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STUDY OF TELEVISION INTERFERENCE BY SMALL WIND TURBINES

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ABSTRACT

Electromagnetic interference to television reception caused by small wind turbines (generating about 5 kW of power) has been studied by carrying out measurements using 1/8th scale models of small windmills in conjunction with a microwave TV system inside an anechoic chamber. Two- and three-bladed windmills with metallized and wooden blades rectangular and trapezoidal in shape were investigated. The locally available TV Channel 9 signal was received and, after up-converting its center frequency to 4.0 GHz, was used as the RF source of the microwave TV system. The television interference (TVI) results were extrapolated to give the TVI effects of the corresponding full-scale windmills at the commercial TV Channel frequencies.

Generally, it was found that the two- and three-bladed machines produced similar TVI effects, the metallized blades producing stronger interference than the wooden blades. Extrapolation of the results obtained indicate that even at the highest TV frequency the signficant TVI effects (video distortion) produced by small wind turbines will not extend out to a distance larger than about 2.5 times the rotor diameter. At lower TV frequencies (or Channel numbers) the distance will be correspondingly smaller. Within this distance, the observed effects will generally be small to negligible over most of the region except possibly in the forward interference direction.

ACKNOWLEDGEMENT

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1. Introduction

With the growing interest in small wind turbines (WTs) or windmills to provide power for individual residential homes or apartment complexes, there is the possibility that such a windmill could be in the vicinity of a TV receiving antenna, and our past experience with large WTs [1,2] has shown that the two may not be compatible. Although the reduced size of small WT blades would cause the scattered field to be less than that from a large WT, we are now concerned with machines that could be in close proximity to a TV receiving antenna, and the interference could still be a problem. The present report describes an investigation undertaken to determine if a small WT will interfere with the nearby reception of TV signals.

At the small distances of interest in this study, analytical predictions of the WT-scattered signal are questionable and, in addition, it is unclear how much video distortion will result from a given ratio of the scattered to primary signal strength. For the present investigation we have therefore relied on measurements carried out using small scale models of WTs in conjunction with the microwave TV system developed under a prior Contract [3]. Tests were conducted by receiving a commercially available TV signal and up-converting it to a microwave frequency compatible with the microwave TV system. This enabled us to perform all tests using scale model

WTs in a controlled environment within an anechoic chamber. The following sections describe the tests conducted, and discuss the results obtained and their implications.

2. Experimental Arrangement

The entire experimental arrangement for performing the various tests is shown as a block diagram in Fig. 1. The microwave TV system in Fig. 1 is a modified version of that discussed in [3], and is only briefly described here. In the original microwave TV system [3], laboratory-generated standard program material (video and audio) were used for information transmission, but for the present investigation it was decided to use a commercial TV program. Therefore, provisions were made so that a commercial TV signal received from a local TV station could be translated up from its original frequency to 4 GHz and retransmitted inside the chamber; after reception its frequency was translated down to a VHF Channel frequency convenient for viewing in the laboratory on the 17-inch Zenith TV receiver that was used in all our previous studies.

Referring to Fig. 1, a Radio Shack VU-60 TV receiving antenna was installed outside the anechoic chamber at our Willow Run Laboratory to receive the TV Channel 9 transmissions from Windsor, Canada, about 31 miles away. The received signal was cabled into the building and fed to a VHF tuner tuned to the Channel 9 frequency. With the antenna oriented to receive a maximum signal, the signal at the input of the tuner was measured, and, typically, the audio carrier component (P_a) was about -55 dBm. The output from the tuner was then fed to a low

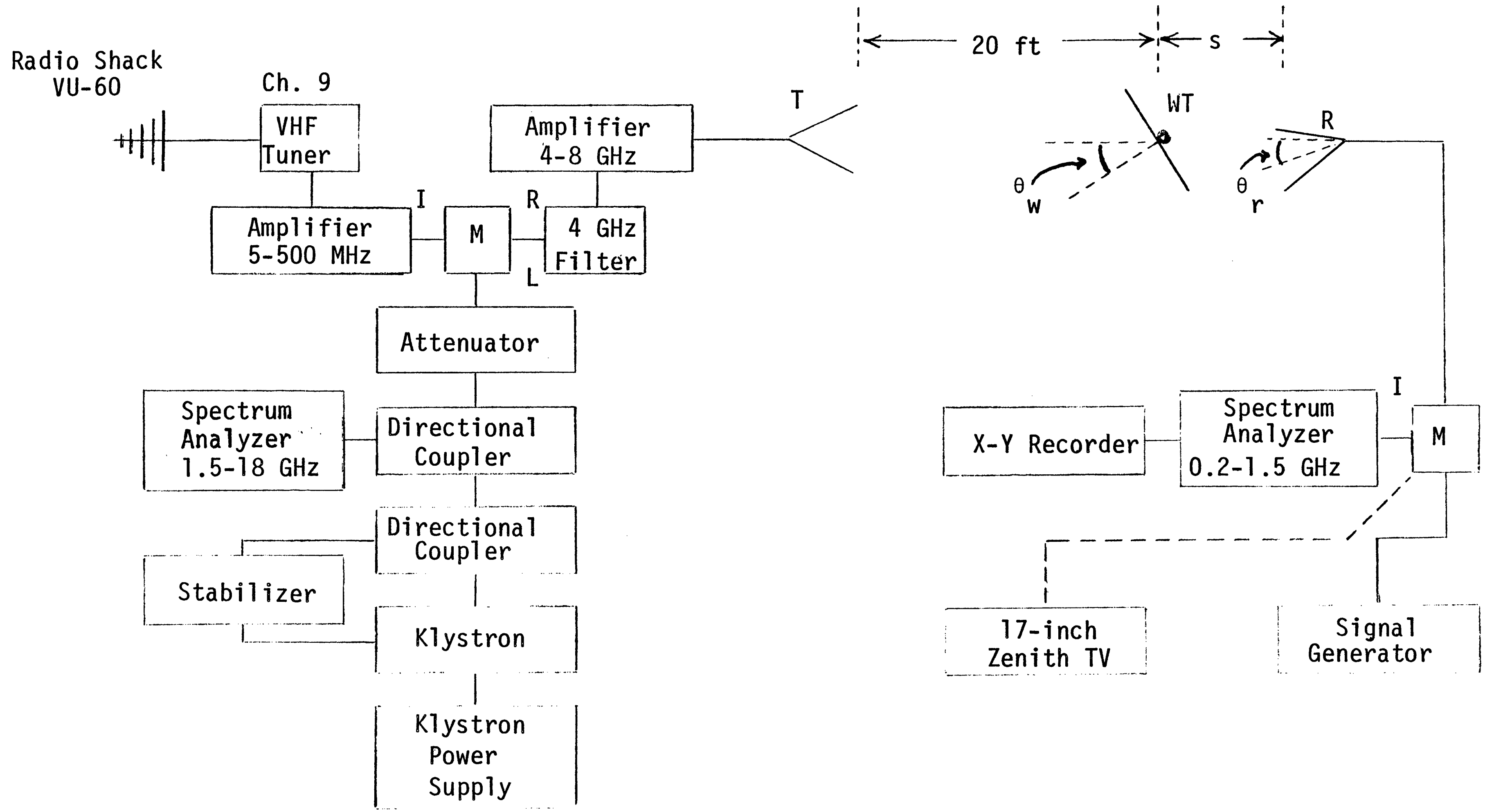


Fig. 1: Block diagram showing the experimental arrangement for TVI measurement.

noise amplifier to increase the signal level by an additional 10 dB to provide a signal of -45 dBm to the input terminal I of the mixer (M). The local oscillator used to translate the signal frequency from 189 MHz (center frequency of the Channel 9) to 4 GHz was a 2 to 4 GHz klystron as shown in Fig. 1. The klystron frequency was stabilized to one part in a million for the 8-hour period during which data were collected. The frequency and power level of the output signal from the klystron were monitored by the high frequency (1.5 to 18 GHz) spectrum analyzer. The frequency of the klystron was set to 3.817 GHz, and its output signal level was adjusted to +5 dBm (using the attenuator) and fed to the L terminal of the mixer. This provided a signal at the output terminal (R) of the mixer at the sum frequency of 4 GHz for the center frequency of Channel 9. In addition to the sum frequency signal component, there were several other frequency components present at the mixer output; these were eliminated by the bandpass filter tuned to 4 GHz and having a 40 MHz passband to ensure that both the video and audio components of the translated signal could pass through undistorted. The received Channel 9 signal, thus translated to 4 GHz, was then fed to the 4 to 8 GHz solid state amplifier which provided a gain of 30 dB so that the signal level at the input of the transmitting antenna was -10 dBm. Figure 2 is a photograph of the transmitter setup.

The signal from the transmitting antenna was radiated inside the anechoic chamber and generally illuminated both the scale model WT and the receiving antenna, as shown in Fig. 3. The output from the receiving antenna was then fed to the R terminal (Fig. 1) of a second

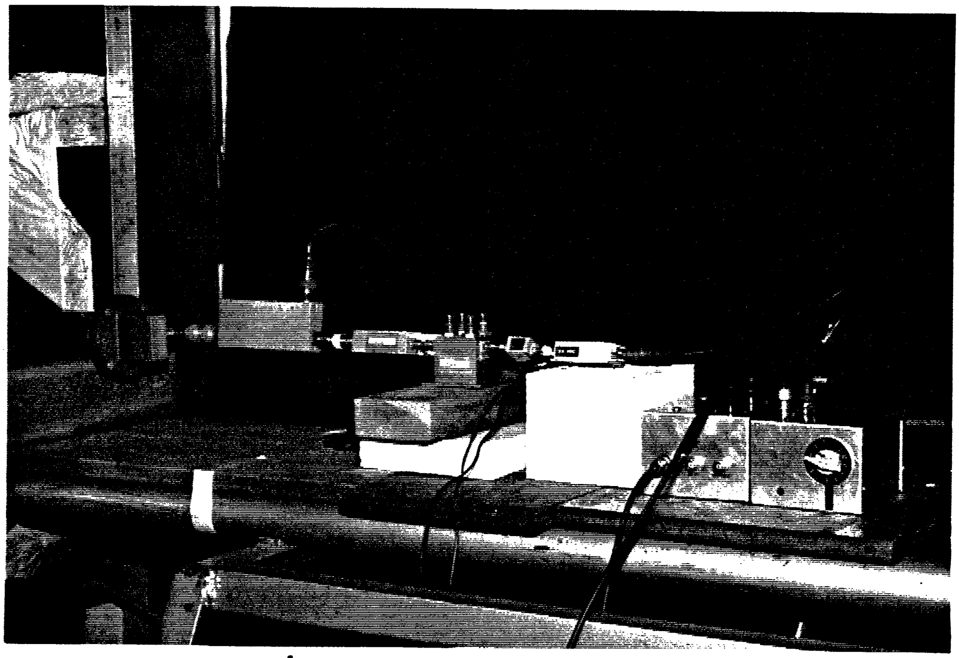


Fig. 2: Photograph of the transmitting equipment setup of the microwave TV system.

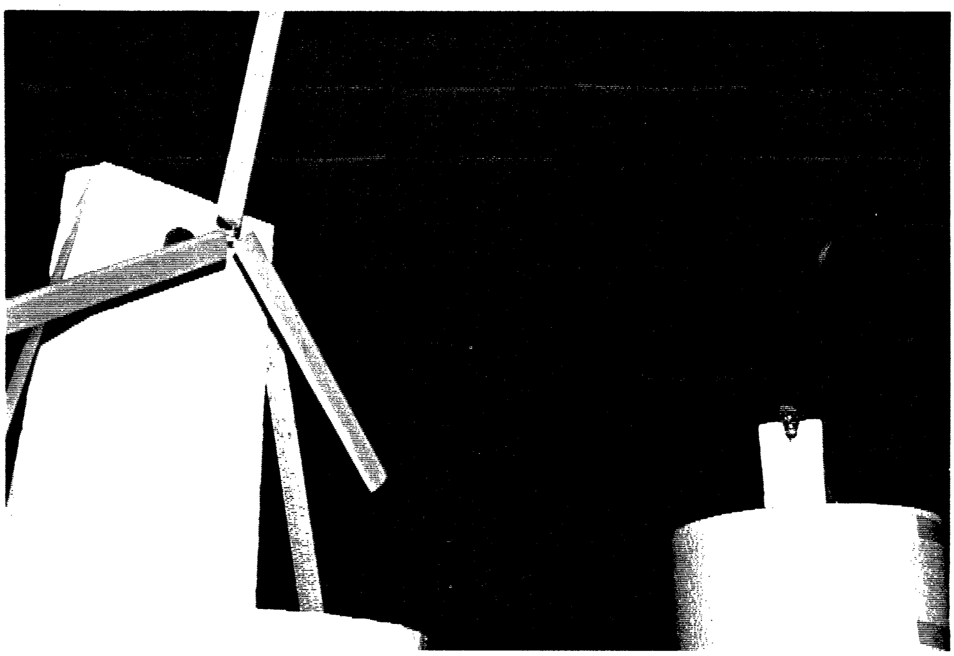


Fig. 3: Photograph showing the three-bladed scale model windmill and the receiving antenna.

mixer (identical to the mixer on the transmitting side). The local oscillator of this second mixer was a Hewlett-Packard 616 signal generator providing zero dBm signal in the frequency range 1.8 to 4.2 GHz. The frequency of the local oscillator was set to 3.787 GHz to produce a 213 MHz signal at the output (I) of the mixer which corresponded to the center frequency of the TV Channel 13. The low frequency (213 MHz) signal obtained from the output terminal (I) of the mixer was then directed either at the spectrum analyzer (0.2 to 1.5 GHz) or to the Zenith TV receiver tuned to Channel 13. The signal directed to the spectrum analyzer was subsequently recorded on the X-Y recorder shown in Fig. 1. The TV receiver was used to visually examine any video distortion caused by the interference.

3. Transmitting and Receiving Antennas

During all measurements the transmitting antenna was an NRL gain-standard horn operating in the frequency range 3.95 to 5.85 GHz and having a nominal gain of 18 dB above isotropic at 4 GHz. The measured E-plane radiation pattern of the NRL horn antenna is shown in Fig. 4 where the level of the isotropic antenna response is also marked so that, if desired, the appropriate response of the transmitting antenna may be obtained.

Two different receiving antennas were used during the present investigation. They were an NRL gain-standard horn similar to the transmitting antenna described above and a 4 GHz half-wave dipole. The measured E-plane pattern of the latter is shown in Fig. 5.

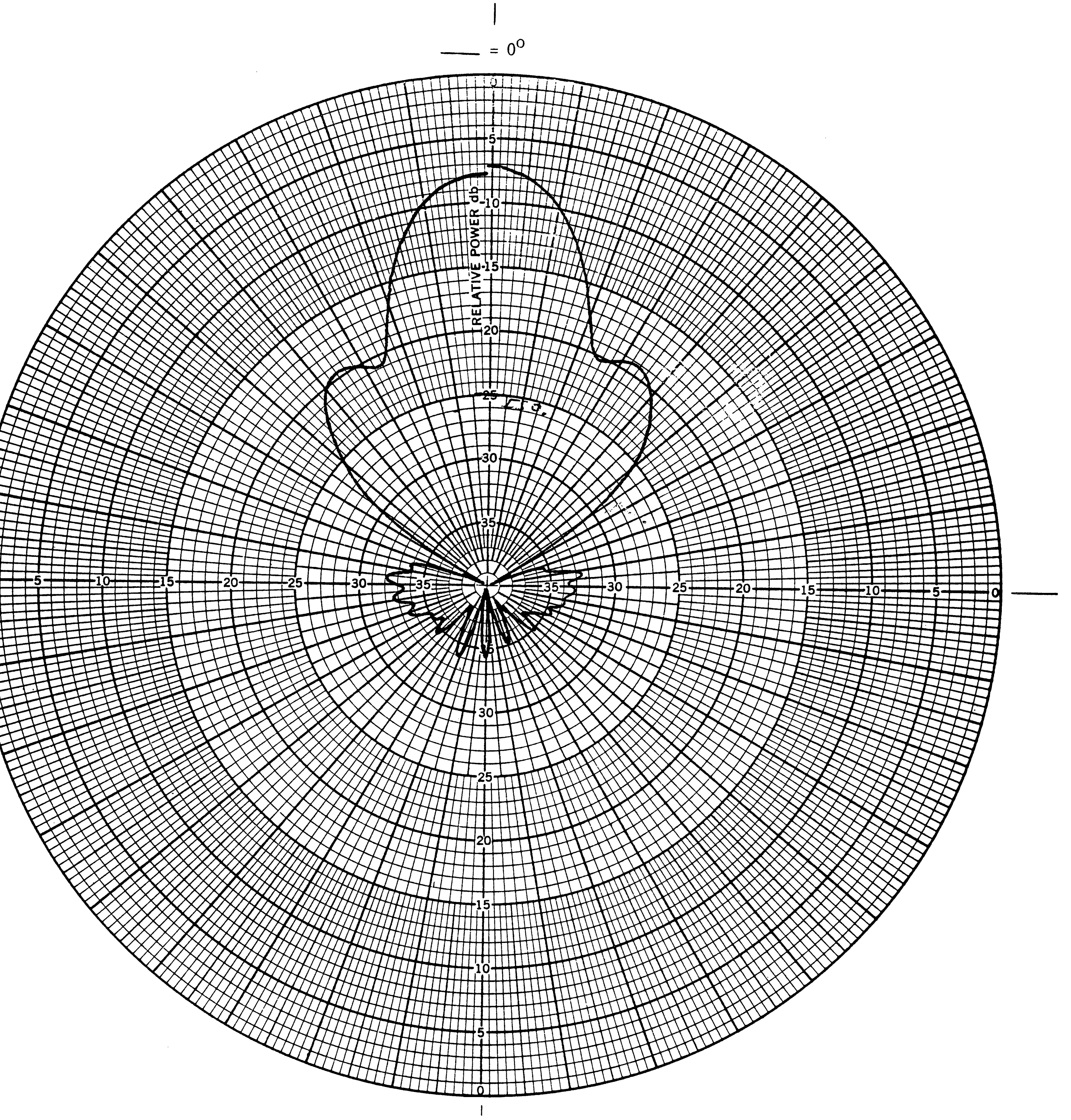


Fig. 4: E-plane radiation pattern of the NRL gain-standard horn measured at 4.0 GHz.

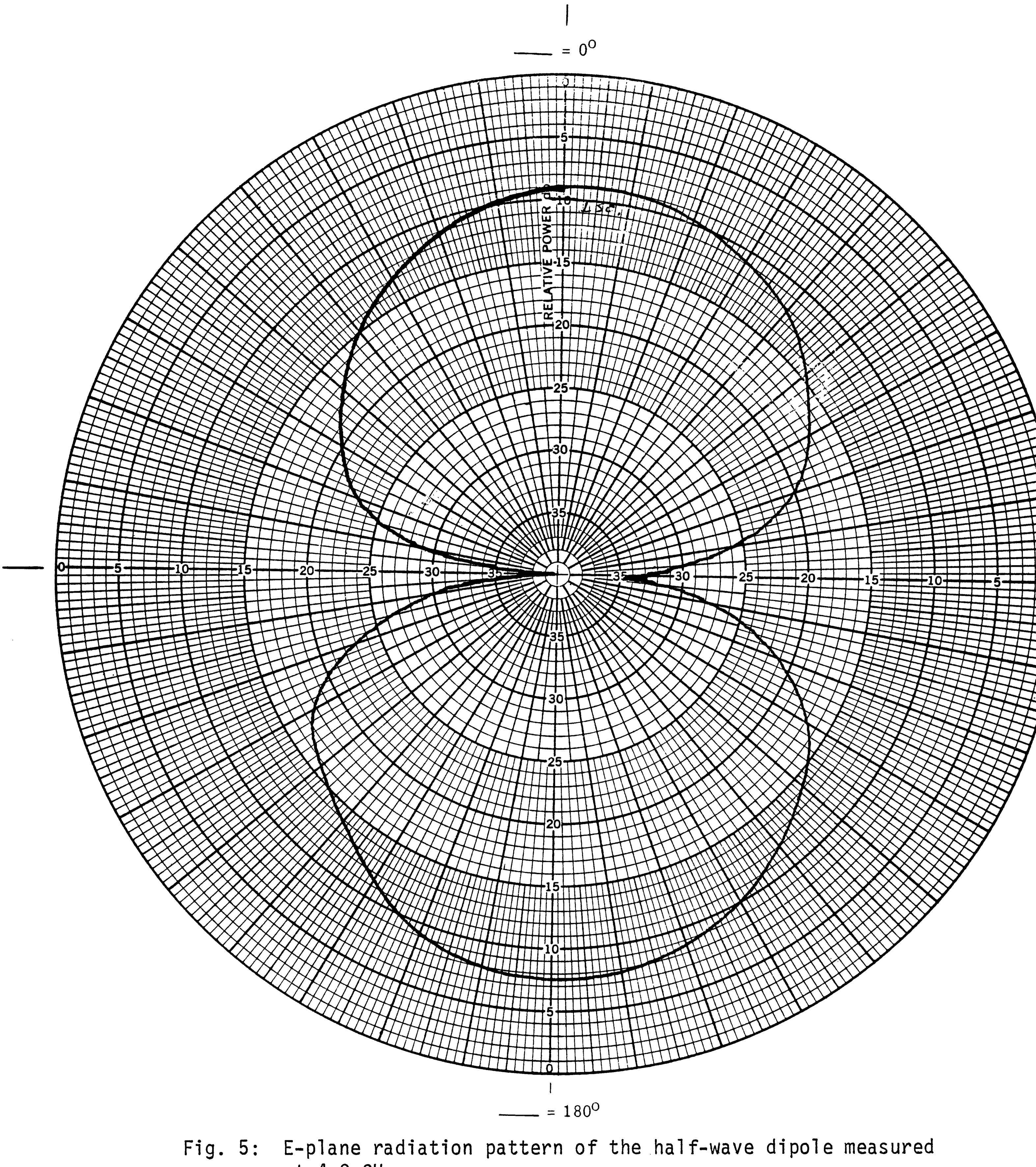


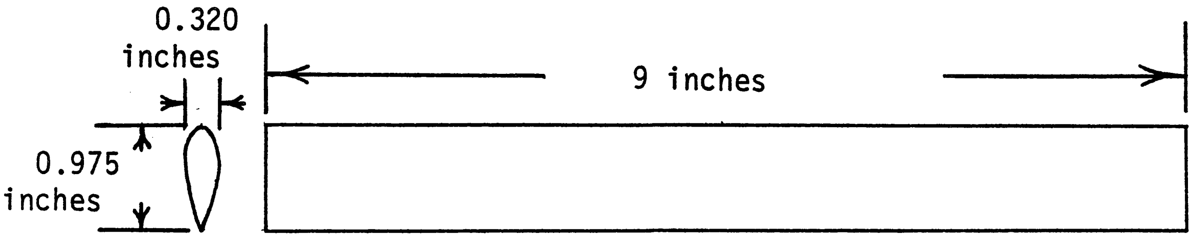
Fig. 5: E-plane radiation pattern of the half-wave dipole measured at 4.0 GHz.

4. Scale Model Wind Turbines

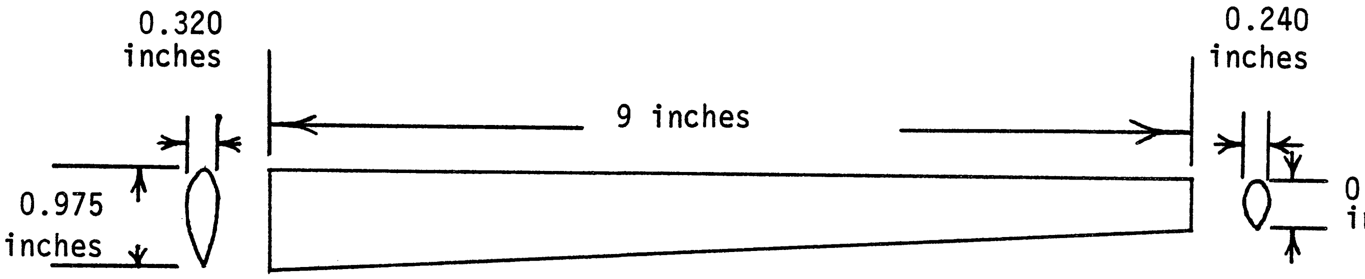
Since the TV interference is predominantly caused by scattering from the rotating blades of a windmill, only the scale models of blades, suitably mounted on a foam tower, were used as model wind turbines. Available information on small windmills [4,5] was reviewed to establish the specific blade configuration and scale factor for the model wind turbines. It was concluded from the review that a typical two- or three-bladed small machine generates about 5 kW of power in optimum wind conditions and consists of a 12-ft diameter (tip-to-tip) rotor with blades having rectangular or trapezoidal cross sections, in general.

To facilitate the measurements within our anechoic chamber (50 ft long, 30 ft wide and 15 ft high) we decided to employ a 1/8th scale model of the chosen full-scale blade configurations. Next, we selected the frequency of operation (i.e., the scale model frequency) to be 4 GHz ($\lambda \simeq 3$ inches) at which the TVI effects of the scale model windmills simulated those of the corresponding full-scale machines at the center frequency (~503 MHz) of TV Channel 19. This choice of scale factor and frequency also satisfied the $2D^2/\lambda$ criterion so that the model windmills could be conveniently located in the far zone of the transmitting antenna located inside the anechoic chamber.

Altogether, fourteen scale model blades, each having the same length, were fabricated from wood; ten of these were similar, each having a rectangular cross section, and the remaining four had a trapezoidal cross section. The detailed cross sections of the rectangular and trapezoidal blades are shown in Fig. 6 where the projected physical area of each blade is also indicated.



projected area = 8.775 sq. inches



projected area = 6.997 sq. inches

Fig. 6: Rectangular and trapezoidal configurations.

Two three-bladed model windmills having rectangular blades, one metallized and one wooden, were then fabricated . Figure 7 is a photograph of a typical three-bladed scale model windmill. The remaining blades were employed to fabricate four two-bladed windmills with metallized and wooden blades having rectangular and trapezoidal cross sections. A photograph of the six scale model WT-blade configurations is shown in Fig. 8.

The scale model rotor blades were mounted on top of a 7-ft high foam tower and provisions were made to rotate the blades in a vertical plane whose orientation could also be adjusted. Although the rotation speed of the scale model WT could be varied from a few rpm to 40 rpm, most of the data was collected with the machines operating at about 20 rpm.

5. Data Collection Procedure

During all of the measurements the phase centers of the transmitting antenna and the WT-rotor blades (i.e., the height of the windmill) were located 7 ft above the floor of the anechoic chamber, and the distance between the two was fixed at 20 ft so that the WT always remained in the far zone of the transmitting antenna. Initially, the phase center of the receiving antenna was also maintained at 7 ft above the floor and recordings of P_a vs time of the spectrum analyzer output (Fig. 1) were obtained with the receiving antenna located either in the forward or backward region of the WT and at variable distances s from the WT (Fig. 1). When appropriate, the ambient levels of the received signals were also

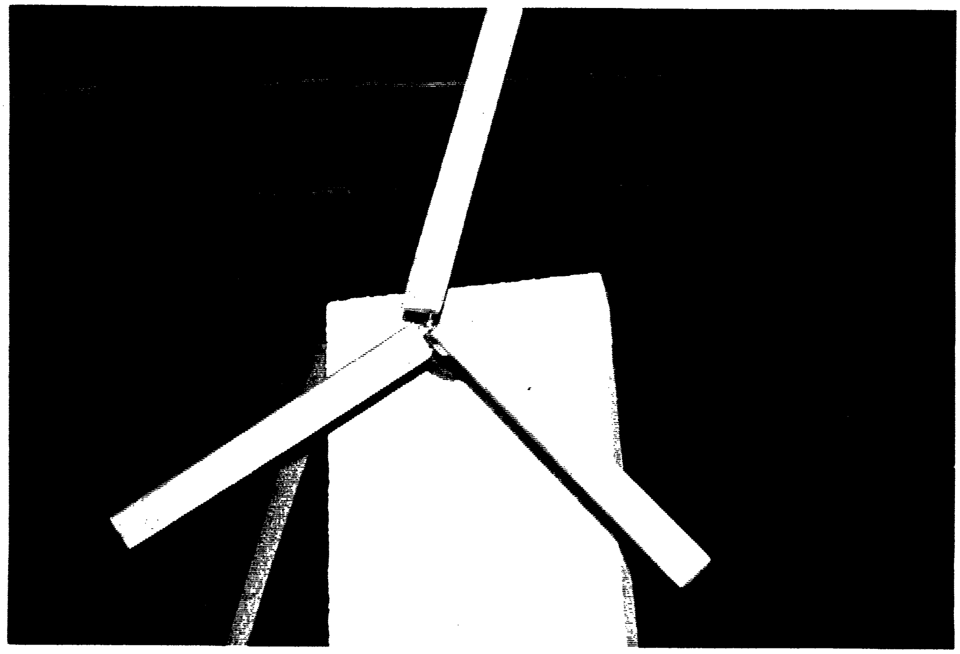


Fig. 7: Photograph showing the scale model of a three-bladed windmill having rectangular blades.

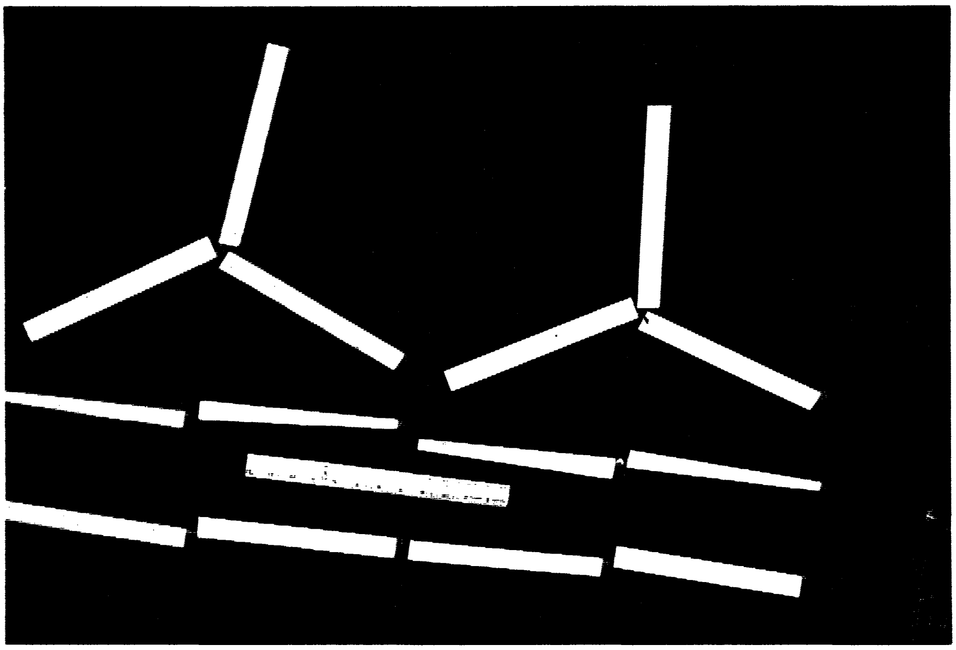


Fig. 8: Photograph showing the blade configurations of six scale model windmills.

measured. Later, similar data were obtained for different heights of the receiving antenna. A typical orientation of the transmitting antenna, the WT and the plane of rotation of its blades, and the receiving antenna located in the forward direction with its main beam oriented to receive maximum signals, is shown in Fig. 1. With the receiving antenna away from the forward direction, data were collected with the receiving antenna beam directed at the WT and at the transmitter. Horizontal polarization was used throughout.

The convention used for the angles θ_w, θ_r describing the orientation of the plane of rotation of the blades and the location of the receiving antenna, respectively, is shown in Fig. 1. The transmitting antenna beam was always directed at the WT. The angle θ_w denotes the angle between the T-WT direction and the normal to the plane of rotation of the blades, measured anti-clockwise from T-WT (Fig. 1); θ_r denotes the angle between the T-WT and WT-R directions, measured anticlockwise. As can be seen from Fig. 1, with the receiving antenna beam directed in the forward direction and the blade rotation plane perpendicular to the T-WT-R direction, $\theta_w = \theta_r = 0$.

In addition to the data obtained in the forward and backward regions of the WT, some data were also collected with the receiving antenna located 0.75, 1.0 and 2.0 ft below, and 1 ft behind the WT, the transmitting antenna location and orientation being the same as before. These measurements were made to study the effects of placing the receiving antenna on the tower that supports the WT.

6. Representative Results

For better appreciation of the detailed TVI effects to be discussed later, we first describe some representative results.

Ambient Field Strength: To determine the ambient field strength and the quality of reception of the desired TV Channel 9 signals, the "spectrum analyzer-recorder-TV receiver" combination on the receive side of Fig. 1 was temporarily connected to the output of the Radio Shack VU-60 antenna on the transmit side of Fig. 1. With the WT stationary, the strength of the received signal was then measured by rotating the antenna until the spectrum analyzer output was a maximum. By tuning the spectrum analyzer through the TV Channel band of frequencies, a chart recording of the output vs frequency was obtained from which the received video and audio carrier signal strengths, P_v and P_a, respectively, in dBm could be obtained. Such a video-audio signal recording for TV Channel 9 is shown in Fig. 9, which indicates that the signals were fairly strong; when received by the TV receiver the same signal provided a sharp and clear picture.

Afterwards, for normal operation, the "spectrum analyzer-recorder-TV receiver" combination was transferred to the receive side, as in Fig. 1, and a similar recording (Fig. 10) was obtained of the signal received by the horn antenna after being processed through the microwave TV system. Comparison of the results in Figs. 9 and 10 shows that the microwave processing did not distort the signal. Figure 10 also shows that the received signal was fairly

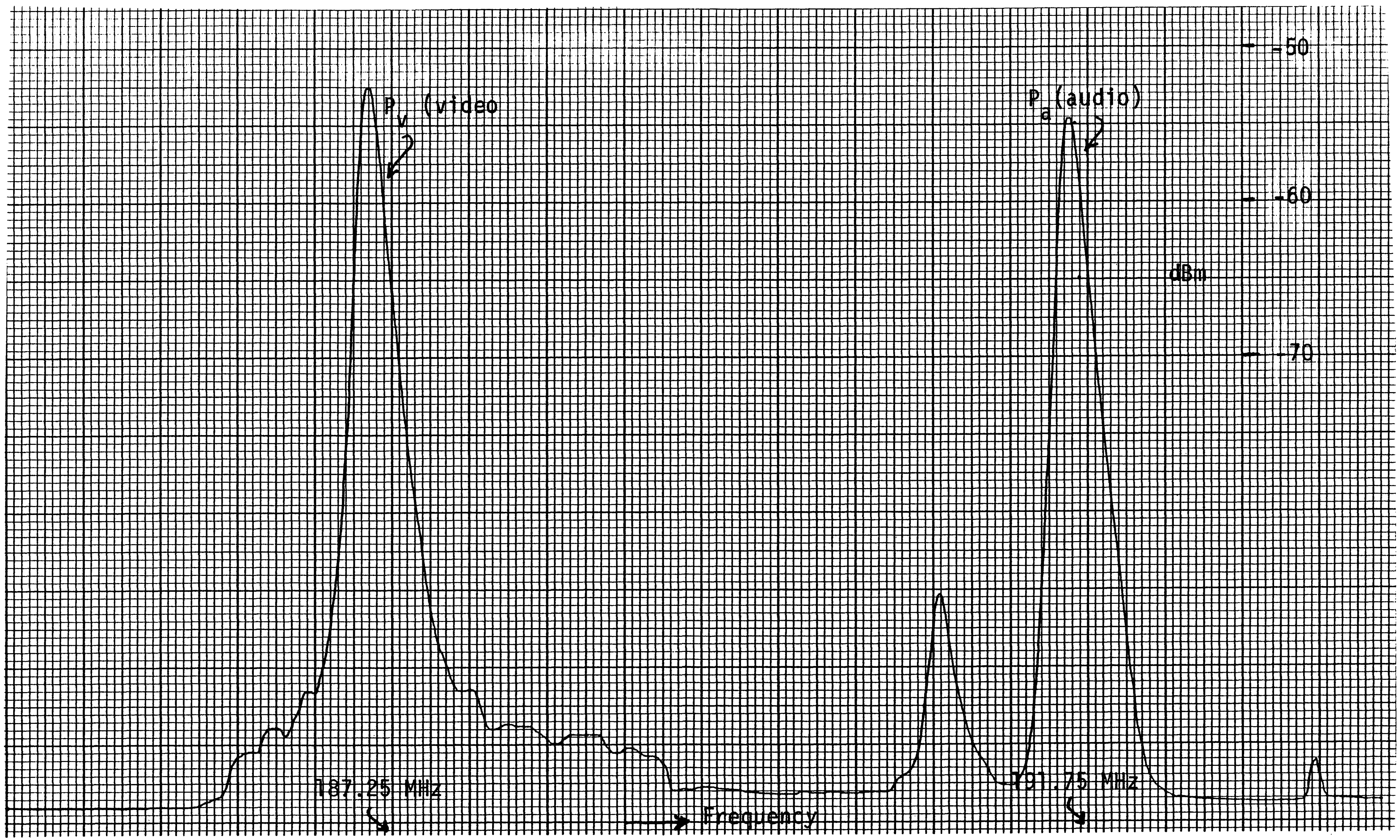


Fig. 9: Video and audio carrier signal strengths received on TV Channel 9.

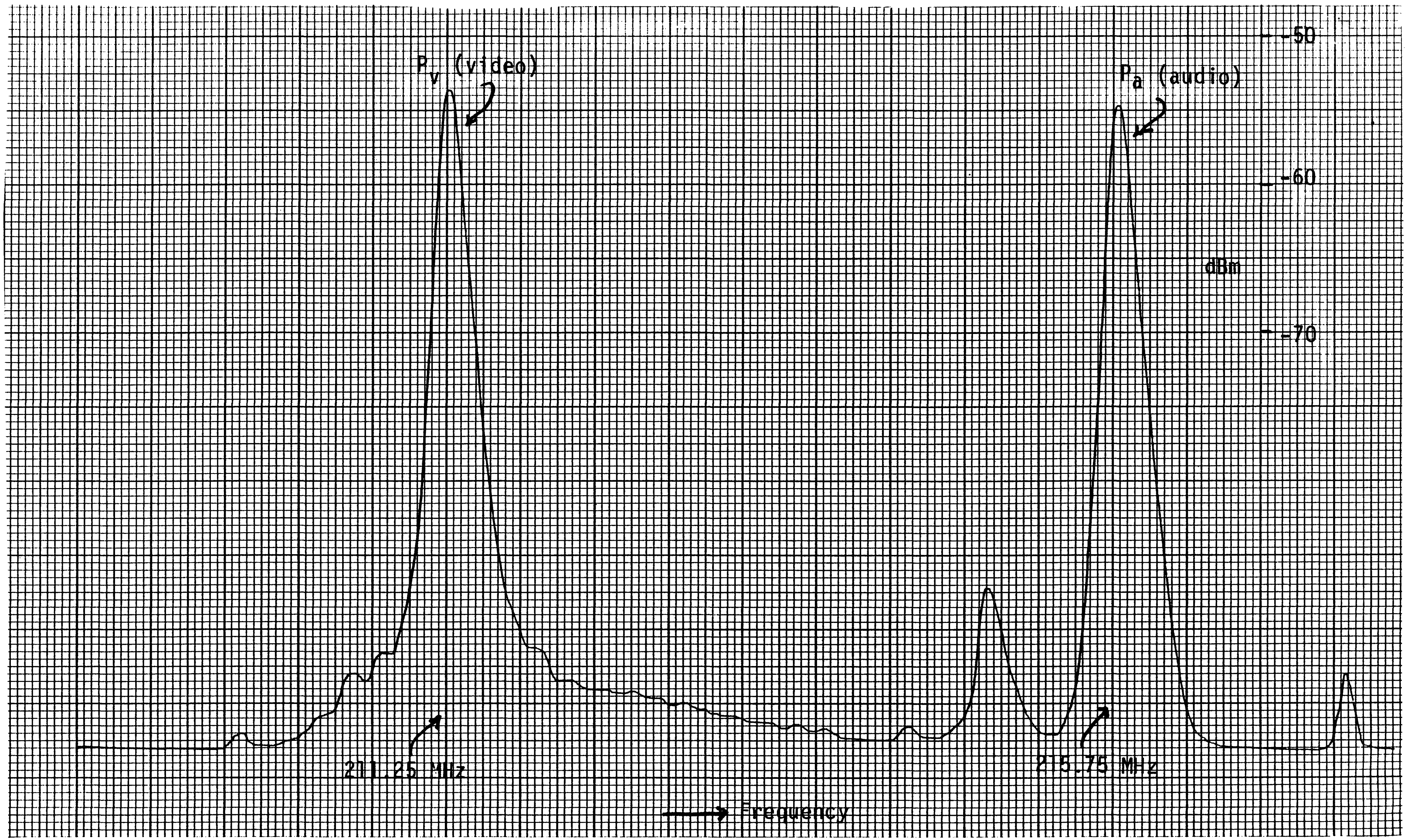


Fig. 10: Video and audio carrier signals (on Channel 13) at the output of the spectrum analyzer on the receive side of the microwave TV system receiving Channel 9 signal.

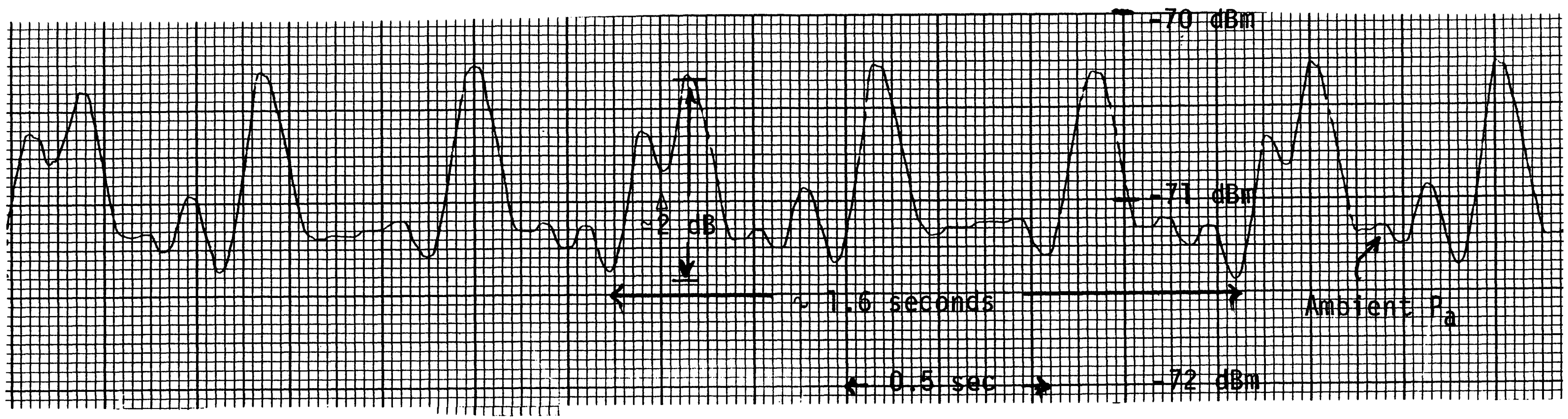
strong, and it provided a clear and sharp picture after reception by the TV receiver tuned to Channel 13.

As a rule, the above procedure was followed to adjust and calibrate the entire experimental system before undertaking any set of detailed TVI measurements.

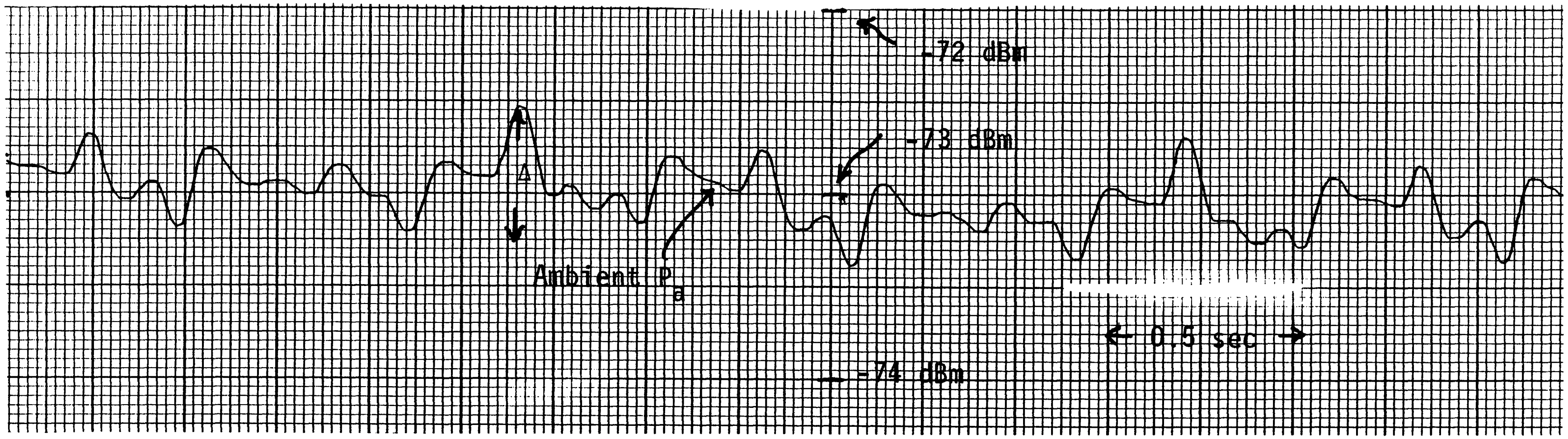
TVI Results (P_a vs Time): With the WT operating (~20 rpm) and the plane of the blade rotation oriented as desired, the TVI results were obtained as P_a vs time with the receiving antenna suitably located and having its main beam directed either at the WT or at the transmitter.

Figures 11(a) and (b) show P_a vs time for the receiving antenna (horn) located in the forward and backward regions, respectively, with its main beam directed at the scale model three-bladed WT having rectangular metal blades. The modulation waveforms in Fig. 11(a) periodic pulses and each of the three blades contributes its characteristic pulse. The period of the pulse contributions from each blade is about 1.6 seconds which is close to one half the time period of the blade rotation frequency of 20 rpm. Similar comments apply to the results shown in Fig. 11(b). The ambient signal level P_a and, more importantly, the total signal variation Δ in dB caused by the modulation are also indicated in Fig. 11. As will be discussed later, the parameter Δ in any particular case determines the amount of video distortion to TV reception caused by the WT.

Similar results obtained with the receiving dipole antenna located on the same tower as a three-bladed WT with rectangular metal blades but 8.5 inches below it are shown in Fig. 12. The modulation waveforms in this case are almost sinusoidal.



(a) Forward interference region; $\theta_w = 0°$, $\theta_r = 45°$, $s = 2.5$ ft.



(b) Backward interference region; $\theta_w = 56°$, $\theta_r = 135°$, $s = 5$ ft.

Fig. 11: P_a vs time obtained with the horn antenna beam directed at the three-bladed WT having rectangular metallized blades. $h_t = h_w = h_r = 7.0$ ft, rpm $\simeq 20$.

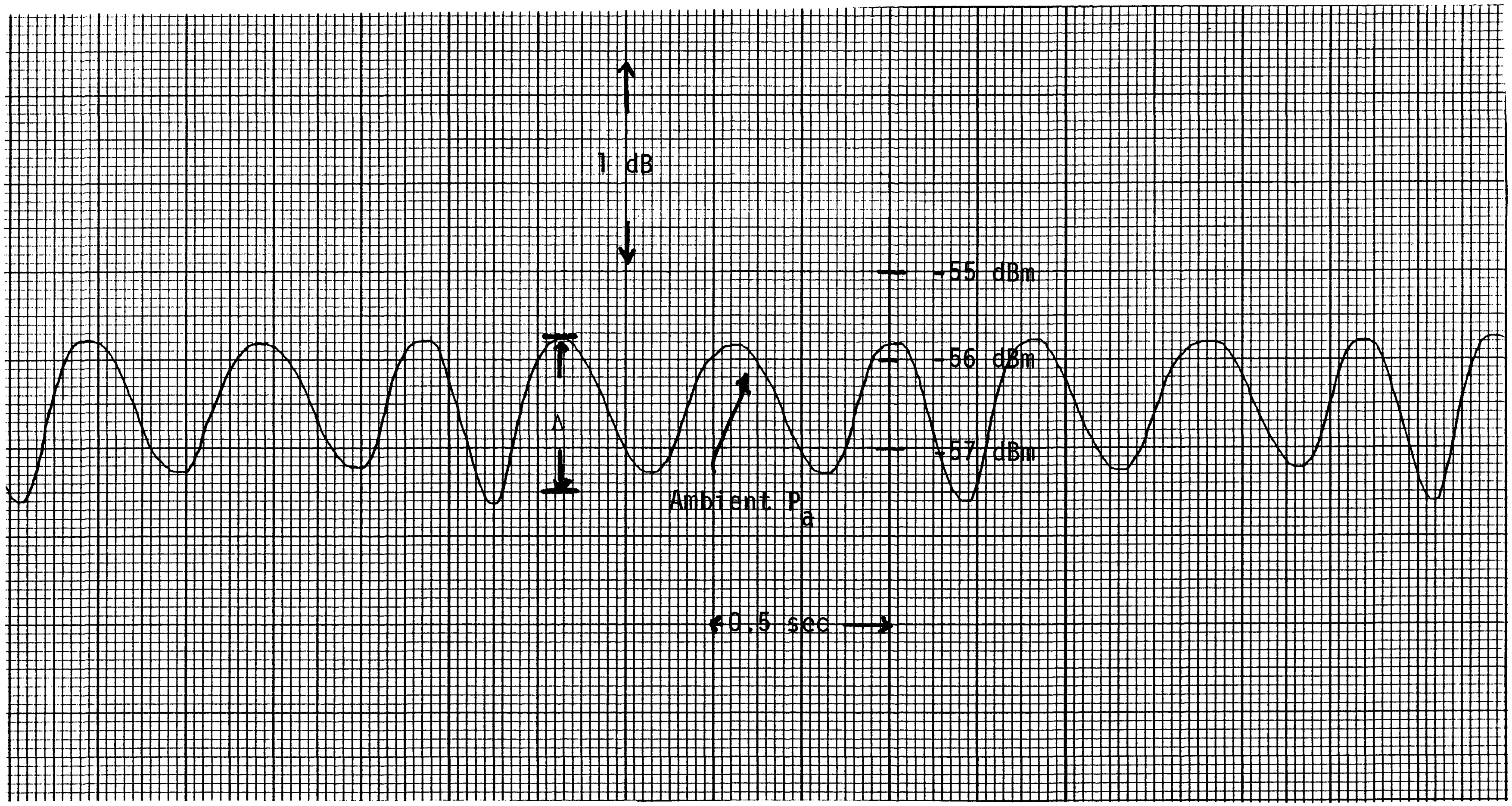


Fig. 12: P_a vs time in the forward direction obtained with the half-wave dipole antenna oriented to receive maximum signals from the WT-T direction. Three-bladed WT with metallized blades. $\theta_w = \theta_r = 0°$, s = 2.5 ft, $h_w = h_t = 7.0$ ft, $h_r \simeq 6.25$ ft, 20 rpm.

P_a vs time obtained with the dipole receiving antenna located in the forward region of a two-bladed WT having trapezoidal metal blades is shown in Fig. 13, which should be compared with the results in Figs. 11 and 12.

In general, the modulation waveforms observed under various conditions ranged from almost sinusoidal to pulsed in nature. The shapes were found to depend on the orientation of the plane of rotation of the blades and the location of the receiving antenna.

From these measurements, the important TVI parameter Δ (and the ambient P_a, if desired) was obtained for various cases, and the picture on the TV receiver was also monitored for any video distortion.

7. Detailed TVI Results

With the desired scale model windmill operating, P_a vs time recordings similar to those discussed in Section 6 were collected using either the horn or the half-wave dipole as the receiving antenna located at variable distances and in different directions from the WT. In all cases the distance between the transmitting antenna and the WT was maintained at 20 ft and its main beam was directed at the windmill. The phase centers of the transmitting antenna and the WT blades were kept at 7 ft above the floor of the anechoic chamber. The height of the receiving antenna phase center above the floor and its distance from the WT were varied during the measurements.

In each case, the total variation Δ (in dB) of the received signal caused by the rotation of the WT blades was obtained from the

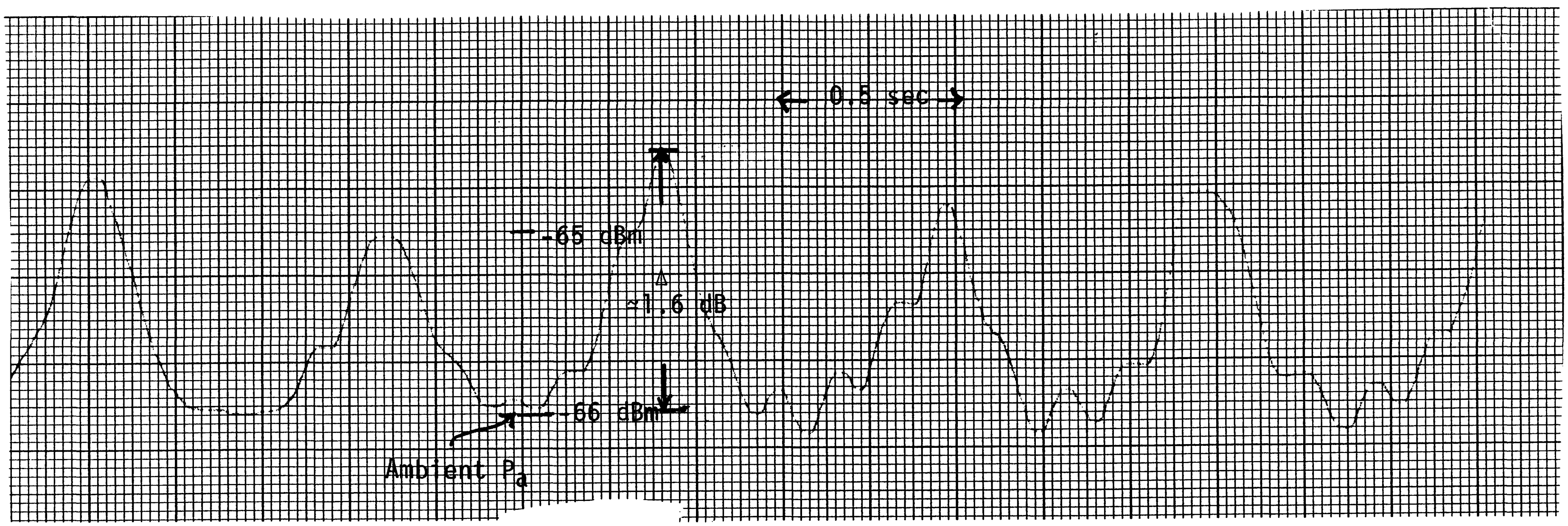


Fig. 13: P_a vs time in the forward interference region obtained with the half-wave dipole antenna beam directed at the two-bladed WT having trapezoidal metallized blades. $h_t = h_w = 7.0$ ft, $h_r = 5.0$ ft, $\theta_w = 56°$, $\theta_r = 45°$, rpm ≈ 20.

P_a vs time recording. The received picture on the TV receiver was also monitored for any video distortion. The results obtained are presented below in tabular form where the following symbols are used to represent the various quantities:

T = transmitter, R = receiver

WT = wind turbine

h_w = height of the WT blade phase center above the floor of the anechoic chamber

h_t = height of the transmitting antenna phase center above the floor of the anechoic chamber

h_r = height of the receiving antenna phase center above the floor of the anechoic chamber

s = distance between the receiving antenna and the WT (Fig. 1)

θ_w = orientation angle of the plane of rotation of the WT blades (Fig. 1)

θ_r = angle representing the location of the receiving antenna (Fig. 1

θ_r = angle representing the location of the receiving antenna

P_a = average level of the received audio carrier signal

Δ = total (maximum) variation of the received audio carrier signal

Ant→T = receiving antenna main beam directed at the transmitter

Ant→WT = receiving antenna beam directed at the WT

Forward interference region TVI data for three different windmills, obtained at various distances from the WT with the NRL horn antenna located at two different heights above the floor, are shown in Tables 1 and 2. Similar results obtained with the half-wave dipole antenna are shown in Tables 3 and 4.

Table 1: TVI data for scale model WTs obtained with the NRL horn antenna. $h_w = h_t = h_r = 7.0$ ft, T-WT distance = 20 ft, rpm ≃ 20, frequency = 4.0 GHz.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-54	1.2	-54	1.2
2.5	65	45	-52	0.0	-64	2.2
5.0	0	0	-54	0.8	-54	0.8
5.0	56	45	-51	0.0	-63	2.0
10.0	0	0	-58	0.8	-58	0.8
10.0	70	45	-56	0.0	-58	0.6
20.0	0	0	-66	0.4	-66	0.4
20.0	72	45	-56	0.0	-68	0.2

(a) Two-bladed WT with metallized rectangular blades.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-54	1.2	-54	1.2
2.5	65	45	-50	0.0	-62	2.0
5.0	0	0	-56	1.0	-56	1.0
5.0	56	45	-52	0.0	-64	1.0

(b) Two-bladed WT with metallized trapezoidal blades.

Table 1: (continued)

s ft	θ_w degrees	θ_r degrees	Ant → T P_a dBm	 Δ dB	Ant → WT P_a dBm	 Δ dB
2.5	0	0	-58	0.2	-58	0.2
2.5	65	45	-51	0.0	-63	6.0
5.0	0	0	-56	0.6	-56	0.6
5.0	56	45	-52	0.2	-63	1.2

(c) Three-bladed WT with metallized rectangular blades.

Table 2: TVI data for scale model WTs obtained with the NRL horn antenna. $h_t = h_w = 7.0$ ft, $h_r = 5.0$ ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≃ 20.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-54	0.0	-54	0.0
2.5	65	45	-52	0.0	-64	0.0
5.0	0	0	-54	0.4	-54	0.4
5.0	56	45	-52	0.0	-64	1.0
10.0	0	0	-59	0.8	-59	0.8
10.0	70	45	-56	0.0	-68	0.4

(a) Two-bladed WT with metallized rectangular blades.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-58	0.0	-58	0.0
2.5	65	45	-56	0.0	-68	0.0
5.0	0	0	-59	0.4	-59	0.4
5.0	56	45	-52	0.0	-64	0.8
10.0	0	0	-58	0.6	-58	0.6
10.0	70	45	-57	0.0	-69	0.4

(b) Two-bladed WT with metallized trapezoidal blades.

Table 2: (continued)

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-58	0.2	-58	0.2
2.5	65	45	-56	0.0	-68	0.2
5.0	0	0	-62	0.8	-62	0.8
5.0	56	45	-56	0.0	-68	0.6
10.0	0	0	-58	0.6	-58	0.6
10.0	70	45	-62	0.0	-74	0.4

(c) Three-bladed WT with metallized rectangular blades.

Table 3: TVI data for scale model WTs obtained with the half-wave dipole antenna. $h_t = h_w = h_r = 7.0$ ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≈ 20.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-70	1.5	-70	1.5
2.5	65	45	-62	0.4	-68	2.0
5.0	0	0	-70	1.2	-70	1.2
5.0	56	45	-65	0.2	-73	1.3

(a) Two-bladed WT with metallized rectangular blades.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBn	Δ dB
2.5	0	0	-70	1.5	-70	1.5
2.5	65	45	-59	0.1	-64	1.4
5.0	0	0	-66	1.3	-66	1.3
5.0	56	45	-59	0.2	-64	1.6

(b) Two-bladed WT with metallized trapezoidal blades.

Table 3: (continued)

s ft	θ_w degrees	θ_r degrees	Ant → T P_a dBm	 Δ dB	Ant → WT P_a dBm	 Δ dB
2.5	0	0	-70	0.8	-70	0.8
2.5	65	45	-66	0.1	-72	2.0
5.0	0	0	-70	0.5	-70	0.5
5.0	56	45	-65	0.1	-72	0.8

(c) Three-bladed WT with metallized rectangular blades.

Table 4: TVI data for scale model WTs obtained with the half-wave dipole. $h_t = h_w = 7.0$ ft, $h_r = 5.0$ ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≈ 20.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-73	1.0	-73	1.0
2.5	65	45	-77	0.2	-83	0.5
5.0	0	0	-80	0.8	-80	0.8
5.0	56	45	-89	0.3	-95	1.6

(a) Two-bladed WT with metallized rectangular blades.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-76	0.8	-76	0.8
2.5	65	45	-74	0.0	-80	0.2
5.0	0	0	-77	0.6	-77	0.6
5.0	56	45	-74	0.0	-80	0.8
10.0	0	0	-78	0.6	-78	0.6
10.0	70	45	-74	0.0	-80	0.4

(b) Two-bladed WT with metallized trapezoidal blades.

Table 4: (continued)

s ft	θ_w degrees	θ_r degrees	Ant → T P_a dBm	 Δ dB	Ant → WT P_a dBm	 Δ dB
2.5	0	0	-78	1.0	-78	1.0
2.5	65	45	-76	0.0	-82	0.2
5.0	0	0	-78	0.6	-78	0.6
5.0	56	45	-76	0.0	-82	0.6
10.0	0	0	-78	0.4	-78	0.4
10.0	70	45	-76	0.0	-82	0.4

(c) Three-bladed WT with metallized rectangular blades.

Initially, data were collected with the NRL horn antenna located in the forward region of the two-bladed WT with rectangular metal blades, under the condition $h_t = h_w = h_r = 7.0$ ft. For a chosen distance between the WT and the receiving antenna, θ_w and θ_r were varied to maximize Δ. It was generally observed that away from the forward direction ($\theta_r \neq 0$), significantly large values of Δ were obtained for $\theta_r = 45°$. Efforts were then made to determine the θ_w which maximized Δ. The combinations of θ_w and θ_r which produced largest Δ at each WT-receiving antenna distance(s) are shown in Table 1(a) which indicates that with the antenna beam directed at the WT, Δ in the forward direction increased with decreasing s, as it should. Similar results for the other two windmills are shown in Tables 1(b) through (c). Based on the results of Table 1 it was decided to use similar combinations of θ_w and θ_r during the remainder of the measurements.

The results in Table 1(a) and 1(b) show that the two-bladed WTs with metallized rectangular and trapezoidal blades produced approximately the same signal variations, implying that the blades had similar scattering characteristics.

A study of Table 1 indicates that the largest signal variation ($\Delta = 6.0$ dB) was produced by the three-bladed windmill for s = 2.5 ft, $\theta_w = 65°$ and $\theta_r = 45°$. At this level of signal variation (i.e., $\Delta = 6.0$ dB), video distortion at an acceptable level was observed on the picture received by the TV set. In all other cases shown in Table 1, varying amounts of video distortion below the acceptable level were observed.

The results in Table 2 were obtained under similar conditions but with h_r = 5.0 ft. These data indicate that reducing h_r generally produced lower values of Δ (c.f. Table 1 results); under this condition, the video distortion observed was well below the acceptable level in all cases.

The general characteristics of the results obtained with the dipole antenna, shown in Tables 3 and 4, are similar to those with the horn antenna, except that the average values of P_a obtained were generally less than with the horn. Video distortions observed for all s were below the acceptable level.

Because of the large Δ obtained with the horn antenna located at s = 2.5 ft, θ_w = 65°, θ_r = 45° and h_r = 7.0 ft (see Table 1(c)), it was felt that additional testing should be performed to determine if there was any unusual phenomenon associated with that geometry. Therefore, with the same values of h_r, θ_w and θ_r, more TVI data were collected by varying s from 30 inches to 26 inches in 0.25 inch increments. The results are shown in Table 5 from which it appears that Δ is an oscillatory function of s. This variation of Δ with s is believed to be the result of in- and out-of-phase combinations of the direct and scattered signals at the receiver.

A small amount of data was collected with the dipole antenna located in the backward interference region of the three-bladed WT having rectangular metallized blades. The results are shown in Table 6. Barely visible video distortions (well below the acceptable level) were observed on the received picture.

Table 5: TVI data as a function of s for a three-bladed scale model WT having rectangular metal blades obtained with the NRL horn antenna. $h_t = h_w = h_r = 7.0$ ft, $\theta_w = 65°$, $\theta_r = 45°$, $P_a \simeq -72$ dBm, frequency = 4.0 GHz, T-WT distance = 20 ft, rpm ≃ 20.

s inches	Ant → WT Δ dB
30.00	6.0
29.75	4.8
29.50	5.4
29.25	4.8
29.00	3.6
28.75	3.0
28.50	3.0
28.25	2.0*
28.00	2.0*
27.75	2.6*
27.50	3.2
27.25	3.1
27.00	3.5
26.75	4.4
26.50	5.0
26.25	5.5
26.00	5.4

*no video distortion observed.

Table 6: TVI data for a three-bladed scale model WT having metallized rectangular blades obtained with the half-wave dipole antenna located in the backward region. $h_t = h_w = h_r = 7.0$ ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≈20.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	180	-69	0.5	-69	0.5
2.5	22	135	-66	0.2	-75	0.6
5.0	0	180	-70	0.2	-70	0.2
5.0	22	135	-66	0.6	-73	0.6

With the dipole receiving antenna mounted directly below the WT on the same tower, some results were obtained with the antenna beam directed at the transmitter. Results found for three values of h_r are shown in Table 7(a) where h_r = 75 inches corresponds to the case when the minimum distance between the tip of a blade and the dipole axis is 9 inches. Table 7(b) shows the results obtained with the dipole mounted 12 inches behind the WT at a height h_r = 82 inches so that the WT was between the transmitter and the receiver. In both cases, the Δ-values obtained produced no significant video distortion of the received picture.

Finally, results for the three-bladed WT having wooden rectangular blades are shown in Table 8, which should be compared with the corresponding results in Tables 3(c) and 4(c). As expected, wooden blades produced smaller variations of the received signals.

8. Discussion of the Results

The main findings from the measurements using metallized blades are summarized below:

(i) the variations (Δ in dB) in the total received signals due to the blade rotation were large when the receiving antenna height was about the same as that of the turbine (i.e., $h_r \simeq h_W$).

The following comments apply to tests made with $h_r \simeq h_W$ and the receiving antenna oriented to receive the maximum primary signals, i.e., the antenna beam directed at the transmitter:

Table 7: TVI data for a three-bladed scale model WT having metallized rectangular blades obtained with the half-wave dipole antenna mounted on the WT tower. $h_t = h_w = 7.0$ ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≈ 20.

			Ant → T	
h_r inches	θ_w degrees	θ_r degrees	P_a dBm	Δ dB
75	0	0	-55	1.8
72	0	0	-66	1.6
60	0	0	-70	0.75

(a) Receiving antenna mounted below the WT and on the same tower; antenna beam directed at the transmitter.

			Ant → T	
h_r inches	θ_w degrees	θ_r degrees	P_a dBm	Δ dB
84	0	0	-75	0.85

(b) Receiving antenna mounted 12 inches behind the WT and on the same tower; antenna beam directed at the transmitter through the WT.

Table 8: TVI data for three-bladed WT having wooden rectangular blades obtained with half-wave dipole antenna. $h_t = h_r$ = 7.0 ft, T-WT distance = 20 ft, frequency = 4.0 GHz, rpm ≈ 20.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-67	0.1	-67	0.1
2.5	65	45	-64	0.1	-72	0.1
5.0	0	0	-68	0.2	-68	0.2
5.0	65	45	-64	0.1	-72	0.1

(a) h_w = 5 ft.

			Ant → T		Ant → WT	
s ft	θ_w degrees	θ_r degrees	P_a dBm	Δ dB	P_a dBm	Δ dB
2.5	0	0	-66	0.1	-66	0.1
2.5	65	45	-64	0.1	-72	0.2
5.0	0	0	-66	0.5	-66	0.5
5.0	65	65	-64	0.1	-72	0.1

(b) h_w = 7.0 ft.

(ii) No significant Δ and, hence, video distortion, was obtained for a WT-to-receiver distance $s > 2.5$ ft in directions away from forward. In these cases, large values of Δ were obtained only when the antenna beam was directed at the WT. Under such conditions, the largest Δ observed was 6.0 dB with the horn antenna at $s = 2.5$ ft and for $\theta_w = 65°$, $\theta_r = 45°$. The large value was due to the fact that, for this geometry, the receiving antenna discriminated (by about 15 dB: see Fig. 4) against the primary signals.

(iii) In the forward region and, in particular, in the forward direction, signal variations of approximately the same order of magnitude were obtained for two- and three-bladed machines. This is probably due to the fact that for both machines the maximum effective blade areas projected in a plane perpendicular to the T-WT-R direction were the same, i.e., they were 2A and A + 2A cos 60° = 2A, respectively, A being the maximum effective area of each blade.

(iv) No video distortion above the acceptable level was observed at $s > 2.5$ ft. All video distortions were of the forward region type [6]. This is due to the fact that for a receiving antenna located near the WT there is little or no time delay between the received primary and scattered signals. As a result, the ambient signal being fairly strong ($P_a \sim -63$ dBm), the video distortion was judged to be acceptable even with $\Delta \simeq 6.0$ dB.

With $h_r < h_w$, the signal variations (video distortion) observed were similar to those in (ii) to (iv) except, as mentioned in (i), that their amplitudes were less.

(v) No significant Δ and video distortion were obtained with the receiving antenna mounted on the WT tower and oriented to receive maximum signals.

(vi) The effects produced by the rectangular and trapezoidal blades were similar. Signal variations caused by the wooden blades were generally less than those due to the metallized blades.

9. The Interference Distance

In this section we use the results of the model measurements to estimate the TV interference distance for the corresponding full scale wind turbines.

It was mentioned earlier that, with a properly oriented receiving antenna in the vicinity of the scale model windmills, no appreciable video distortion was observed for a WT-to-receiver distance $s > 2.5$ ft. Under similar conditions, video distortions at levels below the acceptable were observed in the forward region at $s = 2.5$ ft. Assuming that in a weak signal area ($P_a \lesssim -70$ dBm) video distortion at the acceptable level occurs when $\Delta_0 = 2.6$ dB (i.e., threshold modulation index $m_0 = 0.15$) [6], it appears from the results discussed in Section 7 that the interference distance (at which $\Delta = \Delta_0$) of the present scale model windmills is less than 2.5 ft at the scale frequency of 4.0 GHz.

During the present investigation, significant results were obtained only when the receiving antenna was located in the near zone of the windmills. The scattering behavior of the WT blades and the receiving characteristics of the antenna are then difficult to predict, and since the expected interference distance is less than 2.5 ft, there is no valid formula that would enable us to deduce the interference distance from the measured results.

However, in the forward direction and with the transmitting and receiving antenna beams directed at the WT, the antenna (pattern) effects on the measured Δ (or video distortion) are absent or minimal. Under these conditions, and with the somewhat questionable assumption that the blade scattered field at R is inversely proportional to the WT-to-R distance, the interference distance can be estimated.

We now use the forward direction TVI results obtained with the half-wave dipole antenna for the two-bladed WT having rectangular metallized blades. The appropriate parameters of the scale model windmill are:

projected area of each blade: A = 8.776 sq. inches (5.6613×10^{-3} m^2)

height of the WT: h_w = 7.0 ft (2.13 m)

scale frequency = 4.0 GHz

scale factor = 1/8.

From Table 3(a), the appropriate results for the above machine with $h_r = h_w = 7.0$ ft, and $\theta_w = \theta_r = 0°$ are:

Δ = 1.5 dB (m = 0.075) , s = 2.5 ft.

Under the assumptions discussed above, the interference distance of the above two-bladed WT at 4.0 GHz is

$$\frac{2.5 \times 0.075}{0.15} = 1.25 \text{ ft.}$$

We now use the scaling laws to obtain the interference distance of the corresponding full-scale two-bladed WT with parameters

$A = 70.2$ inch $(45.29 \times 10^{-3}\ m^2)$

$h_w = 56$ ft (18.04 m)

full scale frequency = $\frac{4.0}{8} = 0.5$ GHz, i.e., TV Channel 19 frequency. Thus, the interference distance for TV Channel 19 of the two-bladed full scale WT with rectangular metal blades is

$$1.25 \times 8 = 10.0 \text{ ft (at 0.5 GHz)} .$$

Assuming the highest TV Channel frequency to be 1.0 GHz, the maximum interference distance is

$$10.0 \times 2 = 20 \text{ ft (at 1 GHz)} .$$

The above applies to free space conditions. Assuming a perfectly conducting flat ground the interference distance doubles to become $2 \times 20 = 40$ ft.

From the forward region TVI results of two- and three-bladed WTs with metal blades (Tables 3(a) through (c)), we conclude that the maximum interference distance of the full scale WTs with metal blades studied will not exceed 40 ft (~12 m) at 1.0 GHz.

10. Conclusions

Television interference caused by rotating scale models of representative small two- and three-bladed wind turbines has been investigated experimentally by using a microwave (4.0 GHz, $\lambda \simeq 3$ inches) TV system inside an anechoic chamber. Rectangular and trapezoidal-shaped aerofoil-type blades, metallized and wooden, were studied.

Results obtained in the forward interference direction of the scale model windmills have been used to estimate the interference distances of the full scale wind turbines at TV frequencies.

TVI data measured in the backward interference region and at the WT-tower provided valuable information, but could not be extrapolated to the full-scale case because the receiving antennas were not scale models of conventional TV receiving antennas. However, the results of the present investigation strongly suggest that small metal-bladed WTs (generating about 5 kW of power) would not produce any signficant TVI (hence, video distortion) on the highest UHF TV Channel at distances beyond 40 feet. This distance would be proportionately smaller at lower TV Channel frequencies. Assuming that commonly used small windmills have rotor diameters in the range 12 to 16 feet, it is concluded that significant TVI effects (at the highest TV frequency) due to such a machine would not occur at distances larger than 2.5 times its rotor diameter. Even within this distance, the delay between the primary and secondary signals is so small that any observed video distortion will be within the acceptable range over most of the region except possibly in the forward interference direction. In addition, we remark that effects will be even less for machines having wooden (non-metallic) blades.

It is recommended that further TVI study be conducted by receiving actual commercial TV signals in the presence of rotating full-scale small wind turbines. This should provide more detailed information regarding the TVI effects of small windmills which could not be obtained from the scale model measurements.

11. References

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