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AN EXPERIMENTAL STUDY OF WINDSHIELD ANTENNAS FOR AUTOMOBILES

by

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EXECUTIVE SUMMARY

The FM and AM band performance characteristics of windshield antennas installed on a variety of automobiles have been investigated experimentally. The vehicles chosen were: one each of 1978 models of Cougar and Mark V built by Ford Motor Company, and one 1977 Chevrolet Monte Carlo and two 1978 Grand Prix's built by General Motors Corporation. Six windshield antennas having variable parameters were used on the Cougar; the other cars had their own windshield antennas. All windshield antennas were supplied by the manufacturers of the cars used.

The investigation mainly involved the measurement of horizontal plane radiation patterns and impedances of test antennas in the FM band, the received signal strengths and the effective C and Q of the test antennas in the AM band. In addition, the FM band polarization response and the effects of the motion of windshield wiper on the FM patterns were also measured for selected antennas. At the FM band the pseudo-gain and VSWR of each test antenna were obtained from the measured results. Appropriate test antenna results were compared with corresponding results obtained from a $\lambda/4$-reference monopole antenna.

For each test antenna, some or all of the following results were obtained: (i) horizontal plane radiation patterns at five selected frequencies within the FM band (88, 93, 98, 103, and 108 MHz), (ii) FM band impedance at the appropriate terminals, (iii) the field strengths received at three selected frequencies in the AM band (0.5, 1.1, 1.6 MHz), (iv) relative pseudo-gain at FM frequencies, (v) VSWR vs frequency at FM frequencies, and (vi) antenna system C and Q.

Chapter II describes the results of a field probing measurement carried out to determine the distribution of incident field distribution in the test area. Chapter III shows results indicating that the conditions of the experiment were such that the receiving and transmitting patterns of the windshield antenna were identical. Chapter IV describes the FM band radiation pattern and impedance characteristics of six windshield antennas on 1978 Cougar; the AM band performance of the same antennas are described in Chapter V. Performance of windshield antennas installed on various cars is discussed in Chapter VI. Chapter VII gives miscellaneous results with particular reference to the effect of windshield wiper motion and the incident field polarization on the performance of test antennas.

Significant findings of the investigation are:

i) Typically, both the FM and AM band gains of windshield antennas are about 6 dB less than that of the reference antenna.

ii) Within the FM band, the horizontal plane pattern of a windshield antenna is such that it has maxima in the forward and backward directions with respect to the car, the forward gain being slightly larger; the VSWR's within the FM band range from about 3.5 to 6.5.

iii) The Cougar results indicate that the performance of the antenna is not significantly altered by varying the horizontal element length. The T-shaped antenna appears to have more FM gain than others. Antenna no. 6-2 has been found to provide better FM and AM performance.

iv) The crash pad seems to have significant effects on the antenna performance.

v) The FM band antenna patterns obtained with air signals are different than those obtained with vertically polarized laboratory signals.

Some recommendations are made for further study so that the performance of windshield antenna may be optimized. This would be useful in making a final evaluation of windshield antennas vis-a-vis other competitive antennas.

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I. INTRODUCTION

This report presents the results of an experimental investigation of the performance of windshield antennas mounted on automobiles, and operating in the commercial AM (0.5 to 1.6 MHz) and FM (88 to 108 MHz) bands of frequencies. The automobiles chosen were 1978 Cougar and 1978 Mark V built by Ford Motor Co., and 1978 Pontiac Grand Prix and 1977 Monte Carlo built by General Motors (GM). The Ford vehicles and the test windshield antennas were supplied by Ford Motor Co.; the GM cars were supplied with their own windshield antennas.

The program mainly consisted of the measurement of the horizontal plane radiation patterns and impedances (VSWR's) of test antennas in the FM band of frequencies and the sensitivities of test antennas in the AM band of frequencies. In addition, however, the effective capacitance C and the quality factor Q at the receiver end of the cable connecting the test antenna were measured at the AM band of frequencies.

The goal of the investigation was to obtain sufficient experimental data to evaluate and understand better the performance of Ford-built windshield antennas. In particular, data were collected to study the effects of the following parameters on the performance of windshield antennas: (i) head space, (ii) number of loops in the antenna, and (iii) resistivity of the antenna element. The general performance of windshield antennas relative to other competitive antennas were discussed in our previous report [1] which should be used as a background for the present work.

II. OUTLINE OF THE MEASUREMENT AND DATA REDUCTION PROCEDURES

Measurement techniques and equipment set-up used to obtain the desired results have been described elsewhere [2] [3] and will not be repeated here. The present section describes briefly the pertinent aspects of the procedure followed in the present investigation and also discusses the method used to reduce the measured results to the desired forms.

2.1 Radiation Pattern Measurement at FM Frequencies

Horizontal plane radiation patterns of test antennas were obtained by receiving standard laboratory generated signals at the FM band of frequencies. The RF signals originating in the Field Laboratory Facility (FLF) were cabled through a 3 dB attenuator into a directional coupler which allowed constant monitoring of the transmitted power level in a thermistor mount and a power meter. With the help of a buried coaxial cable, the main signal from the directional coupler was fed to a log-periodic antenna (50 to 500 MHz range) placed in an antenna carriage mounted on a 30'-tall aluminum tower located at the transmitting end of an outdoor antenna range. From inside the FLF it was possible to remote control the antenna carriage so that the log-periodic antenna could be moved vertically up and down, and also be rotated around its axis. Thus, both the height of the antenna above ground and its polarization could be changed, as desired, from the FLF.

During radiation pattern measurements it is desirable to place the test antenna sufficiently far from the transmitting antenna so that the far field criteria are satisfied. The required distance may be obtained from the following relationship:

$$R = \frac{2D^2}{\lambda} \tag{1}$$

where,

R is the minimum distance between the test and the transmitting antenna,

D is the maximum linear dimension of the test antenna, and

λ is the operating wavelength.

Within the operating frequency range (88-108 MHz) an average wavelength is taken to be λ = 10' at 100 MHz. Since the body of the car (on which the test antenna is mounted) plays a large role in the reception of signals by the test antenna, the appropriate value of D for the test antenna can be assumed to be equal to the body length (approximately 20') of the car. Using these values of D and λ in Eq. (1) the required R is found to be about 80'. Since the test site is located 150' away from the antenna tower, the far field criteria were satisfied during the present measurement.

As mentioned earlier, patterns were obtained by using the test antenna mounted on the desired car as a receiving antenna. The car with the test antenna was placed on car hoist tracks attached to an azimuthal positioner at the test site. Azimuthal position of the car was controlled and monitored by an operator in the FLF. The RF signals received by the test antenna were carried through a coaxial cable, lying above ground, to the FLF where the pattern recording was carried out.

At the FLF the incoming signals were fed to the front input of a spectrum analyzer which selected the desired signal from the ambient RF signals, also received by the test antenna, and converted it into a 21 MHz signal. From the 21 MHz output in the back of the spectrum analyzer, the desired signal was, at first, fed into a wide range microwave receiver where it was amplified further and amplitude moderated by a 1000 Hz signal, and then to a polar pattern recorder. Reference patterns were obtained similarly with the help of a monopole antenna, $\lambda/4$ long at 98 MHz, mounted on a 5'-diameter circular ground plane located on the center of the car-hoist tracks.

2.2 Procedure for Pattern Measurement at FM Frequencies

The procedure used in obtaining the radiation patterns of test antennas may be best described in a stepwise fashion as follows:

i) calibrate the spectrum analyzer to 0 Hz and -30 dBm using its internal signal sources,

ii) set band width to 100 KHz,

iii) set frequency span/division to 100 KHz/division,

iv) set sweep to manual mode,

v) with sweep in center of display, search the vicinity of the desired frequency (88, 93, 98, 103, or 108 MHz) for a region free of ambient RF signals,

vi) adjust unit oscillator to obtain maximum signal, peaked at the specific frequency, received by the test antenna,

vii) adjust power supply to provide 0.3 mw reading on the power meter,

viii) adjust receiver to the IF (20 MHz) of the spectrum analyzer,

ix) attenuate signal, using the spectrum analyzer or receiver attenuators to obtain maximum pattern recorder levels without occurrence of saturation,

x) record pattern of the test antenna (windshield antenna mounted on car or reference antenna mounted on ground plane) by actuating the recorder and rotating azimuthal positioner.

2.3 FM Pattern Data Reduction

A measure of the FM band gain of a test (windshield) antenna mounted on a car relative to that of a $\lambda/4$-monopole can be obtained from their horizontal plane radiation patterns measured at FM frequencies. The gain of the windshield antenna relative to the monopole antenna is defined as:

$$G = \frac{W_T}{W_R} \tag{2}$$

where,

W_T is the total power received (transmitted) by the test windshield antenna, and

W_R is the total power received (transmitted) by the $\lambda/4$-monopole (or reference) antenna.

To determine the total power received (transmitted) by an antenna, it is necessary to know its complete three dimensional radiation pattern. In the present study only horizontal plane patterns were measured. On the basis of these measured patterns a parameter called the "pseudo-gain" G' can be defined which will be proportional to the actual gain be defined by Eq. (2). Assuming that the vertical plane patterns of the windshield and monopole antennas are similar, W_T and W_R can be approximated as:

$$\begin{aligned} W_T &\propto A_T \\ W_R &\propto A_R \end{aligned} \tag{3}$$

where,

A_T is the total area of the measured horizontal plane pattern of the windshield, and

A_R is the total area of the measured horizontal plane pattern of the monopole antenna.

Thus, the pseudo-gain is defined as:

$$G' = \frac{A_T}{A_R} \quad . \tag{4}$$

It is evident from Eqs. (2) - (4) that G′ is proportional to G.

A_T and A_R are obtained numerically from the measured horizontal plane pattern. The pseudo-gain characteristics of each of the windshield antennas were determined in this manner and will be presented in the following chapters, as needed.

2.4 Impedance Measurement at FM Frequencies

Preliminary measurements indicated that the FM impedance of the windshield antenna remained the same when the car was inside the FLF or outside on the range. Therefore, for convenience, all impedance measurements were taken with the test car inside the FLF. Generally, the impedance of each test antenna mounted on the desired car was taken at five frequencies in the FM band: 88, 93, 98, 103, and 108 MHz.

Standard equipment set-up was used during the measurement. Using a variable voltage power supply driving a unit oscillator, an RF signal of desired frequency was generated and cabled to a 3 dB attenuator into a dual directional coupler input. Two vector voltmeter (VV) probes were attached to the coupler -- the reference probe (Channel A) onto the incident port and the test probe (Channel B) onto the reflected port. A 50 ohm termination was used between each probe and the appropriate coupler port. The desired load (short, 100 Ω and test antenna) was connected to the output of the coupler. A spectrum analyzer was used to select the desired frequency while the desired power level was obtained by monitoring the channel A of the vector voltmeter probe.

The systematic procedure used during each impedance measurement is as follows:

i) attach a short to the output of the directional coupler,

ii) set spectrum analyzer at 88 MHz and attach a length of coaxial cable to its input (this acts as a receiving antenna while in the vicinity of unit oscillator),

iii) adjust unit oscillator so that an 88 MHz signal is observed on the spectrum analyzer,

iv) adjust variable voltage power supply so that the vector voltmeter amplitude scale reads 100 mV on Channel A,

v) switch vector voltmeter to Channel B, read and record the amplitude and phase angle,

vi) repeat steps (i) - (v) for 100 Ω load and the test antenna, and

vii) repeat steps (i) - (vi) for 98, 98, 103, and 108 MHz.

The above procedure yielded the following quantities: Channel A amplitude = A, Channel B amplitude = B, and the phase angle = ϕ. The desired VSWR and the complex impedance values were determined from the above values by entering them into a set of data reduction equations which were programmed into a portable calculator. Impedance values for the test antennas were then plotted on Carter charts.

2.5 Measurement of AM Sensitivity

AM sensitivity measurements were performed while the car was located at the test site and facing the tower. A spectrum analyzer placed inside the car (AC power was supplied by an inverter placed in the car and running off the car battery) was used to receive the desired signals from the commercial radio stations (AM). Before coupling the spectrum analyzer to the test antenna it was calibrated with the help of its internal signal sources of 0 MHz and -30 dBm. Each of the three AM radio stations (0.76, 1.1, and 1.6 MHz) were then tuned in, and their respective amplitudes (in dBm) were read and recorded. A set of similar AM field strength measurements were also taken using a $\lambda/4$ (at 98 MHz) monopole mounted at the center of the roof of the car. Using the same calibration settings, reference amplitudes were read and recorded at the same frequencies.

Since all the test antennas were electrically short at AM frequencies, their horizontal plane patterns can be expected to be omnidirectional. This was demonstrated conclusively in our previous study of automobile antennas [2]. Therefore, instead of measuring the actual AM band patterns of the windshield antennas, we measured the field strengths received by each antenna using the local AM broadcast transmitters (i.e., air signals) as sources. The field strength received by each (stationary) antenna may be considered to be a measure of its sensitivity.

2.6 Measurement of C and Q at AM Frequencies

Measurements of AM band C and Q of the test antenna may be performed with the car at any location but, for convenience, they were performed at the test site located outside in the antenna range. Measurements were carried out with a Q-meter placed in the car (AC power was supplied by an inverter placed in the car and running of the car battery). Three inductor canisters of different frequency ranges, referred to as inductor 1, 2, and 3 (of ranges 0.5 - 1.4, 0.8 - 2.0, and 1.5 - 4.5 MHz, respectively), were used along with the Q-meter. C and Q values were obtained at each of the three selected frequencies in the AM band. The following procedure was used during the measurement:

i) plug inductor 1 into Q-meter,

ii) select appropriate frequency range, and tune to 0.5 MHz,

iii) set $\pm$ scale to 0,

iv) set power level to 1,

v) with C-scale tuned off-resonance, set Q to 0,

vi) turn C-scale until Q-needle peaks, then turn C-scale to nearest value,

vii) turn ± scale to obtain maximum value under Q-needle,

viii) read and record C value, ± value and Q value (these values are designated as "meter"),

ix) if cable is needed to reach from Q-meter to the test antenna lead, then attach this cable to Q-meter and repeat steps (iii) - (viii); these values are designated as "meter and cable",

x) attach the test antenna lead to cable, or if step (ix) was omitted, then directly to the meter; repeat steps (iii) - (viii) and designate obtained values as "meter and cable and antenna" in former case or "meter and antenna" in the latter case,

xi) replace inductor 1 with inductor 2, select the appropriate frequency range and tune to 1.0 MHz,

xii) repeat steps (iii) - (x),

xiii) repeat step (xi) for inductor 3 and 1.5 MHz, and

xiv) repeat steps (iii) - (x).

With the help of a pocket calculator and a specific data reduction program, the desired values of C and Q for the test antenna were determined from the measured values of C, ± C and Q obtained for each of the three categories meter, meter and cable, and meter and cable and antenna.

III. FIELD PROBING AT THE TEST SITE

For the purpose of proper interpretation of the radiation pattern data obtained at the test site, it is desirable to know the distribution of the incident signal level within a desired space above the test site. To this end, an investigation was carried out by probing (receiving) a given RF signal of constant power and frequency at certain specific locations immediately above the test site.

3.1 Test Set-Up and Procedure

A method was developed to probe the incident field in a 7'-square planar region oriented vertically above the turntable located at the test site. The test site was located 150' away from the transmitting antenna fed by RF signals originating from the FLF. The plane of probing, oriented normal to the incident field direction may be visualized as divided into 49 grids, each 1' square. By recording the incident signal strengths at each of these 49 grid points the distribution of the incident field in this plane was determined. Provisions were also made so that the transmitting antenna height above ground and its polarization could be adjusted and that their effects on the field distribution could be measured.

Fig. 1 shows the schematic arrangement of the experimental set-up used during the field probing. The transmitting antenna was a log-periodic antenna operating in the range of 50-500 MHz and mounted on a 30'-tall aluminum tower as described in Section 2.1.

At the test site (Fig. 1) a set of car hoist tracks were mounted on an azimuthal positioner such that they can rotate at ground level. A structure

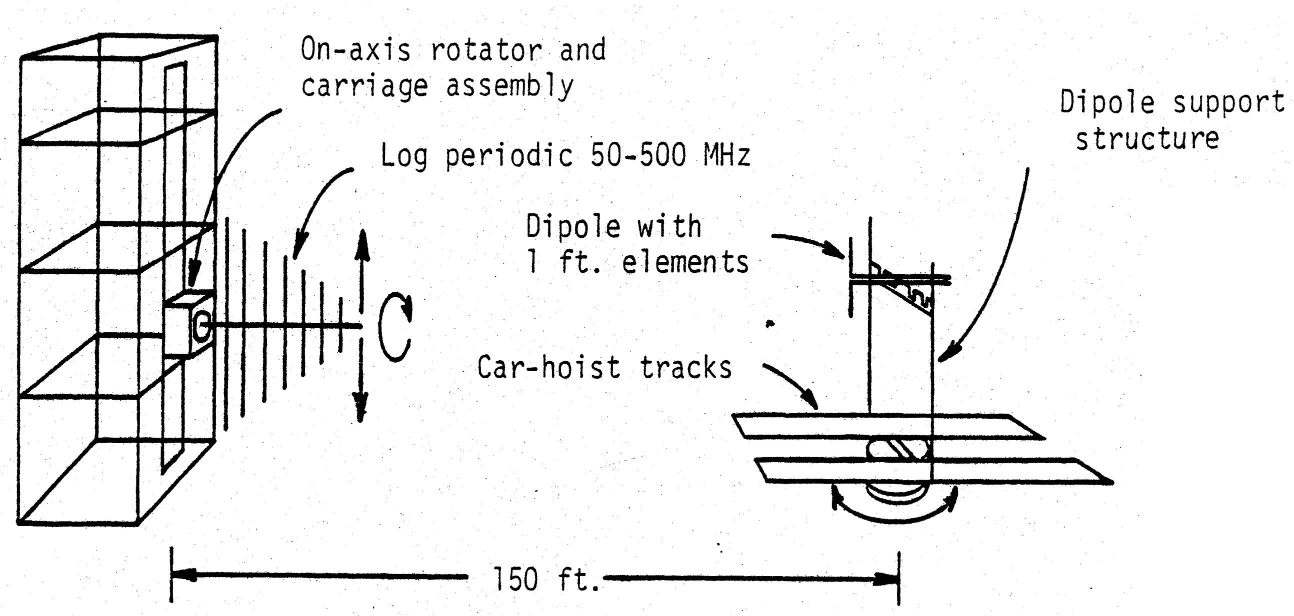


Figure 1. Schematic arrangement used during field probing.

consisting of two vertically oriented 1 3/4"-diameter fiberglas tubes, drilled at 1'-increments, were attached to the tracks. Supported horizontally between the two tubes was a wooden bar measuring 1" x 4" x 7 1/2' and containing slots at 1'-increments to accommodate a receiving antenna (this choice of the structural materials was made so as to give no RF return). The receiving antenna used was a dipole utilizing 1'-long elements -- this was chosen to best optimize both resolution and signal level reception simultaneously with respect to the other parameters used, such as grid size, signal frequency and strength, etc. The schematic arrangement of the receiving antenna position control is shown in Fig. 2. Thus, by positioning the horizontal bar at the desired vertical position and the receiving antenna at the desired horizontal positions, the 49 positions for field probing were obtained (Fig. 2).

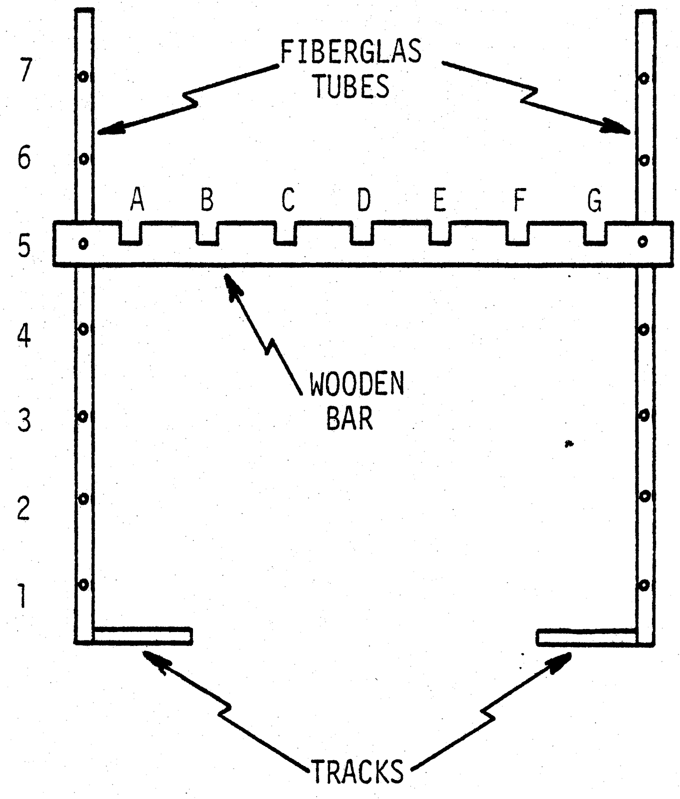


Figure 2. Receiving antenna position control mechanism (view from tower).

The entire experimental set-up used for field probing is shown in Fig. 3. The experiment was controlled from the FLF excluding the changing of the physical locations of the dipole which was done manually. The generation of RF signal and its transmission were done in a manner described in Section 2.1. The signal received by the dipole was run through a length of unburied cable to the FLF. This signal was attenuated 23 dB before being fed to a wide-range microwave receiver; further attenuation of 7 dB was introduced by engaging a series of built-in step attenuators in the receiver. The signal was then fed into a combination polar-rectangular plot recorder for each desired transmitting-receiving antenna configuration.

For data presentation, the transmitting antenna position is designated as a function of its height above ground; the four positions used are 6, 12, 18,

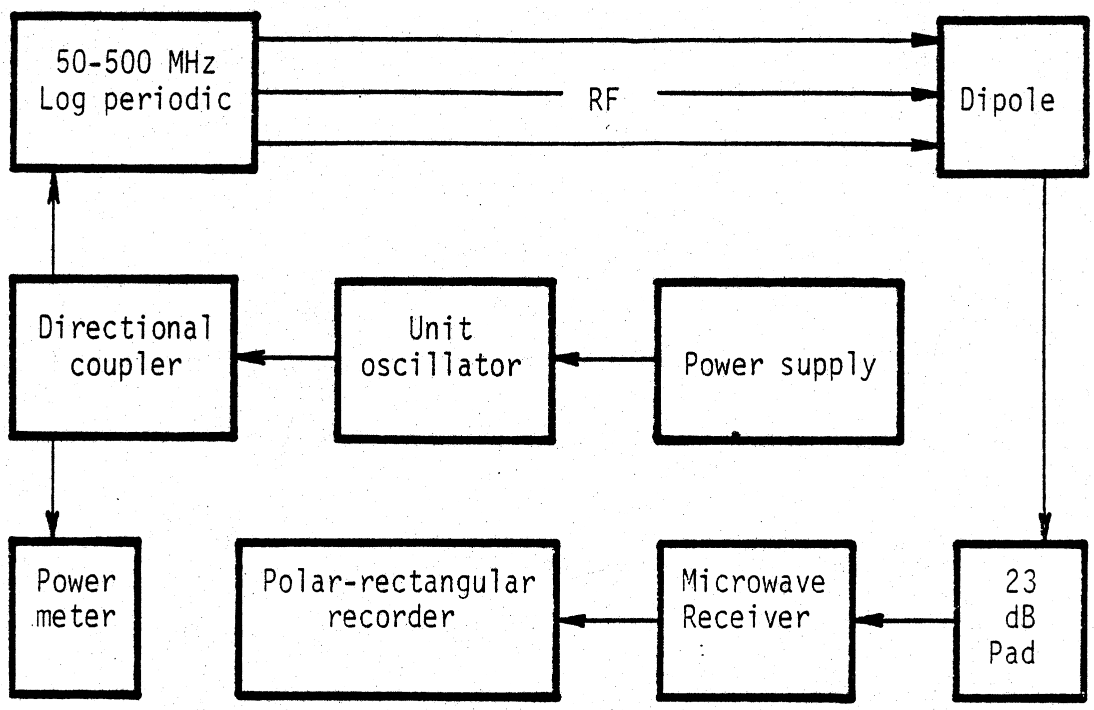


Figure 3. Block diagram of the experimental equipment.

and 24 feet. The polarization is designated as vertical or horizontal (which describes the orientation of the E-field with respect to ground), the transmitting and receiving antennas being oriented to the same polarization. The receiving antenna position in space is described by a number and a letter (Fig. 2). Numbers 1 through 7 correspond to seven vertical positions, 1 being closest to the ground and 7 being the farthest. Letters A through G correspond to seven horizontal positions (as viewed from the tower), A being the extreme left position and G being the extreme right position (Fig. 2).

The procedure used for taking field probing measurement may be described in stepwise fashion as follows:

i) locate dipole in position 1-A and the transmitting antenna at 6' position,

ii) make short-trace recording of signal level,

iii) raise transmitting antenna to 12', 18', and then to 20' while making short-trace recording at each of these heights,

iv) repeat steps (i) - (iii) for dipole positions 1-B through 1-G, and

v) repeat steps (i) - (iv) for vertical positions 2-7.

Four maps were obtained from the above procedure. By switching to the other polarization, four additional maps were obtained. The probing of the field was carried out at 98 MHz with the transmitting antenna radiating 2.25 mw of power.

3.2 Results

Tables 1 (a-d) and 2 (a-d) show the field plot-maps obtained for vertically and horizontally polarized incident signals, respectively. It can be seen from plot-maps that there exists a notable asymmetry in the signal level distribution, horizontally from position A through position G, regardless of the transmitting antenna height, but only when using vertical polarization. With horizontal polarization the plots exhibit a general pattern of horizontal symmetry.

A second observation can be made by comparing the field-plots shown in Tables 1(b) and 2(b), taken with the transmitting antenna located 12' above ground. With this height of the transmitting antenna, the field strength values obtained at each grid point with both polarizations are found to be comparable; this is especially apparent for values obtained with the dipole at vertical positions 4', 5', and 6'. This is a desirable characteristic and since the car-mounted antennas are generally between 4 and 6' above the tracks, it was decided to use 12' as a standard height for the transmitting antenna while performing subsequent pattern measurements.

TABLE 1

7	-8.6	-8.6	-6.8	-6.5	-6.4	-6.2	-6.1
6	-8.8	-8.4	-7.9	-7.3	-7.2	-6.8	-6.8
5	-8.7	-8.6	-7.8	-7.6	-7.1	-6.9	-6.0
4	-9.0	-8.6	-7.8	-7.1	-6.9	-6.7	-6.6
3	-8.6	-7.8	-7.3	-6.9	-6.9	-6.6	-6.9
2	-7.9	-7.6	-7.1	-6.1	-5.9	-6.2	-6.5
1	-7.1	-6.4	-6.3	-5.9	-5.7	-4.8	-5.8
	A	B	C	D	E	F	G

1(a) H = 6'

7	-6.4	-6.4	-5.4	-5.1	-5.2	-5.1	-5.1
6	-7.0	-6.9	-6.5	-6.2	-5.9	-5.8	-5.7
5	-6.7	-6.7	-6.1	-6.4	-6.2	-5.7	-5.6
4	-7.2	-7.3	-6.7	-6.1	-5.6	-5.4	-5.1
3	-7.2	-6.6	-6.1	-5.9	-5.5	-5.4	-5.2
2	-6.5	-6.5	-6.1	-4.9	-4.5	-4.7	-4.9
1	-6.2	-5.6	-5.3	-4.8	-4.4	-3.2	-5.6
	A	B	C	D	E	F	G

1(b) H = 12'

Table 1. Measured electric field distribution along a vertical plane in the test area. Frequency = 98 MHz, vertical polarization. Values shown are relative to -10 dB.

Note: H is the height of the transmitting antenna above ground

TABLE 1 (Cont.)

7	-5.1	-5.0	-4.0	3.7	3.5	3.5	3.4
6	5.4	5.2	5.0	4.7	4.2	4.4	4.1
5	5.2	5.0	4.6	5.0	4.6	4.2	4.5
4	5.7	5.6	4.9	4.5	4.0	4.0	3.9
3	5.2	4.7	4.4	4.4	4.3	4.1	4.0
2	4.5	4.6	4.2	3.6	3.5	3.7	3.7
1	3.9	3.5	3.6	3.2	3.2	3.2	3.7
	A	B	C	D	E	F	G

1(c) H = 18'

7	5.2	5.0	3.8	5.4	5.1	2.9	2.5
6	5.3	5.1	5.0	4.7	4.2	4.4	4.1
5	4.5	4.5	3.8	3.8	3.5	3.2	3.1
4	4.7	4.5	3.8	3.0	2.9	2.6	2.8
3	4.2	3.5	3.0	2.8	2.8	2.6	2.7
2	3.2	3.1	2.7	1.9	1.5	1.9	2.2
1	2.4	1.9	1.8	1.4	1.4	0.4	1.0
	A	B	C	D	E	F	G

1(d) H = 24'

Table 1. Measured electric field distribution along a vertical plane in the test area. Frequency = 98 MHz, vertical polarization. Values shown are relative to -10 dB.

Note: H is the height of the transmitting antenna above ground.

TABLE 2

7	-8.3	-8.5	-7.9	-7.9	-8.1	-8.4	-8.4
6	-9.2	-9.1	-9.1	-9.2	-9	-9.1	-8.9
5	-10	-9.7	-10.2	-10.2	-10.2	-10.2	-10.3
4	-10.4	-10.5	-10.4	-10.6	-10.7	-11.1	-10
3	-12.1	-11.1	-11.4	-11.3	-11.4	-11.7	-12.3
2	-15	-14.5	-14.3	-13.9	-12.7	-13.2	-13.5
1	-18	-16.8	-16.3	-16.1	-16.6	-17.4	-19
	A	B	C	D	E	F	G

2(a) H = 6'

7	-4.1	-4.0	-3.8	-3.6	-3.5	-3.5	-3.6
6	-4.8	-4.7	-4.5	-4.7	-4.4	-4.7	-4.7
5	-5.5	-5.4	-5.5	-5.4	-5.6	-5.4	-5.7
4	-6.3	-6.1	-5.8	-6.0	-6.0	-6.0	-6.5
3	-7.1	-7.1	-6.8	-7.0	-7.0	-7.2	-7.4
2	-10.3	-10.1	-9.7	-9.6	-8.3	-9.5	-8.8
1	-13.2	-12.8	-11.9	-11.8	-12.1	-13	-13.9
	A	B	C	D	E	F	G

2(b) H = 12'

Table 2. Measured electric field distribution along a vertical plane in the test area. Frequency = 98 MHz, Horizontal Polarization. Values shown are relative to -10 dB.

Note: H is the height of the transmitting antenna above ground.

TABLE 2 (Cont.)

7	-1.2	-1.1	-1.0	-0.6	-0.6	-0.7	-1.0
6	-1.8	-1.7	-1.9	-1.8	-1.8	-1.9	-2.1
5	-2.4	-2.3	-2.6	-2.5	-2.6	-2.8	-2.9
4	-2.9	-2.7	-2.8	-2.8	-3.0	-3.2	-3.7
3	-4.2	-4.1	-3.9	-4.1	-4.2	-4.3	-4.6
2	-7.3	-7.0	-6.6	-6.5	-5.4	-5.6	-5.8
1	-10.2	-9.5	-8.8	-8.8	-9.0	-9.9	-10.7
	A	B	C	D	E	F	G

2(c) H = 18'

7	+0.2	+0.4	+0.3	+0.8	+0.8	+0.6	+0.4
6	-0.3	-0.2	-0.3	-0.2	-0.0	-0.5	-0.5
5	-0.8	-0.5	-0.9	-0.9	-0.8	-0.9	-1.3
4	-1.4	-1.2	-1.1	-1.1	-1.2	-1.2	-2.0
3	-2.4	-2.2	-2.2	-2.2	-2.3	-2.5	-2.8
2	-5.3	-5.2	-5.0	-4.7	-3.5	-3.8	-4.2
1	-8.4	-7.6	-6.7	-6.6	-6.9	-7.9	-9.0
	A	B	C	D	E	F	G

2(d) H = 12'

Table 2. Measured electric field distribution along a vertical plane in the test area. Frequency = 98 MHz, Horizontal Polarization. Values shown are relative to -10 dB.

Note: H is the height of the transmitting antenna above ground.

IV. RECEIVING AND TRANSMITTING PATTERNS OF AN ANTENNA

All the test antennas used in the present investigation were passive and contained no non-reciprocal elements. Under these conditions, and in the absence of any non-reciprocal medium at the test site, the receiving and transmitting patterns of such antennas must be identical. This follows from the well-known reciprocity theorem which may be stated as [4] "If an emf is applied to the terminals of an antenna A and the current measured at the terminals of another antenna B, then an equal current (both in amplitude and phase) will be obtained at the terminals of antenna A if the same emf is applied to the terminals of B." It is assumed that the emfs are of the same frequency and that the medium is linear, passive, and also isotropic. Although the validity of this theorem is an established fact, we present in Figs. 4 and 5, the transmitting and receiving horizontal plane patterns of a typical windshield antenna measured at 108 MHz. In both cases the windshield antenna was mounted on a test car placed on the rotating platform. Fig. 4 shows the transmitting patterns of the windshield antenna measured with a fixed receiving antenna located at four selected heights above ground. The receiving pattern of the same windshield antenna measured with a fixed transmitting antenna located at the same selected heights above ground are shown in Fig. 5. It is evident from Figs. 4 and 5 that the corresponding transmitting and receiving pattern of the windshield antenna are similar, as predicted by the reciprocity theorem.

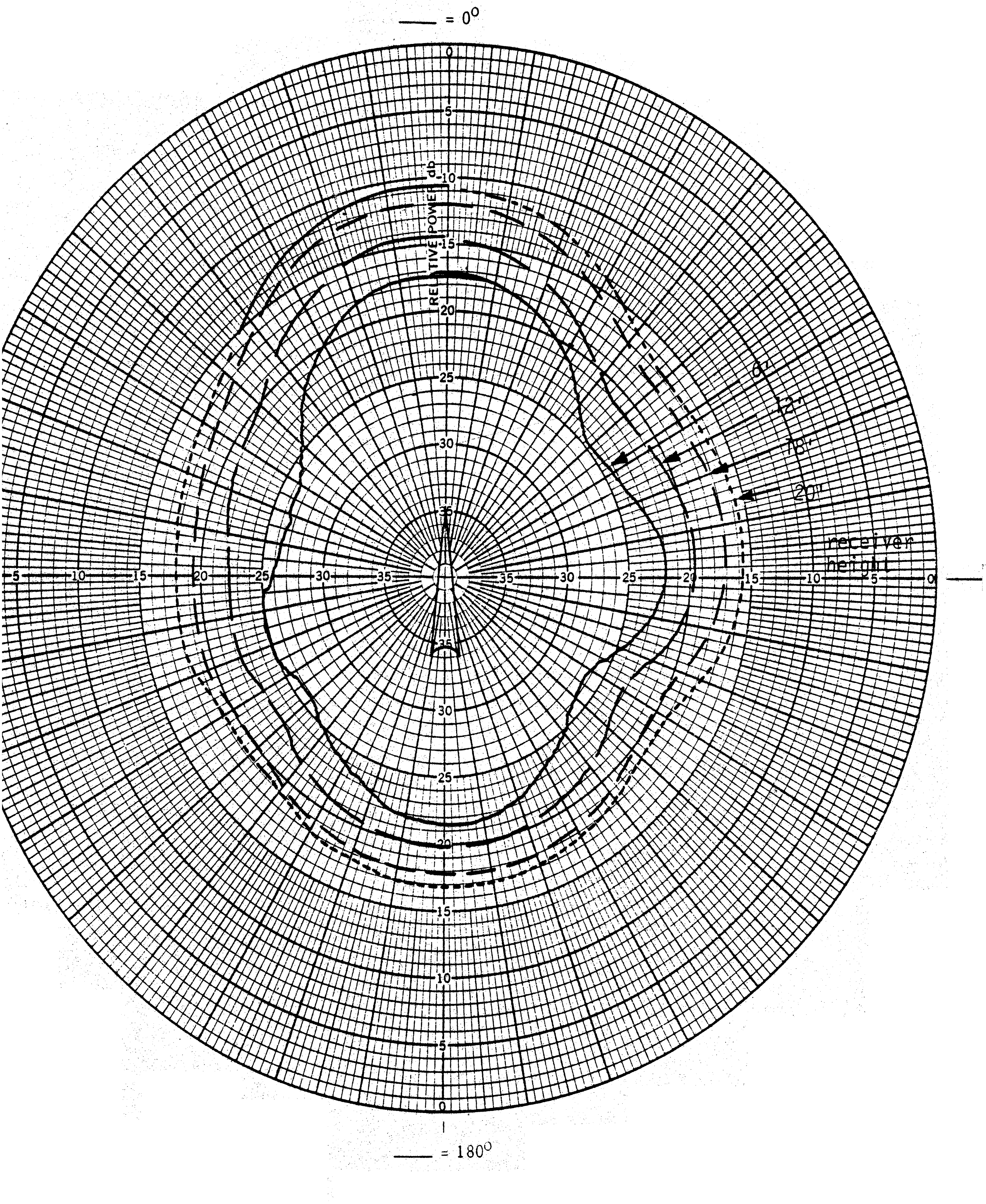


Figure 4. Transmitting patterns of a windshield antenna on 1978 Grand Prix (blue). Transmitted power = 2.15 mW, Frequency = 108 MHz.

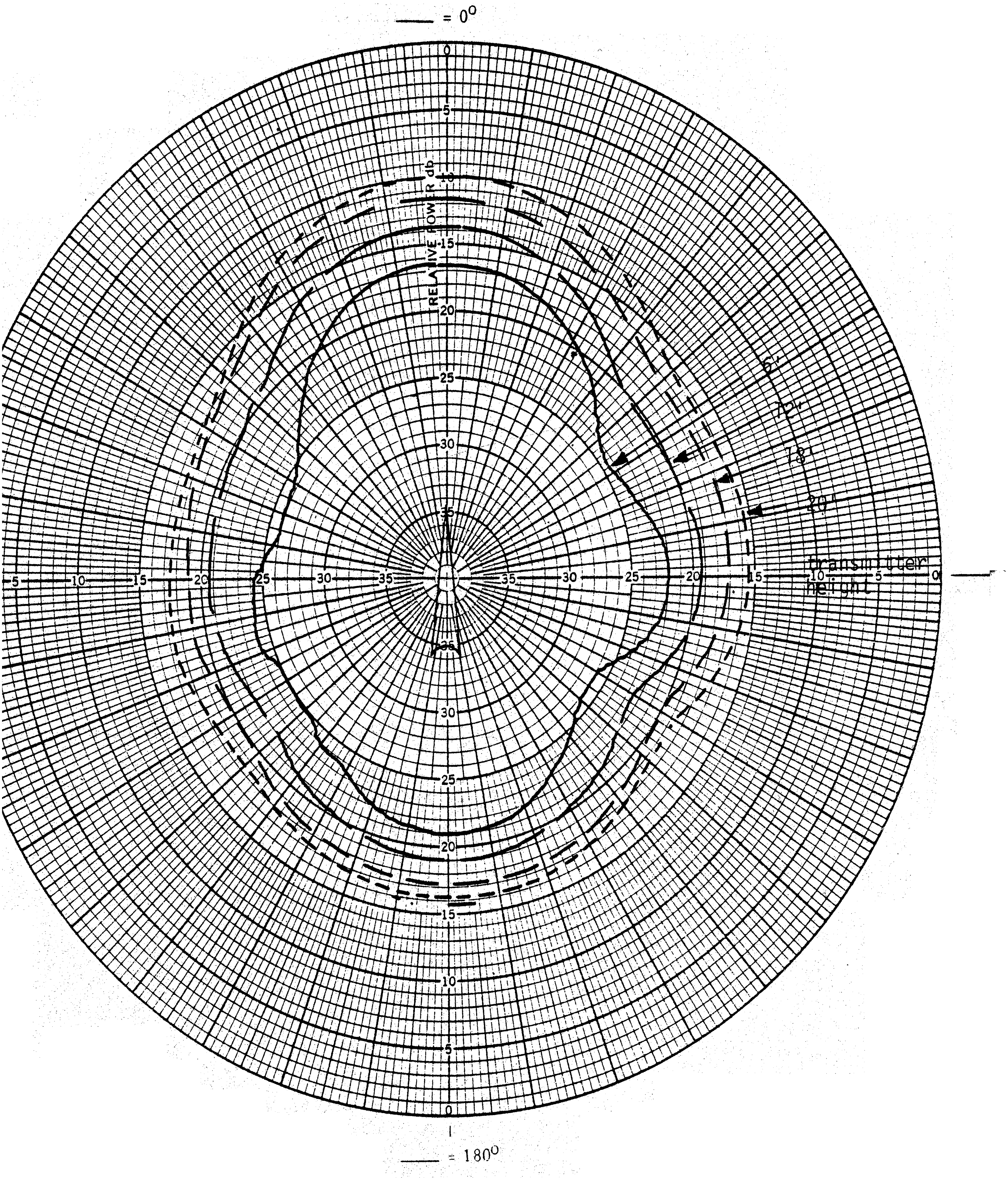


Figure 5. Receiving patterns of a windshield antenna on 1978 Grand Prix (blue). Transmitted power = 2.15 mW, Frequency = 108 MHz.

V. FM BAND PERFORMANCE OF WINDSHIELD ANTENNAS ON 1978 COUGAR

The results of an investigation of the FM band performance of a number of windshield antennas mounted on a 1978 Cougar (with sunroof) are presented in this chapter.

5.1 Test Antennas

Six windshield antennas, printed by Ford Motor Co. on the windshields of 1978 Cougars were investigated. The types of basic configurations used in the antennas are as shown in Figs. 6 and 7; four of the antennas consisted of four horizontal elements, as shown in Fig. 6, and two antennas had five horizontal elements

is characterized by the following physical parametrics: head, side, loop, and center spacing. Measured values of these four parameters for each antenna are shown in Table 3. The head and side spacing, shown in Table 3, are measured with respect to the windshield trim moulding.

A pictorial representation of a four-element windshield antenna along with some reference points are shown in Fig. 8, where 0 is referred to as the input. For each windshield antenna the resistance between its input 0 and various reference points were measured, and the results are shown in Table 4.

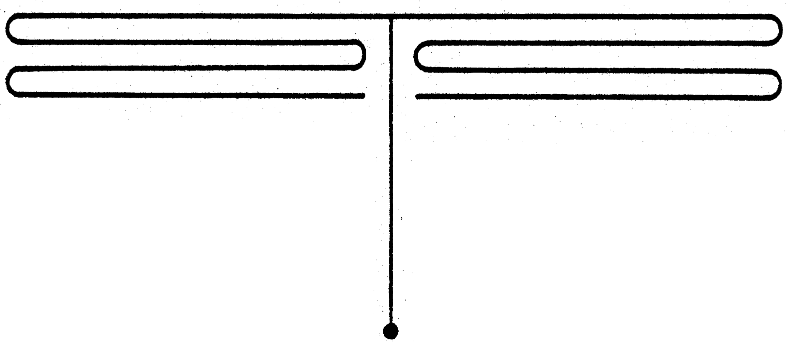


Figure 6. Sketch of a four element windshield antenna.

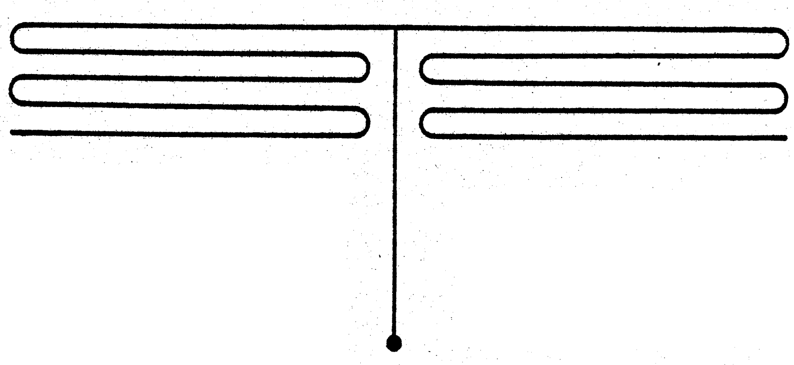


Figure 7. Sketch of a five element windshield antenna.

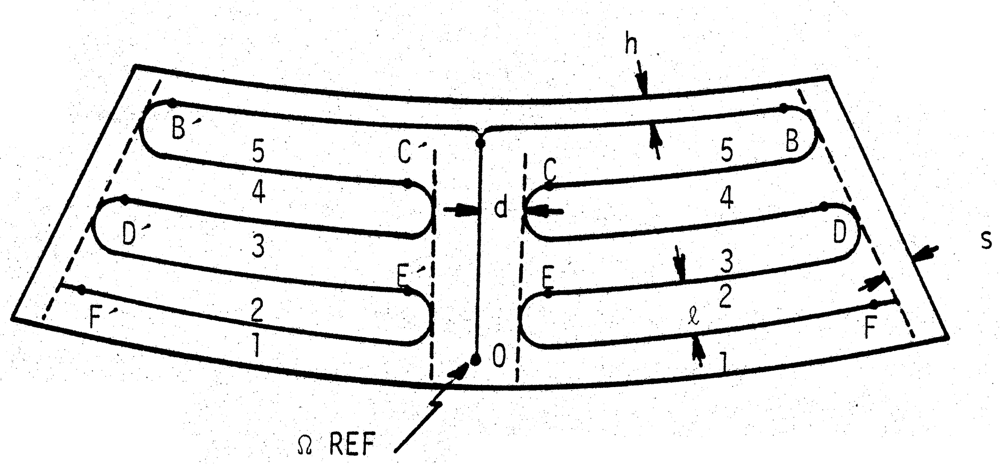


Figure 8. Five element windshield antenna printed on the windshield. Various physical parameters of the antenna and reference points are also shown.

Antenna Parameter	Antenna Model Number					
	XF 243253	XF 243254	XF 243255	XF 243256	XF 243257	XF 243258
Head Spacing (h)	1/2"	1 3/8"	2"	15/16"	1"	2"
Side Spacing (s)	1 9/16"	2 1/8"	2 1/4"	2 3/4"	1 11/16"	2 1/8"
Loop Spacing (l)	3/8"	3/8"	3/8"	3/8"	3/8"	3/8"
Center Spacing (d)	2 1/2"	2 9/16"	2 9/16"	2 9/16"	2 9/16"	2 1/2"
Number of Elements	3	3	3	5	3	5
Element Resistance (average)	70 ohms	67.5 ohms	59.5 ohms	87.5 ohms	69.5 ohms	87.5 ohms

Table 3. Physical parameters of six windshield antennas on 1978 Cougar.

Resistance measured between reference point 0 and ⏚	Antenna Model Number					
	XF 243253	XF 243254	XF 243255	XF 243256	XF 243257	XF 243258
	Resistance in ohms					
A	16	16	12	13	17	10
B	35	33	28	28	34	26
B′	34	34	29	29	33	27
C	50	46	43	41	46	39
C′	55	51	45	46	50	45
D	66	66	56	54	61	52
D′	74	69	63	62	68	62
E				68		65
E′				80		79
F				80		79
F′				95		96

Table 4. Measured element resistance between various reference points (see Figure 8) for six windshield antennas 1978 Cougar.

For convenience, each windshield antenna will be identified later by the last number appearing in its model number as shown underlined in Tables 3 and 4 (e.g., 3, 7, 4, 5, etc.)

5.2 Radiation Patterns and Pseudo-Gain

The horizontal plane radiation patterns of six windshield antenna configurations, measured at five selected frequencies in the FM band (88, 93, 98, 103, and 108 MHz), are shown in Figs. 9 - 13; for comparison, the corresponding pattern obtained with the reference monopole antenna is also shown in each figure. Figure 14 shows in one plot the patterns of antenna no. 6 obtained at five different frequencies; this can be used to study the detailed variation of the antenna pattern as a function of frequency.

Pseudo-gain of the six antennas has been determined from the measured patterns by using the method discussed in Section 2.3. The results are shown in Table 5 which indicates that basically the six antennas have similar performance. It is found that all the antennas, except the antenna no. 7, tend to have the largest pseudo-gain at 98 MHz. From the viewpoint of maximum pseudo-gain and its variation within the frequency band, the antenna no. 8 appears to be the best. During the investigation, it has been found that the pseudo-gain (also the pattern) of the windshield antenna is strongly influenced by the positioning of the crash pad (e.g., a 10 dB variation was observed) and less sensitive to the coaxial cable termination of the frame.

5.3 Impedance Characteristics

The measured impedance characteristics of the six windshield antennas are shown in Figs. 15 (a) - (f). The corresponding VSWR's (relative to 50 ohms) of the same antennas are shown in Table 6. A review of Table 6 suggests that the six antennas (with the exception of the results for antenna no. 5 at 98,

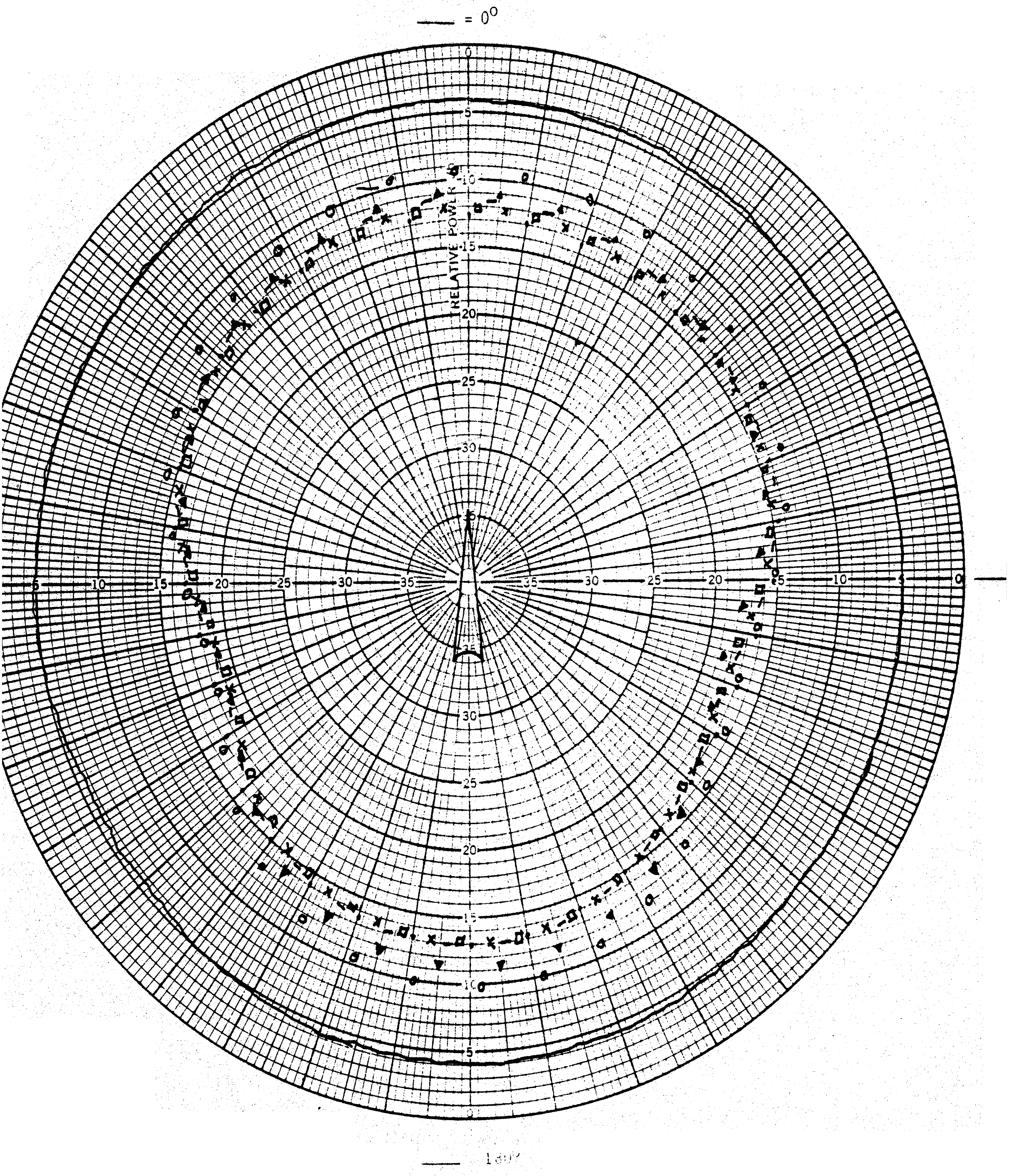


Figure 9. Radiation patterns of reference and six windshield antennas on 1978 Cougar measured at 88 MHz. .... antenna 3, ▫▫▫▫ antenna 4, ---- antenna 5, ΔΔΔΔ antenna 6, xxxx antenna 7, ∘∘∘∘ antenna 8.

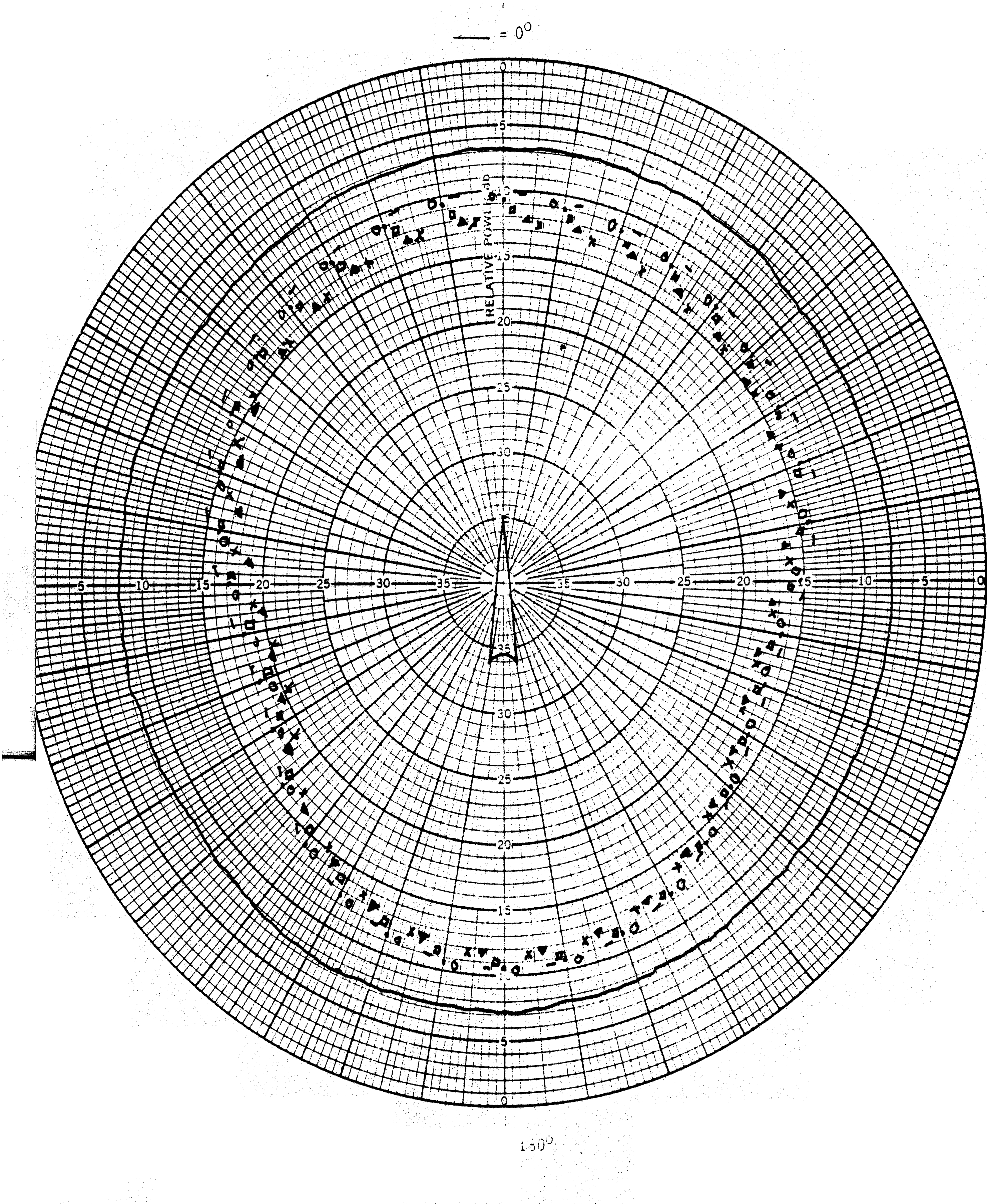


Figure 10. Radiation patterns of reference and six windshield antennas on 1978 Cougar measured at 93 MHz. ···· antenna 3, ▫▫▫▫ antenna 4, ---- antenna 5, ΔΔΔΔ antenna 6, xxxx antenna 7, ∘∘∘∘ antenna 8.

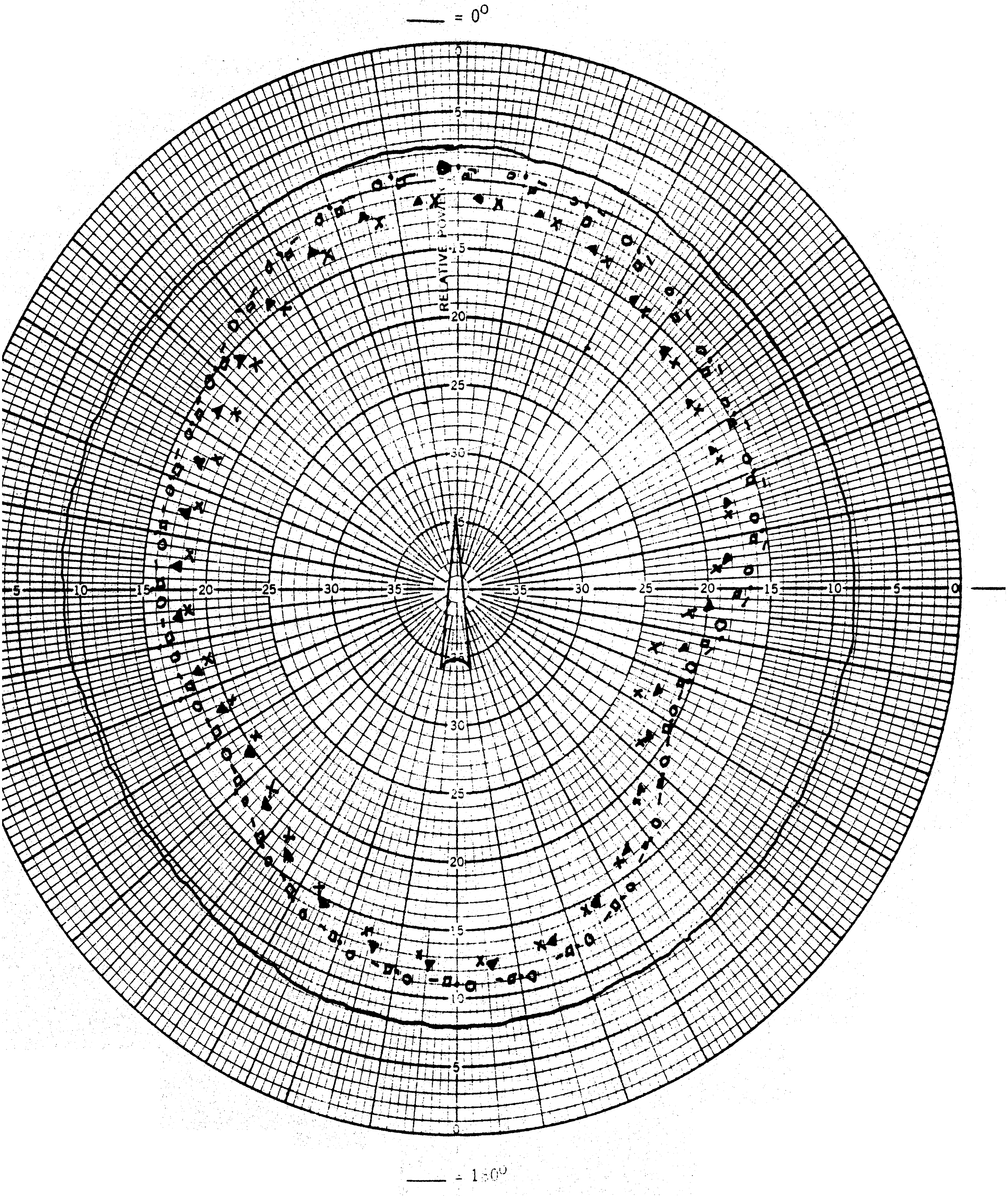


Figure 11. Radiation patterns of reference and six windshield antennas on 1978 Cougar measured at 98 MHz. .... antenna 3, ▫▫▫▫ antenna 4, ---- antenna 5, ΔΔΔΔ antenna 6, xxxx antenna 7, ∘∘∘∘ antenna 8.

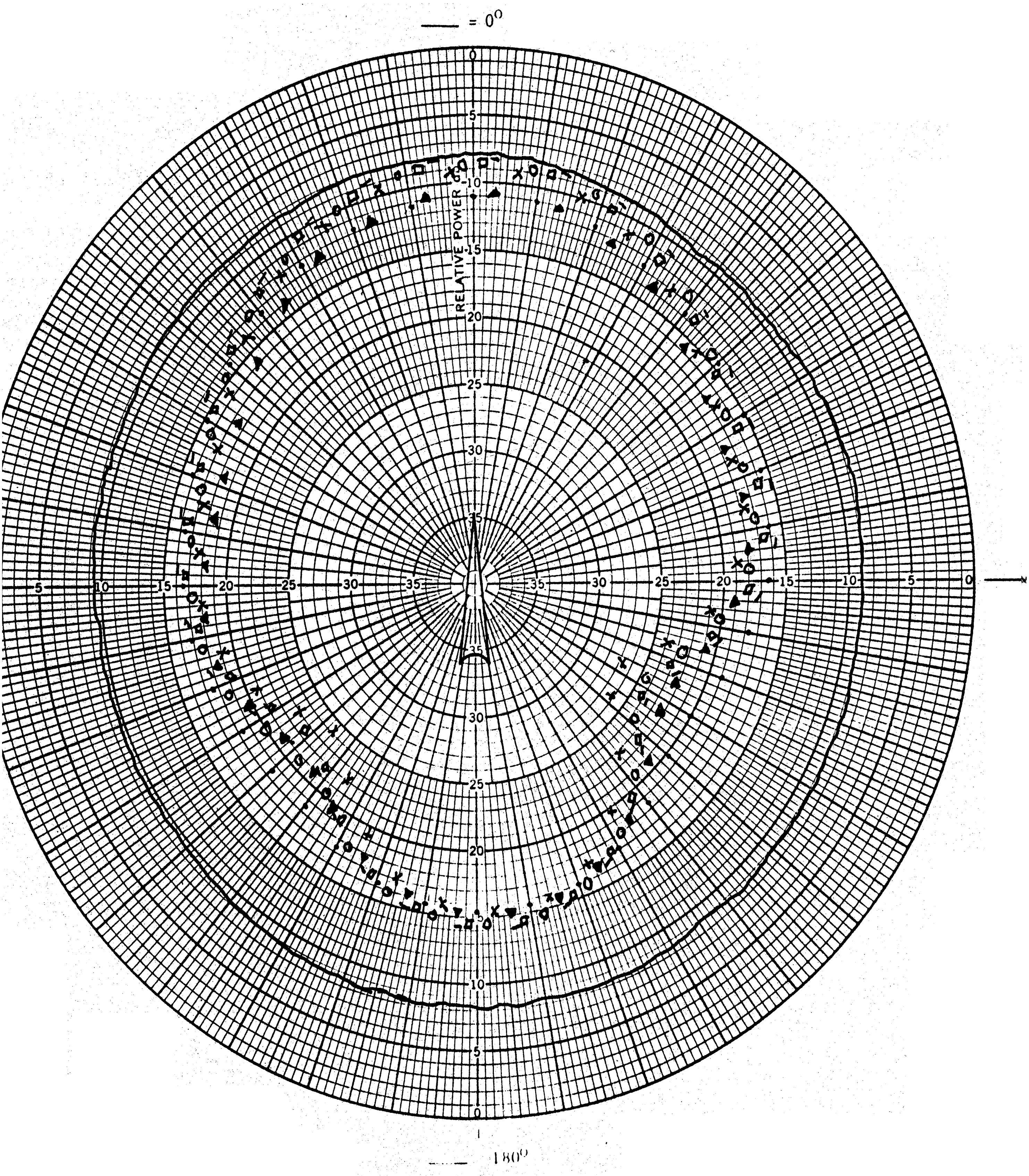


Figure 12. Radiation patterns of reference and six windshield antennas on 1978 Cougar measured at 103 MHz. ···· antenna 3, ▫▫▫▫ antenna 4, ---- antenna 5, ΔΔΔΔ antenna 6, xxxx antenna 7, ∘∘∘∘ antenna 8.

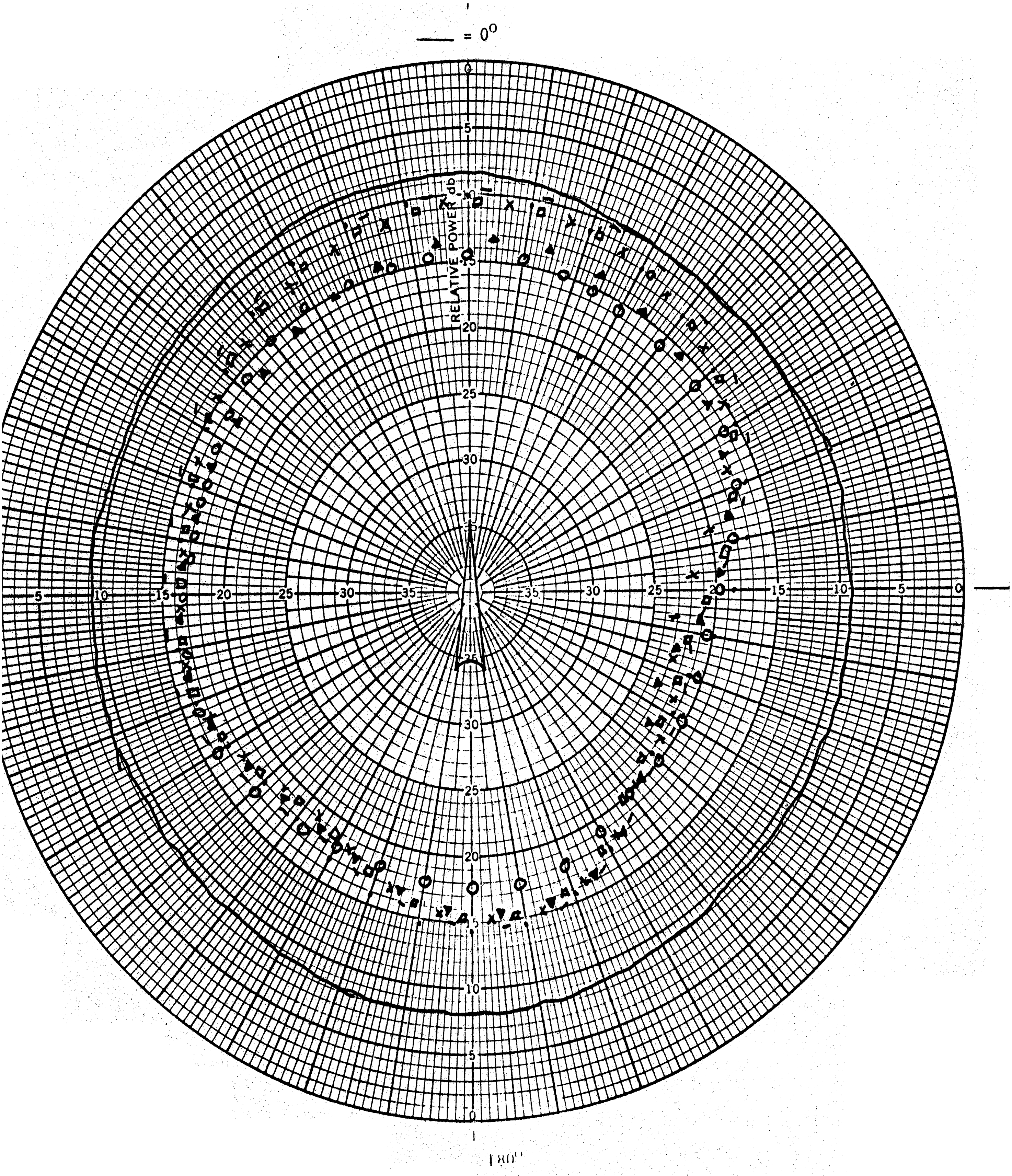


Figure 13. Radiation patterns of reference and six windshield antennas on 1978 Cougar measured at 108 MHz. ···· antenna 3, ▫▫▫▫ antenna 4, ---- antenna 5, ΔΔΔΔ antenna 6, xxxx antenna 7, ∘∘∘∘ antenna 8.

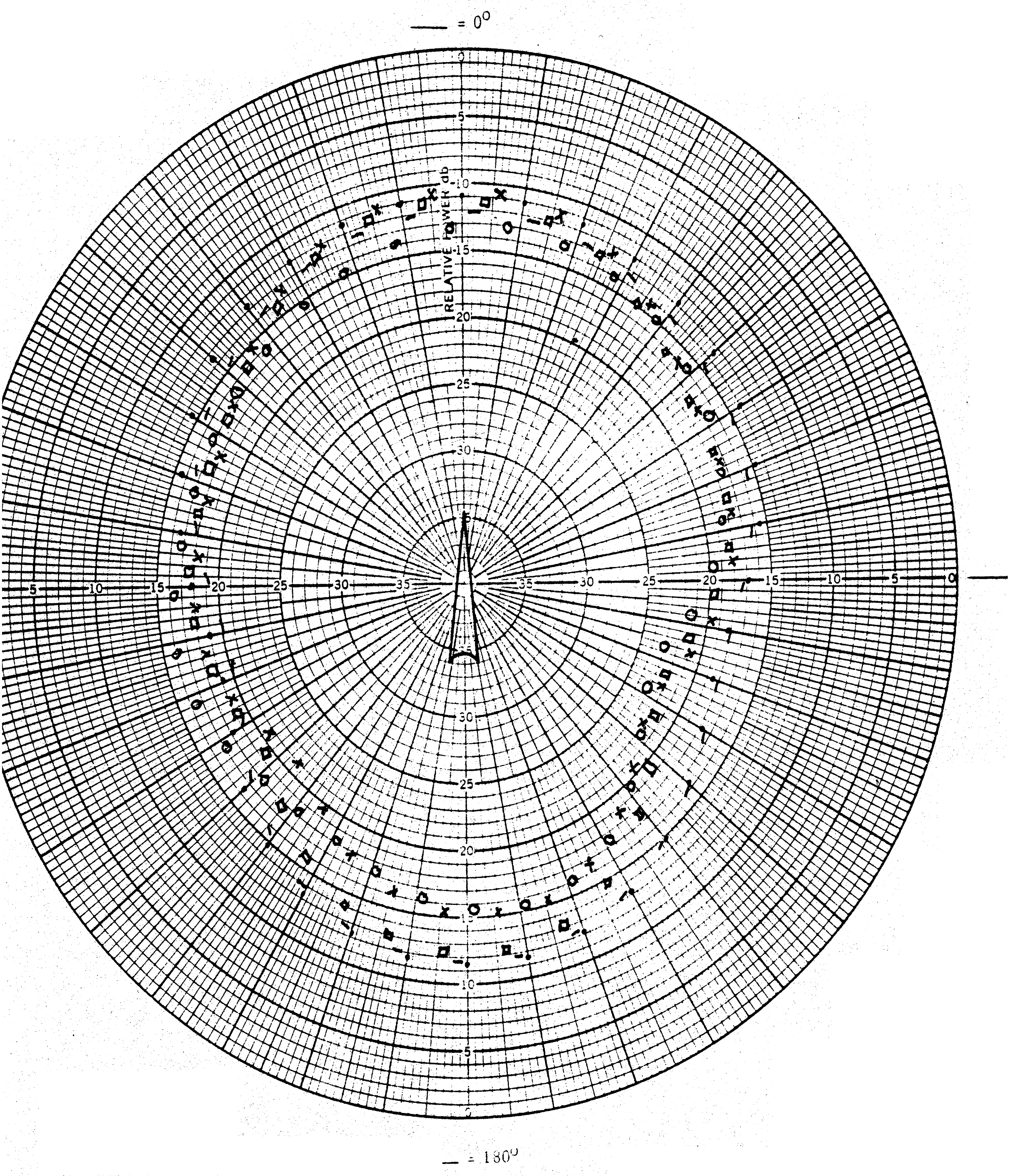
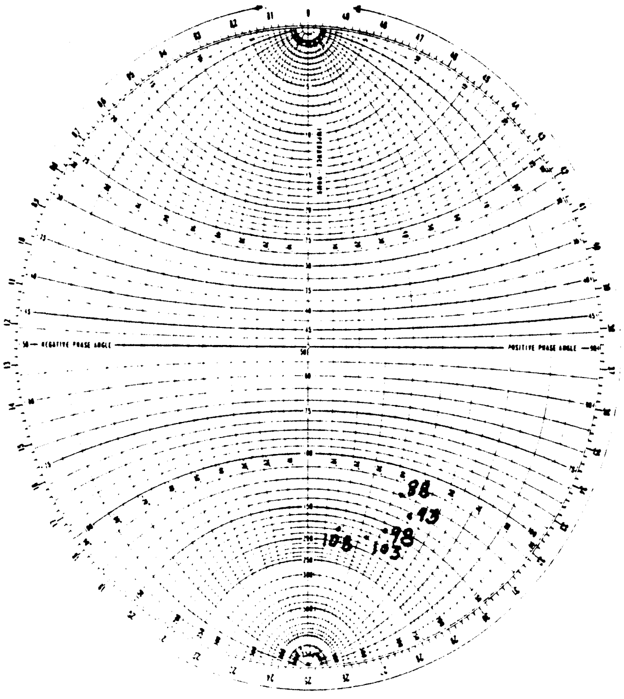


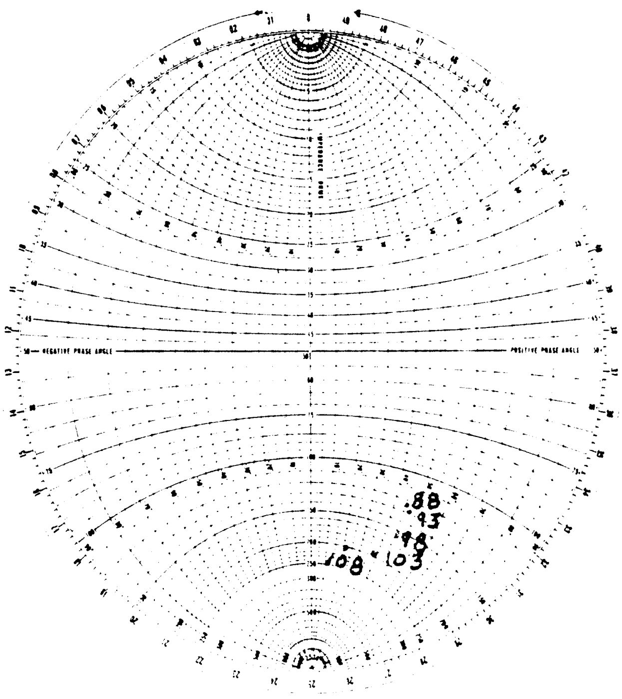
Figure 14. Radiation patterns of antenna 6 on 1978 Cougar as a function of frequency. .... 88 MHz, ---- 93 MHz, ▫▫▫▫ 98 MHz, xxxx 103 MHz, oooo 108 MHz.

Freq. MHz	Antenna Identification Number						
	3	4	5	6	7	8	Aver. Over Antennas
	Pseudo-gain in dB						
88	-9.76	-9.94	-9.55	-9.22	-9.81	-7.45	-9.50
93	-5.78	-6.22	-5.30	-7.22	-7.10	-5.70	-6.32
98	-4.81	-5.36	-4.53	-6.79	-7.27	-4.84	-5.75
103	-6.10	-5.26	-4.61	-7.00	-6.04	-5.36	-5.79
108	-5.64	-6.26	-5.15	-7.69	-6.16	-7.99	-6.63
Aver. Over Freq.	-6.42	-6.61	-5.83	-7.58	-7.28	-6.26	

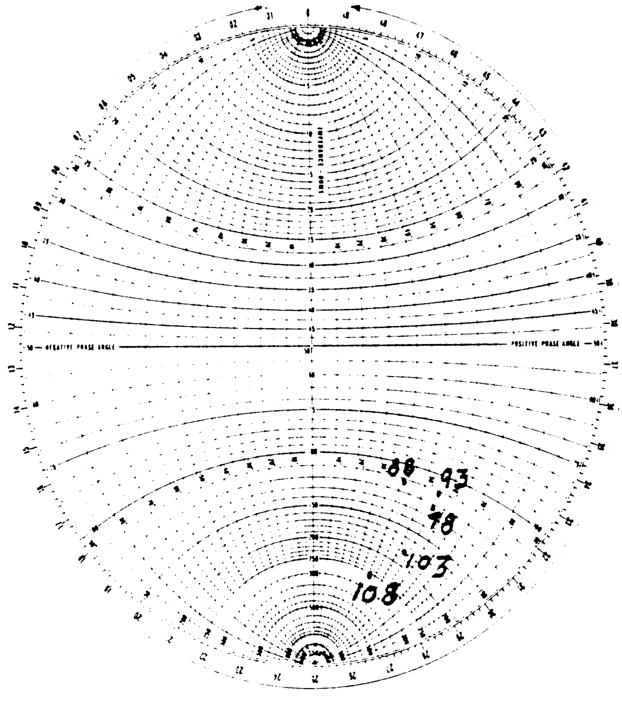
Table 5. Pseudo-gain (relative to a $\lambda/4$-monopole antenna) versus frequency for six windshield antennas on 1978 Cougar.



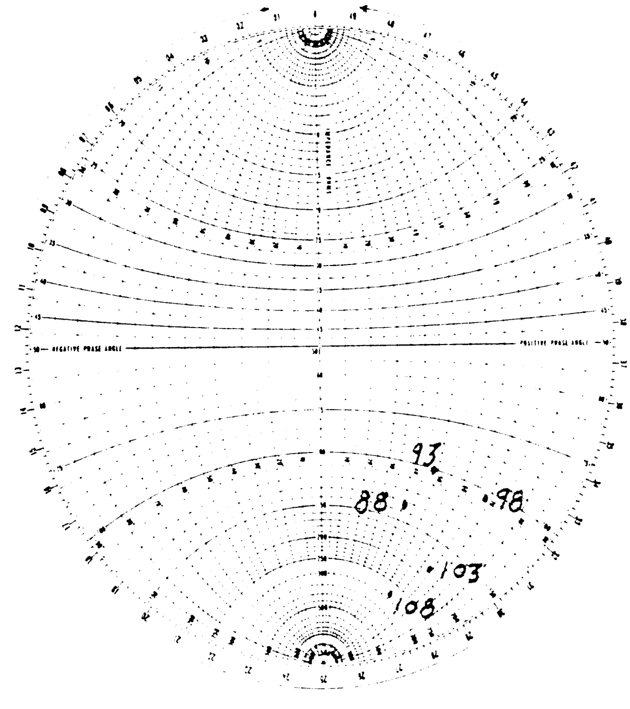
(a) antenna 3



(b) antenna 4

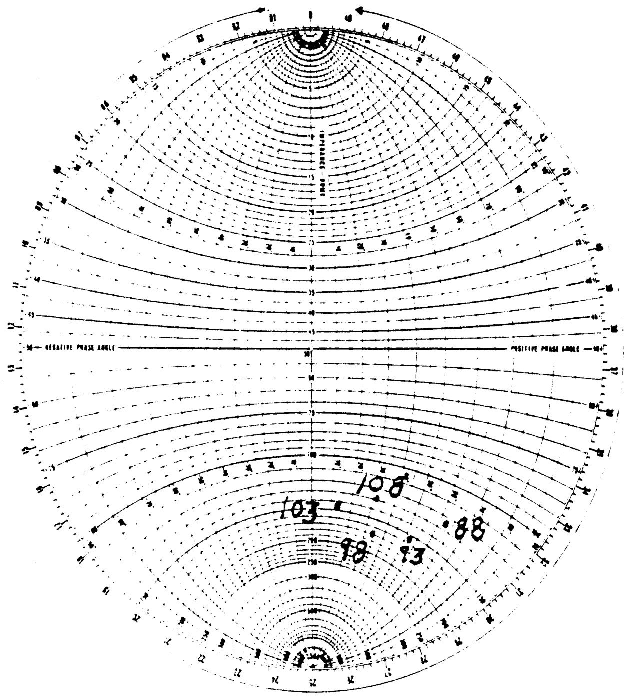


(c) antenna 5

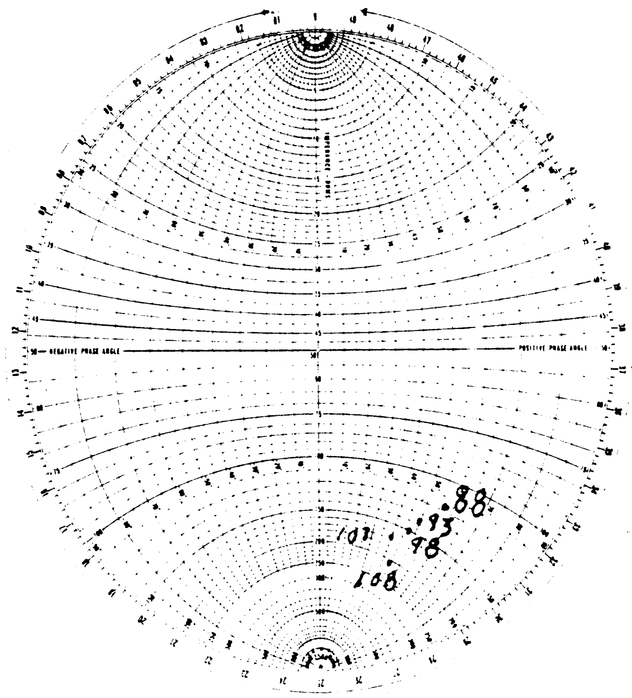


(d) antenna 6

Figure 15. Measured impedance characteristics of six windshield antennas on 1978 Cougar.



(e) antenna 7



(f) antenna 8

Figure 15. Measured impedance characteristics of six windshield antennas on 1978 Cougar.

Freq. MHz	Antenna Identification Number						
	3	4	5	6	7	8	Average Over Antennas
	VSWR						
88	3.65	3.88	3.76	6.14	3.35	5.06	4.31
93	4.56	4.56	3.55	5.45	4.56	4.71	4.57
98	4.56	4.88	7.00	4.26	5.06	4.71	5.08
103	4.41	5.06	9.00	3.00	6.41	4.56	5.41
108	3.76	4.41	10.11	3.26	7.00	6.14	5.78
Aver. Over Freq.	4.19	4.56	6.66	4.42	5.28	5.04	

Table 6. VSWR versus frequency for six windshield antennas on 1978 Cougar.

103, and 108 MHz) exhibit similar VSWR characteristics over the entire FM band of frequencies. The cause for this exception is presently unknown and was not investigated because of the lack of time and funds. Ignoring this exception, it is reasoned that neither the physical variations nor the small variations in the resistance of the elements built into the six antennas contributed significantly to their impedance behavior.

5.4 Effect of the Linear Segments

As shown in Fig. 6, 7, or 8, the windshield antenna may contain a variable number of horizontal linear segments. An investigation was conducted to determine how the RF characteristics of a windshield antenna depend on the number of horizontal linear segments in the antenna. For this purpose, the radiation patterns and impedance of the windshield antenna no. 6 were measured as functions of its number of horizontal linear segments.

The desired linear segments (starting with EF and E´F´ in Fig. 8) of the antenna were systematically removed by soaking them with nitric acid. To minimize handling of the windshield so that the antenna set-up did not change significantly for each configuration, each linear segment was removed with the windshield in the vehicle. However, this procedure took several days to correct the required set of data and it was necessary to rearrange some of the instrumentation in the car during this time. For identification purposes, the test antenna (i.e., antenna no. 6) after systematic removal of its horizontal elements will be designated (with reference to Fig. 8) as follows:

Designation of Test Antenna	Lengths of Linear Segments
6-5	AF, AF´
6-4	AE, AE´
6-3	AD, AD´
6-2	AC, AC´
6-1	AB, AB´

Note that with the above notation, 6-5 denotes the five element windshield antenna (no. 6) and 6-1 denotes the basic T-version (i.e., one element) of the same antenna.

Figs. 16-20 show how the measured horizontal plane patterns of the test antenna change at each selected frequency as a function of the number of its horizontal linear segments. The corresponding pseudo-gain of the antenna as a function of the number of its horizontal linear segments are shown in Table 7. The results indicate that the number of horizontal linear segments of the antenna does not significantly affect its radiation pattern and pseudo-gain. It is believed that the variations in the patterns shown in Figs. 14-19 were related to the changes in the equipment placement that might have taken place within the vehicle rather than to the fact that the number of elements were changed.

The impedance of antenna no. 6 was also measured to determine if the removal of the horizontal linear segments had any appreciable effect. However, the results did not change significantly with the number of elements. Therefore, impedance data were collected for only 6-4 and 6-1 configurations, and are shown in Figs. 21 (a) - (b). These results should be compared with the results for the configuration 6-5 shown in Fig. 15(e).

5.5 T-Shaped Antenna

The results discussed in Section 5.5 indicated that the T-shaped version (i.e., no. 6-1) of the windshield antenna was similar and comparable to that of the antenna no. 6-5. The former being simpler to fabricate, it was decided to investigate further the properties of a T-shaped windshield antenna. For this purpose, three T-shaped antennas were obtained by removing the horizontal linear segments of antenna no. 6. Referring to Fig. 8, the three T-shaped

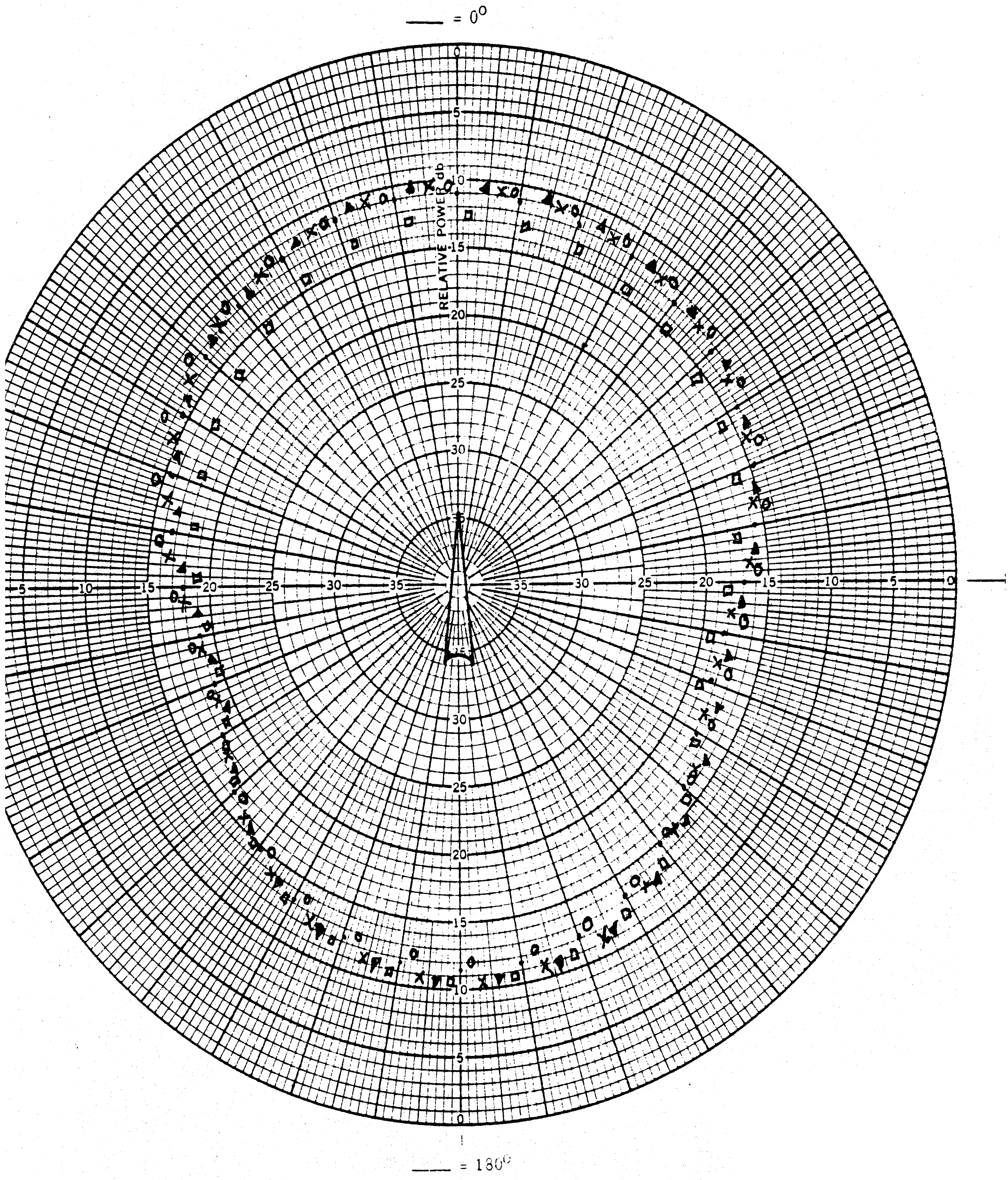


Figure 16. Radiation patterns of five windshield antenna configurations on 1978 Cougar measured at 88 MHz. ∘∘∘∘ antenna 6-1, xxxx antenna 6-2, ΔΔΔΔ antenna 6-3, ▫▫▫▫ antenna 6-4, ... antenna 6-5.

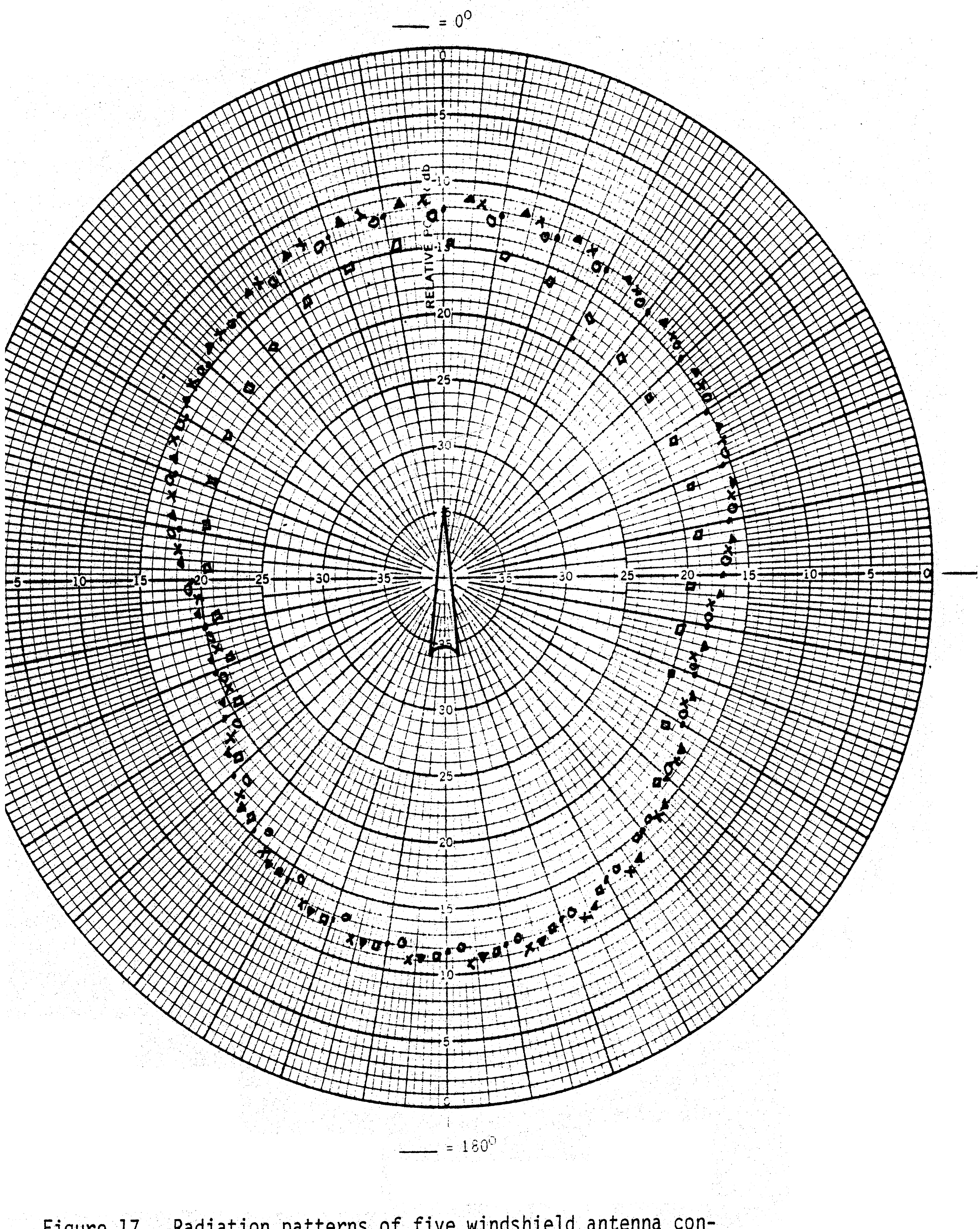


Figure 17. Radiation patterns of five windshield antenna configurations on 1978 Cougar measured at 93 MHz. ∘∘∘∘ antenna 6-1, xxxx antenna 6-2, ΔΔΔΔ antenna 6-3, ◘◘◘◘ antenna 6-4, ····· antenna 6-5.

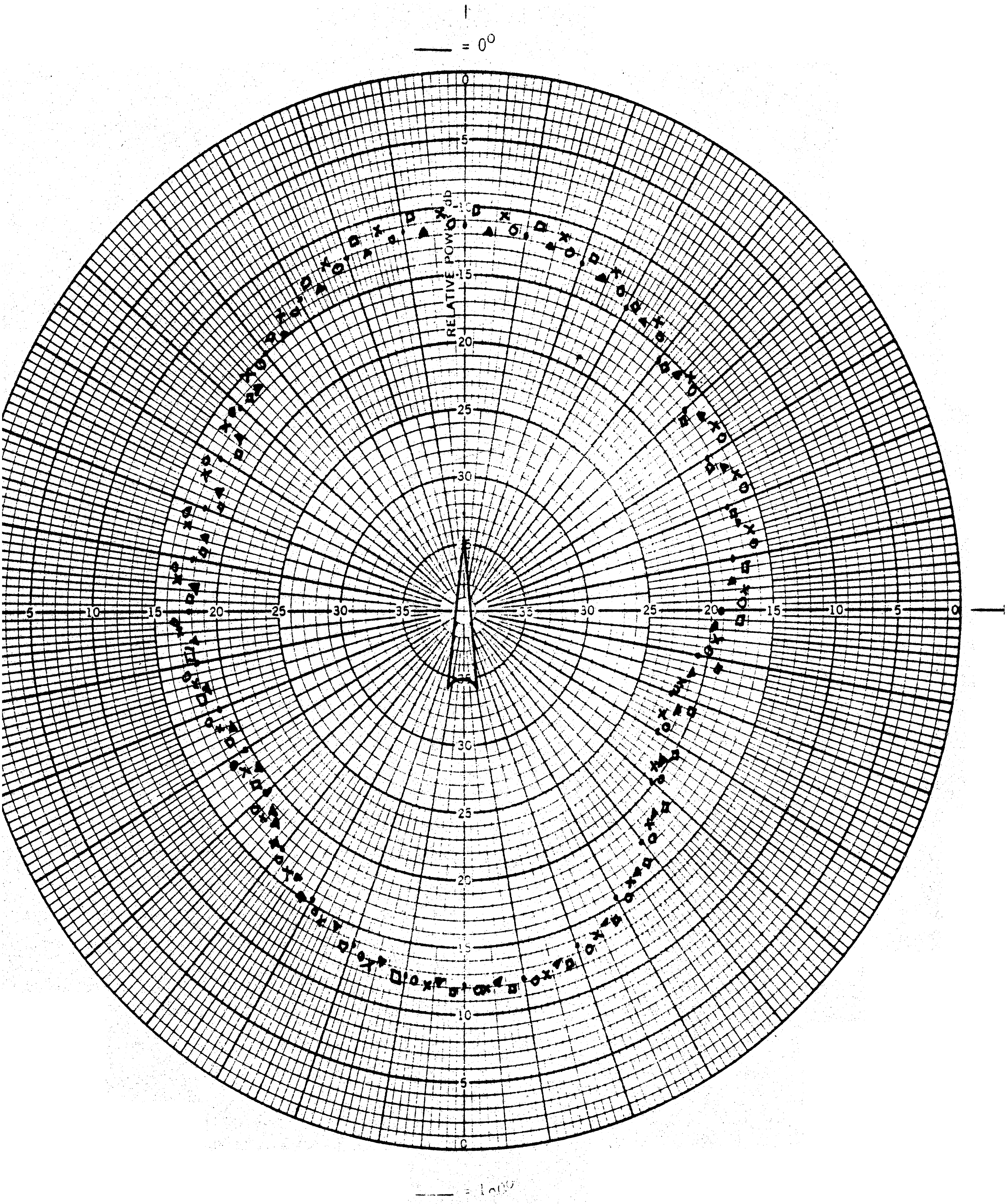


Figure 18. Radiation patterns of five windshield antenna configurations on 1978 Cougar measured at 98 MHz. ∘∘∘∘ antenna 6-1, xxxx antenna 6-2, ΔΔΔΔ antenna 6-3, ▫▫▫▫ antenna 6-4, ···· antenna 6-5.

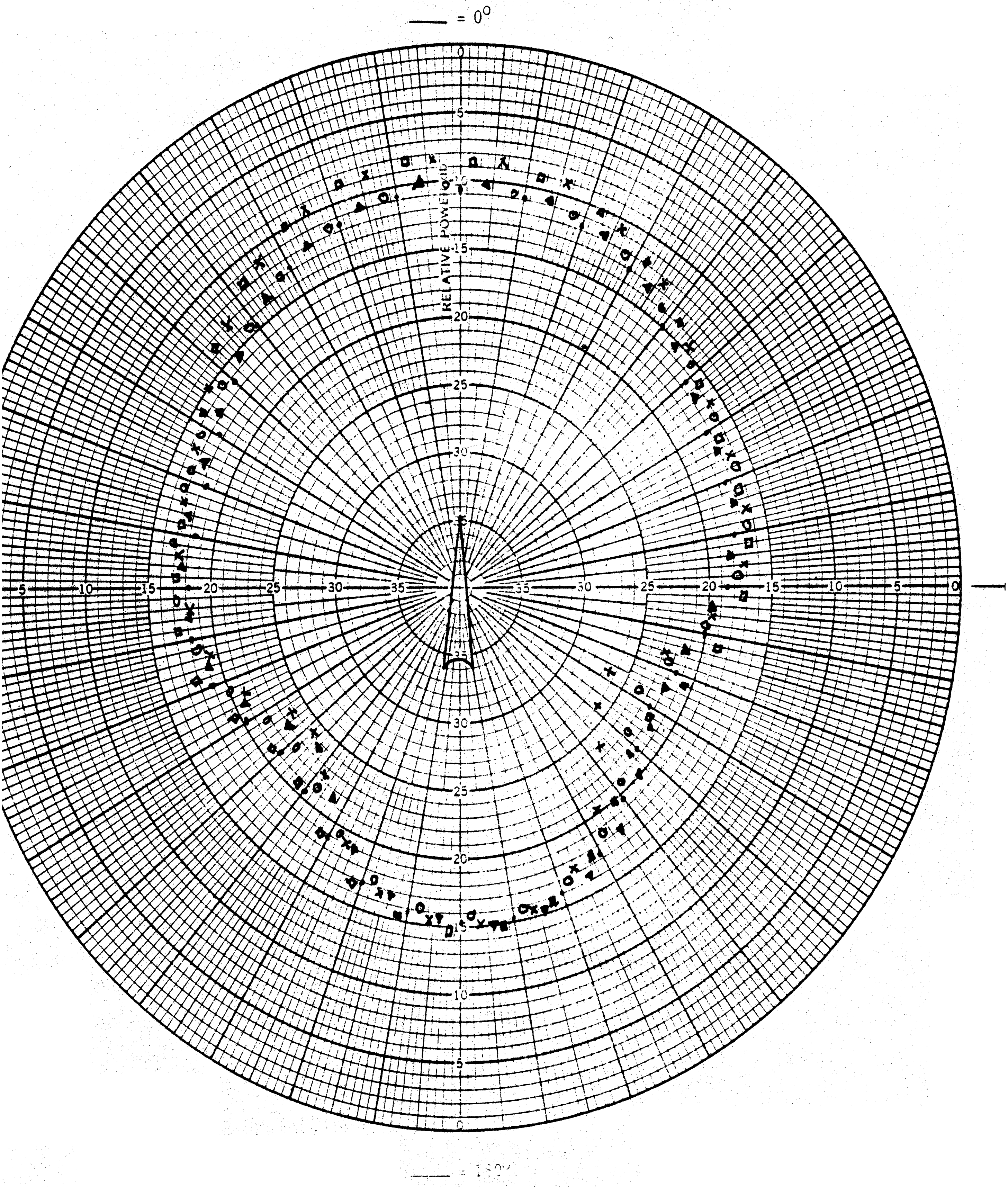


Figure 19. Radiation patterns of five windshield antenna configurations on 1978 Cougar measured at 103 MHz. oooo antenna 6-1, xxxx antenna 6-2, ΔΔΔΔ antenna 6-3, ▫▫▫▫ antenna 6-4, ···· antenna 6-5.

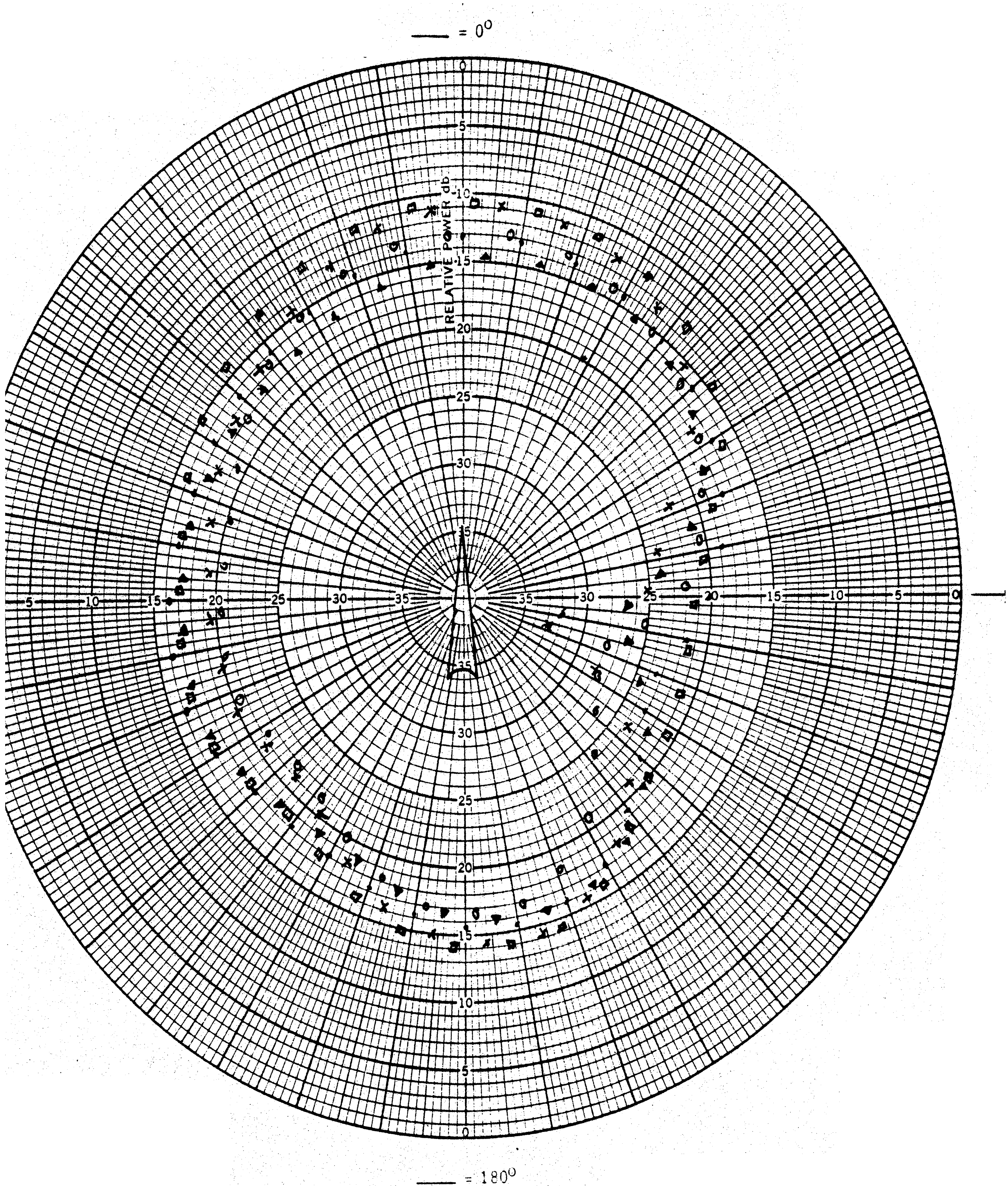
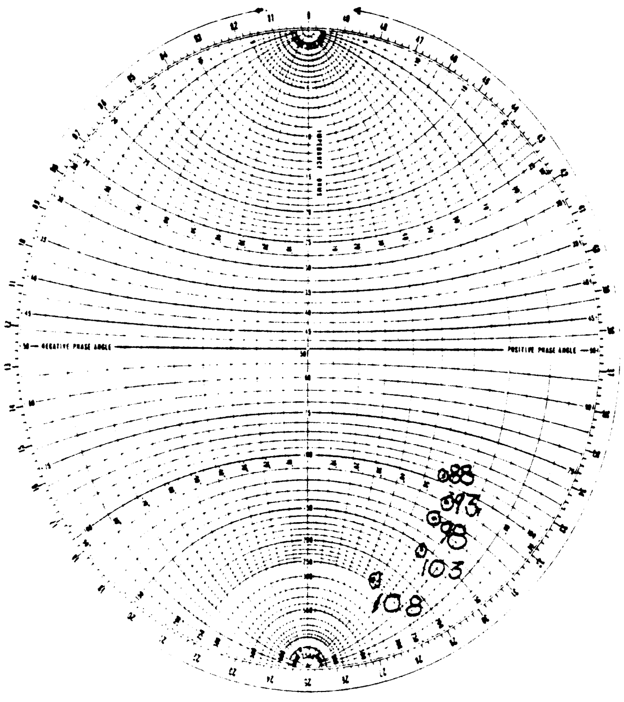


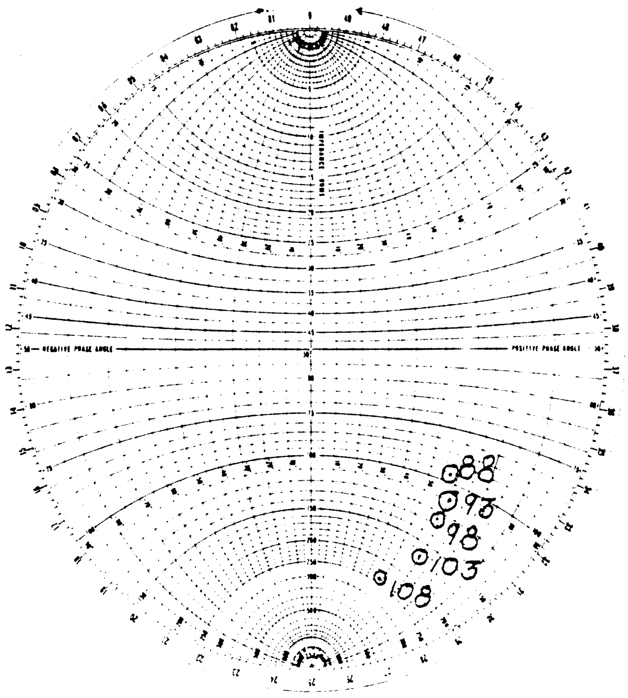
Figure 20. Radiation patterns of five windshield antenna configurations on 1978 Cougar measured at 108 MHz. oooo antenna 6-1, xxxx antenna 6-2, ΔΔΔΔ antenna 6-3, ▫▫▫▫ antenna 6-4, :··· antenna 6-5.

Freq. MHz	Antenna Identification Number					
	6-5	6-4	6-3	6-2	6-1	Average Over Antennas
	Pseudo-gain in dB					
88	-9.22	-9.98	-8.43	-8.50	-8.66	-8.95
93	-7.22	-8.65	-6.45	-6.53	-7.25	-7.22
98	-6.79	-5.93	-6.53	-5.94	-6.08	-6.25
103	-7.00	-5.34	-6.53	-5.33	-6.50	-6.14
108	-7.69	-6.20	-8.67	-7.11	-8.81	-7.70
Aver. Over Freq.	-7.58	-7.22	-7.32	-6.68	-7.46	

Table 7. Pseudo-gain (relative to $\lambda/4$-monopole antenna) versus frequency for variable element antenna No. 6 on 1978 Cougar.



(a) antenna no. 6-4



(b) antenna no 6-1

Figure 21. Impedance characteristics of antennas 6-4 and 6-1 on 1978 Cougar.

configurations consisted of the vertical element OA and the full horizontal segment BB´ (designated 6-1), 1/2 of BB´ (designated 6-1-1/2) and 1/4 of BB´ (designated 6-1-1/4). The three antennas are sketched in Fig. 22.

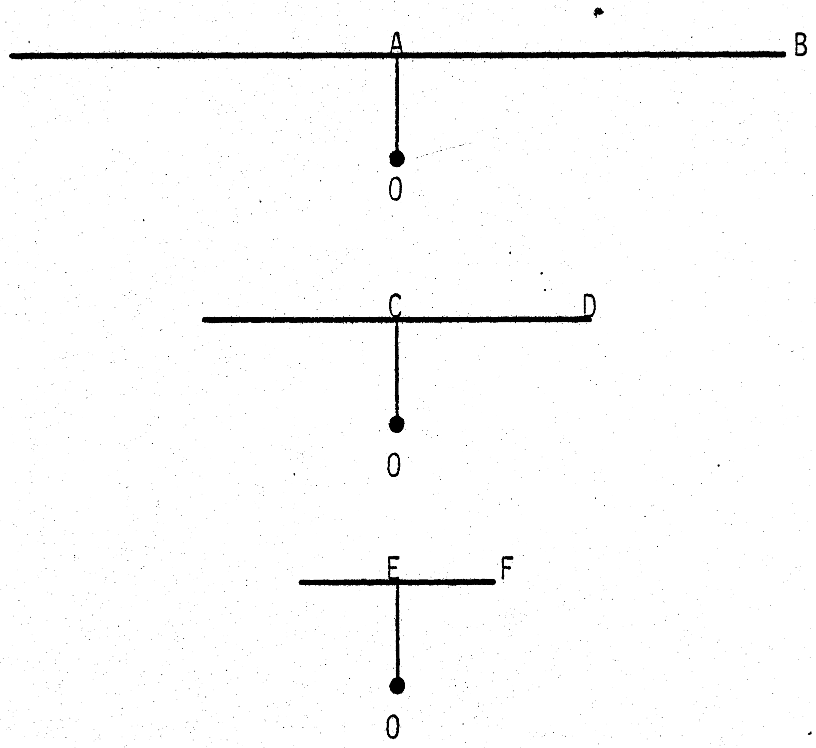


Figure 22. Sketches of three T-shaped antennas. CD = 1/2 AB, EF = 1/4 AB, OA = OC = OE = 23", AB = 23.75".

Figs. 23-27 show the measured patterns of the three T-shaped antennas at selected frequencies in the FM band. The results indicate that the shortening of the horizontal element does not appreciably affect the pattern shape of the antenna. Table 8 shows the pseudo-gain of the three antennas as determined from the patterns shown in Figs. 23-27. It should be noted that the pseudo-gain

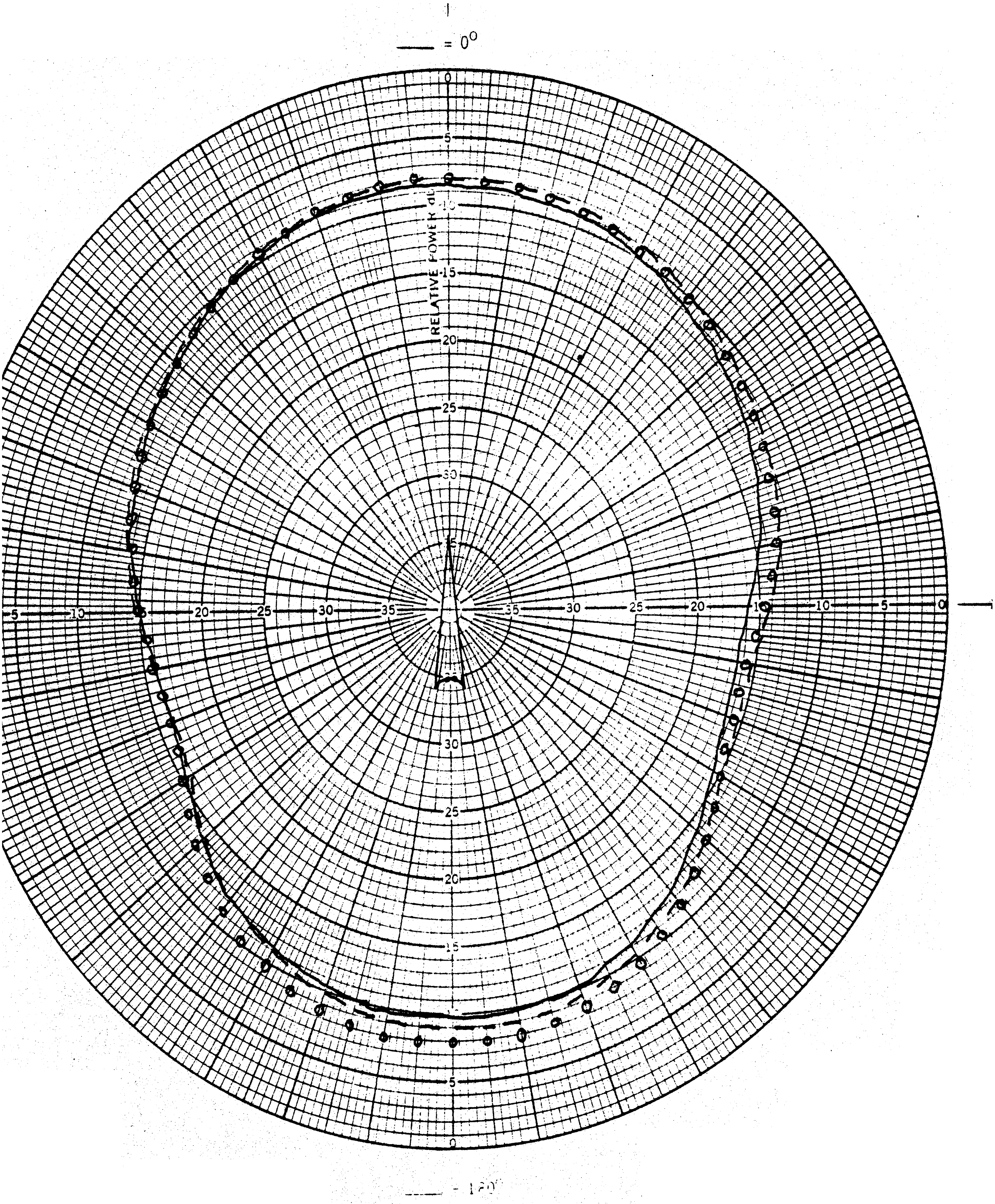


Figure 23. Radiation patterns of T-shaped antennas on 1978 Cougar measured at 88 MHz. —— antenna 6-1, ---- antenna 6-1-1/2, ○○○○ antenna 6-1-1/4.

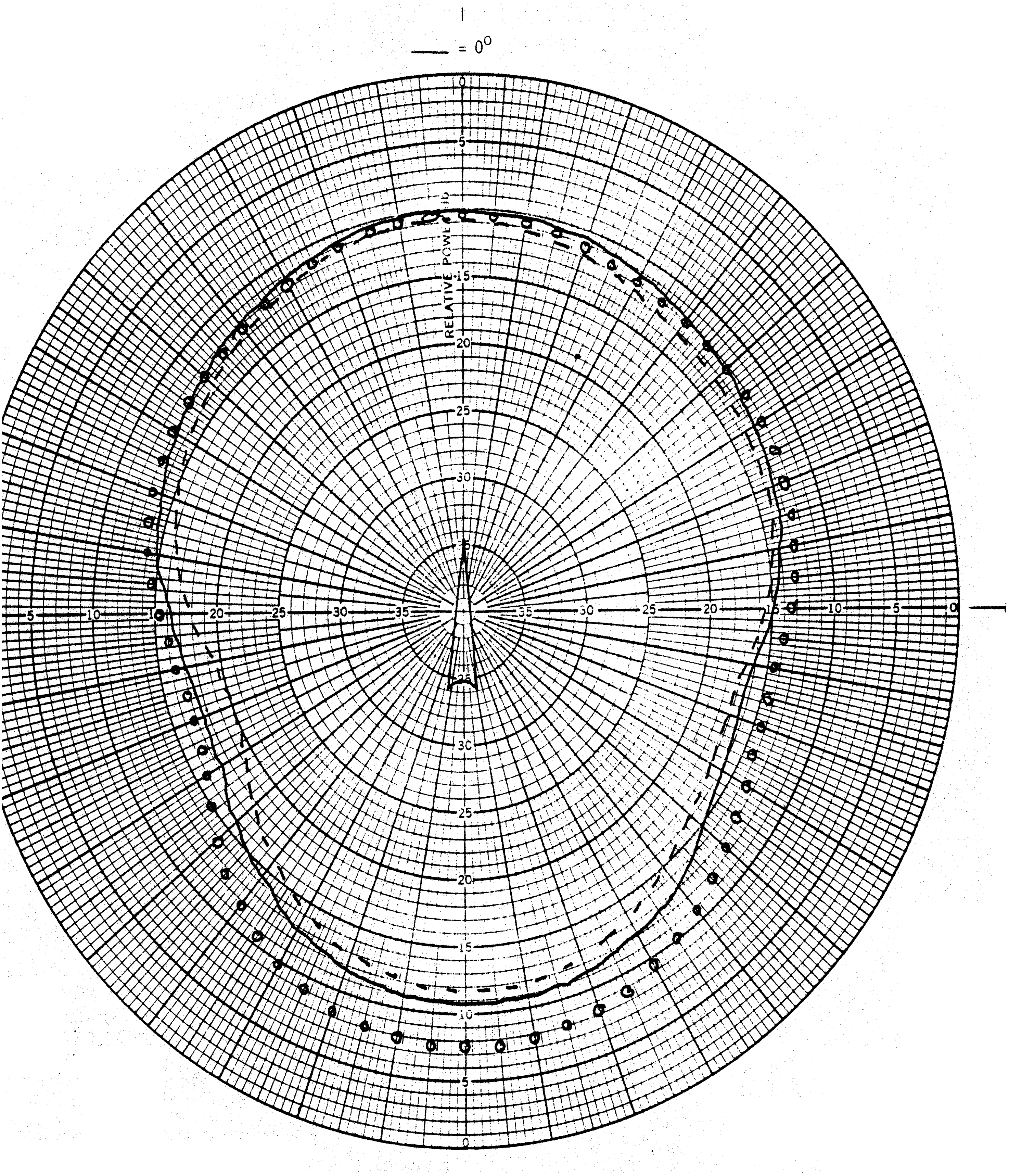


Figure 24. Radiation patterns of T-shaped antennas on 1978 Cougar measured at 92.7 MHz. ——— antenna 6-1, ---- antenna 6-1-1/2, oooo antenna 6-1-1/4.

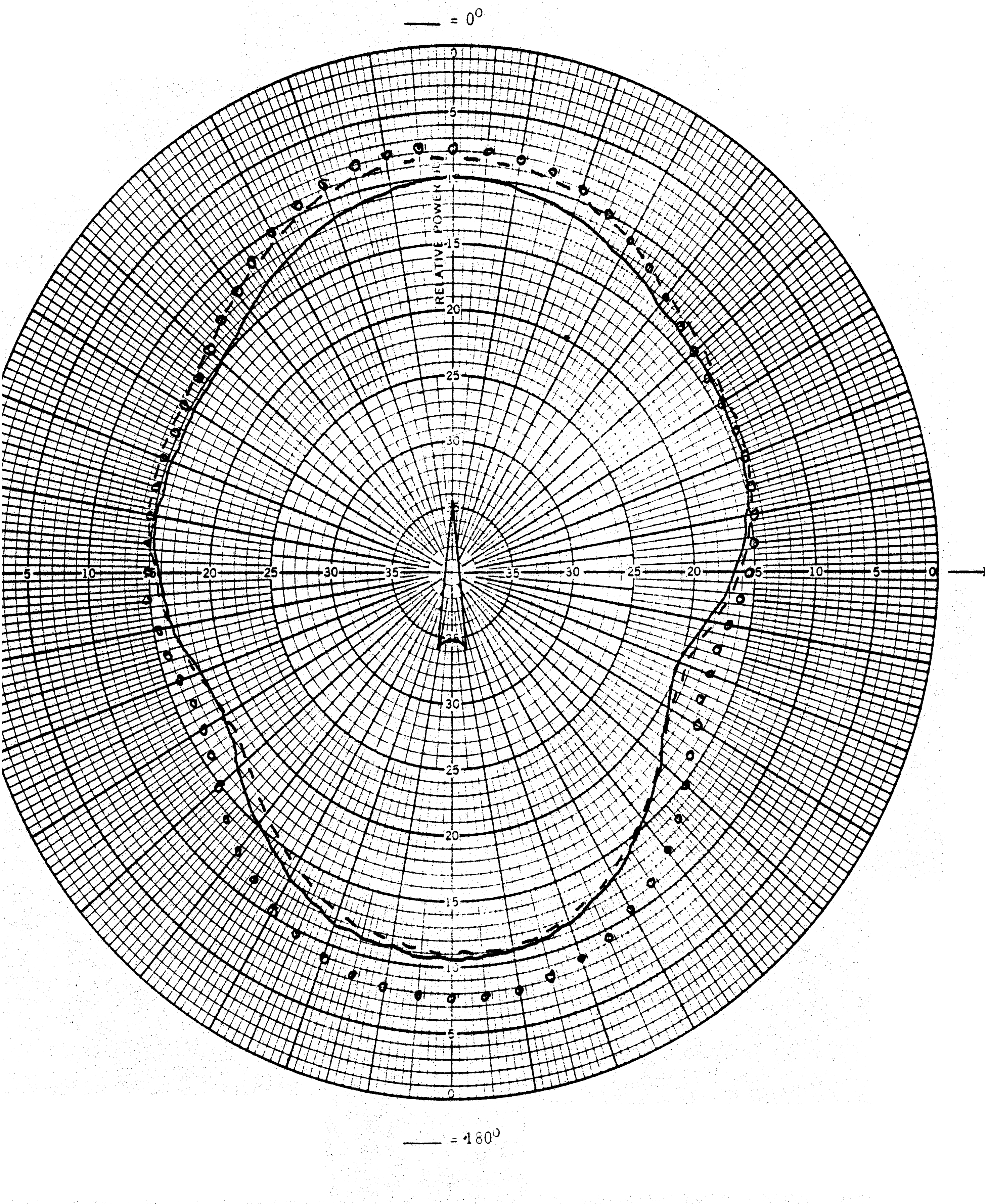


Figure 25. Radiation patterns of T-shaped antennas on 1978 Cougar measured at 97.8 MHz. ——— antenna 6-1, ---- antenna 6-1-1/2, oooo antenna 6-1-1/4.

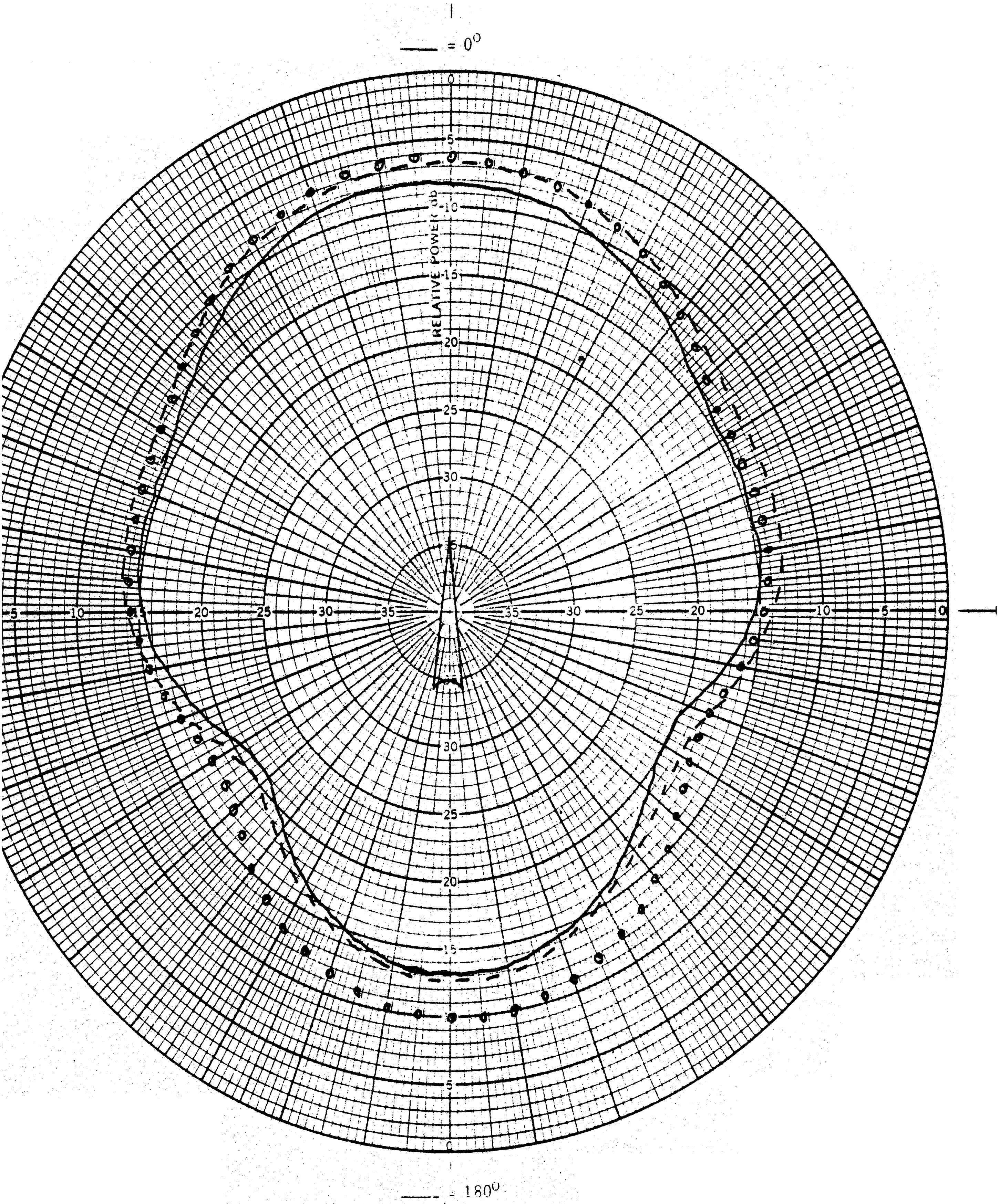


Figure 26. Radiation patterns of T-shaped antennas on 1978 Cougar measured at 102.3 MHz. —— antenna 6-1, ---- antenna 6-1-1/2, ∘∘∘∘ antenna 6-1-1/4.

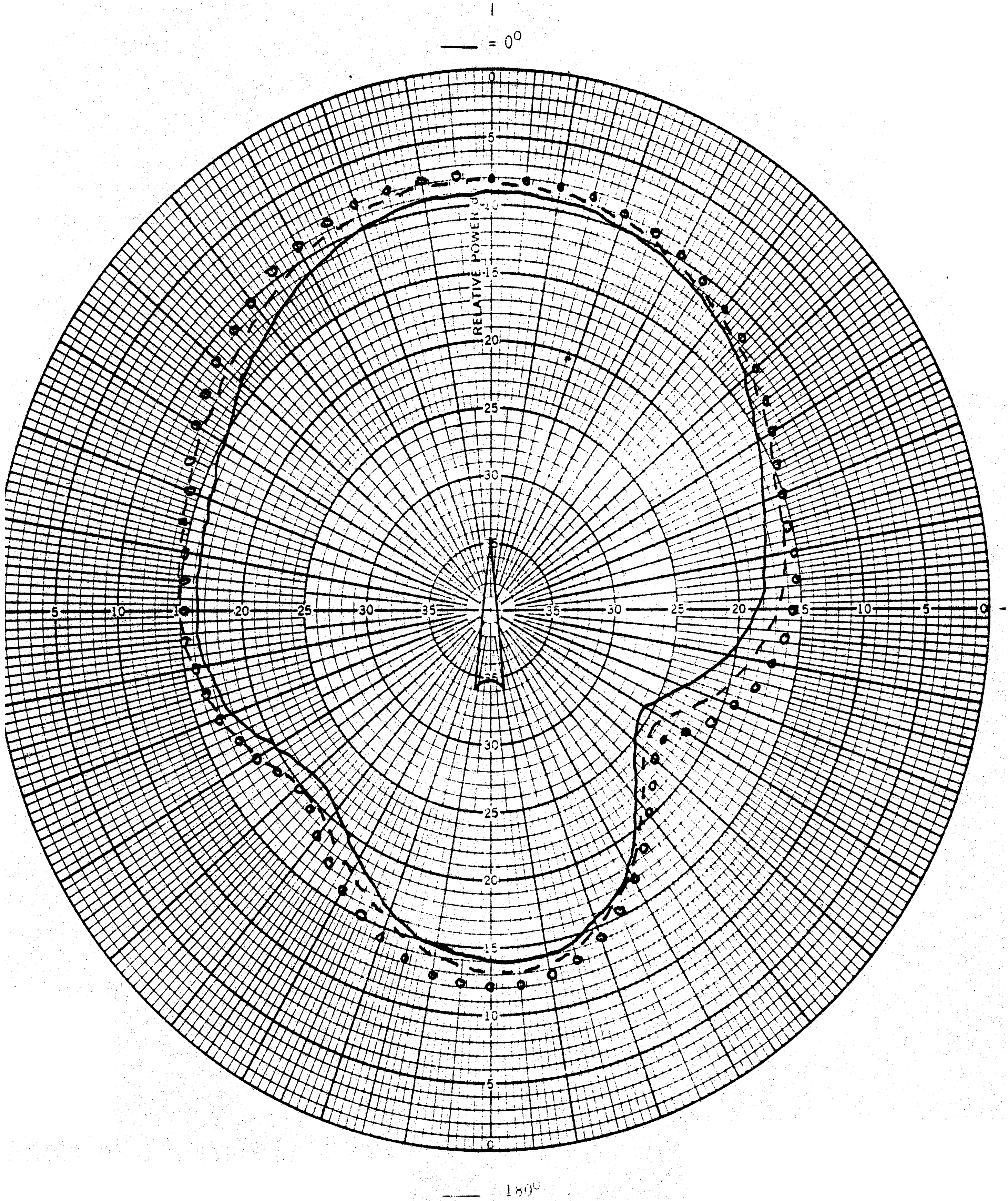


Figure 27. Radiation patterns of T-shaped antennas on 1978 Cougar measured at 108 MHz. —— antenna 6-1, ---- antenna 6-1-1/2, oooo antenna 6-1-1/4.

Freq. MHz	Antenna Identification Number			
	6-1	6-1-1/2	6-1-1/4	Average Over Antennas
	Pseudo-gain in dB			
88	-8.84	-8.21	-7.94	-8.33
93	-7.28	-8.34	-5.94	-7.19
98	-6.04	-5.59	-3.90	-5.18
103	-6.29	-5.07	-4.43	-5.26
108	-7.43	-6.04	-5.79	-6.42
Aver. Over Freq.	-7.18	-6.65	-5.60	

Table 8. Pseudo-gain (relative to $\lambda/4$-monopole antenna) versus frequency for T-shaped antennas on 1978 Cougar.

data for antenna 6-1 of Table 8 differs slightly from those presented in Table 7. This variation is attributed to the physical changes made in the instrumentation set-up inside the vehicle. The results of Table 8 suggest that the FM band pseudo-gain of the Cougar windshield antenna can be increased by using a T-shaped antenna having a relatively short horizontal element. However, we did not collect sufficient data to optimize the FM performance of such an antenna.

Although the antenna 6-1-1/4 appears to have larger pseudo-gain than the corresponding multi-element windshield antenna (compare Tables 8 and 5), further testing should be performed to provide higher credibility for the results shown in Table 8.

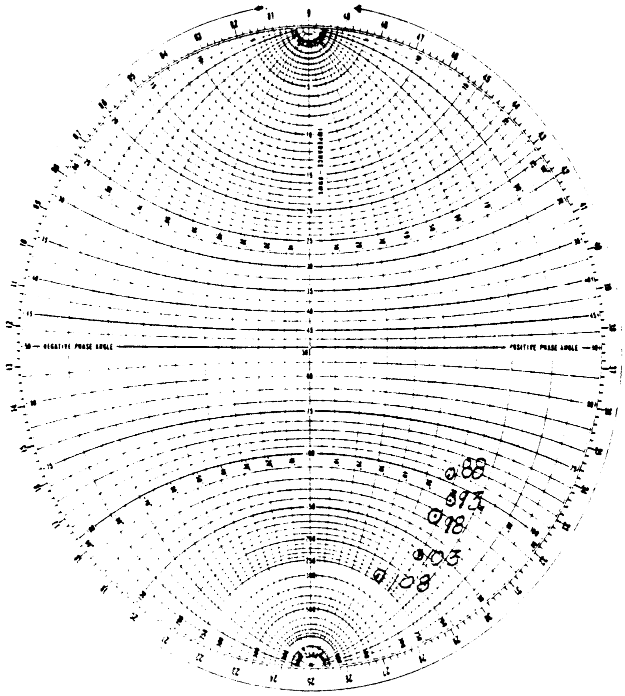
The impedance characteristics of the antennas 6-1 and 6-1-1/4 are shown in Figs. 28 (a) and (b), respectively. It is found that for the amount of element shortening used, the impedance characteristics did not change appreciably. Moreover, a comparison of Figs. 14(e) and 28(b) indicates that the overall FM impedance characteristics of the two antennas 6-5 and 6-1-1/4 are approximately the same.

5.6 Effect of the Crash Pad

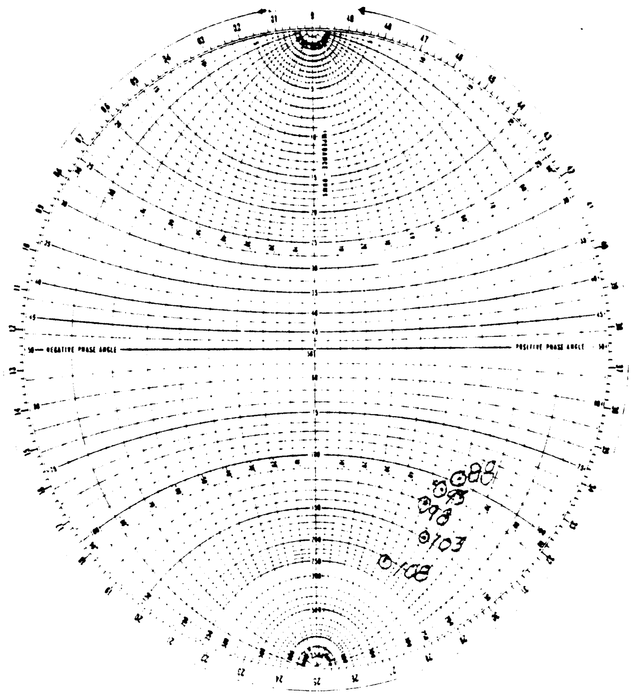
The radiation patterns of windshield antenna no. 7 were measured both with and without the crash pad of the 1978 Cougar installed. The results are shown in in Figs. 29-33. The corresponding pseudo-gains are shown in Table 9. From these results it is apparent that the crash pad has an appreciable influence on the electrical performance of the windshield antenna. In addition to the results shown here, test personnel observed as much as a 10 dB variation in the pseudo-gain (or the average level of the measured pattern) of the windshield antenna as the position of the crash pad relative to the windshield was varied by fractions of an inch. Time and funds did not allow us to perform a carefully controlled investigation to determine any correlation between the crash pad location and windshield performance. Any future windshield study should be addressed to this problem.

5.7 Discussion

On the basis of the results presented in this chapter, the following comments can be made with regard to the FM band performance of windshield antennas installed on 1978 Cougar:



(a) antenna no. 6-1



(b) antenna no. 6-1-1/4

Figure 28. Impedance characteristics of T-shaped antennas on 1978 Cougar.

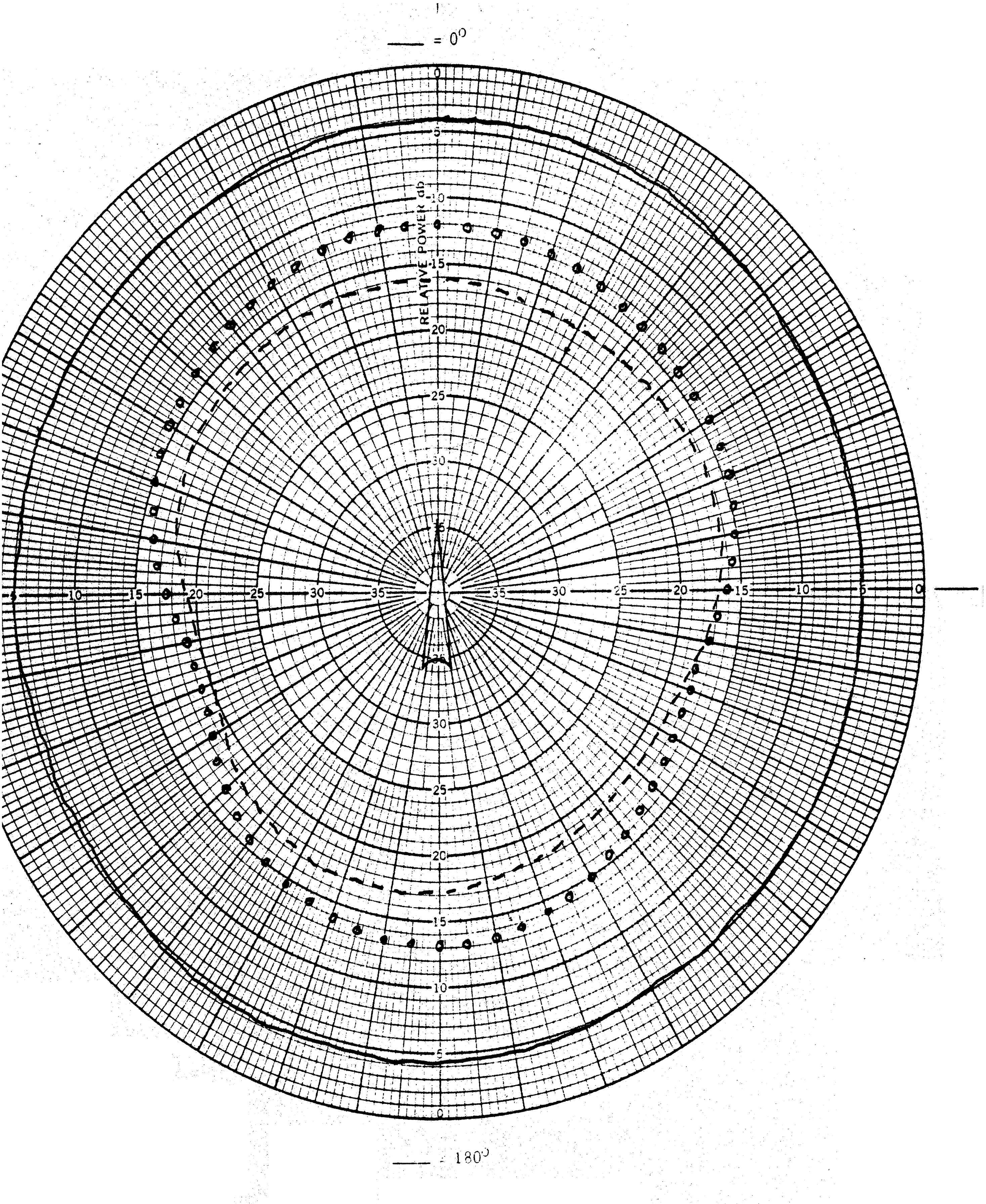


Figure 29. Radiation patterns of reference and windshield antennas on 1978 Cougar (with and without crash pad) measured at 88 MHz. —— reference, ---- with crash pad, ∘∘∘∘ without crash pad.

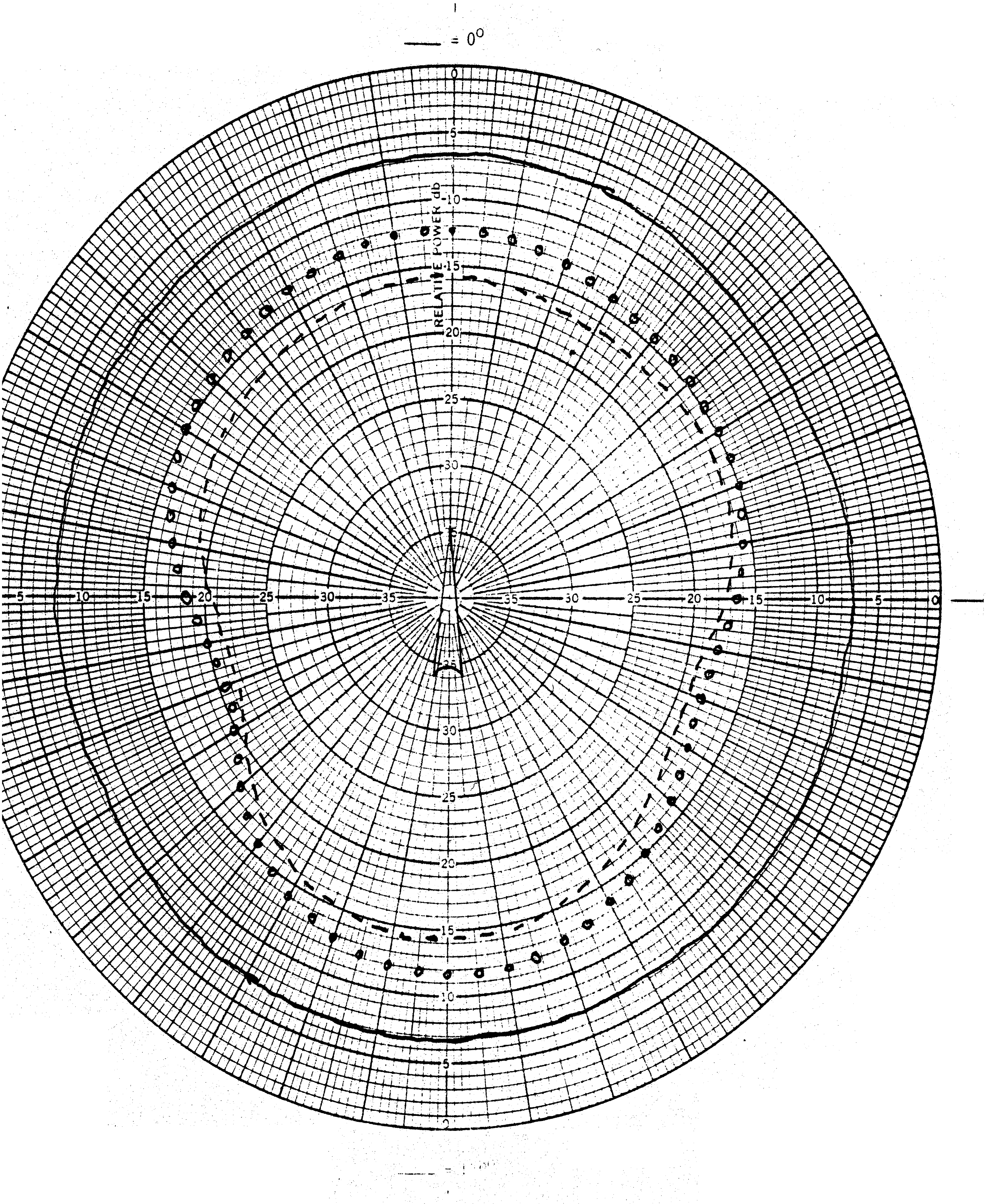


Figure 30. Radiation patterns of reference and windshield antennas on 1978 Cougar (with and without crash pad) measured at 92.8 MHz. —— reference, ---- with crash pad, oooo without crash pad.

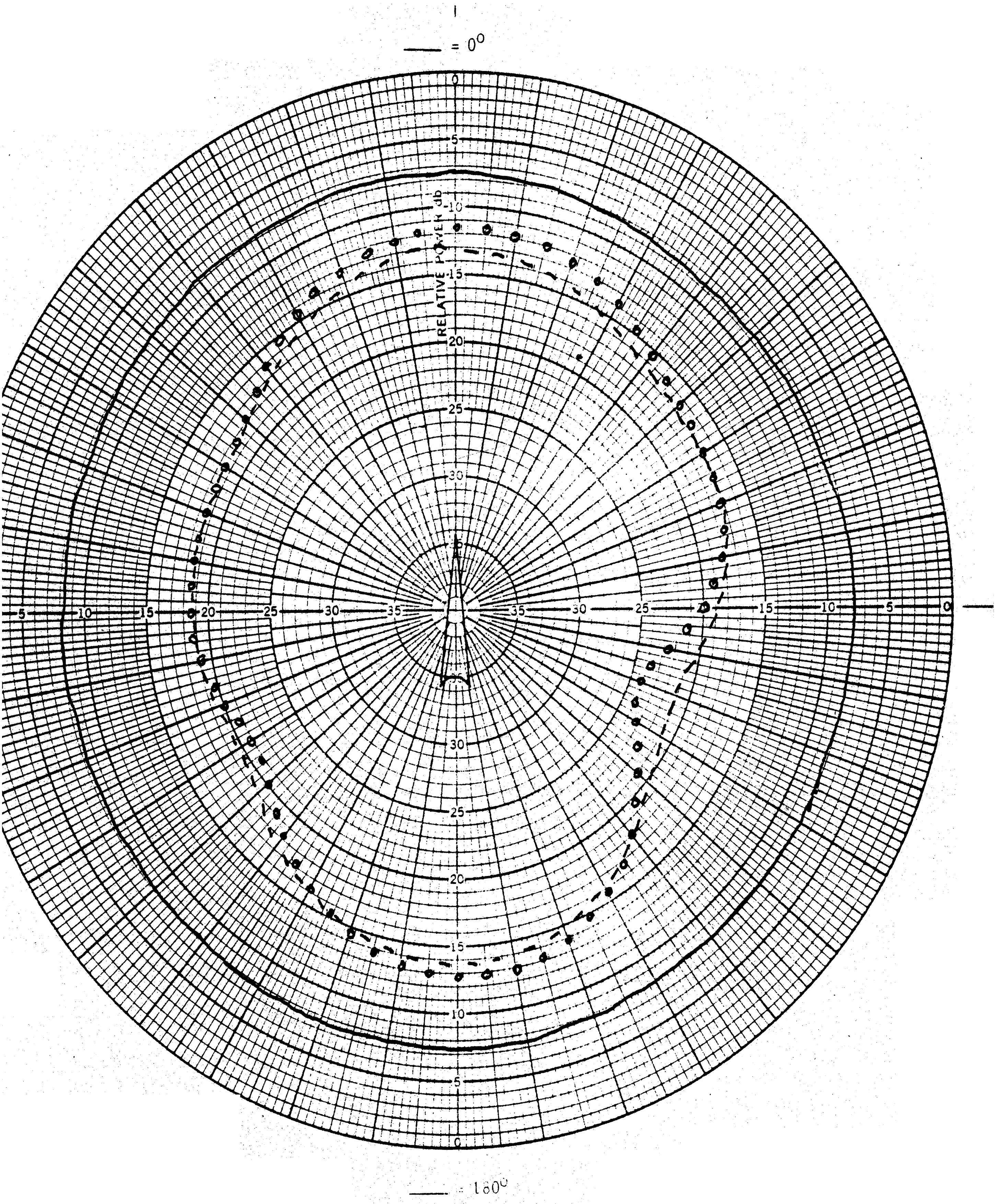


Figure 31. Radiation patterns of reference and windshield antennas on 1978 Cougar (with and without crash pad) measured at 97.7 MHz. —— reference, ---- with crash pad, oooo without crash pad.

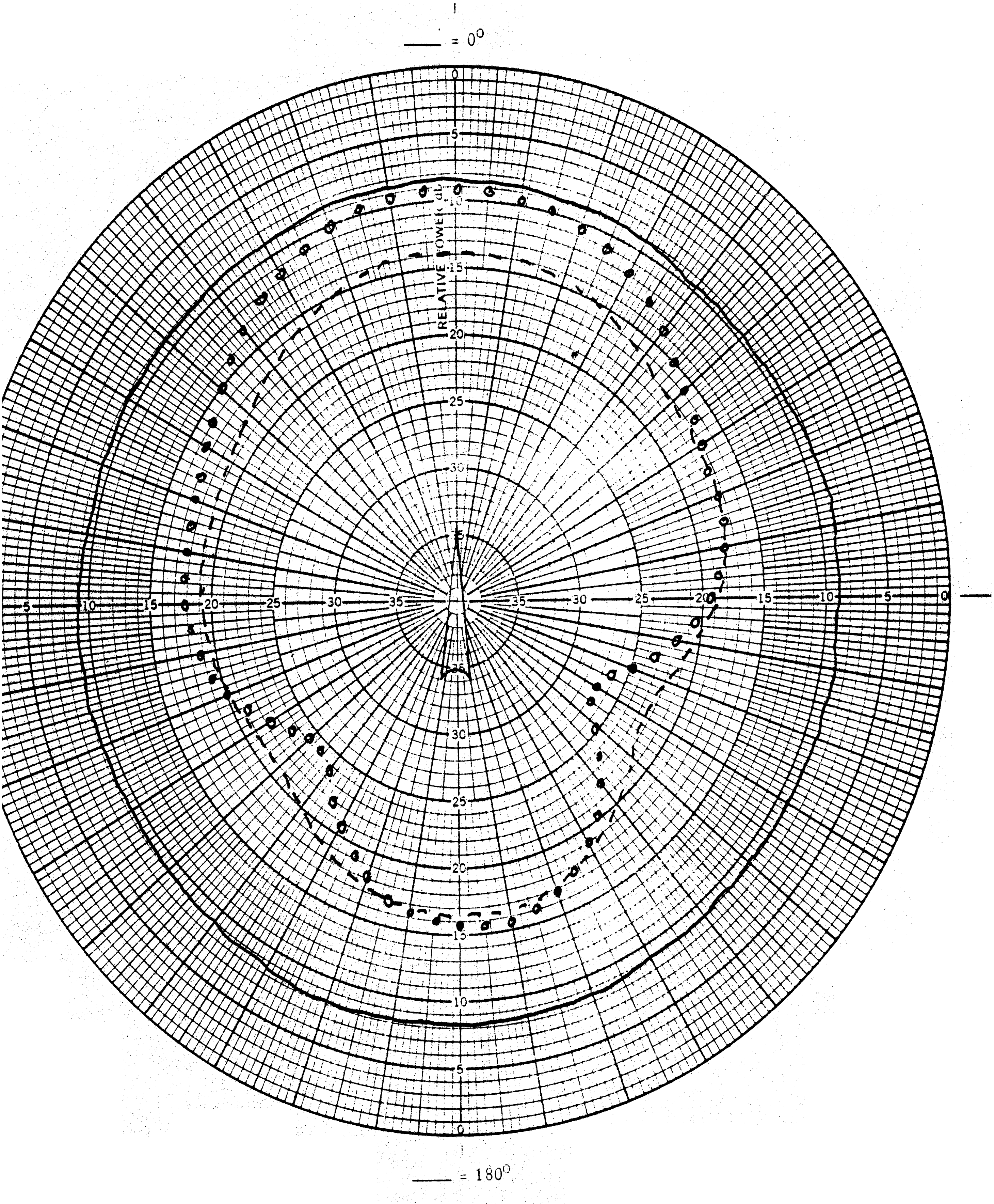


Figure 32. Radiation patterns of reference and windshield antennas on 1978 Cougar (with and without crash pad) measured at 102.6 MHz. —— reference, ---- with crash pad, °°°° without crash pad.

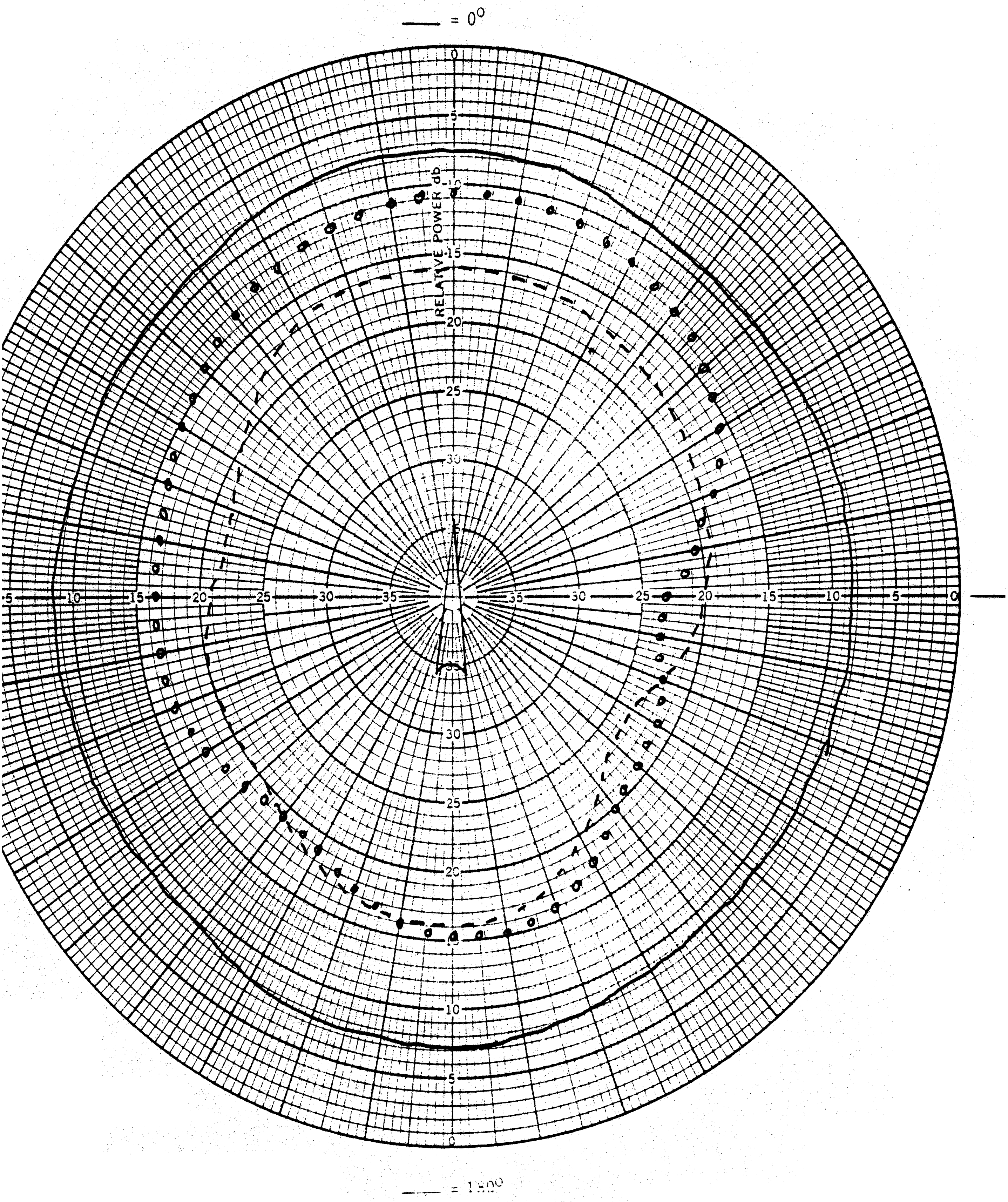


Figure 33. Radiation patterns of reference and windshield antennas on 1978 Cougar (with and without crash pad) measured at 108 MHz. —— reference, ----with crash pad, ∘∘∘∘ without crash pad.

Frequency MHz	Pseudo-gain in dB	
	with crash pad	without crash pad
88	-9.81	-12.63
93	-7.10	-9.41
98	-7.27	-7.91
103	-6.04	-8.53
108	-6.16	-9.59

Table 9. Pseudo-gain (relative to $\lambda/4$-monopole antenna) versus frequency for windshield antenna No. 7 on 1978 Cougar (with and without crash pad).

i) The six test antennas with variable parameters (element length, element resistance, head space, etc.) have basically similar performance; the radiation pattern and impedance characteristics of the antennas are not appreciably affected by the range of variation of the parameters used.

All antennas have maximum gain in the forward and backward directions with respect to the car; relative to a $\lambda/4$-reference antenna maximum pseudo-gain of about -6 dB occurs at 98 MHz. The VSWR's generally stay within 3.5 to 6.5 for all antennas with the exception of one for which a VSWR of 10 has been observed.

ii) The change of the horizontal element length (or the number of loops) does not significantly affect the performance of multi-element antennas, although the configuration 6-2 appears to have the larger gain.

iii) T-shaped antenna (one element) configurations have more gain than the multi-element configurations.

iv) The location of the crash pad with respect to the antenna significantly affects its performance.

VI. AM BAND PERFORMANCE OF WINDSHIELD ANTENNAS ON 1978 COUGAR

The AM band performance data obtained with the windshield antennas, mounted on the 1978 Cougar, are described and discussed in the present chapter. Since the antennas used are the same as in Chapter V, similar designations will be used here to represent the test antennas. The sensitivity, effective C and Q of each test antenna, given in the following sections, were obtained in a manner described in sections 2.5 and 2.6.

6.1 Results for Six Windshield Antennas (No.'s 3-8)

Sensitivity: The sensitivities of six windshield antennas measured at 3 selected air signal frequencies (i.e., commercial broadcast signal frequencies) in the AM band are shown in Table 10. The measured sensitivities at the same frequencies of the reference $\lambda/4$ antenna ($\lambda/4$ long at 98 MHz) are also shown in Table 10. The sensitivity data for the reference antenna were taken concurrently with each of the six test antenna data sets. These reference values were found to repeat, at each of three frequencies used, within an acceptably small range (within a dB). Therefore, an average of the reference values were calculated at each frequency, and are used to represent reference sensitivity in Table 10.

C and Q: The effective C and Q values for the six antennas, measured at three selected frequencies are shown in Table 11. It is believed that the C and Q values are primarily determined by the cabling used in the antennas.

6.2 Effect of the Linear Segments

Sensitivity, C and Q of the antenna no. 6 were measured after successive removal of the horizontal linear elements in a manner described in Section 5.4. The measured sensitivities of the antenna configurations 6-5 through 6-1 are shown in Table 12 for three selected frequencies. Note that at each frequency the antenna 6-5 through 6-2 have approximately equal sensitivity. The antenna

Antenna	Frequency in MHz		
	0.76	1.1	1.6
	Sensitivity in dBm		
Ref.	-61.3	-69.0	-76.0
No. 3	-68.0	-75.0	-82.0
No. 4	-68.0	-74.0	-83.0
No. 5	-67.0	-74.0	-82.0
No. 6	-67.0	-75.0	-82.0
No. 7	-68.0	-74.0	-82.0
No. 8	-66.0	-72	-80
Aver. Over 3-8	-67.3	-74.0	-81.8

Table 10. AM-band sensitivities of reference ($\lambda/4$-monopole antenna) and six windshield antennas on 1978 Cougar.

Antenna No.	Frequency in MHz					
	0.5		1.0		1.5	
	C pF	Q	C pF	Q	C pF	Q
3	99.90	138.36	104.30	103.70	99.70	81.49
4	85.60	193.32	89.60	121.64	83.00	109.22
5	81.10	163.33	85.70		100.00	139.31
6	84.10	163.25	99.40	130.60	93.20	110.64
7	88.80	116.75	96.40	124.18	92.40	99.00
8	84.50		89.20	171.54	83.70	137.17
Aver.	87.33	155.00	94.10	130.33	92.0	112.81

Table 11. AM-band C and Q for six windshield antennas on 1978 Cougar.

Antenna	Frequency in MHz		
	0.76	1.1	1.6
	Sensitivity in dBm		
Ref.	-61	-69	-76
6-5	-67	-75	-82
6-4	-67	-74	-82
6-3	-68	-74	-83
6-2	-68	-73	-83
6-1	-77	-81	-89
Aver. Over 6-5 to 6-1	-70	-75	-84

Table 12. AM band sensitivities of reference ($\lambda/4$-monopole antenna) and five configurations of antenna No. 6 on 1978 Cougar.

6-1 shows a noticeable deterioration of the sensitivity which is attributed to the fact that for this configuration the effective element length becomes too short.

Measurements of C and Q were performed only for the original configuration (6-5) of antenna no. 6 (see Table 11). This is because C and Q are essentially determined by the given lead cable of the antenna, and not by the antenna itself. Since all the antennas, 6-5 through 6-1, were fed using the same lead cable, this C and Q remained constant and further measurements were unnecessary.

6.3. T-Shaped Antenna

As discussed in Section 5.5, the T-shaped antenna was the final configuration, designated as 6-1, obtained from antenna no. 6; two modified versions of antenna 6-1, designated as 6-1-1/2 and 6-1-1/4, were also obtained by successively reducing the length of the horizontal element to half of its length. Table 13 shows the sensitivity values obtained for the three antenna configurations. It is found that the sensitivity of the T-shaped antenna is not appreciably affected by the range of element length reduction used. The effective C and Q of the antenna were not measured for reasons stated in Section 6.2.

6.4 Discussion

On the basis of the results presented above, the following comments can be made with regard to the AM band performance of windshield antennas on 1978 Cougar:

i) The six antennas with variable parameters have essentially the same sensitivity which is about 6 dB less than that of the $\lambda/4$-reference antenna. Although the measured C and Q were found to depend on the specific antenna used, the observed variations are believed to be caused by the antenna cabling and not by the antenna configuration itself.

Antenna	Frequency in MHz		
	0.76	1.1	1.6
	Sensitivity in dBm		
Ref.	-61	-69	-76
6-1	-77	-81	-89
6-1-1/2	~-77	~-81	~-89
6-1-1/4	-76	-82	-89

Table 13. AM-band sensitivities of reference (λ/4-monopole antenna) and three configurations of T-shaped antennas on 1978 Cougar.

ii) Antennas 6-5 through 6-2 have almost equal sensitivity (within 1 dB) which varied from -4 to -6 dB (relative to the $\lambda/4$-reference antenna) within the AM band. Maximum reduction of sensitivity occurs with antenna 6-1 whose relative sensitivity varies from -11 to -16 dB within the AM band.

iii) Within the range of values used, the reduction of element length does not significantly affect the sensitivity of the T-shaped antenna.

VII. WINDSHIELD ANTENNAS VERSUS CAR LINE

The performance of windshield antennas mounted on 1978 Cougar has been discussed in Chapters V and VI. In order to evaluate the effects of the vehicle, appropriate FM and AM radiation and impedance data were collected with windshield antennas installed on a 1978 Mark V (with sunroof and bench seat), two 1978 Grand Prix's (one, with sunroof and bench seat; the other, without sunroof and with bucket seats), and a 1977 Chevrolet Monte Carlo (without sunroof and with bench seat). For the purpose of completeness, data for windshield antenna 6-2 (which provides optimum AM and FM performance) on 1978 Cougar (with sunroof and bench seat) are also presented in this chapter.

During the course of the investigation, discussed in the present chapter, it was observed that the FM radiation patterns and AM sensitivities of windshield antennas were quite sensitive to car line changes. However, FM impedance and AM C and Q results for different car lines were very similar to the Cougar data discussed in earlier chapters; therefore these results will not be discussed here.

7.1 Test Results

Measured FM band horizontal radiation patterns of windshield antennas on five car lines are shown in Figs. 34-38. The results indicate that the windshield antenna tends to provide best coverage in the forward region of the car. The corresponding pseudo-gains of the antennas obtained from the measured patterns are shown in Table 14. The AM sensitivity results for the windshield antennas on the same car lines are shown in Table 15.

Results shown in Tables 14 indicate that the FM pseudo-gain of the windshield antenna on 1978 Cougar is typically 2-3 dB more than that obtained with

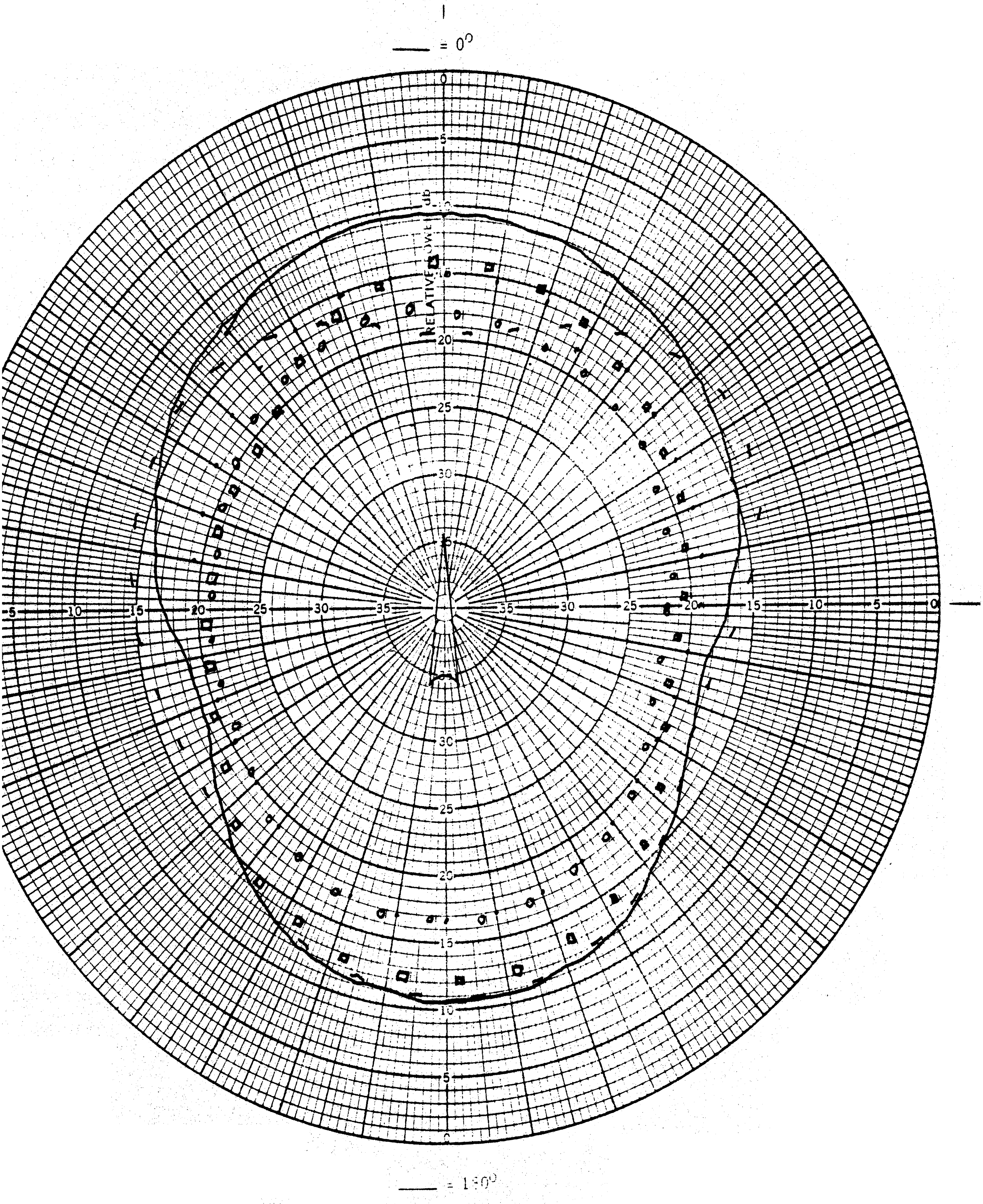


Figure 34. Radiation patterns of windshield antennas on various cars measured at 88 MHz. ——— 1978 Cougar, ···· 1978 Mark V, ---- 1977 Monte Carlo, ∘∘∘∘ 1978 Grand Prix (black) ▫▫▫▫ 1978 Grand Prix (blue).

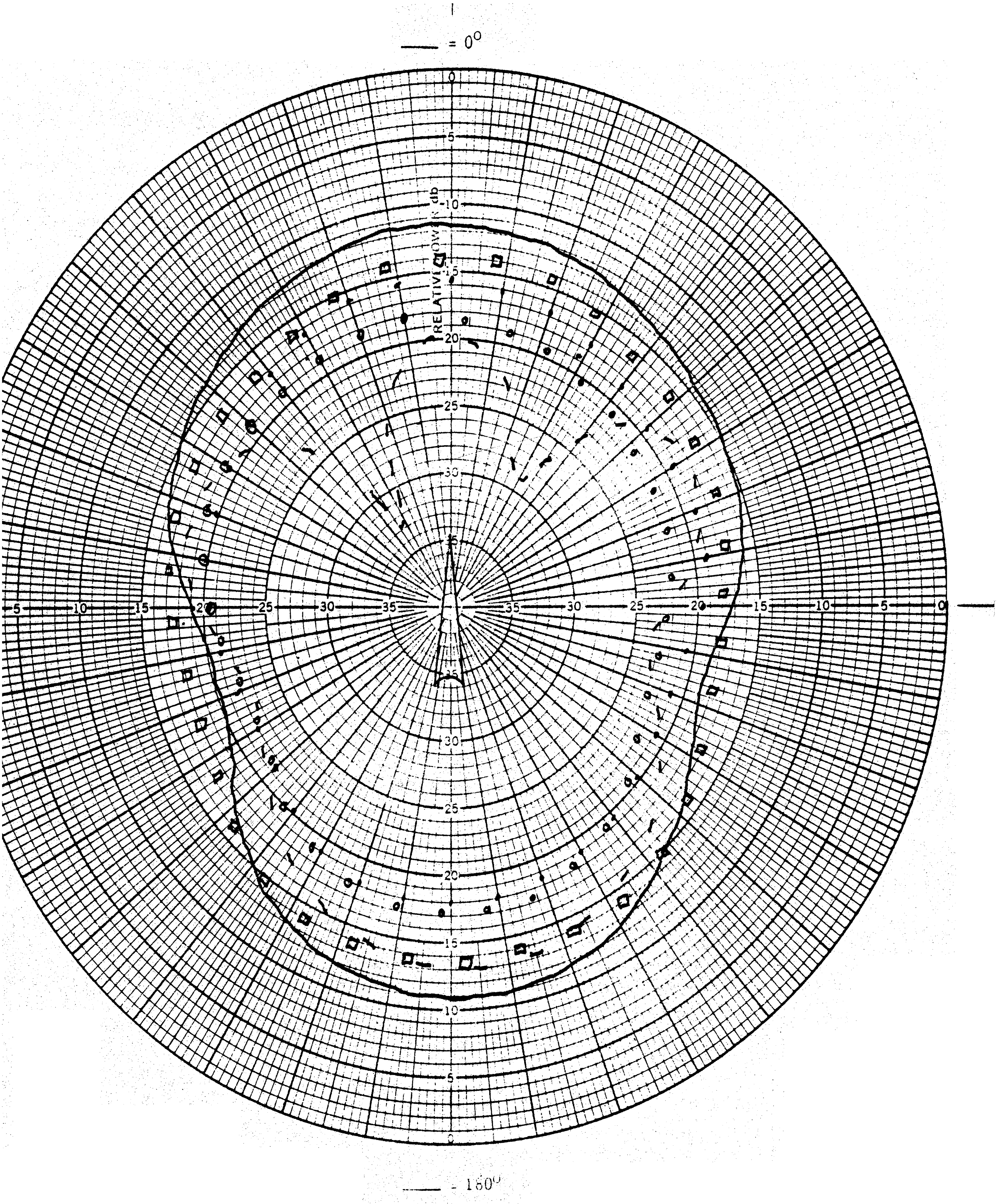


Figure 35. Radiation patterns of windshield antennas on various cars measured at 93 MHz. —— 1978 Cougar, ···· 1978 Mark V, ---- 1977 Monte Carlo, oooo 1978 Grand Prix (black) ▫▫▫▫ 1978 Grand Prix (blue).

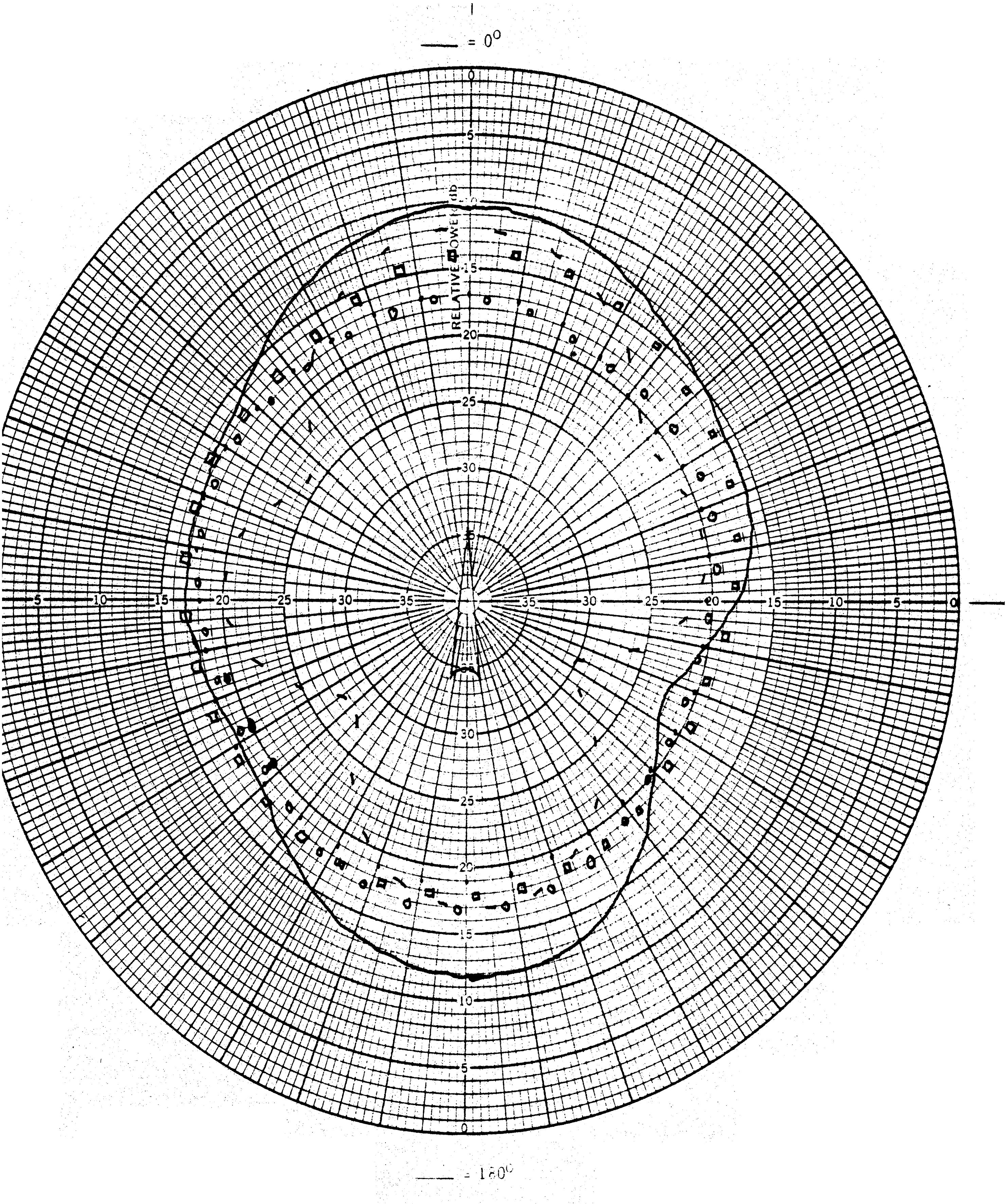


Figure 36. Radiation patterns of windshield antennas on various cars measured at 97.8 MHz. ——— 1978 Cougar, ···· 1978 Mark V, ---- 1977 Monte Carlo, oooo 1978 Grand Prix (black) ▫▫▫▫ 1978 Grand Prix (blue).

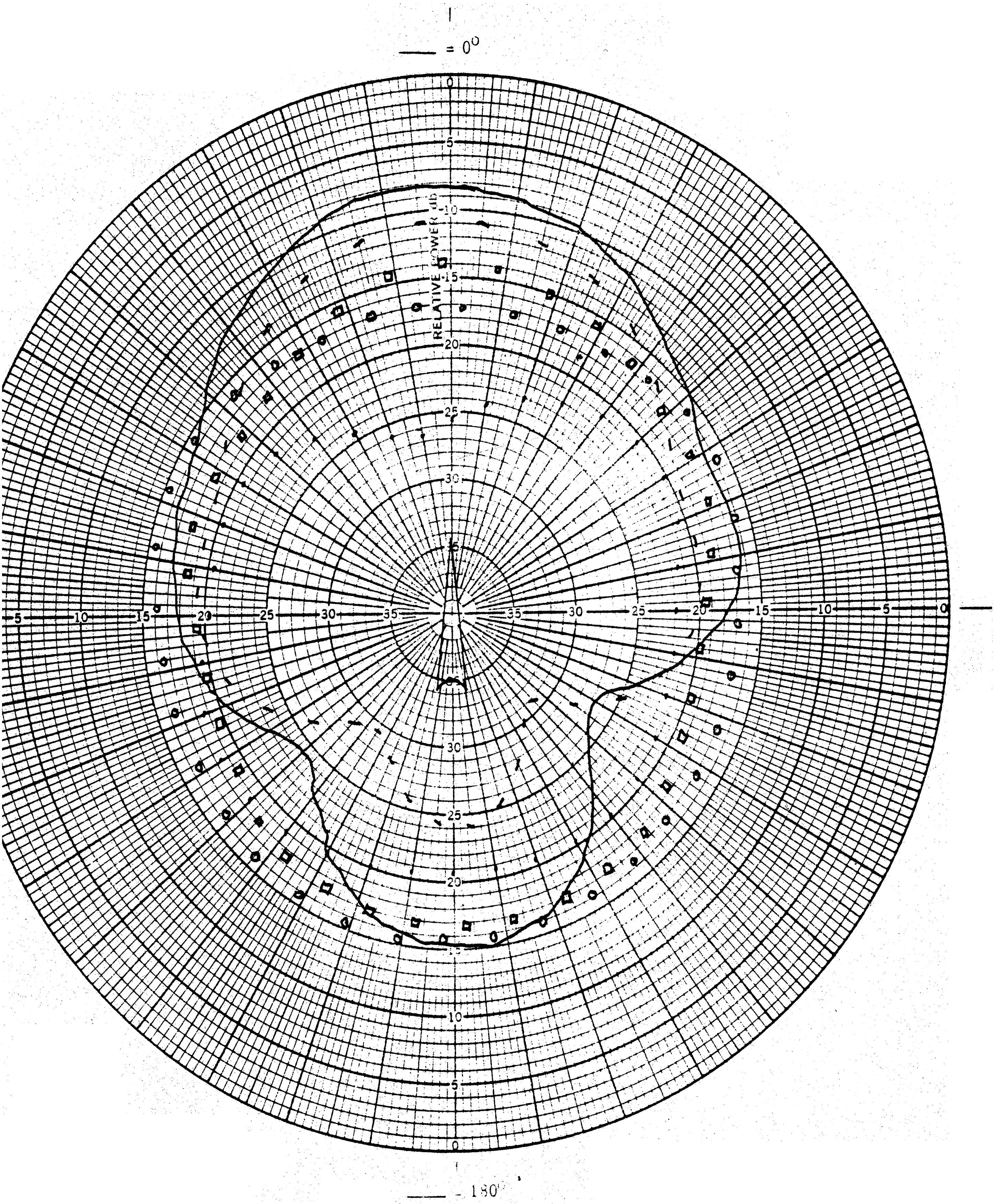


Figure 37. Radiation patterns of windshield antennas on various cars measured at 102.9 MHz. ——— 1978 Cougar, ···· 1978 Mark V, ---- 1977 Monte Carlo, oooo 1978 Grand Prix (black) □□□□ 1978 Grand Prix (blue).

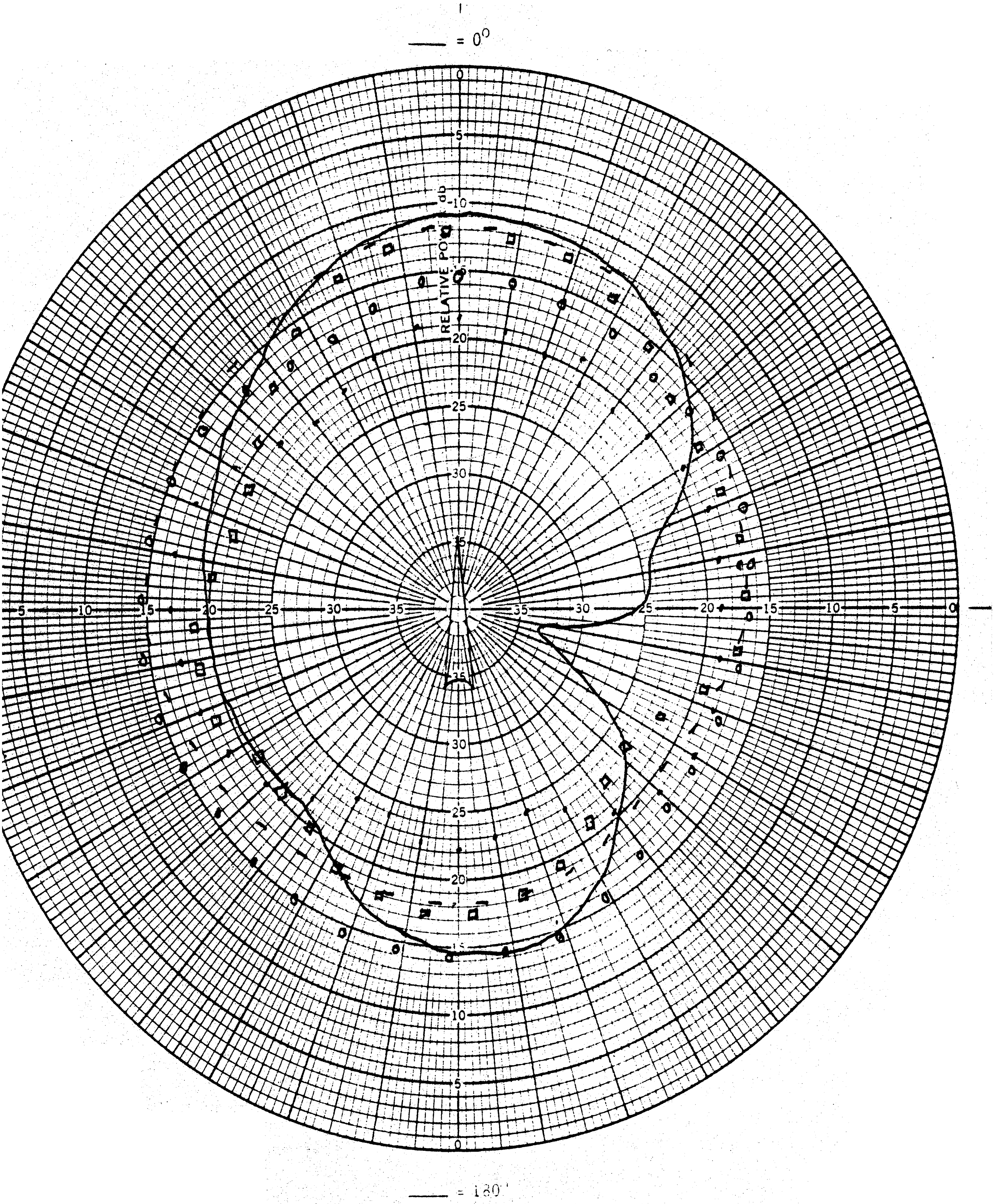


Figure 38. Radiation patterns of windshield antennas on various cars measured at 108 MHz. —— 1978 Cougar, ···· 1978 Mark V, ---- 1977 Monte Carlo, oooo 1978 Grand Prix (blue) □□□□ 1978 Grand Prix (blue).

Frequency MHz	Car Line				
	78 Cougar with sunroof	78 Mark V with sunroof	78 Grand Prix with sunroof	78 Grand Prix without sunroof	77 Monte Carlo without sunroof
	Pseudo-gain in dB				
88	-8.50	-13.18	-10.41	-15.04	-9.59
93	-6.53	-11.31	-8.19	-12.52	-10.91
98	-5.94	-10.18	-9.10	-11.16	-9.79
103	-5.93	-12.67	-8.68	-7.26	-8.30
108	-7.11	-10.97	-8.54	-7.59	-6.54

Table 14. Pseudo-gain (relative to $\lambda/4$-monopole antenna) versus frequency for windshield antennas on various cars.

Frequency MHz	78 Cougar with sunroof	78 Mark V with sunroof	78 Grand Prix with sunroof	78 Grand Prix without sunroof	λ/4-monopole
0.76	-68	-68	-70	-70	-61
1.1	-73	-77	-29	-29	-69
1.6	-83	-84	-87	-86	-76

Table 15. AM field strengths measured from standard broadcast stations with windshield antennas on various cars. Results for the reference antenna are also shown.

other car lines, Ford or competitive cars. The Cougar windshield antenna also provides the best AM performance as can be seen from Table 15. It is speculated that the poor FM performance associated with the 1978 Mark V (Table 14) is related to its crash pad installation.

7.2 Discussion

Both FM and AM sensitivity of windshield antennas have been found to depend on the car line used. The impedance, C and Q of the antennas do not vary appreciably with car lines. Our investigation of the effects of car lines on the performance of windshield antennas is not conclusive. However, results obtained in the AM band provide sufficient evidence to recommend the use of an antenna with two horizontal elements (one loop). It would be advisable to continue the AM investigation to correlate AM windshield antenna performance with both the height and width of the windshield.

VIII. MISCELLANEOUS DATA

To assist in further evaluation of the windshield antenna concept three additional sets of results are described in the present chapter. These results pertain to the reception of arbitrarily polarized signals, the reception of air signals from commercial FM radio stations and the effect of windshield wipers.

8.1 Variable Polarization

Since the signals from commercial FM radio stations are generally elliptically polarized, it was reasoned that it would be desirable to measure the response of the windshield antenna with a rotating linearly polarized incident signal . A laboratory controlled variable linearly polarized signal was obtained by rotating the transmitting antenna (log-periodic dipole mounted so that its boom was horizontal to the ground) about its boom axis. With the transmitting antenna rotating, the pattern of the windshield antenna was taken by rotating the vehicle in the horizontal (azimuthal) plane as noted in Chapter 2. The rotational rate of the vehicle was chosen sufficiently less than that of the transmitting antenna so that all senses of linear polarization were received by the test antenna during each 10 degrees of horizontal rotation of the vehicle. The transmitting antenna being located at a height of 12' above ground, it can be seen from Tables 1(b) and 2(b) (given in Chapter 3) that the windshield antenna was immersed in an E-field of approximately equal intensity for both vertical and horizontal polarizations.

Fig. 39 shows a typical polarization response for a windshield antenna on a 1978 Cougar (with dash out) measured at 98 MHz under laboratory conditions. The maximum and minimum levels of Fig. 39 are associated with the vertically and horizontally polarized E-fields, respectively. It is evident from Fig. 39 that the polarization response of the Cougar windshield antenna varies as a

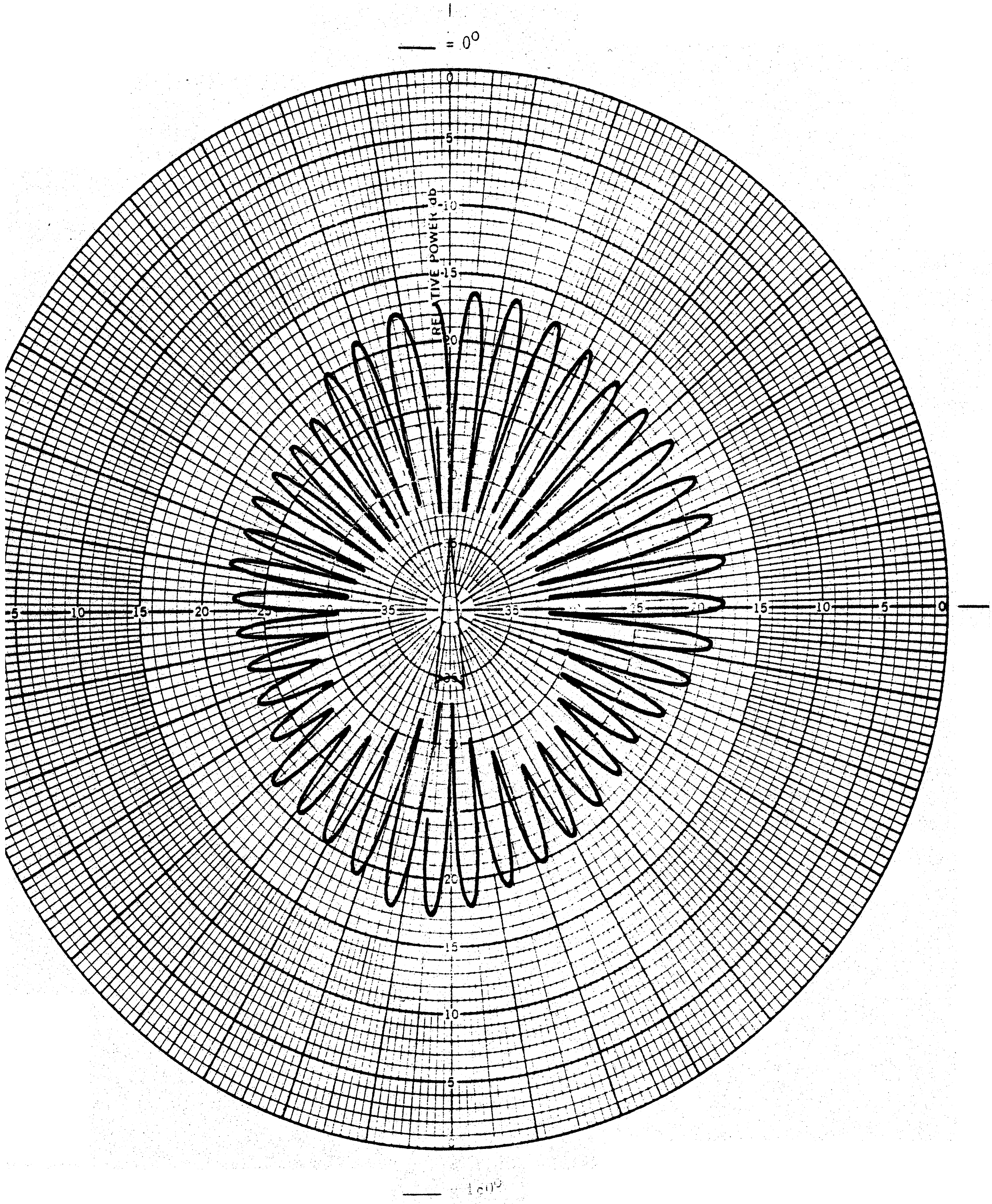


Figure 39. Polarization response of a windshield antenna on 1978 Cougar (dash out) measured at 98 MHz.

function of the azimuthal position of the vehicle relative to the RF source. For example, it can be seen from Fig. 39 that the vertical and horizontal polarization responses of the antenna in the forward and rear directions of the car differ by approximately 15 dB; similar responses in the $\pm 120^0$ directions relative to the front of the car differ by about 5 dB.

8.2 Windshield Antenna Patterns with Air Signals

Horizontal radiation patterns of windshield antennas on 1978 Cougar and 1977 Chevrolet Monte Carlo were measured using the air signals from a local FM radio station. The results are shown in Fig. 40. Comparison of these results with the appropriate results shown in Fig. 35 for the same car lines using a vertically polarized RF source, exemplifies the pattern variations that may exist in the case of elliptically polarized signals.

8.3 Effect of Windshield Wiper

Figs. 41 and 42 illustrate the effect of windshield operation on the performance of the Cougar and competitor windshield antennas, respectively. During this study no attempt was made to reduce the stronger wiper interference associated with the Ford vehicle. However, this problem was addressed as a part of a previous study [

8.4 Discussion

The results presented in this chapter lead to the following comments with regard to the FM band performance of windshield antennas on 1978 Cougar:

i) The response of the antenna to the vertically polarized signals can be 15 dB larger than that to the horizontally polarized signals. The polarization response of the antenna is directional.

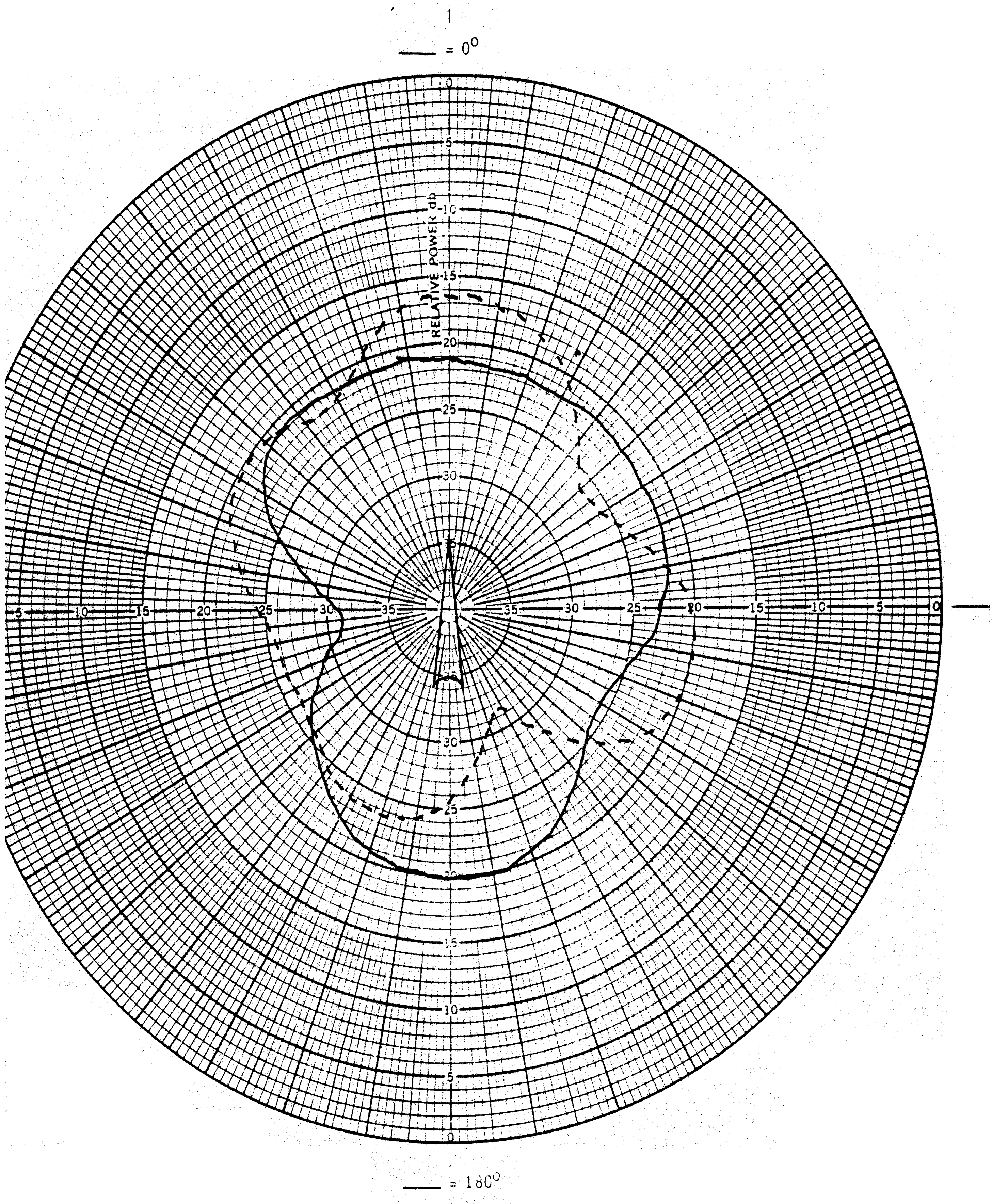


Figure 40. Windshield antenna radiation patterns, when receiving air signals at 98 MHz. —— 1978 Cougar (dash out), ---- 1977 Monte Carlo (plastic dash).

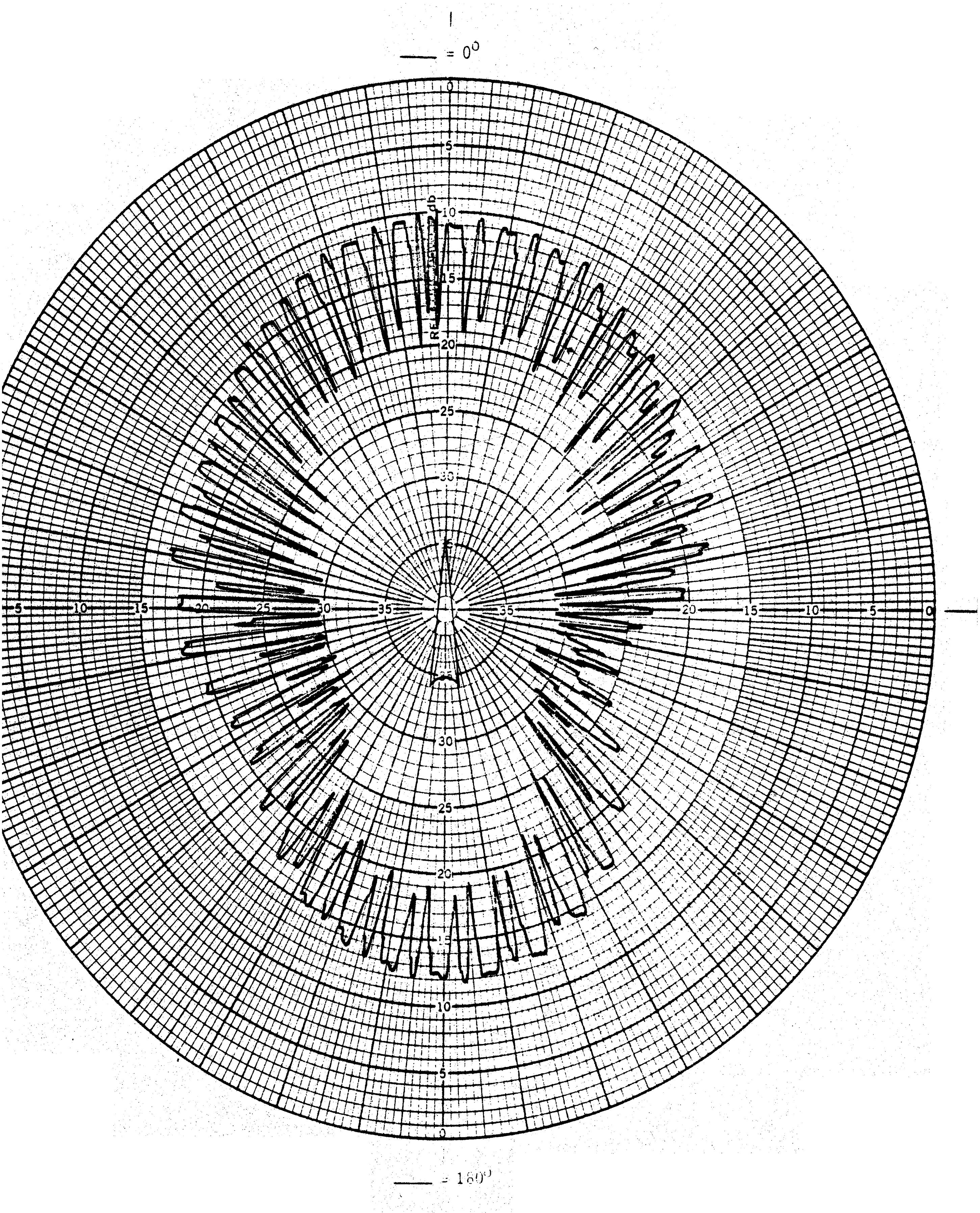


Figure 41. Radiation pattern of windshield antenna on 1978 Cougar (dash fastened) with windshield wipers running. Frequency = 97.8 MHz.

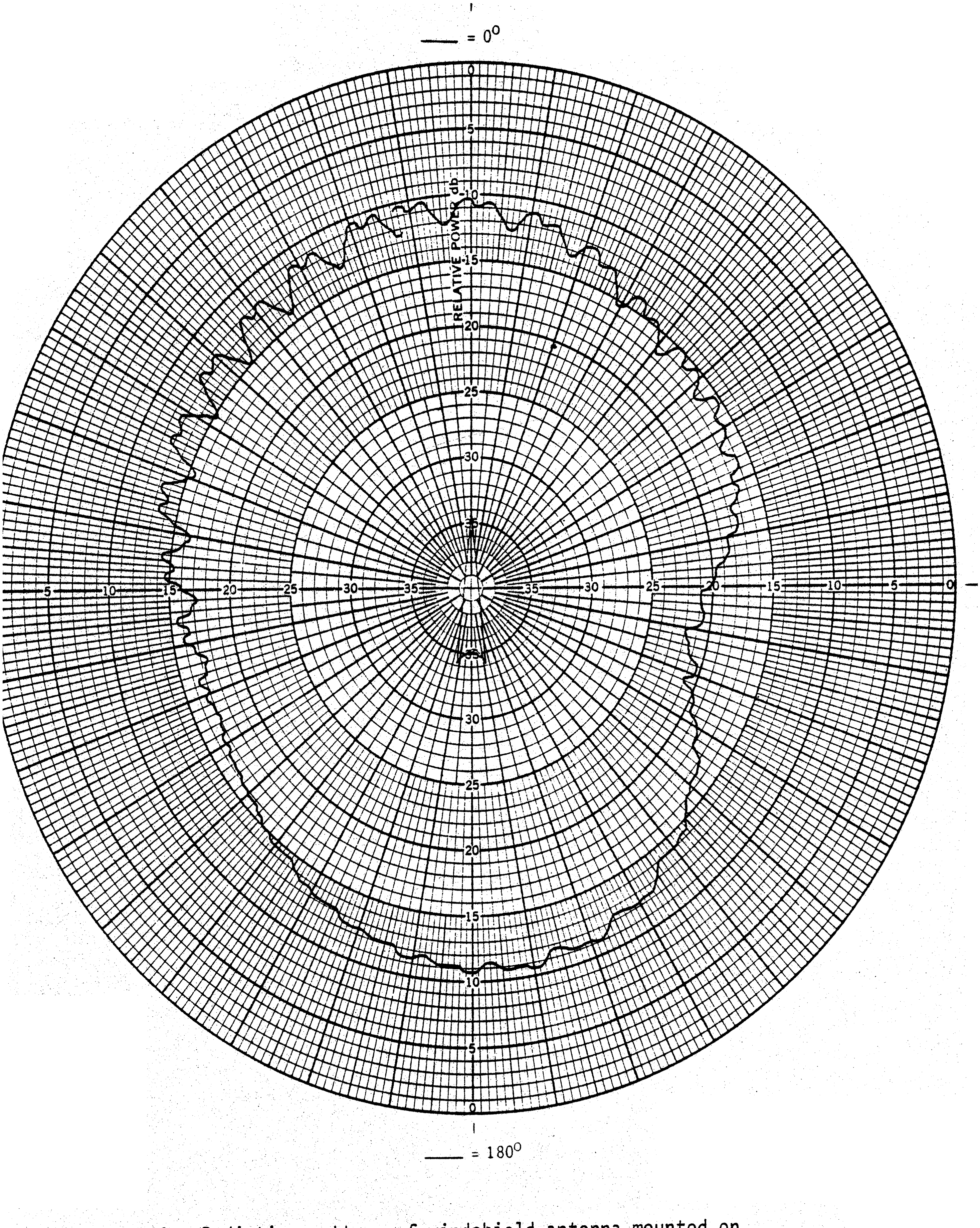


Figure 42. Radiation pattern of windshield antenna mounted on 1978 Grand Prix (black) with windshield wipers running. Frequency = 98 MHz.

ii) The patterns obtained with elliptically polarized air signals can be significantly different than those obtained with vertically polarized signals.

iii) Motion of the windshield wiper introduces significant variation in the antenna patterns.

IX. CONCLUSIONS

Based on the results presented in earlier chapters, the following observations are made with regard to the performance of windshield antennas:

i) In the FM band the directional characteristics of the windshield antenna are such that the pattern has maxima along the longitudinal directions of the car, the maximum in the forward direction being larger.

ii) The six windshield antennas (with variable parameters) on 1978 Cougar provide similar FM and AM performance. Generally, with most of the antennas, a maximum relative pseudo-gain of -6 dB occurs at about 98 MHz; all antennas, with the exception of one, maintain a VSWR within 3.5 to 6.5 in the FM band. Typically, AM sensitivity of each antenna is about 6 dB less than that of the reference antenna.

iii) The performance of a multi-element antenna is not significantly affected by the change of total element length, although it has been found that the antenna no. 6-2 provides optimum FM and AM performance. The T-shaped antenna appears to have more FM band gain than the multi-element antennas.

X. RECOMMENDATIONS

To optimize the performance of windshield antennas, it is recommended that further research be addressed to the following problems:

i) Relate the FM performance of the antenna to the need for a metal crash pad and its grounding, and to the size and location of the crash pad with respect to the windshield.

ii) Study the effects of car size and car interior on the performance of the windshield antenna.

iii) Study in more detail the effects of the height and width of the windshield on the AM performance of the antenna.

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