MEASUREMENTS OF INTERFERENCE TO TELEVISION RECEPTION NEAR LARGE HORIZONTAL AXIS WIND TURBINES*

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ABSTRACT

Measurements are described to determine the television interference (TVI) effects in the vicinity of a large horizontal axis wind turbine (WT). The interference manifests itself in the form of distortions of the television (TV) video reproduction, or picture. The on-site measurements were conducted by receiving the available commercial TV signals at a number of test sites judiciously selected in the neighborhood of the operational WT. The experimental setup and measurement techniques, the types of measurements, and the reduction of the data necessary to estimate the interference effects are discussed. Representative results obtained from measurements performed with the operational MOD-1 WT at Boone, NC, and their interpretation are also given. Similar measurement techniques and data collection procedures apply also to vertical axis WTs.

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I. INTRODUCTION

The interference to television (TV) reception caused by the rotating blades of large horizontal axis wind turbines (WTs) has been reported previously in [1-4] where the initial theoretical predictions of such effects were confirmed by observations made in the vicinity of the experimental MOD-0 WT at Plum Book, Ohio. Since then, an extensive program of theoretical and experimental research related to the electromagnetic interference effects of large WTs [5-12], particularly the television interference (TVI) effects, has been carried out. As a result of this, the TVI effects produced by large horizontal axis WTs have been quantified [4,10] and theoretical techniques have been developed for their analysis [10] and prediction [12]. Some of these results have been verified by on-site measurements made with operational MOD-OA [8], MOD-1 [10] and MOD-2 [11] WTs, and the procedures for the performance of such tests have now been standardized [10,11].

Although the TVI effects of large horizontal axis WTs are fairly well understood at the present time, theoretical predictions [12] assume an idealized scattering model of the WT located above a smooth and homogeneous spherical earth. Unfortunately, WTs are often installed in rough terrain for which there is presently no acceptable electromagnetic model to compute the required field quantities. In such cases, and also to obtain the detailed information regarding the interference effects of an operating WT in an actual environment required for a site assessment, it is often necessary to rely on measurements. These are carried out by receiving commercially available TV signals at test sites selected in the neighborhood of the operational WT.

The present paper describes how the TVI effects of large WTs are determined from measurements carried out in their vicinity. The experimental arrangement and measurement procedures, the types of measurement required for a detailed understanding of the effects produced and for a site assessment, and selected results obtained from the measurements made with the MOD-1 WT, are discussed. Although only large horizontal axis WTs are considered, similar procedures are also appropriate for large vertical axis WTs [13].

II. The TVI PHENOMENON

To put the paper in proper perspective, we shall begin with a brief description of the interference effects on TV reception caused by a WT. Previous studies [2,4,8] have shown that the rotating blades of a large horizontal axis WT can interfere with TV reception by producing video distortion. Generally, at a given distance from the WT, the interference increases with increasing frequency, and is therefore worse on the upper UHF TV Channels than on the lower ones. It also decreases with increasing distance from the machine, but in the worst cases can still produce objectionable video distortion at distances up to a few miles [10]. For ambient (i.e., primary or direct) signals well above the noise level of the receiver, there is in general no significant dependence on the ambient signal strength, and no audio distortion has been observed [3,4].

The interference is caused by the time varying (pulse) amplitude modulation of the received signal produced by the rotation of the blades. As shown in Fig. 1, in a neighborhood of a WT the signal scattered by the blades (acting as a time varying multipath source) combines with the primary signal, thereby amplitude modulating the total signal received [3]. The modulation waveform generally consists of sinc-like pulses whose width is inversely proportional to the electrical length of a blade with amplitude directly proportional to the equivalent scattering area [3,4], repeating at twice the rotation frequency of the blades. If sufficiently strong, these extraneous pulses can distort the received picture, whereas the audio information, being transmitted by frequency modulation, remains unaffected.

When the blades are stationary the scattered signal may appear on the TV screen as a ghost whose position (i.e., separation from the direct picture) depends on the difference between the time delays suffered by the direct and scattered signals. A rotation of the blades then causes the ghost to fluctuate, and if the ghost is sufficiently strong, the resulting interference can be objectionable. In such cases the received picture displays a horizontal jitter in synchronism with the blade rotation. As the interference increases, the entire (fuzzy) picture also shows a pulsed brightening, and still larger interference can disrupt the TV receiver's vertical sync, causing the picture to 'roll' (flip) or even break up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering, primarily specular, off the broad face of a blade, and is called the backward region interference. As the angle ϕ (see Fig. 1) between the WT-transmitter and WT-receiver directions increases, the separation of the ghost decreases, and a somewhat greater interference is now required to produce the same amount of distortion. In the scattering region where the WT is almost in line between the transmitter and the receiver ($\phi \simeq \pi$ in Fig. 1), there is virtually no difference in the times of arrival of the primary and secondary signals. The ghost is then superimposed on the undistorted (direct) picture, and the video distortion due to interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. This type of interference is called the forward region interference. In all cases, the amount of interference depends on the strength of the scattered signal relative to that of the primary signal at the receiver, and this decreases with increasing distance from the WT.

The observed video distortion also depends on this ratio, i.e., on the modulation index m of the total received signal, and the modulation threshold m_0 is defined to be the largest value of m for which the distortion is still judged to be acceptable [4]. The threshold is obviously subjective, but as a result of laboratory simulation studies [3,4], scale model measurements [6], and field testing using operating WTs [8,10,11], it has been established [4,12] as 0.15 for $\phi = 0°$ increasing uniformly to 0.35 for $\phi = 180°$. The latter value is for a strong ambient signal, and could be as small as 0.15 in a low signal area. The video distortion is judged acceptable for $m < m_0$, and a discussion of the resulting distortion as a function of m obtained under various conditions can be found in [4].

The video distortion that is observed at any one time depends on the operational state of the WT and this is, in turn, determined by the wind conditions. The following characteristics of large WTs are relevant to our discussion:

(i) They operate at 10-40 rpm in 10-30 mph winds, and the machines are designed to cut out for wind speeds outside this range.

(ii) The nacelle pointing direction can be yawed in azimuth through 360°. The nacelles of downwind and upwind machines are aligned with and against the wind flow respectively, and wind direction therefore determines the plane of rotation of the blades.

(iii) The blade pitch varies with wind speed.

Most machines are computer controlled to respond to the changing wind conditions at the WT site, and the video distortion observed at any one place and time is therefore a function of the wind. The experiments described are designed to measure the maximum interference that can occur at the test sites.

III EXPERIMENTAL ARRANGEMENT

A schematic block diagram of the experimental setup required for performing the measurements is shown in Fig. 2 where only those components pertinent to the data collection have been included. The rotatable receiving antenna is usually a commercial TV antenna located at the test site at a convenient height (~20 ft) above ground. With any given TV transmission a portion of the signal is scattered by the WT and this, together with the desired direct signal, is picked up by the antenna and is fed to a spectrum analyzer connected to a paper tape recorder which provides a record on paper for later evaluation.

The combination of spectrum analyzer and paper tape recorder is used to measure the ambient levels of the video and audio carrier signals without the WT in operation and to record the total signal received as a function of time, including any modulation produced by the scattering off the operating WT. The general quality of the ambient TV reception and the existence of any WT-produced video distortion are observed on the TV screen, and the video recorder is employed whenever it is felt desirable to record the program. Usually, the equipment is powered from a commercially available 60 Hz supply; in the absence of such power at the test site, a portable power supply is necessary.

It is desirable to place all the test instruments inside a vehicle (station wagon or van) with the receiving antenna and its associated tower and rotor assemblies installed on the roof of the vehicle in a demountable fashion. When equipped in this manner, the vehicle can serve as a mobile laboratory and can be easily moved from site-to-site. The following is a list of the minimum equipment needed for the mobile laboratory: spectrum analyzer, paper tape recorder, two TV receivers, video recorder, directional receiving antenna, antenna tower and rotor, two walkie-talkies, portable power supply (optional), line conditioner (optional) and a station wagon or a van.

We have found it convenient to use two TV receivers, with one displaying the received program while the other is used in conjunction with the video recorder; however, the second is not essential. The walkie-talkies are necessary to communicate between the test and WT sites; and to avoid extraneous interference, the one at the test site should not be used for transmission when video recording is in progress. On occasion, it has been found [3] that the WT interference actually caused the video recorder to lose its synchronization, thereby adding distortion to that rightfully attributable to the windmill. In such cases, it is necessary to use a TV camera to photograph the picture on the screen of the TV receiver to assure a faithful record of the true interference. Apart from the personnel controlling the WT, two people are sufficient to operate the equipment and perform the tests.

IV. TYPES OF MEASUREMENT

At each test site, some or all of the following types of measurements are performed for every available TV Channel of interest,

(i) Received Signal Strength: With the WT stationary, the strength of the received signal is measured by rotating the main beam of the receiving antenna until the output is a maximum. By tuning the spectrum analyzer through the TV Channel band of frequencies, a chart recording the output versus frequency is obtained from which the video and audio signal strengths in dBm (dB above one milliwatt) can be found. Similar measurements are also performed at the WT site with the receiving antenna at the base or (preferably) on top of the WT tower. These measurements provide information about the expected quality of TV reception in the area, and also the ambient field strengths of the various TV Channels at a test site relative to those at the WT site which play an important role in the TVI effects produced by the WT [3,10,11].

(ii) Blade Scattering (Static). With the WT blades locked in a desired position (usually vertical or horizontal) and their pitch set for maximum power, the WT is yawed in azimuth through 360°. By measuring the TV signals received with the antenna beam pointed at the WT, the maximum blade-scattered signals are determined. The equivalent scattering parameters of the WT-blade can be determined from these measurements [10,11].

(iii) Antenna Response: As the antenna is rotated, the output of the spectrum analyzer is recorded as a function of antenna beam pointing angle, with and without the WT blades rotating. These measurements serve to determine (a) the horizontal plane pattern of the antenna in the actual test environment, (b) the effect of the WT on the received signal, and (c) the amount of signal modulation produced by the blade rotation.

(iv) TV Interference: These dynamic measurements require the WT blades to be rotating. With the antenna beam positioned to receive the maximum signal (this generally occurs when the beam is directed at the distant TV transmitter) the spectrum analyzer output is recorded as a function of time, while observing the received picture on the TV screen for any video distortion. Video recordings are made at this time if it is felt desirable to preserve the video effects for future reference. Sometimes the measurements are repeated with the antenna beam pointed at the WT to simulate the worst possible situation of a mis-positioned antenna; the result is usually a high level of interference [8,10].

Generally, all of the measurements discussed above are required for a detailed evaluation of the TVI effects of a WT and also for a complete TVI assessment of a given WT site. The dynamic measurements ((iii) and (iv)) made on the desired TV Channels are sufficient when only the TVI effects of the WT at a given site are of interest.

V. REMARKS FOR DATA INTERPRETATION

The following comments may be helpful for appreciating and interpreting the results presented later.

Paper Tape Recorder Output

During all but the signal strength measurements, the spectrum analyzer is tuned to the audio carrier frequency of the TV Channel signal under consideration. This is done because the audio carrier is frequency modulated and, after first (envelope) detection by the spectrum analyzer, appears noise-like (ideally constant) in time. Hence its output, as recorded by the paper tape recorder, directly indicates the audio carrier signal strength P_a in dBm. Any extraneous amplitude modulation is then easy to identify in the paper tape recorder output.

Quality of Reception

According to TV industry specfications [14], good video reproduction is obtained if the received video signal produces a minimum of 1 mV (rms) across the input terminals of a TV receiver presenting an impedance of 75 Ω, and if the signal produces only 0.2 mV, the picture quality will be snowy and of generally poor quality. The corresponding video signal powers P_v at the input terminals of the receiver are 1.3×10^{-5} and 5.3×10^{-7} W, i.e., -49 and -63 dBm, respectively. During our measurements of P_v, the simultaneous observation of the picture quality produced by the TV receiver (1976 Zenith Model 17GC45) were generally consistent with the criteria.

For measurements of WT interference, the spectrum analyzer is tuned to the audio carrier frequency of the TV signal. Since the relevant ambient signal strength is then P_a, it is convenient to express the criteria for quality of reception in terms of this parameter. From our measurements and observations with the present receiver on all TV Channels, it has been found that the quality of reception is approximately related to P_a as follows:

$P_a \geq -56$ dBm	good reception
-56 dBm $> P_a \geq -70$ dBm	poor (snowy) reception
$P_a < -70$ dBm	extremely poor (unacceptable) reception

This implies

$$\frac{P_a}{P_v} \simeq -7 \text{ dB} \quad .$$

Observed Video Distortion

As mentioned earlier, the amount of video distortion observed at any site is determined by the modulation level (or index) m of the received signal [4], and this can be obtained from dynamic measurements of the signal vs time (P_a vs time). Under certain conditions, the maximum possible modulation can be derived from the static measurements and then used to obtain the equivalent scattering area of a blade [10,11].

Any extraneous modulation appears as a fluctuation in dB above and below the ambient level, and from the total dB variation Δ, the modulation index can be obtained using the relationship

$$\Delta = \log_{10} \frac{1 + m}{1 - m} .$$

Thus, the threshold modulation in the backscattering direction $m_o = 0.15$ corresponds to a total signal variation $\Delta_o = 2.6$ dB increasing uniformly with angle to 0.35 (or $\Delta_o = 6.3$ dB) in the forward direction. The latter value is for a strong ambient signal ($P_a \geq 56$ dBm) and could be as small as $m_o = 0.15$ ($\Delta_o = 2.6$ dB) in a weak signal area.

VI SELECTED RESULTS AND THEIR INTERPRETATION

The results of measurements made with the MOD-OA, MOD-1 and MOD-2 WTs are analyzed and discussed in [8], [10] and [11], respectively. Representative results of signal strength and dynamic measurements performed at selected test sties in the neighborhood of the MOD-1 at Boone, NC, are presented here. The static measurements and the determination of the scattering area of a WT-blade will be the subject of a future paper, and, hence, will not be described.

A. The MOD-1 WT [15]

The MOD-1 WT is a two-bladed horizontal axis machine designed to generate 2 MW of power at a rated rotor speed of 35 rpm in a 35 mph wind.

The height of the top of the tower, or more precisely the rotor axis, is 140 ft; the steel blades are 240 ft tip-to-tip with a coning angle of nine degrees and are individually controlled. The WT is located on a mountain top called Howard's Knob, at an elevation of 4420 ft above sea level. This is one mile north of the city of Boone, which is located in a valley about 1500 feet below the WT site in the Blue Ridge Mountains. Further details about the WT and the nearby region may be found in [10,15].

B. Test Sites, TV Stations and Receiving Antennas

Signals on nine commercial VHF TV Channels were generally available for reception in the Boone area. Strong signals (audio carrier in the range of -30 to -40 dBm) were available on all of the nine TV Channels at the WT site, and they provided excellent reception at this site when the WT was not operating. Since most of the TV transmitters are far away (more than 60 miles from the WT), and because of the strong shadowing effect of the surrounding mountains, the ambient signals at locations away from the WT were generally weak (less than -70 dBm) for all of the TV Channels, and not all Channels could be received at any one place.

The geometry of the two test Sites A and I with respect to the WT and the direction of the transmitters of the two stronger TV Channels are shown in Fig. 3. Under normal conditions (i.e., the mainbeam of the receiving antenna directed toward the desired transmitter and the WT not operating), the quality of reception at Site A was good on Channel 3 and unacceptable on Channel 5; on both Channels the reception was only fair to poor at Site I.

During the time when the data were taken, the wind was generally blowing from the southeast. By referring to Fig. 3 it can be seen that for Channel 3 reception Site A was in the backward region of interference, and that the plane of rotation of the blades was such that signals specularly scattered off the blades could reach the site. Nearly similar conditions applied to Site I for Channel 3 reception, but, for reception of Channel 5, Site I was in the forward region of interference.

Most of the data presented were collected with a commercially available high gain TV receiving antenna (Winegard Model No. CH8200) located at a height of 20 ft above ground. This is a modified log periodic antenna designed to cover the entire band of commercial VHF and UHF channel frequencies. The gain (above isotropic) of the receiving antenna is about 9.5 and 13 dB, with front-to-back ratio 22 and 26 dB, on Channels 3 and 5, respectively. The total half-power (3 dB) beamwidth of the antenna is about 70° on both of the above two Channels.

C. Ambient Signals

The measurements were made with the WT stationary using the Winegard antenna. At each site and for all of the desired TV Channels, the received video and audio powers, P_v and P_a, respectively, were obtained from the recordings of the spectrum analyzer output in the manner described in Section IV. In addition, the quality of reception was examined using the TV receiver.

With the spectrum analyzer tuned to the audio frequency for a particular TV Channel, the output P_a was recorded as the antenna was rotated through 360°. This was done to measure the horizontal plane pattern of the antenna in the actual environment, and to determine the direction from which the TV signal was received. The recording for Channel 3 at the base of the WT (the actual site was about 50 ft from the base of the tower in the SE direction) is shown in Fig. 4. With the antenna now oriented to receive the maximum signal, the spectrum analyzer was then tuned through the TV Channel band of frequencies and the output recorded. Figure 5 shows the results for Channel 3 at the same site. As is true for all TV Channels [14], the audio power peak occurs at a frequency 4.5 MHz above the video power peak. The recieved video and audio carrier signal strengths P_v and P_a can be obtained directly in dBm, and from Fig. 5 we have P_v = -22 dBm, P_a = -27 dBm. At the transmitter, the audio signal power radiated is 7 to 10 dB below the video [14], but because of different losses suffered during propagation, the ratio of P_a to P_v may differ from this, and may vary from Channel-to-Channel and from site-to-site. It was observed that P_a was, in general, 0 to 10 dB below P_v, but in a few instances P_a actually exceeded P_v [10]. Recordings similar to these were made at all sites, and were used to judge the quality of reception at a particular site and on a desired Channel.

D. Dynamic Results at Sites A and I

The nature and degree of television interference caused by the operating MOD-1 WT was determined by carrying out dynamic tests at various sites. As indicated in Section IV, the tests involved the measurement of P_a vs antenna beam pointing direction as the antenna was rotated in a horizontal plane, and P_a vs time for the antenna pointed at the TV transmitter and at the WT. The latter have been referred to as TVI tests, and while they were being performed, the quality of TV reception was simultaneously monitored using the TV receiver. Whenever it was felt desirable, the received picture was video recorded for later evaluation. In the following we discuss the results of the dyanmic measurements conducted using the TV Channels 3 and 5 at two of the test sites mentioned earlier.

The antenna response under dynamic conditions obtained on Channel 3 and at Site A is shown in Fig. 6, where the angles corresponding to the transmitter (T) and WT directions are indicated. The time scale is inserted on the abscissa so that the time behavior can also be examined.

A recording such as that in Fig. 6 generally indicates the type of TVI that may occur, and the severity of the interference for a given pointing direction of the antenna. The variable amplitude modulation pulses in Fig. 6 are typical of backward region interference, and the three second spacing between the pulses is half the rotation period (six seconds) of the blades rotating at 10 rpm. When the antenna was pointed at or close to the transmitter, the modulation pulses produced very small ($\Delta \sim 0.5$ dB) variations in the received signal, but in directions close to the WT, the pulses are quite strong. The total signal variation ($\Delta \sim 15$ dB) is then larger than the 2.5 dB corresponding to the threshold level of interference. From Fig. 6 it can be concluded that video distortion well below the threshold would occur with the Winegard antenna properly oriented to receive the Channel 3 signal, and the ambient level (~ -68 dBm) is such as to provide poor reception. However, if the antenna were pointed at the WT instead, the average received signal would be about 15 dB lower, corresponding to unacceptable reception, and the modulation pulses would produce severe video distortion.

For quantitative analyses of the interference, more detailed measurements of the modulation pulses are desirable. The appropriate P_a vs time data are shown in Figs. 7a and 7b for the antenna pointed at the transmitter and the WT, respectively. The difference in the average power levels P_a is about 15 dB, representing the antenna response in the direction T relative to that in the direction of the WT. As a result of the blade rotation, the total variation Δ in the received signals in the directions T and WT are 0.5 and 14 dB, respectively.

In order to bring out the effects of the receiving antenna on the observed TVI effects, P_a vs time recordings were obtained under dynamic conditions using a Channel Master antenna (gain 4.5 dB, front-to-back ratio 12 dB, beamwidth 70° on Channel 3) and a half-wave dipole (gain 2.2 dB, front-to-back ratio 0 dB, beamwidth 90°). The results are shown in Figs. 8(a,b) and 9, respectively. Comparison of the results shown in Figs. 8 and 9 with those of Fig. 7 indicates that the amplitude of the modulation pulses increases with a decrease in the antenna gain. This clearly demonstrates that in the backward region of interference the observed TVI effects can be reduced considerably (or even eliminated) by using a properly oriented antenna having a sufficiently high gain. It is appropriate to note here that under the conditions of Fig. 9, the TVI effects could be completely eliminated at the expense of a slight reduction in the received signal by properly positioning the sharp null in the antenna pattern (i.e., pointing the end of the dipole at the WT).

The dynamic response of the Winegard antenna obtained at Site I on Channel 5 is shown in Fig. 10 where the occurrence of the strong modulation pulses (in most directions) indicates that the site was in the forward region of interference. The signal vs time obtained with the antenna directed at the transmitter and the WT are shown in Fig. 11 where it is found that the signal variations obtained in the two cases are $\Delta \sim 7.5$ and 13.0 dB ($m \simeq 0.41$ and 0.62, respectively). This shows that the site was not precisely in the forward scattering region. In both cases the observed video distortion was quite strong.

The results obtained at Site I on Channel 5 suggest that the TVI effects in this direction could remain severe at distances beyond the site in the same radial direction from the WT. Indeed, if the conditions pertaining to this site were the same, the interference in this direction would exceed the threshold level (for which $m = 0.15$) out to a distance $0.41/0.15 \times 1.6 = 4.4$ miles.

As mentioned earlier, Site I was in the backward region for the reception of Channel 3 signals. Figure 12 shows P_a vs time on Channel 3 obtained at Site I with the antenna directed at the transmitter. The total Δ is about 3.0 dB and the observed video distortion was slightly above the threshold level. Comparing Fig. 12 with Fig. 7a it is found that with the antenna oriented towards the Channel 3 transmitter, the observed video distortion was more pronounced at Site I than at A, although the former was at a larger distance from the WT.

VI. CONCLUSIONS

Complete on-site measurements required for the estimation of the TVI effects of large horizontal axis WTs, and for the TVI assessment of their sites, have been discussed. Similar measurement techniques and data collection procedures apply also to vertical axis WTs. If only the TVI effects at a specific site near the WT are of interest, dynamic measurements conducted on all of the available TV Channels at that site are sufficient to estimate the effects. Generally, it would require a large number of measurements to determine the TVI effects in a region around the WT, i.e., to perform a full TVI assessment of the WT site. In a future paper we shall discuss the analytical techniques developed to quantitatively explain the results obtained from on-site measurements, and to adequately predict the TVI produced by a large WT.

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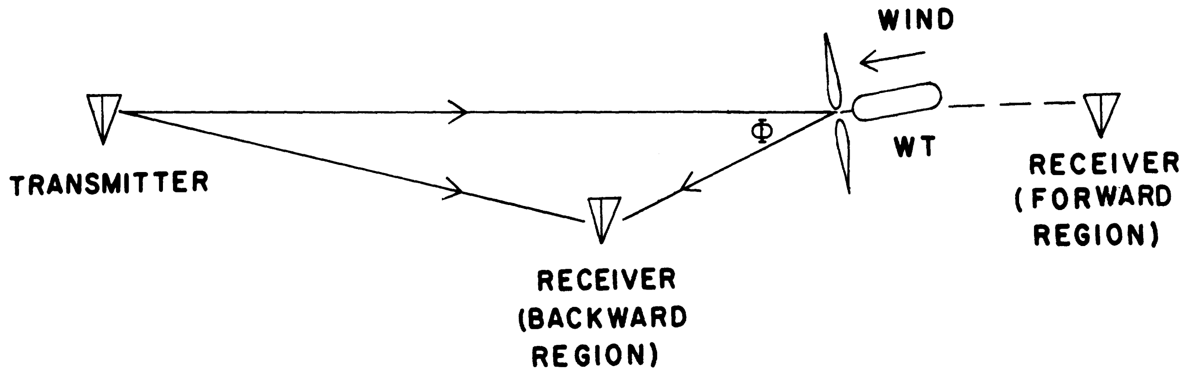
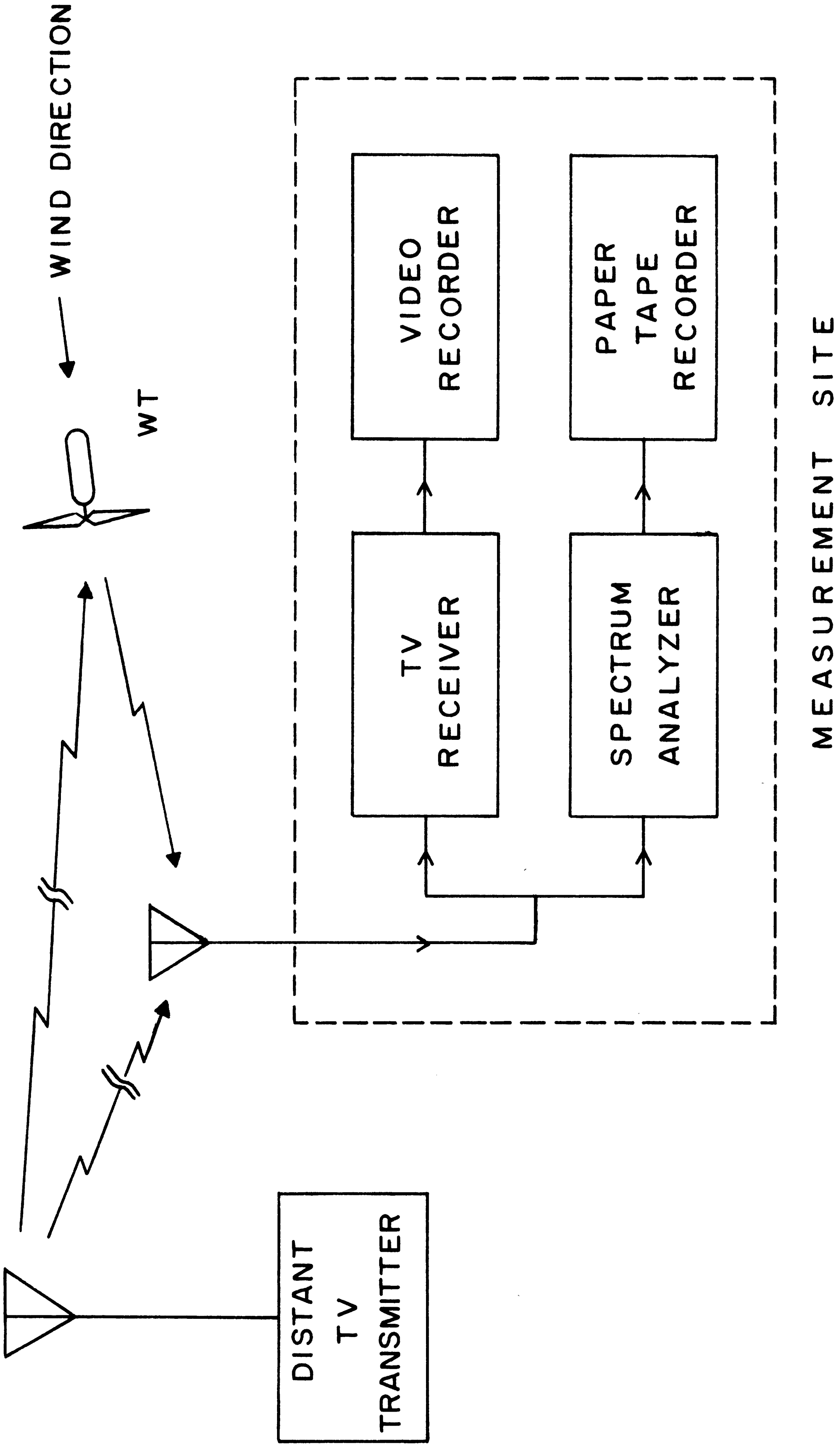
Figure 1



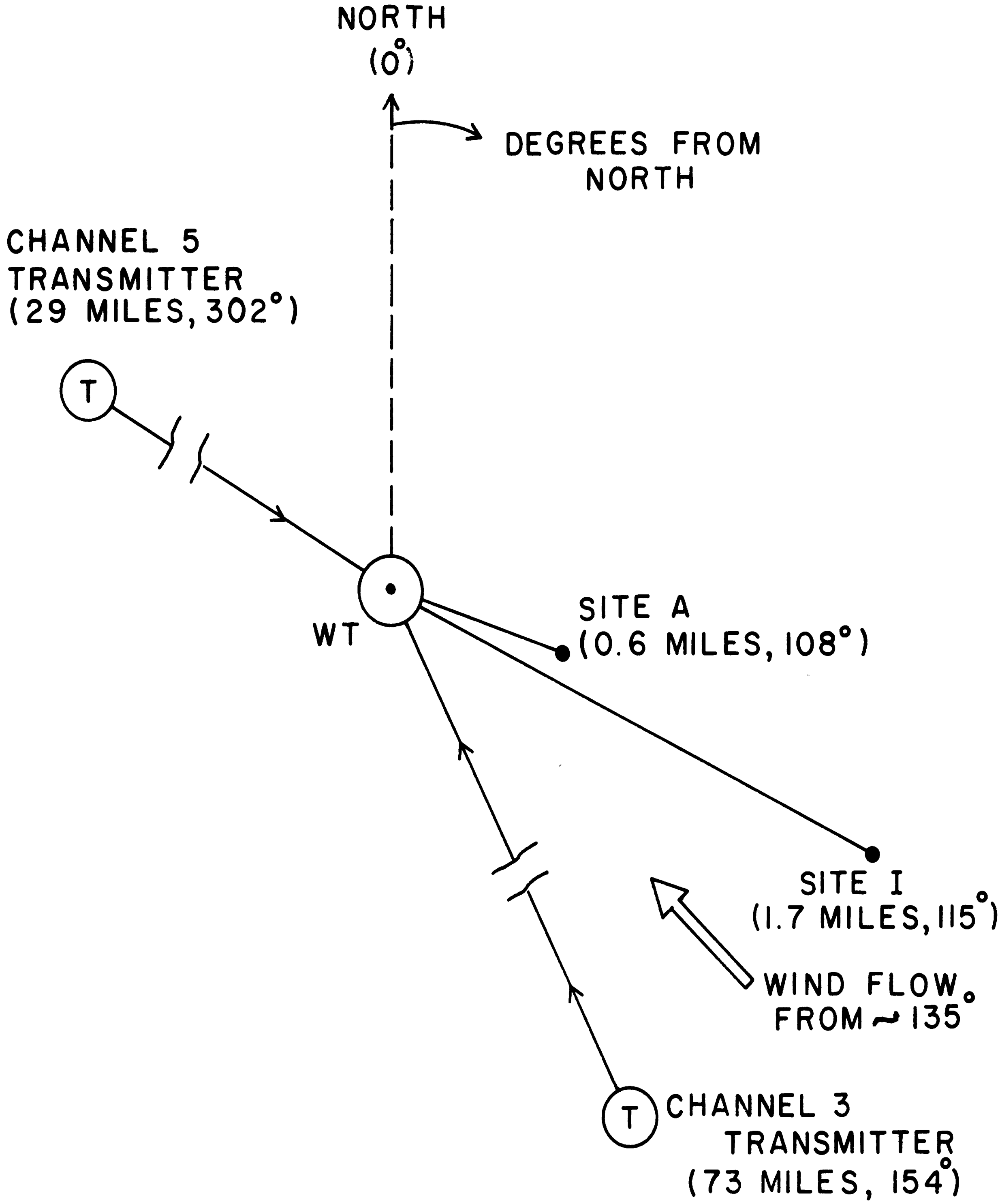
WIND
TRANSMITTER
Φ
WT
RECEIVER
(FORWARD
REGION)
RECEIVER
(BACKWARD
REGION)

Figure 2



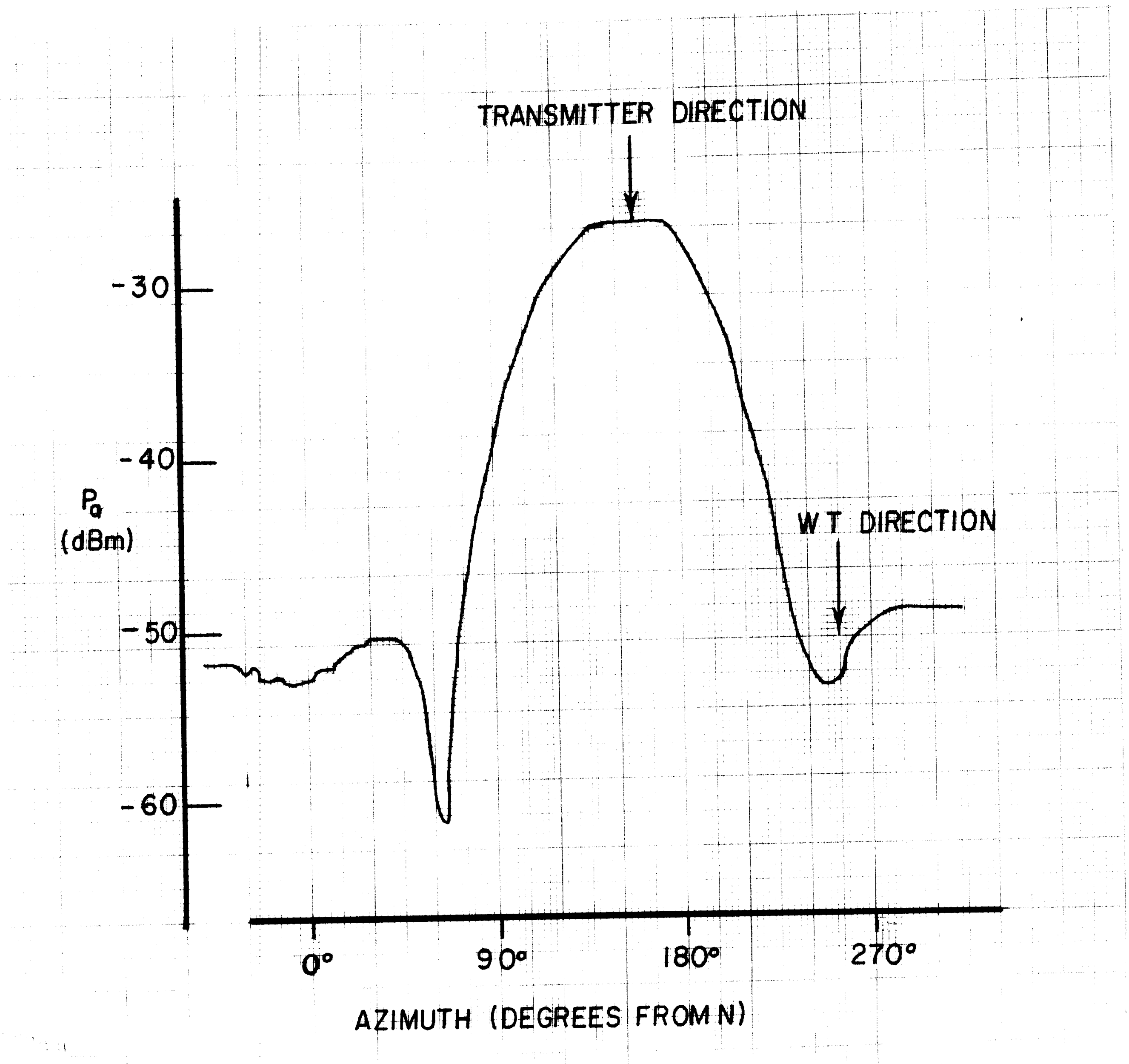
WIND DIRECTION
WT
VIDEO RECORDER
PAPER TAPE RECORDER
TV RECEIVER
SPECTRUM ANALYZER
MEASUREMENT SITE
DISTANT TV TRANSMITTER

Figure 3



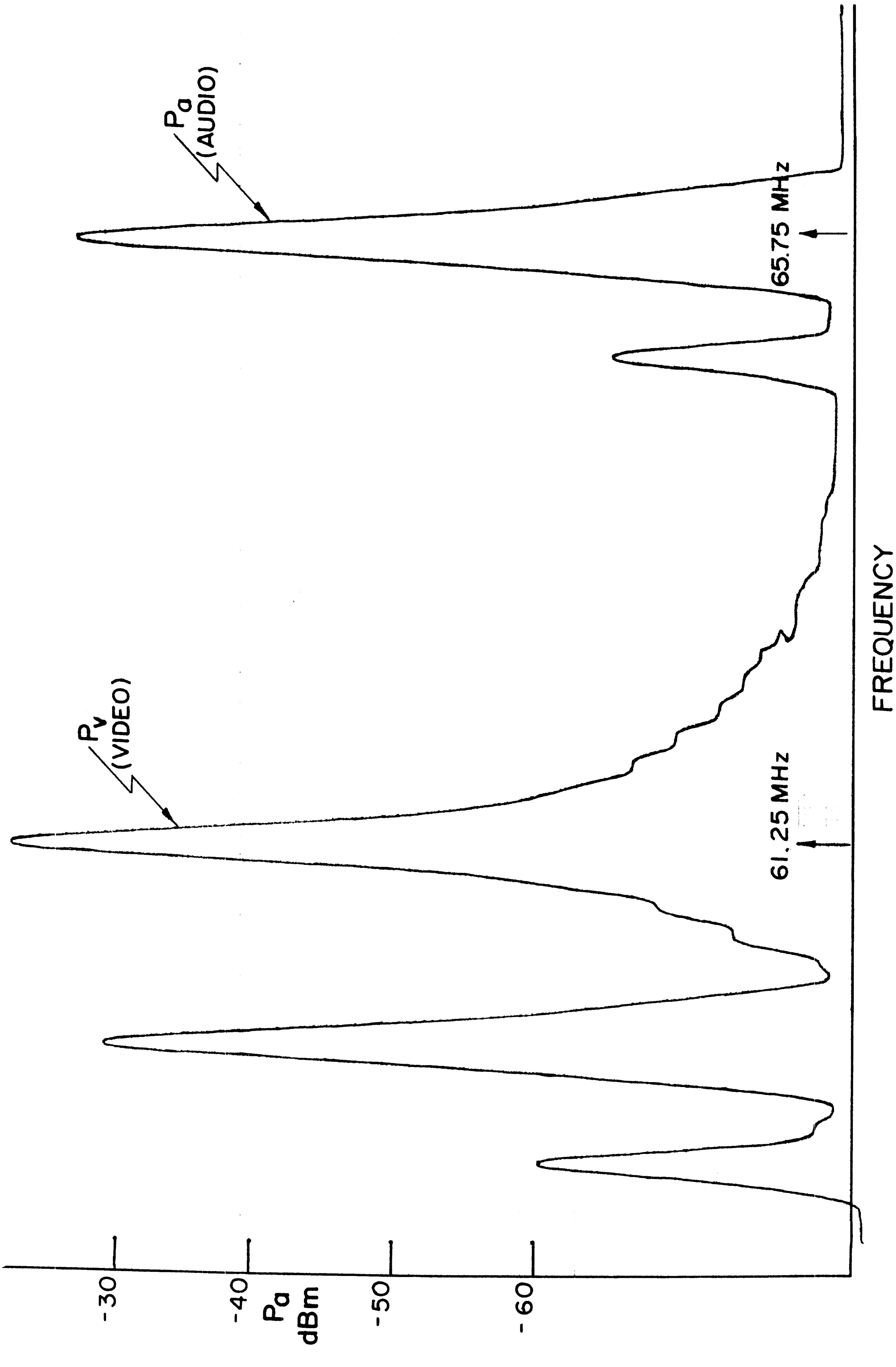
NORTH
(0°)
DEGREES FROM
NORTH
CHANNEL 5
TRANSMITTER
(29 MILES, 302°)
T
WT
SITE A
(0.6 MILES, 108°)
SITE I
(1.7 MILES, 115°)
WIND FLOW
FROM ~ 135°
T
CHANNEL 3
TRANSMITTER
(73 MILES, 154°)

Figure 4



TRANSMITTER DIRECTION
WT DIRECTION
-30
-40
-50
-60
P_a
(dBm)
0°
90°
180°
270°
AZIMUTH (DEGREES FROM N)

Figure 5



-30
-40
-50
-60
P_a
dBm
P_v
(VIDEO)
P_a
(AUDIO)
61.25 MHz
65.75 MHz
FREQUENCY

Figure 6

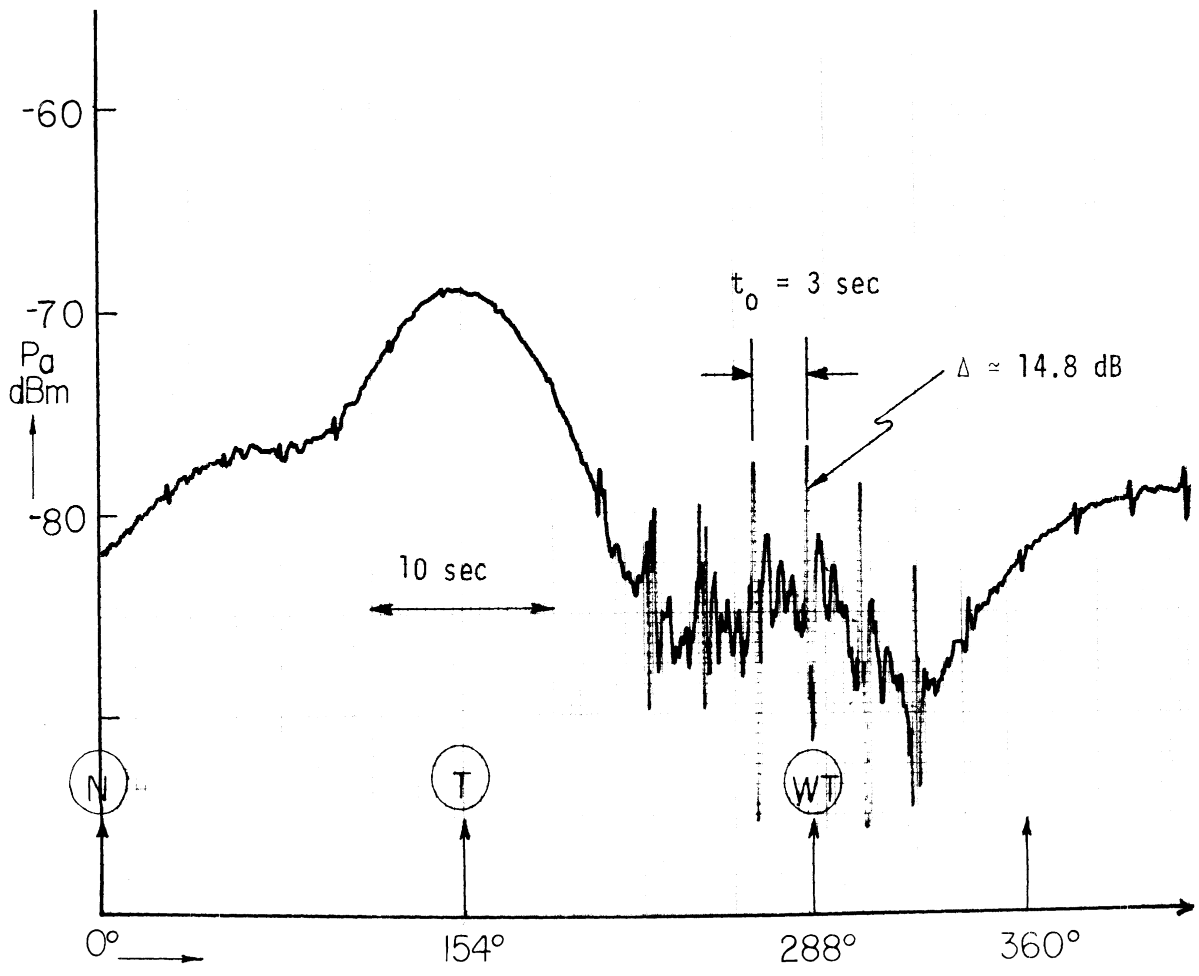
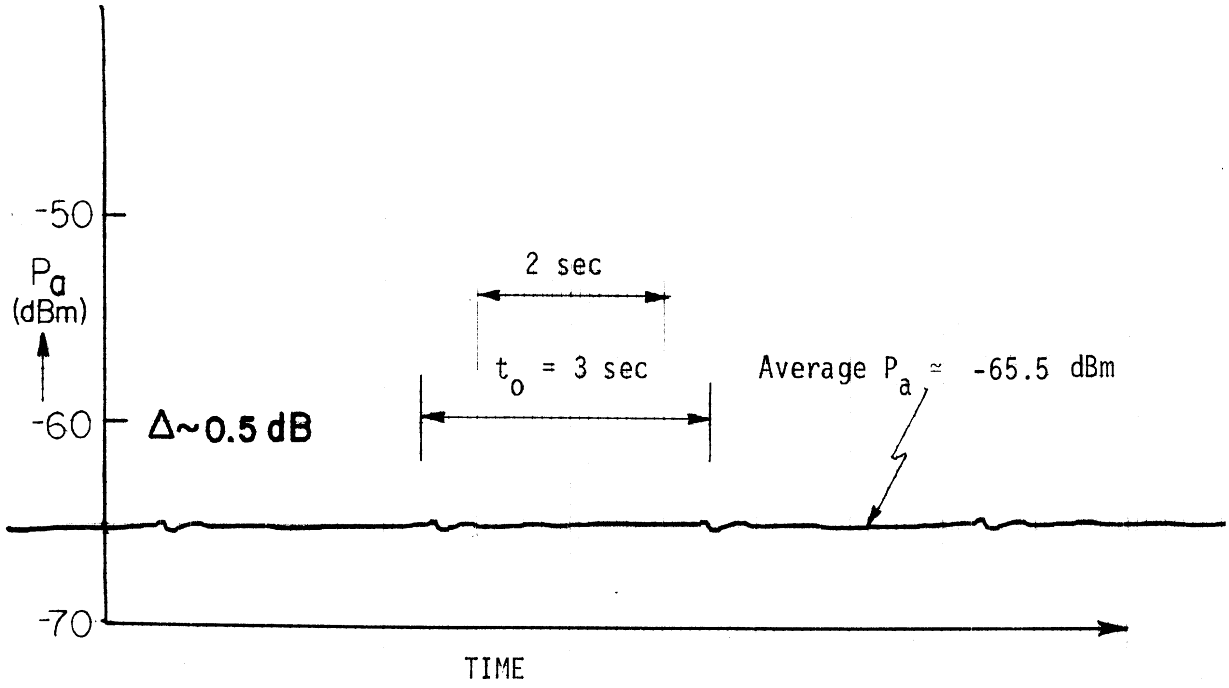


Figure 7

(a) Antenna beam directed at T



(b) Antenna beam directed at WT

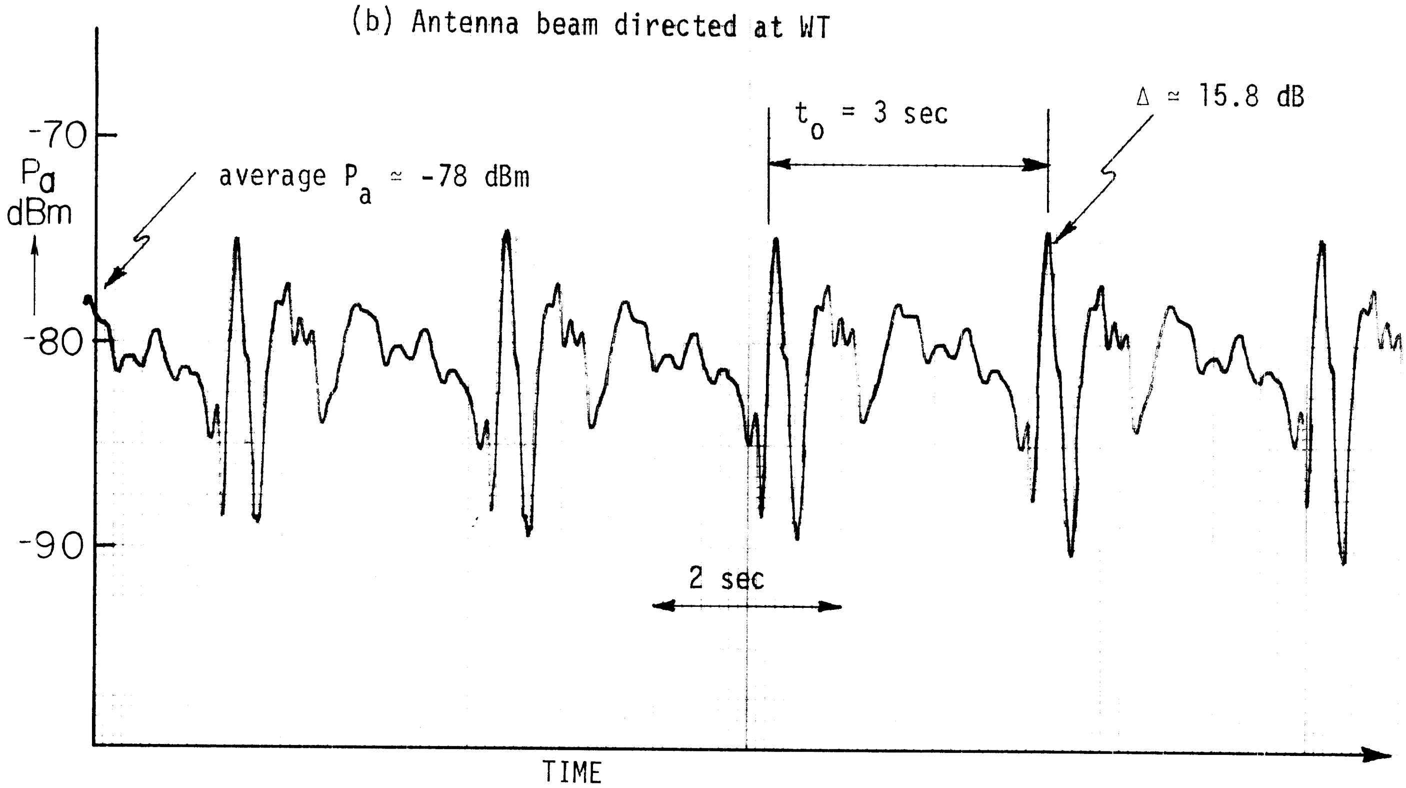
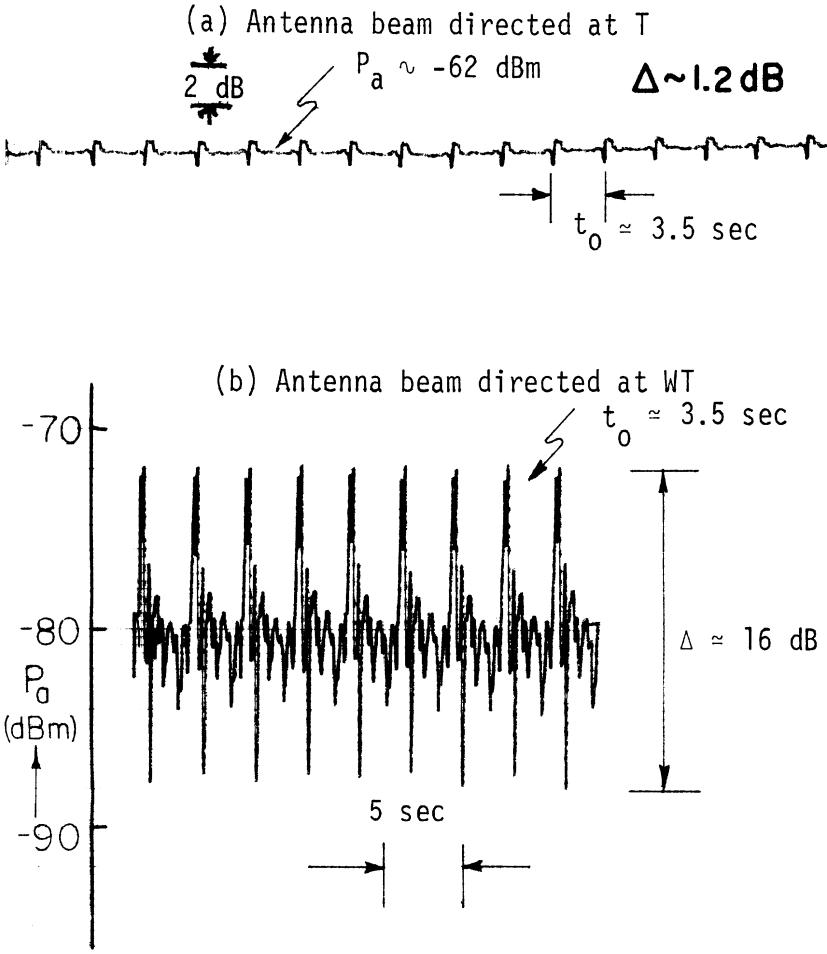


Figure 8



(a) Antenna beam directed at T
2 dB
Pa ∿ -62 dBm
Δ~1.2 dB
to ≃ 3.5 sec
(b) Antenna beam directed at WT
to ≃ 3.5 sec
-70
-80
-90
Pa
(dBm)
Δ ≃ 16 dB
5 sec

Figure 9

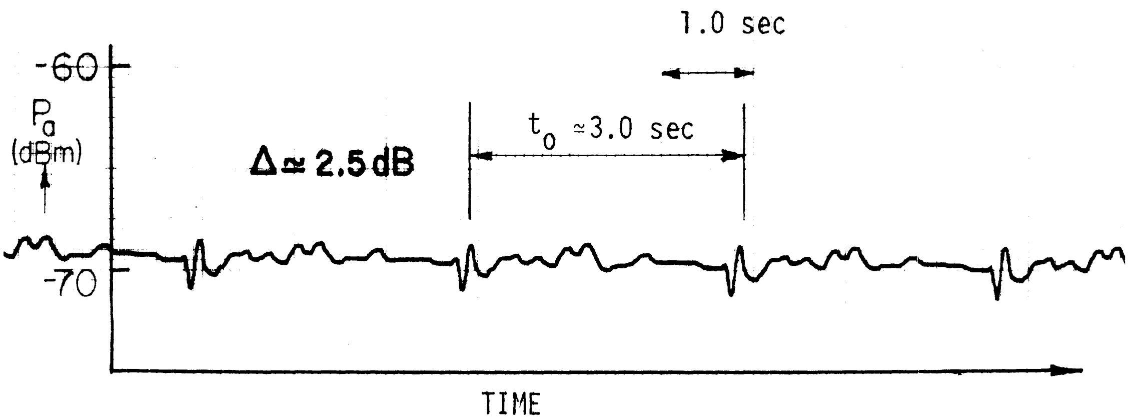


Figure 10

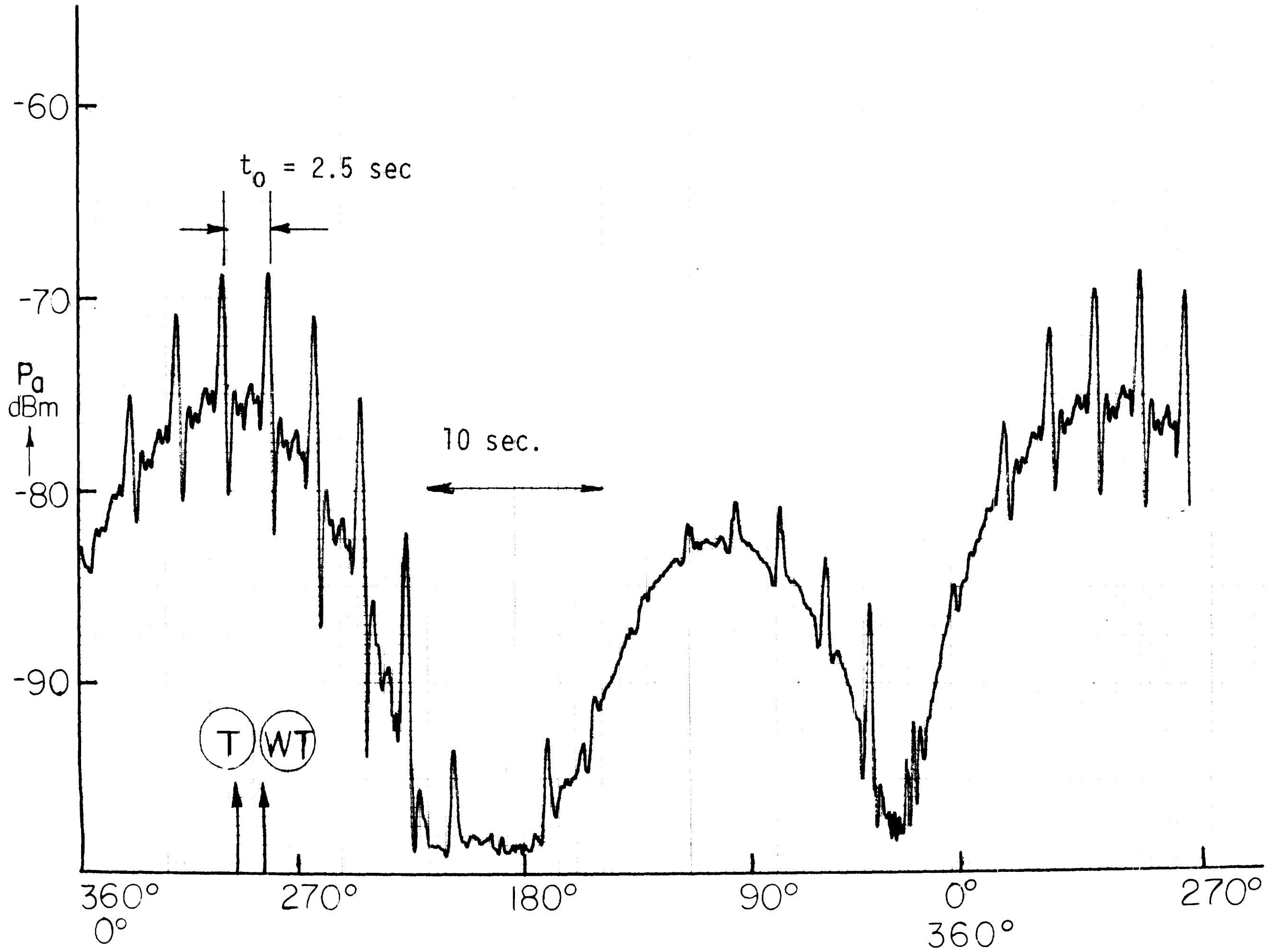
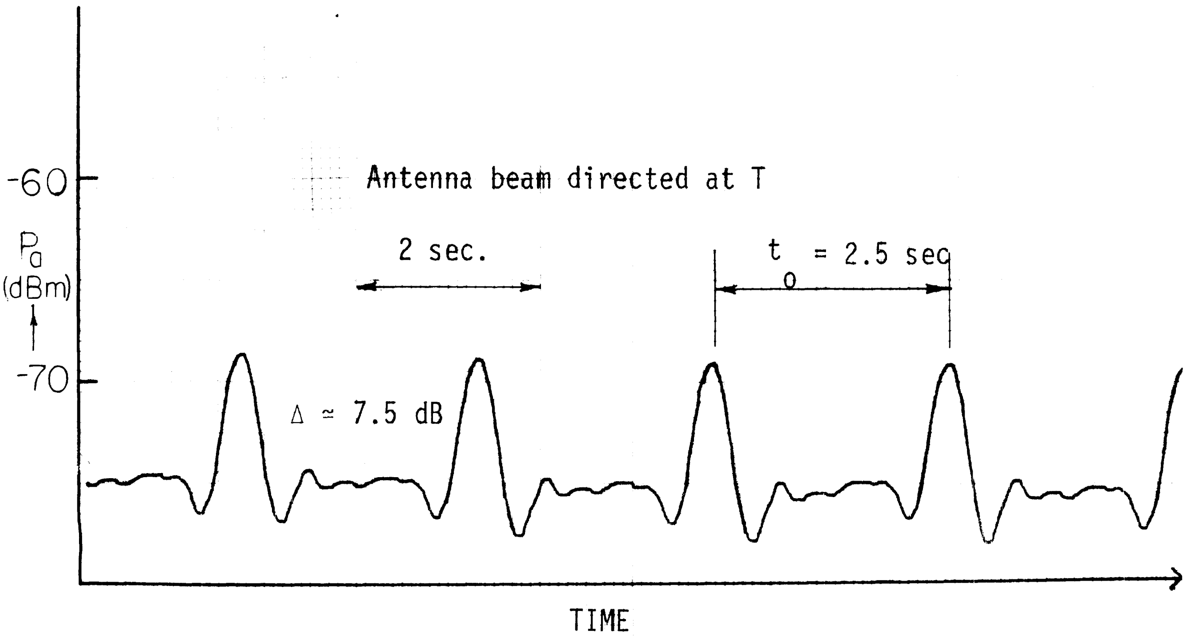
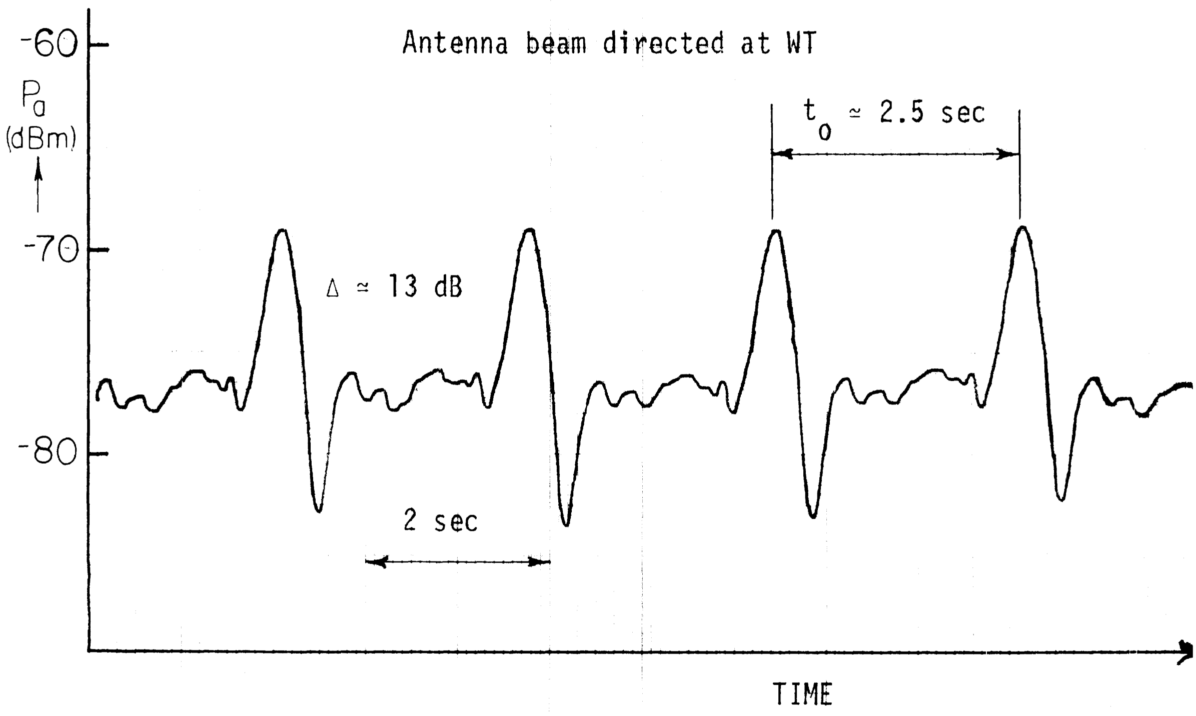


Figure 11

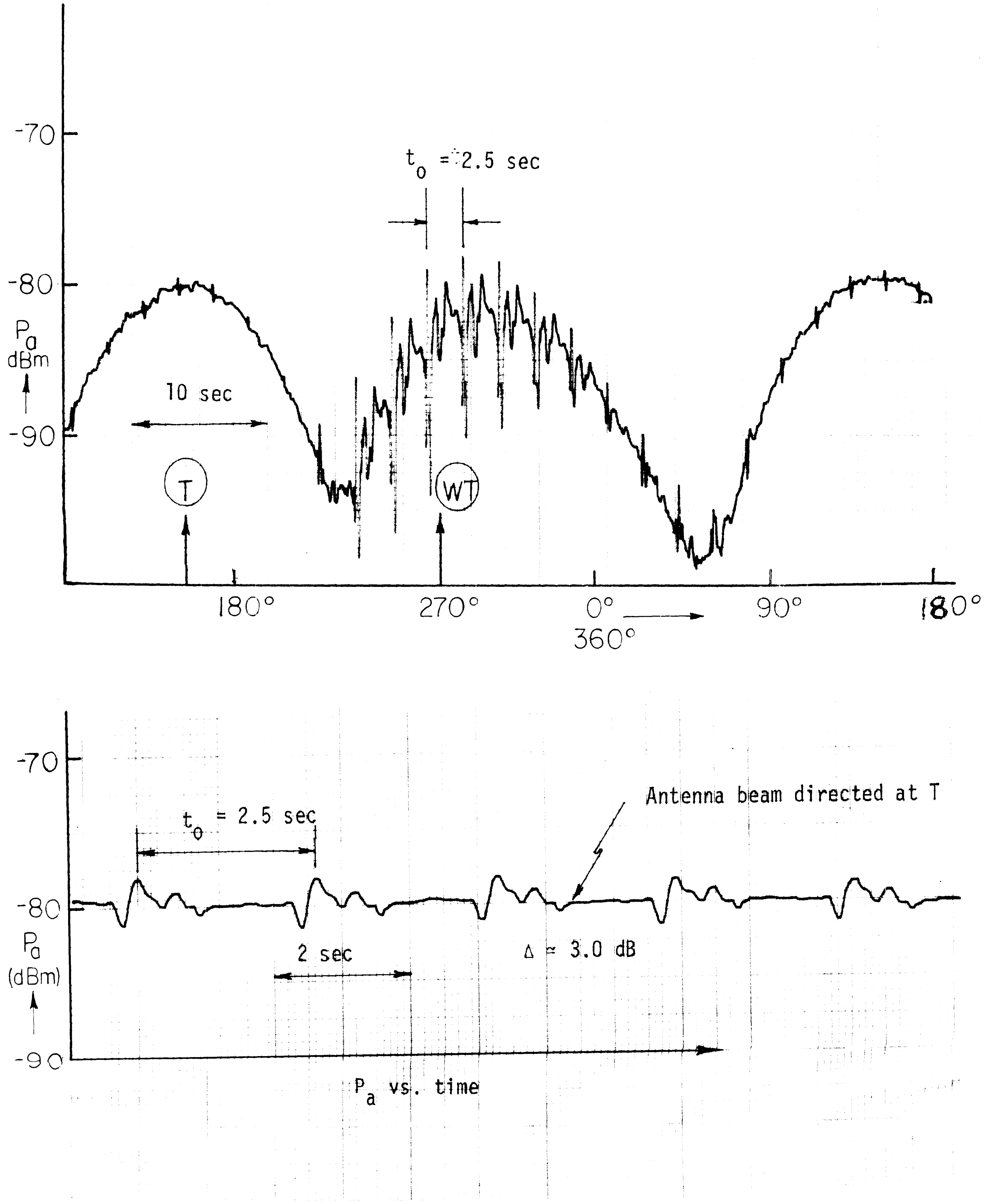


-60
-70
P_a (dBm)
Antenna beam directed at T
2 sec.
t_o = 2.5 sec
Δ ≃ 7.5 dB
TIME



-60
-70
-80
P_a (dBm)
Antenna beam directed at WT
t_o ≃ 2.5 sec
Δ ≃ 13 dB
2 sec
TIME

Figure 12



-70
-80
-90
P_a dBm
t_o = 2.5 sec
10 sec
T
WT
180°
270°
0°
360°
90°
180°
-70
-80
-90
P_a (dBm)
Antenna beam directed at T
t_o = 2.5 sec
2 sec
Δ ≈ 3.0 dB
P_a vs. time