Electromagnetic Interference to Television Reception Caused by Horizontal Axis Windmills*

by

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ABSTRACT

Electromagnetic interference to television (TV) reception produced by horizontal axis wind turbine generators or windmills has been identified and quantified by comprehensive theoretical and experimental studies. It is found that the rotating blades of a windmill can produce pulse amplitude modulation of the total signal received, and that for an antenna so located as to pick up the specular or forward scattering off the blades, this extraneous modulation can distort the video portion of a TV signal reproduction in the vicinity of the windmill. The distortion is worst at the higher frequencies, and therefore poses more of a problem at UHF than VHF. Based on laboratory studies as well as on-site measurements, a modulation level has been established at which the video interference is judged 'acceptable', and this threshold of interference is substantially independent of the ambient signal strength. A theory has been developed to compute the interference region about a windmill for any given TV transmitter, and the results are in good agreement with those obtained from on-site measurements with an operational windmill.

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I. INTRODUCTION

It is possible that in years to come large wind turbine generators (WTG) or windmills will be used to generate power not only for rural communities but as inputs to the National Grid, thereby bringing about a revival of one of mankind's earliest methods of harnessing nature [1][2]. In 1973 a wind energy program was initiated jointly by the National Science Foundation (NSF) and the NASA Lewis Research Center and in 1975 the responsibility for planning and executing a sustained wind energy program was transferred to the newly formed Energy Research and Development Administration (ERDA), and thence to the U. S. Department of Energy (DOE). As part of the program, a 100KW WTG was designed and fabricated and is now in operation at the NASA Lewis Plum Brook facility near Sandusky, Ohio. The rotor of the machine consists of two blades of aerofoil shape with a total diameter of 37.5m and a fixed coning angle of 7 degrees. The rotor is mounted atop a tower 30m in height (Fig. 1) and is intended to produce 133KW of power (100KW at the actual generator) when rotating at 40 rpm in an 18 mph wind [3][4].

With the knowledge gained from this prototype machine, other and larger generators are being developed and put into operation (e.g. at Clayton, NM in 1977) and the national goal of energy sufficiency by the 1980's could well see the rapid deployment of this non-polluting and not visually unattractive system of electric power generators throughout the United States [2]. Even as presently conceived, these windmills could have two or three-blade rotors up to 60m in diameter [5]. The blades themselves may be twisted and tapered from root to tip, consisting of a metallic skin on a framework of girders or made of composite materials, and with their aerodynamic shape, they would be rather similar to the wings of an aircraft. Because of the observed fact that a low flying aircraft can interfere with TV reception by producing a momentary jitter or flipping of the picture, it seemed possible that the windmill blades could act in the same manner. Indeed, the problem could be more severe. Whereas aircraft interference is a transitory phenomenon, a windmill would be fixed in its location and affect the performance of TV or other systems in that region of space where the signal scattered off the moving blades is received.

The existence of such interference could have a bearing on the deployment and public acceptance of large horizontal axis windmills as a means of power generation, and a study was therefore undertaken to (i) determine if windmills could interfere with TV reception, (ii) quantify the levels of interference that were found, and (iii) assess the impact of these levels on the siting of windmills. To meet these objectives, a rather comprehensive program was performed involving laboratory measurements and simulation, on-site measurements using the existing NASA/ERDA windmill at Plum Brook, and rigorous analyses and computations. The program also included an investigation of the impact of windmill-produced interference on the performance of broadcast FM receivers, aircraft navigation and microwave link systems (see [6,7,8] for details), but this paper addresses only the interference to TV reception.

II. GENERAL CONSIDERATIONS

For a better appreciation of the studies that were performed and to analyze the various results obtained, it is appropriate to start with a general discussion of windmill-produced interference and the problem of quantifying it theoretically. In a neighborhood of the windmill, the total signal at a TV receiver will consist of the desired direct or primary signal plus a secondary one due to scattering by the windmill. If sufficiently strong, the latter signal may produce unacceptable interference, and its effects on reception can be examined knowing the detection characteristics of the TV receiver.

A. Signal Analysis of TV reception

The principles of operation of a TV receiver receiving only the direct signal from the transmitter are well-known. Nearby stationary objects like buildings, water towers, bridges or the stationary blades of a windmill may produce reflected signals which reach the receiver delayed in time, and such multipath sources can cause multiple images or 'ghosts' on a TV picture even when the receiving antenna is matched. Nevertheless, the use of a matched directional suitably oriented antenna will usually correct the problem unless the receiver is located in a region of strong multipath, and we shall therefore ignore the effect of a stationary windmill on TV reception.

In the absence of multipath sources, the composite signal at the input of a receiver may be represented [9] as

$$y(t) = [1 + f_V(t)] \cos (\omega t + \phi_1) + B\cos [(\omega + \Delta\omega)t + \phi_A(t) + \phi_2] \quad (1)$$

where $f_V(t)$ is the video information transmitted in the form of amplitude modulation of a carrier of radian frequency ω, $d\phi_A(t)/dt = f_A(t)$ is the audio information transmitted as phase (frequency) modulation of an audio carrier of radian frequency $\omega + \Delta\omega$ ($\Delta\omega$ is called the audio sub-carrier, and normally $\Delta\omega/2\pi$ = 4.5 MHz), B is the amplitude of the audio carrier level relative to that of the video carrier (usually $B \ll 1$), and ϕ_1, ϕ_2 are the arbitrary constant phases of the video and audio carriers respectively.

The first detector of a TV receiver envelope detects the signal (1). To see the process more clearly, (1) is written approximately as

$$y(t) \simeq [1 + f_V(t) + B\cos \{\Delta\omega t + \phi_A(t) + \phi_2 - \phi_1\}] \cos \{\omega t + \phi_1 + \alpha(t)\} \quad (2)$$

with

$$\alpha(t) \simeq \frac{B}{1 + f_V(t)} \sin \{\Delta\omega t + \phi_A(t) + \phi_2 - \phi_1\} \quad (3)$$

from which it is evident that envelope detection yields the undistorted video information $f_V(t)$ and a frequency modulated audio subcarrier signal which, on second detection, gives the desired audio information $f_A(t)$. Lowpass and bandpass filters at the output of the envelope detector separate the video and audio signals and direct them to the appropriate channels of the TV receiver for further processing.

In the stationary multipath situation the detection process can be analyzed in a similar manner to the above, but if the secondary signal is produced by reflection off the rotating blades of a windmill, the crucial distinction is that the equivalent source is now time-varying, leading to extraneous amplitude and/or phase modulation of the net input to the receiver. Let the video and audio carriers be amplitude and phase modulated by $f_{m_1}(t)$, $\delta_1(t)$ and $f_{m_2}(t)$, $\delta_2(t)$ respectively. Under the approximation $|f_{m_1}(t)|$, $|f_{m_2}(t)| \leq |$, the composite signal entering the receiver is [6]

$$y(t) \simeq [\{1 + f_v(t)\}\{1 + f_{m_1}(t)\} + B\,\{1 + f_{m_2}(t)\} \cos\{\Delta\omega t + \emptyset_A(t) + \delta_1(t) - \delta_2(t) + \emptyset_2 - \emptyset_1\}] \cos\{\omega t + \delta_1(t) + \alpha_1(t) + \emptyset_1\} \tag{4}$$

where

$$\alpha_1(t) \simeq \frac{B[1 + f_{m_2}(t)]}{[1 + f_v(t)][1 + f_{m_1}(t)]} \sin\{\Delta\omega t + \emptyset_A(t) + \delta_2(t) - \delta_1(t) + \emptyset_2 - \emptyset_1\} \tag{5}$$

and the other quantities are as before. When the signal (4) is envelope-detected, examination of the resulting expressions shows that the video output may be distorted by extraneous amplitude modulation but not by phase modulation, whereas the audio output is affected by phase modulation only if $\delta_1(t) \neq \delta_2(t)$ and not at all by amplitude modulation unless this is sufficiently strong to change the efficiency of the second detection in the audio channel. These results have been confirmed [6] by laboratory experiments.

It is therefore concluded that any TV interference that a windmill may provide is most likely to be video distortion attributable to amplitude modulation of the net input to the receiver. Obviously, the level of interference depends on the nature and magnitude of the modulation which a windmill actually produces, and we will now relate these to the field quantities involved.

B. Fields Received in the Presence of a Windmill

The total electric field at a receiving point R can be written as

$$E(R,t) = E^T(R) + E^B(R,t) \qquad (6)$$

where $E^T(R)$ is the direct field of the transmitter T at the receiver R and $E^B(R,t)$ is the secondary field which reaches R after reflection at a rotating blade B of the windmill. For simplicity the fields will be treated as scalar with an assumed RF time dependence $e^{j\omega t}$ which has been omitted from (6). All of the quantities in (6) are complex, and the time dependence of the secondary field and, hence, total field, is due to the blade rotation. We can separate out the time dependence by writing

$$E^B(R,t) = |E^B(R)| f_m(t) e^{i\delta(t)} \qquad (7)$$

where $|E^B(R)|$ is the maximum value of the secondary field amplitude during any one rotation of the blade, $f_m(t)$ is a real function of time having maximum value unity, and $\delta(t)$ is the time varying RF phase of the secondary field. If we also express the direct field as

$$E^T(R) = |E^T(R)| e^{i\delta_o},$$

the total field becomes

$$E(R,t) = E^T(R) \, \{1 + m f_m(t) e^{i\gamma(t)}\} \qquad (8)$$

in which $\gamma(t) = \delta(t) - \delta_o$ is the RF phase difference between the secondary and direct fields and

$$m = \left|\frac{E^B(R)}{E^T(R)}\right| \quad . \qquad (9)$$

Assuming $m \ll 1$, the amplitude of the total received signal is then

$$|E(R,t)| = |E^T(R)| \, \{1 + m f_m(t) \cos \gamma(t)\}, \qquad (10)$$

showing the amplitude modulation resulting from the blade rotation. The modulation index and function are m and $f_m(t)$ respectively, with $|f_m(t)| \leq 1$. In the static case $f_m(t) = 1$.

To interpret (10) in terms of observable quantities, we note that as a function of time $\cos \gamma(t)$ is rapidly varying compared with $f_m(t)$, and attains its extreme values $\pm$ 1 many times during a single variation of $f_m(t)$. The envelope of (10) is therefore

$$|E(R,t)|_{envelope} = |E^T(R)|\{1 \pm mf_m(t)\} \qquad (11)$$

and represents the total field that is actually observed. The maximum and minimum departures from the ambient level in dB are

$$\Delta_{1,2} = 20 \log_{10}(1 \pm m),$$

giving rise to the (dB) modulation

$$\Delta = \Delta_1 - \Delta_2 = 20 \log_{10} \frac{1 + m}{1 - m}. \qquad (12)$$

To calculate m in any given situation, an available computer program [10] was modified [6] to compute $|E^T(R)|$ and $|E^B(R)|$ from the known analytical expressions [11,12] for an electromagnetic field in the presence of a smooth, homogeneous, spherical earth of arbitrary permeability, permittivity and conductivity. The program is quite general and computes the field of a horizontally or vertically polarized isotropic antenna radiating 1 KW effective power for specified transmitter and receiver heights and transmitter-receiver separation. In the case of $E^B(R)$, the direct field at the blade is first obtained, and the physical optics approximation is then used to find the amplitude of the field scattered by the blade in the specular direction. The equivalent (flat plate) scattering area determined in this manner is in good agreement with values measured using actual blades as well as small scale models. From this, the effective strength of the blade regarded as a secondary source of radiation is deduced, and the computer program invoked again to give the secondary field at the receiver.

As an illustration of the results obtained, Fig. 2 shows the direct and secondary field strengths computed for TV channel 43 (f = 650 MHz) as functions of the distance r of the receiver from the windmill at Plum Brook. The windmill is 80 Km from the transmitter and each blade has an equivalent scattering area of $12m^2$. The transmitter, receiver and windmill are assumed to lie on the same great circle, and curves 1 and 2 are the direct field at a receiver on the near and far sides respectively of the windmill as viewed from the transmitter. Because of the large distance of the transmitter from the receiver, the direct field varies rather uniformly with r and is, of course, larger in the first case, whereas the secondary field has a lobe structure out to about 1 Km from the windmill. At distances beyond this, the strength of the secondary field relative to the direct field falls off more rapidly on the near side of the windmill, implying that any interference extends out to a smaller distance in this direction. The modulation index m at a given distance is obtained by computing the ratio $|E^B(R)/E^T R|$ from Fig. 2, and will generally decrease with r. As we shall see later, the interference at any point depends crucially on m and, hence, r.

C. Windmill Modulation Function

The modulation function $f_m(t)$ represents the time dependence of the scattered field envelope introduced by the blade rotation, and leads to a time variation in the amplitude of the total received field. The blade rotation frequency may vary, but is typically about 30 rpm (0.5Hz). If the blade were to produce a continuous (sinusoidal) amplitude modulation at the rotation frequency, the AGC circuit of the TV receiver could almost certainly compensate for it, in which case there would be no video distortion; but if the modulation function were discontinuous (i.e., some sort of repetitive pulse waveform), the higher frequencies which it contains could affect the video reception. It is therefore of interest to examine the type of modulation produced by a windmill.

Since the modulation function is due to blade scattering, it necessarily depends on the geometry and material of the blade, the blade rotation frequency, the frequency and polarization of the illumination, and the directions of the transmitter and receiver relative to the blade. An exact determination would therefore require the solution of a rather complicated boundary value problem, and though, in principle, it would be feasible to obtain a numerical solution for a sequence of incremented positions of the blade, it is doubtful if this type of solution would bring out the features which are common to any rotating structure. We shall therefore seek an approximate result sufficient to reveal the gross features of the modulation.

Consider a rectangular metal plate of dimensions L_1 and L_2 lying in the x z plane of a Cartesian coordinate system as shown in Fig. 3. The origin of coordinates is at the center of the plate and is also the origin of a spherical polar coordinate system $(r, \theta, \emptyset)$. The plate is illuminated by a phase electromagnetic wave incident from the direction $\theta_o, \emptyset_o$ with its electric vector in the xy plane, i.e., horizontal, and the scattered field is received in the direction $\theta, \emptyset$. For a plate rotating in the xz phase at an angular frequency Ω, the modulation waveform of the horizontal component of the scattered electric field is [6, 13]

$$f_m(t) = \text{sinc}\,\{\frac{L_1}{\lambda}\,(p\,\sin\Omega t + q\,\cos\Omega t)\}\;\text{sinc}\,\{\frac{L_2}{\lambda}\,(p\,\cos\Omega t - q\,\sin\Omega t)\} \tag{13}$$

where

$$p = \sin\theta_o\,\cos\emptyset_o + \sin\,\theta\,\cos\emptyset$$

$$q = \cos\theta_o + \cos\theta$$

$$\text{sinc}\,x = \frac{\sin\pi x}{\pi x}$$

and λ is the wavelength of the incident illumination.

For a high aspect ratio plate, $L_1 >> L_2$, and the time dependence of $f_m(t)$ is primarily determined by the first factor in (13). The equation then shows that in the directions of specular and forward scattering ($\emptyset = \pi - \emptyset_o$ and $\pi + \emptyset_o$, respectively) where the scattering is a maximum, the modulation is independent of time. In directions near to these, however, the modulation function is a sinusoid with frequency twice the rotation frequency, and in directions which are well away, the waveform consists of sinc-like pulses of width proportional to L_1^{-1} repeating at twice the rotation frequency. Measured data [6, 13] support these conclusions, and Figs. 4(a)-(c) show the modulation observed with a rotating plate for three different combinations of incident and receiving directions.

The fact that there is no time-varying modulation in the directions of maximum scattering is a consequence of choosing a planar plate rotating in its own plane, and is not true in a more realistic situation of a blade which is non-planar and/or twisted out of its plane of rotation. Nevertheless, our simple model is capable of providing meaningful information for an actual blade if we confine attention to directions somewhat away from those of maximum scattering. For a remote transmitter we can choose $\theta_o = \pi/2$. The specular direction is then $\theta = \pi/2$, $\phi = \pi - \phi_o$, but because the windmill is usually much higher than the receiving antenna, it is possible that the closest we can come to this direction is $\theta = \pi/2 + \alpha$, $\phi = \pi - \phi_o$, where α is some small non-zero angle. Under these conditions, (13) implies

$$f_m(t) \simeq \text{sinc}\left(\frac{L_1}{\lambda}\sin\alpha\cos\Omega t\right)\text{sinc}\left(\frac{L_2}{\lambda}\sin\alpha\sin\Omega t\right). \qquad (14)$$

For $L_1 >> L_2$, the modulation pulse is primarily determined by the first factor, and if its width $2t_1$ in time is measured by the separation of the first minima on either side of the maximum,

$$t_1 = \frac{1}{\Omega}\sin^{-1}\left\{\left(\frac{2L_1}{3\lambda}\sin\alpha\right)^{-1}\right\}. \qquad (15)$$

This type of pulse modulation is capable of producing video distortion.

III. ON-SITE MEASUREMENTS OF TV INTERFERENCE

The interference caused by the NASA/ERDA windmill was observed and studied by conducting a number of on-site measurements of the TV signals available at Plum Brook.

A. Measurement Procedure

The relevant features of the windmill and a systematic procedure for conducting the tests are described in [6, 7] and will not be repeated here. A typical experimental arrangement is shown in Fig. 5 , where only those components which are pertinent to the data collection have been included. The TV signals were those of channels 3, 5, 8, 25 and 43 whose transmitters are located in Cleveland approximately 80 Km away, and Channel 13 with its transmitter in Toledo 67 Km away. Two TV receivers were used: a 1976 Zenith model 17GC45 which has been rated [14] superior for its rejection of interference, and a 1977 Curtis Mathis model B317. With any given TV channel, a portion of the signal is scattered off the windmill blades and this, together with the direct signal, was picked up by the receiving antenna and fed simultaneously to the test receiver and a spectrum analyzer. The receiving antenna was a commercially available directional antenna placed 10 m above the ground.

The received TV program was observed to see if there was any video distortion and, in the initial tests, the signal after detection was fed to a video recorder whenever the picture was worth preserving. On occasions, however, it was found that the windmill interference actually caused the video recorder to lose synchronization, thereby adding distortion to that rightfully attributable to the windmill. We therefore used a TV camera to photograph the picture on the screen of the test receiver, thereby assuring a faithful and reproducible color video recording.

The spectrum analyzer was tuned to the audio carrier frequency of the TV signal. Its vertical output was recorded on paper tape to provide a record of the total received signal level as a function of time, including any modulation produced by scattering from the windmill blades. At both the test site and the WTG control center the WWV time code was recorded to permit subsequent correlation of the interference with the windmill configuration, e.g. pointing direction, blade azimuth position, etc.

B. Total Signal Received

For brevity we shall discuss only the results obtained with TV Channel 43 at receiving sites 1 and 2 (see Fig. 6) located 0.5 and 0.4 Km respectively from the windmill. At both sites the main beam of the antenna was directed at the transmitter so as to maximize the direct signal received. As a result, at site 1 any specular scattering off the windmill blades was picked up by the backward lobe of the antenna, and at site 2 the almost-forward scattered field was received by the main beam. It is important to note that at the first site, typical of those in the 'backward' (scattering) zone, there is a time delay between the arrival of the direct and scattered fields, whereas at the second site, typical of the 'forward' (scattering) zone, the delay is negligible.

Figure 7 shows the total received signal as a function of time at site 1. The pulse-like modulation produced by the blades rotating at 20 rpm is clearly evident. The pulses repeat every 1.5 s, indicating that the blades scatter singly, and a barely visible amount of video distortion was found to occur in synchronism with the pulses. The deviations of the received signal above and below the ambient level are about 0.8 and 1.0 dB respectively, implying a modulation index $m \simeq 0.11$. Using the theory presented in Section IIB and taking account of the directional properties of the antenna, the predicted deviations are 0.9 and 1.0 dB, implying $m = 0.10$, in excellent agreement with the observations. However, the measured time duration of the pulses is only in fair agreement with the predicted value 172 ms obtained from (15) with $L_1 = 40\lambda$, $\alpha = 5.5$ degrees and $\Omega = 2\pi/3$ radian/s.

A recording of the output from the spectrum analyzer at site 2 is presented in Fig. 8, and shows the modulation pulses produced by the rotating blades. The modulation index in this case is 0.13, which is slightly higher than for Fig. 6. However, no video distortion was observed and, as we shall see later, this is attributable to the negligible time delay between the direct and scattered signals.

C. Observed Interference

The above are only two examples of the on-site data that were gathered. The entire series of measurements is described in [6,7], and from the results obtained, the following conclusions can be drawn.

For a receiver in the backward scattering zone of the windmill, the delayed multipath signals leads to a ghost image on the TV screen that, at low and moderate levels of interference, jitters horizontally in synchronism with the blade rotation to produce a form of video distortion that can be quite painful to the eye. In the forward zone, the interference appears as an intensity modulation of the received picture, again in synchronism with the blade rotation, and a somewhat larger modulation index is now required to give the same level of video distortion. In both cases noticeable distortion occurs only when the modulation waveform is pulsed in nature. Each blade contributes individually and the resulting sinc-like pulse usually appears when the blade is close to horizontal. All other things being equal, the modulation index and the resulting video distortion increase with increasing TV channel numbers, i.e. frequency, and with decreasing distance from the windmill. No audio distortion was found in any of the tests.

The following additional conclusions relate to a receiver in the backward scattering zone. The video distortion shows no significant dependence on the ambient level of the signal, provided this is well above the noise level of the receiver, and appears independent of the test receiver used. Interference is observed only when a blade is positioned to direct a specularly reflected signal to the receiver. The azimuth and pitch angles of the blades are therefore key factors affecting the level of interference, and for any given transmitter and receiver locations, interference can occur only if the wind is such as to position the windmill appropriately.

IV. LABORATORY SIMULATION STUDY

The measurements at Plum Brook verified that a windmill could distort the video portion of a TV signal and showed how the distortion depended on some of the parameters involved. Because of the environmental conditions near to the windmill and the lack of a full range of receiver sites, the results were necessarily limited in scope, but the information gained from these and other [6] measurements made it possible to simulate the interference, and to examine the distortion under the controlled conditions that a laboratory affords. The key objectives of the study were to establish the modulation level at which the interference is first perceived on a TV screen, and the threshold level corresponding to the most severe interference still judged to be acceptable for most viewing purposes. The latter specified the maximum extent of the interference region about a windmill.

A. Experimental Set-up

Figure 9 shows a block diagram of the equipment. The TV signal was received with a commercial log-periodic antenna mounted on the roof of the laboratory about 120 feet above the ground. With the UHF channels it was found desirable to use a pre-amplifier, but this was by-passed at VHF where the signals were stronger. The signal was taken through a set of variable attenuators to a coaxial T-junction where it was split into two branches, the direct line representing the primary signal from the transmitter to the receiver, and the multipath line simulating the signal reflected off the moving windmill blades. Simulation was effected by a time delay followed by a repetitive pulse amplitude modulation. The signals were then recombined and fed to the test receiver and a spectrum analyzer. The latter was always tuned to the audio carrier frequency of the particular TV channel, and its vertical output was fed to a strip chart recorder to show the input to the test receiver as a function of time. The strip chart was used to determine the effective modulation level and could be set to a desired value with the attenuators and the DC bias at the AGC terminals of the receiver's tuner.

Figure 10a is typical of the modulation waveforms applied and should be compared with the waveform in Fig. 10b measured on Channel 43 at Plum Brook. Since the blades were rotating at 40 rpm, the pulse repetition period in Fig. 10b is 0.75 s, but for convenience all our laboratory tests were made with a repetition period of 0.5 s, corresponding to a blade rotation speed of 60 rpm. The change does not affect the nature of the interference phenomena, and in all other respects the study provided a faithful simulation of the interference provided by a windmill such as the one at Plum Brook.

B. Test procedures

The tests were made with the Zenith receiver used at Plum Brook and a 1967 Airline model GEN 12349A which is typical of older color receivers. The RF signals were the TV channels 2, 4, 7, 9 and 50 whose transmitters are located near Detroit, Michigan approximately 60 Km from the laboratory, and channels 11, 13 and 24 originating in Toledo, Ohio about 90 Km away. Each channel was modulated with pulses of width τ = 50,100 or 200 ms having a 500 ms repetition period. The backward zone interference was simulated by introducing a time delay between the direct and multipath signals and suitably attenuating the latter. Two sections of coaxial line provided a constant 625 ns delay at all of the TV frequencies, corresponding roughly to the time delay in one of the Plum Brook measurements. For the forward zone the direct line in Fig. 9 was eliminated, so that only the modulated signal was applied to the receiver and the spectrum analyzer.

For a given TV channel and modulation pulse width, each simulation test had two parts. The first served to establish the critical modulation level as a function of the ambient RF signal at the input to a receiver. This is defined as the smallest modulation Δ_c which produces video distortion detectable to an observer viewing the picture from a distance of 5 feet. Although the criterion is obviously subjective, the same observers were used throughout the study and the results were reproducible when the tests were repeated at a later time. In the second part of the test, the modulation Δ was increased in small steps from zero and the degree of video distortion observed. Four categories of video reception were distinguished: (i) no video distortion, corresponding to $\Delta < \Delta_c$; (ii) distortion judged acceptable for at least small periods of viewing. This corresponds to $\Delta_c < \Delta < \Delta_o$ the upper limit being the modulation threshold; (iii) distortion judged unacceptable and intolerable for prolonged viewing; and (iv) disruptive distortion ($\Delta \geq \Delta_1$) occasionally resulting in picture break-up due to loss of vertical sync by the test receiver.

C. Results

The simulation tests performed were quite extensive, and we present here only the results obtained for modulation pulses of width τ = 100 ms, which is typical of the windmill at Plum Brook.

With both branches of the signal path (see Fig. 9) in operation, simulating backward zone interference, the critical modulation Δ_c for the two receivers and a variety of signal strengths on each of the available TV channels is shown in Tables 1 a, b. Data which are of questionable accuracy are marked with symbols whose meaning is explained in the caption, and due to systematic and occasionally erratic valuations in the signal strength of Channel 13, all of the data in Table 1a are suspect for this channel. For completeness, however, the data are included. The degrees of video distortion observed on the two receivers are listed in Tables 2a,b for channels 7 and 50, selected because of the reliability and consistency of the data they provided. Since the results for the Zenith receiver were the same at all signal strengths, Table 2a shows only the data for an ambient signal - 60 dB/mW, but even with the Airline model, Δ_c and Δ_o are almost independent of the signal level.

With the direct signal path in Fig. 9 eliminated, simulating forward zone interference, the critical modulation Δ_c is shown in Table 3. For the Zenith receiver Δ_c decreases rapidly with decreasing signal strength whereas the Airline model's sensitivity is almost uniform, but with both receivers the values of Δ_c at all signal levels exceed those for the backward interference zone. The modulation threshold Δ_o behaved in a similar manner.

The results indicate that there is no single value of the modulation threshold applicable to all signal levels in both the back and forward interference zones, but since the backward zone encompasses the majority of space around a windmill and here Δ_o is almost constant at 2.6 dB, this value was chosen for the entire region about a windmill where unacceptable video distortion may occur. From (12) the corresponding threshold modulation index is m_o = 0.15, and one effect of using this is to over-estimate the actual video distortion in the forward zone, particularly for high signal levels.

V. TV INTERFERENCE REGION OF A WINDMILL

The judicious siting of a windmill requires a knowledge of its interference to TV reception in its surrounding area. The results of the previous sections indicate that the amplitude modulation of the total received signal generally decreases with increasing distance from the windmill, and that the video distortion could be unacceptable if the modulation index m is greater than or equal to a threshold value $m_o = 0.15$. On the assumption that the orientation of the windmill and the pitch and coning angles of the blades are such as to direct the maximum scattered singal to the receiver, the region about the windmill where $m \geq m_o$ is defined as the interference region. It should be emphasized, however, that the situation is not 'black and white'; and since the interference decreases with increasing distance, the boundary of the region is simply the distance at which the distortion is judged to pass from unacceptable to acceptable for small periods of viewing.

Using computed data for the field strength as a function of distance over a smooth homogeneous spherical earth for specified transmitter and receiver heights, in conjunction with the theoretical relations presented earlier, a graphical method has been developed [8] to determine the interference region in any given situation. It is also possible to determine the approximate shape of the region using elementary considerations, relying on the graphical comparison to specify the maximum dimensions, and since this is a much simpler procedure, we shall confine our discussion to it.

Let the scattering center of the windmill and the phase centers of the receiving and (distant) transmitting antennas all lie in the horizontal plane shown in Fig. 11. The windmill blades rotate in a vertical plane through M-M (See Fig. 11) so oriented as to direct the specularly reflected or forward scattered field to the isotropic receiver. The modulation index of the total received field is the ratio of the secondary and direct field amplitudes at R, and since the secondary field is proportional to the direct field $E^T(B)$ at the windmill and the equivalent scattering area A_e of the blade, we can write approximately

$$E^B(R) = E^T(B)\,\frac{KA_e}{T}\begin{cases}\cos\phi/2 & \text{for } 0 \le |\phi| \lesssim \pi-\lambda/L \\ \text{sinc}\,(\frac{L}{\lambda}\sin\ ) & \text{for } \pi-\lambda/L \lesssim |\phi| \le \pi\end{cases} \quad (16)$$

where K = 0.3V/m, r is the distance of the receiver from the windmill and L is the physical length of the blade.

For given $E^T(B)$ and r, $E^B(R)$ achieves its maximum value in the directions $\phi = 0$ and π of back and forward scattering respectively, and the distances r_1 and r_2 in these directions at which the modulation index equals its threshold m_o are

$$r_1 = \frac{KA_e}{m_o}\left|\frac{E^T(B)}{E^T(R_1)}\right| , \qquad r_2 = \frac{KA_e}{m_o}\left|\frac{E^T(B)}{E^T(R_2)}\right| \quad (17)$$

with $R_1 = (r_1, 0)$ $R_2 = (r_2, \pi)$. These are implicit relations from which r_1 and r_2 can be obtained using the computed field strength curves. In general, $|E^T(R_2)| < |E^T(R_1)|$ implying $r_2 > r_1$. From (16) the backward portion of the interference region is given by

$$r(\phi) = r_1 \cos\phi/2 \qquad (0 \le \phi \lesssim \pi - \lambda/L) \quad (18)$$

which is a cardioid centered on the windmill with its maximum towards the transmitter. The forward portion of the region is

$$r(\phi) = r_2\,\text{sinc}(\frac{L}{\lambda}\,\text{sinc}\,\phi) \qquad (\pi - \lambda/L \lesssim \phi \le \pi) \quad (19)$$

which is a narrow lobe pointing away from the transmitter. The approximations inherent in this approach are to assume that the propagation of the scattered signal from the windmill takes place as though over a flat earth, and to neglect the ϕ variation of the transmitter-receiver distance in using the field strength curves. As an illustration of the accuracy obtained, Fig. 12 shows the interference region for the NASA/ERDA windmill on channel 52 computed using the exact [8] and approximate methods. Observe that the region of unacceptable interference extends out several Km from the windmill, but it should be emphasized that the calculations were performed on the basis of an omnidirectonal receiving antenna and an idealized earth. If the antenna is not omnidirectional, the interference region will differ in all directions except $\phi = 0$, and the effects of local topography could also decrease (or increase) the level of interference at any given location.

VI. CONCLUSIONS

The electromagnetic interference to television reception caused by a horizontal axis windmill has been examined theoretically and experimentally. The most important conclusion is that the rotating blades produce pulse amplitude modulation of the total received signal, and if the modulation is sufficiently strong, it can distort the video portion of the TV signal. The modulation pulses and the resulting interference have been predicted theoretically, and recorded and characterized experimentally using the operating NASA/ERDA windmill at Plum Brook. It is found that the level of observed interference increases with frequency and is therefore worst at the upper UHF frequencies. It decreases with increasing distance from a windmill, but in the most severe cases it can still produce objectionable video distortion at distances up to a few Km. No audio distortion has been observed.

Based on laboratory simulation studies confirmed by field tests, a modulation threshold level has been established below which the video distortion is judged acceptable for short periods of viewing, and this is substantially independent of the ambient field strength and the TV receiver. Using the threshold value and the theory that has been developed, it is then possible to compute the distance from a windmill at which the interference to a TV channel changes from 'severe' to 'acceptable': in effect, to compute the region of interference about the windmill. The size of this region increases with increasing scattering by the windmill blades and is therefore greater for a larger blade and for metallic rather than composite materials. In our calculations it has been assumed that the receiving antenna is omnidirectional with the windmill positioned to direct the maximum blade-scattered signal to be receiver. In circumstances other than this, the interference will be less, and local topography could also affect the actual interference observed. Depending on the prevailing winds, some (or all) parts of the interference region could suffer interference for only a small fraction of the total viewing time.

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Signal (dB/mW)	TV channel no.							
	2	4	7	9	11	13	24	50
-50	4.0	---	0.9	---	---	---	---	---
-55	3.4	1.0	0.8	---	0.8	3.8*	---	0.6
-60	4.6	1.2	1.0	0.8	0.9	4.0*	0.6	0.7
-65	4.9	0.9	1.0	0.8	0.8	3.0*	0.7	0.7
-70	4.8	1.1	1.2	1.1	0.9	2.9*	0.9	2.0#
-75	---	1.0	1.5#	1.6	1.0	3.0*	1.2#	2.0#
-80	---	2.6#	1.6#	2.1#	1.3#	3.0#	---	---
-85	---	2.7#	1.7#	2.0#	1.6#	3.2*#	---	---

(a)

Signal level (dB/mW)	TV channel no.						
	2	4	7	11	13	24	50
-50	0.8	---	2.2	---	---	---	---
-55	0.5	1.5	2.1	0.9	2.9	---	1.9
-60	0.4	1.4	1.5	0.8	3.3	1.6	1.8
-65	0.5*	1.3	1.8	0.8	3.1	1.5	1.6
-70	0.4*	1.6	1.2	0.8	2.5	1.9	1.8
-75	0.4*	1.8	1.2	0.8	2.2	1.8	1.8#
-80	0.4*	1.8	1.2	0.6#	2.0#	1.8	2.0#
-85	0.4*#	---	---	0.8#	2.0#	---	---

(b)

Table 1. Critical modulation level Δ_c (in dB) required to produce minimum observable video distortion in the backward zone as a function of the ambient audio carrier signal strength on various TV channels with (a) the Zenith receiver, (b) the Airline receiver. Symbols:

\# Signal very weak and picture 'snowy': data unreliable.

* Ambient signal variations large: data mostly unreliable.

Channel No	Δ_c (dB)	Δ_o (dB)	Δ_1 (dB)
7	1.1	2.8	3.1
50	0.7	2.6	3.0

(a)

Signal level (dB/mW)	Δ_c (dB)	Δ_o (dB)	Δ_1 (dB)	
-55	2.1	2.5	5.4	Channel 7
-60	1.5	2.6	7.5	Channel 7
-65	1.8	2.7	6.1	Channel 7
-70	1.2	3.0	5.5	Channel 7
-55	1.9	2.8	4.3	Channel 50
-60	1.8	2.6	4.2	Channel 50
-65	1.6	2.6	4.4	Channel 50
-70	1.7	2.7	4.4	Channel 50

(b)

Table 2. Modulation levels required for different degrees of backward zone video distortion on two TV channels observed with (a) the Zenith receiver for an audio carrier signal strength -60 dB/mW, (b) the Airline receiver as a function of the audio carrier signal strength.

Signal level (dB/mW)	Zenith		Airline
	Channel 7	Channel 50	Channel 50
-50	29	--	--
-55	25	--	2.6
-60	20	--	2.9
-65	15	17	3.0
-70	5.5	13	3.2
-75	3.5	10	3.2
-80	3.5	5	2.8#
-85	2	4	2.6#

Table 3. Critical modulation level Δ_c (in dB) required to produce minimum observable video distortion in the forward zone as a function of the ambient audio carrier signal strength.

LIST OF FIGURE CAPTIONS.

1. 100 KW NASA/ERDA experimental wind turbine generator at Plum Brook, Ohio.

2. Calculated field strengths ($|E^T(R)|$, $|E^B(R)|$) as functions of distance (r) from the windmill: f = 650MHz, transmitter-windmill distance = 80 Km, transmitter height = 300 m, receiver height = 10m, windmill height = 30m, relative permittivity of earth ϵ = 15, conductivity of earth σ = 0.01℧/M.

3. Rotating rectangular metal plate illuminated by a plane electromagnetic wave.

4. Experimental modulation waveforms for a rotating rectangular metal plate: f = 12.18 GHz (λ = 2.461 cm), plate rotation frequency = 10 Hz, $L_1 = 5\lambda$, $L_2 = 2\lambda$.
(a) $\phi_o = 135°$, $\phi = 45°$, (b) $\phi_o = 115°$, $\phi = 55°$, (c) $\phi_o = 145°$, $\phi = 55°$.

5. Schematic block diagram of a typical on-site measurement set-up.

6. Geometry of the receiver, transmitter and windmill during on-site measurement.

7. Received channel 43 signal showing the modulation pulses due to the backward scattering by the WTG blades. Blade rotation frequency = 20 rpm.

8. Received channel 43 signal showing the modulation pulses due to the forward scattering by the WTG blades. Blade rotation frequency = 20 rpm.

9. Block diagram showing the experimental arrangement for simulation and measurement of interference by a WTG.

10. (a) Modulation pulses applied to the input of the test receiver during the simulation measurement.

    (b) Modulation pulses at the input of the test receiver observed during the on-site measurement (channel 43) at Plum Brook. Blade rotation frequency = 40 rpm.

11. Geometry of the WTG blade scattering.

12. TV interference region of the NASA/ERDA WTG at Plum Brook for TV channel 52 (transmitter distance = 120 Km), computed using the graphical (——) and approximate (---) methods.