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MEASUREMENTS OF LEAKY COAXIAL CABLES AND POSSIBLE APPLICATIONS TO TRAIN COMMUNICATION

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MAY 1974

FINAL REPORT

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16. Abstract

The electrical and radiation properties of the Radiax have been measured. The main results are: i) the surface wave exists, ii) the radial radiation follows $1/r^2$ relation for frequency below 190 MHz and $1/r$ relation for frequency near 400 MHz, iii) the transverse radiation pattern is nearly omnidirectional, iv) the coherent bandwidth is on the order of 3 MHz and the operating frequency range is several hundred megahertz; and v) better coupling efficiency is observed at lower frequency. Possible applications for railroad communication are discussed.

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PREFACE

The work described herein has been performed as part of a continuing program to evaluate and develop communication systems for high speed ground vehicles. This program on communications for high speed ground transportation is sponsored by the Federal Railroad Administration through the Office of Research, Development, and Demonstrations.

The work consists of the measurement and evaluation of the electrical and coupling characteristics of two sizes of a commercial coaxial cable called, RADIAX. The characteristics of the cables are described and their application to both narrowband and wideband transmission is discussed. Recommendations for further field tests are presented.

Some of the measurements were carried out by A.R. Farara and R.J. Jones. Their contributions are gratefully acknowledged.

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1. INTRODUCTION

The availability of adequate communication services between fixed terminals and high-speed trains is of primary importance in the rail transportation field both from the standpoint of improving their competitiveness with respect to other means of transportation and improving management and safety (command and control). It seems reasonable to believe that services like two-way telephones and eventually video-telephones, and entertainment services such as commercial television or CATV will increase the convenience and desirability of traveling by trains. Conventional two-way radio mobile telephone service between the ordinary telephone network and the Metroliner is already available between New York City and Washington, DC and has been well received by the public. This particular system developed by Bell Laboratories[1] uses radio communication in the lower UHF region (400 MHz) and therefore, is subject to all the problems associated with spectrum crowding which are so familiar in mobile communication.

The desirability of having larger bandwidths available for communicating with high-speed trains has prompted the investigation of different communication techniques. One solution that has been receiving increasing attention, especially in Japan, is the use of leaky wave cables generally of the slotted type, which are installed parallel to and in close proximity to the vehicle track[2]. This system has unique features for communication with trains in tunnels or with subways and has also been proposed for open tracks and for communication in the urban environment.

A particular inexpensive and flexible version of slotted cable (Figure 1-1) is manufactured by the Andrew Corp., under the trade name, RADIAX, and has been used in special applications such as communication with trains in tunnels, communication with miners underground, and communication inside skyscrapers[3].

The purpose of this study has been to conduct a series of measurements on Radiax cables. The results of the measurements

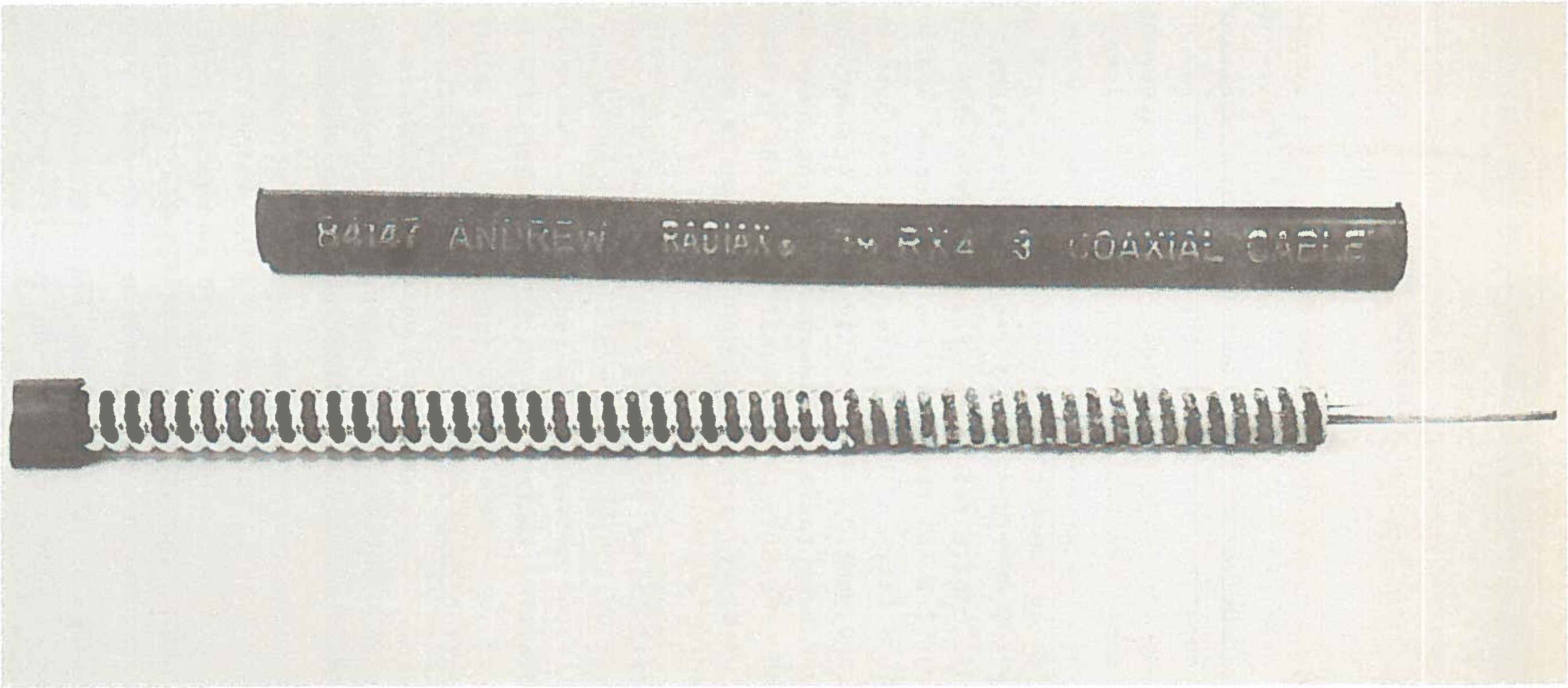


Figure 1-1. Typical RADIAX Cable (Cutaway View)

will be used to describe the characteristics of the cable and to determine its transmission parameters in order to assess its potential as a transmission link for wayside communications systems.

The report is in three parts. Section 2 contains measurements of the cable characteristics; Section 3 presents the measured coupling characteristics and discusses possible further tests; finally in Section 4 the results of the measurements are presented. All the measurements reported here were conducted at an outdoor field site located at MITRE, Bedford, MA. Two types of Radiax cable, each approximately 200 feet in length, were used.

2. CHARACTERISTICS OF RADIAX CABLES

The basic electrical characteristics of two Radiax cables were determined by measuring the VSWR, attenuation, pulse dispersion, and phase, for signals propagating from a transmitter through the line to the point where coupling takes place. These characteristics will be used to determine possible carrier frequencies for the signal, the allowable bandwidth, and the transmission distance before a repeater is needed. The measurements were made on two types of Radiax: RX4-3 and RX5-1 with diameters of 1/2" and 7/8" and lengths of 130 ft. and 200 ft. respectively.

2.1 INPUT VOLTAGE STANDING WAVE RATIO (VSWR)

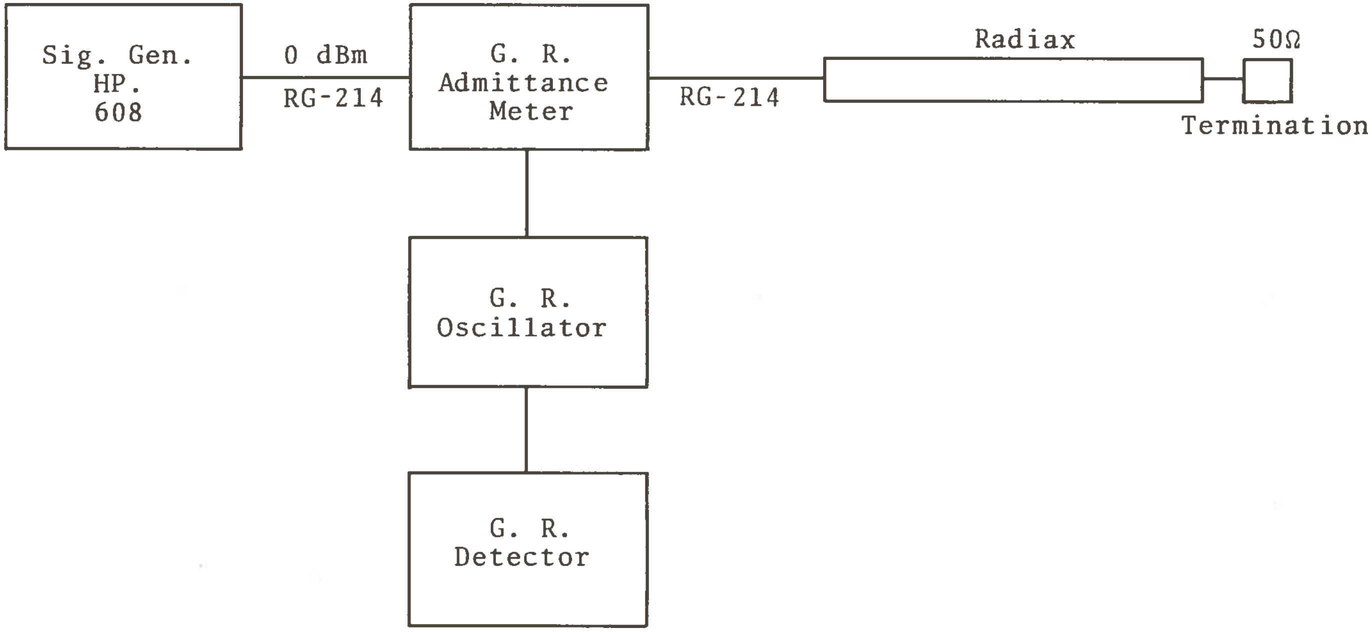
The block diagram of the measurement set-up is shown in Figure 2-1. A GR admittance meter was used to determine VSWR. Measurements were made every 50 MHz from 100 MHz up to 400 HHz. Figures 2-2 and 2-3 show the results for RX4-3 and RX5-1 respectively. The measured VSWR for both Radiax cables is about 1.1.

2.2 ATTENUATION

The attenuation of the two Radiax cables was measured in two ways: the first method employed a power meter to measure the power at the input and output of the Radiax. The power differences gave the total attenuation. The second method used a Hewlett-Packard Vector Voltmeter which yielded the attenuation of the Radiax cable directly. The results of the two methods agree quite well. The results of the measurements made over a frequency range from 50 MHz through 400 MHz are shown in Figure 2-4 and 2-5 for RX4-3 and RX5-1 respectively. The manufacturer's attenuation data are shown in Figures 2-6 and 2-7.

2.3 PULSE RISE TIME AND PULSE DISPERSION

The pulse rise time and pulse dispersion measurements are important to determine distortions that may occur during the



VSWR Measurement

Figure 2-1. Block Diagram for VSWR Measurement

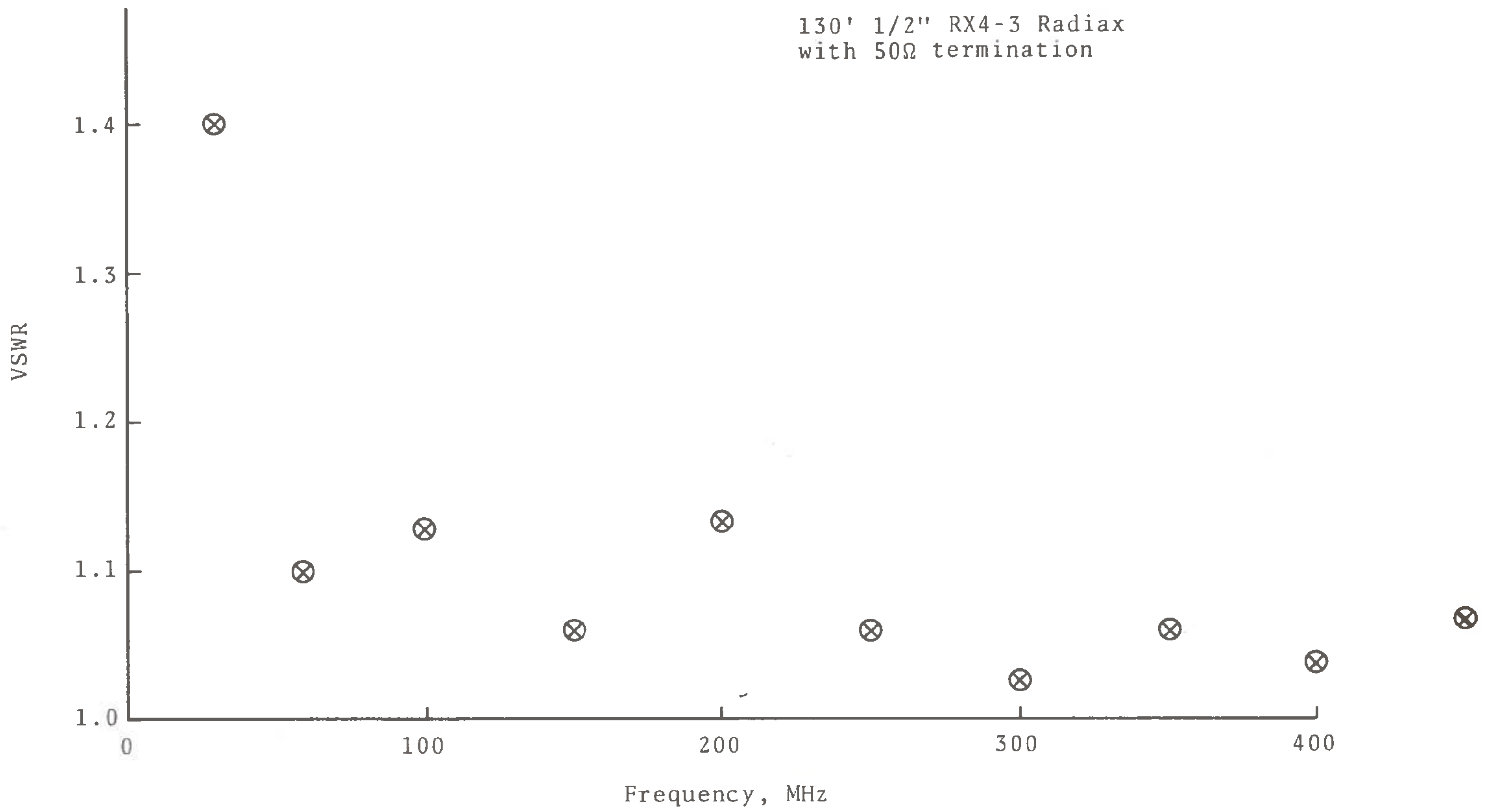


Figure 2-2. VSWR for 130-Foot RX4-3 (1/2")

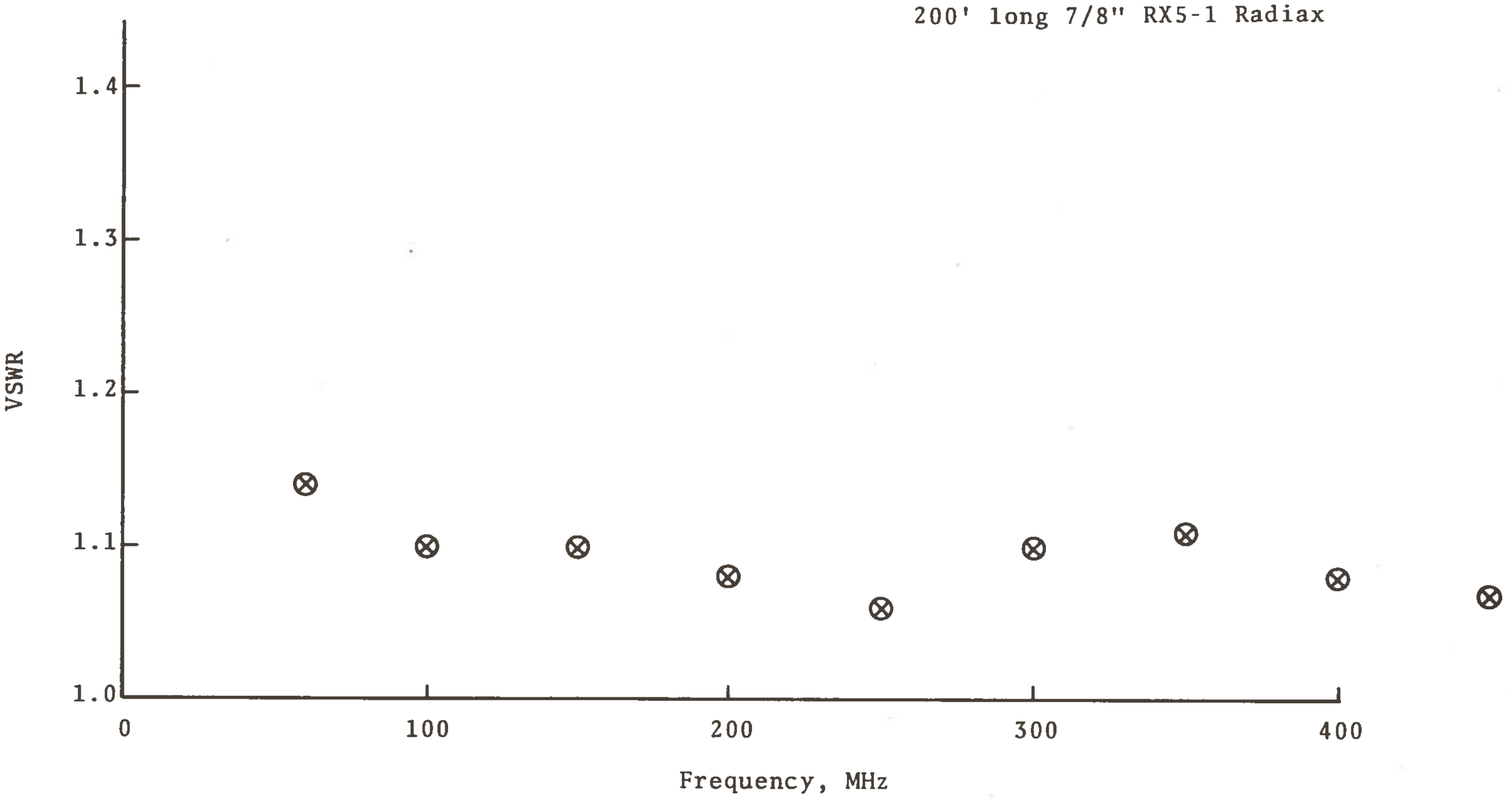


Figure 2-3. VSWR for 200-Foot RX5-1 (7/8")

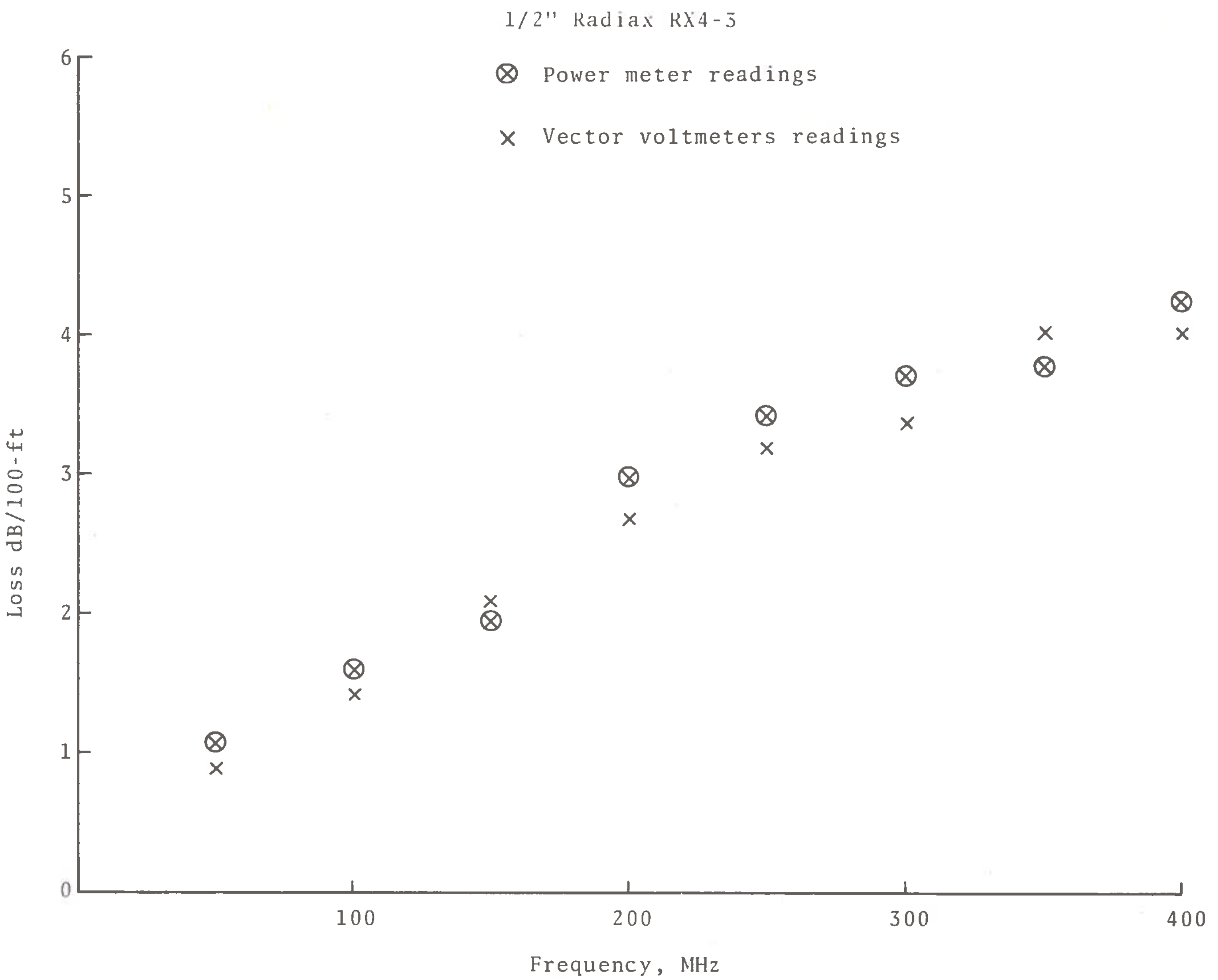


Figure 2-4. Losses Versus Frequency, RX4-3

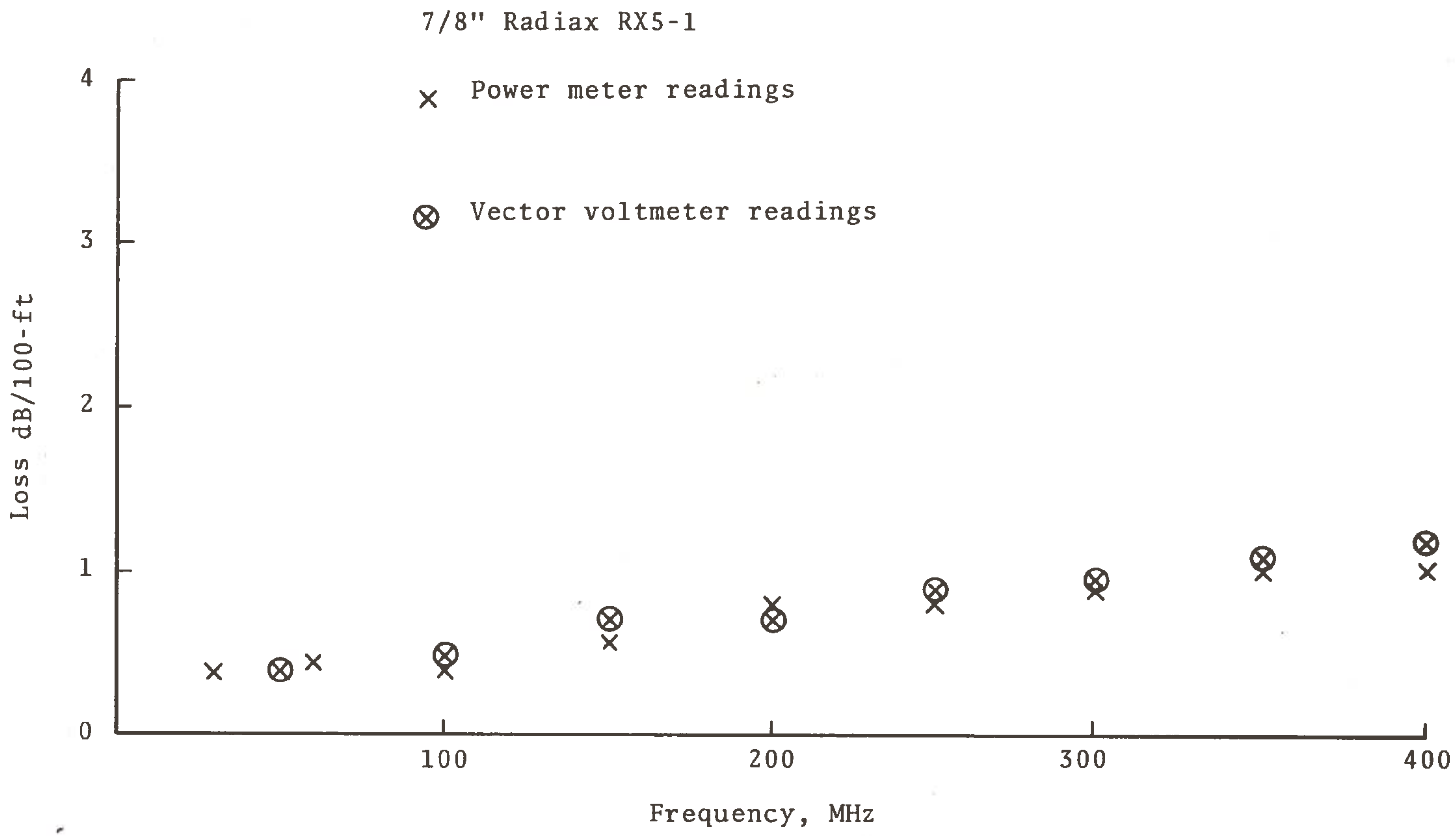


Figure 2-5. Losses Versus Frequency, RX5-1

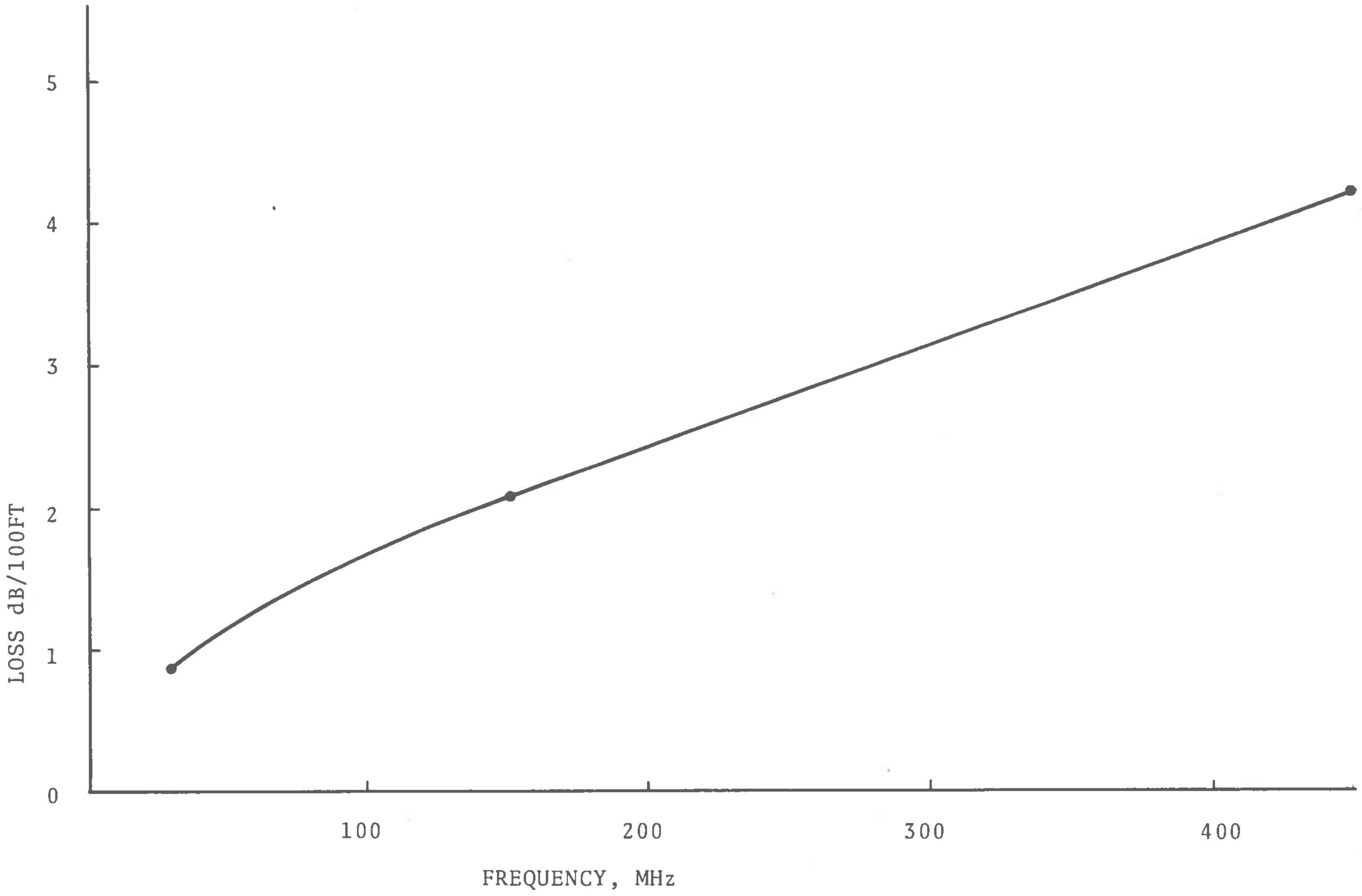


Figure 2-6. Manufacturer Specified Losses Versus Frequency, RX4-3

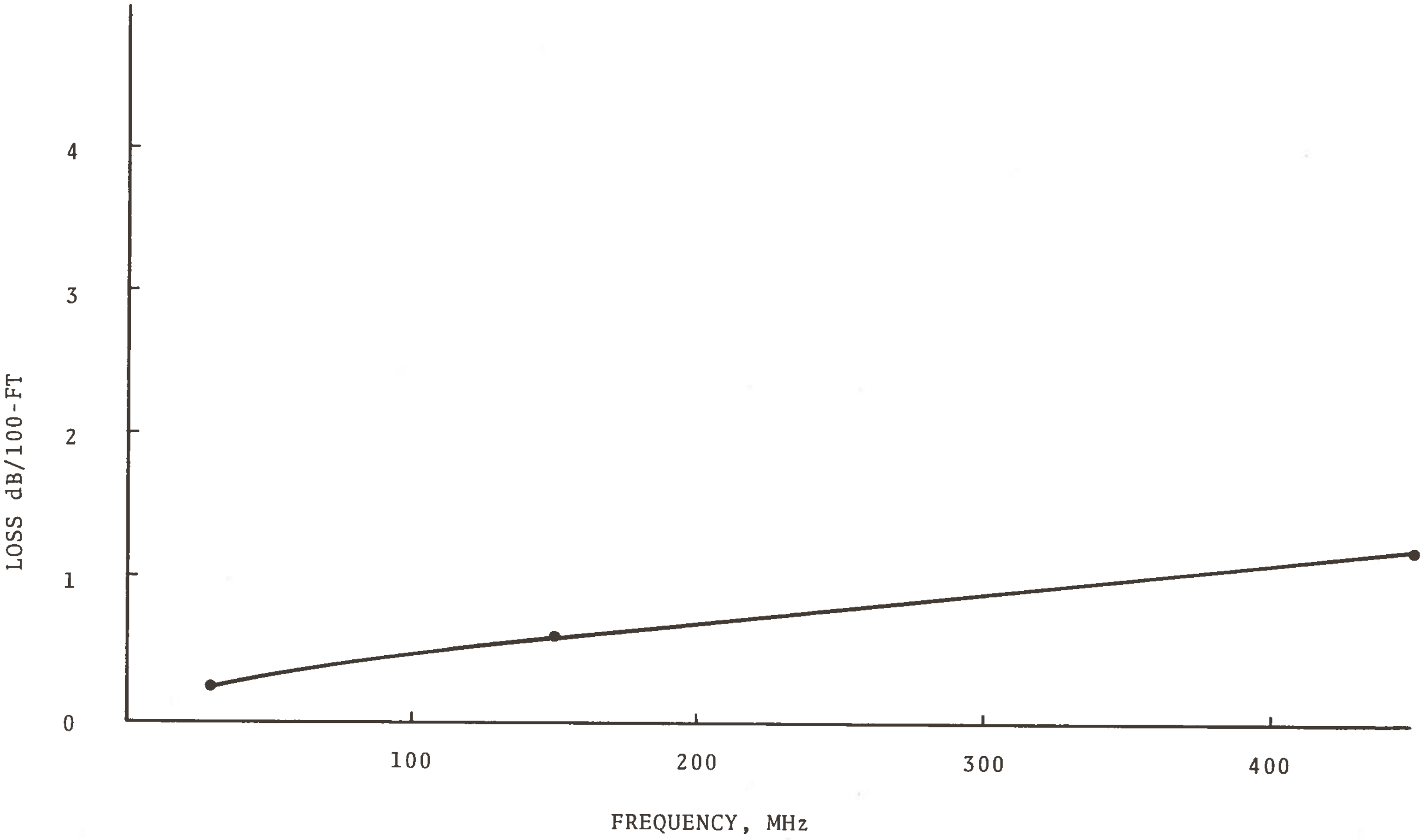


Figure 2-7. Manufacturer Specified Losses Versus Frequency, RX5-1

transmission of signals through the Radiax. Such measurements indicate the limitation imposed by the cable on the bandwidth of the signal. Figure 2-8 shows the block diagram for the pulse rise time and pulse dispersion measurements. Typical results of the measurements are shown in Figures 2-9 and 2-10 for RX4-1 and RX5-1 respectively. From these figures one can see that the rise times and the pulse widths do not show any appreciable changes. The measurements were repeated at four discrete frequencies, 100, 200, 300 and 400 MHz, and the rise times were scaled from the polaroid film. The results of the scaling are shown in Table 2-1. Note that there is no significant pulse spread, which implies very little dispersion. All measurements were made using switching and sampling techniques.

TABLE 2-1. RESULTS OF RISE TIME SCALING

RADIAX	FREQUENCY (MHz)	RISE TIME (n sec)	
		INPUT	OUTPUT
RX4-3	100	1.0	1.6
	200	0.9	1.3
	300	1.3	1.7
	400	1.1	1.6
RX5-1	100	1.0	1.0
	200	1.1	1.1
	300	1.2	1.3
	400	1.1	1.3

2.4 PHASE MEASUREMENTS

To complete the characterization of the cables, measurements were made to determine the linearity of the phase shifts as a function of frequency. A block diagram of the set-up is shown on Figure 2-11. The measurements were made for RX4-3 over a frequency range of 10 MHz with the center frequency near 200 MHz. The relative phase and frequency relationship is shown in Figure 2-12. In addition to the above phase measurement, we also made

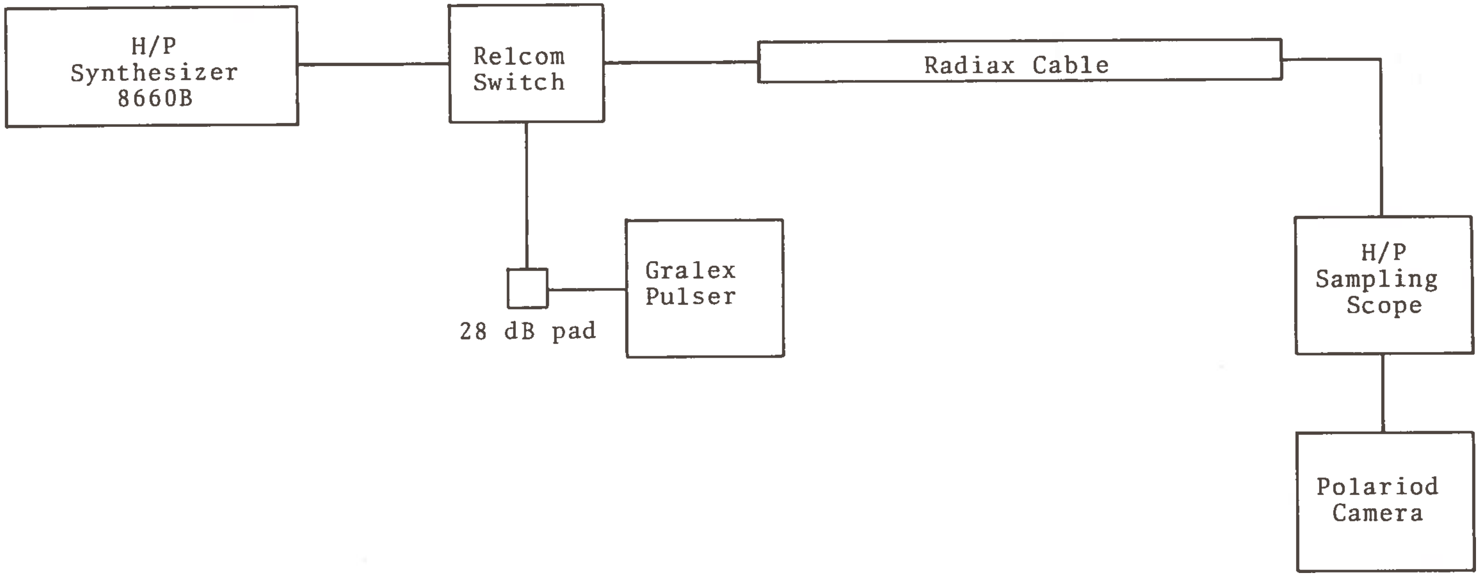
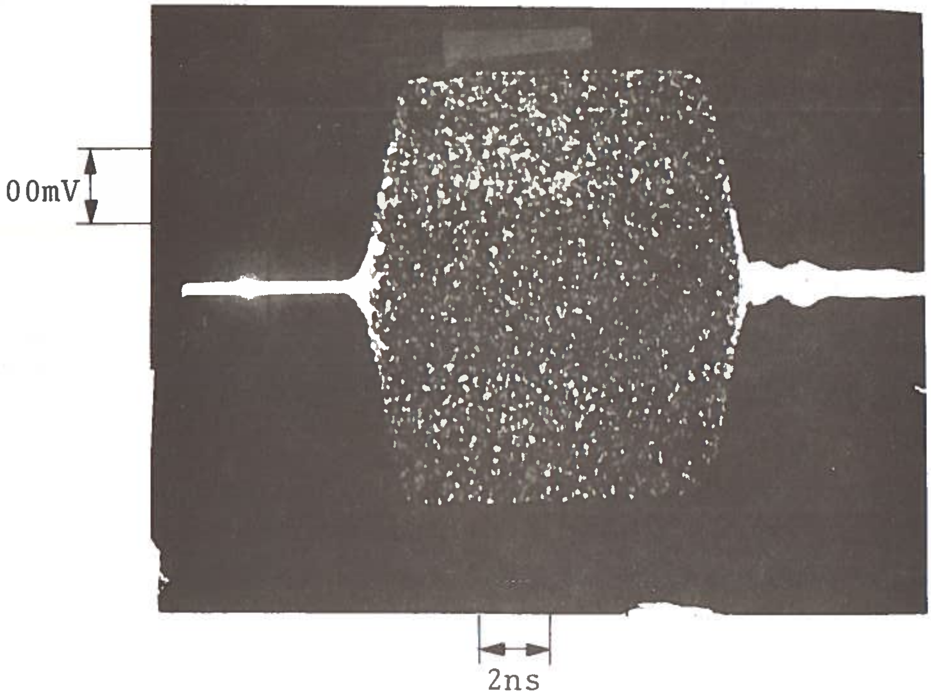


Figure 2-8. Block Diagram of Impulse Measurement Set-Up



Input to Radiax

1/2" Radiax
(RX4-3)

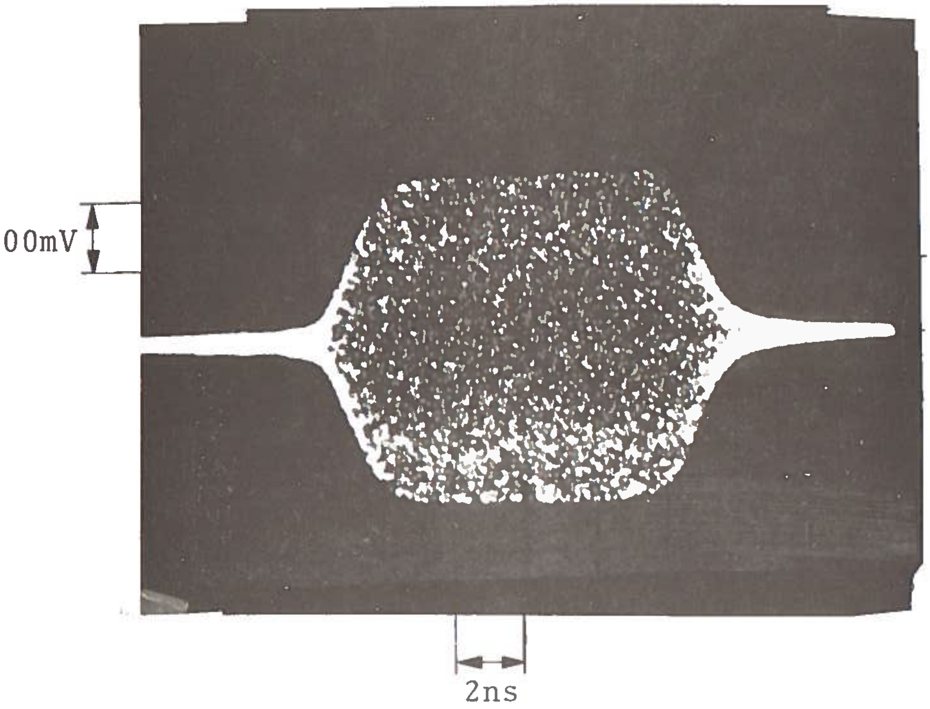
Frequency: 100MHz

Scale:

Vertical: 200mV/DIV

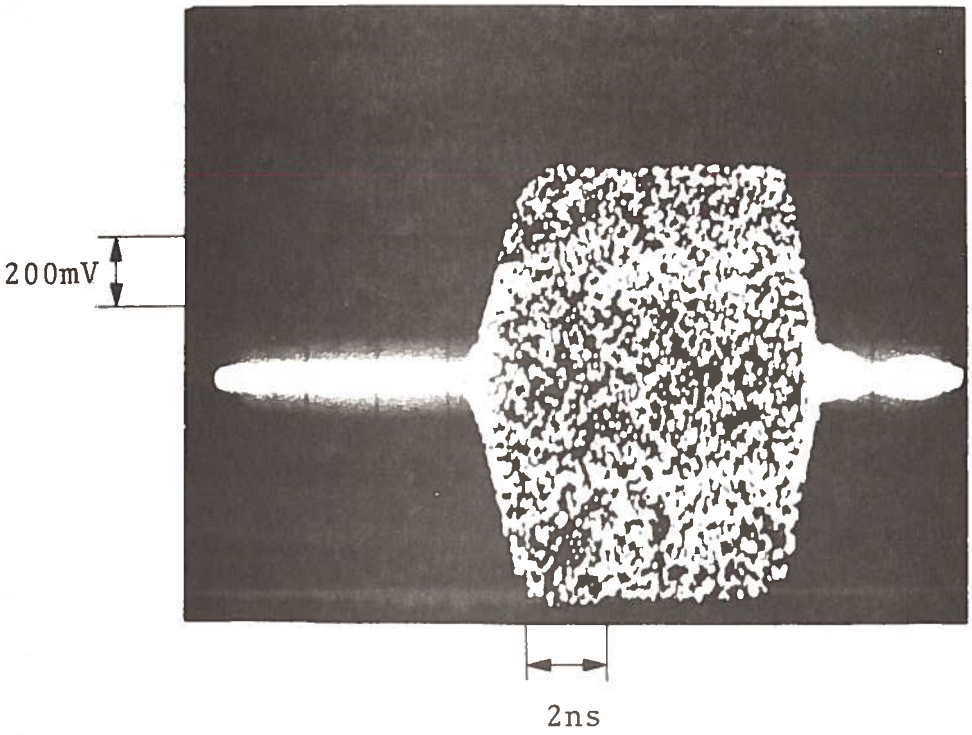
Horizontal: 2 nsec/DIV

Pulse Width: ≈ 8 nsec



Output from Radiax

Figure 2-9. Impulse Measurement of RX4-3 at 100 MHz



7/8" Radiax
(RX5-1)

Frequency: 400MHz

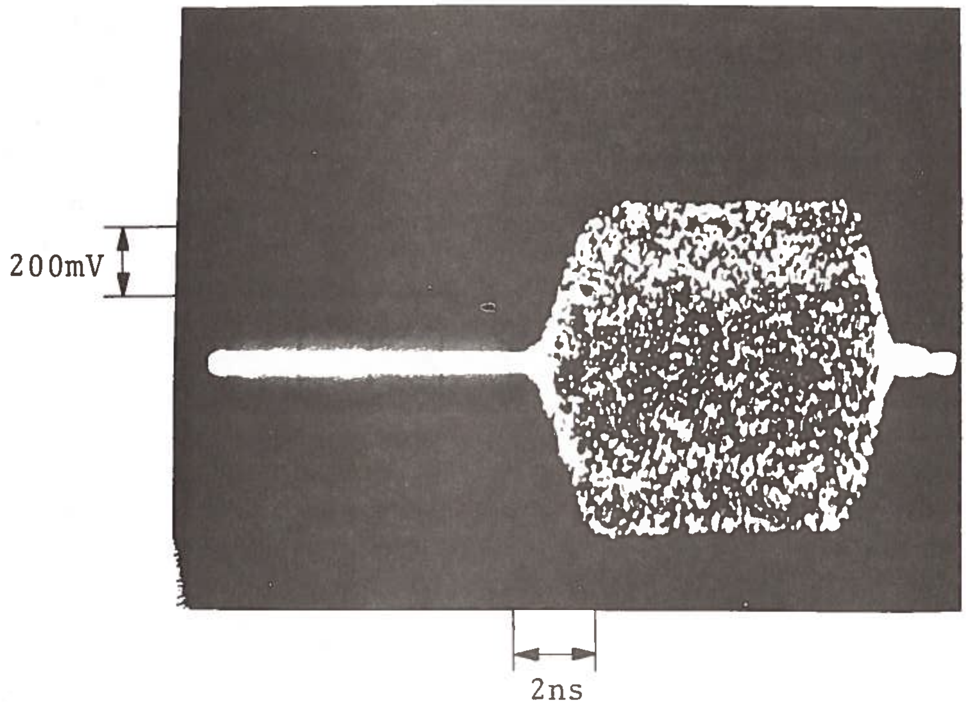
Scale:

Vertical: 200mV/DIV

Horizontal: 2 nsec/DIV

Pulse Width ≈ 8 nsec

Input to Radiax



Output from Radiax

Figure 2-10. Impulse Measurements of RX5-1 at 400 MHz

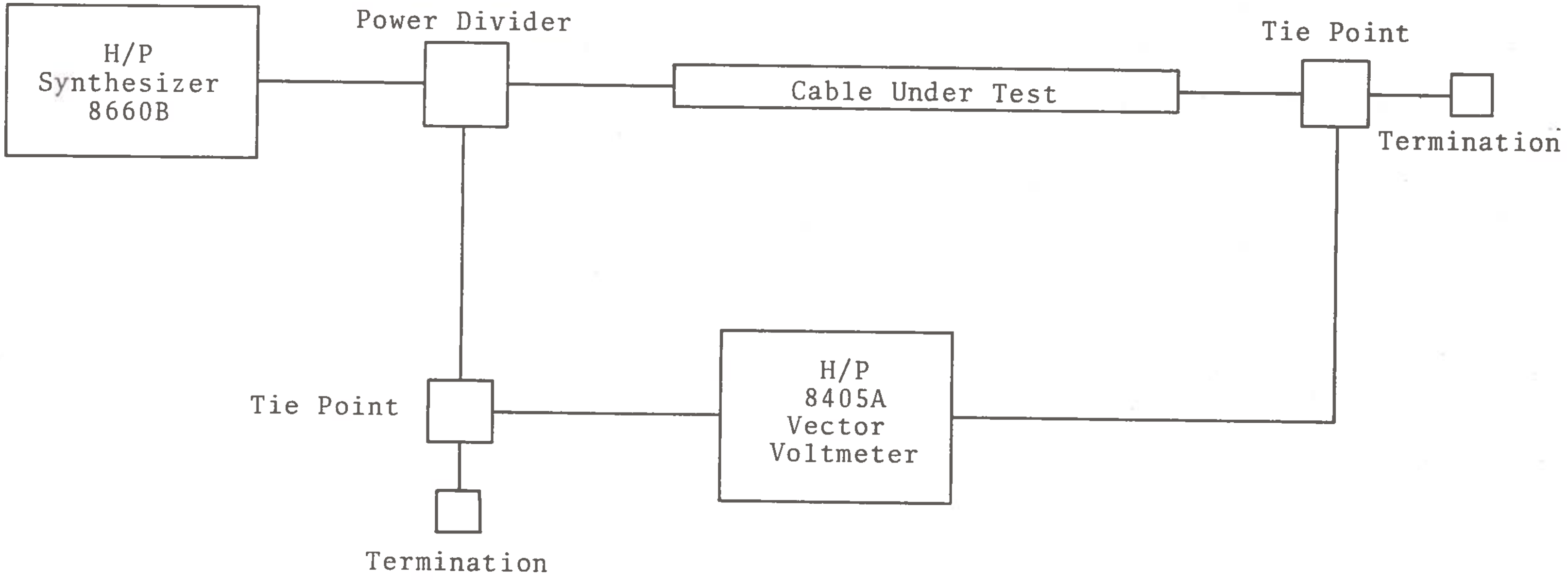


Figure 2-11. Block Diagram of Phase Measurement Set-Up

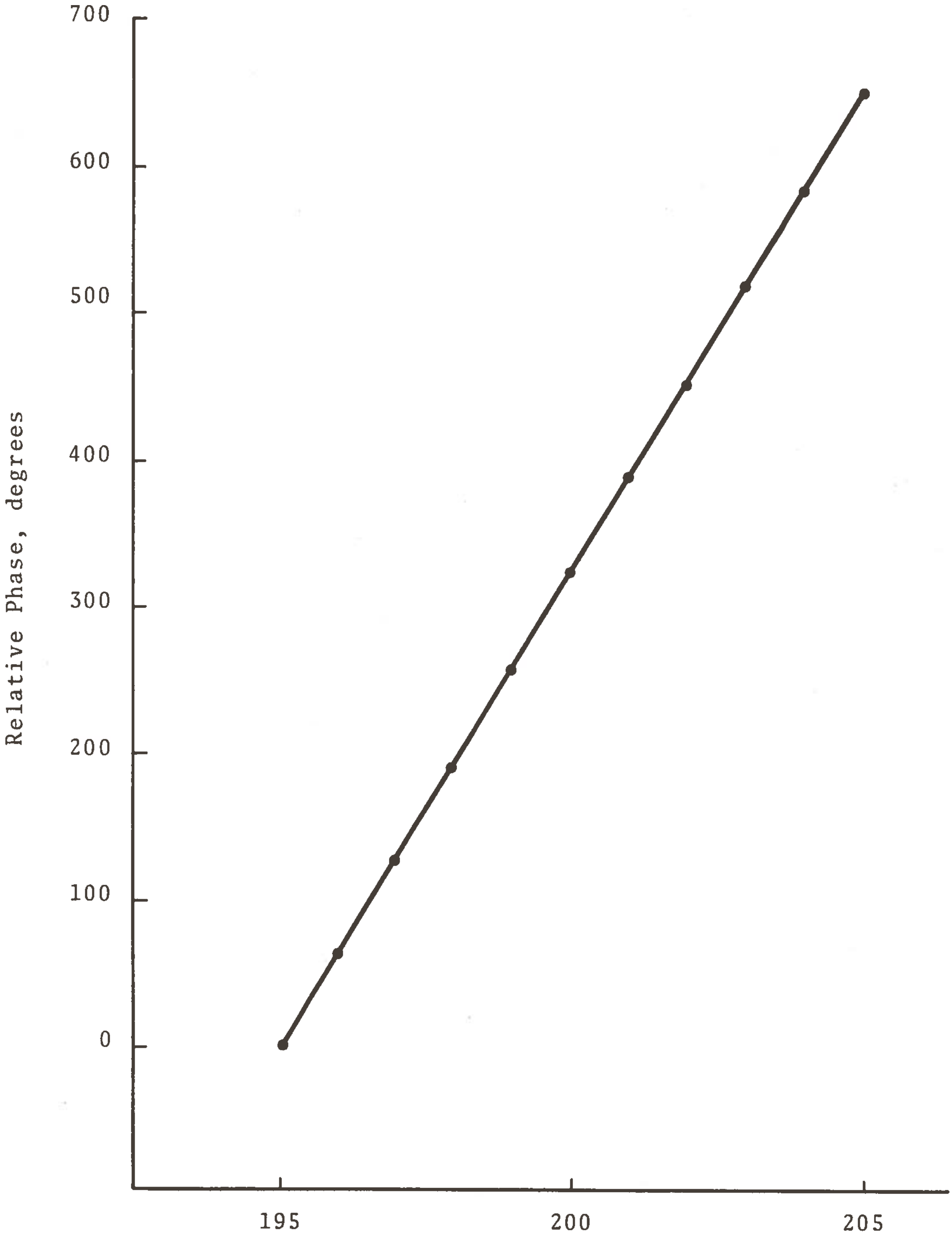


Figure 2-12. Relative Phase Versus Frequency

observations of the phase shift due to a sudden disturbance, which was produced by shaking the Radiax cables to simulate the wind or other environmental disturbances. A phase shift of 10° was observed for RX4-3 and 1° for RX5-1. The difference between the two cables may be due to the fact that the RX5-1 has a larger diameter and is therefore more rigid. The results of this test indicate that phase disturbances of this kind do not present any serious problem for the signal transmitted in the Radiax.

The results of all the measurements described above indicate that the Radiax cable characteristics are much like those of ordinary coaxial cables. The transmission of nanosecond pulses over distances fo the order of hundreds of feet is essentially distortion free.

3. COUPLING CHARACTERISTICS

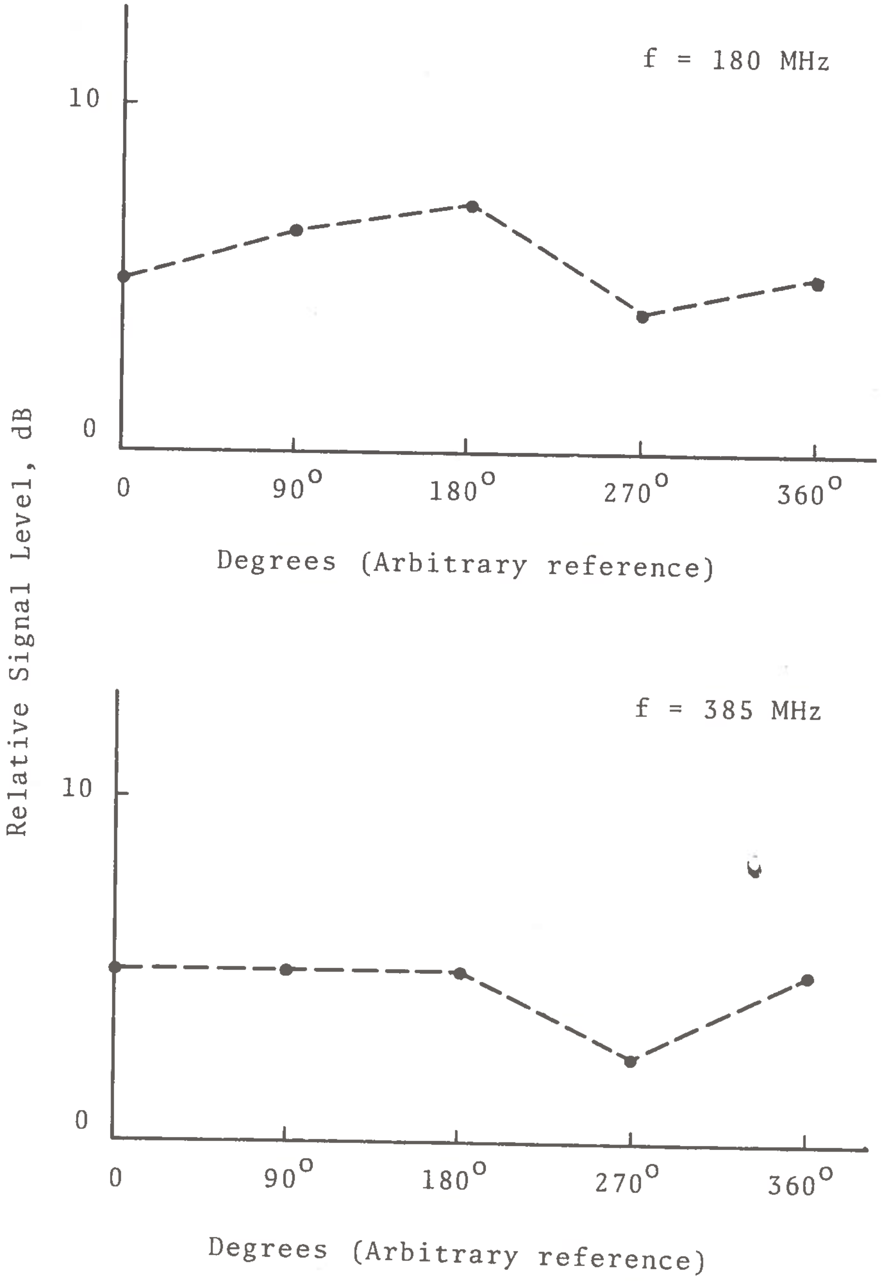
The coupling characteristics of the Radiax were measured in two stages. The first measurements were conducted during the winter months of 1972 - 1973. The primary measurements were of coupling losses between the Radiax cables and a half-wave dipole antenna over a frequency range from about 100 MHz to more than 400 MHz in both the transverse and longitudinal direction. The transverse radiation pattern of the Radiax was also measured. The second series of measurements was conducted from a mobile van which housed electronic measuring equipment. It consisted of the measurements described in Section 2 above plus additional coupling loss measurements using a moving platform for the antenna. All measurements were one-way, from the cable to an external receiving antenna, reciprocal coupling losses were observed to be the same within a few dB.

3.1 RADIATION PATTERNS

Radiation patterns were measured, and turned out to be omnidirectional as expected. Since the slots of the Radiax and the spacing between them are much smaller than the wavelength, the Radiax may be considered as a line radiator with the cross section of the line much smaller than the wavelength. The results of the measurement are shown in Figure 3-1 for cable RX4-3 at two frequencies, 180 and 385 MHz. The antenna used for these measurements was a half-wave dipole oriented parallel to the axis of the cable. The measurements were made by rotating the cable while the antenna remained at a fixed position about 10 feet from the cable. One can see that the overall variation is not more than three dB at a distance of about two wavelengths at 180 MHz and about four wavelengths at 385 MHz.

3.2 COUPLER MEASUREMENTS

Two types of antennas were used for measuring the coupling losses in order to determine the efficiency of each as a coupler. They were a loop and a half-wave dipole, which are the simplest and most common couplers.



Radiation Pattern, RX4-3

Figure 3-1. Transverse Radiation Pattern of RX4-3 at 180 MHz (upper) and 385 MHz (lower)

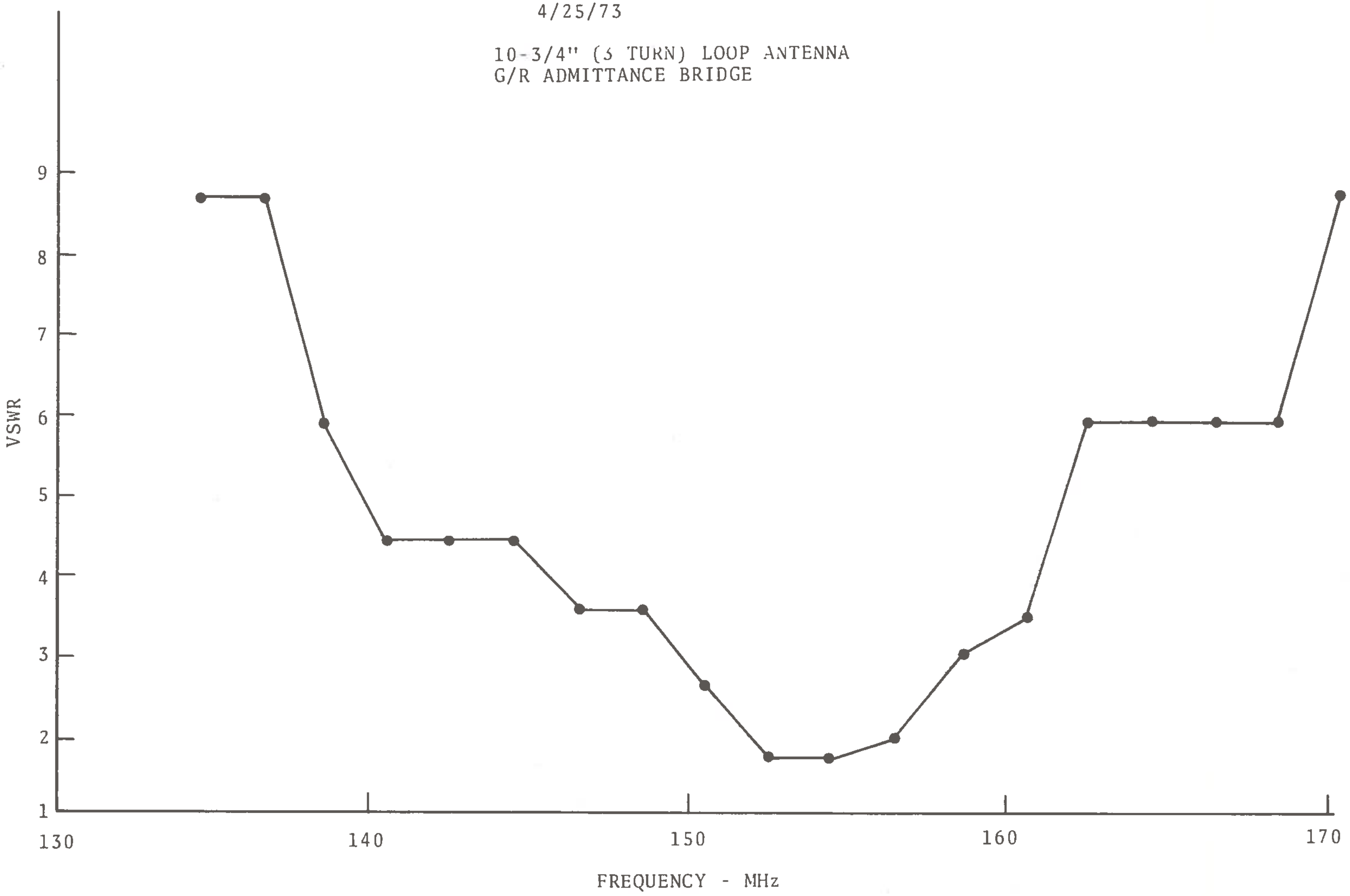
Figure 3-2 shows the VSWR of a 3-turn loop antenna, which was about 1.6 at 155 MHz. The variations of received power with distance from the cable for three different orientations of the loop antenna are shown in Figures 3-3 to 3-5. Typically the coupling characteristics can be described as follows; the fields fall off very rapidly within the first 2 feet from the Radiax which is within a distance, $\lambda/2\pi$, and then much more gradually except for discrete nulls. Figures 3-6 and 3-7 show the longitudinal variation of the coupling with the loop antenna three feet and six feet from the cable. In this case, the orientation of the plane of the antenna is parallel to the ground. Note the recurring nulls, as deep as 30 dB, with spacings very close to $\lambda_o/2$, where λ_o is the free space wavelength. Further discussion of this effect will be presented in Section 3.3.4.

Figure 3-8 shows the transverse coupling of a dipole antenna with its axis oriented parallel to the cable. The characteristics of the transverse coupling exhibit near field and far field phenomena similar to the loop. Figures 3-9 and 3-10 show the longitudinal variation of the coupling with the antenna at three feet and six feet, respectively from the line. Spatial oscillations of the field with the period about $\frac{\lambda_o}{2}$ were observed here as well. From the results shown in the above figures it appears that the coupling losses are a few dB less for the dipole antenna than for the loop.

3.3 COUPLING MEASUREMENTS

Additional coupling measurements for both types of Radiax were made over a frequency range from 100 MHz to over 400 MHz in both transverse and longitudinal directions. The Radiax cables were either hung about 4 feet above the ground from wooden posts 10 feet apart, or laid on the ground. The couplers were half-wave dipole antennas, one antenna for each frequency.

The system block diagram is shown in Figure 3-11. The antenna was mounted on a four-wheel platform and continuous measurements were recorded on a HP strip chart recorder while



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10-3/4" (3 TURN) LOOP ANTENNA
G/R ADMITTANCE BRIDGE

Figure 3-2. VSWR Measurement of a Loop Antenna

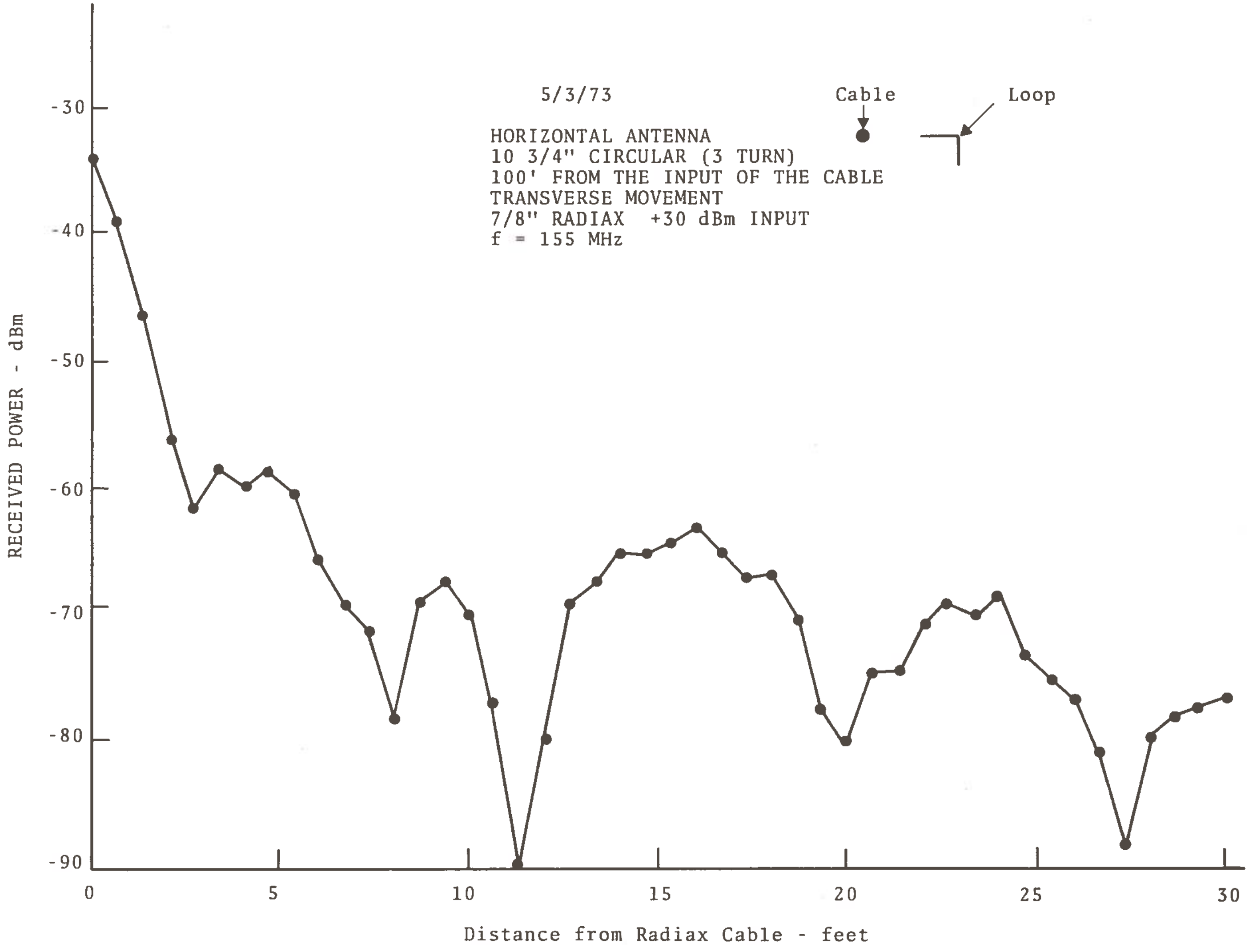


Figure 3-3. The Transverse Coupling of a Loop Antenna with the Axis of the Antenna Normal to the Ground at 155 MHz

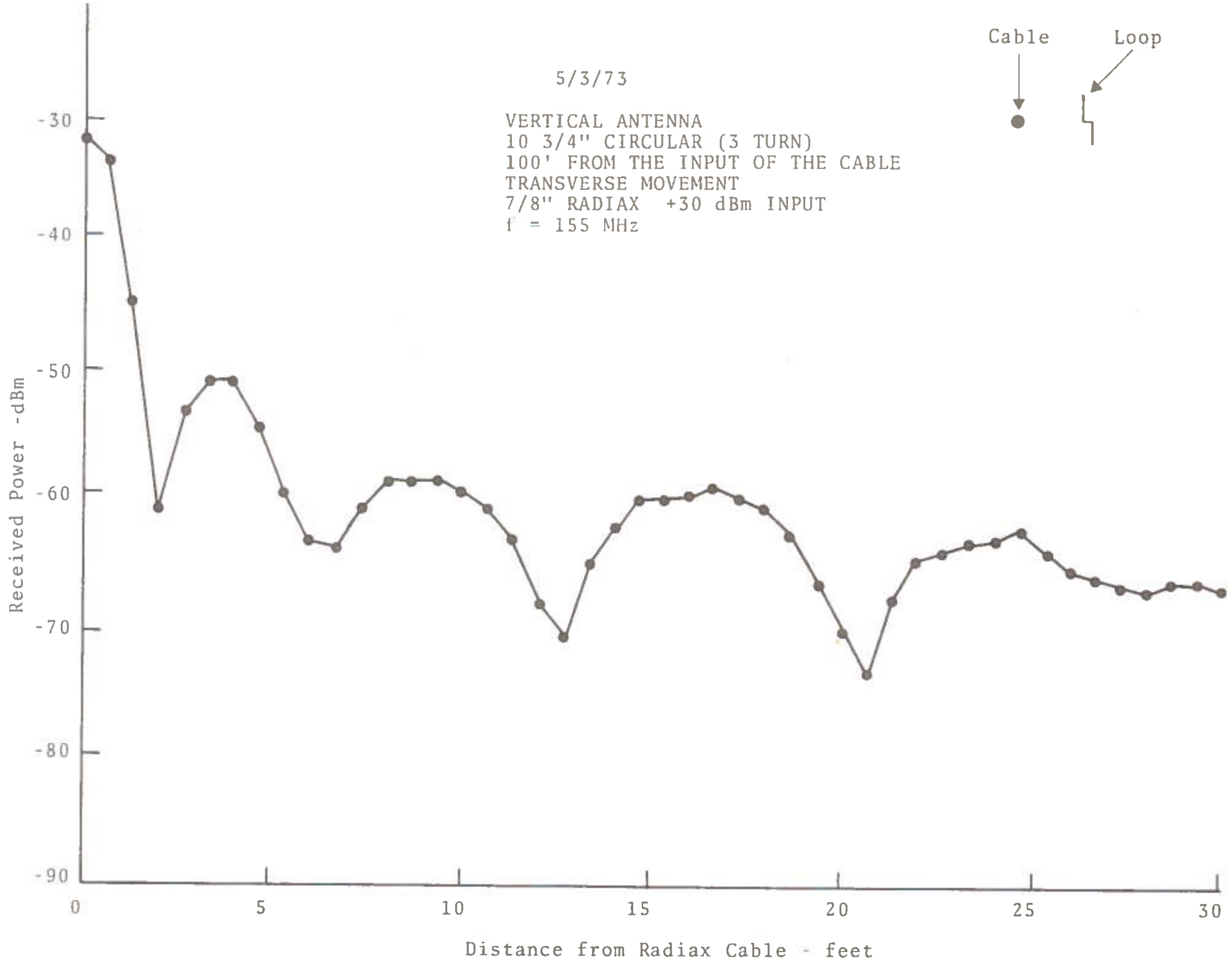


Figure 3-4. The Transverse Coupling of a Loop Antenna with the Axis of the Antenna Normal to the Radiax Cable at 155 MHz

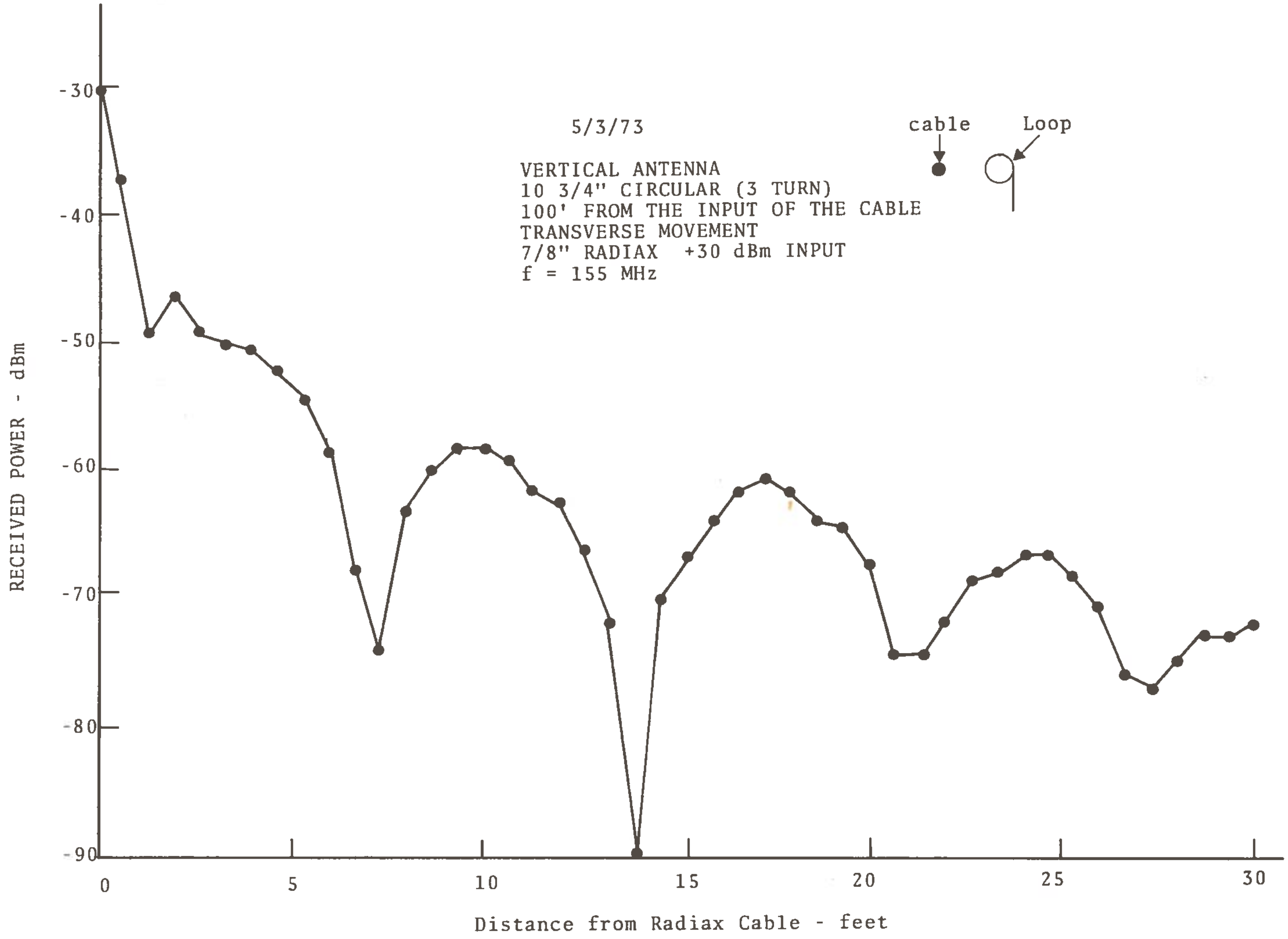


Figure 3-5. The Transverse Coupling of a Loop Antenna with the Axis of the Antenna Parallel to the Radiax Cable at 155 MHz

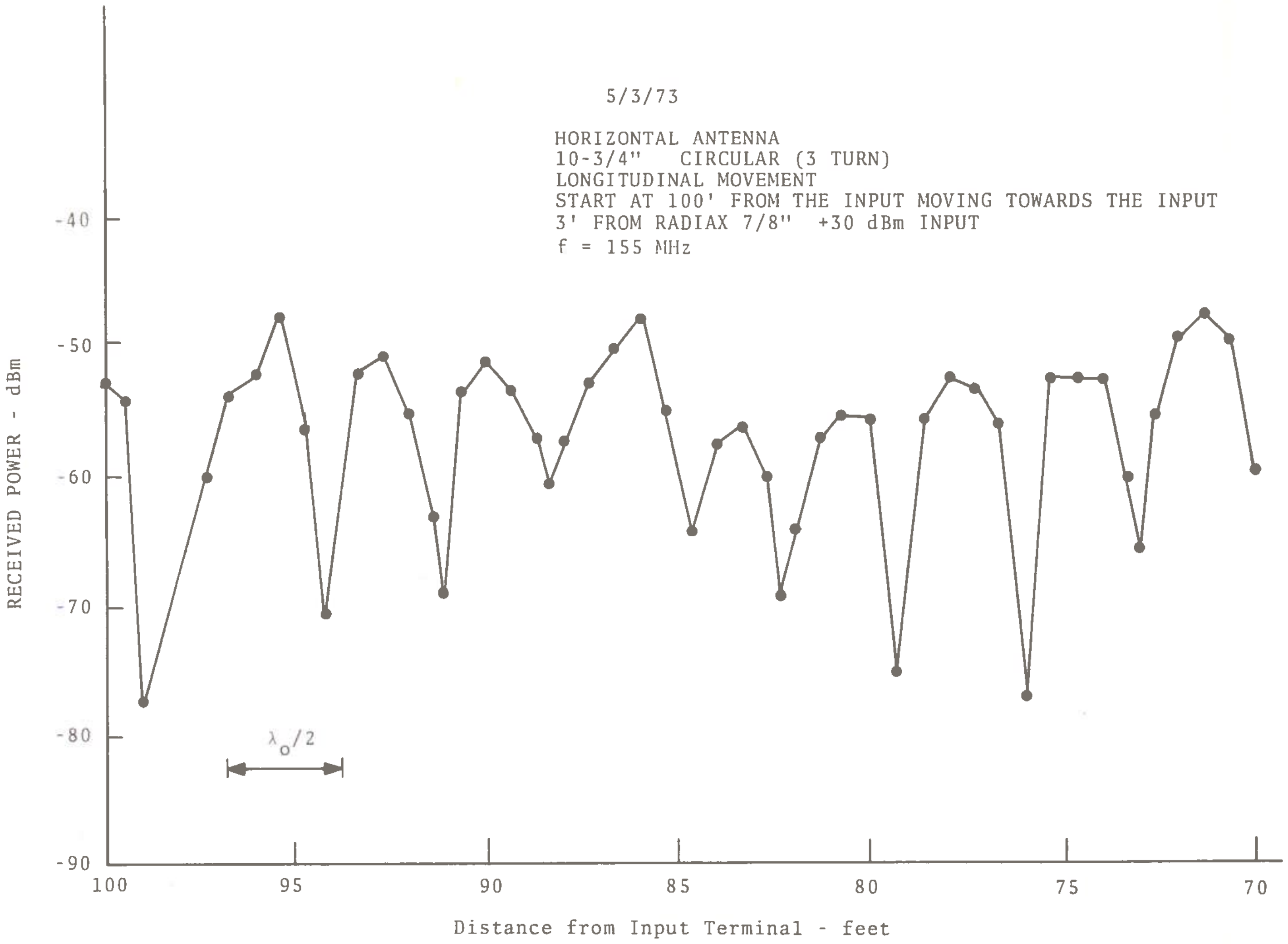


Figure 3-6. The Longitudinal Coupling of a Loop Antenna with the Axis Normal to the Ground, Three Feet from the Radiax Cable at 155 MHz

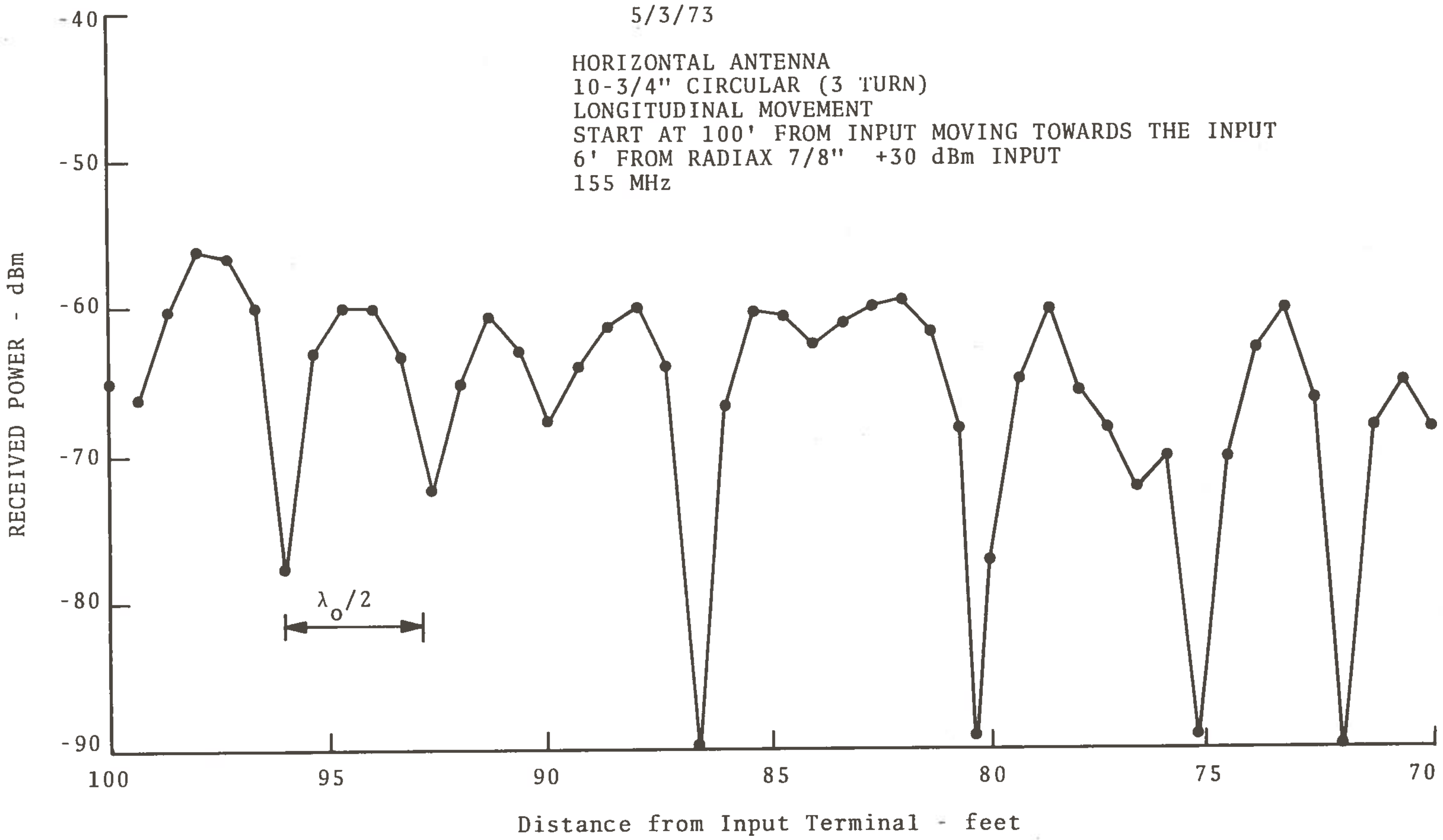
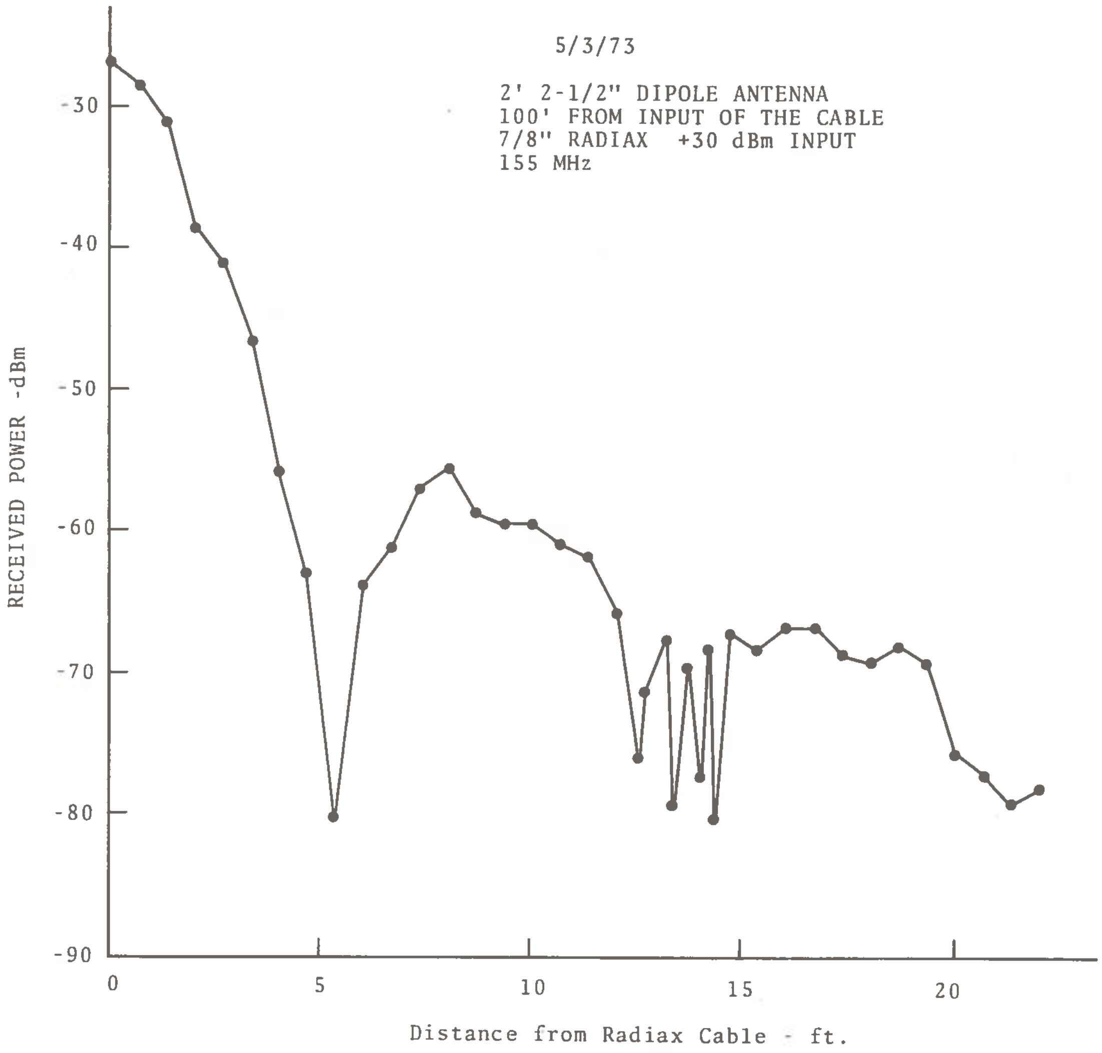


Figure 3-7. The Longitudinal Coupling of a Loop Antenna with the Axis Normal to the Ground, Six Feet from the Radiax Cable at 155 MHz



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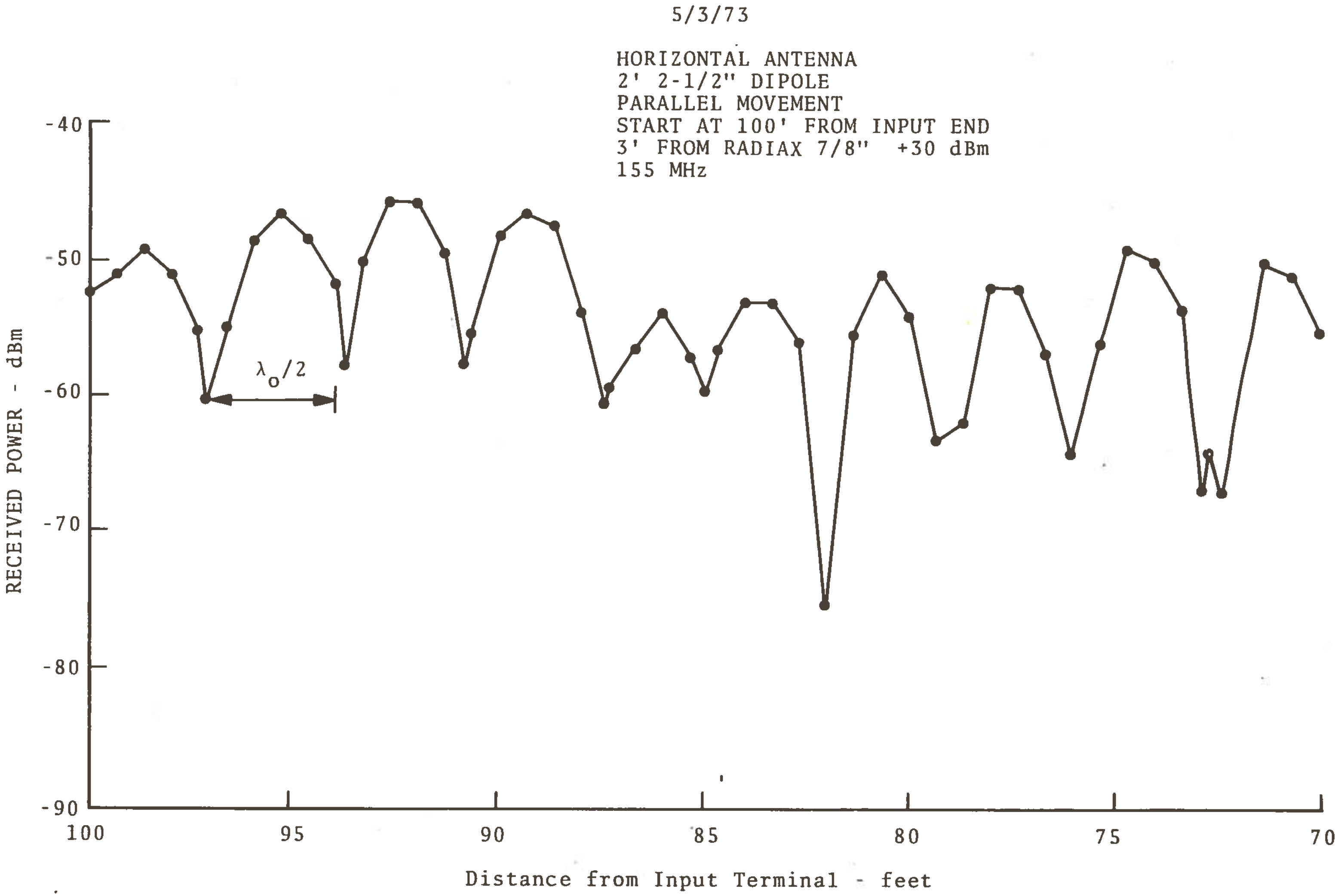
2' 2-1/2" DIPOLE ANTENNA
100' FROM INPUT OF THE CABLE
7/8" RADIAX +30 dBm INPUT
155 MHz

Figure 3-8. The Transverse Coupling of a Dipole Antenna with the Dipole Parallel to the Cable at 155 MHz



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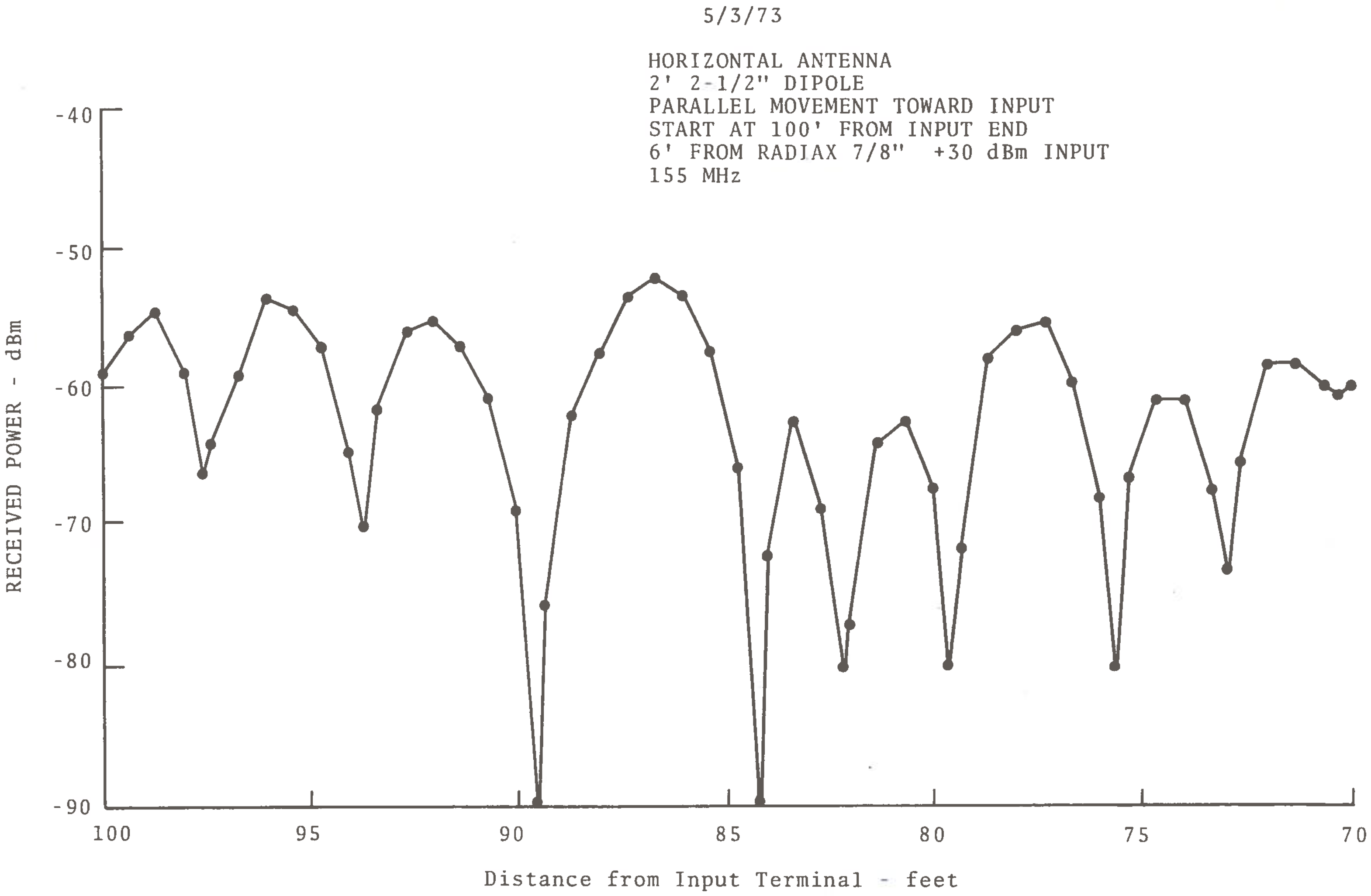
HORIZONTAL ANTENNA
2' 2-1/2" DIPOLE
PARALLEL MOVEMENT
START AT 100' FROM INPUT END
3' FROM RADIAX 7/8" +30 dBm
155 MHz

Figure 3-9. The Longitudinal Coupling of a Dipole Antenna with the Dipole Three Feet from the Cable at 155 MHz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HORIZONTAL ANTENNA
2' 2-1/2" DIPOLE
PARALLEL MOVEMENT TOWARD INPUT
START AT 100' FROM INPUT END
6' FROM RADIAX 7/8" +30 dBm INPUT
155 MHz

Figure 3-10. The Longitudinal Coupling of a Dipole Antenna with the Dipole Six Feet from the Cable at 155 MHz

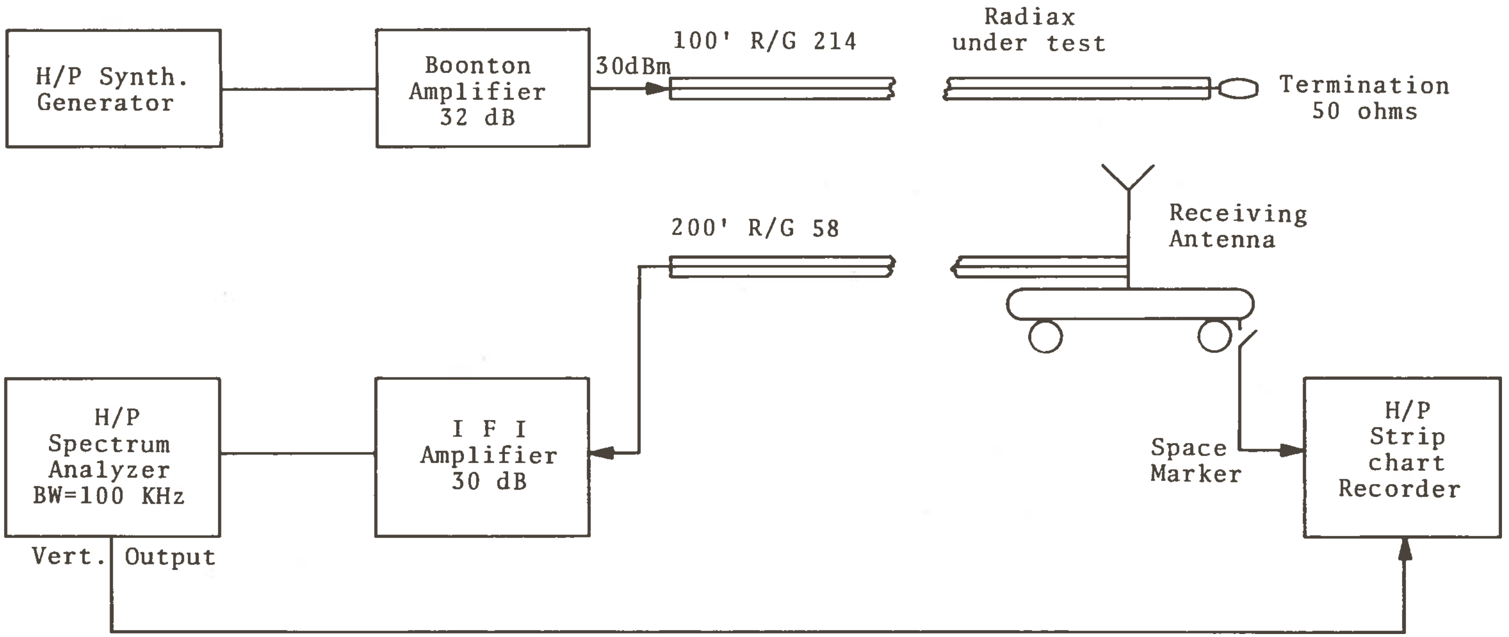


Figure 3-11. The Block Diagram of the Coupling Measurement Set-Up

the input at the 100-foot RG214 coaxial cable was held constant at 30dbm, and the received power was measured at the output of the RG58 coaxial cable. The data recorded on the chart were then reduced and plotted. Corrections for the RG214 and RG58 cable losses were made using the measured curve of Figure 3-12.

3.3.1 Transverse Coupling

Measurements of transverse coupling were conducted at discrete frequencies and various positions of the cables. The measurements were made at three frequencies -154.7, 190.7 and 385.0 MHz and two positions of the cables - 4 feet above the ground and on the ground - at distances up to about 50 feet from the cable. The transverse plane was located about 55 feet from the input terminal of the cable.

Figures 3-13 to 3-15 show the transverse coupling with RX4-3 cable hanging on the wooden posts four feet above the ground. The general characteristics of the coupling losses can be described as follows. The received power decreases very rapidly within a distance of one wave length and then more gradually with some oscillations and discrete nulls. The steep decrease in power is due to the near field effect. The gradual decrease may be approximated by a power law, a far field phenomena which will be discussed in Section 3.3.1.1. The results of transverse coupling measurements with RX4-3 cable on the ground are shown in Figures 3-16 to 3-18 at the same three discrete frequencies. The absence of the steep decrease in power is primarily due to the location of the antenna in a plane four feet above the ground. However, the far field results are similar to those for the cable on the post. The large nulls observed for both cable positions are probably due to the specular reflections.

Similar measurements were made for RX5-1 cable. Figures 3-19 to 3-21 show the transverse coupling with the cable four feet above the ground. Figure 3-22 shows the results of the coupling measurement at 385 MHz with the RX5-1 cable on the ground. The transverse coupling characteristics for RX5-1 are

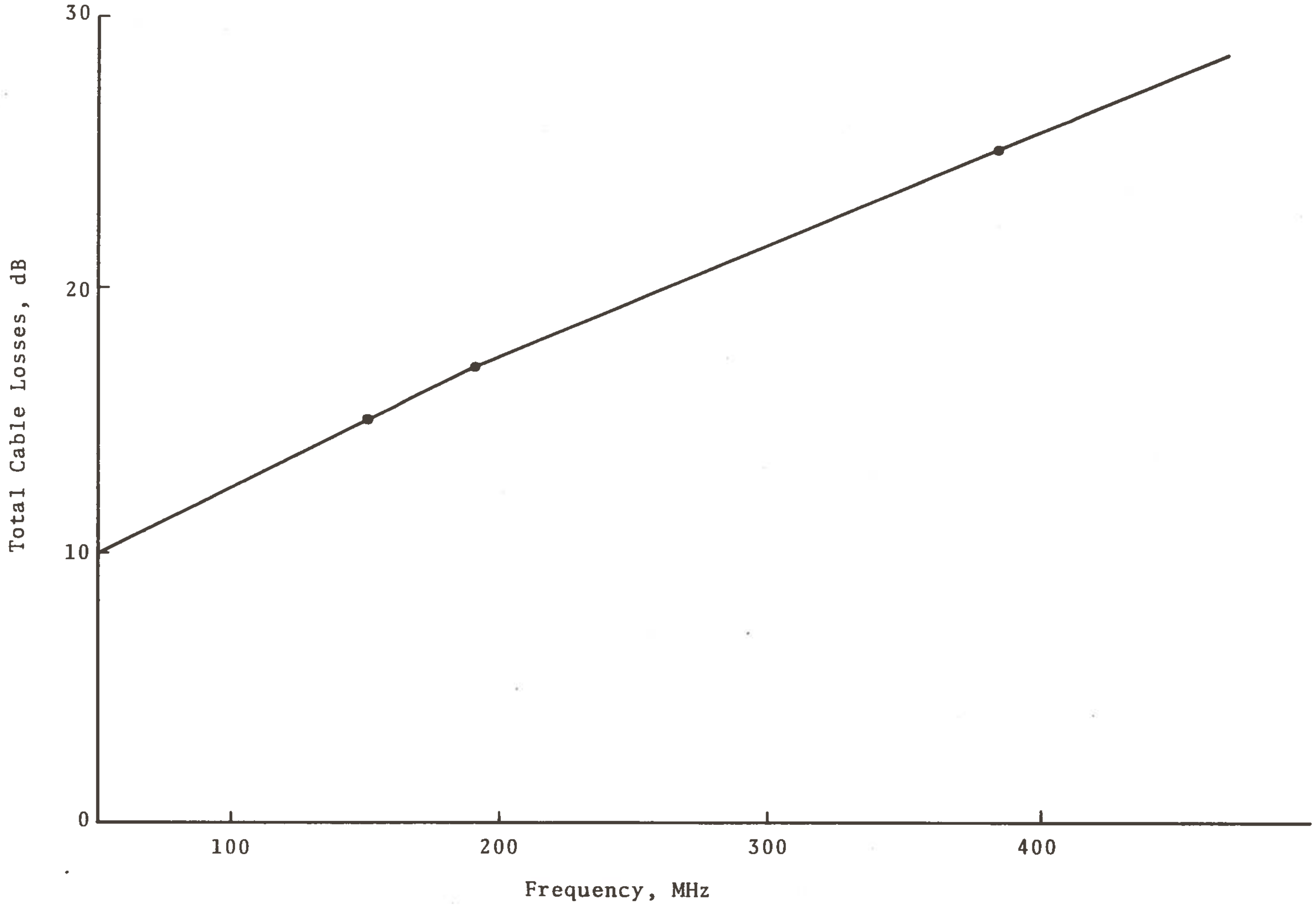


Figure 3-12. The Total Losses of Connecting Cables: 100 Feet of RG214 Plus 200 Feet of RG58

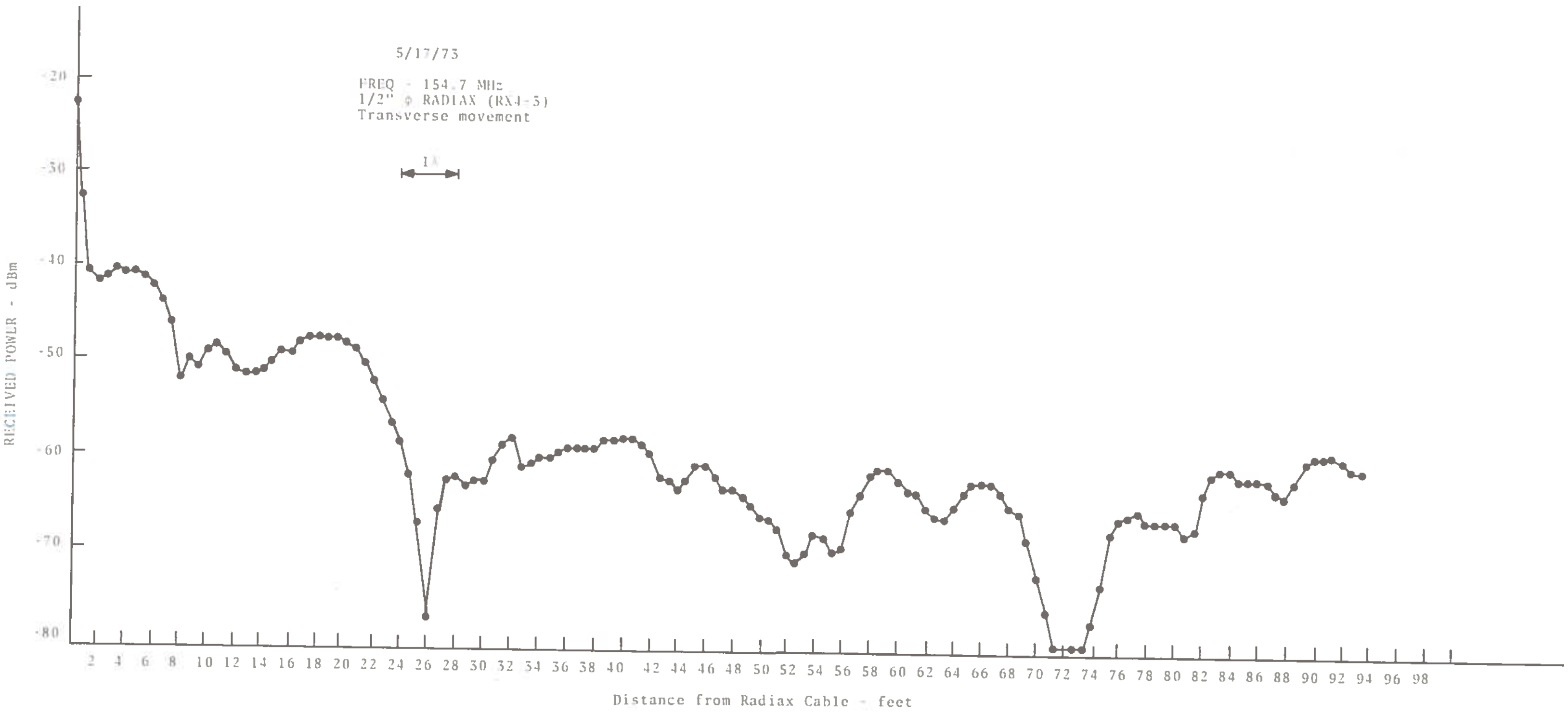


Figure 3-13. Transverse Coupling of a Dipole Antenna with RX4-3 at 154.7 MHz

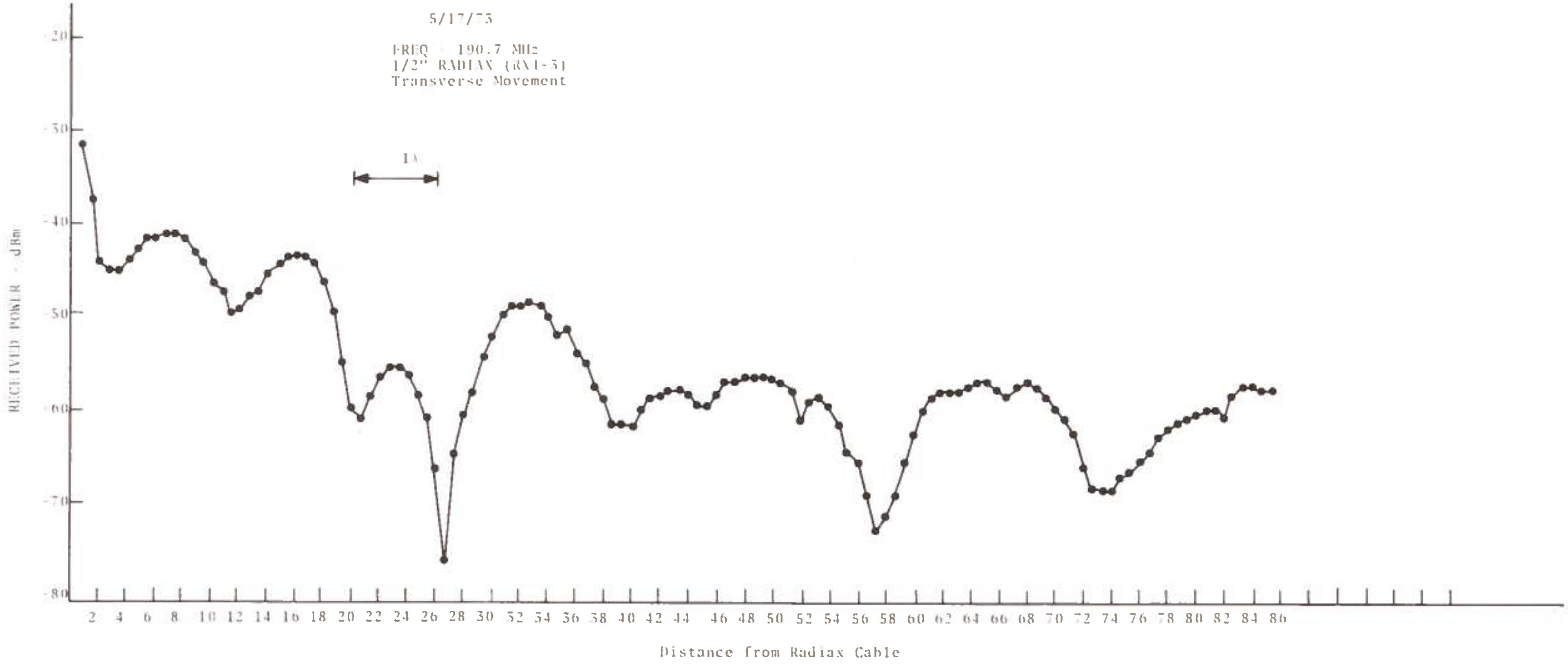


Figure 3-14. Transverse Coupling of a Dipole Antenna with RX4-3 at 190.7 MHz

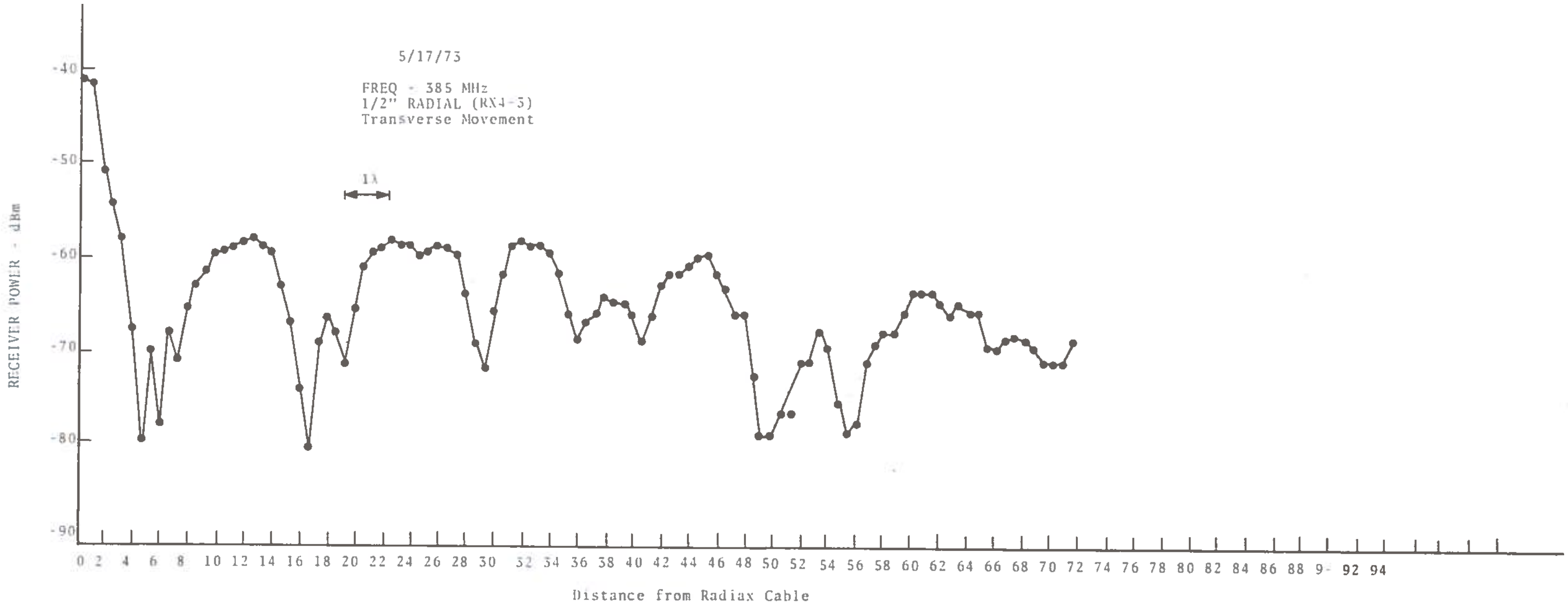


Figure 3-15. Transverse Coupling of a Dipole Antenna with RX4-3 at 385 MHz

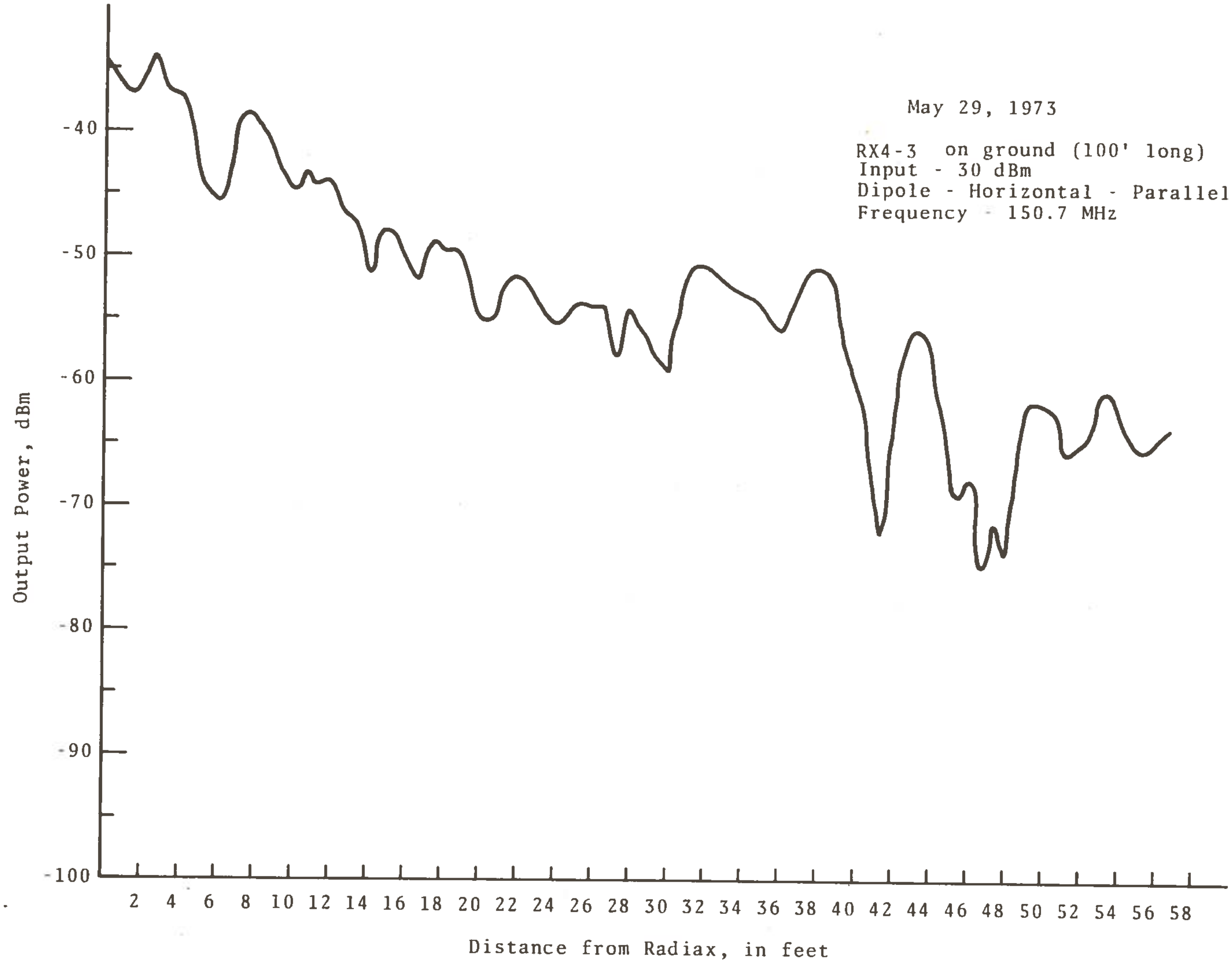
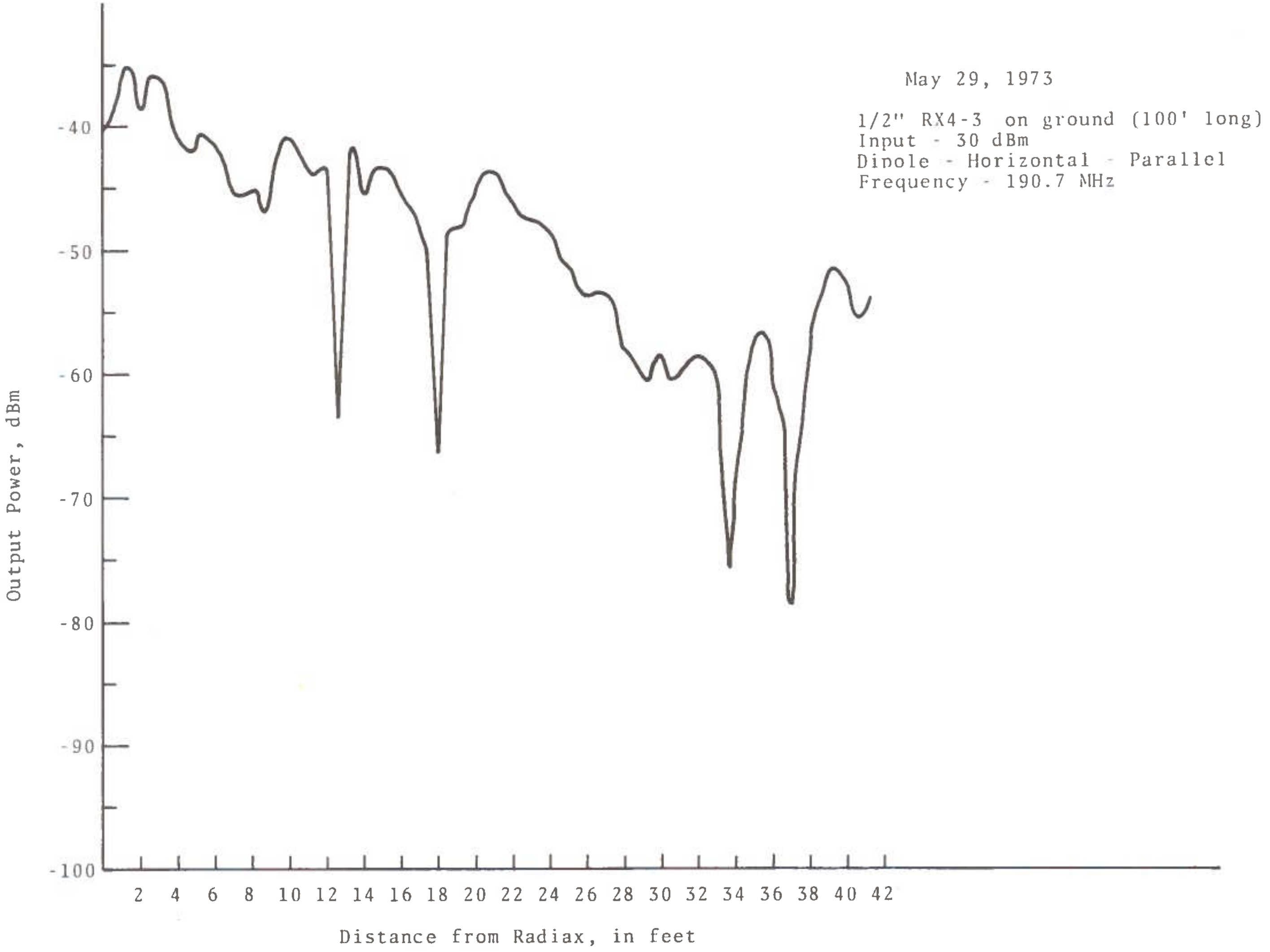


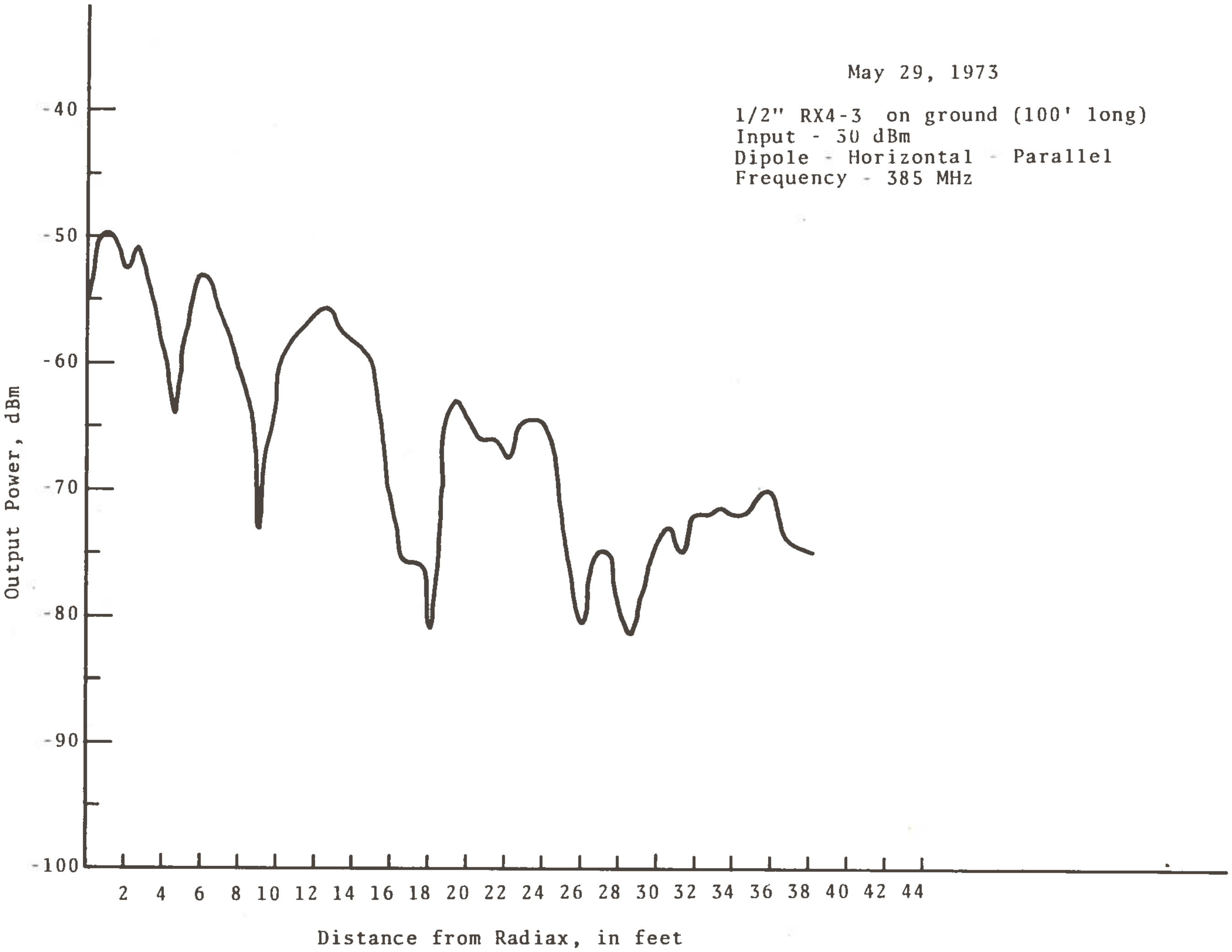
Figure 3-16. Transverse Coupling of a Dipole Antenna with RX4-3 on the Ground at 150.7 MHz



May 29, 1973

1/2" RX4-3 on ground (100' long)
Input - 30 dBm
Dipole - Horizontal - Parallel
Frequency - 190.7 MHz

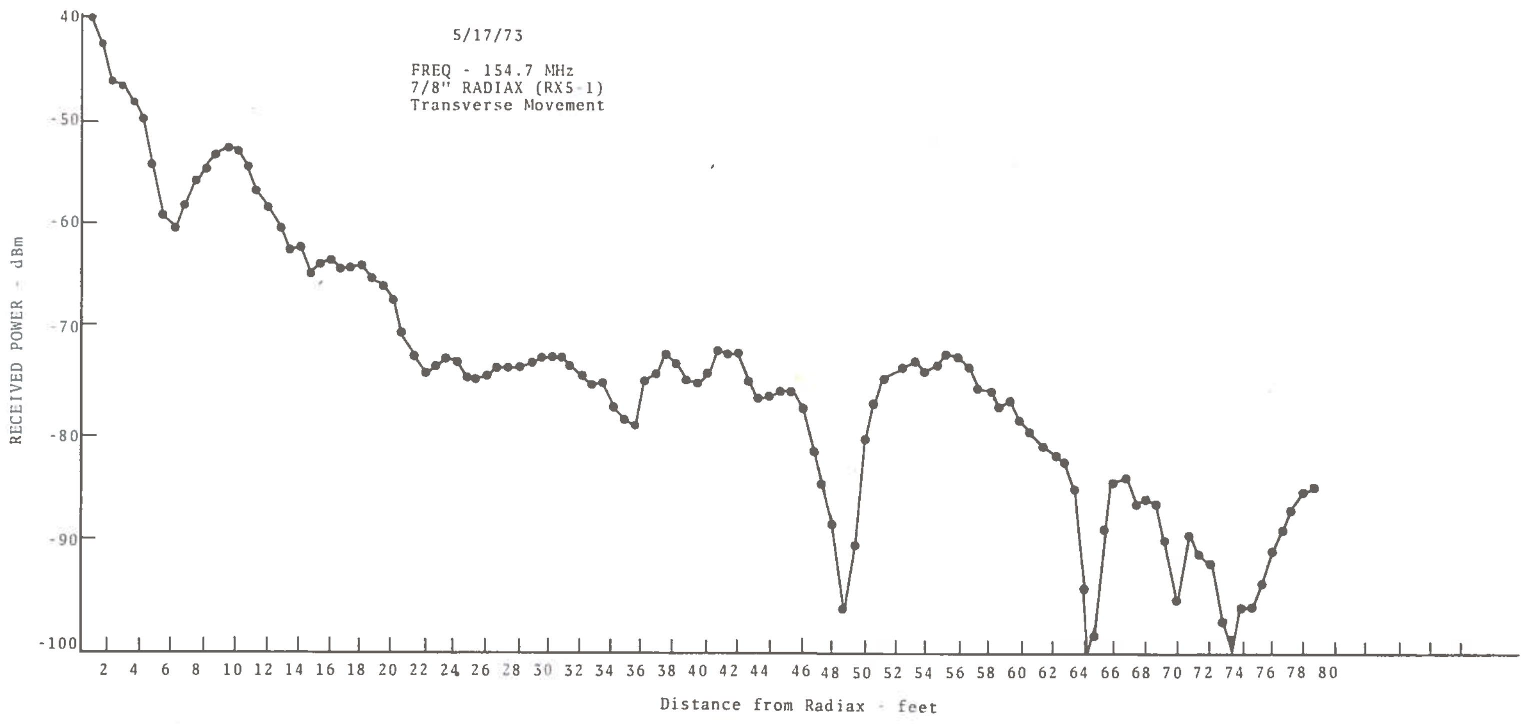
Figure 3-17. Transverse Coupling of a Dipole Antenna with RX4-3 on the Ground at 190.7 MHz



May 29, 1973

1/2" RX4-3 on ground (100' long)
Input - 30 dBm
Dipole - Horizontal - Parallel
Frequency - 385 MHz

Figure 3-18. Transverse Coupling of a Dipole Antenna with RX4-3 on the Ground at 385 MHz



5/17/73

FREQ - 154.7 MHz
7/8" RADIAX (RX5-1)
Transverse Movement

Figure 3-19. Transverse Coupling of a Dipole Antenna with RX5-1 at 154.7 MHz

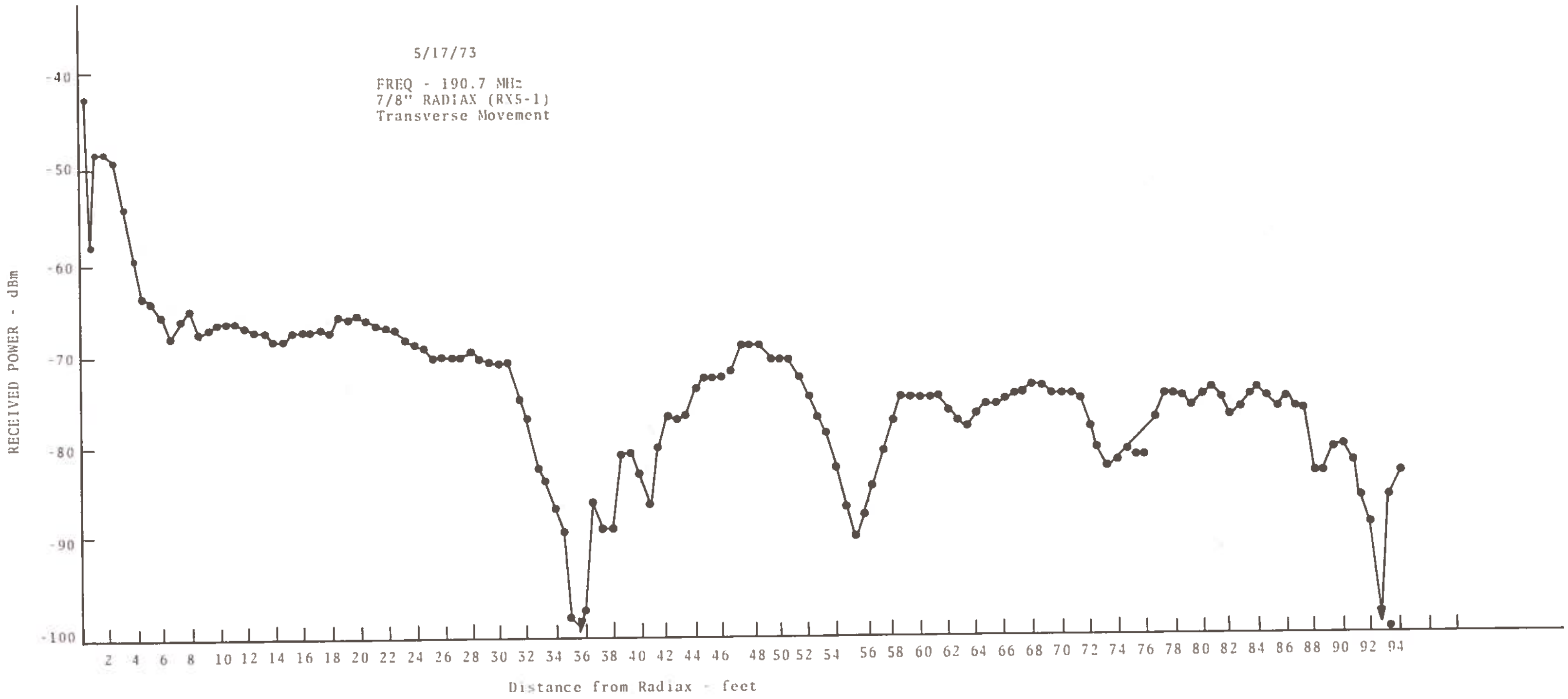
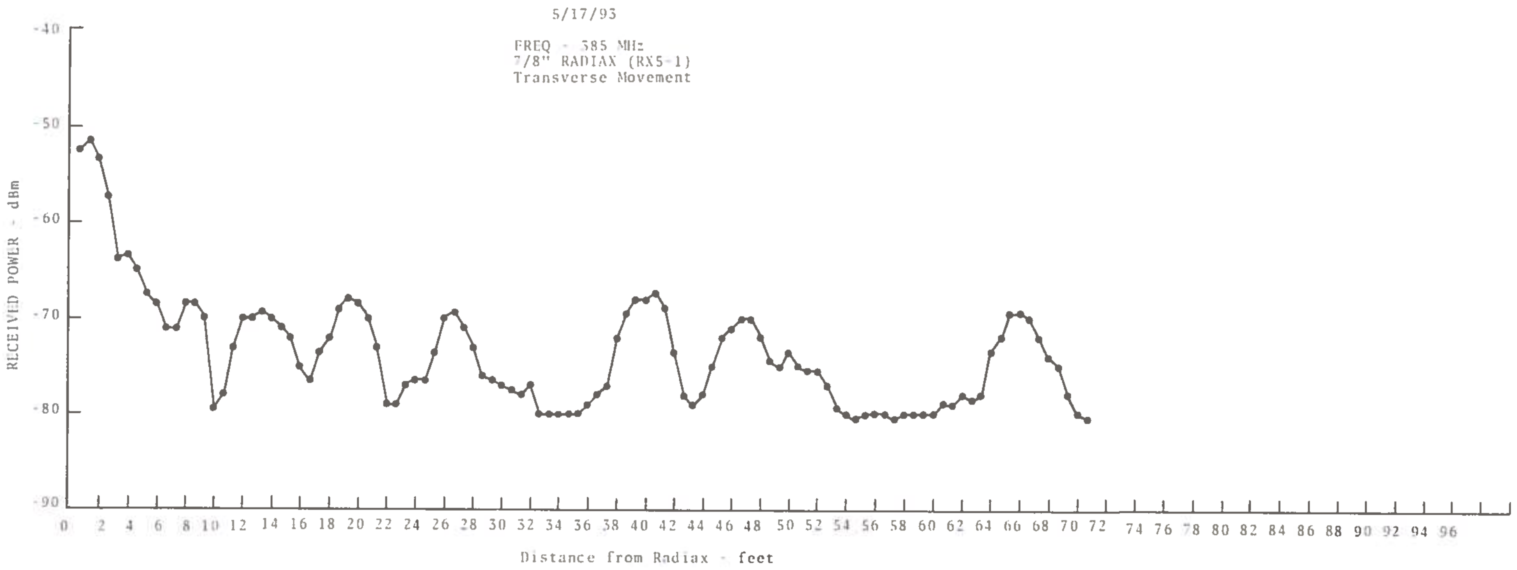


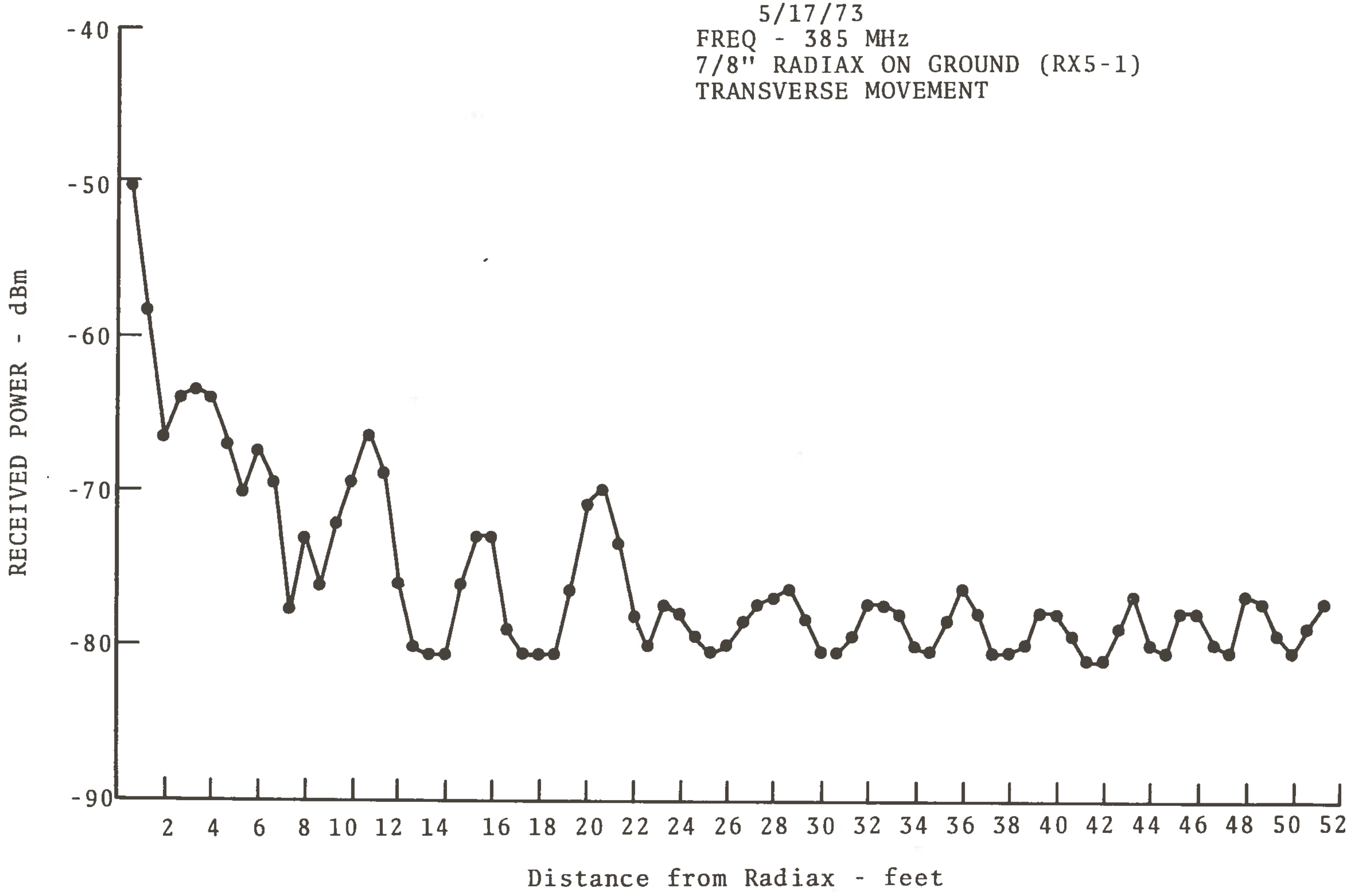
Figure 3-20. Transverse Coupling of a Dipole Antenna with RX5-1 at 190.7 MHz



5/17/93

FREQ - 385 MHz
7/8" RADIAX (RX5-1)
Transverse Movement

Figure 3-21. Transverse Coupling of a Dipole Antenna with RX5-1 at 385 MHz



5/17/73
FREQ - 385 MHz
7/8" RADIAX ON GROUND (RX5-1)
TRANSVERSE MOVEMENT

Figure 3-22. Transverse Coupling of a Dipole Antenna with RX5-1 on Ground at 385 MHz very similar to those for RX4-3 cable. The cable position does not lead to any appreciable difference in the transverse coupling characteristics.

3.3.1.1 Power Law - Transverse coupling measurements were made at various locations along the Radiax cables in order to characterize the transverse coupling as a function of frequency and distance. The measurements were made at 105.5, 142.5, and 411 MHz in the region between one and thirty feet from the cables. Figures 3-23 to 3-26 show the transverse coupling curve at 105.5 and 142.5 MHz for RX4-3 and RX5-1 cable respectively. These curves are clearly good fits to a $1/r^2$ power law. At 411 MHz, however, the fit is better with a $1/r$ relationship as shown in Figures 3-27 and 3-28. We may conclude that the variation in transverse coupling up to thirty feet from a leaky coax is a strong function of frequency and will thus affect the choice of operating frequency for a cable-based rail communication system.

3.3.2 Longitudinal Coupling

A series of measurements were carried out of the longitudinal variation of coupling loss at a constant transverse distance from the cable. The measurements were made at 154.7, 180.7, and 385 MHz with the cable either laid on the ground or suspended from stakes about four feet high.

The procedure involved moving a dipole antenna, mounted on a wheeled carrier, in a direction parallel to the cable while measuring the power output as a function of distance by means of a spectrum analyzer and strip chart recorder connected to the antenna. Data taken over a distance of about 100 feet are plotted in Figures 3-29 to 3-38 for the various configurations and frequencies. The mean, maximum and minimum coupling losses obtained from these results for each type of cable are shown in Table 3-1. Radiax RX4-3 shows about 10 dB less coupling loss than the Radiax RX5-1. In general the mean coupling loss is more severe at high frequency for both cables. Peak-to-null differences as large as 40 dB have been observed and the average peak-to-null difference

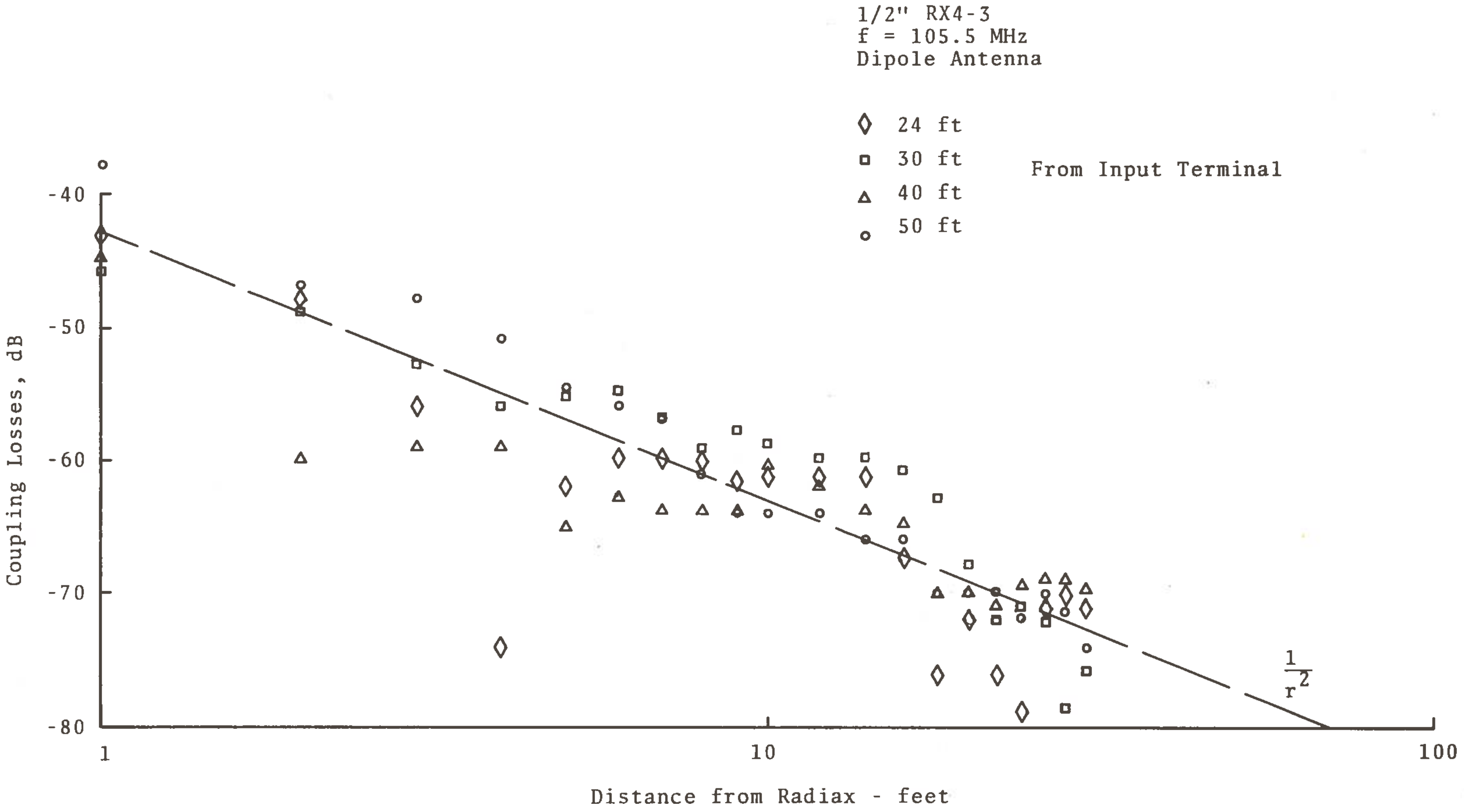


Figure 3-23. The $1/r^2$ Relationship of Transverse Coupling with RX4-3 at 105.5 MHz

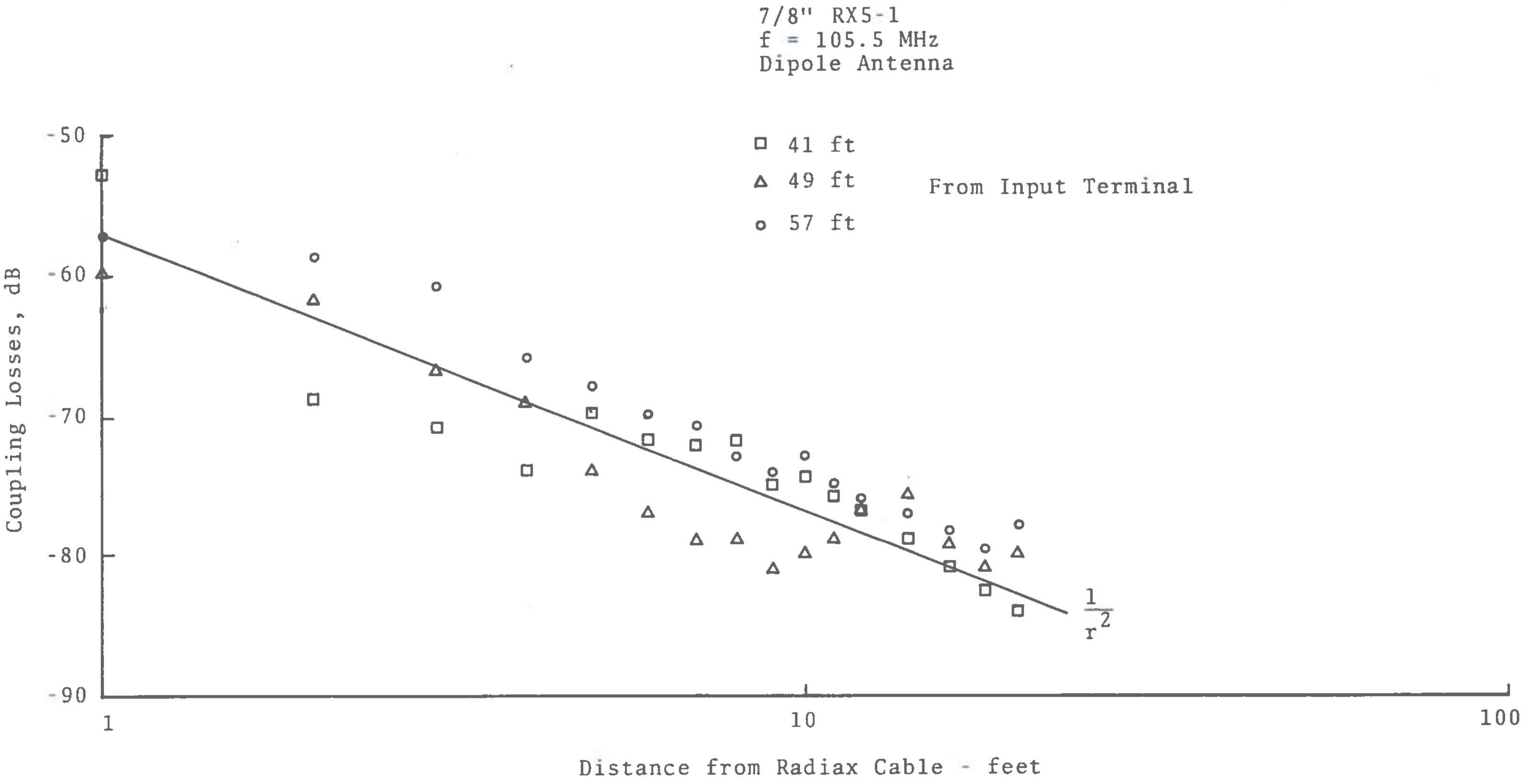


Figure 3-24. The $1/r^2$ Relationship of Transverse Coupling with RX5-1 at 105.5 MHz

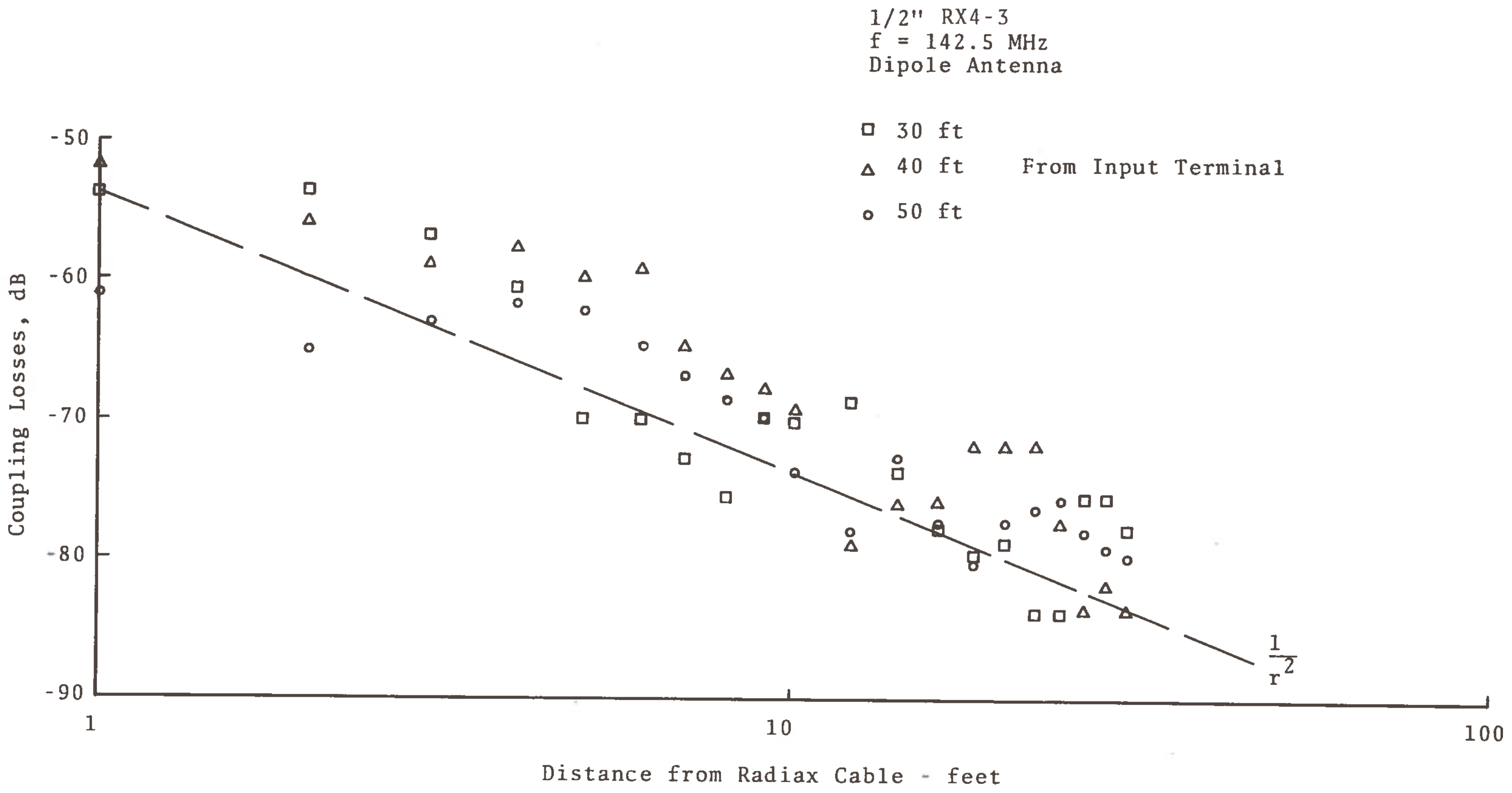


Figure 3-25. The $1/r^2$ Relationship of Transverse Coupling with RX4-3 at 142.5 MHz

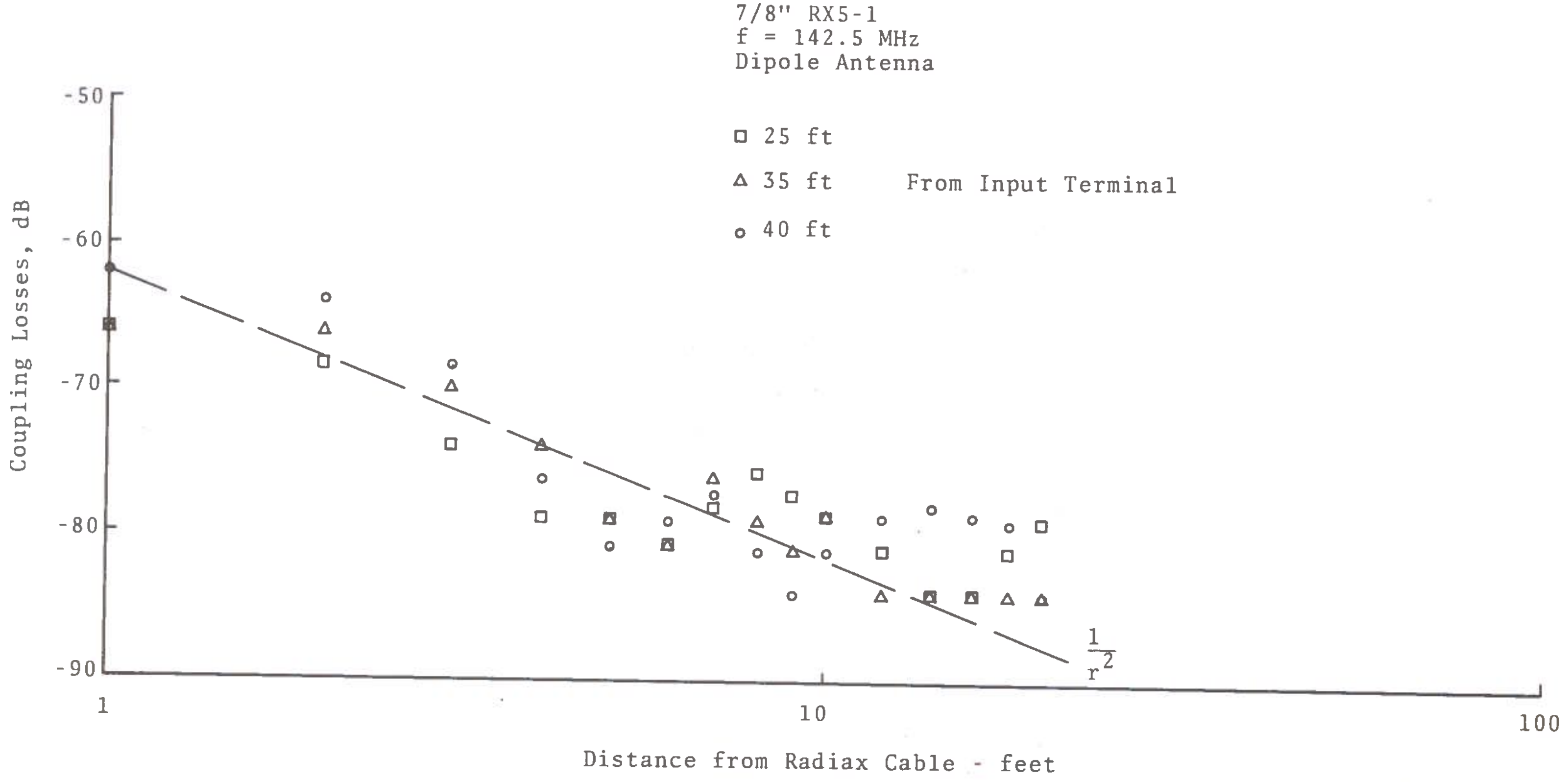


Figure 3-26. The $1/r^2$ Relationship of Transverse Coupling with RX5-1 at 142.5 MHz

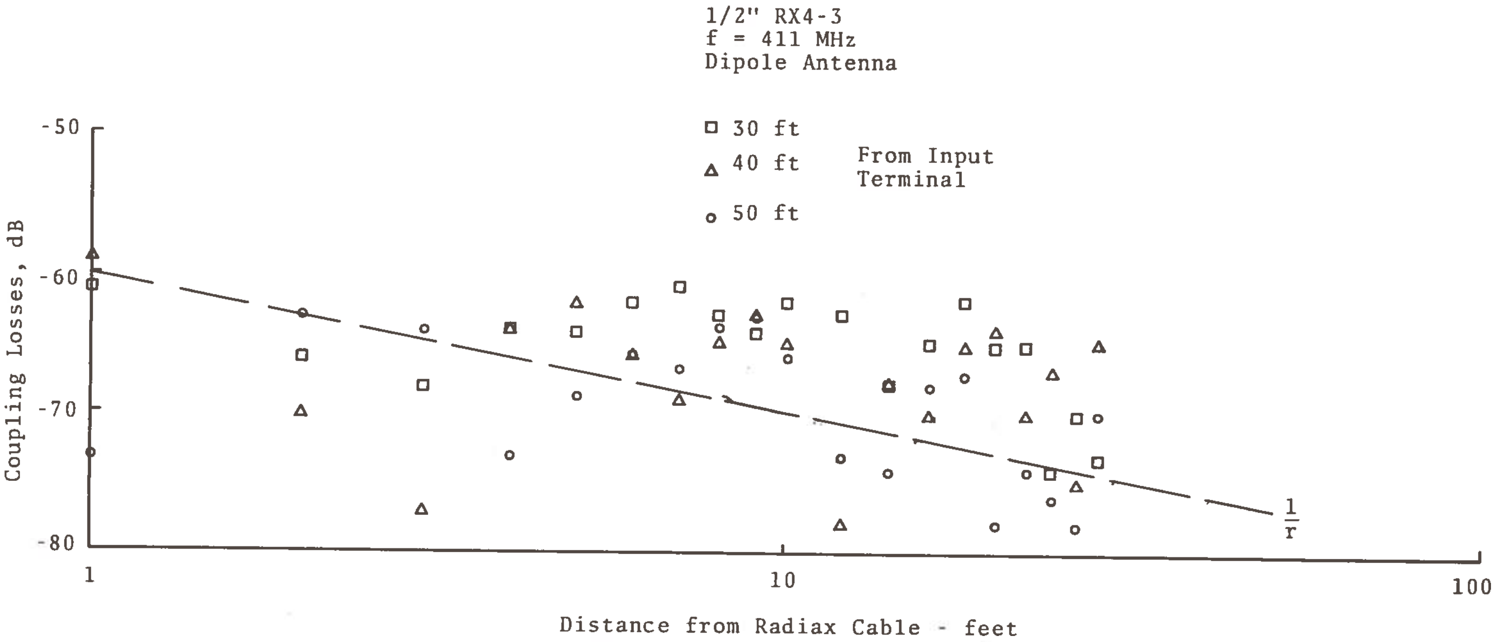


Figure 3-27. The 1/r Relationship of Transverse Coupling with RX4-3 at 411 MHz

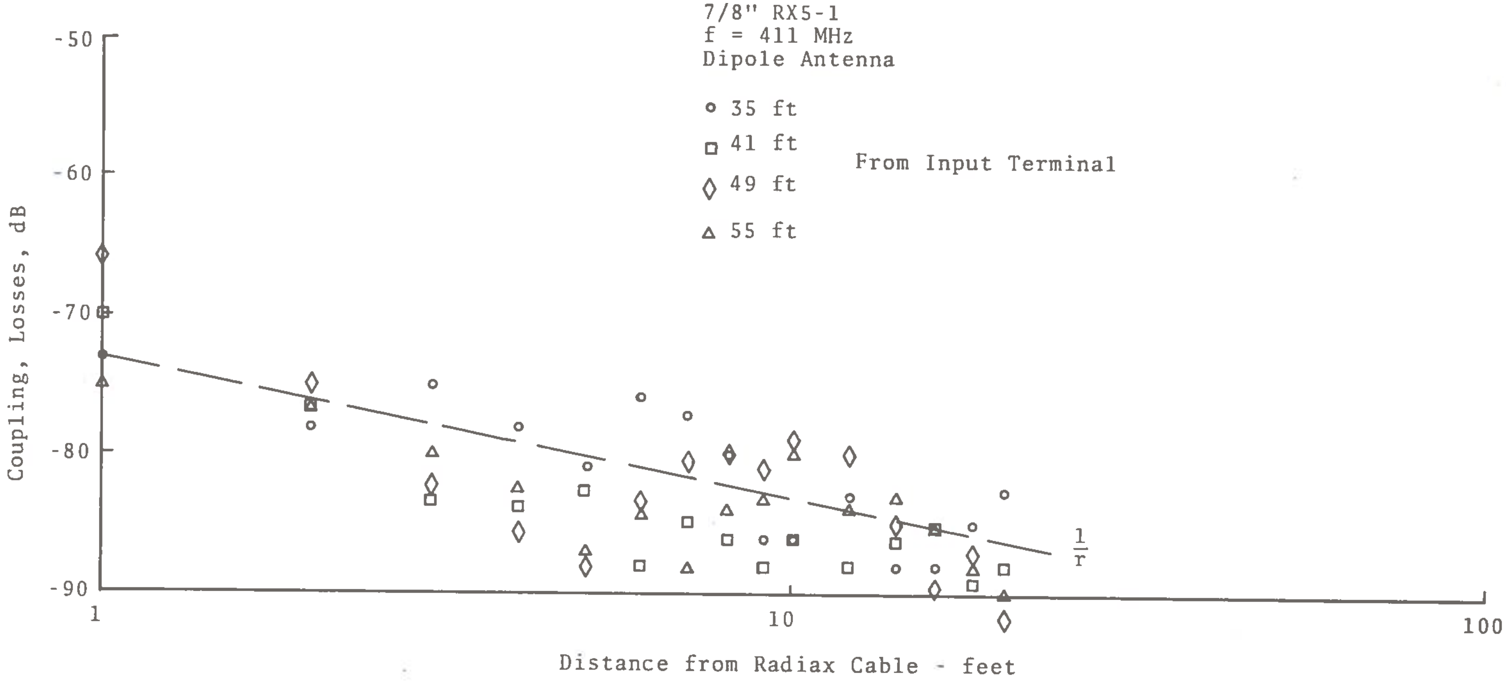


Figure 3-28. The 1/r Relationship of Transverse Coupling with RX5-1 at 411 MHz

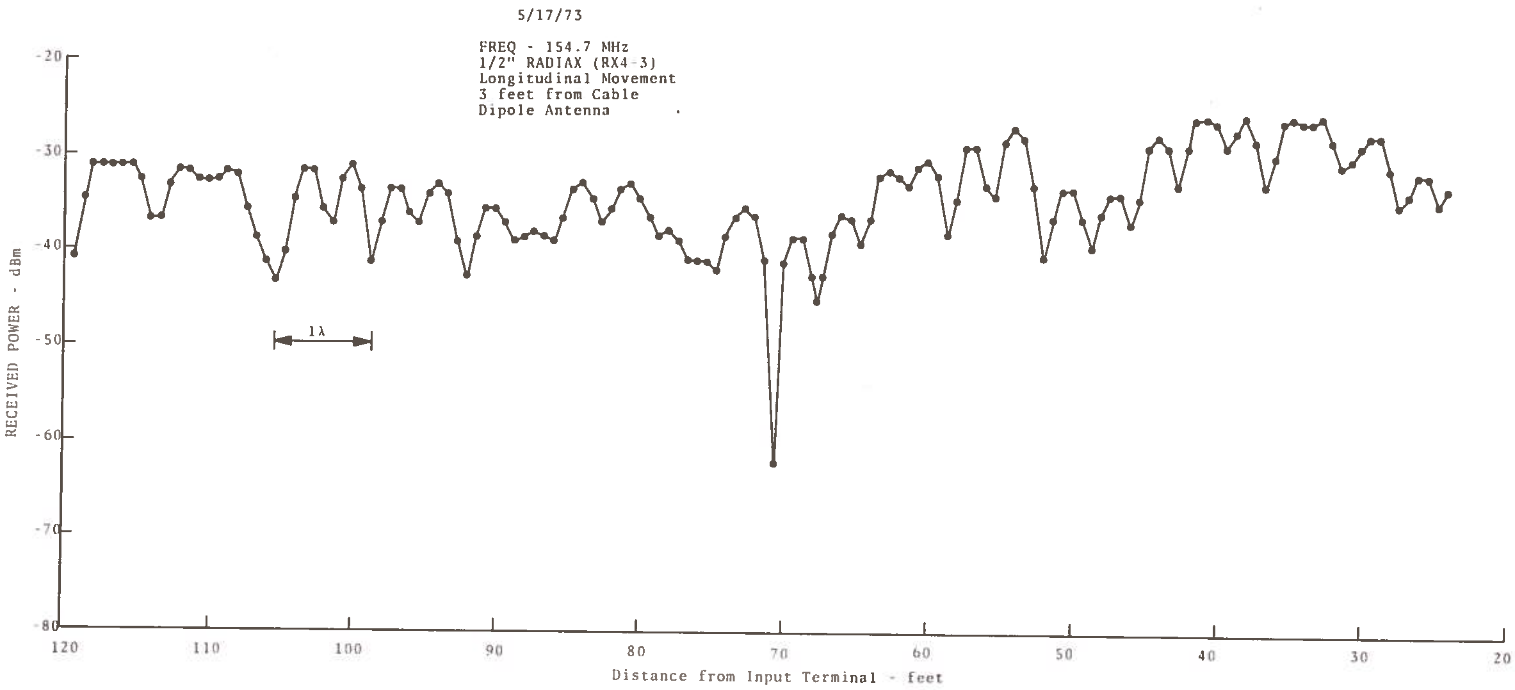


Figure 3-29. The Longitudinal Coupling of RX4-3 with Dipole Antenna at 154.7 MHz

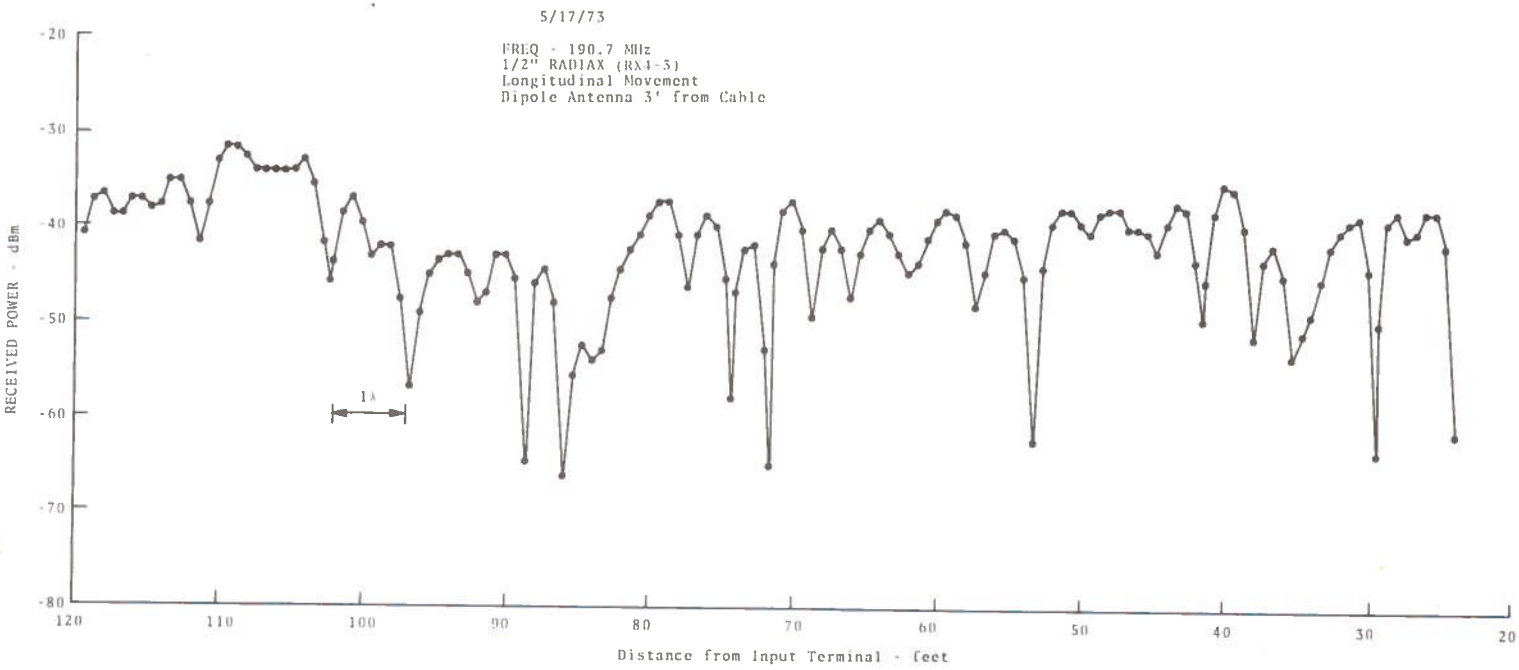


Figure 3-30. The Longitudinal Coupling of RX4-3 with Dipole Antenna at 190.7 MHz

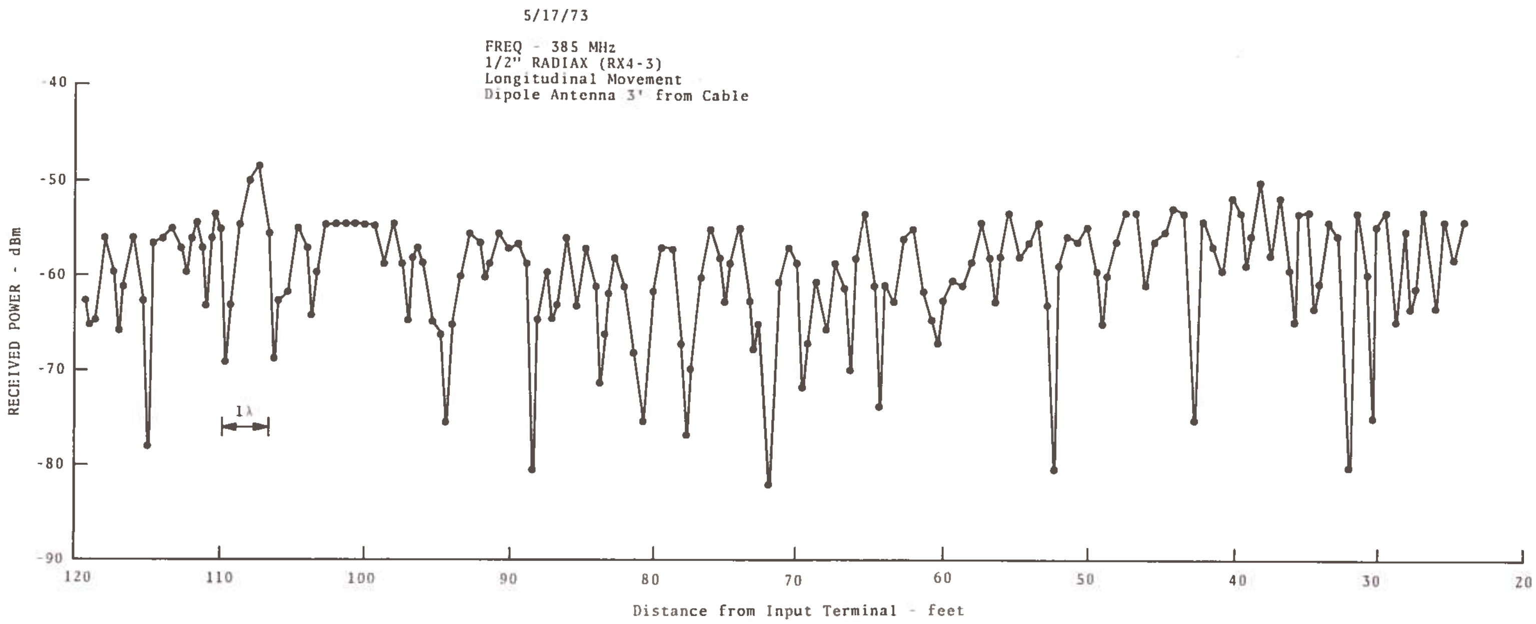
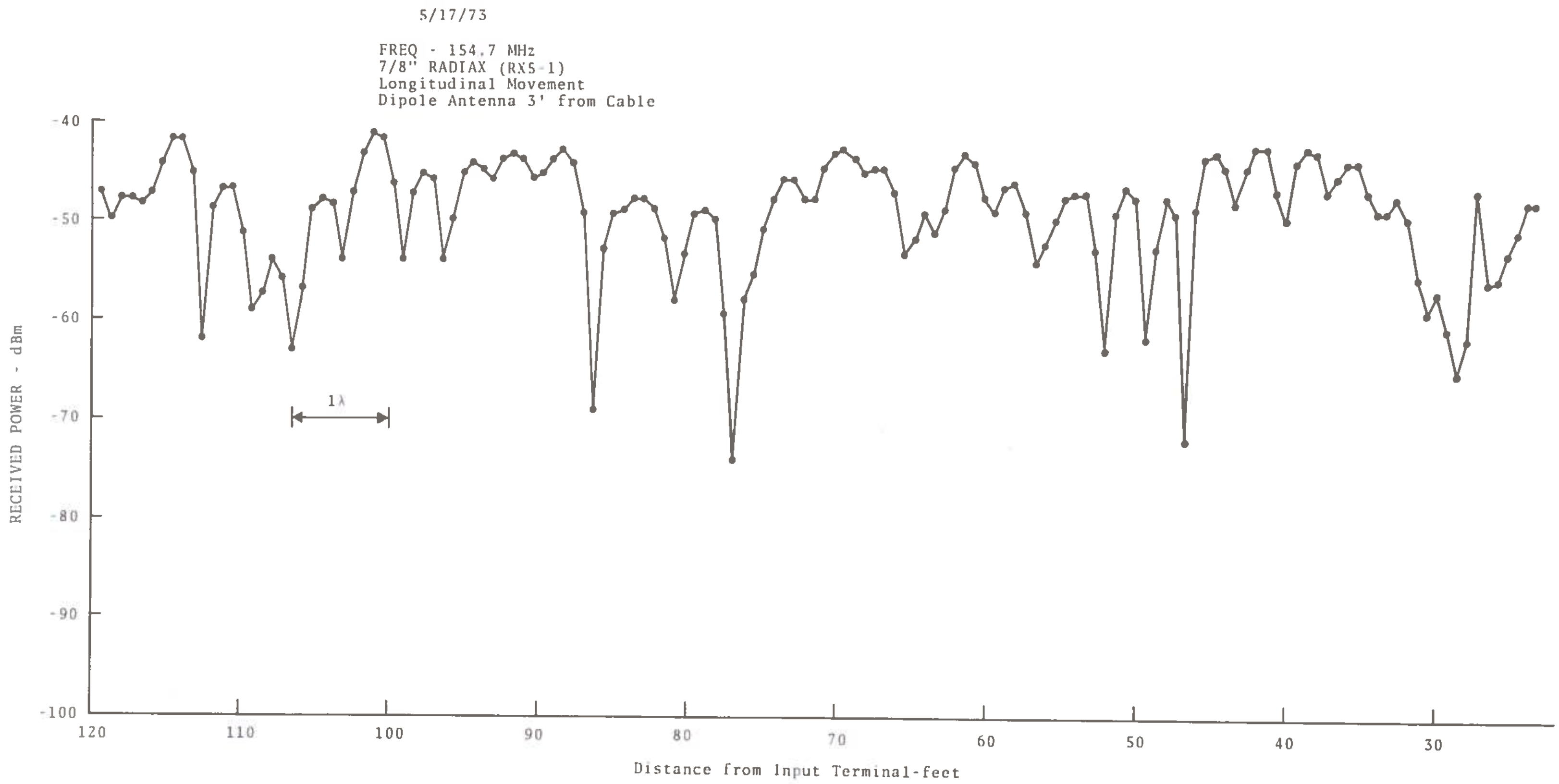


Figure 3-31. The Longitudinal Coupling of RX4-3 with Dipole Antenna at 385 MHz



5/17/73

FREQ - 154.7 MHz
7/8" RADIAX (RX5-1)
Longitudinal Movement
Dipole Antenna 3' from Cable

Figure 3-32. The Longitudinal Coupling of RX5-1 with Dipole Antenna at 154.7 MHz

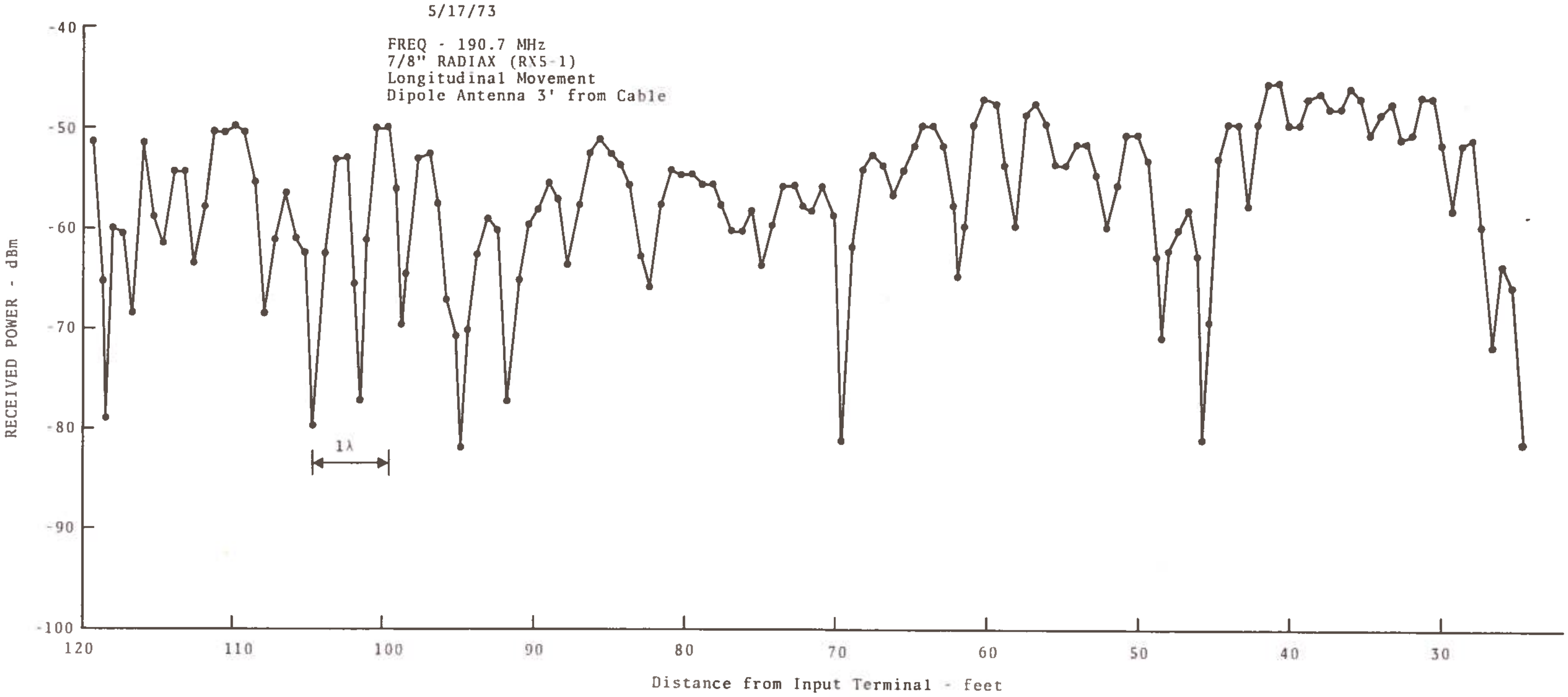


Figure 3-33. The Longitudinal Coupling of RX5-1 with Dipole Antenna at 190.7 MHz

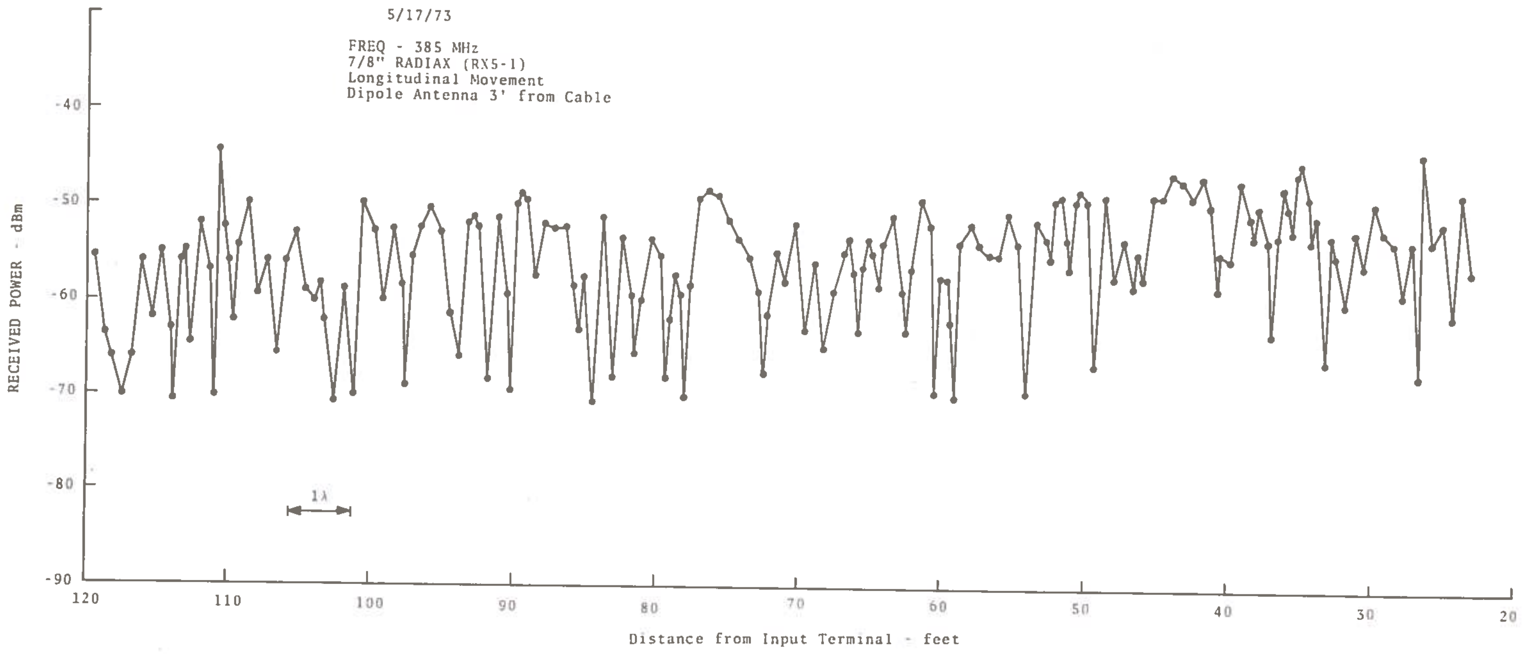


Figure 3-34. The Longitudinal Coupling of RX5-1 with Dipole Antenna at 385 MHz

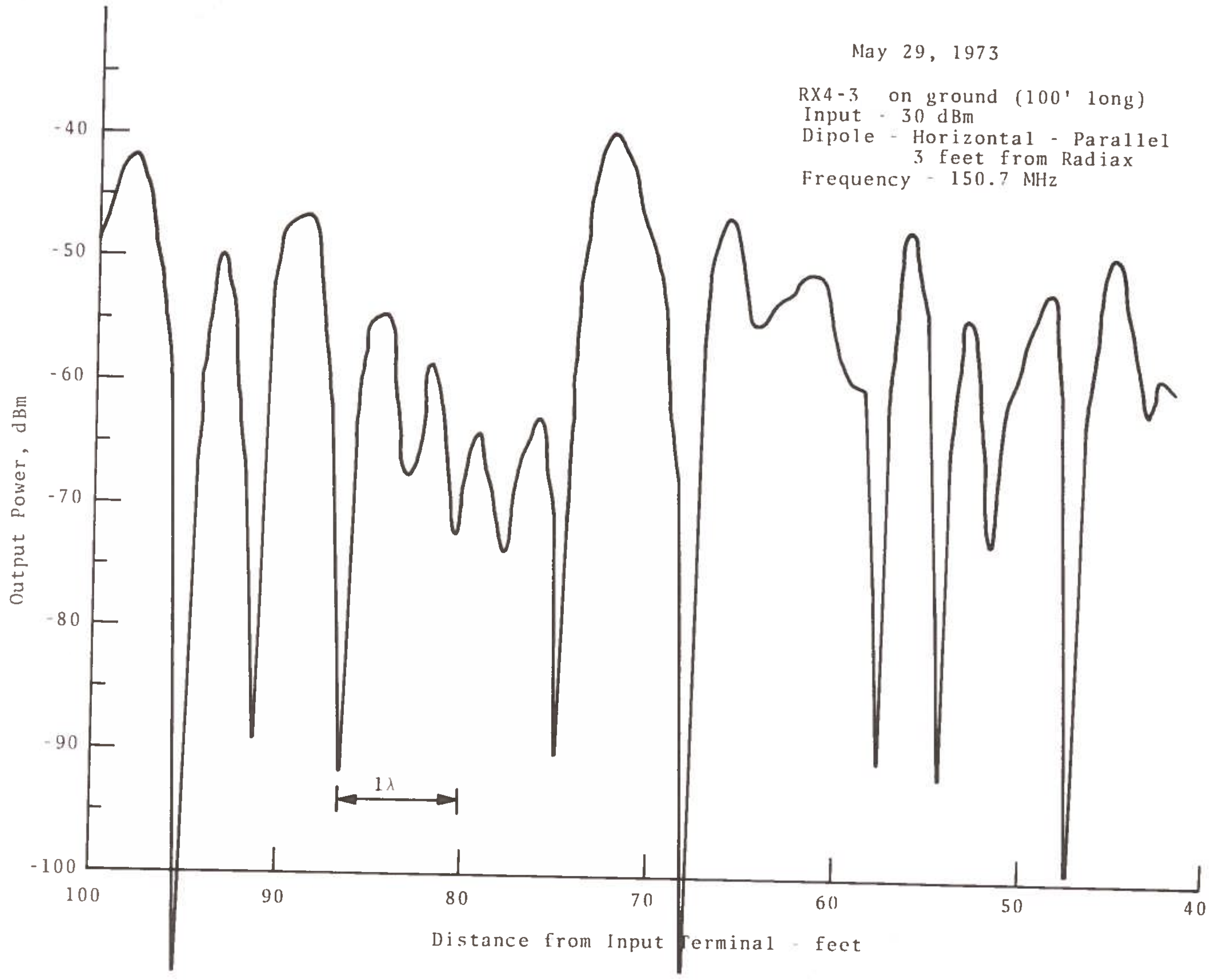
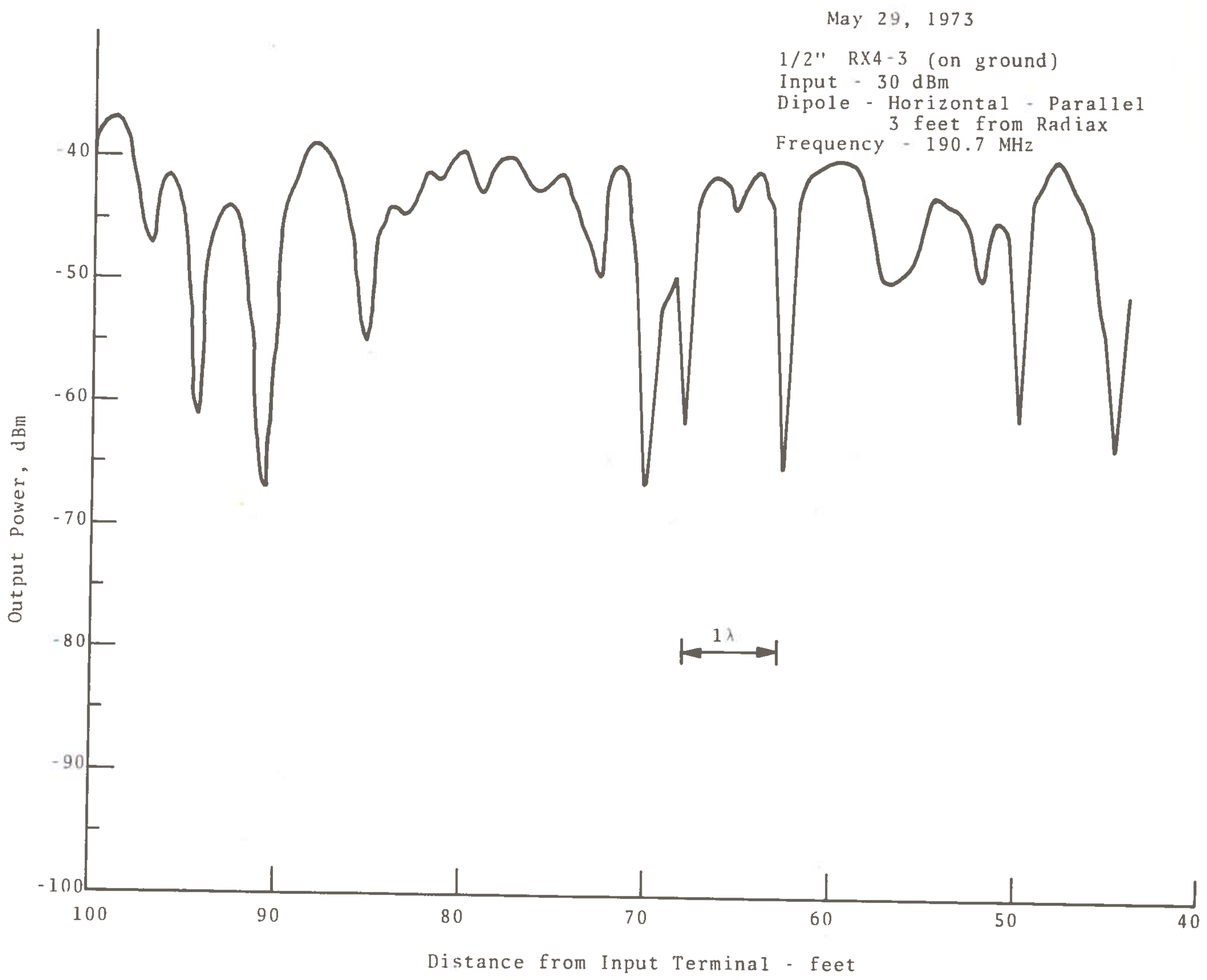


Figure 3-35. The Longitudinal Coupling of RX4-3 on Ground with Dipole Antenna at 150.7 MHz


May 29, 1973

1/2" RX4-3 (on ground)
Input - 30 dBm
Dipole - Horizontal - Parallel
3 feet from Radiax
Frequency - 190.7 MHz

Figure 3-36. The Longitudinal Coupling of RX4-3 on Ground with Dipole Antenna at 190.7 MHz

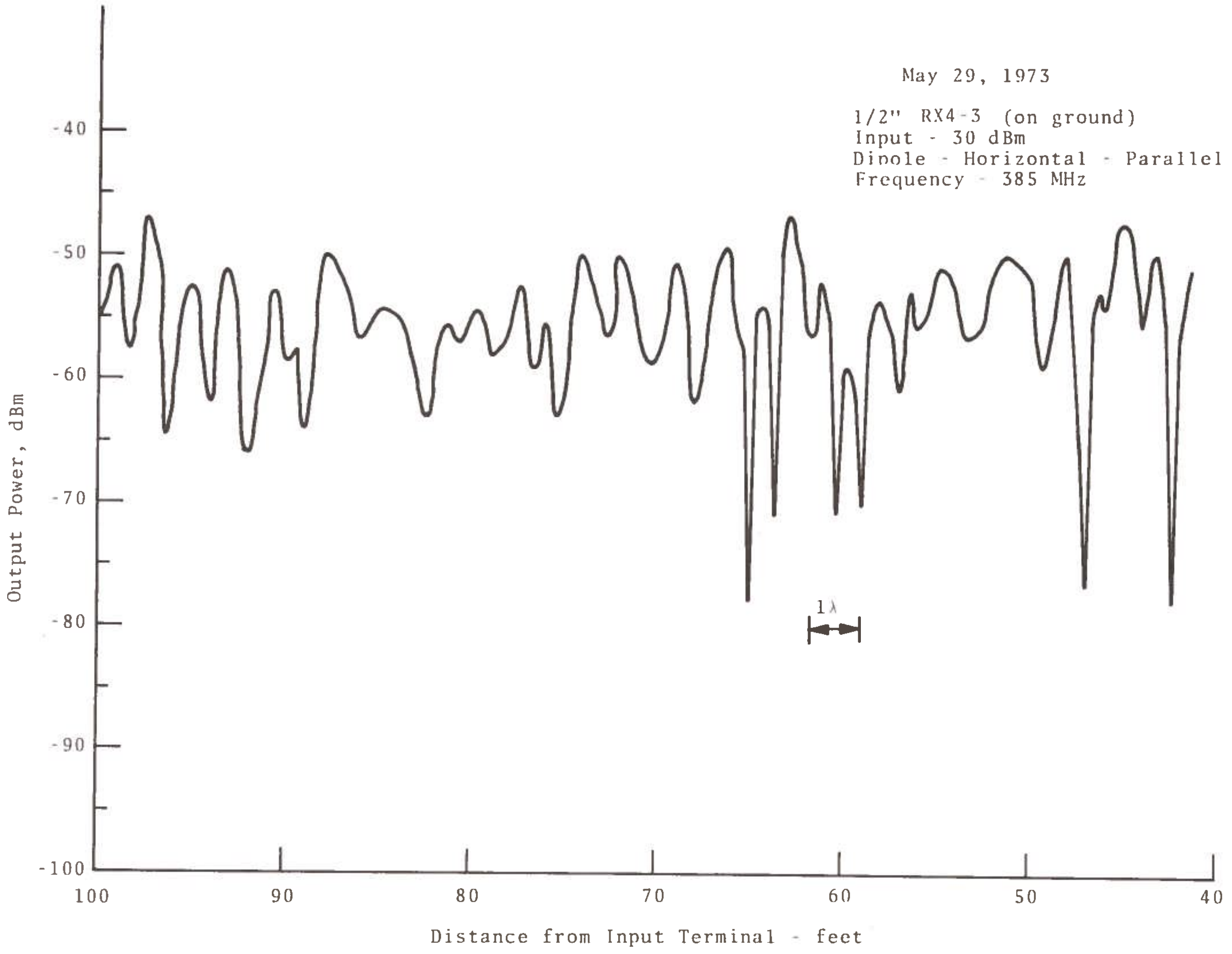


Figure 3-37. The Longitudinal Coupling of RX4-3 on Ground with Dipole Antenna at 385 MHz

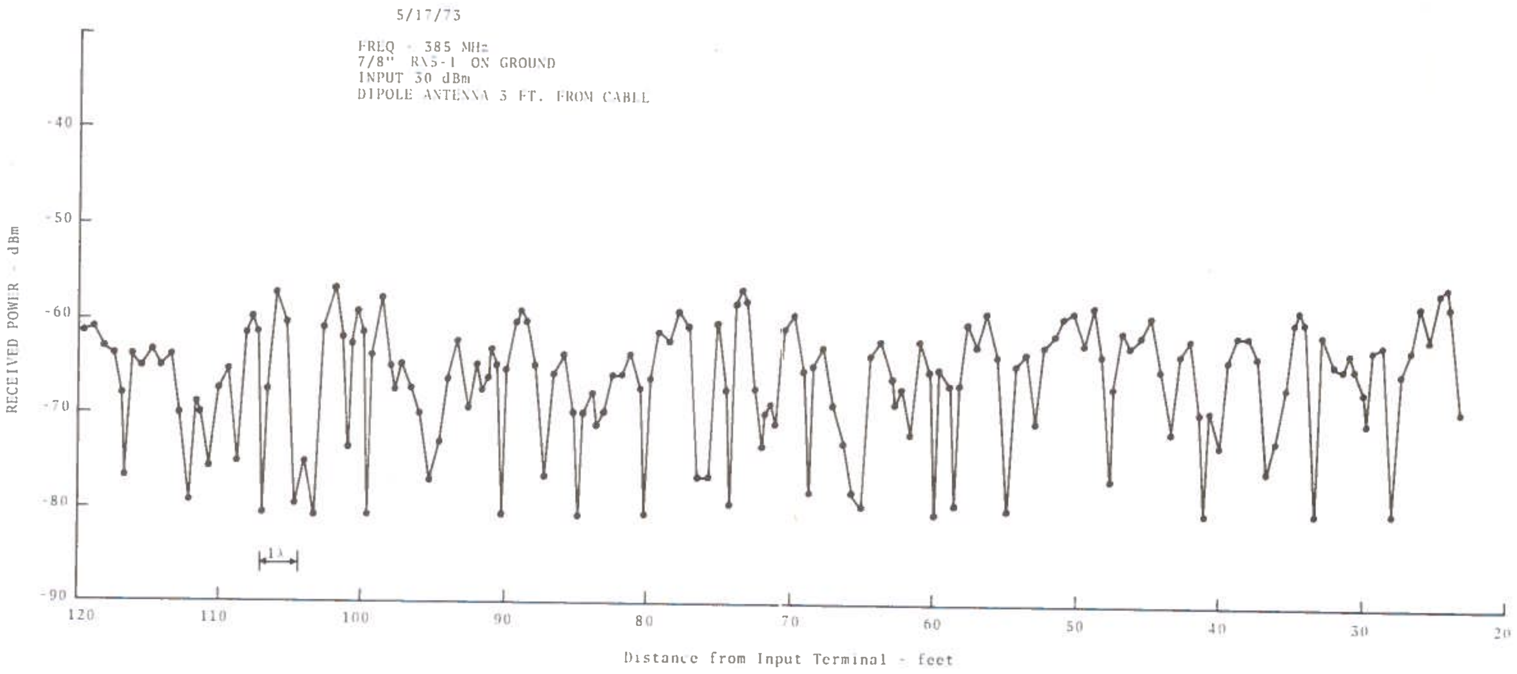


Figure 3-38. The Longitudinal Coupling of RX5-1 on Ground with Dipole Antenna at 385 MHz

TABLE 3-1. COUPLING LOSSES

	Frequency (MHz)	Coupling Losses, dB		
		Ave.	Min.	Max.
RX4-3	385	-65	-55	-87
	190.7	-58	-45	-80
	154.7	-50	-41	-82
RX5-1	385	-73	-60	-85
	190.7	-71	-59	-95
	154.7	-67	-60	-84

is about 30 dB. The most obvious phenomenon is the periodic fluctuation of the received power observed in all the measurements. The average spatial period was calculated by counting the number of the periods over the entire measured distance. Table 3-2 shows the averaged spatial period which appears to be very close to the half-wavelength.

TABLE 3-2. AVERAGED SPATIAL PERIOD

Frequency (MHz)	RX4-3 (ft.)	RX5-1 (ft.)
154.7 $1/2\lambda=3.2$ ft.	3.4	3.4
190.7 $1/2\lambda=2.6$ ft.	3	3.1
385 $1/2\lambda=1.25$ ft.	1.5	1.6

This particular phenomenon is very similar to a standing wave on a transmission line with mismatched termination where reflection takes place. Further discussion will be given in Section 3.3.4.

3.3.3 Pulse Dispersion and Phase

In order to complete the characterization of the transmission channel, measurements were made of the pulse dispersion and phase of coupled signals. These measurements were different from those of Section 2.3 in that the channel includes not only the transmission inside the Radiax cable, but also any transmission on its surface and in the free space between the Radiax and the receiving antenna. These measurements thus characterize the entire transmission channel in terms of its usable bandwidth per channel and its phase.

Figure 3-39 shows a block diagram of the set-up to measure pulse dispersion at a frequency of 155 MHz. A dipole antenna oriented parallel to the Radiax was placed about five feet from the cable and seventy-five feet from its input terminal. A typical transmitted pulse is shown in Figure 3-40. The upper picture shows the input pulse, and the bottom picture shows the output at the receiving antenna. Note that the output pulse is longer as are its rise and decay times. As measured from these pictures, the dispersion of this pulse is about 0.3 μsec. and may be due to the reflection of the Radiax surface wave from the cable termination. Since the distance between the coupling point and the termination is about 125 feet, the required round-trip time for a pulse is 0.25 μsec., which is about equal to the observed stretching. Additional contributions to the dispersion may arise from multipath effects.

Figure 3-41 shows a block diagram of the set-up used to measure relative phase shift as a function of coupling distance. The relative phase at 155 MHz was determined as the dipole antenna was moved away from the Radiax. The results of several such measurements are shown in Figure 3-42. Note that the phase varies linearly with distance beyond about six feet (at 155 MHz one wavelength is 6.34 feet). Between three feet and six feet the phase fluctuates as much as 250 degrees. Closer than this the phase of the coupled signal is essentially a constant. These results are important for the determination of the proper coupling distance to be used with a given type of communication line and modulation scheme. The variation of the coupling distance will depend on the precise mode of installation of the Radiax and the

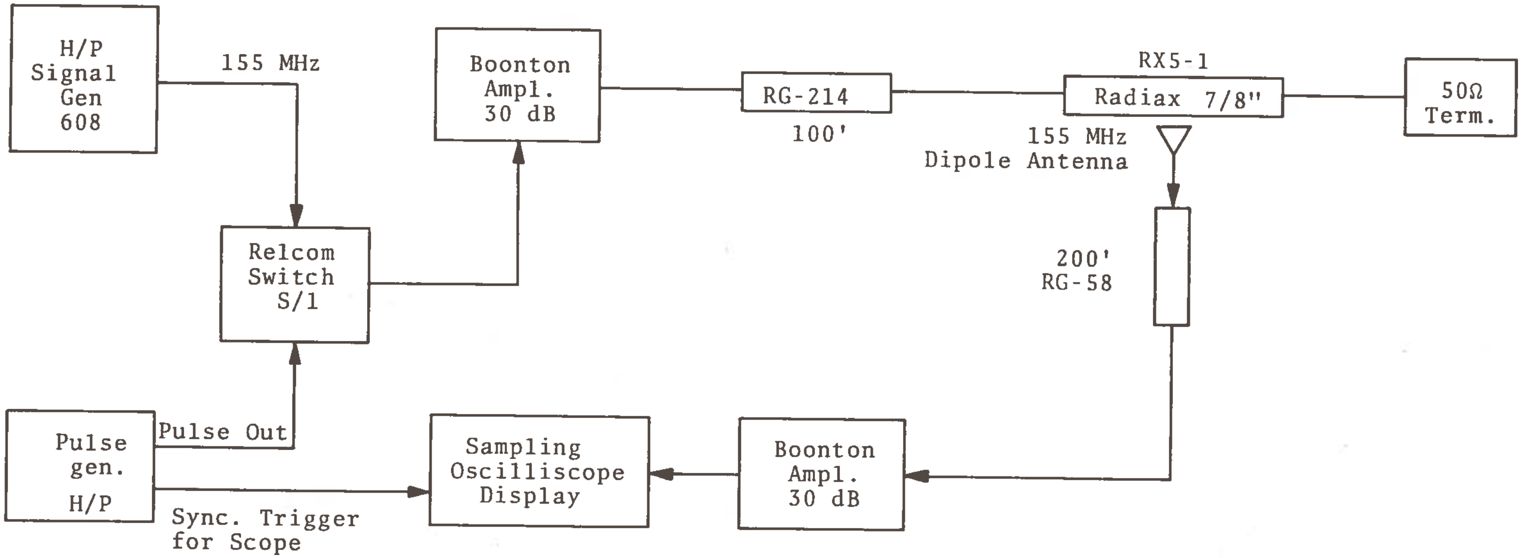
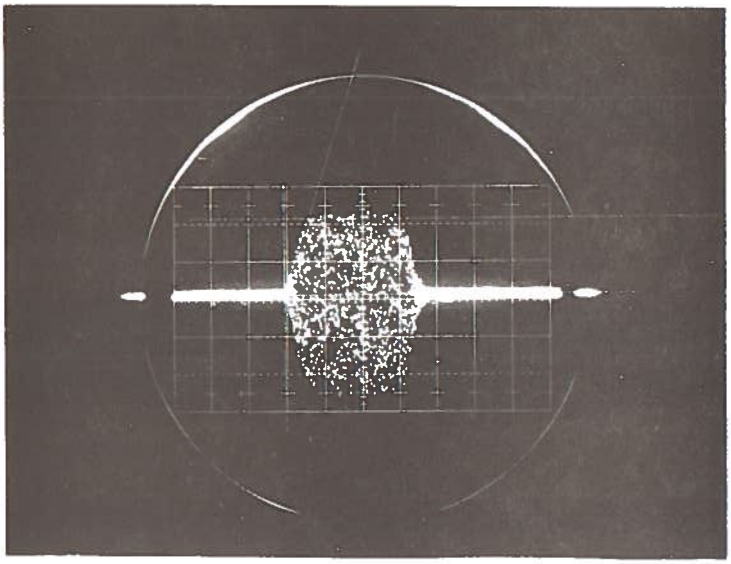


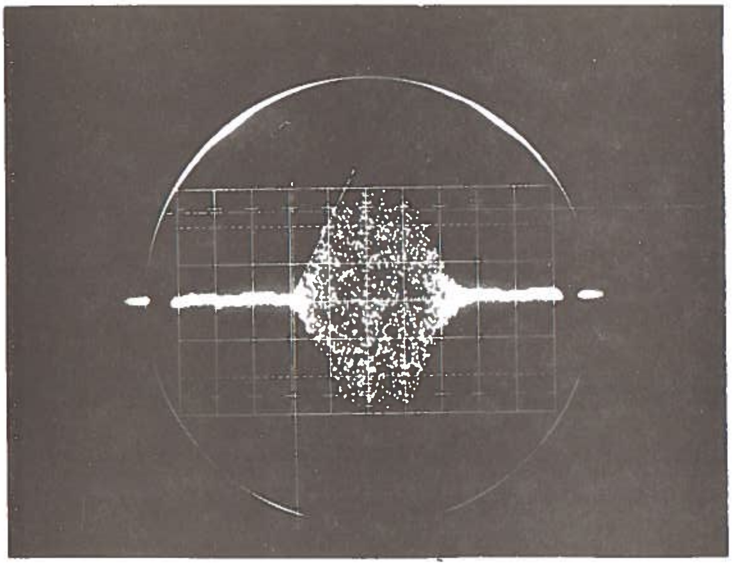
Figure 3-39. Block Diagram for the System Pulse and Response Measurement



.5 μsec/DIV.

200 mV/DIV.

Input to the Radiax Cable



.5 μsec/DIV.

10 mV/DIV.

Output from the Receiver

Figure 3-40. Pulse Response Measurements, Input (upper) and Output (lower)

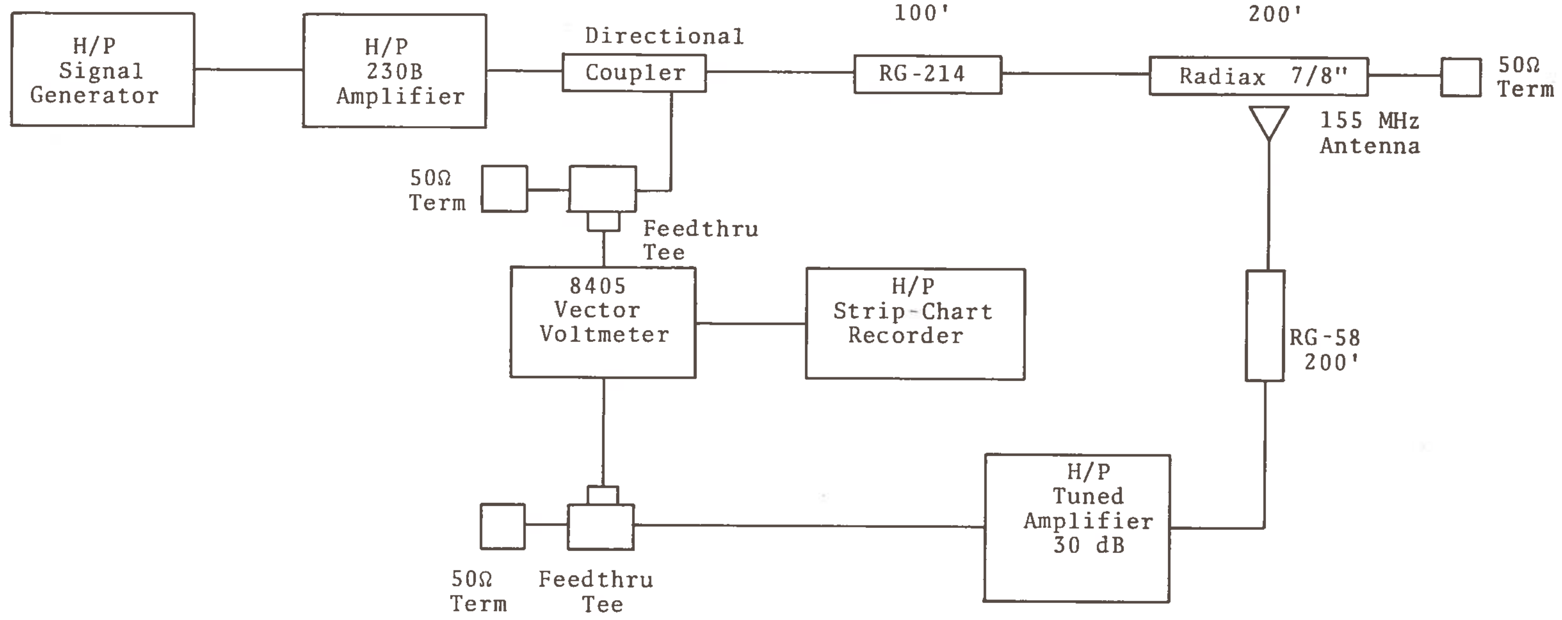


Figure 3-41. Block Diagram for the System Phase Measurement

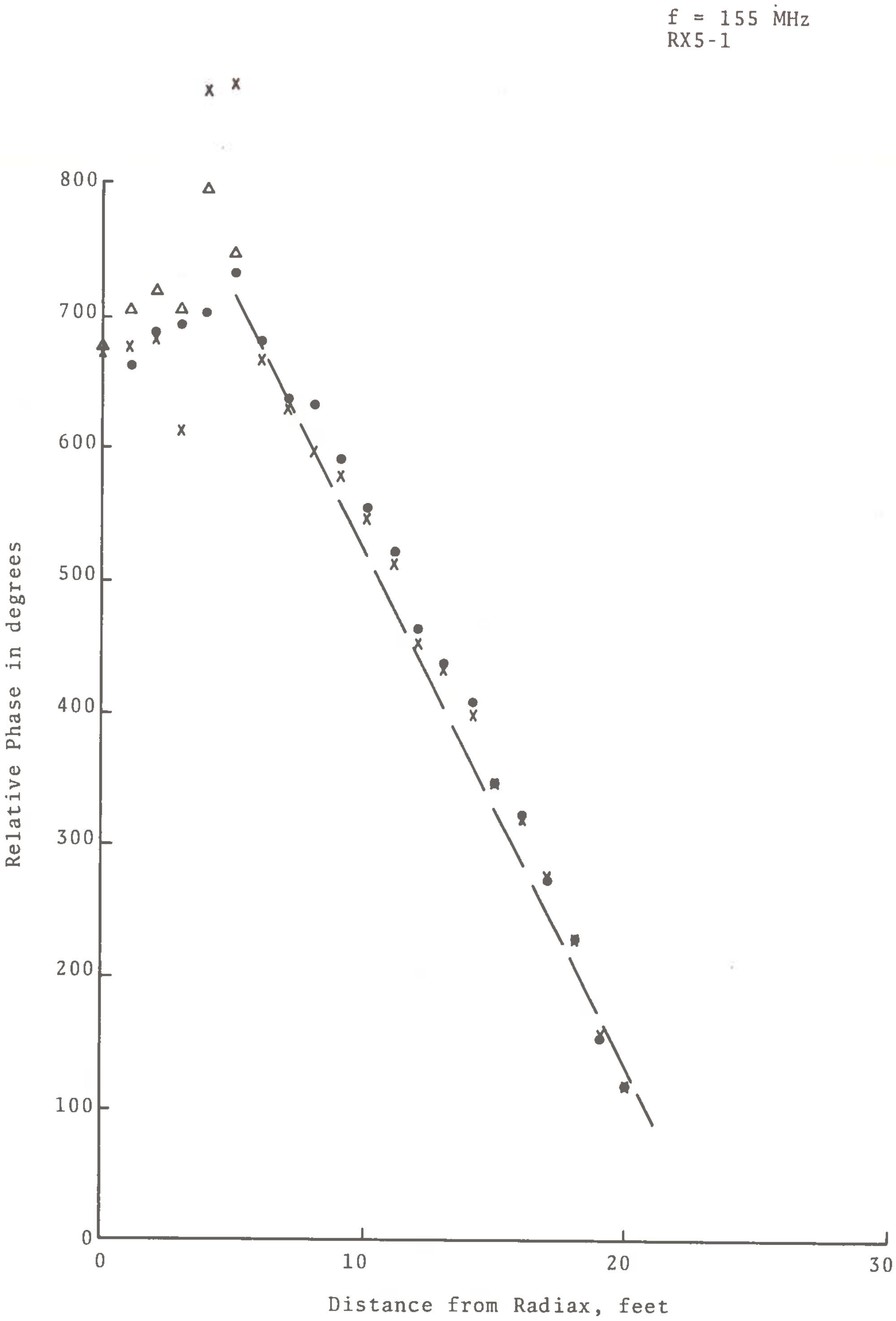


Figure 3-42. The Relative Phase Relationship with the Distance

lateral rocking motion of the train while moving at a very high speed. This variation of the coupling distance introduces phase fluctuations which would appear as noise to a phase modulated (PM) analog system as well as a frequency modulated (FM) system. In a digital communication system, this induced rate of change of phase could result in random bit errors for both phase shift keying (PSK) and frequency shift keying (FSK) systems.

3.3.4 Standing Wave Phenomenon

In Section 3.3.2 we have noted that standing waves were observed at all frequencies. Tests were made to determine whether this phenomenon was due to the propogation of e-m waves on the outer surface of the Radiax. The tests consisted of measuring the amplitudes and periods of fluctuation with and without a metal plate mounted at the end of the cable. The Radiax, RX5-1 was about 200 feet in length and four feet above ground supported by wooden posts 10 feet apart. It was terminated by a 50Ω load. A metal plate four feet square was mounted normal to the cable at the terminator end. Hence a surface wave propagating down the Radiax would be reflected by the metal plate. The measurement frequency was set at 385 MHz so that the size of the plate was comparable to the wavelength. An electric probe was used to measure the surface field intensity as a function of the longitudinal distance. The probe was placed in contact with the dielectric cover of the Radiax. Figure 3-43 shows the amplitude fluctuation of the output of the probe over a 30-foot section of the Radiax with a metal plate mounted at the cable end. Similar measurements over the same section but without the metal plate are shown in Figure 3-44. Note the discontinuities of the measurements due to the posts.

A number of conclusion maybe drawn. They are 1) the peak to peak amplitude is increased by about 10 dB with the metal plate, 2) the longitudinal periodicity is about 1.25 ft. which is approximately one half of the free space wavelength of 2.54 ft., and 3) the long period amplitude fluctuation may be due to the wooden support posts. The results of this test indicate that means should be developed to eliminate or reduce the effect of

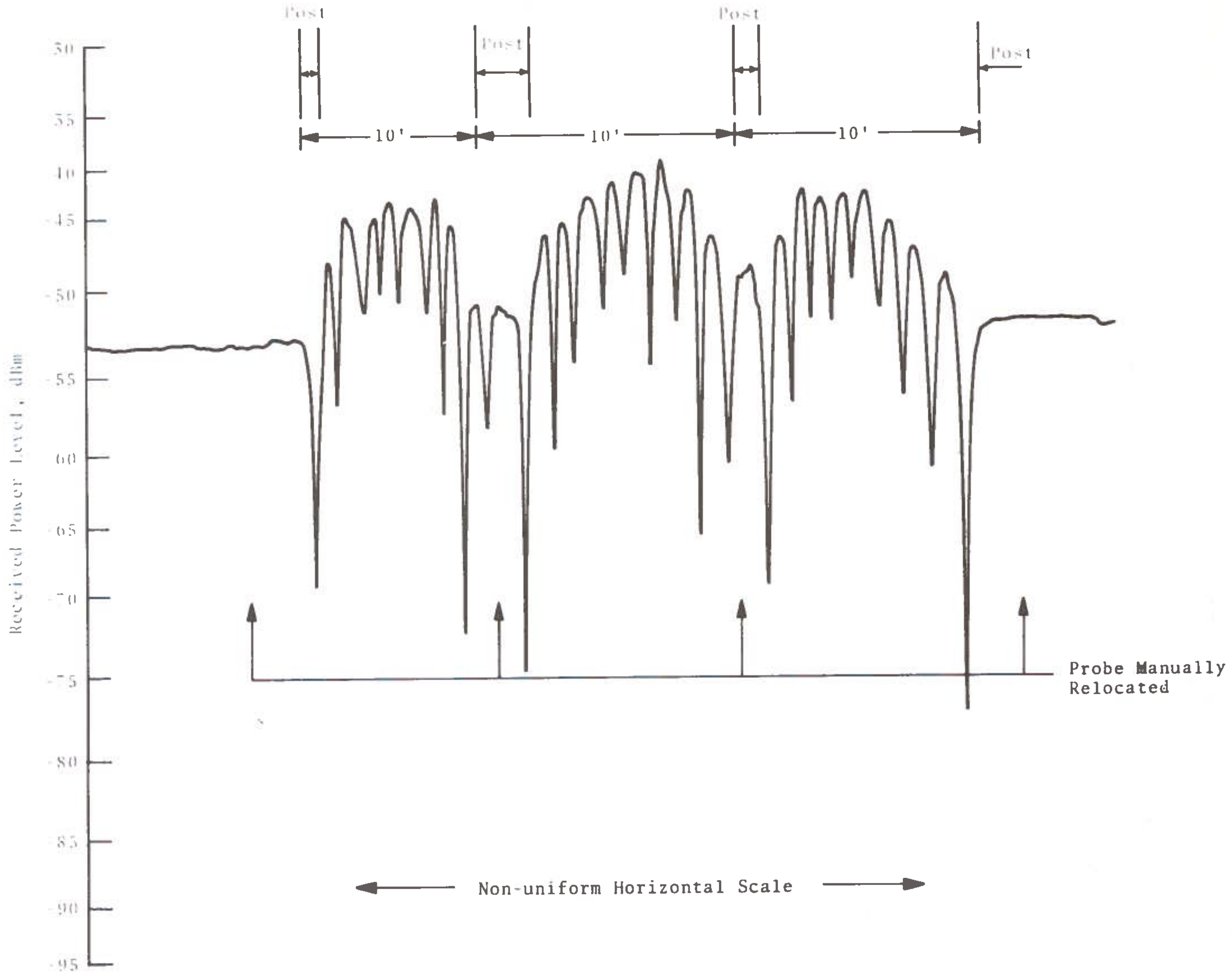


Figure 3-43. The Measured Standing Wave with Reflecting Terminal

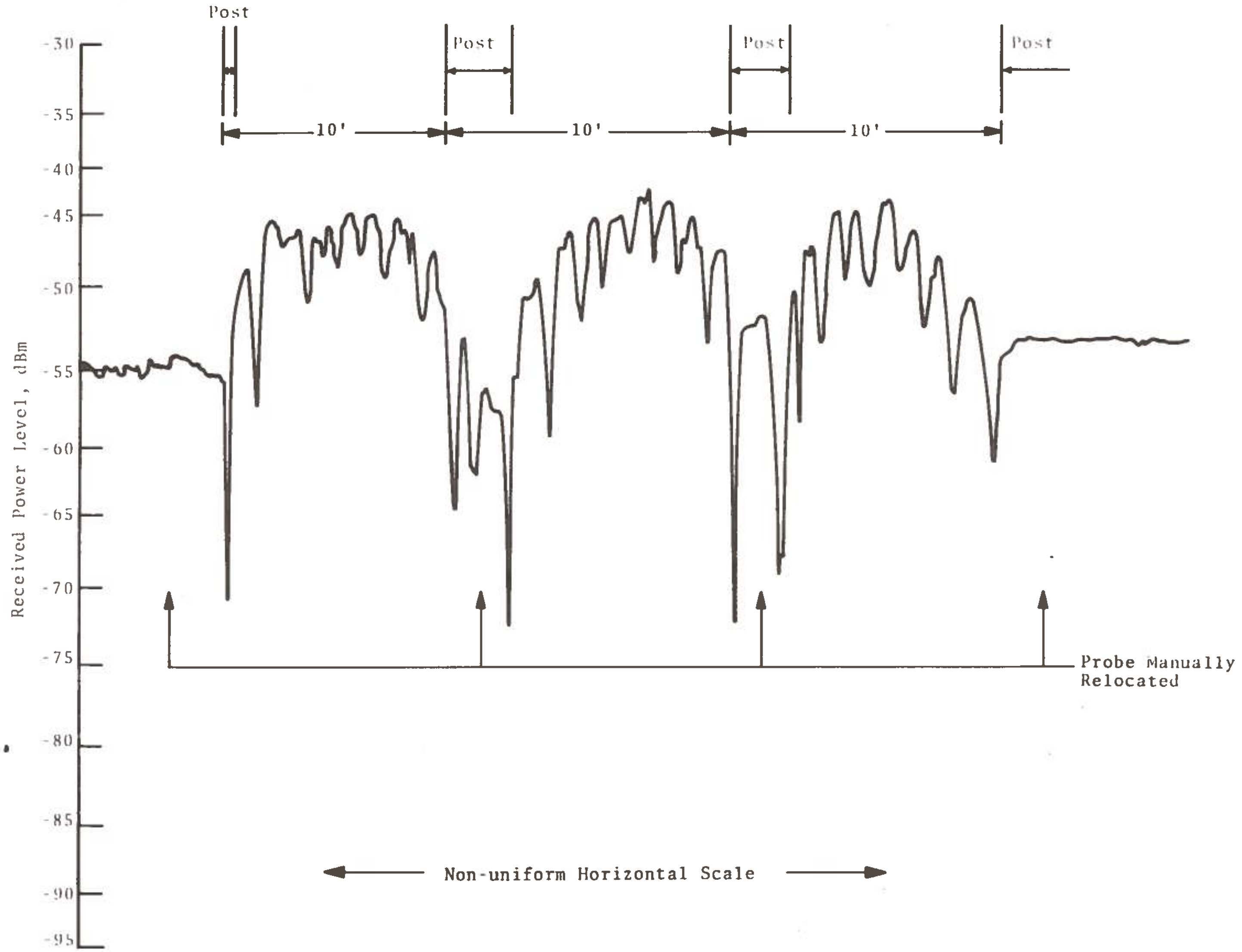


Figure 3-44. The Measured Standing Wave with Open Terminal

surface waves. One possibility is to wrap a high attenuation material around the Radiax near the terminal end, to reduce reflections. Further tests and development will be carried out at a new test site.

3.4 CONCLUSIONS

The transmission characteristics of the Radiax cable are very similar to those of a regular coaxial cable and may be summarized as follows:

1) The VSWR is less than the manufacturer's rated value of 1.3 in the frequency range from 100 to 400 MHz.

2) The attenuation is higher than that of regular coaxial cable due to radiation from the Radiax. The attenuation of RX4-3 is twice that of RX5-1, for which the measured loss is 0.5 to 1.0 dB per 100 feet. Corresponding values for ordinary coax are 0.4 to 0.9 dB per 100 feet.

3) Cable movement has little effect on the phase of the signal.

4) Pulse dispersion is negligible for the lengths tested.

The coupling characteristics may be summarized as follows:

1) The radiation pattern of the cable is omnidirectional within 3 dB.

2) At frequencies below 150 MHz, the coupling between the cable and a parallel dipole antenna appears to vary as r^{-2}, where r is the transverse distance from the cable. At higher frequencies, around 400 MHz, the coupling relationship is more nearly r^{-1} out to a distance of about 30 feet from the cable.

3) The average value of coupling losses for RX4-3 is up to 17 dB less than for RX5-1. The coupling losses increase monotonocially with the frequency.

4) The peak to null variation of the coupling loss is about 30 dB. It is believed that the major contribution to this large deviation may be the presence of a surface wave and multipath.

5) Standing wave patterns have been noted on the surface of the Radiax. These standing waves are due to the interaction of a surface wave with an improper termination at the end of the Radiax and not with other objects in the neighborhood of the cable.

6) At transverse distances greater than one wavelength the phase shift varies linearly with distance. At distances less than one-half wavelength from the Radiax, the phase is approximately constant. From one-half to one wavelength there appears to be a transition region in which the phase fluctuates as much as 250 degrees. Phase fluctuations introduced by normal lateral train oscillations will be long period and will probably not contribute significantly to the doppler spread.

7) Pulse dispersion has been observed in coupled signals and can be related to surface wave and multipath effects.

3.5 RECOMMENDATIONS FOR FURTHER TESTS

The measurements described above have shown that a leaky Radiax cable may be suitable for wayside communications with high speed, automatic trains. In order to explore this potential, further tests should be conducted with a cable one thousand feet or more in length so that realistic transmission and environmental effects may be studied.

3.5.1 Evaluation of Diversity Techniques for Improved Coupling Characteristics

One disturbing feature of the Radiax cable is the relatively large amplitude fluctuations in the coupled signals that are observed as single coupler is moved along the cable parallel to its axis. At least two techniques are available to reduce these fluctuations: spatial diversity and frequency diversity. The former sums the signals from two or more couplers spaced an odd number of quarter wavelengths apart. The latter transmits the same information at two different frequencies, thereby shifting peaks and nulls so that when the signals are filtered, detected, and summed, the amplitude fluctuation will be reduced. These and other techniques for amplitude control should be tested and evaluated with a representative installation.

3.5.2 Demonstration of Voice Communication

The measurements reported above indicate that voice communication between stationary and moving terminals through a Radiax cable may be subject to severe fading. In order to determine the voice quality that can be achieved a link should be set up with the fixed and mobile vans as terminals. Tests and demonstrations could then be carried out to compare the effects of various coupling and modulation on the perceived performance of the voice communication channel.

3.5.3 Demonstration of Digital Communication

In view of the non-uniformity of the radiation from standard Radiax, it is important to determine its effect on the bit error rate of a digital data channel. This is undoubtedly the most crucial aspect of a wayside-to-vehicle communication system since it has a direct impact on the reliability of the command and control system. Measurements should be made between stationary and mobile terminals using various keying techniques in order to determine the optimum performance that can be achieved with this line. Standard methods of measuring bit error rates would be used.

3.5.4 Measurement of Electromagnetic Interference

A leaky waveguide is susceptible to electromagnetic interference, especially on the downlink (vehicle-to-wayside). In this direction the input signal is at a low level and localized; the noise input may be widely distributed along the line, resulting in an unacceptable low S/N at the output. In general, two types of interference may be distinguished:

1. Background noise. The level of this noise in the frequency bands of interest and its daily variations should be measured at the output terminals of a long

cable in order to estimate the mobile transmitter power required for an adequate signal-to-noise ratio.

2. Impulsive man-made noise. The principal sources of this noise are the power and propulsion systems. Interference may arise from the power distribution system, the power conditioning unit, or the train propulsion system. The effect of such impulsive noise may be to increase the bit error rate in the digital data link. Measurements of the effect should be carried out in a realistic environment, i.e. alongside a test track carrying high-speed vehicles.

3.5.5 Determination of Environmental Effects

One aspect of Radiax cable performance that could not be fully tested at the MITRE site was the effect of weather conditions such as rain, snow, and changes of temperature. In January of 1973 some measurements were made which indicated that the effect of snow was minimal. However, large variations in temperature could have many unfortunate consequences of an engineering if not an electromagnetic nature. The expansion coefficients of aluminium and copper are large and differ by about a factor of two. A measurement program using 1000 feet of Radiax cable in the North Temperate Zone could at the same time assess and seek solutions to the engineering problems of installing and maintaining the cable in such an environment. The effects of sag or buckling and means for minimizing them could be studied and evaluated.

4. DISCUSSION OF RESULTS

4.1 CHANNEL CHARACTERISTICS

Four parameters are commonly used to characterize a communication channel. They are:

1) The Doppler spread B. It is the frequency at which the channel fades, due to variations in multipath length.
2) The fading period T. It is the inverse of the Doppler spread, i.e. $T = 1/B$.
3) The multipath L. It represents the average duration of the output when a delta function is used as the input.
4) The coherence bandwidth W. It is the frequency range over which the channel fades coherently. $W = 1/L$.

If we transmit a signal of duration T_T such that $T_T < T$, the fading is approximately constant during the duration of the symbol or flat (in time). If, on the other hand, $T_T > T$, then the fading signal changes substantially during the duration of a symbol. If we transmit over this channel with bandwidth $W_T < W$, the fading is frequency independent or flat (in frequency). If, on the other hand, $W_T > W$, the fading is frequency dependent.

For rail communications, the fading rate depends on the frequency and the speed of the train. Typical values are given in Table 4-1 based on the relationship,

$$f_r = 2v/\lambda$$

where v is the speed of the train and $\lambda/2$ is the minimum spatial period.

These values are the slowest data rates for which the fading can be considered flat (in time). For example, assuming binary transmission it is clear that at 100 MHz and with a train going at 25 miles/hr, the fading is flat whenever the data rate is higher than 7.5 bits/sec. At 450 MHz and with a train whose speed is 300 miles/hr that data rate must be higher than 400 bits/sec.

TABLE 4-1. VALUES OF FADING RATE

V (miles/hr)	f (MHz)					
	100	200	300	400	450	900
25	7.5	14.9	22.4	29.8	33.5	67.1
50	14.9	29.8	43.5	58.0	65.3	130.5
100	29.8	59.6	89.4	119.2	134.1	268.2
150	44.7	89.4	134.1	178.8	201.2	402.3
300	89.4	178.8	268.6	357.6	402.3	804.6

Our measurements of pulse dispersion on Radiax indicate a multipath spread value $L \approx 0.3$ μsec. This corresponds to a coherent bandwidth of 3 MHz per channel.

4.2 NOISE EFFECTS

It is well known that at the frequencies used for these measurements, man-made noise often dominates receiver noise. However, during the course of the measurements, no appreciable man-made noise was observed. A number of reasons may be cited to account for this fact:

1) The tests were conducted in a rural area.

2) The receiver sensitivity was about -100 to -90 dBm at a bandwidth of 100 kHz, which is at least 25 dB above the thermal noise level.

3) Most of the measurements were made by transmitting from the Radiax to a dipole coupler so that the noise picked up along the Radiax has been attenuated twice, i.e. coming into and out from the Radiax.

4) The 200-feet length of Radiax cable may not have been long enough for a realistic test of the noise effects.

On a number of occasions a 200-foot length of Radiax cable was connected to a spectrum analyzer, but no appreciable noise was observed. However, in order to determine the effects of man-made noise, more extensive noise measurements should be conducted with several thousands of feet of cable in various simulated environments.

4.3 TRANSMISSION OVER THE RADIAX

Two kinds of narrowband transmission are of interest in the use of the Radiax: voice transmission and data transmission. The requirements for these transmission are different. Data for command and control requires communications (possibly two-way) between a fixed terminal and a mobile one (the train). Voice communication involves the transmission of several independent telephone conversations over the same transmission line and therefore gives rise to all the typical multiple-access problems.

4.3.1 Data Transmission

The necessary data rate to transmit command and control information will probably be small, in the order of few Kbps, and certainly easily accommodated by an ordinary voice channel. Under these circumstances, and with the values mentioned in 4.1 for channel parameters, the transmission of data will not be impaired by frequency selective fading since the fading will be flat in frequency (and probably also in time, unless extremely low data rates are considered). In this case, errors are produced primarily by noise, most likely nongaussian since the important sources of noise are impulsive in nature, and by fading (flat). The presence of deep fades could be reduced by the use of some form of diversity. For example, space diversity appears feasible, although its use would add somewhat to the cost of the receiver.

4.3.2 Voice Transmission

Voice transmission requires that the system be able to handle multiple, independent telephone conversations. Two major access methods are Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA).

4.3.2.1 FDMA - There are two types of FDMA systems: half-duplex and full-duplex. The half-duplex system requires only one standard frequency assignment to provide two-way telephone communication. The full-duplex system provides two standard frequency channels to establish a two-way telephone transmission. In both cases, Frequency Modulation (FM) is used to modulate the transmitted carrier by the voice signal and the bandwidth is 25 KHz per rf channel.

4.3.2.2 TDMA - To employ the TDMA format, it is first necessary to convert each telephone conversation to a digital bit stream. The conversion can be accomplished in several ways. Continuously Variable Slope Delta Modulation (CVSD) at a 32 Kbps rate, may be considered representative.

In order to simplify the TDMA design, separate frequencies are used for transmit and receive. The procedure for transmitting with TDMA may be described as follows. In the TDMA format, each user transmits and receives only in a specified timed slot once every frame. A frame consists of a single time slot allocation for each potential user of the system. To use this system, each local terminal must possess a digital buffer or memory into which digitized voice is fed. When the terminal transmits during its time slot, it must burst out the data in the memory at a significantly higher rate than that at which it was entered. The higher rate depends on the data rate per channel, total number of channels to be transmitted over the same system, the length of the transmission system, the buffer or memory size at the receiver and of course, the bandwidth of the transmission line. In the receive operation, the process is reversed and the received data is entered in a memory at a high rate and read out at the initial conversion rate (from digital to analog). The advantages of TDMA are:

1) It is more resistant to interference and cross-talk than the FDMA system using analog FM transmission.
2) It uses regenerative repeaters, to prevent the propagation and accumulation of man-made noise along the entire length of the cable as in an analog system.

3) It can be used by the master terminal for ranging the local terminal. That is, the master terminal can measure the time lag between its transmission and reception from each train and thus determine the train position.

4) The digital wave form can be used to combat the possible effects of multipath propagation, i.e. an anti-multipath modem may be provided to reduce multipath degradation.

The disadvantages of TDMA are:

1) Equipment costs will be 1 1/2 to 2 times those for FDMA.

2) It requires at least twice as much bandwidth as the full-duplex FDMA System for the same number of simultaneous telephone transmissions.

3) It is more complex to interface with the ordinary FDMA telephone system.

4.3.3 Wideband Transmission

Wideband transmission may include additional voice channels, command and control, commercial television, and video telephone. The base band requirements may be given as follows:

12 full duplex voice channels	96 KHz
Command and control telemetry	4 KHz
1 Commercial television channel	6 MHz
1 Video telephone channel	1 MHz

Based on the parameters discussed in 4.1 the coherent bandwidth of the Radiax is about 3 MHz which is narrower than the required baseband for television channel. However, if the limitation of the coherent bandwidth is due to the reflection of the surface wave at the termination as discussed in Section 3.3.3, then with proper termination for the surface wave, the coherent bandwidth may be increased sufficiently to accommodate wideband transmissions, including television.

5. REFERENCES

1. C.E. Paul, "Telephone Aboard the Metroliner", Bell Laboratories Record, March 1969, pp 77-84.
2. Sumitomo Electric Industries Ltd., "Leaky-Wave Coaxial Cable", Patent UK1179520, Feb. 1968; publ. 28 Jan. 1970; prior. 3 Feb. 1967, Japan.
3. J.S. Brown, "RADIAX, a New Slotted Cable for Short Range Radio Communication", International Conf. on Communication Record, Seattle Washington, pp 52-12, 52-15, June 1973.