WIND TURBINE INTERFERENCE TO TELEVISION RECEPTION

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D. L. Sengupta and T.B.A. Senior

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NOTICE

ABSTRACT

Laboratory scattering measurements using a scale model blade indicated that the equivalent scattering area (A_e) and the equivalent length (L_e) of a MOD-2 blade are 140 m^2 and 63 m, respectively. Using these results, the WT generator siting and TV reception handbook has been updated to accommodate the increased height (h_3) of large WTs like the MOD-2 machine. Television interference (TVI) tests performed at the Cable Television (CATV) antenna location at Rich Mountain indicate that the CATV system will not be affected by the MOD-1 machine. Other limited TVI tests indicate that there are some residential homes within 1 to 2 km of the MOD-1 WT which could experience varying amounts of interference to TV reception. More detailed tests are necessary to quantify the interference and to develop means to reduce and/or overcome the observed interference.

TABLE OF CONTENTS

WIND TURBINE INTERFERENCE TO TV RECEPTION

This is a summary report of a fourth year's study of the effects of wind turbine generators (WTs) or windmills on the electromagnetic environment. The present report is concerned with the interference to TV reception in the vicinity of large horizontal axis windmills. Since the investigation was a continuation of a sustained research program, it is appropriate to begin with a brief summary of our previous studies.

1. Previous Studies

Over the past three years we have investigated theoretically and experimentally the interference caused by a variety of windmills on the performance of electromagnetic systems.

1.1 First Two Years

During the first two years the interference produced by large horizontal axis WTs on a selected number of electromagnetic systems was identified and quantified [1,2]. The work was originally motivated by the possibility of interference to TV reception in the vicinity of a windmill. Analyses of blade scattering [3] established that the rotating blades of a WT could produce pulse amplitude modulation of the total field received in its vicinity, and an examination of the basic detection process in a TV receiver showed that this extraneous modulation could cause video (but not audio) distortion [1]. This led to an intense study [2] of TV interference using field tests with the operational 100 kW MOD-0 WT at Plum Brook, Ohio, plus scale model measurements, and laboratory simulations. One outcome was the establishment of a threshold for the modulation index (m_0 = 0.15 or 2.6 dB) representing the largest value for which the video distortion was still judged acceptable for small periods of viewing; and the dependence of this threshold on the ambient signal level was explored. Examples of the interference at different modulation levels were recorded on a video tape furnished to the sponsor. Knowing the threshold and the equivalent scattering area of the particular windmill blade, it is then possible to define an interference zone about a WT for each of the TV channels available in its vicinity, the zone being that where the video distortion could be unacceptable. Using analyses and computations of the propagation and scattering phenomena, a simple technique was developed [4] for computing the interference zones for large horizontal axis WTs such as the MOD-0, MOD-0A and MOD-1 machines. A detailed discussion of the interference to TV reception caused by large horizontal axis windmills may be found in [5].

In addition to the TV work, the possibility of windmill interference to other electromagnetic systems was also examined. In the case of FM broadcast reception, laboratory simulations [2] have shown that interference is detectable only at very high modulation levels or where the ambient signal is itself low, and for all practical purposes the interference will be negligible except possibly within a few tens of meters of the WT.

Theoretical studies [2] of the interference to two specific air navigation systems, VOR and DVOR, indicate that no significant degradation in the performance of these systems will occur if the WT is sited according to the standard guidelines (for stationary scattering objects) established by the FAA.

We also analyzed the performance of two typical microwave communication link systems whose repeater stations could be located in the vicinity of a WT. It was found that the blade rotation produces a frequency smearing of the received baseband signal energy, but the maximum smear is much less than the total FDM bandwidth of the channel. Using then the threshold value for the interference-to-signal (RF carrier) level allowed by the telephone companies, the concept of a forbidden zone around the link receiver was developed, the zone being that where the placement of a windmill could cause unacceptable interference, and illustrative examples were given in [2].

1.2 Third Year

In spite of the wide ranging nature of the first two years' investigation, there are other systems and/or circumstances where WT-generated interference could be a problem and the objective of the third year's study, described in [6], was to treat some of these.

The use of circular polarization for television transmission has been suggested in order to eliminate the reception of extraneous multipath signals due to single reflections. This could significantly affect the interference caused by a windmill. To this end, the scattering of circularly polarized electromagnetic waves by a slowly rotating rectangular metal plate and the reception of such incident and scattered waves by an arbitrarily polarized receiving antenna were investigated theoretically and experimentally. It was found that a similarly polarized receiving antenna discriminates against the scattered signals in the backward scattering region. The video distortion to TV reception within the backward interference zone of a windmill will therefore be less with circularly polarized signals than with conventional horizontally polarized signals, all other conditions being equal.

Our previous analyses [2] based on the "worst case" assumptions, i.e., the WT blades oriented to direct the maximum scattered signals to the receiving point with the receiving antenna isotropic, show that the interference zone of a large WT can be quite large at the upper UHF TV Channel frequencies. However, directional receiving antennas are used in many practical situations; also the interference zone is merely the region where video distortion could possibly occur, and gives no information about the probability of its occurrence. In order to assess the practical severity of the TV interference problem, the use of a directional receiving antenna and various statistical (and other) factors governing the occurrence of interference were theoretically examined. It was found that the availability and correct orientation of a directional antenna will decrease the maximum interfering distance as well as the actual possibility of interference throughout the backward portion of the interference zone.

A variety of measurements were carried out in a microwave anechoic chamber using scale models of the MOD-OA WT, the Darrieus and the Giromill to determine their electromagnetic scattering characteristics. It was found that the scattering cross section of a scale model

MOD-OA WT blade is about 5 dB greater than for the Darrieus, and 5 dB less than that for the Giromill.

A laboratory microwave (4 GHz) TV system was developed for studying the TV interference effects produced by a variety of WTs using scale models. The TV channel frequency at which these effects are applicable for a given WT is determined by the scale factor of the model and the frequency of the microwave signal used. Results were obtained which are representative of the interference produced by the Giromill, Darrieus and MOD-O machines.

The possible interference to the performance of a Loran-C system caused by large horizontal axis windmills was investigated theoretically and it was found that under normal conditions no degradation in performance is likely to occur due to the siting of a WT near a Loran-C transmitter.

2. Present Study

All of our investigations during the present period have been related to the television interference (TVI) problems associated with large horizontal axis WTs.

As mentioned earlier, theoretical and experimental studies described in [1,2] culminated in the preparation of a (large) horizontal axis WT siting handbook. All site calculations there were for a smooth, homogeneous spherical earth, horizontal polarization (applicable to the vast majority of existing TV stations), omnidirectional receiving antennas and fixed heights above earth for the TV transmitting antenna (h_1), the receiving antenna (h_2) and the phase center for the blade-scattered signals (h_3). The choices h_1 = 300 m, and h_2 = 10 m are reasonable under all circumstances, as was the choice h_3 = 30 m for a MOD-0 machine. However, 30 m is less realistic for the MOD-1, and would be entirely inappropriate for the very large MOD-2 machine presently under construction. To cover these large machines, it was therefore necessary to recompute the curves in [4] for the appropriate values of h_3, and since the size of the interference zone increases with increasing h_3, such extension (or up-dating) of the handbook is essential for machines which are substantially different from those discussed in [4]. To obtain the interference zone of a MOD-2 machine, it is necessary to know the equivalent scattering area of the MOD-2 blade. This was obtained from scattering measurements carried out in a microwave anechoic chamber using a scale model MOD-2 blade.

In addition to the above, measurements of on-site television interference (TVI) were carried out at Boone, NC, and Block Island, RI, using the operational MOD-1 and MOD-0A WTs, respectively. The purpose of these measurements was to observe and record the interference to TV reception in the vicinity of the windmills. The test set-up was identical to that used during our past on-site measurements at Plum Brook [2], and the available commercial TV signals were again used as the source of the RF signals. At a test site near the WT, the total received signal (direct plus scattered off the WT blades) was recorded on a strip chart recorder, and the interference effects were observed on the screen of a TV test receiver, and, as appropriate, recorded on video tape. Data were collected at all available VHF and UHF channel frequencies.

3. Task Summary

3.1 MOD-2 Blade Scattering

The MOD-2 WT has a center-pivoted single blade with full tip control. The maximum scattering will occur when the blade is viewed specularly, but in contrast to the case with the MOD-0A and MOD-1 machines, the equivalent scattering area is that of the entire blade, suggesting that its value will be more than twice that of the MOD-1.

Scattering characteristics of a MOD-2 blade have been measured at 3.034 GHz (λ = 9.89 cm) in an anechoic chamber using a 1:100 scale model of the blade. The model was initially constructed in three parts: a center section of length 24.0 cm and width 3.8 cm with no twist, and two outer sections of length 33.7 cm each tapering in width down to 1.27 cm, with a 6° twist. From each outer section a tip of length 12.6 cm was then cut off and reattached with a pin.

The equivalent scattering area (A_e) and the equivalent length (L_e) of the blade, as obtained from the measured data, are 140 m^2 and 63 m, respectively. These values were used to obtain the interference zone of the MOD-2 WT. We remark that in relation to the projected blade area with tips removed, the value of A_e implies a scattering efficiency η = 0.67. This is identical to the efficiency for a MOD-0 blade [2]. Appendix 1 describes the MOD-2 blade scattering measurements.

3.2 Updated Siting Handbook for Large WTs

The previously published [4] WT Siting Handbook has been revised. As a result of data that have become available since that time, it is apparent that a change in height at which the WT reflects TV signals can have just as much effect as a change in the blade area responsible for the reflections. Since the tower height used in [4] is 30 m, the curves given there are applicable only to a MOD-OA (or similar) machine. In addition, on-site and laboratory measurements of the WT-produced interference have shown that the modulation threshold used to specify the interference zone increases with decreasing time delay of the secondary (scattered) signal relative to the primary. This not only reduces the interference zone radius in the forward scattering region but also permits some simplification in the method used to calculate the entire zone. Three numbers now suffice and these are tabulated as functions of the frequency and distance to the TV transmitter for MOD-OA, MOD-1 and MOD-2 machines. For these same machines with blades other than metallic, information is provided to enable the corresponding numbers to be obtained. The method is described in detail in another technical report [7], and hence will not be discussed further.

3.3 TVI Tests on Block Island, RI

Electromagnetic interference to television reception produced by the MOD-OA WT at Block Island, RI, has been studied by carrying out a number of on-site measurements at selected test sites and residential homes in the vicinity of the operating windmill. The commercial TV signals available on the island were used as the RF sources. Our measurements indicate that a properly oriented directional antenna having side and back lobes at least 15 dB down could provide interference-free reception at those homes 0.2 km or more from the WT that are in the backward interference region. At distances of less than 0.2 km it would be difficult, if not impossible, to avoid the interference even with the best antenna. In addition, there are also a few homes which are up to 0.5 km from the WT and in the forward region, and for these the TVI problem would not be corrected by the use of good antennas. The entire measurement program and the results obtained are described in a technical report [8], and will not be discussed further.

3.4 TVI Tests at Boone, NC

Limited TVI tests were performed at a selected number of residential homes in the vicinity of the MOD-1 WT, and varying amounts of interference were observed on the received pictures. It was generally found that the MOD-1 machine could cause TVI within about 2 km of the machine. More systematic tests are necessary to quantify the interference.

Detailed TVI tests were carried out at the CATV antenna site on Rich Mountain, about 2 km from the MOD-1 site. These indicate that the operating WT should not affect the performance of the CATV transmission in the area.

The on-site tests and results are described in Appendix 2.

4. Conclusions

The equivalent scattering area of a MOD-2 metal blade has been obtained from electromagnetic scattering measurements with a scale model blade. Using these results, the WT generator siting and TV reception handbook has been updated to accommodate large WTs like the MOD-2 machine.

On-site TVI tests performed at Block Island indicate that with the planned location for the antenna system, the CATV system should not experience any significant interference caused by the MOD-OA WT.

TVI tests performed at the CATV antenna location at Rich Mountain indicate that the CATV system will not be affected by the MOD-1 machine. There are some residential homes up to 2 km from the MOD-1 WT which could experience varying amounts of interference to TV reception. More detailed tests are necessary to quantify the interference and to develop means to reduce and/or overcome the observed effects.

5. Acknowledgements

It is a pleasure to acknowledge the assistance of our colleagues in the performance of this study. We are particularly grateful to Mr. J. E. Ferris who was responsible for all the on-site field tests and for the measurements of blade scattering; and to Messrs. I. J. LaHaie and R. Ziemelis for their assistance during the on-site measurements

Completion of the TVI tests on Block Island would not have been possible without the help of A. Birchenough of the NASA Lewis Research Center, and the excellent cooperation of F. Renz and H. Dupont of the Block Island Power Company.

Thanks are due to Mr. R. Bumgarner, of Blue Ridge Electric Membership Corporation, for coordinating the test programs in various homes at Boone, NC. We are also grateful to some residents in the area for their hospitality and excellent cooperation during the tests performed at their homes. Last, but not least, the assistance and advice provided by Dr. R. McConnel of SERI were much appreciated.

6. References

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APPENDIX 1: EQUIVALENT SCATTERING AREA OF THE MOD-2 WT BLADE

Each of the MOD-OA and MOD-1 machines has two fully controllable blades and because of their twist, pitch and coning, the two blades scatter electromagnetic energy separately and independently of one another. Maximum TV interference then occurs under conditions of specular reflection off a single blade, and the equivalent scattering area A_e required for the interference zone calculations is that of a single blade alone.

The MOD-2 WT is the first of the second generation machines and has a center-pivoted single blade with full tip control. The maximum scattering will again occur when the blade is viewed specularly, but in contrast to the case with the MOD-OA and MOD-1 machines, the equivalent scattering area is that of the entire blade, suggesting that its value will be as much as twice that of the MOD-1.

The configuration of the blade is shown in Figure 1.1, where the station locations are measured in inches from the axis of rotation. The blade appears to have five distinct parts: a center section between the bolted splices at STA$\pm$480; two outer sections between STA$\pm$480 and $\pm$1260, followed by the tips. From Figure 1.1, the projected areas of the center, outer and tip sections are approximately 88, 60 and 26 m^2, respectively, leading to a total blade projected area of 260 m^2, of which the tips make up 52 m^2. The overall length is 91 m, but only 64 m if the tips are excluded.

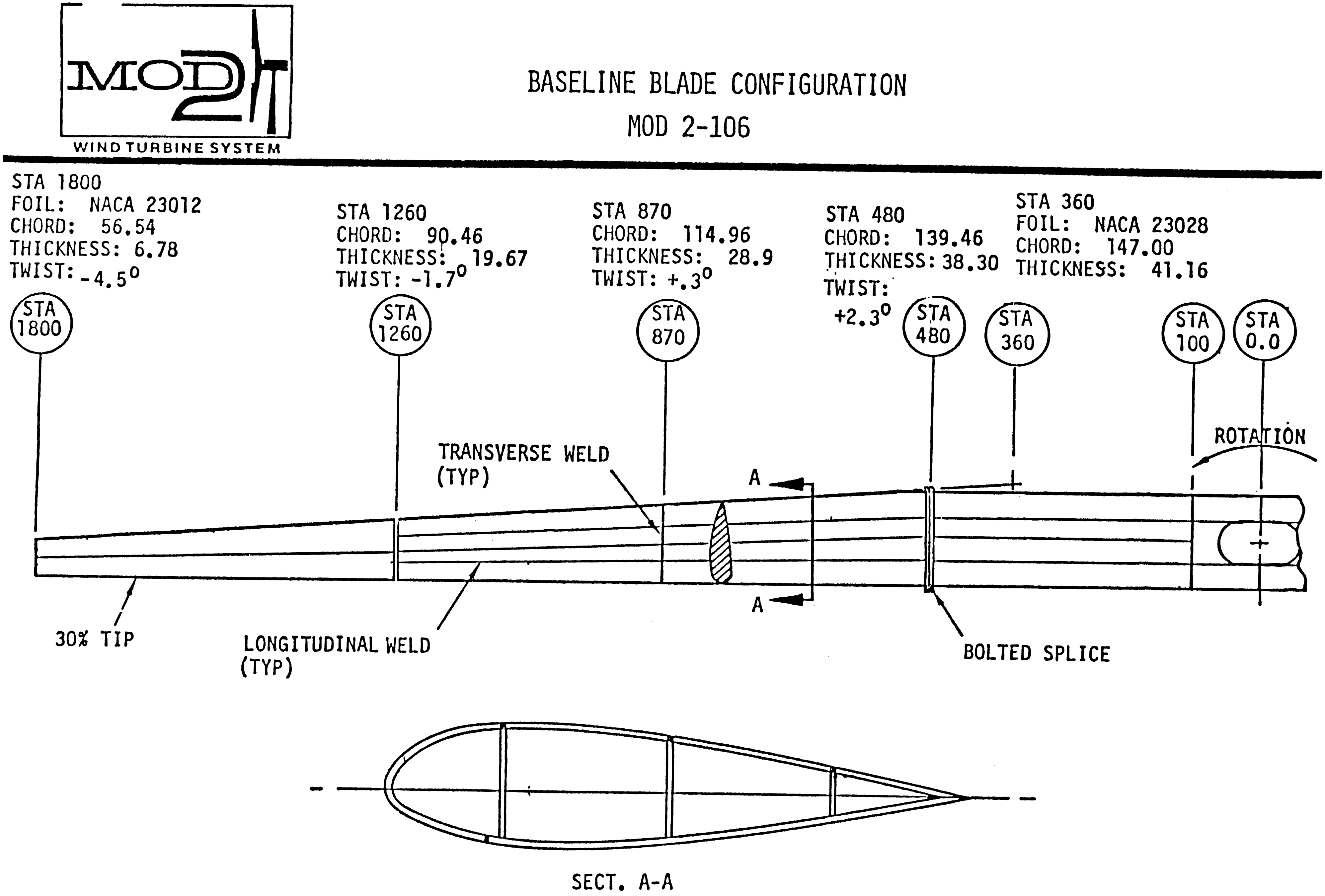

Figure 1.1 MOD-2 Blade Configuration.

Because the blade is so different from the previous ones, it is not evident how much the tips will contribute to the scattering, or what the scattering efficiency is, and we therefore carried out some measurements using a small scale model of the blade. The blade constructed for this purpose was made of wood and metallized by coating with silver paint. The tip sections were attached with pins so that they could be rotated about the blade axis to simulate a drive condition, or even removed. The blade was approximately a 1:100 scale model, and is shown in Figure 1.2. The overall length (including tips) was 91.4 cm, and the model was initially constructed in three parts: a center section of length 24.0 cm and width 3.8 cm with no twist, and two outer sections of length 33.7 cm each, tapering in width down to 1.27 cm, with a 6° twist. From each outer section a tip of length 12.6 cm was then cut off and reattached with a pin.

The backscattering cross section was measured at a frequency of 3.034 GHz (λ = 9.89 cm) in an anechoic chamber using a standard cw system. The measurements were made at a distance R = 12 m, which is slightly less than the far field distance $2L^2/\lambda$ = 16.9 m implied by the total blade length L. Calibration was with respect to a sphere 15.2 cm in diameter, whose scattering cross section at 3.034 GHz is -17.4 dBm^2. The blade was positioned horizontally on a styrofoam support pedestal with its front face towards the transmitting/receiving antenna and then adjusted in tilt or in direction until the scattering observed on rotation about a vertical axis was a maximum. Measurements were made with both horizontal and vertical polarization, but since the results were virtually identical, it is sufficient to discuss those for horizontal polarization alone.

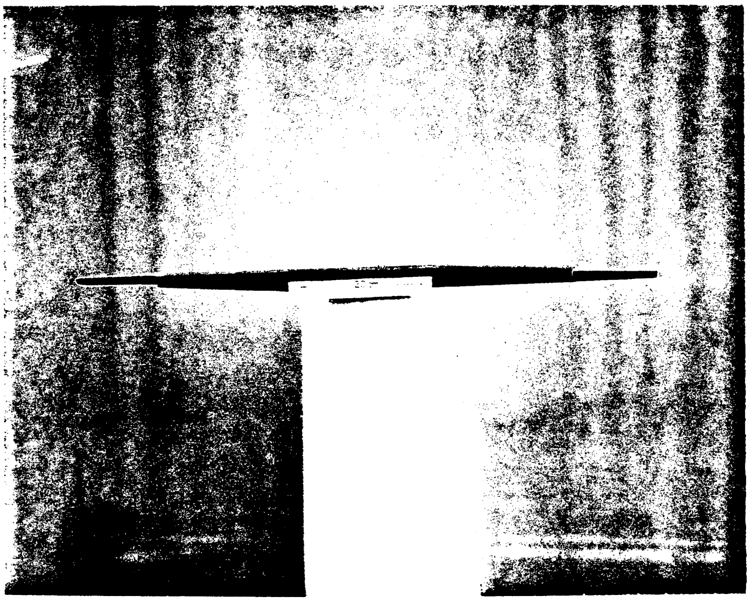

Figure 1.2 Photograph of the 1:100 scale model WT blade.

The backscattering pattern as a function of rotation about a vertical axis is shown in Figure 1.3 for the complete blade with no additional twist applied to the tip sections. The peak on the left is the specular return from the front and with this maximized the blade was no longer quite symmetrical about a vertical plane, thereby accounting for the somewhat lower peak on the right produced by the back of the blade. The left-hand peak is 13.8 dB above the return of the calibrating sphere, implying σ = -3.6 dBm^2. The equivalent scattering area $A_e = \lambda/2\sqrt{\sigma/\pi}$ of the model is therefore A_e = 184 cm^2. Since the half width of the peak measured at the -3 dB level is 1.5°, the effective blade length is $L_e = 0.222\ \lambda/\sin(1.5°)$ = 84 cm, which is only a little less than the actual length.

The corresponding pattern when the tip sections and their attachment pins are removed is given in Figure 1.4. The peak return is now -5.8 dBm , implying A_e = 143 cm^2, and since the half width of the peak is 2°, L_e = 63 cm. With the tips replaced but twisted 20° or more above the axis of the blade simulating the situation under full power conditions, there was almost no change in the peak return. It would therefore appear that the results for the tips twisted or removed are appropriate to the practical situation, and when converted to their full scale values using factors of 10^4 and 10^2 for the area and length respectively, we obtain:

equivalent scattering area : A_e = 140 m^2

effective blade length : L_e = 63 m

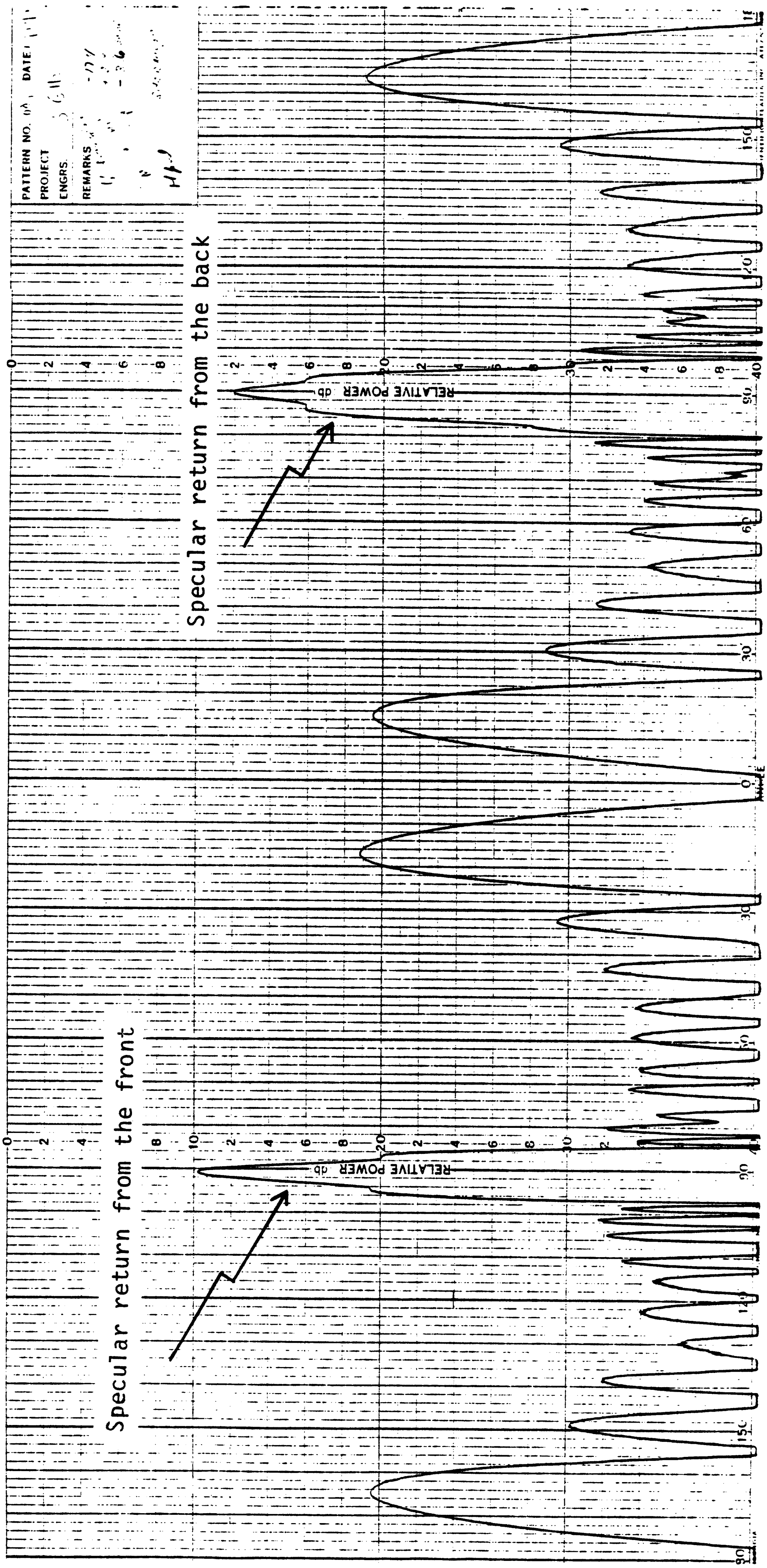

Figure 1.3 Backscattering pattern of the 1:100 scale MOD-2 blade with tips (unrotated) at 3.034 GHz with horizontal polarization.

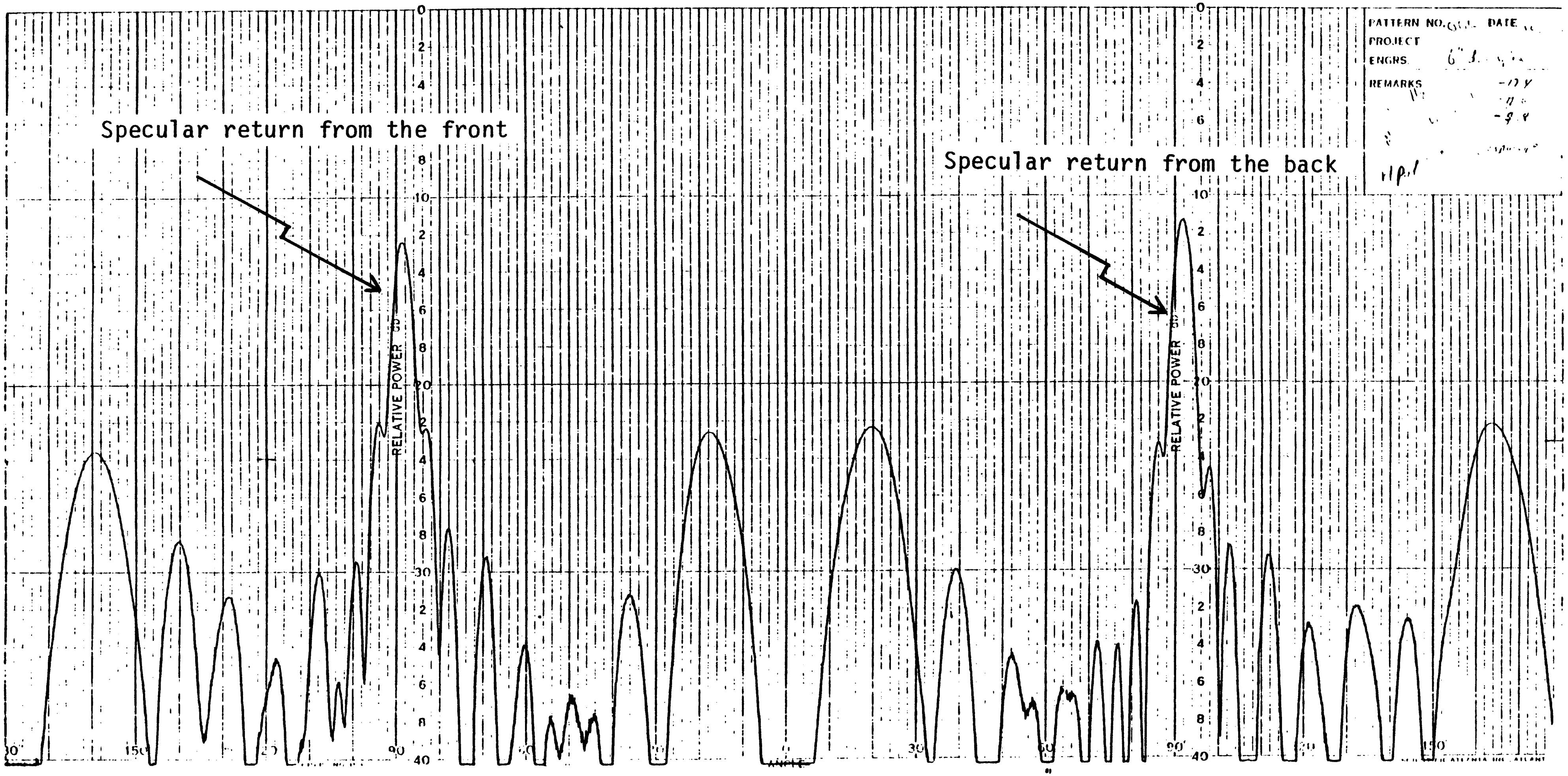

Figure 1.4 Backscattering pattern of the 1:100 scale MOD-2 blade without tips at 3.034 GHz with horizontal polarization.

These are the values used in calculations of the interference zone, and we remark that in relation to the projected blade area with the tips removed, the value of A_e implies a scattering efficiency $\eta = 0.67$. This is identical to the efficiency for a MOD-OA blade.

APPENDIX 2: TELEVISION INTERFERENCE TESTS AT BOONE, NC

A series of on-site television interference (TVI) tests were carried out at some residential homes [1,2], and at the existing commercial CATV antenna site [3] near the MOD-1 wind turbine (WT) at Boone, NC. The purpose of the tests was to obtain sufficient data to ascertain the impact of the wind turbine on the (direct) reception of TV signals in its vicinity, and on the indirect reception provided by the CATV system. An additional objective of the tests performed at the residential homes was to evaluate the ability of specific high gain receiving antennas to overcome or reduce TVI effects caused by the WT. Due to unavoidable conditions, to be discussed later, the tests performed at the residential homes were limited in scope and hence, the results should be considered as preliminary. However, the tests conducted at the CATV antenna site were detailed and provided definitive results.

2.1 Description of the WT and Test Sites

The MOD-1 WT, described in [4], is shown schematically in Fig. 2.1. At present, the MOD-1 is the largest wind turbine in operation. It is a horizontal axis machine with two-bladed rotor and generator assembly mounted on a steel truss tower 46 m in height. The rotor diameter is 61 m, and each of its metallic blades has an equivalent electromagnetic scattering area A_e = 40 m^2 [5]. The rated power output of the MOD-1 WT is 2 MW [4], achieved with a turbine rotor

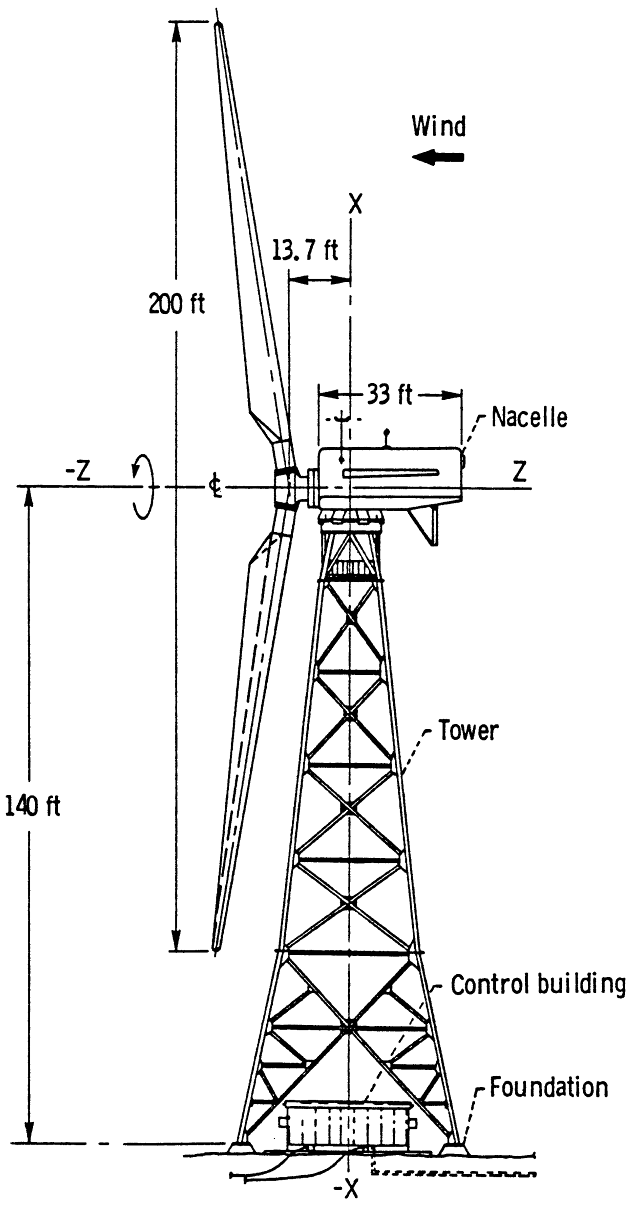

Figure 2.1. Mod-1 2000-kilowatt wind turbine.

speed of 35 rpm and a rated wind speed of 25.5 mph. The wind turbine is operated in 11 to 35 mph winds; at wind speeds outside this range, the blades are placed in a feathered position, and no power is generated.

The WT is located at the summit of Howard's Knob, part of the Blue Ridge Chain in the Appalachian Mountains. The city of Boone, location of the Appalachian State University, is 1.6 km to the southwest of the WT site. Figure 2.2 reproduces a portion of the U.S. Geological Survey map of the Boone quadrangle showing the topographical characteristics of the WT site and the surrounding area.

Interference tests were performed at the following five test sites (marked in Fig. 2.2): (i) Home 1 located about 3.2 km NNW of the WT, (ii) Home 2 located about 2.3 km NNW of the WT, (iii) Home 3 located about 0.8 km W of the WT, (iv) Home 4 located about 1 km E of the WT, and (v) the CATV antenna tower site located about 2 km W of the WT. The four homes are generally located 200 to 300 m below the WT site which is 1348 m above sea level (Fig. 2.2). The CATV antenna tower is located on Rich Mountain which is 1458 m above sea level (Fig. 2.2).

The CATV antenna system, maintained by the United Antenna Service of Boone, receives commercial TV signals from eleven TV transmitters located in the surrounding region, and retransmits them in the form of CATV signals to about 200 homes in Boone which, together, comprise about 50 percent of the population located within 8 km radius of the WT site. The four residential homes mentioned earlier are not on

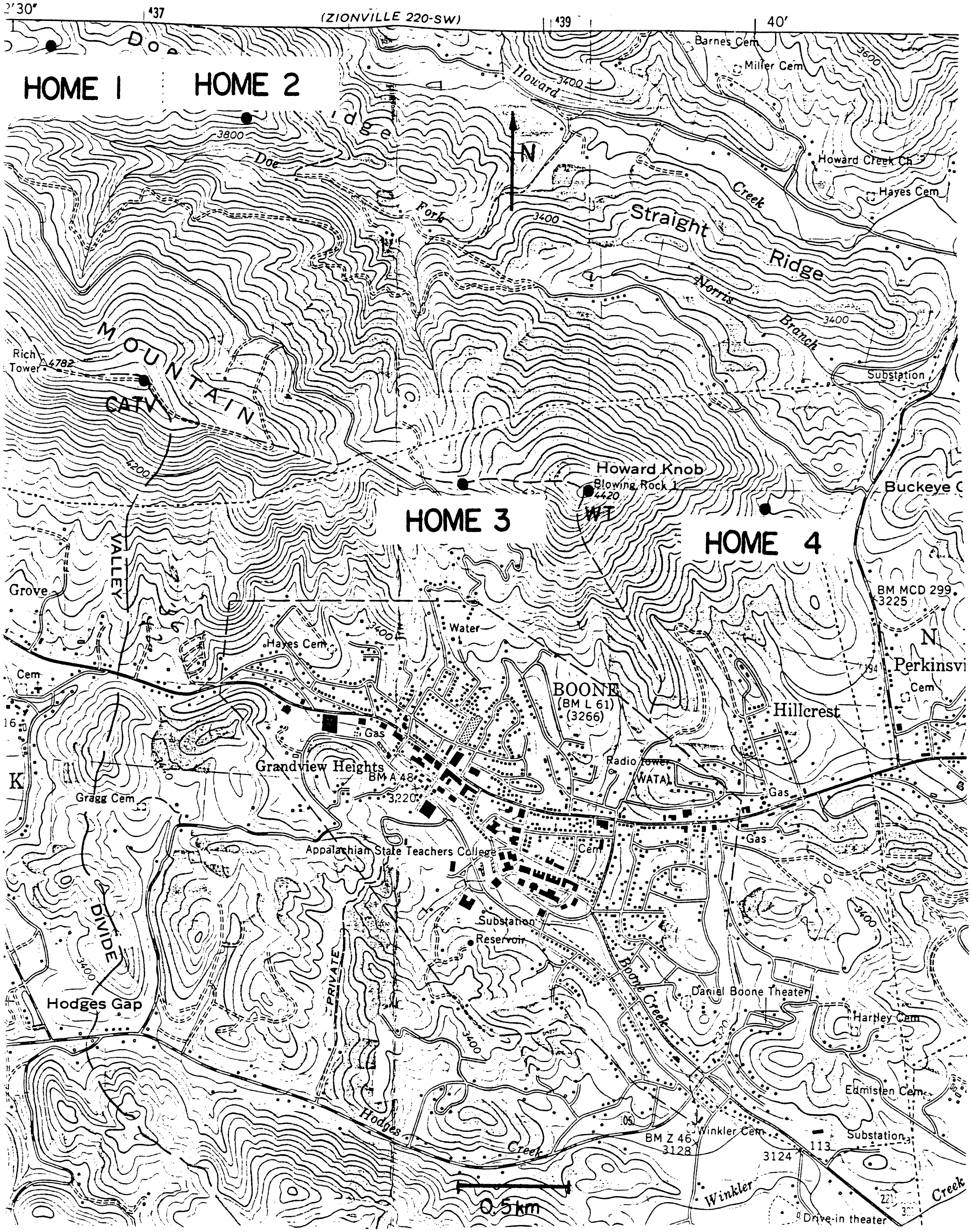

Figure 2.2. Map showing the topographical characteristics of the WT site and the surrounding area.

the CATV network and they receive their TV signals via their own receiving antennas. In addition to its own low gain receiving antenna, Home 2 has a high gain receiving antenna for TV Channel 3 provided by the Blue Ridge Electric Membership Corporation (BREMCO).

2.2 Available TV Signals

The CATV antenna tower supports eleven directional antennas to receive eleven available TV channel signals originating from distant TV transmitters located in the surrounding area. Figure 2.3 shows the location of the WT site, the CATV antenna tower site, and the approximate distance and direction of each of the transmitters from the CATV antenna site. To receive the maximum signal from a desired TV transmitter, the appropriate antenna beam is directed towards that transmitter. It is evident from Fig. 2.3 that when the Channels 8 and 12 antennas are oriented to receive the maximum direct signals from the transmitter, they would also receive maximum (or near maximum) WT-scattered secondary signals. For these two TV channels, the receiving antennas are located in the forward zones of the interference regions of the WT. For TV Channels 7 or 9 the receiving antennas are in the backward zone of the WT interference region, and in such cases the receiving antenna will generally provide some discrimination against the secondary signals. Similar considerations can be used to categorize the location of the receiving antennas in the WT interference regions for the other TV channels.

Amongst the available TV channels, Channels 3, 7, 8 and 9 appear to be popular with the home viewers, Channel 3 being the one most often

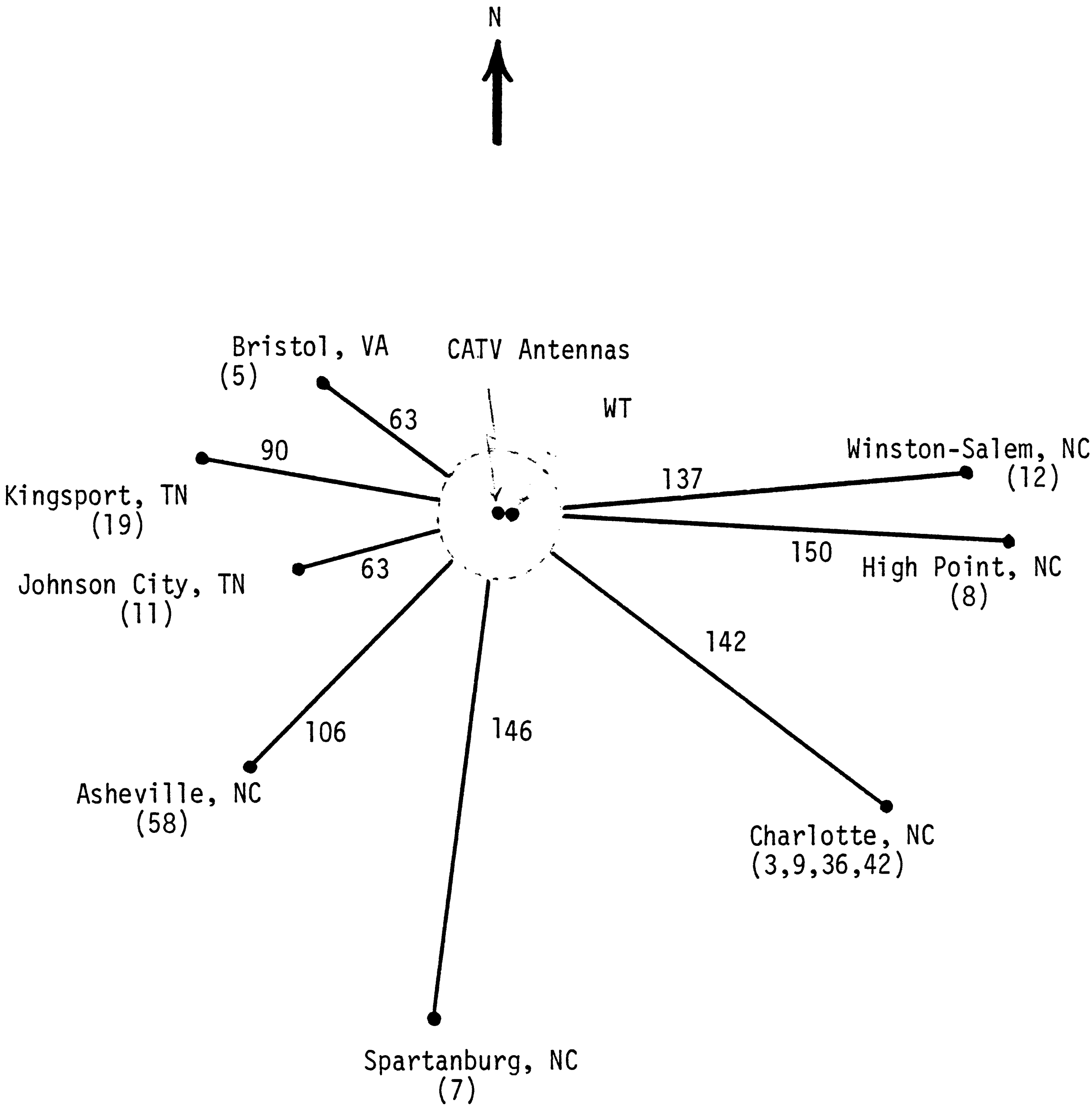

Figure 2.3. TV Channels and their transmitters in relation to the WT at Boone. The distances are given in km. (Numbers within parentheses refer to specific TV Channels. Numbers without parentheses are distances)

watched. It is appropriate to note that, when watching TV Channels 3, 8 and 9, Homes 1 and 2 are almost in the forward interference zones; for Channel 7 they are in the backward zone. Home 3 is possibly in the forward zone for Channel 8 and is in the backward zones for Channels 3, 7 and 9. Home 4 is in the backward zone for all four Channels.

2.3 The Test Set-up and Procedure

The typical set-up for performing the tests is shown in Figure 2.4 where we include only those components which are pertinent to the data collection. The RF signals used originated from the TV transmitter shown in Fig. 2.3. With any given transmitter, a portion of the signal is scattered off the WT blades and this, together with the direct signal, is picked up by the receiving antenna and fed simultaneously to a TV receiver and a spectrum analyzer. The receiving antenna used was a commercially available directional antenna for TV reception. The received TV picture was observed to see if there was any video distortion. The spectrum analyzer was tuned to the audio carrier frequency and its vertical output was recorded on paper tape for later evaluation. This provided a recording of the received signal as a function of time and included any modulation (of the received signal) produced by scattering from the rotating blades of the WT.

Generally, the aim of the test program was to collect static and dynamic test data at a given site. The static test was to record the total received signal as a function of time with the WT having its blades locked in a desired position whilst yawing through 360°; in the dynamic tests, similar recordings were obtained with the

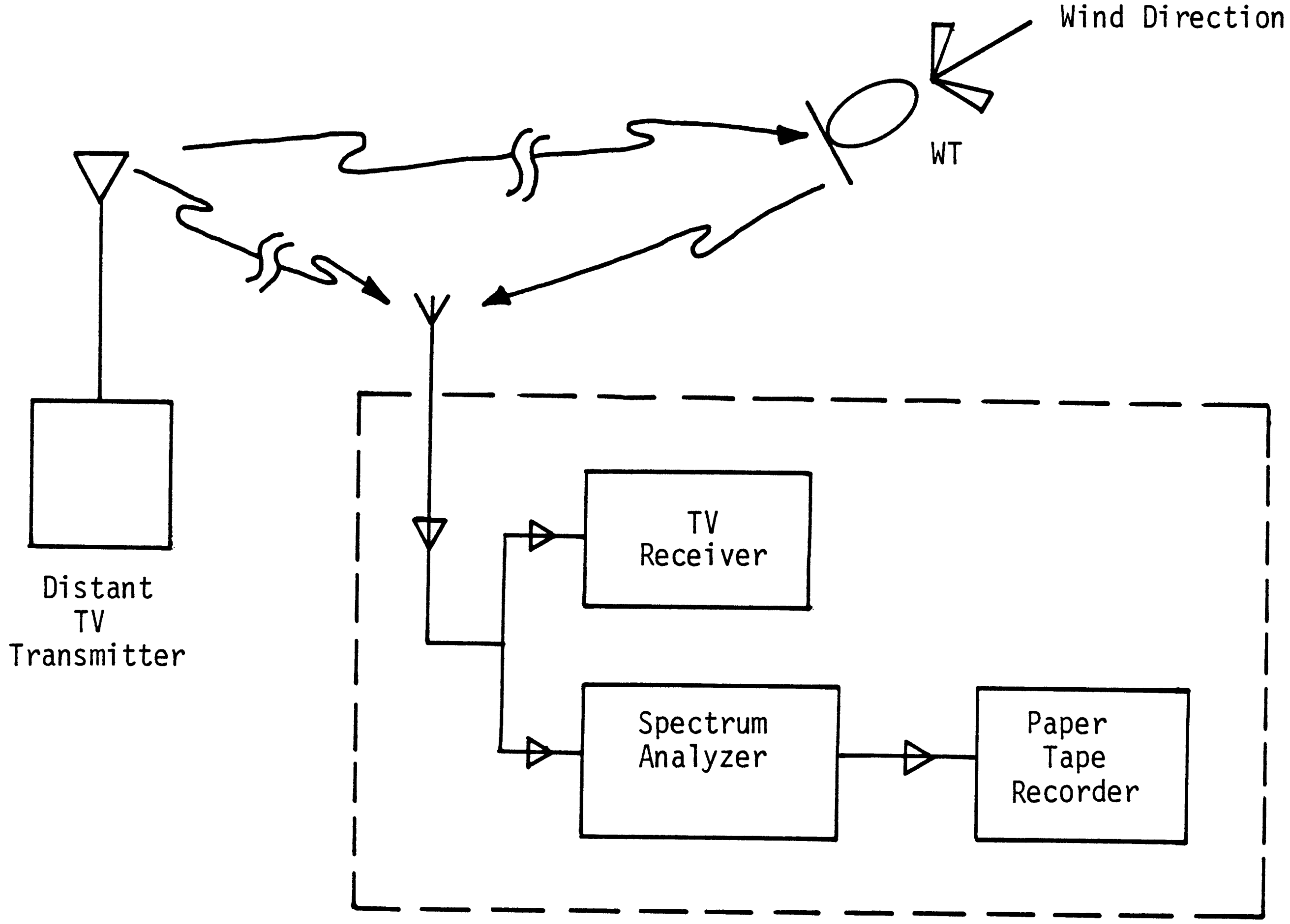

Figure 2.4. Schematic diagram of the TVI test set-up.

WT operating under normal conditions. Tests at the CATV site were conducted with a commercial TV receiving antenna. At all of the residences except Home 2, data were collected using the home owner's receiving antennas, whilst at Home 2, a recently installed high gain receiving antenna was also used.

The signals scattered by a rotating blade combine with the direct signal to produce an effective amplitude modulated signal at the receiver. Thus, as a function of time, the output of the spectrum analyzer will vary above and below the ambient level of the direct signal, and it is conventional to quote the total variation of the field amplitude in dB from which the percentage modulation (m) of the received signal (caused by the rotating WT-blade scattering) can be obtained [5]. Usually, a total signal variation of $\geq$ 2.6 dB (i.e., m $\geq$ 15 percent) causes unacceptable video distortion in the received picture in the backward interference zone [5]. In the forward direction, the signal variation causing unacceptable video distortion depends on the ambient signal strength [6]; it increases with increasing signal strength, and for an ambient signal strength of $\sim$-60 dBm, the required signal variation could be as large as 6.5 dB (m $\simeq$ 0.35) or higher [6].

2.4 Residential Home Site Results

Data were collected at the chosen residential home test sites during two trips to Boone. The aim of the first visit, described in [1], was to make a preliminary investigation of the TVI reported by the residents. The purpose of the second visit, described in [2], was to obtain more detailed information. Unfortunately, the planned objectives of our second visit were not fully realized for the following reasons: (i) due to unfavorable wind conditions, the WT was not operating during most of the test periods, precluding the collection of the desired dynamic data; (ii) the computer control system of the WT required that during yawing of the WT with its blades locked, the blades could only be in the feathered position--under this condition, the static data are not sufficient to provide an estimate of the maximum scattering (hence, maximum modulation) produced by the blade; and (iii) only one of the homes having a high gain receiving antenna was available for conducting the required tests.

On our second trip, we conducted static tests at three homes using the home owner's receiving antennas; static and dynamic tests were performed at a fourth place (Home 2) using the high gain receiving antenna already installed there. In addition, at all homes, the patterns of the receiving antennas were obtained using the available TV signals as RF sources.

For the reasons mentioned earlier, the TVI tests conducted at these homes were inconclusive and the limited results obtained cannot be used to properly assess the degree of TVI produced by the WT. Nevertheless, some significant results were found, as discussed below.

Home 1: The maximum signal strength received on Channel 3 was about -64 dBm; the received picture quality was fair. Channels 8 and 9 reception was very poor (snowy), the Channel 8 reception being slightly worse. The receiving antenna pattern measured at the Channel 3 frequency indicated an antenna side-lobe level of about -12 dB. The spectrum analyzer revealed the presence of an unidentified interference signal in the Channel 3 band. Static results obtained on Channel 3 showed the existence of a weak interference signal originating from the WT. The owners of Home 1 reported experiencing TVI effects on Channel 3. As we could not perform dynamic tests at this home, it is not possible to make any comment regarding the reported interference.

Home 2: We used the high gain receiving antenna (for Channel 3) installed here before our arrival. The measured pattern at the Channel 3 frequency indicated a side-lobe level of about -14 dB; the maximum received signal on Channel 3 was about -74 dBm. With the WT operating at 10 rpm, we conducted a dynamic test at the Channel 3 frequency. Modulation pulses (approximately ±4 dB amplitude) introduced by the WT were clearly seen on the strip recorder output; the interference effects observed on the TV screen were slightly above the acceptable level but tolerable. A small rotation of the antenna beam, away from the direction of the Channel 3 transmitter, slightly increased the TVI effects, thereby indicating the home was not exactly in the forward zone of interference.

Home 3: At this home a peculiar combination of two receiving antennas was used: an outside antenna (which was directed towards the WT, apparently in the wrong direction for receiving the desired signals) and a "rabbit-ears" antenna both connected to the TV receiver. We rotated the outside antenna to receive the Channel 3 signal, and the reception improved significantly. Static tests on Channel 3 indicated signficant amounts of WT scattered signals, implying the possibility of noticeable interference effects with the

WT operating. Received signal strengths on Channels 3 and 7 were -72 dBm and -54 dBm, respectively. Again an unidentified interference signal was found in the Channel 3 band of frequencies. Static tests on Channel 7, carried out during our first visit [1], indicated ±2 dB fluctuations of the received field strengths.

The home owners reported significant TVI caused by the operating WT. Due to lack of favorable winds we could not conduct any dynamic tests. However, it appears that because of its close proximity to the WT, Home 3 could be quite vulnerable to the WT-generated TVI effects; the limited results discussed above tend to confirm this.

Home 4: The pattern of this home's receiving antenna was measured at the Channel 3 frequency; the side-lobe level of the antenna was found to be -12 dB and the maximum field strength received on Channel 3 was about -60 dBm. The spectrum analyzer again indicated the existence of the unidentified interference signal mentioned above. Static tests on Channel 3 showed some indication of WT-generated interference [2], but the severity of the interference could not be judged. Our previous static tests on Channel 8 [1] indicated a 4 dB total fluctuation in the received signal caused by the WT-blade scattering. As the WT was not operating, we could not study the actual interference effects. However, the results discussed indicate that Home 4 could be vulnerable to TVI produced by the operating WT.

2.5 CATV Antenna Site Results

The maximum ambient signal strengths on selected TV channel frequencies measured by the spectrum analyzer at the test site are shown in Table 1. The results were obtained by directing the receiving antenna beam towards the desired transmitter. Table 1 indicates that the signal strengths on all channels except 36 and 42 were quite strong.

Table 1

Maximum Ambient Signal Strengths on Selected TV Channels at the CATV Antenna Site

TV Channel Number	Signal strength in dB above one milliwatt, i.e., dBm
3	-45
7	-56
8	-56
12	-46
36	-66
42	-72

Figures 2.5 and 2.6 show the signals received on Channels 8 and 12 as functions of time with the WT rotating at 20 rpm and the receiving antenna beam directed towards the WT. The effects of the WT blade scattering on the received signals may be identified in Figs. 2.5 and 2.6, and it is found that the total signal variations on Channels 8 and 12 are 0.6 and 0.5 dB, respectively. With such small signal level variations (or low modulation levels), and considering that the

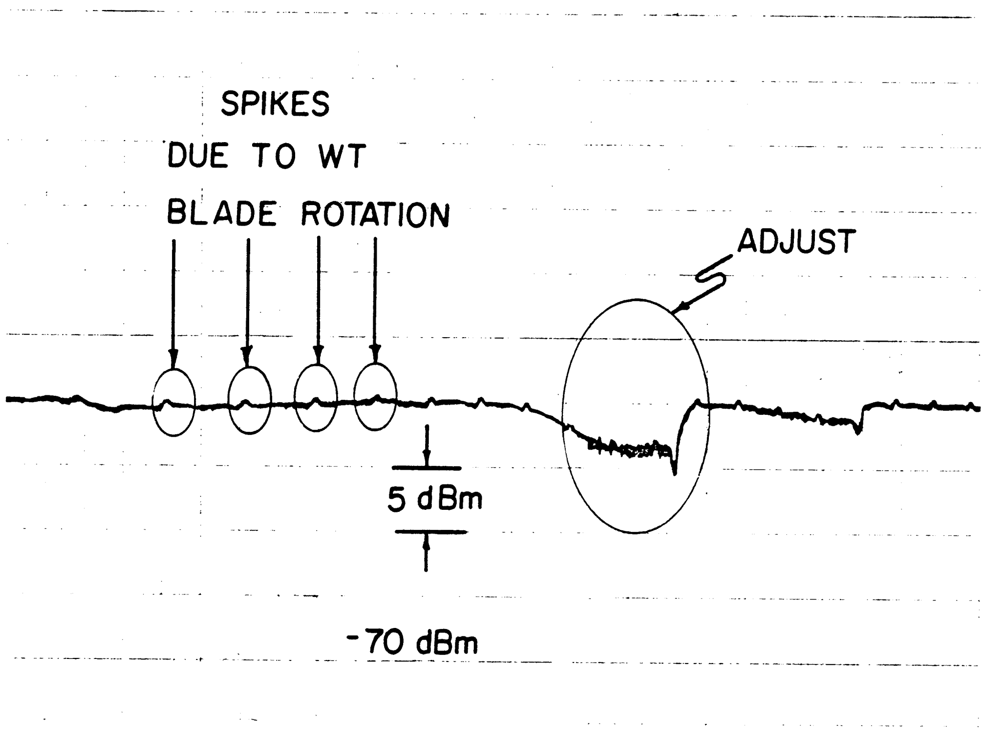

Figure 2.5. Channel 8 signal as a function of time at the CATV antenna tower site. WT to receiver distance = 2 km; WT blade rotation frequency = 24 rpm.

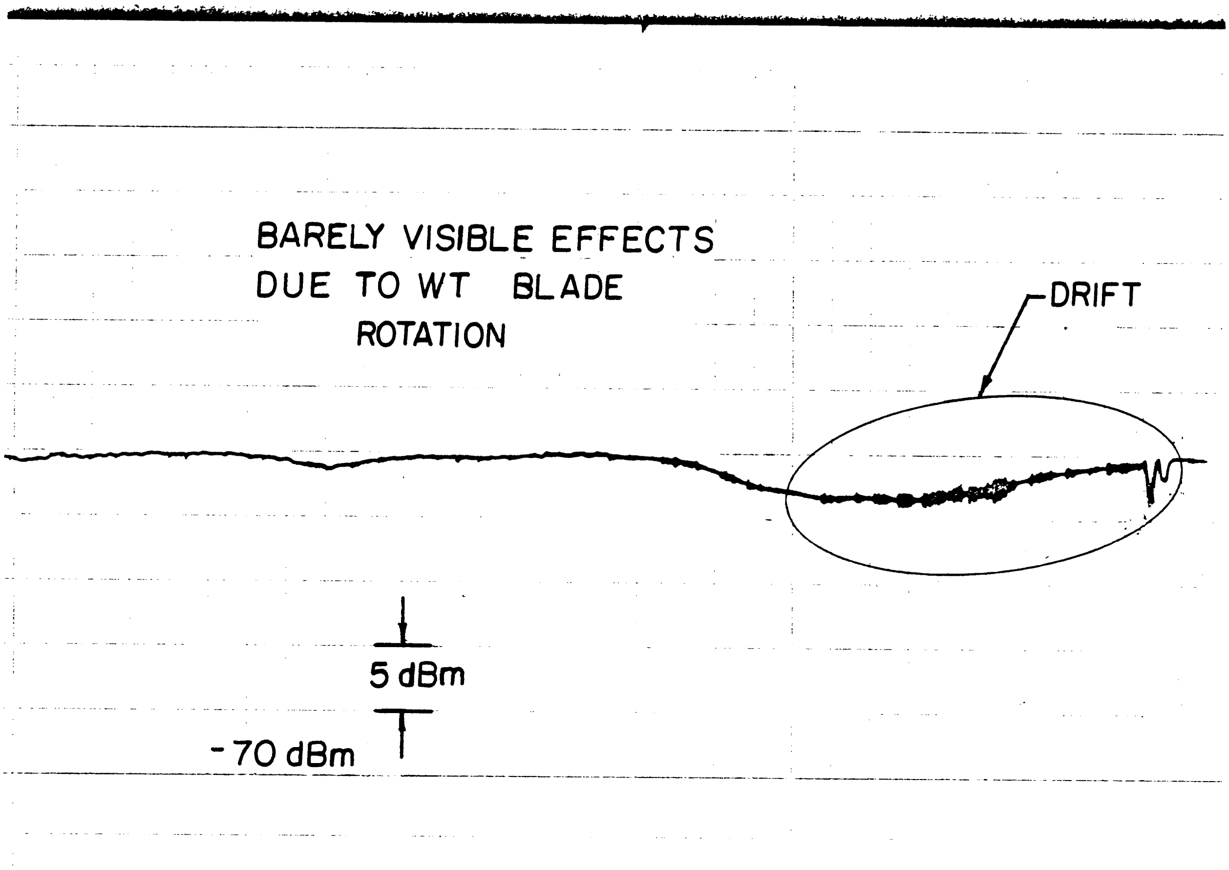

Figure 2.6. Channel 12 signal as a function of time at the CATV antenna tower site. WT to receiver distance = 2 km; WT blade rotation frequency = 24 rpm.

receiving antenna was generally in the forward interference zone, no video distortion was observed in the received picture.

At the UHF TV Channel 42 frequency, the ambient signal level was -72 dBm and the total signal variation was 1.6 dB, as shown in Fig. 2.7; the variation is less than 2.6 dB, and no video distortion was observed in the received picture.

On all other TV channels, the observed signal variations were found to be less than 0.5 dB and no video distortion was observed that could be identified with the WT-blade rotation.

For an omnidirectional receiving antenna, the expected maximum total variation in dB (hence, the modulation index m) in the received signals caused by the WT blade scattering can be obtained from the following approximate relationship:

$$m = \frac{2A_e}{\lambda d} ,$$

where A_e = equivalent scattering area of the WT blade,

λ = operating wavelength, and

d = distance between the receiving antenna and the WT.

With $A_e = 40\ m^2$ and $d = 2$ km, the expected signal variations on all of the available TV channels have been calculated using this formula. The results are shown in Table 2.

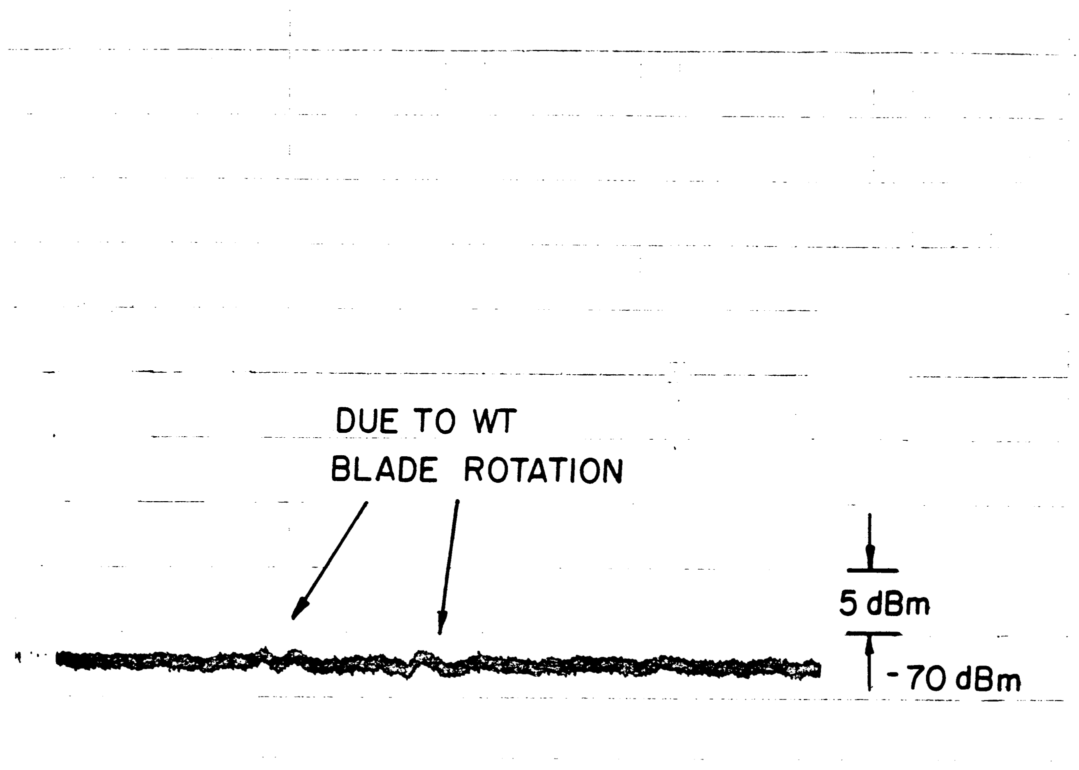

Figure 2.7 Channel 42 signal as a function of time at the CATV antenna tower site. WT to receiver distance = 2 km; WT blade rotation frequency = 24 rpm.

Table 2

Maximum Signal Variation and Amplitude Modulation Index of the Received Signal at the Test Site

TV Channel Number	Total Variation in the Received Signal (dB)	Amplitude Modulation Index (m in percent)
58	1.7	10
42	1.6	9
36	1.4	8
19	1.2	7
12	0.5	3
11	0.5	3
9	0.5	3
8	0.4	2
7	0.4	2
5	0.2	1
3	0.15	0.8

The on-site test results discussed earlier were obtained with the WT blades rotating in a vertical plane determined by the prevailing wind direction; it was not possible to yaw the machine while it was running. However, the results obtained are consistent with those given in Table 2 which can then be used to estimate the maximum impact of the WT blade scattering on the reception of TV signals by the CATV antennas at the Rich Mountain site. It should be noted that an actual CATV antenna is not omnidirectional and, consequently, for those TV channels for which the antenna is in the backward interference zone, it will discriminate against the interference signals caused by the WT blade scattering.

2.6 Conclusions

It appears from the TVI tests performed at the residential homes that the MOD-1 WT will cause varying amounts of noticeable interference to TV reception at or near all the four homes visited. Our limited tests could not quantify the actual interference observed except at Home 2 where forward zone type of interference was observed at slightly above acceptable (but still tolerable) levels on Channel 3. We could not evaluate the capability of a high gain antenna to overcome or reduce the backward zone type of interference caused by the WT. It is therefore desirable that more TVI tests be carried out at or near the residential homes in the vicinity of the WT so that the interference be quantified and methods derived to overcome and/or reduce the effects.

On the basis of the results obtained at the CATV test site and the theoretical calculations, it is concluded that the reception of the eleven available TV Channel signals by the antennas located on the CATV antenna tower at Rich Mountain will not be significantly affected by the WT blade rotation, and consequently the reception of CATV by the subscribers will not be affected appreciably.

2.7 References

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