MEASUREMENTS OF TELEVISION INTERFERENCE PRODUCED BY LARGE HORIZONTAL AXIS WIND TURBINES

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ABSTRACT

Television interference (TVI) effects of large horizontal axis wind turbines (WTs) can be determined from measurements carried out in their vicinity. Such on-site measurements are performed by receiving the available commercial TV signals at test sites selected near an operational WT. Generally, at each test site some or all of the following data are collected on each desired TV Channel: (i) ambient signal strength with the WT stationary; (ii) the horizontal plane response of the receiving antenna as a function of its beam pointing angle, obtained under static (WT stationary) and dynamic (WT operating) conditions; (iii) received signal versus time, obtained under dynamic conditions, with the antenna beam directed at the desired TV transmitter and at the WT; (iv) under the conditions of (iii) the received picture is also monitored for any video distortion and, if desirable, a video recording is made for later evaluation. The necessary experimental setup, measurement techniques and reduction of data to estimate the TVI effects are described. Typical results obtained in the vicinity of the MOD-1 WT at Boone, NC, are discussed.

INTRODUCTION

Previous studies [1-3] have shown that the rotating blades of a large horizontal axis wind turbine (WT) or windmill can interfere with TV reception by producing video distortion. 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. It also decreases with increasing distance from the machine, but in the worst case can still produce objectionable video distortion at distances up to a few kilometers. For ambient (primary or direct) signals well above the noise level of the receiver, there is in general no signficant dependence on the ambient signal strength, and no audio distortion has been observed.

The interference is caused by the time-varying amplitude modulation of the received signal produced by the rotation blades. As shown in Fig. 1, in a neighborhood of a WT the signals scattered by the blades (acting as a time-varying multipath source) combine with the primary signal, thereby amplitude modulating the total signal received. The modulation waveform generally consists of sinc-like pulses (whose width is inversely proportional to the electrical length of a blade) 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 shows a pulsed brightening, and still larger interference can disrupt the TV receiver's vertical sync, causing the picture to roll over ('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 in Fig. 1) between the WT-transmitter and WT-receiver direction increases, the separation of the ghost decreases, and a somewhat greater interference is now required to produce the same amount of distortion. In the forward scattering region when the WT is almost in line between the transmitter and the receiver, there is virtually no difference in the times of arrival of the primary and secondary signals. The ghost is then superimposed on the undistorted picture and the video interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. In all cases, the amount of interference depends on the strength of the scattered signal relative to the primary signal, and this decreases with increasing distance from the WT.

The amount of observed video distortion depends on the ratio of the scattered (or interference) and ambient signal strengths at the input to the receiver, 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. The threshold is obviously somewhat subjective, but as a result of laboratory simulations [1], scale model measurements [4], and field tests using MOD-0 machines at Plum Brook [1] and Block Island [2], it has been established [5] as 0.15 for $\phi = 0$ increasing uniformly to 0.35 for $\phi \simeq 180$ degrees. The latter value is for a strong ambient signal, and could be as small as 0.15 in a low signal area. With the WT blades oriented to direct the maximum scattered signal to the receiver, the region where $m > m_0$ is defined as the interference zone [1]. On the assumption of a smooth spherical earth and an omni-directional receiving antenna, a method has been developed [5] for calculating the interference zone of a WT for any given TV Channel. The computation requires the knowledge of the effective length (L) and equivalent scattering area (A) of a WT blade. The interference zone consists of two regions called the backward and forward interference regions. The former, corresponding to specular scattering off the blades, is approximately a cardioid centered on the WT with its maximum pointing towards the transmitter. The latter, produced by forward scattering, is a narrow lobe directed away from the transmitter. The shape of an interference zone is only weakly dependent on the transmitter distance and TV Channel number, but its size increases markedly with increasing frequency (i.e., the TV Channel number).

It appears from the discussion given above that the TVI effects of large horizontal axis WTs are fairly well understood. However, the theoretical prediction of the effects assumes an idealized scattering model of the WT located above a smooth and homogeneous earth. Frequently, WTs are installed in a rough terrain for which there is presently no acceptable model to compute the required fields. In such cases and also for actual WTs, it is often necessary to determine the TVI effects by measurements. The present paper describes how the television interference effects of large horizontal axis wind turbines are determined from measurements carried out in their vicinity. Such measurements are conducted by receiving commercially available TV signals at test sites selected in the neighborhood of the operational WT of interest.

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 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 fed to a spectrum analyzer and a TV receiver. The vertical output of the spectrum analyzer is connected to a paper tape recorder which provides a record on paper tape 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 transported 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 antenna, antenna tower, antenna rotor, two walkie-talkies, portable power supply (optional), line conditioner (optional) and a station wagon or van.

We have found it convenient to use two TV receivers, with one displaying the received program, whilst 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 site and the WT, 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 [1] 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 preferable to use a TV camera to photograph the picture on the screen of the TV receiver, thereby assuring a faithful and reproducible color video recording.

TYPES OF MEASUREMENT

At a test site some or all of the following types of measurement are performed on all of the available TV Channels: (i) Ambient 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. The ambient field strength at the site is then determined from the data by eliminating the effects of the antenna and the associated system losses. Similar measurements are also performed at the WT site with the receiving antenna (preferably) placed on top of the WT tower. These measurements provide information about the expected quality of TV reception in the area, and also the field strengths of the various TV Channels relative to those at the WT site, which play an important role in the TVI effects produced by the WT. (ii) Static or Blade Scattering. With the WT blades locked in a desired position (usually vertical) and their pitch set for maximum power, the WT is yawed in azimuth through 360 degrees. By measuring the TV signals received with the antenna beam pointed at the WT, the maximum blade-scattered signals are determined. From these results, the equivalent scattering area (A) of each blade can be determined. These measurements are important because the interference caused by the WT is directly proportional to A. (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 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 are performed with the WT rotating by recording the received signal versus time with the antenna beam positioned to receive the maximum signal (this generally occurs when the beam is directed at the TV transmitter), while observing the received picture on the TV screen for any video distortion. Video recordings are made if it is felt desirable to preserve the video effects for future evaluation. 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.

DATA INTERPRETATION

The amount of video distortion observed at any site is determined by the modulation level (or index) of the received signal, and this can be obtained from dynamic measurements of the signal 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.

During all of the measurements the spectrum analyzer is tuned to the audio carrier frequency of the TV Channel. This is done because the audio signal is frequency modulated and, after first (or envelope) detection by the spectrum analyzer, is noise-like and ideally constant. Extraneous amplitude modulation is then easy to identify in the paper tape recorder output. It is assumed that the modulation suffered by the video signal is approximately the same as that of the audio signal (P_a).

The dynamic tests yield recordings of P_a (in dBm, i.e., dB above one milliwatt) versus time. Any extraneous modulation shows up as fluctuations in dB above and below the ambient level, and from the total dB variation Δ, the modulation index can be obtained using the relationship $\Delta = 20 \log_{10}(1+m)/(1-m)$. 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 (i.e., $\Delta_o = 6.3$ dB) in the forward direction. The latter is for a strong ambient signal ($P_a \geq -60$ dBm) and could be as small as 0.15 (or Δ_o = 2.6 dB) in a weak signal area.

TYPICAL RESULTS

Electromagnetic interference to television reception caused by the MOD-1 WT at Boone, NC, has been studied [3] by carrying out detailed measurements at a number of test sites in the vicinity of the WT.
In the present section we shall discuss some representative results obtained from dynamic measurements at one test site located 1.6 miles southeast of the WT.

The MOD-1 WT is a two-bladed horizonal axis machine designed to generate two MW of power at a rated rotor speed of 35 rpm in a 25 mph wind. The height to the top of the tower or, more precisely, the rotor axis is 140 ft. The steel blades are 240 feet tip-to-tip with a coning angle of 9 degrees, and are individually controlled. The WT is located on a mountain top called Howard's Knob, elevation 4420 feet, 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.

Strong signals (audio carrier signals in the range -30 to -40 dBm) on nine VHF TV Channels were available at the WT-site, and these provided excellent reception at this site when the WT was not operating. Most of the TV transmitters being far away and also due to the strong shadowing effects of the surrounding mountains, the ambient signals on all of the TV Channels were generally weak (less than -70 dBm) at all locations in the region around the WT, and not all of the Channels could be received. At the present test site, only Channels 2,3,5,8, and 11 could be received. The site was in the forward interference region for Channels 5 and 11, and was in the backward interference region for others. With the WT stationary, the quality of reception was fair-to-poor on Channel 5 and very poor (unacceptable) on other Channels.

The Channel 2 dynamic response of the antenna obtained at the site is shown in Fig. 3 which indicates no (insignificant) modulation when the antenna is oriented to the transmitter direction; and for this orientation of the antenna no video distortion was observed.

The dynamic antenna response, and signal vs. time with the antenna oriented towards the transmitter obtained on Channel 3 are shown in Fig. 4. As indicated in the figure, with the antenna properly oriented to receive maximum signal, the total signal variation caused by the interference is $\Delta \simeq 3.0$ dB, and the observed video distortion was slightly above the threshold value.

The dynamic response of the antenna on Channel 5 is shown in Fig. 5 where the occurrence of the modulation pulses 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. 6 where it is found that the signal variations obtained in the two cases are $\Delta \simeq 7.5$ and 13.0 dB or $m \simeq 0.41$ and 0.62, respectively. This indicates that the site was not precisely in the forward scattering direction. In both cases, the observed video distortion was quite strong.

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

CONCLUSIONS

On-site measurements required to estimate the TVI effects of large WTs have been discussed. If the interference effects at a site are of interest only, then the dynamic measurements at that site are sufficient for the estimation of such effects. Of course, TVI effects at other sites can be determined by conducting similar measurements there. However, to determine the effects in the entire region around the WT in this manner would require a large number of measurements. We have developed [5] an approximate theory which can adequately predict the TVI produced by a large WT. The key information needed to apply the theory is the equivalent scattering area of a blade, the ambient signal strengths (of all of the TV Channels of interest) at the WT and at the receiving sites of interest, and the characteristics of the receiving antenna.

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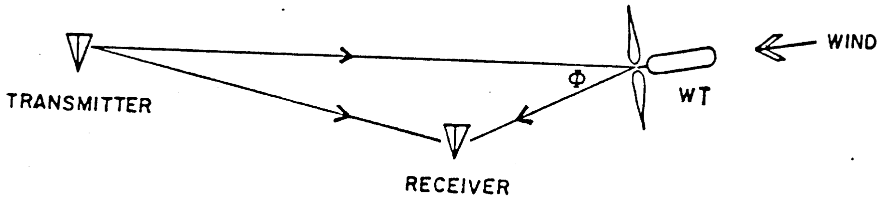

Fig. 1 Geometry of the WT Blade Scattering.

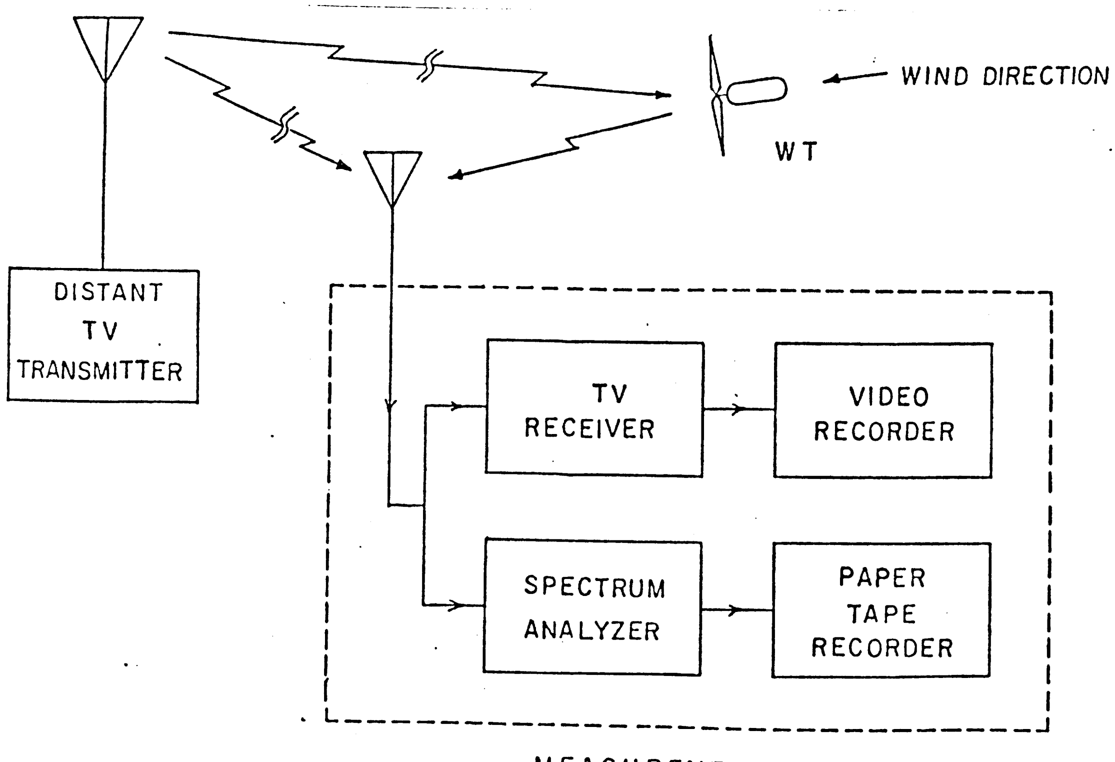

Fig. 2 Schematic Block Diagram of the Measurement System.

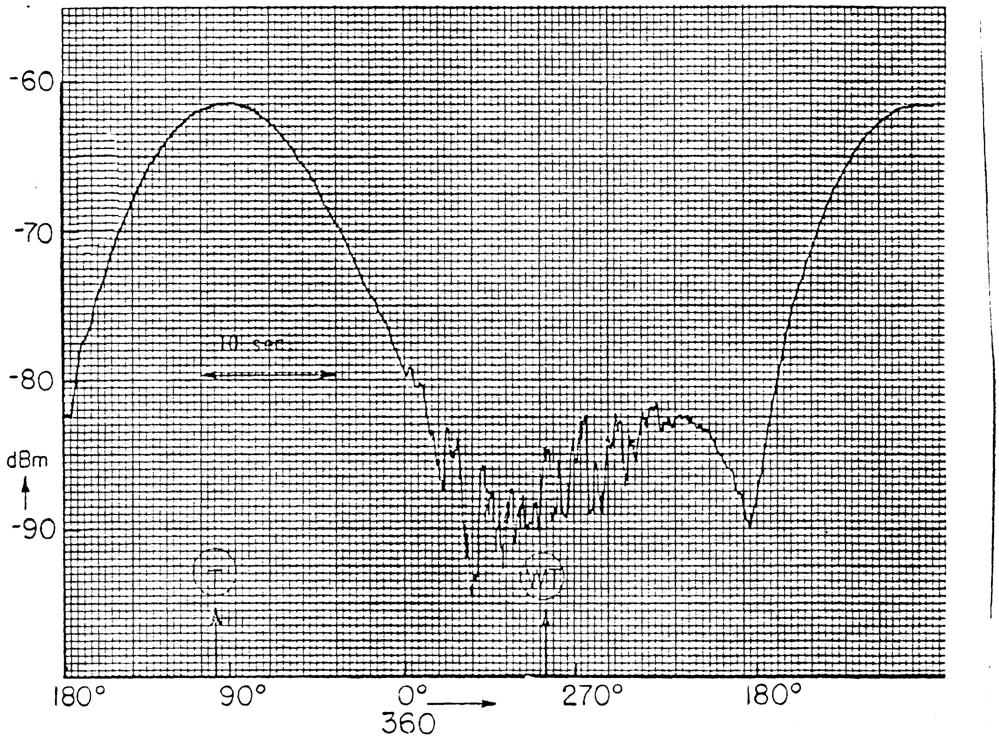

Fig. 3 Dynamic Response of the Receiving Antenna on Channel 2.

(rpm = 12, blade pitch = -6°, Nacelle Direction = 117° from N)

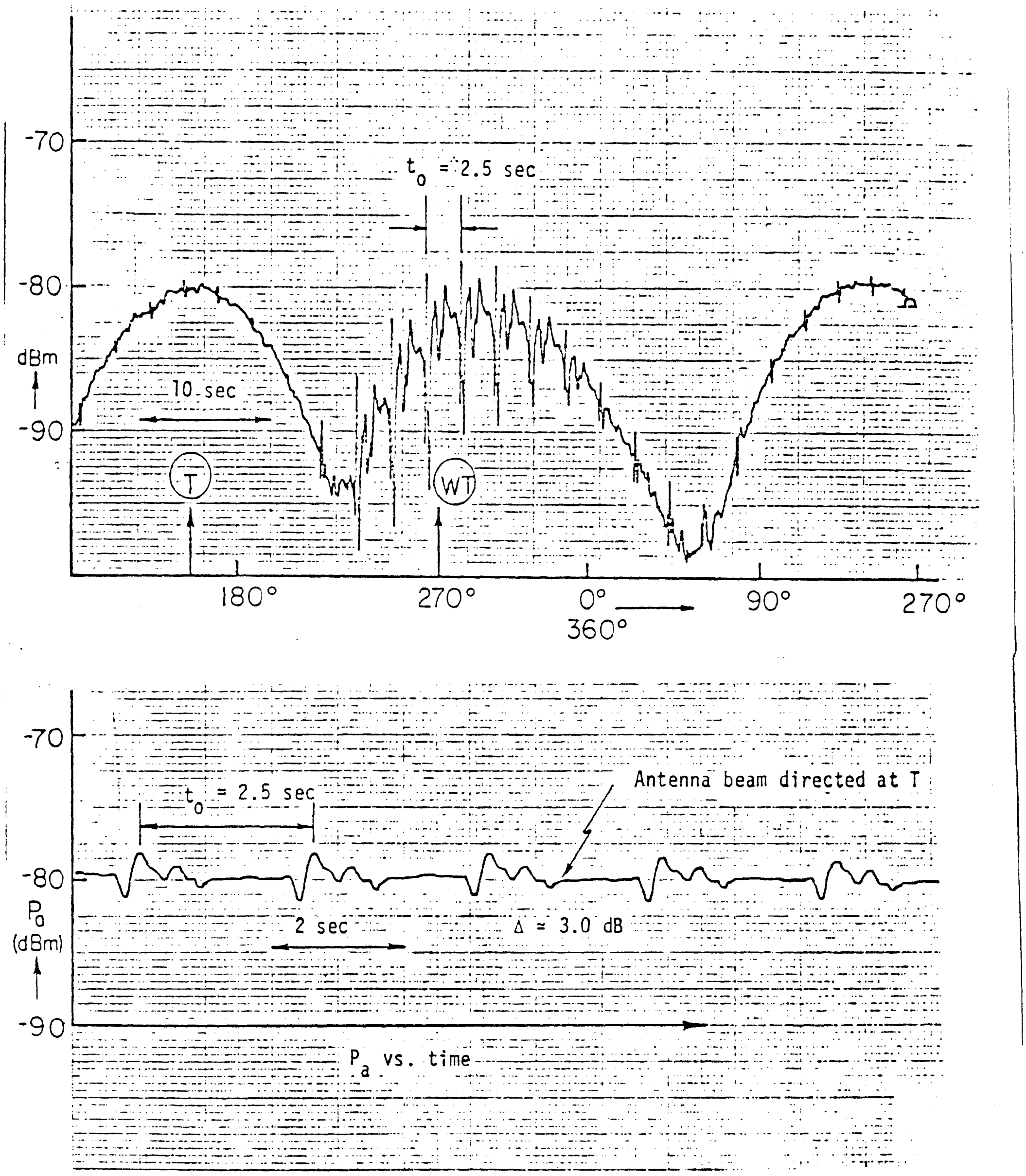

Fig. 4 Dynamic Response (Upper Trace) and P_a vs Time (Lower Trace) on Channel 3. (rpm = 12, blade pitch = -6°, Nacelle Direction = 117° from N)

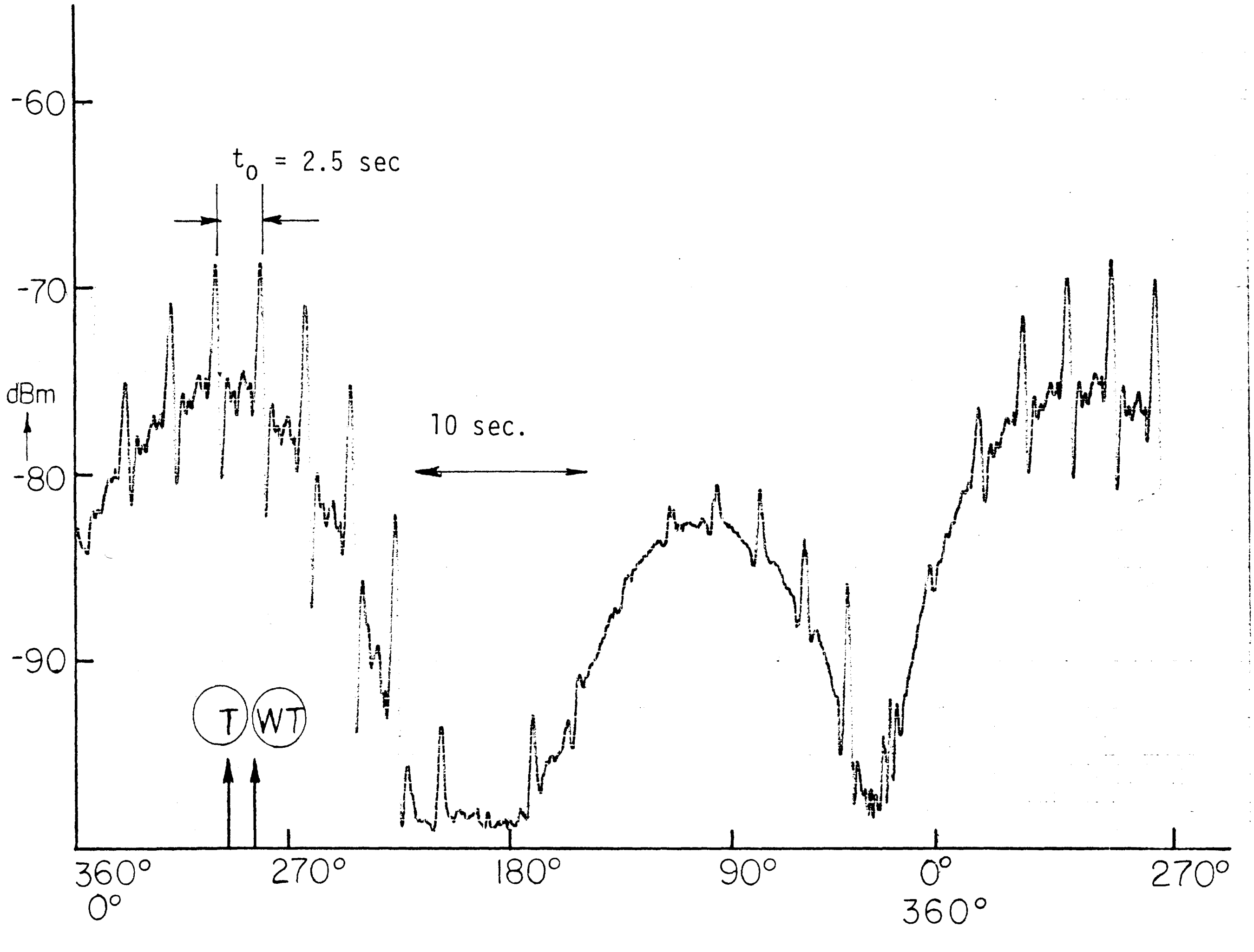

Fig. 5 Dyanmic response of the Winegard antenna on Channel 5
(rpm = 12, ϕ_p = -6°, nacelle direction = 117° from N)

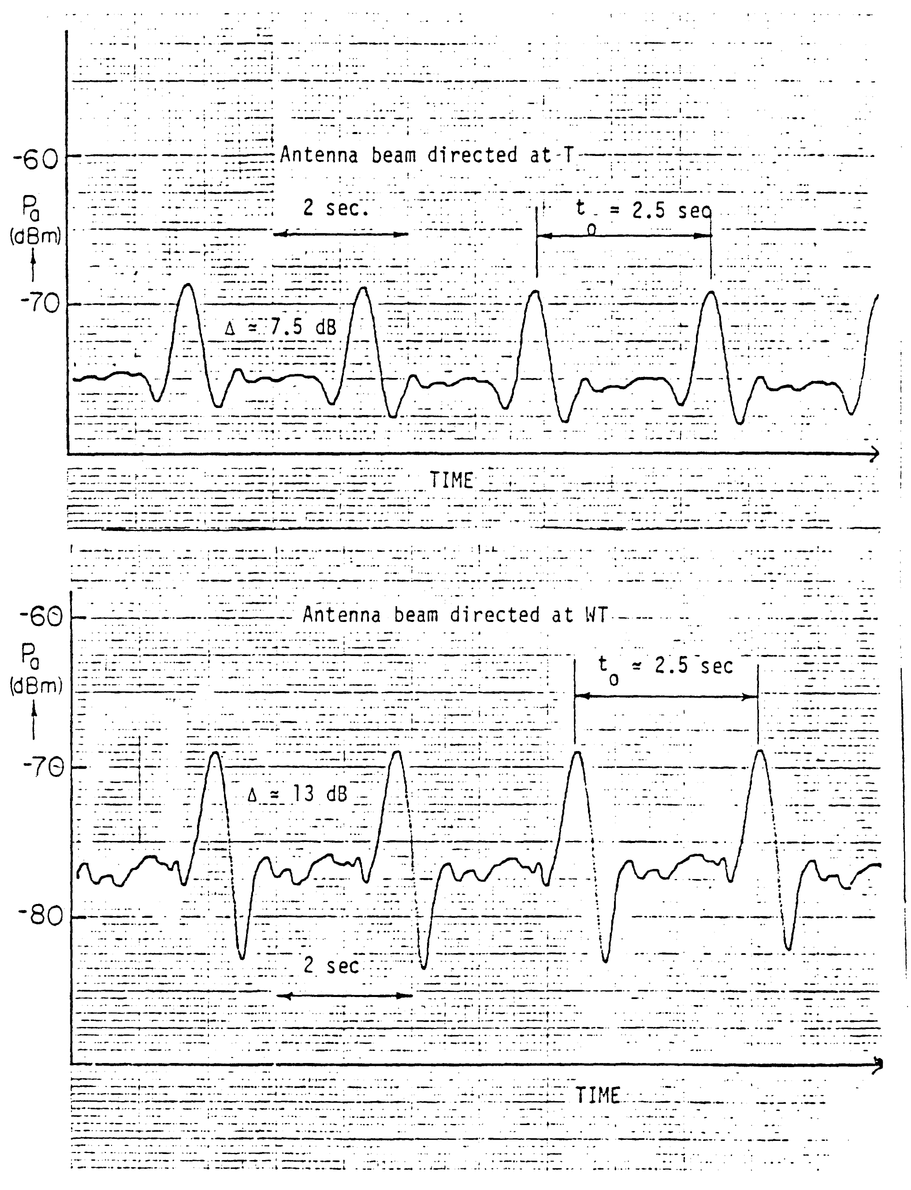

Fig. 6 P_a vs Time on Channel 5. (rpm = 12, blade pitch = -6°, Nacelle Direction = 117° from N)