4.873	25.5	0.6	0.7	< .1	1.6	1.5	1.0	0.6
22	u2p38	4.873	26.9	2.2	2.1	3.7	5.0	13.2	2.0	2.9
24	u2p44	4.940	17.8	0.5	0.8	< .1	0.9	< .1	1.0	0.2
25	u2p47	5.004	28.7	1.4	2.6	1.5	1.6	< .1	2.6	1.9
26	u2p53	4.495	8.5	0.2	0.7	< .1	1.2	< .1	1.9	< .1
27	u2p55	4.497	12.5	0.3	0.8	< .1	1.0	< .1	1.3	0.1
28	u2p57	4.497	23.6	0.8	1.0	0.1	1.3	0.2	1.3	0.3
29	u2p59	4.489	17.3	0.8	0.9	< .1	1.0	< .1	1.2	0.2
30	u2p61	4.656	19.3	0.5	0.8	< .1	1.0	0.1	1.1	0.2
31	u2p63	5.033	24.2	1.2	2.4	0.7	3.7	0.8	2.9	0.6
32	u2p65	5.105	18.1	0.4	1.1	< .1	1.3	0.2	1.5	0.3
33	u2p67	5.143	10.1	0.4	0.9	< .1	1.1	< .1	1.4	0.1
34	u2p69	5.174	13.3	0.8	0.8	< .1	1.0	< .1	1.3	0.1
35	u2p7	3.485	20.6	0.3	0.9	< .1	1.2	< .1	1.3	0.2
35	u2p10	3.485	10.2	0.0	0.7	< .1	0.9	< .1	1.7	0.7
35	u2p11	3.485	10.2	0.0	0.7	< .1	0.9	< .1	2.3	0.6
36	u2p73	5.241	24.7	0.4	1.2	< .1	3.1	2.3	1.4	0.6
37	u2p77	5.316	23.5	0.3	0.8	0.2	2.4	0.8	1.8	0.7
38	u2p81	5.279	28.7	0.4	1.0	0.9	ND	< .1	1.2	1.1
39	u2p79	5.293	7.0	0.2	0.7	< .1	1.0	< .1	1.6	< .1
40	u2p83	4.570	32.5	1.1	0.0	< .1	ND	< .1	1.8	3.4
41	u2p85	5.134	22.9	0.3	2.5	0.3	5.0	1.6	2.7	0.6
41	u2p88	5.134	23.9	0.3	2.9	< .1	7.9	3.5	2.8	0.8
42	u2p91	4.844	18.2	0.2	0.7	< .1	0.9	< .1	1.4	0.2
42	u2p89	4.844	11.1	0.2	0.7	< .1	0.8	< .1	1.7	0.1
42	u3p1	4.844	21.6	0.4	0.7	< .1	1.3	0.3	1.4	0.4
43	u3p5	6.927	28.0	0.4	9.2	5.5	0.0	< .1	2.1	2.5
45	u1p72	4.642	14.9	0.6	0.7	< .1	0.8	< .1	1.4	0.3

Legend: Dist = path length: A = excess path loss: S = standard deviation: SA = standard deviation, excess path loss (etc): D10 = delay spread 10 dB threshold: D15 = delay spread 15 dB threshold: Dm = delay spread noise plus 3 dB threshold.

Table 2. Broadband LMDS Area Coverage Survey: Summary of Processed Data Using 40-m Transmitter Height (con't.).

Station	DYR (dB)	SDYR (dB)	CBW (MHz)	SCBW (MHz)	A/Ch (dB)	SA/Ch (dB)	Med A/Ch (dB)	DA/Ch (dB)	SDA/Ch (dB)	Med DA/Ch (dB)
1	30.7	1.1	463	8	1.6	1.0	8.5	2.3	3.6	1.0
2	31.7	1.4	481	9	6.5	1.0	6.4	2.7	4.5	1.3
3	28.3	1.1	339	15	14.5	2.1	14.3	2.5	3.3	1.4
4	28.9	0.9	385	14	12.6	1.3	12.4	2.4	3.0	1.4
4	24.9	1.1	399	32	17.5	1.4	17.3	2.6	3.2	1.5
5	20.0	1.2	166	35	21.6	1.6	21.5	3.4	2.8	2.6
6	31.7	0.6	430	16	-7.8	1.4	-8.0	2.5	3.2	1.3
7	21.3	1.2	300	91	21.3	1.6	21.0	3.1	3.1	2.1
8	30.2	1.8	440	46	9.5	2.5	9.3	2.5	2.9	1.5
9	13.8	1.9	17	24	27.3	3.1	27.0	5.5	4.1	4.4
10	19.5	2.1	174	67	20.0	3.4	19.1	4.3	4.0	3.1
11	20.5	1.9	231	82	18.0	3.1	17.6	3.4	3.2	2.4
12	32.3	1.2	410	15	-0.3	1.7	-0.7	2.4	3.4	1.3
13	25.2	1.2	351	27	13.7	2.3	13.3	3.0	3.1	1.9
14	32.8	0.9	471	19	-1.0	0.9	-1.0	2.4	3.4	1.2
15	27.1	1.2	385	42	11.9	1.8	11.8	2.5	3.5	1.4
16	30.3	1.7	489	32	9.9	2.4	9.4	3.0	3.6	1.9
17	24.9	1.2	342	45	12.5	1.7	12.3	3.0	2.9	2.0
18	22.5	1.2	347	58	16.9	1.0	16.8	3.0	3.0	1.9
19	32.6	1.0	410	46	-4.6	1.3	-4.7	2.7	3.5	1.5
20	20.6	1.2	272	59	18.7	1.3	18.7	3.5	3.1	2.4
21	17.1	1.2	127	98	24.3	1.7	24.2	4.4	3.3	3.2
22	13.4	2.4	38	50	25.9	3.9	25.5	6.0	4.8	4.2
24	23.8	1.1	364	37	16.2	1.1	16.1	2.5	3.0	1.4
25	10.7	2.4	14	14	30.1	4.1	29.8	9.7	6.0	8.3
26	30.8	0.9	424	17	7.4	2.4	8.2	2.3	3.4	1.1
27	28.3	1.1	392	15	11.2	1.6	11.1	2.2	3.1	1.1
28	19.2	1.2	189	71	22.0	2.5	21.8	3.1	3.1	2.0
29	24.2	1.1	329	29	15.4	1.7	15.5	2.5	3.2	1.5
30	22.5	1.2	334	53	17.7	1.5	17.7	2.8	3.0	1.8
31	16.6	1.8	63	36	23.4	4.4	22.3	5.5	5.0	3.8
32	22.2	1.1	249	26	16.9	2.3	17.1	3.0	3.1	1.9
33	27.8	1.0	351	17	8.4	1.5	8.3	2.5	3.1	1.5
34	26.4	1.1	366	22	11.9	2.0	11.8	2.3	3.1	1.3
35	24.2	1.1	299	28	19.4	2.2	18.6	2.8	2.9	1.8
35	28.8	2.2	411	14	9.5	2.0	9.1	2.5	3.5	1.3
35	30.9	1.1	416	15	10.1	1.9	9.2	2.7	4.6	1.4
36	15.9	1.2	91	62	22.8	2.2	22.3	3.7	3.1	2.7
37	18.6	1.2	153	81	23.7	2.4	23.3	4.1	3.1	3.0
38	13.7	1.3	12	2	27.4	2.4	27.7	5.3	3.3	4.5
39	30.3	0.9	462	14	5.8	1.8	5.5	2.6	3.2	1.5
40	08.1	1.4	10	1	35.1	2.3	34.9	9.2	5.0	8.1
41	15.7	1.2	71	28	24.3	3.3	23.8	5.0	3.5	4.0
41	14.4	3.5	52	26	26.5	4.2	26.5	6.9	5.3	5.3
42	24.1	1.0	385	33	17.0	1.7	17.1	2.9	2.7	2.0
42	28.8	1.0	460	22	9.8	2.1	9.7	2.8	3.1	1.8
42	20.7	1.2	317	80	20.1	1.8	20.0	3.6	3.0	2.7
43	10.9	1.3	11	2	27.8	2.9	27.5	9.0	5.4	7.7
45	27.6	1.1	433	17	13.8	1.2	14.0	3.1	3.0	2.2

Legend: DYR = ratio of peak of PDP to average value of its tail: CBW = correlation bandwidth: A/Ch = average excess path loss for ten 20 MHz wide channels: Med A/Ch = median excess path loss for ten 20 MHz channels: DA/Ch = average max-min excess path loss for ten 20 MHz channels: Med DA/Ch = average max-min excess path loss for ten 20 MHz channels.

Table 3. Broadband LMDS Area Coverage Survey: Summary of Processed Data Using 16-m Transmitter Height.

Station	File	Dist (Km)	A (dB)	SA (dB)	D10 (ns)	SD10 (ns)	D15 (ns)	SD15 (ns)	Dm (ns)	SDm (ns)	DYR (dB)
1	u1p2	1.981	-3.4	0.4	0.7	< .1	0.8	< .1	5.2	0.5	41.7
1	u3p37	1.981	-0.5	0.3	0.9	< .1	1.2	0.1	2.1	0.2	27.1
2	u1p4	2.743	30.4	0.6	2.3	0.9	ND	ND	8.2	9.3	14.6
3	u1p8	2.819	27.8	0.6	4.0	1.6	18.8	19.2	8.9	6.1	17.4
3	u1p7	2.819	27.3	0.4	2.4	0.9	6.4	1.3	5.2	1.3	18.9
4	u1p10	3.749	28.0	0.4	5.5	0.4	ND	ND	5.1	0.7	13.0
4	u1p11	3.749	20.7	0.4	1.5	< .1	1.7	0.3	1.7	0.3	19.6
5	u1p14	4.084	18.2	0.3	1.0	< .1	1.2	0.1	1.6	0.2	24.6
6	u1p17	4.435	9.0	0.1	0.9	< .1	1.0	< .1	1.5	0.1	30.6
7	u1p20	4.252	30.4	0.8	0.0	< .1	ND	ND	5.2	8.9	4.9
8	u1p22	4.627	22.2	0.4	1.0	0.2	2.7	0.4	2.5	0.5	20.4
8	u1p25	4.627	3.5	1.4	0.9	0.3	1.0	0.4	1.8	0.6	31.7
9	u1p32	5.437	26.9	0.5	4.1	1.4	ND	ND	3.7	0.7	12.4
10	u1p35	5.588	13.1	0.6	1.0	0.7	1.4	0.2	2.3	0.7	25.3
11	u1p38	6.377	6.9	0.2	0.7	< .1	0.9	< .1	1.7	0.1	30.5
12	u1p42	5.452	12.8	1.7	0.8	1.4	1.0	< .1	1.7	1.3	27.1
13	u1p46	5.351	19.7	0.2	0.9	< .1	1.7	0.2	1.7	0.3	21.0
14	u1p44	6.855	0.5	0.1	0.7	< .1	0.8	< .1	1.4	< .1	32.1
15	u3p80	4.431	22.4	0.5	1.6	< .1	2.2	1.2	1.8	0.4	17.4
16	u1p29	5.258	8.9	0.3	1.0	< .1	1.2	< .1	2.0	0.3	27.2
17	u3p8	4.707	7.8	0.3	1.0	< .1	1.5	< .1	3.0	1.5	31.4
18	u3p10	4.758	22.3	0.4	0.8	0.4	1.4	0.5	1.5	1.2	20.0
19	u3p12	4.798	8.1	0.3	1.2	< .1	1.5	< .1	2.2	0.4	30.1
20	u3p14	4.749	20.2	0.3	1.4	< .1	1.8	0.2	1.8	0.3	19.7
21	u3p16	4.873	19.4	1.0	1.1	0.1	1.4	0.2	1.6	0.5	20.9
22	u3p18	4.873	21.8	0.7	0.7	0.1	1.1	0.4	1.1	0.5	19.5
23	u3p20	4.946	30.4	0.6	ND	ND	ND	ND	2.2	2.1	9.1
24	u3p22	4.940	19.7	0.3	0.9	< .1	1.1	< .1	1.2	0.2	21.5
25	u3p24	5.004	24.7	0.6	1.5	0.3	8.8	< .1	1.7	0.7	14.9
25	u3p26	5.004	20.0	0.3	1.4	0.1	2.0	0.3	1.8	0.3	19.1
26	u3p28	4.495	14.5	0.2	0.7	< .1	0.8	0.1	1.9	0.1	27.2
27	u3p30	4.497	20.9	0.2	1.0	< .1	1.2	0.2	1.5	0.3	21.5
28	u3p32	4.497	24.1	0.3	3.1	1.0	5.8	0.5	4.9	0.6	18.6
29	u3p35	4.489	21.4	0.3	0.9	< .1	1.4	0.2	1.5	0.3	20.6
30	u3p42	4.656	24.1	1.3	1.5	0.3	2.0	1.1	1.7	0.6	16.6
31	u3p45	5.033	13.7	0.3	0.8	< .1	0.8	< .1	1.1	0.3	25.6
32	u3p47	5.105	10.7	0.2	0.7	< .1	0.9	< .1	1.9	0.1	29.3
33	u3p50	5.143	22.6	0.7	1.4	3.4	4.1	2.2	2.3	3.6	16.8
34	u3p53	5.174	29.3	0.8	ND	ND	ND	ND	2.3	5.2	8.9
35	u1p51	3.485	32.1	0.4	19.5	0.6	ND	ND	12.9	1.5	9.7
35	u1p52	3.485	11.7	0.1	1.1	< .1	1.4	< .1	1.8	< .1	28.5
36	u3p55	5.241	25.8	0.5	2.6	3.9	ND	ND	2.4	3.9	13.6
37	u3p58	5.316	28.4	0.6	40.2	< .1	ND	ND	3.5	3.2	9.0
38	u3p64	5.279	21.4	0.3	0.8	< .1	1.2	0.5	1.3	0.6	19.5
39	u3p62	5.293	13.0	0.2	0.8	< .1	1.1	< .1	1.9	0.2	26.5
40	u3p66	4.570	18.6	0.9	0.7	< .1	0.9	0.1	1.2	0.3	22.5
40	u3p73	4.570	2.0	0.9	0.7	< .1	0.7	0.0	1.8	0.1	32.2
41	u3p74	5.134	17.3	0.3	1.4	< .1	1.7	< .1	1.7	0.2	21.5
42	u3p78	4.844	20.7	0.5	0.9	0.2	1.5	0.6	1.5	0.8	19.9
43	u3p82	6.927	27.1	0.5	ND	ND	ND	ND	2.1	2.4	9.1
45	u1p49	4.642	25.8	0.4	3.7	0.9	9.9	1.0	4.9	1.7	15.7
46	u4p1	1.808	30.9	0.6	3.1	0.2	5.4	1.5	3.1	0.5	14.4
47	u4p7	3.080	35.4	0.3	4.5	4.4	ND	ND	1.3	1.5	11.4

Table 3. Broadband LMDS Area Coverage Survey: Summary of Processed Data Using 16-m Transmitter Height (con't.).

Station	SDYR (dB)	CBW (MHz)	SCBW (MHz)	A/Ch (dB)	SA/Ch (dB)	Med A/Ch (dB)	DA/Ch (db)	SDA/Ch (dB)	Med DA/Ch (dB)
1	0.8	450	31.0	-4.6	1.0	-4.7	2.8	2.0	2.0
1	1.0	340	23.0	-0.7	1.7	-0.6	4.3	5.1	2.3
2	1.7	2	< .1	26.4	2.2	26.8	21.3	6.5	20.0
3	1.0	2	< .1	25.8	1.7	25.9	19.3	7.3	17.7
3	1.2	55	28.0	27.4	2.7	27.0	5.9	4.4	4.4
4	1.8	25	13.0	28.6	3.9	29.3	7.9	5.4	6.4
4	1.1	179	31.0	18.9	1.8	18.8	3.1	3.2	2.1
5	1.1	319	23.0	17.0	1.6	16.8	3.0	3.1	1.9
6	1.2	359	9.0	7.6	1.8	6.8	2.6	4.4	1.0
7	1.4	10	1.0	37.2	3.3	36.8	10.8	5.3	10.1
8	1.2	207	78.0	21.6	2.7	21.3	4.7	3.5	3.6
8	1.7	362	21.0	2.0	1.8	1.8	2.5	3.5	1.1
9	1.3	13	5.0	26.3	3.4	25.6	5.8	4.2	4.4
10	1.4	310	27.0	13.5	3.2	13.3	3.8	3.8	2.6
11	1.1	491	9.0	6.6	1.3	6.5	2.4	3.4	1.3
12	1.9	389	49.0	11.8	2.8	11.4	3.0	3.2	1.9
13	1.1	273	56.0	18.6	2.7	17.6	3.5	3.2	2.4
14	0.7	454	8.0	-0.5	1.1	-0.4	2.4	3.3	1.3
15	1.2	126	53.0	22.6	4.8	21.1	4.6	4.3	2.9
16	0.9	306	14.0	8.4	2.7	7.9	3.0	3.0	2.1
17	1.3	280	22.0	6.0	2.1	5.5	3.3	3.6	2.0
18	1.3	212	68.0	22.1	2.0	22.0	3.6	2.7	2.9
19	1.0	283	23.0	6.9	2.8	5.8	3.0	3.3	2.0
20	1.1	190	40.0	19.5	4.0	18.0	3.6	3.2	2.4
21	1.3	220	38.0	18.3	2.6	18.2	3.4	3.9	2.3
22	1.3	243	101.0	21.3	2.2	21.1	3.5	2.8	2.6
23	1.3	11	2.0	30.6	3.8	31.0	8.4	4.9	7.3
24	1.1	255	62.0	18.6	2.0	18.0	2.9	3.1	1.8
25	1.2	66	49.0	24.6	4.0	23.2	4.7	3.9	3.3
25	1.2	163	39.0	18.4	2.4	18.4	3.1	2.9	2.3
26	1.0	440	22.0	13.5	1.7	13.6	2.9	3.0	2.0
27	1.1	268	37.0	19.2	2.1	19.0	3.1	3.1	2.1
28	1.1	75	52.0	22.4	2.6	22.5	6.2	4.2	4.9
29	1.1	253	66.0	20.2	2.5	19.8	3.4	2.8	2.6
30	1.7	101	63.0	23.1	3.4	22.4	3.8	3.3	2.7
31	1.2	401	19.0	13.3	1.5	13.1	2.6	3.7	1.4
32	1.1	463	17.0	10.0	1.8	9.5	2.9	2.9	2.0
33	1.4	69	43.0	22.2	4.2	21.8	6.3	5.0	4.6
34	2.5	11	2.0	31.9	4.0	31.0	9.0	5.3	7.8
35	1.3	11	2.0	34.0	4.2	33.0	12.5	5.5	11.7
35	0.8	287	11.0	10.6	3.0	9.9	2.9	3.2	1.8
36	1.9	14	6.0	25.7	3.7	25.1	6.7	4.4	5.4
37	1.4	11	2.0	31.4	4.1	31.4	9.1	5.7	7.7
38	1.2	239	100.0	20.4	1.7	20.4	3.6	3.3	2.6
39	1.2	357	15.0	12.0	2.2	11.8	2.9	3.0	2.0
40	1.4	374	49.0	18.7	1.5	18.5	3.0	2.8	2.1
40	1.1	485	14.0	1.5	1.4	1.4	2.9	4.0	1.5
41	1.1	201	24.0	16.1	2.4	16.0	2.8	2.8	1.9
42	1.3	222	82.0	21.8	3.3	21.3	6.0	4.5	4.7
43	1.3	11	2.0	27.2	3.6	26.3	7.3	4.9	6.0
45	1.7	24	9.0	25.1	2.5	25.1	6.9	5.0	5.2
46	1.5	57	26.0	30.4	2.9	30.0	6.5	3.6	5.7
47	1.2	11	2.0	33.9	1.9	33.7	5.7	3.6	4.7

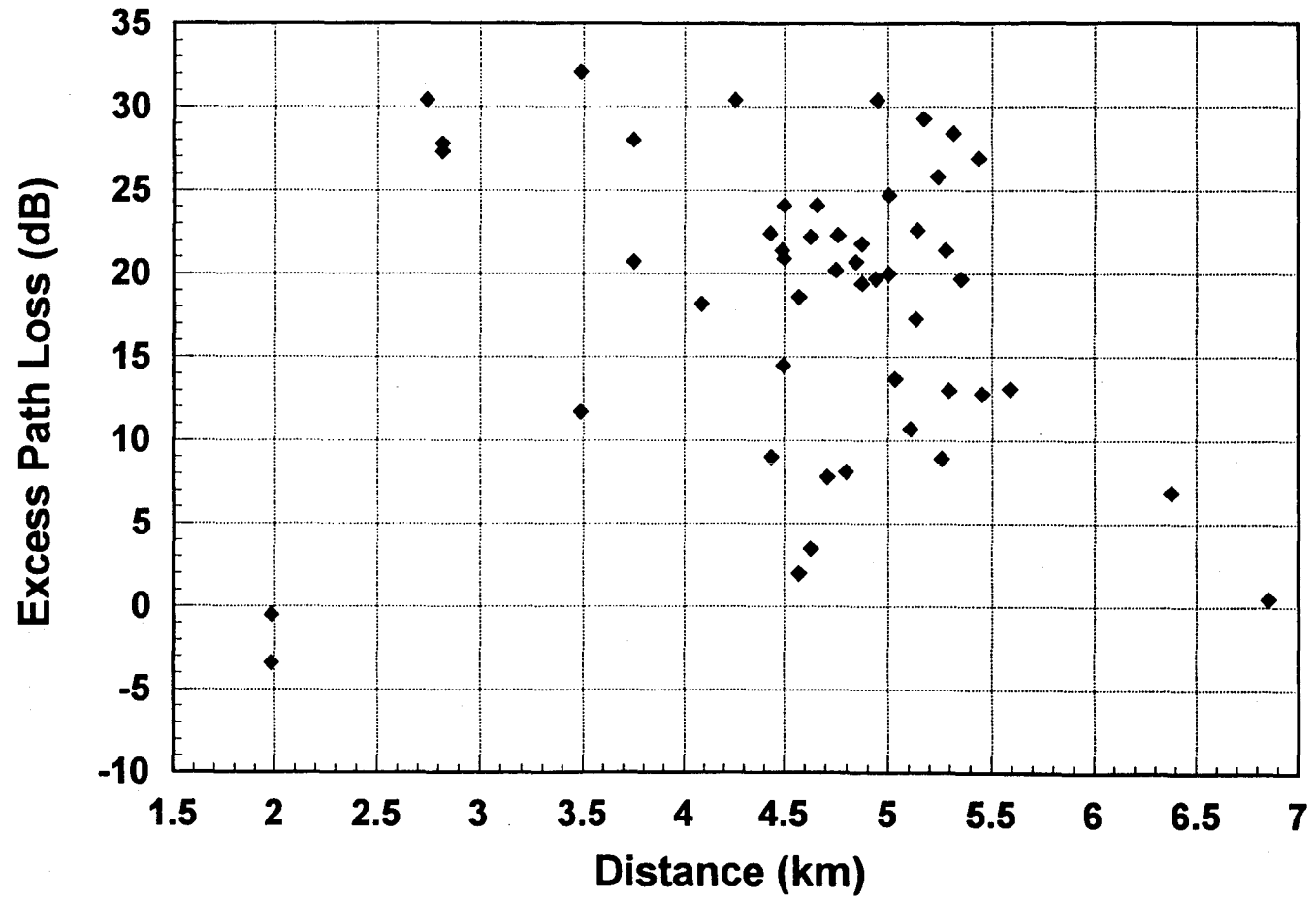


Figure 22. Area coverage survey: excess path loss versus distance, transmitter height 16 meters.

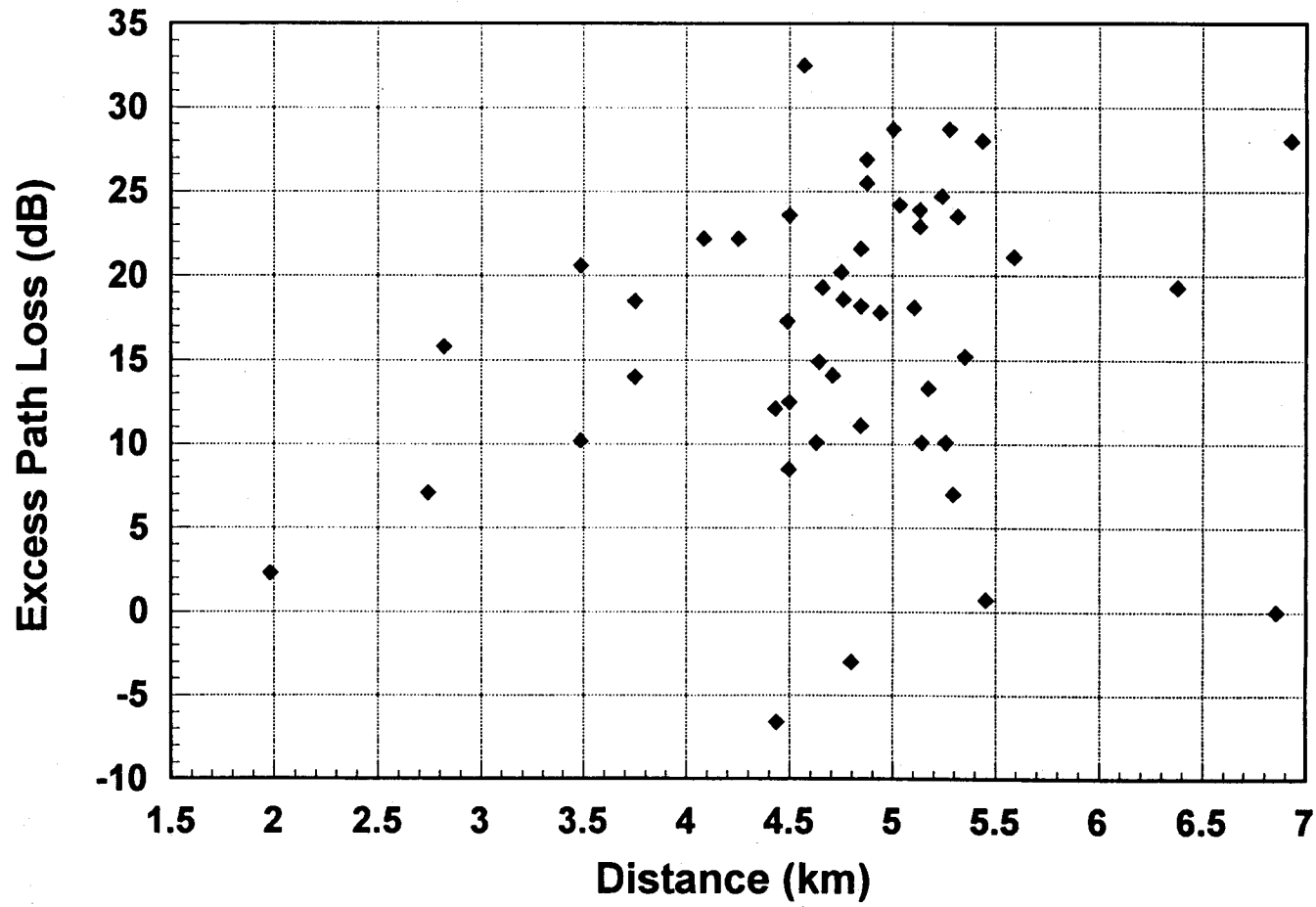


Figure 23. Area coverage survey: excess path loss versus distance, transmitter height 40 meters.

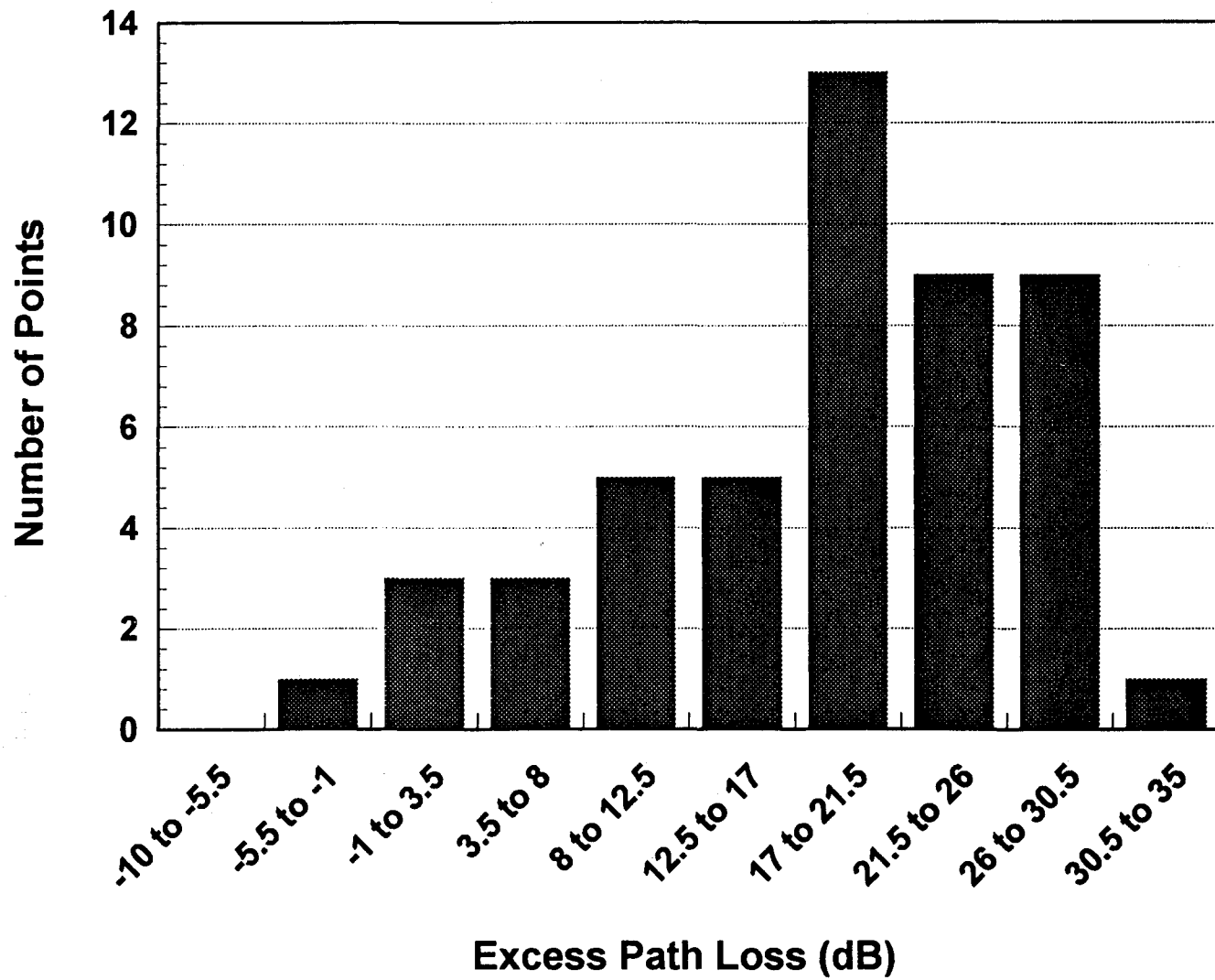


Figure 24. Area coverage survey: histogram of excess path loss, transmitter height 16 meters.

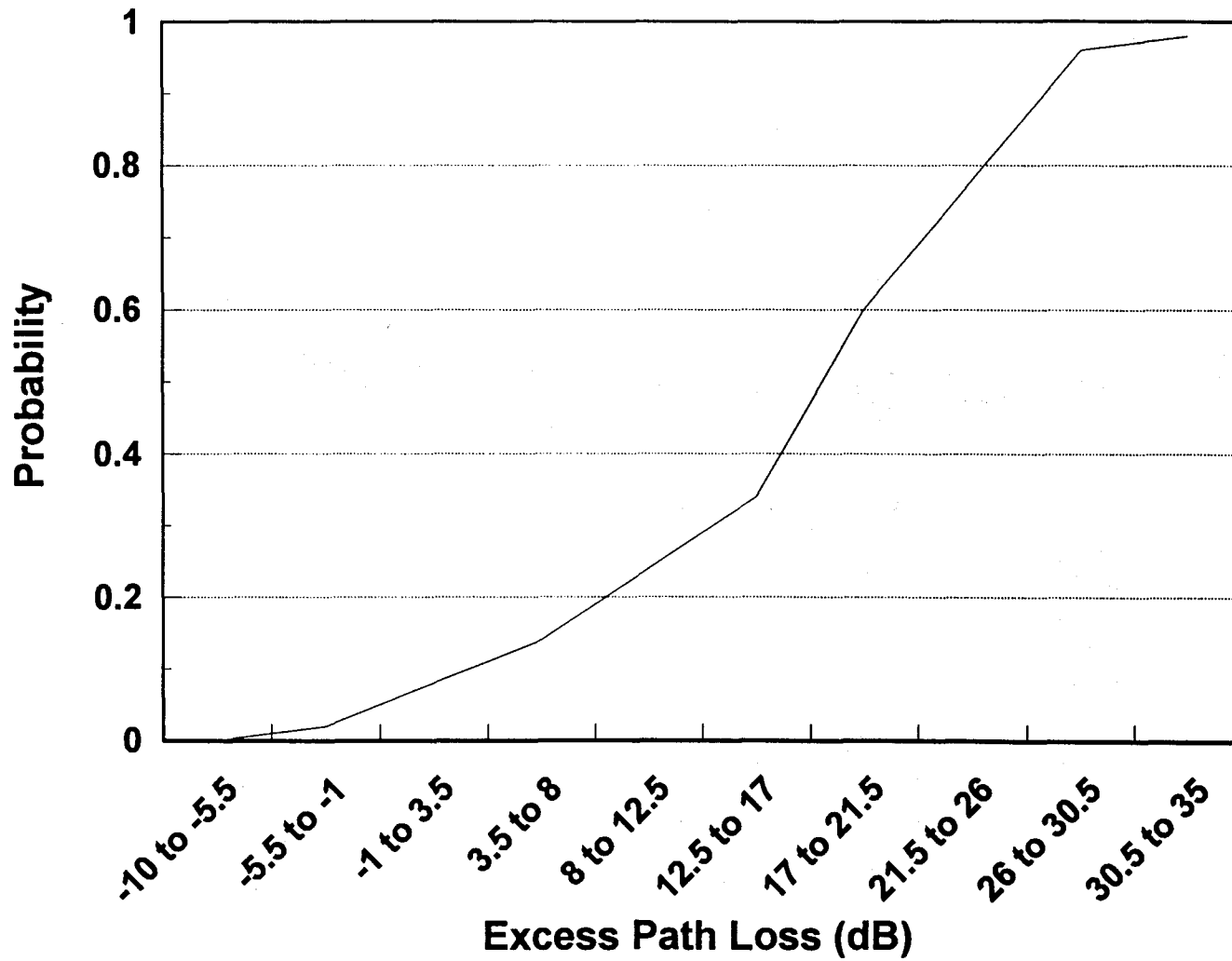


Figure 25. Area coverage survey: CDF of excess path loss, transmitter height 16 meters.

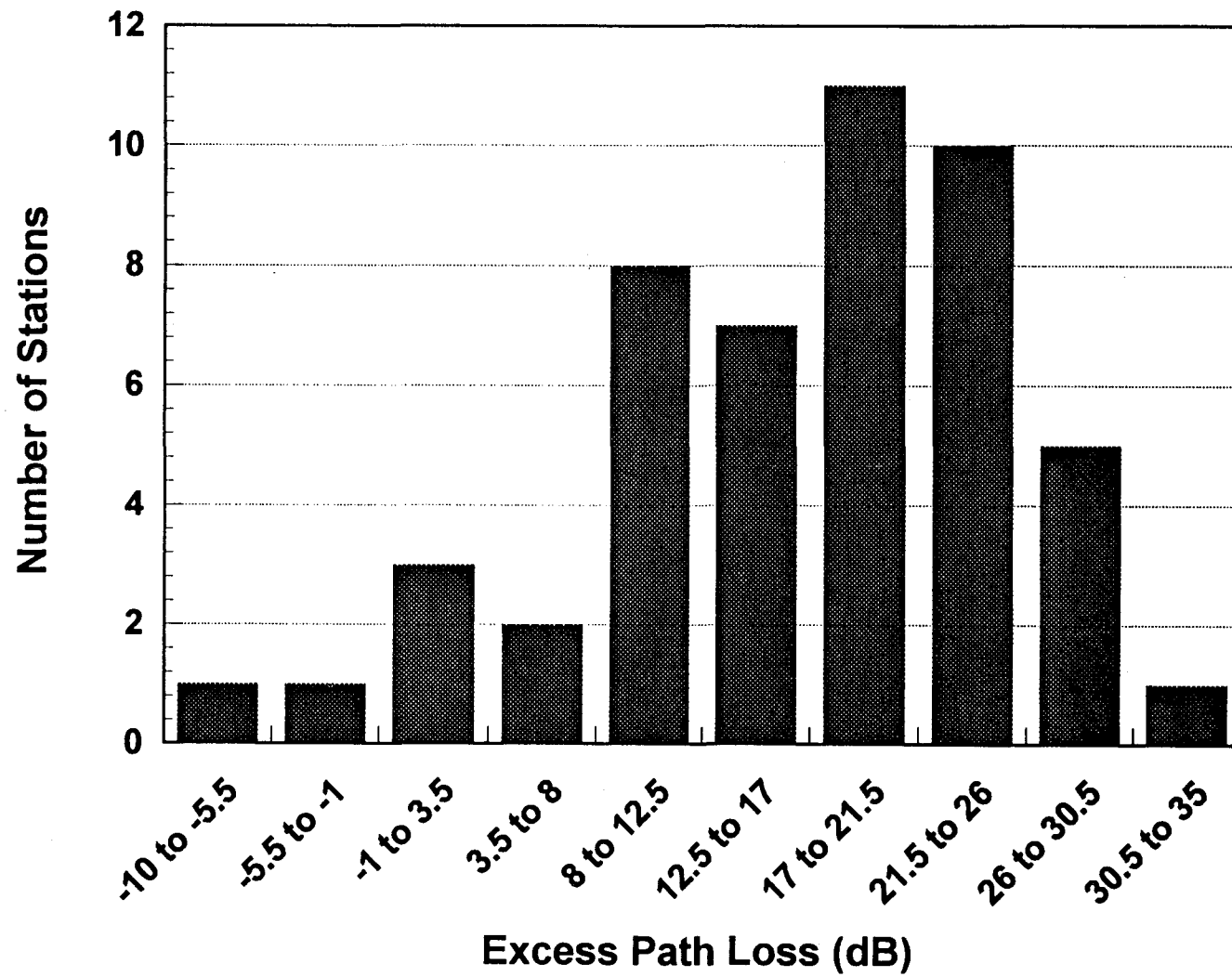


Figure 26. Area coverage survey: histogram of excess path loss transmitter height 40 meters.

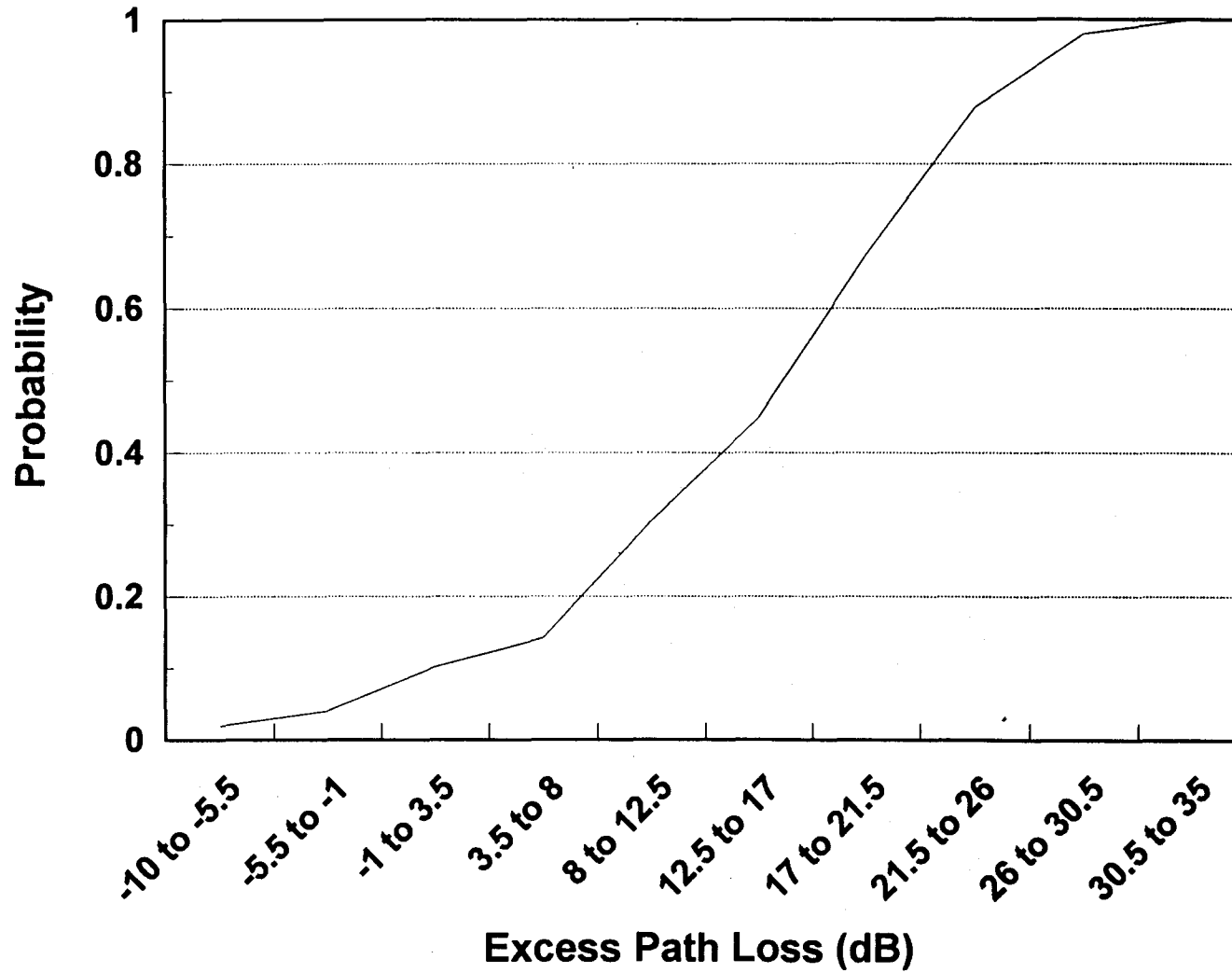


Figure 27. Area coverage survey: CDF of excess path loss, transmitter height 40 meters.

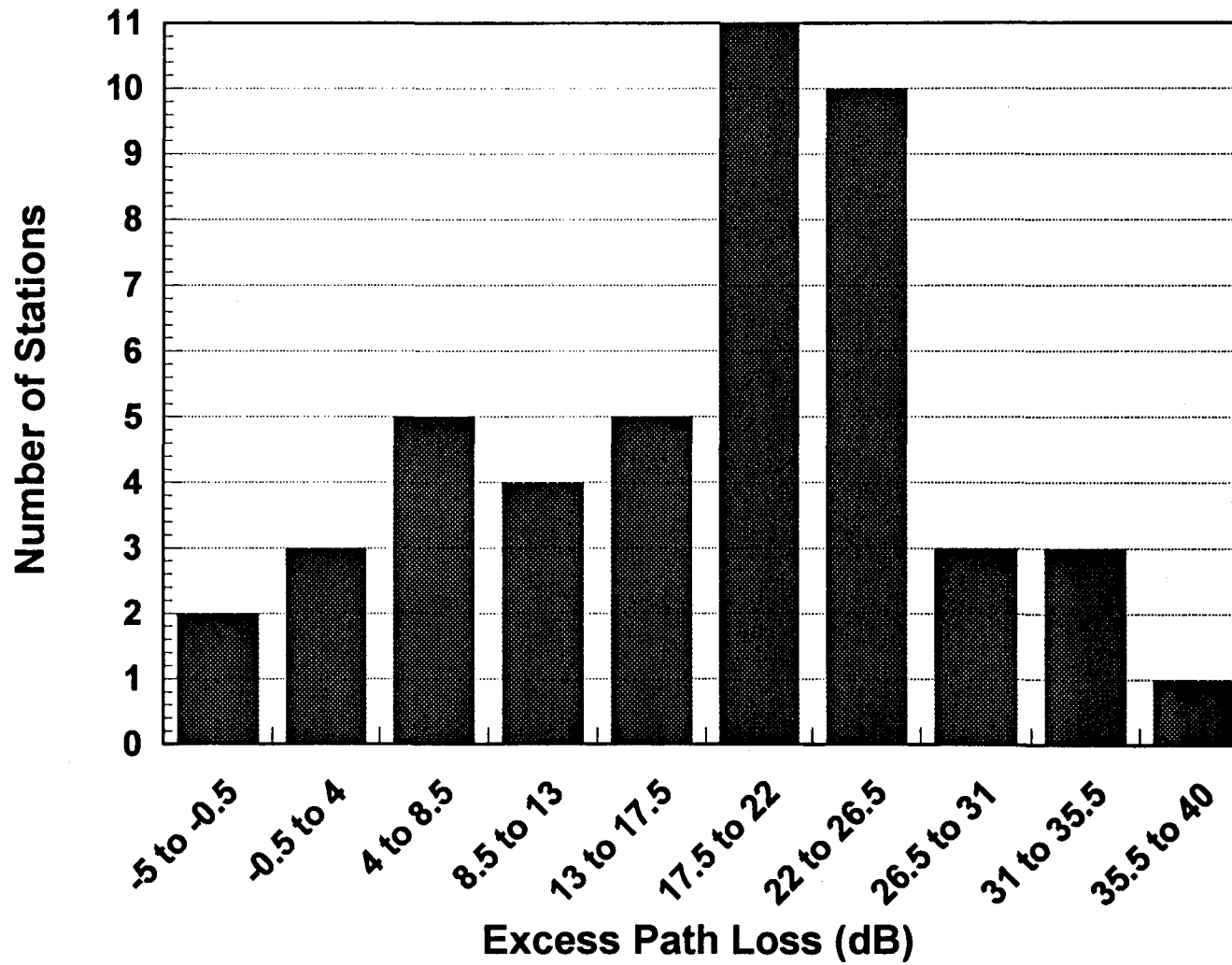


Figure 28. Area coverage survey: average excess path loss/channel, transmitter height 16 meters.

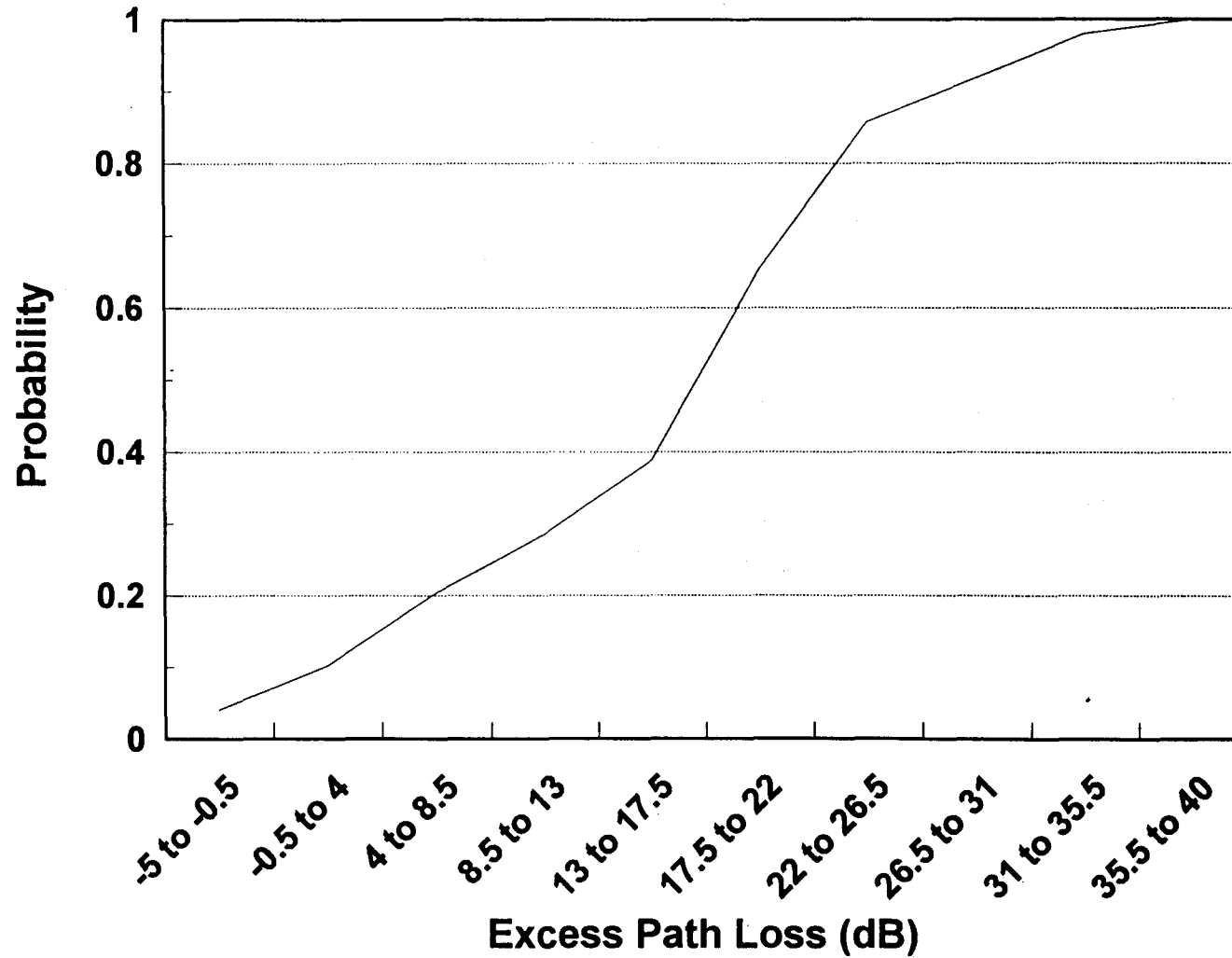


Figure 29. Area coverage survey: CDF of average excess path loss/channel, transmitter height 16 meters.

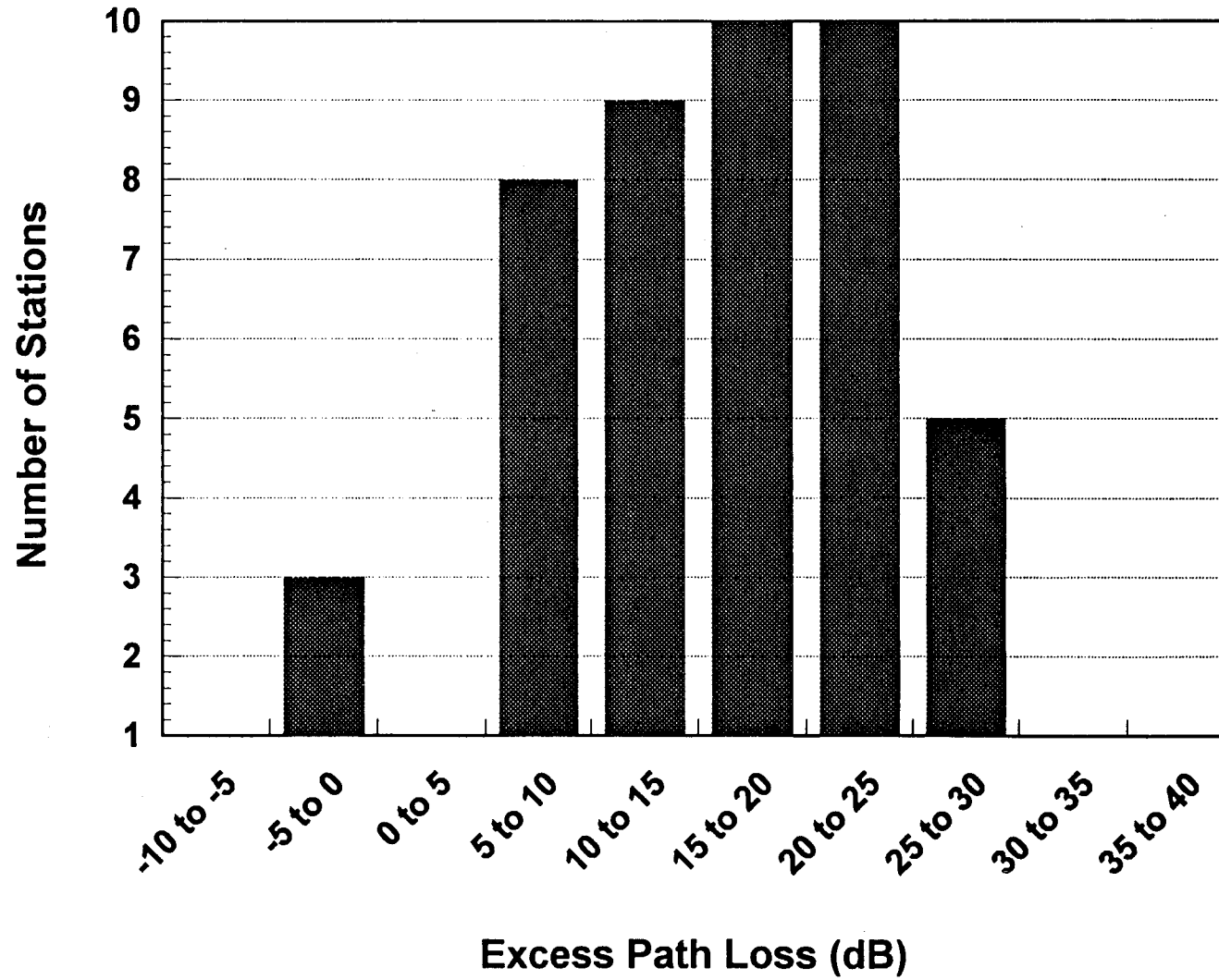


Figure 30. Area coverage survey: histogram of average excess path loss/channel, transmitter height 40 meters.

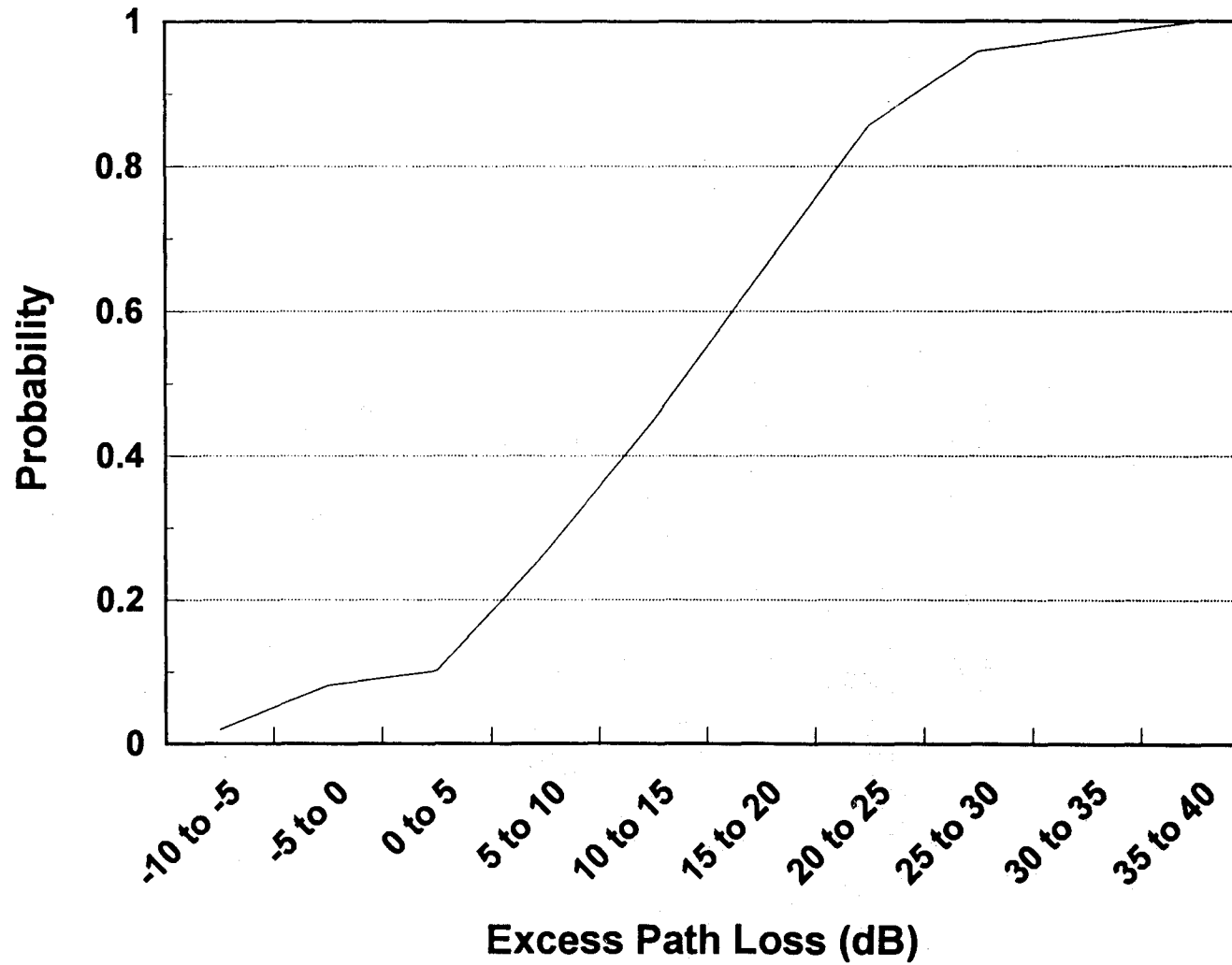


Figure 31. Area coverage survey: CDF of average excess path loss/channel, transmitter height 40 meters.

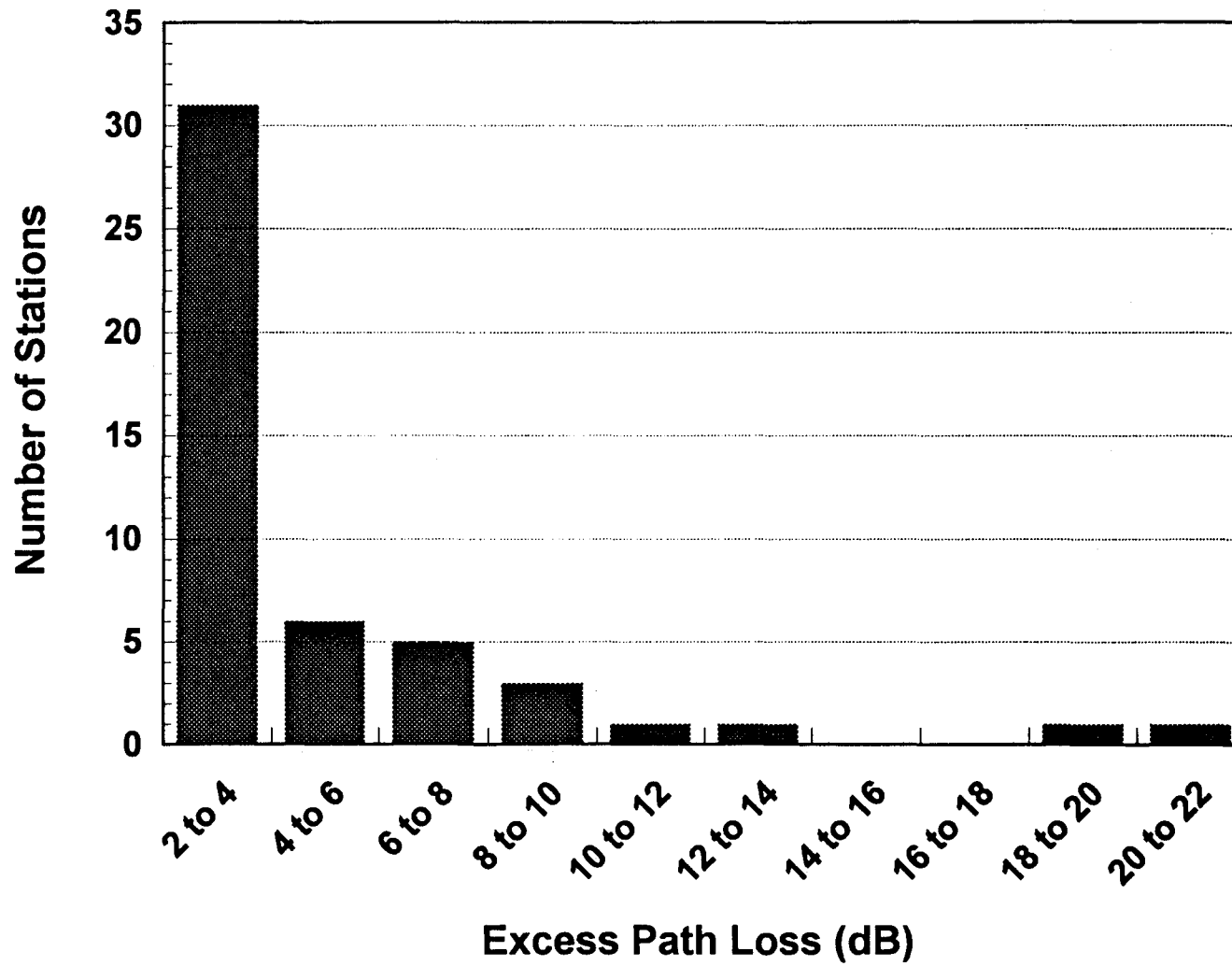


Figure 32. Area coverage survey: histogram of average Δ excess path loss/channel, transmitter height 16 meters.

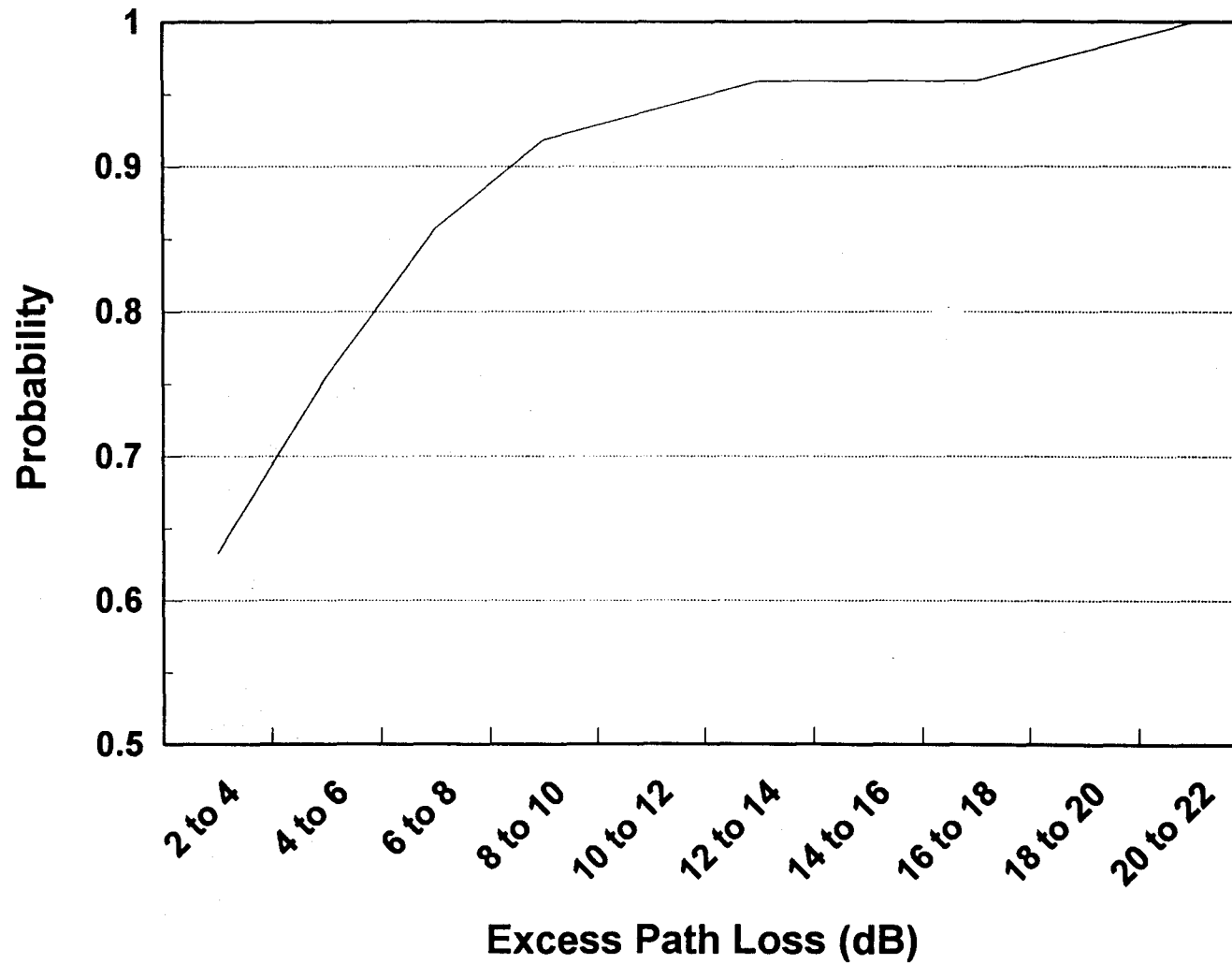


Figure 33. Area coverage survey: CDF average Δ excess path loss/channel, transmitter height 16 meters.

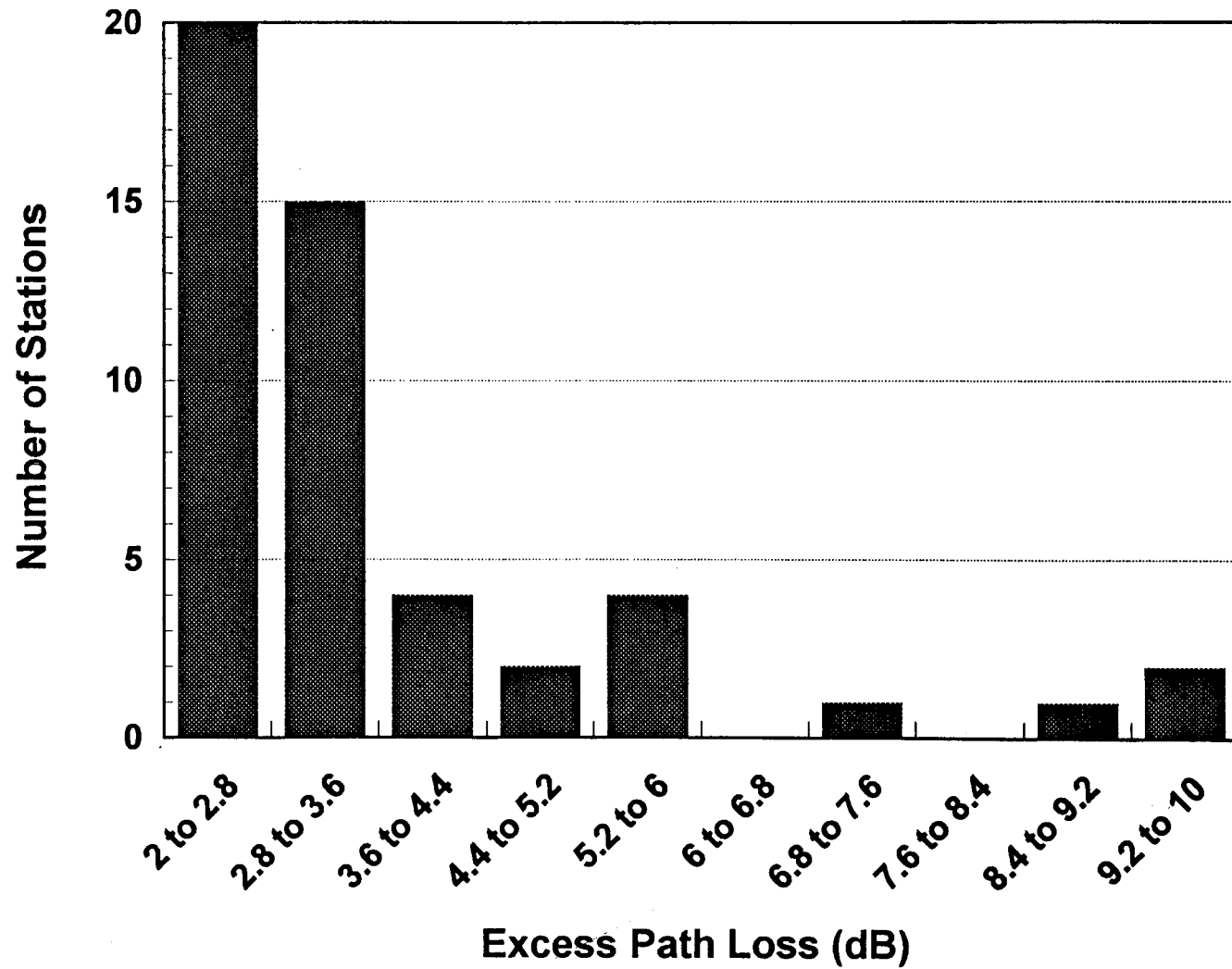


Figure 34. Area coverage survey: histogram of average Δ excess path loss/channel, transmitter height 40 meters.

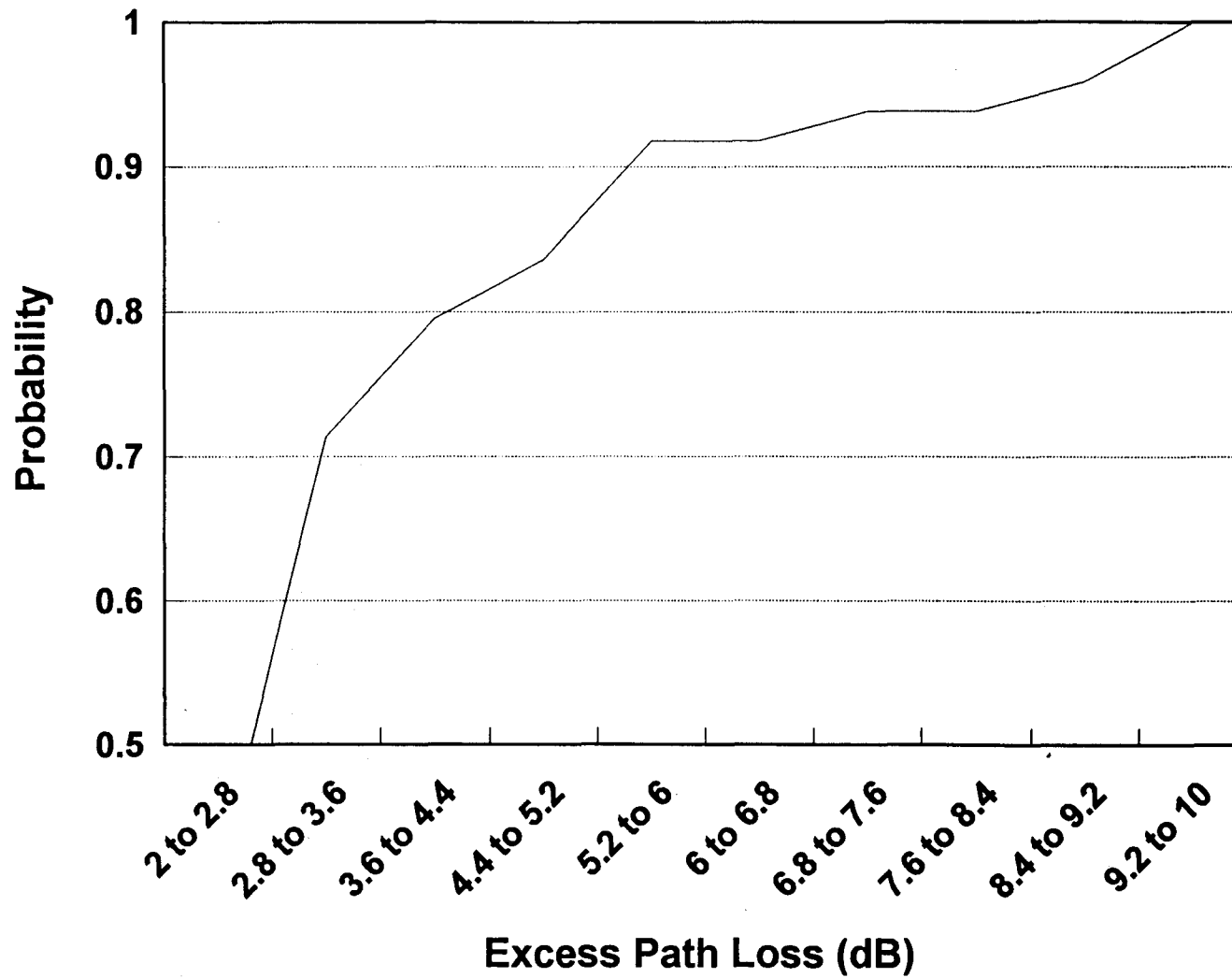


Figure 35. Area coverage survey: CDF of average Δ excess path loss/channel, transmitter height 40 meters.

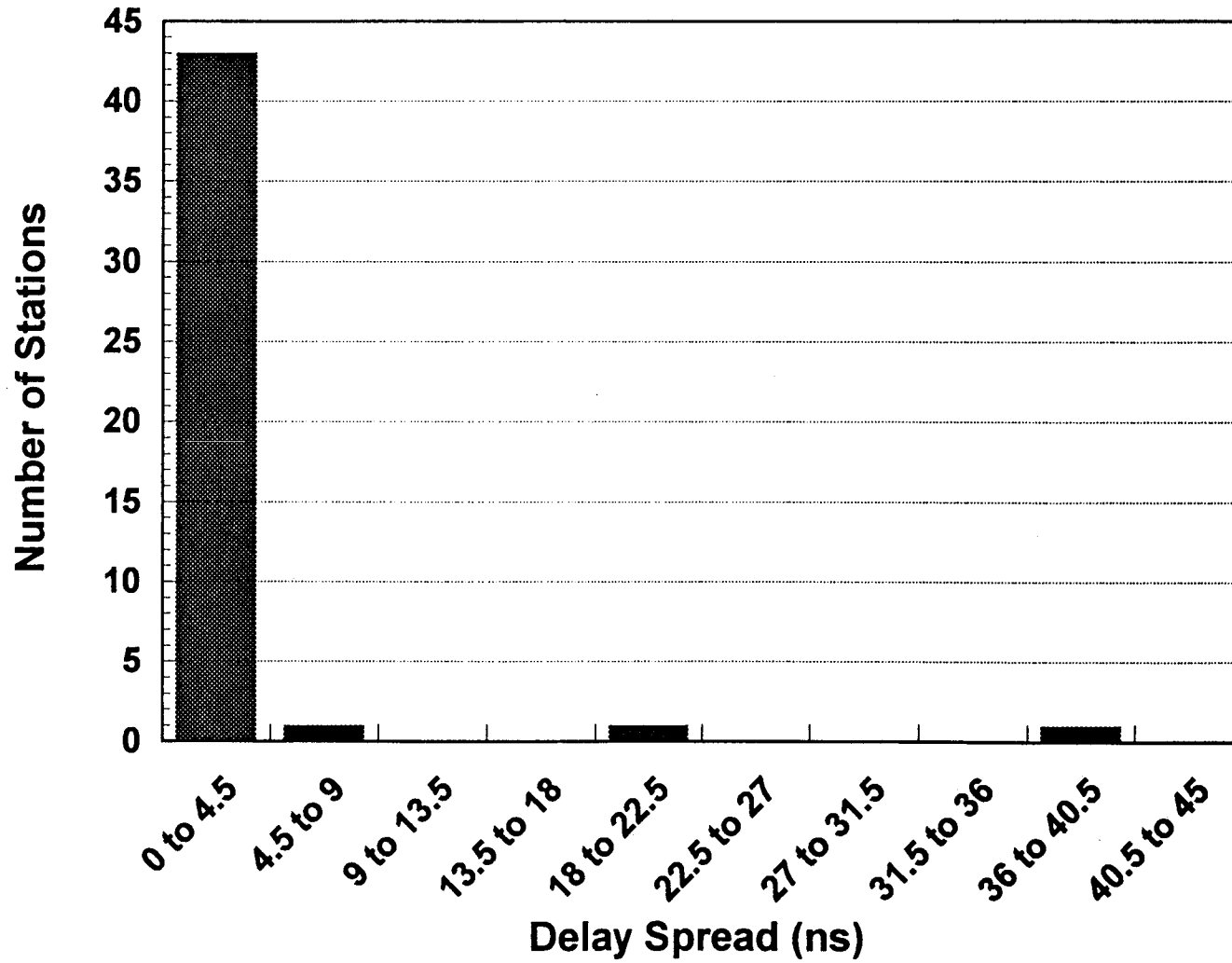


Figure 36. Area coverage survey: histogram of average delay spread, 10 dB threshold, transmitter height 16 meters.

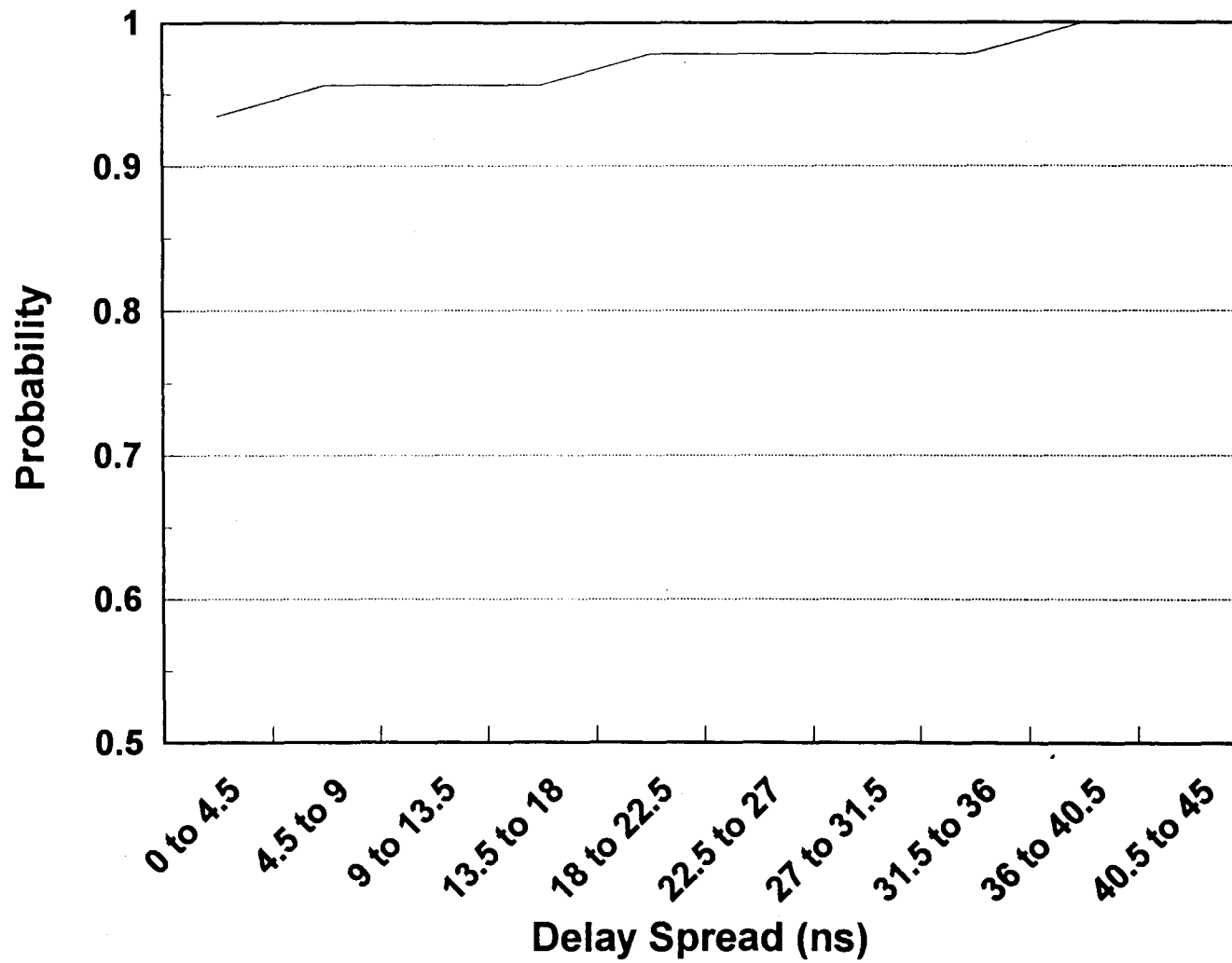


Figure 37. Area coverage survey: CDF of average delay spread, 10 dB threshold, transmitter height 16 meters.

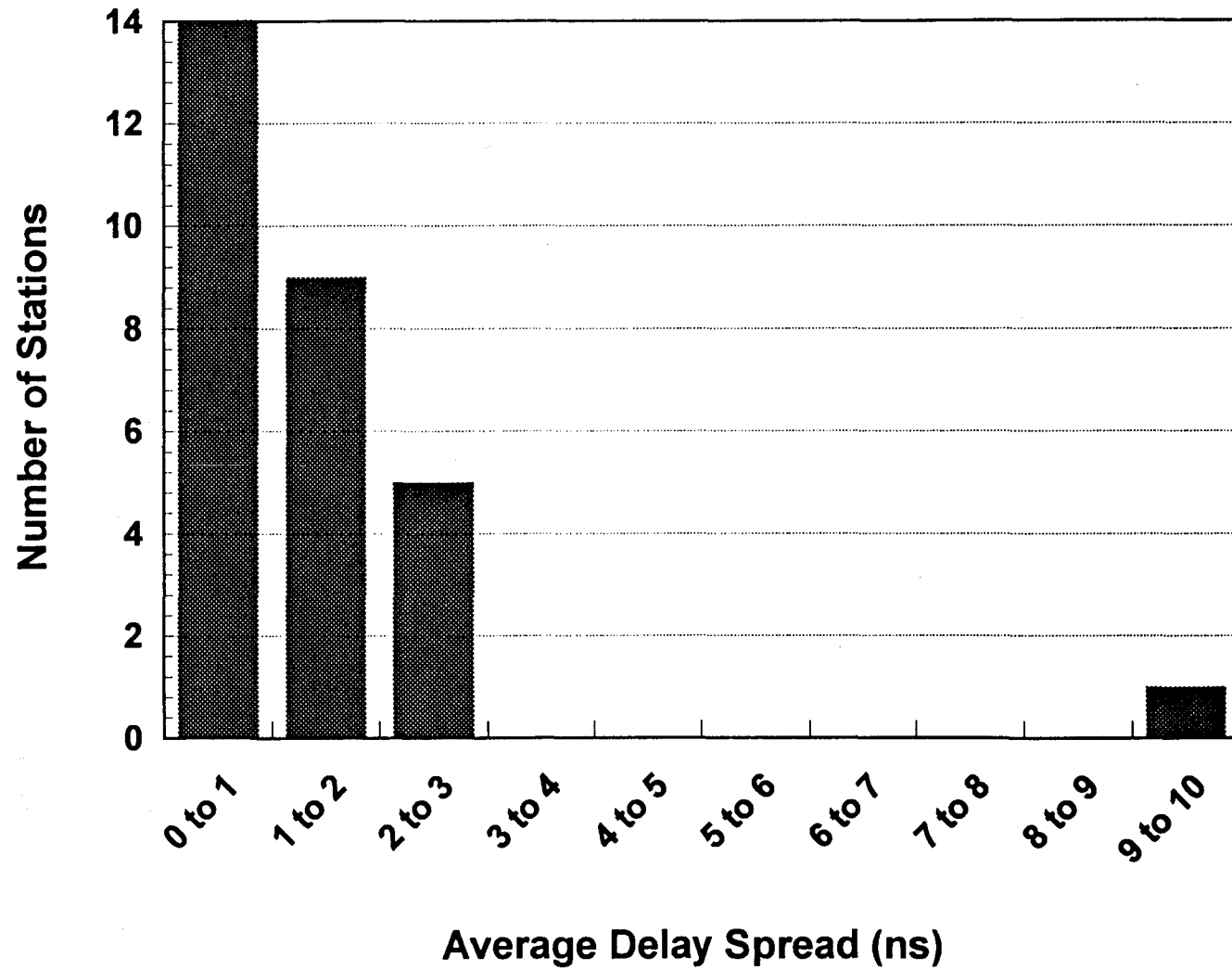


Figure 38. Area coverage survey: distribution of average delay spread, 10 dB threshold, transmitter height 40 meters.

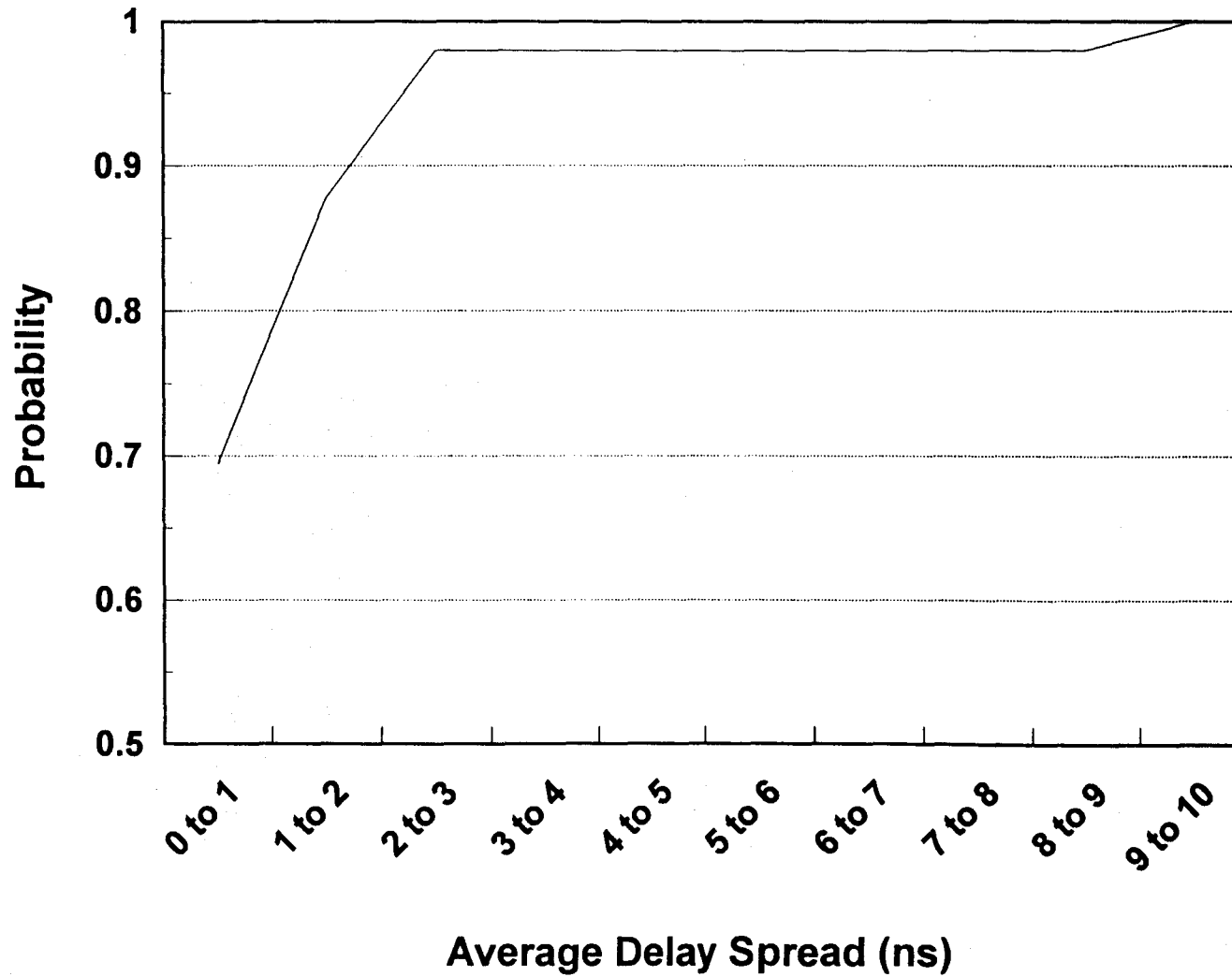


Figure 39. Area coverage survey: CDF of average delay spread, 10 dB threshold, transmitter height 40 meters.

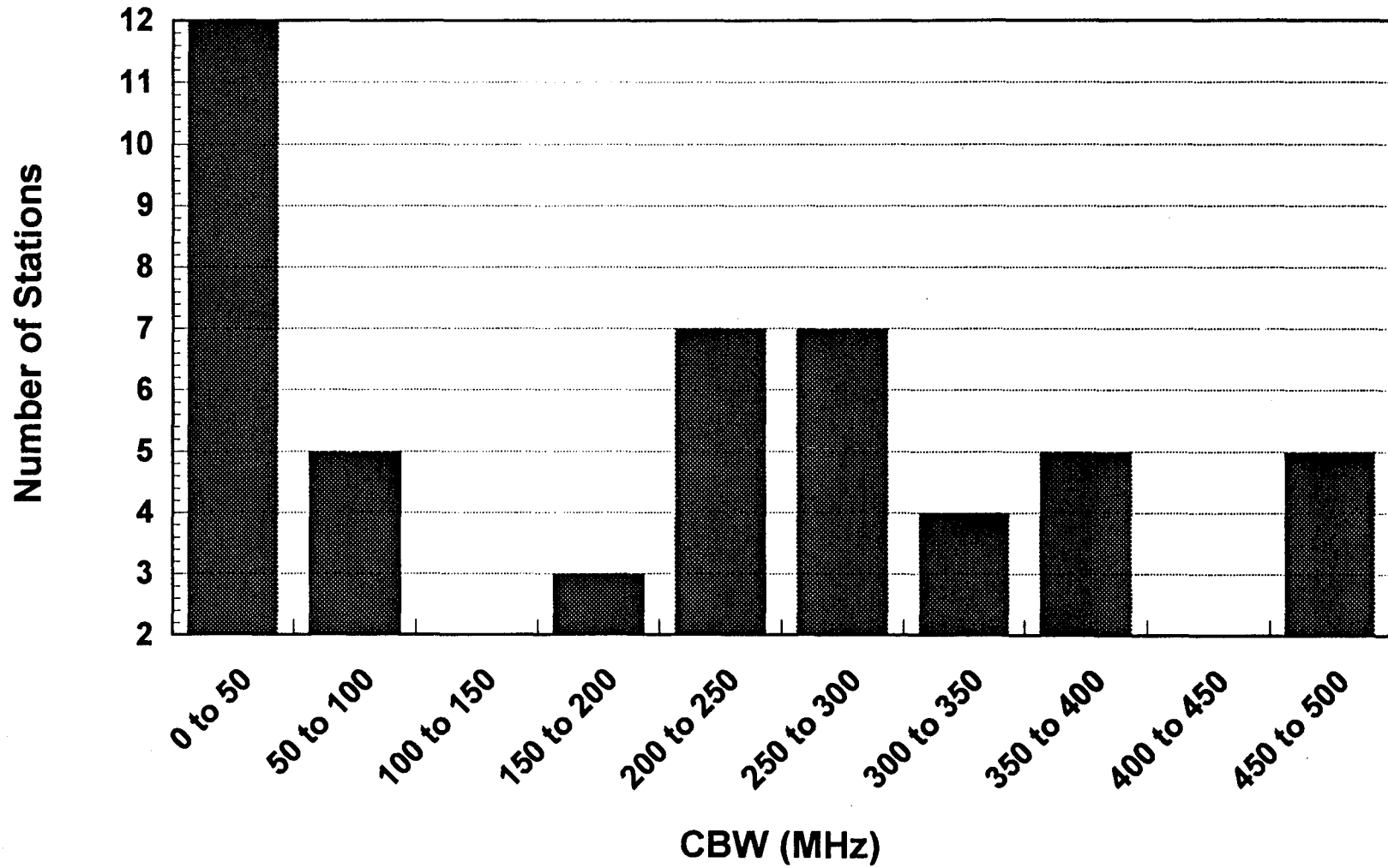


Figure 40. Area coverage survey: distribution of average correlation bandwidth, transmitter height 16 meters.

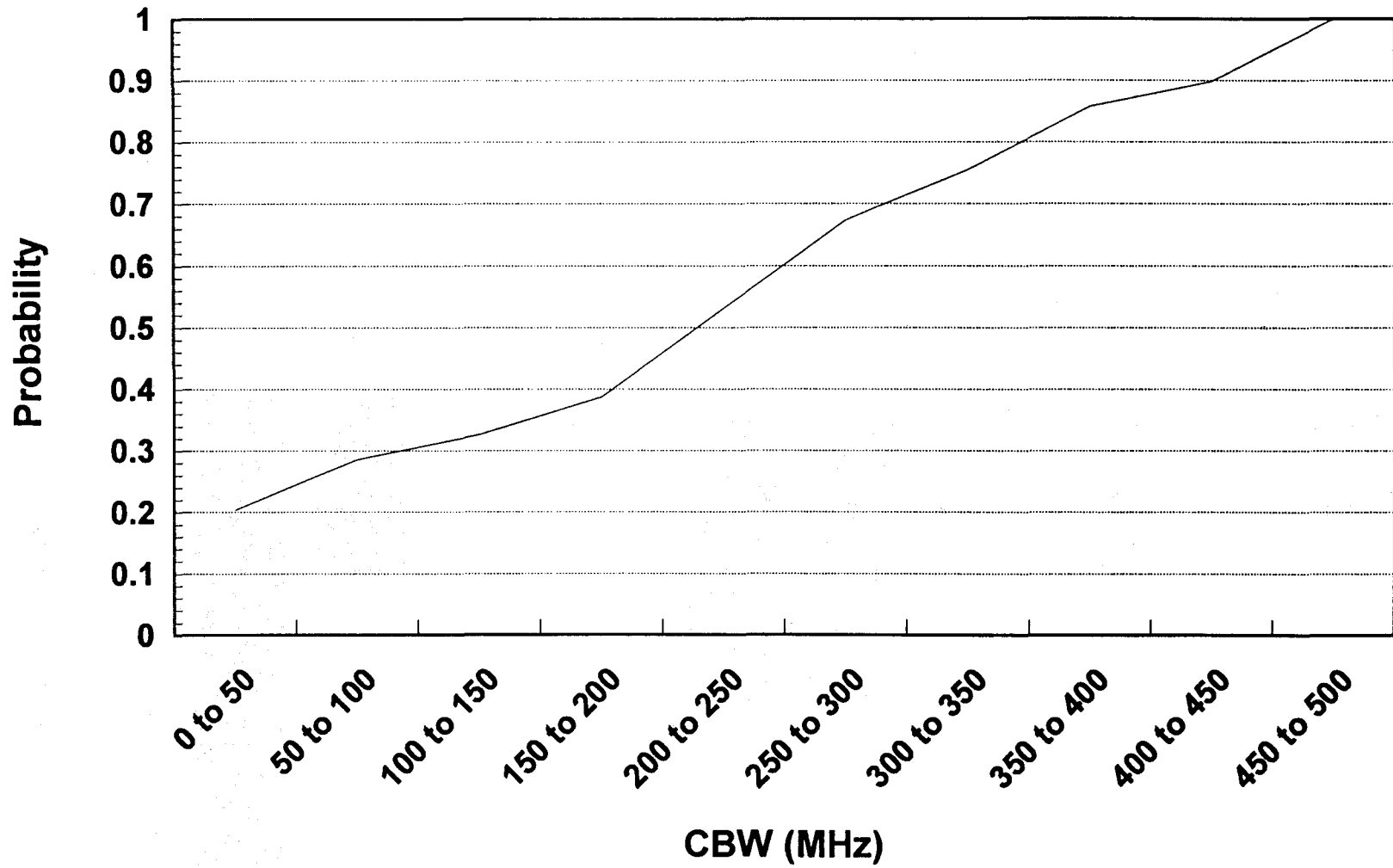


Figure 41. Area coverage survey: CDF of average correlation bandwidth, transmitter height 16 meters.

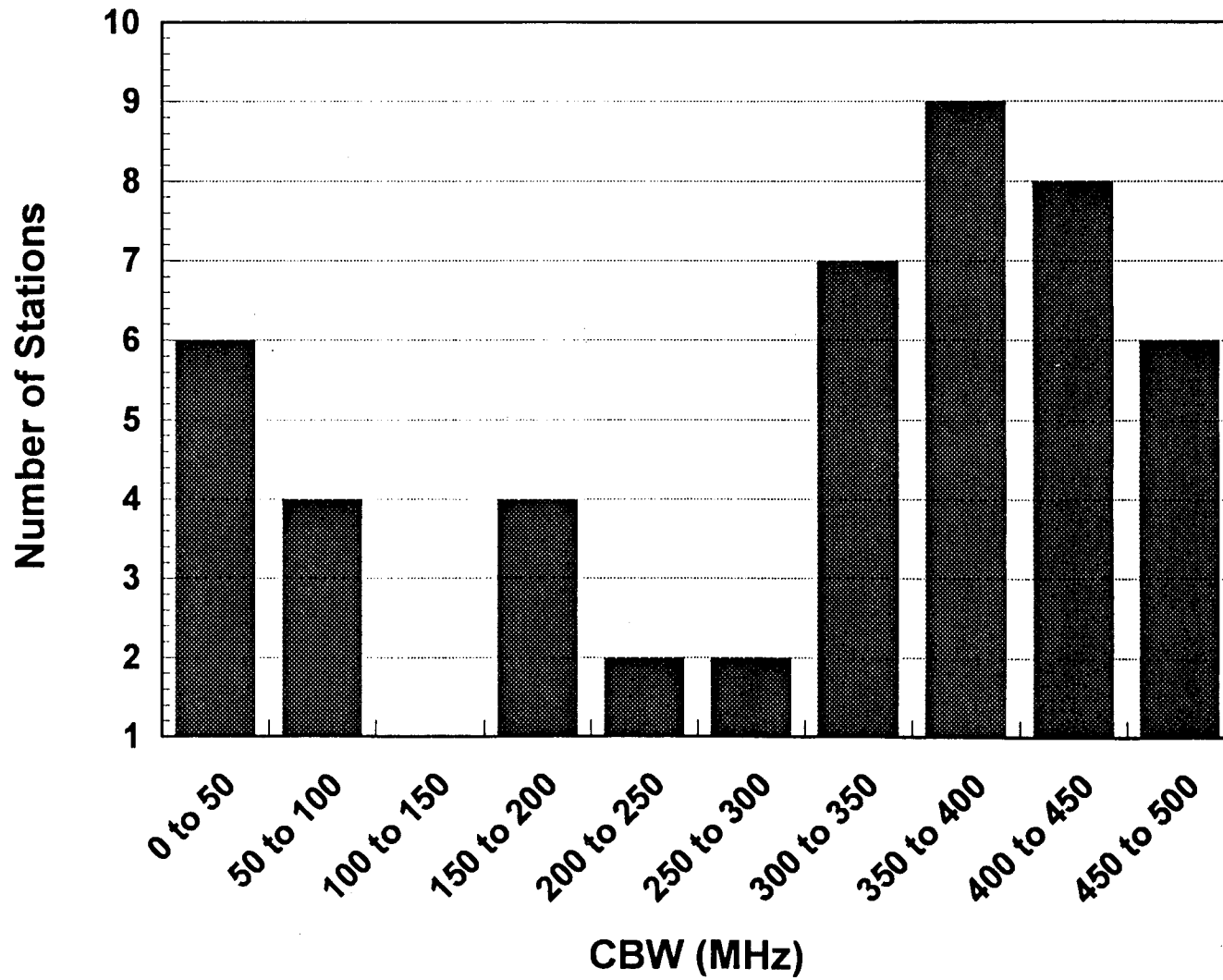


Figure 42. Area coverage survey: distribution of average correlation bandwidth transmitter height 40 meters.

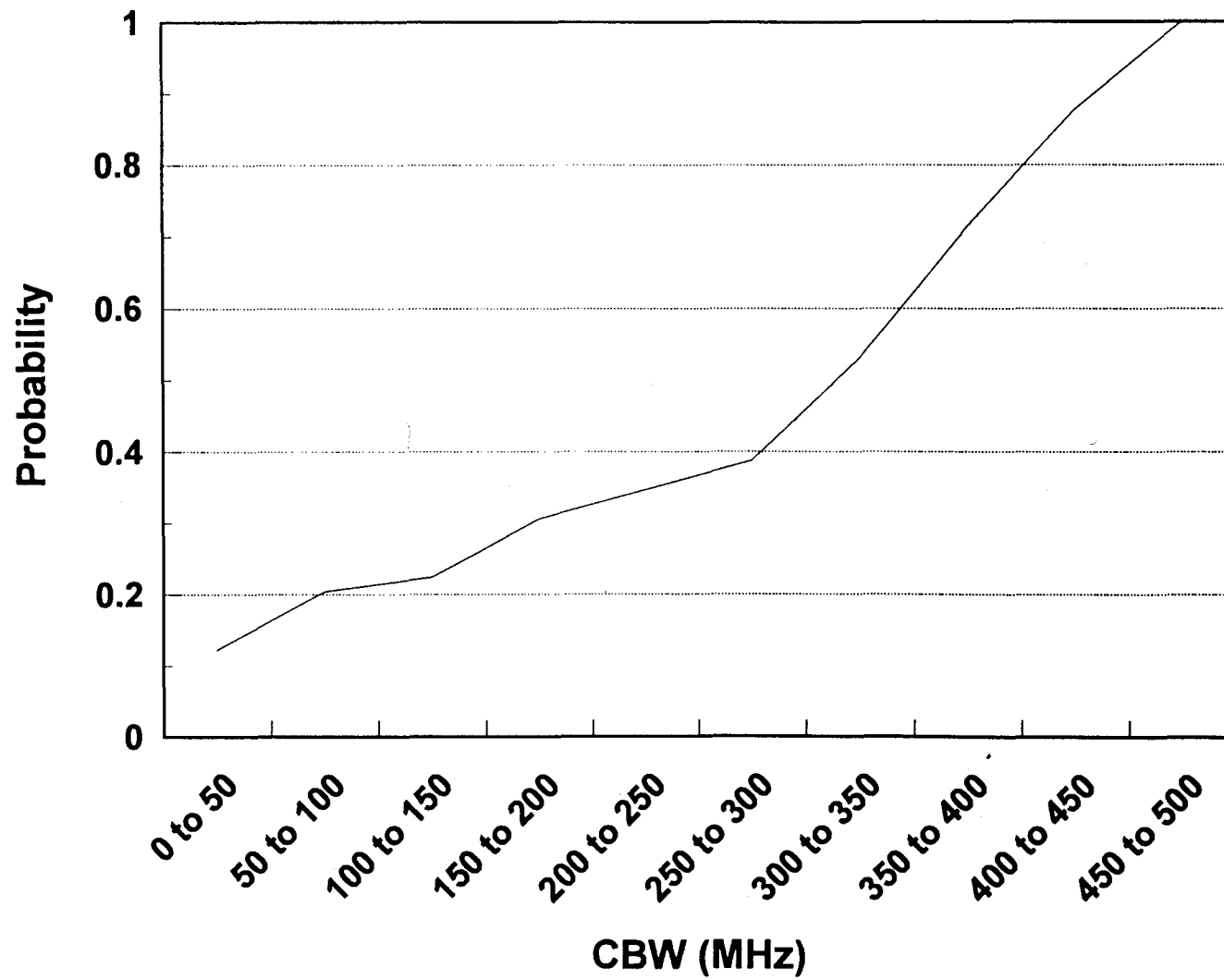


Figure 43. Area coverage survey: CDF of correlation bandwidth, transmitter height 40 meters.

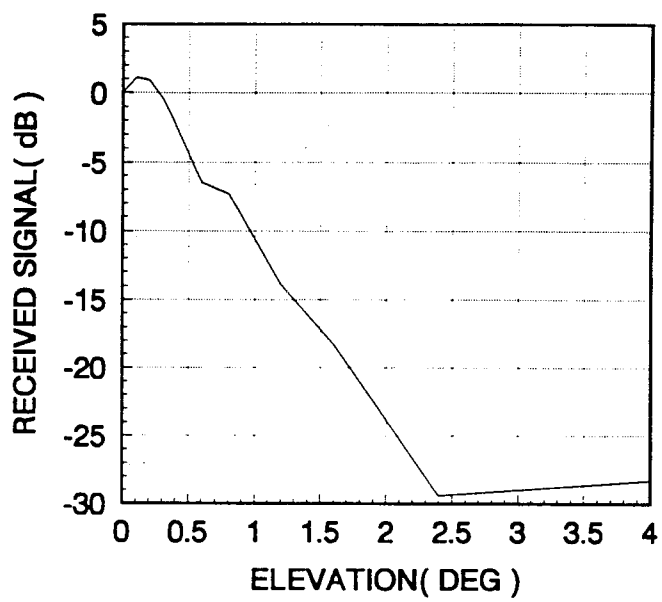


Figure 44. Antenna pattern, elevation, for 1.2 m² flat plate reflector at 28.8 GHz.

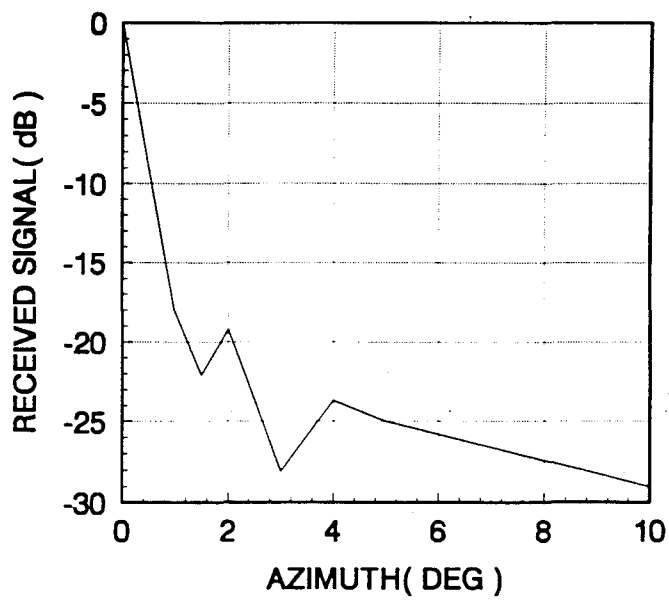


Figure 45. Antenna pattern, azimuth, for 1.2 m² flat plate reflector at 28.8 GHz.

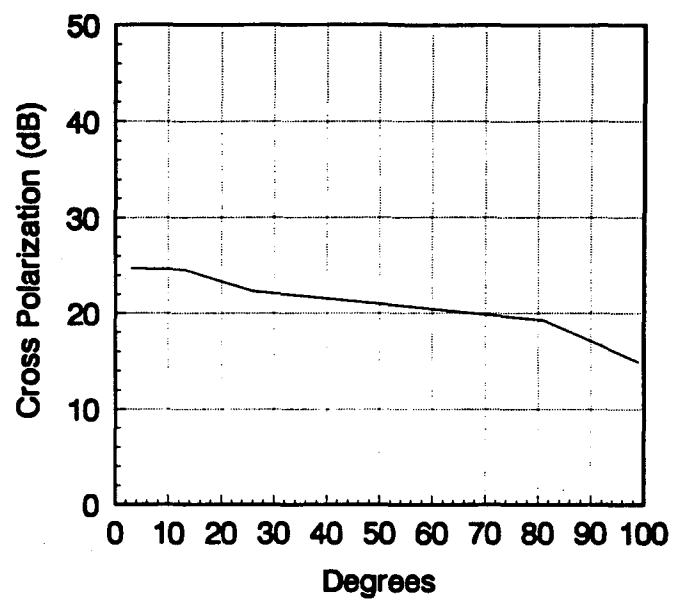


Figure 46. Cross polarization for 1.2 m² flat plate reflector at 28.8 GHz.

Table 4. Narrowband Passive Repeater Study Data

Station	Date	Transmitter Williams Towers 5th Floor		OLOS (b)	File	Code	PHI (deg)	A (dB)	A cal (dB)	DS (ns)	CBW (MHz)
		Rx Elev(ft)	Rx D(ft)								
46	1/5/93	5293	5931	1	u4p1	s	5.0	31.0	36.0	3.1	57.0
2	12/18/92	5279	9000	1	u1p4	l	0.4	30.0	20.5	2.3	2.0
47	1/5/93	5293	10106	1	u4p7	s	-0.02	35.0	5.0	4.5	11.0
6	12/18/92	5321	14550		u1p17	s	-0.46	9.0	0.0	0.9	359.0

Legend

Transmitter Height = 52 ft for Williams Towers 5th floor.

A = average excess path loss

A cal = calculated value using knife edge diffraction model

DS = delay spread

OLOS(b) = obstructed line of site, building

CBW = correlation bandwidth

PHI = diffraction angle

Code: s = short, l = long

Table 5. Broadband Diffraction Study Data

Path Angle (degrees)	TxPower (dbm)	Sys Gain (db)	FS Loss (db)	Rec Signal (dbm)	Cal Rep Gain (db)	Rep Loss (db)
3	17.8	73.9	207.8	-17.6	104.5	6
13	17.8	73.9	206.4	-16.3	104.4	6
26	17.8	73.9	205.9	-15.1	104.3	5.8
81	17.8	73.9	206.4	-16.9	102.1	4.3
109	17.8	73.9	206.8	-19.5	99.8	4.2

*Note - Repeater was 1.2 m square aluminum plate mounted on a tripod.

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15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.) A broadband millimeter wave study was completed to characterize the radio channel for Local Multipoint Distribution Systems in Boulder, Colorado. The study determined characteristics for proposed 20-MHz channels centered at 30.3 GHz using two transmitter heights in a suburban environment. Distributions of delay spread, correlation bandwidth, frequency selective fading and scatter plots of signal loss are presented. The median signal loss for the 40-m transmitter height was 15 dB. Maximum delay spreads for this height were below 10 ns with a median value of less than 1 ns. Data was also collected to characterize a flat plate reflector proposed for use at 28.8 GHz. Cross cell interference and signal diffraction measurements were also made.			
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