1. Belrose, J. S.

INTERIM REPORT NO. 2

2. THE EFFECTS OF RE-RADIATION

FROM

HIGHRISE BUILDINGS, TRANSMISSION LINES, TOWERS AND OTHER STRUCTURES

UPON AM BROADCASTING DIRECTIONAL ARRAYS

February 2, 1978

INTERIM REPORT NO. 2

THE EFFECTS OF RE-RADIATION FROM HIGH-RISE BUILDINGS, TRANSMISSION LINES, TOWERS AND OTHER STRUCTURES UPON AM BROADCASTING DIRECTIONAL ARRAYS

(DOC Project No. 4-284-15010)

CONTENTS

2 February, 1978

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Department of Communications

1. INTRODUCTION

This is the second interim report describing a research investigation (Departmental Project No. 4-284-15010) into the effects of re-radiation from high-rise buildings, transmission lines, towers and other structures upon directional AM broadcast antennas. It describes work that has been carried out during the period 26 October, 1977 until 2 February, 1978 and is prepared for the sixth meeting of a Working Group (chaired by DOC) on Re-Radiation Problems in AM Broadcasting scheduled for 2 February, 1978. Reference should be made to the first interim report before reading this one.

The purpose of the research project is:

(a) To assess the magnitude of the re-radiation problem by experimental antenna modelling measurements, employing initially the NRC antenna modelling range (known as the Ship Range Facility) at fixed frequencies (scale model frequencies of 300 and 600 MHz were used); and employing swept frequency techniques to gain additional insight into properties of the re-radiators utilizing the radio anechoic chamber at the University of Toronto, a scale factor of 1000 was used (thus, the available frequency range of 450 to 1050 MHz scales to cover the lower part of the AM broadcast band 450 to 1050 kHz).

(b) To numerically model the situation, to evaluate various theoretical, computational approaches to the problem from the point of view of accuracy compared to experiments, complexity, etc since computational cost of analysis employing computers is of major concern. The ultimate objective is to predict pattern distortion effects.

(c) To evaluate possible ways and means of alleviating such problems.

This report describes work concerned with objectives (a) and (b). While it was not intended to begin a serious investigation concerned with objective (c) before next fiscal year (1978/79), Appendices VII and VIII of the first interim report contain information and suggestions that are to our knowledge unique and could lead to valuable and practical methods of control of re-radiation from power lines, but this matter needs further detailed investigation.

As in the first interim report, the format of this report is the same. That is, the main body of the report only briefly summarizes the experimental and analytical work carried out, since the detail is contained in the appendices of the report. Appendix I summarizes the work carried out by the NRC; Appendix II the work carried out at the University of Toronto; and Appendix III describes a numerical modelling approach which predicts the effect of re-radiation from a single thin tower (work carried out at CRC).

Since the magnitude of the re-radiation effect can be large, and since the CBC's experience at the CBL/CJBC site near Hornby, Ontario seems to show that re-radiation can affect an omni-directional broadcast antenna, the CBC (letter dated 12 January, 1978) have expressed concern that this kind of situation should be included in the study. While such experimental model measurements have not so far been made, it will be clear in Appendix III that the numerical modelling work can certainly predict the effect of re-radiators on the pattern of an omni-directional antenna, since naturally any computational approach taken would not be restricted to a particular directional array (an omni-directional radiator is the limiting situation of a directional array).

2. PROGRESS TO DATE

The project is still without the management and technical direction by a Senior Antenna Engineer (or research scientist) with a background in antennas and radiating systems, however, Dr. R. Chugh, a Post-Doctorate Fellow, with an antenna engineering background acquired at the University of Manitoba, has joined the Directorate in October, 1978. He is actively working on numerical approaches to the problem (see Appendix III).

2.1 NRC Work

The NRC in this reporting period (see Appendix I) have investigated the effects of two buildings, for various distances between the buildings (centre-to-centre spacings of 4 inches (100 feet) to 36 inches (900 feet) employing a scale model frequency of 300 MHz), and for various orientation of this centre-to-centre line with respect to the direction of the main beam of the directional array. In all cases, the distance from the mid-point between the buildings was positioned at 2 metres (2000 feet) in the direction of the main beam from the array and the building heights were 8 inches (200 feet) which for a 4-inch (100 foot) square building was previously determined to produce maximum re-radiation (quarter wave resonance). A rather simple procedure (applicable for thin quarter wave monopoles) was used to predict the pattern degradation caused by the buildings with reasonable success.

The measurements for a single building were also extended to greater distances of the building from the antenna array, by employing a scale model frequency of 600 MHz (rather than 300 MHz as reported in Interim Report No. 1). The results of this work are plotted in Figure 8 of Appendix I, which shows the scatter signal (dB) relative to the main beam from the array, as a function of distance of the building from the array, for distances of 0.5 metres (1000 feet) to 3.0 metres (4000 feet). The scatter signal decreased from -12 dB to -25 dB over this range of distances; however, as noted in the report on the work (top of page 5, Appendix I), the interference pattern produced by the broadcast array and the scatterer for these greater distances (4 to 6 wavelengths or 3000 to 4000 feet) contain rapid fluctuations and reading the scatter value in the array minimum becomes difficult.

The scatter from thin monopoles was also extended to include monopoles of greater height, such that quarter wave and three-quarters wave resonance effects in the scatter signal were observed. These results are theoretically predicted in Appendix III.

2.2 University of Toronto Work

The experimental arrangement for the University of Toronto work has been changed, such that the results presented in this report in Appendix II are easier to interpret. The transmitting antenna, which is directed towards the re-radiators (a power line or two buildings) is rotated with the re-radiator(s) and, therefore, as in the case of the NRC work, the distant receiving antenna measures the pattern of transmitting antenna for a particular frequency with and without re-radiators. As before, the received signal in a swept frequency experiment, for various experimental arrangements (as shown in Figure 1 for power lines and Figure 12 for two buildings) with and without re-radiators can be measured.

The results show that re-radiation from power lines can be very strong and highly directive near the resonant frequencies of the system. Two situations are noted: "null filling" where the frequency is chosen such that re-radiation is strong (the re-radiating system is resonant), and "specular reflection". In the latter situation, a frequency is chosen such that the re-radiating system is not resonant, but strong effects are observed affecting the main beam of the array when the re-radiating system, a power line, is so orientated that "specular reflection" from it occurs (incident and reflected angles of incidence are equal). The measurements show that isolation of one or two towers from the sky wires introduces strong new resonances, while reducing somewhat existing resonances. The work has also revealed an important new phenomena. The power-carrying wires, heretofore neglected in the experimental model studies, serve to conduct power away from localized resonances, so that such wires would have to be taken into account in analyzing detuning techniques.

A word of caution should, however, be injected here. It is very difficult to realistically model a power line complete with power-carrying wires and so the question remains as to whether this effect would be noticeable in the real-world situation with ground conductivity importantly affecting the magnitude of the resonances and with real power-carrying wires connecting generator and load over long hydro lines. Standing waves are certainly invariably found along hydro lines, and in some instances, RF chokes have been employed to isolate sections of the line, but as one might expect, have increased the amplitudes in the affected sections of the line (reference comments in letter from A.G. Day, CAB, dated 13 January, 1978). Little is known about causes and cures, the efforts having been concentrated on the towers and sky wires. If power-carrying wires are important, this is an additional complexity to the problem.

Re-radiation from single quarter-wave buildings, at 2 km from the transmitting antenna, is about 20 dB below the level of the signal incident upon it. Resonant re-radiation from a pair of such buildings is about 8 dB higher in level. It is clear that groups of buildings could have a profound effect on the radiation patterns of nearby AM broadcast antennas.

2.3 CRC Work

Finally, CRC work has been directed towards detailed computational approaches to calculate the effect of single thin towers (TV towers or other tall communication towers) on the directional pattern of AM broadcast antennas. The NRC measurements provide the validation of the computational work. The conclusions drawn from the present work which is for a single tower are: the scattered field from the tower is dependent upon the tower height and its distance from the broadcast array, and this distance would have to be more than 24 wavelengths* (4½ miles for a broadcast frequency of 1000 kHz) in order to have a field of less than -40 dB in the null direction. Concerning the dependence upon the height of the tower, the scattered field has two peaks at heights of about 0.225 and 0.770 wavelengths.

The recently published paper by Alford (1977) concerns re-radiation from the insulated guys used to support a tall (1100 feet) tower. While the method employed seems to be novel, i.e., the guys

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* neglecting ground conductivity effects on the efficiency of the re-radiator and on propagation of the ground wave. These effects will have to be addressed later in the research programme.

together with the strain insulators are treated as a high pass filter, the paper like other ones by this author concerns detuning alone rather than the total effect, viz. the effect of the guyed tower on the directional pattern of the AM broadcast array ... although admittedly, tower and guy detuning is related to re-radiation effects. The paper however brings an important point to mind, viz. that when we consider detuning of structures, the guys will have to be taken into account. In fact, perhaps the guys could be used to detune the tower ... an idea not suggested by the work of Alford. This again is perhaps an area where a fresh approach might be beneficial, as opposed to the "time honoured" method of resonant sleeves or "skirts" for tower tuning.

3. Future Work This Fiscal Year

Since the NRC facility is an outdoor ground level pattern range, it cannot be used during winter months. Therefore, work during the remainder of this fiscal year will be spent in organizing the measured patterns and in constructing new models (e.g., a more realistic model power line) for a new measurement program to be carried out next spring and summer.

The University of Toronto experimental work is not restricted in this way, nevertheless, the remainder of the contract period (until 31 March 1978) will be spent mainly in work on antenna modelling theories as well as in processing experimental data already acquired and of course, in writing the final report on this phase of the work done.

The direction of future work at CRC will be to extend the numerical analysis to include the effect of more than one tower, by employing more efficient methods for reducing the integral equations to matrix equations suitable for computational calculation (already at the time of writing this seems to be well in hand); and to consider thick towers since buildings undoubtedly radiate as thick monopoles.

As mentioned in the first interim report, the purpose of these documents is to stimulate feedback from members of the Working Group and their associates, since this feedback could alter the direction of future work.

REFERENCES

Alford, Andrew, "Re-Radiation from Tall Guyed Towers Located in a Strong Field of a Directional AM Radio Station", IEEE Trans. on Broadcasting, BC-23, 97-106, December 1977

INTERIM REPORT ON NRC WORK

Introduction

This report covers the experimental work carried out from 1 October 1977 to 30 November 1977 and is a continuation of the scale model tests described in the first interim report dated 11 October 1977.

The procedure used for measuring the amount of re-radiation produced by such items as buildings and transmission lines was outlined in the first report but for completeness will be briefly repeated here.

A two element scale model array is used to produce a figure-of-eight pattern with minima approaching -40 dB. A source of scattered energy is next placed in the vicinity of the array and a new pattern plotted. Energy radiated at the azimuths of the original minima is assumed to be caused entirely by the item under test. This work was carried out on an outdoor ground level pattern range containing a flush mounted 20-foot diameter turntable. Scale model frequencies of 300 and 600 MHz were used. Fig. 1 illustrates the coordinate system used to locate the scatterers with respect to the array.

Re-Radiation from Buildings

As in Interim Report #1, dimensions given within brackets refer to full scale heights or distances.

Earlier tests with 4-inch (100 foot) square buildings at 300 MHz indicated that a building height of 8 inches (200 feet) produced maximum re-radiation. This is in fact the dimension at which the building behaves as a quarter wave monopole. This height was used to investigate the pattern behaviour when two closely spaced buildings were in the vicinity of the broadcast array.

Two buildings were positioned at a distance S = 2 meters (2000 feet) as shown in Fig. 2. Measurements were made with the two buildings at various spacing from each other along the lines indicated in the figure, i.e., 1 - 1, 2 - 2, 3 - 3, and 4 - 4. It will be noted that in three of the cases, as the building spacing is increased, one of the buildings comes closer to the array while the other moves away. When the models are placed along the line 1 - 1, their distances to the center of the array remain equal. It is this latter arrangement which was investigated in greater detail. Building center-to-center spacings ranging from 4 inches (100 feet) to 36 inches (900 feet) were used.

Fig. 3 shows a pattern of the array only, i.e., no scatterers in the vicinity. For reference purposes, Fig. 4 is a plot of the array pattern when only one building is located at the point shown in Figure 2. Two buildings were then used to obtain a series of patterns which are summarized in Fig. 5. Here the scatter signal is plotted against building spacing along the line 1 - 1. It can be seen that at a center-to-center spacing of about 20 inches (500 feet) there is a very pronounced dip in the scatter signal.

It is now apparent, with the help of 20 - 20 hindsight, that more measurements should have been made with spacings between 16 and 24 inches to produce a more complete plot.

The reduction in scatter into the array null at the 20-inch spacing can be explained as follows. Since the two buildings are placed symmetrically with respect to the array, the scatter signals from them will be equal in magnitude and phase. At a spacing of 20 inches, the buildings are half a wavelength apart and the scatter into the array nulls will cancel.

As the buildings are further separated, the spacing will approach a full wavelength at 40 inches and the scatter signals will add in phase to produce a total that should be about 6 dB higher than the scatter from a single building. This is indeed what happens experimentally as can be seen in Fig. 5.

Also shown in Fig. 5 is a plot of expected scatter signal calculated as outlined in Appendix A.

For spacings much less than half a wavelength, the scattered energy approaches the value obtained for a single building; in fact, the total radiation patterns are almost identical. See Fig. 6 where the case of two buildings at 8 inches (200 feet) center-to-center is shown and compare this with Fig. 4. The expression derived in Appendix A clearly shows this. As the spacing decreases, the array factor 2 cos $\pi d/\lambda$, approaches a value of 2. At the same time, the factor containing the mutual impedance between the two scatterers approaches 0.48 giving a combined value of 0.96 - very close to unity.

As a final indication that, knowing the effective mutual impedances involved, one can treat the building problem strictly as an array to find the total pattern, Fig. 7 is presented. This figure shows the experimental pattern for the case of two buildings with a center-to-center spacing of 12 inches (300 feet). Added to the plot are points which have been calculated following the procedure outlined in Appendix B. Taking into account the fact that, for some unknown reason, the experimental plot is not symmetrical about the $\pm$ 90 degree axis as it should be, agreement with the calculated values appears to be close enough to warrant some confidence in the approach.

Single Building at Various Distances

Previous measurements on buildings were all carried out at 300 MHz. This allowed a maximum separation from the broadcast array of 3 wavelengths on the turntable. In order to accommodate more distant pisitions of a building, a frequency of 600 MHz was adopted. A 2-inch (100 foot) square, 4-inch (200 foot) high building was placed at various distances along a line 90 degrees from the array null, i.e., ϕ = 90 in Fig. 1. A plot of scatter signal against distance is shown in Fig. 8. Also on the same graph is a line indicating calculated scatter using mutual impedance values from Krauss - Antennas, and Schelkunoff - Antenna's, Theory and Practice. Only three points have been calculated (for 1, 2 and 3 λ) as this is the extent of the information in the above references. At distances of 4 to 6 wavelengths, the interference pattern produced by the broadcast array and

and the scatterer contains rapid fluctuations and reading the scatter value in the array minimum becomes difficult.

Scatter from Thin Monopoles

Earlier measurements on a thin monopole (Interim Report #1) were done solely for the purpose of showing that a building behaved essentially as a fat monopole, however, it has turned out that thin monopoles themselves are of considerable interest. This is so when one considers such items as TV towers or other tall communication towers which in some cases are much more than a quarter of a wavelength high (at broadcast frequencies). With this in mind, measurements were made at both 300 and 600 MHz. The monopole was located at a distance of 2 meters and 1 meter, respectively. This translates to a full scale distance of 2000 feet in both cases. Angular position of the monopole was at ϕ = 90 degrees.

The results of these tests are shown in Fig. 9 where scatter signal is plotted against monopole height. Two peaks in the scatter signal are evident, occurring at heights which are close to a quarter of a wavelength and three-quarters of a wavelength.

Conclusions

It has been shown that a rather simple procedure can be used to predict pattern degradation caused by buildings. The examples given in this report are all for buildings of resonant height as the required self and mutual impedances could be readily found in the literature. There appears to be no reason, however, why the same procedure could not be applied to buildings of non-resonant height and/or irregular shape provided one had the appropriate impedance values. These are perhaps easier to measure than calculate.

An extension to the case of more than two buildings should also be possible.

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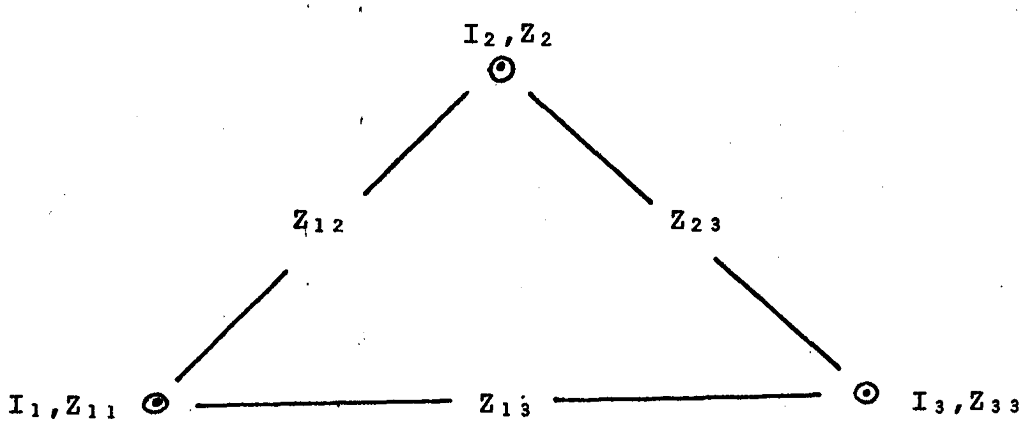
11 January 1978

APPENDIX A

Calculation of Scatter from Two Buildings

It has been shown in Interim Report #1 that a building of resonant height can be treated as a monopole to calculate the amount of scatter it will produce. The following analysis extends the procedure to the case of two buildings.

Consider an antenna and two scatterers as shown below.



I_1 - the current in the driven antenna;

I_2 and I_3 - the currents in the scatterers;

Z_{12}, Z_{13} and Z_{23} - mutual impedances as indicated;

Z_{11}, Z_{22} and Z_{33} - self impedances of the elements.

The following circuit equations can be written:

$$V = I_1 Z_{11} + I_2 Z_{12} + I_3 Z_{13}$$

$$0 = I_1 Z_{12} + I_2 Z_{22} + I_3 Z_{23}$$

$$0 = I_1 Z_{13} + I_2 Z_{23} + I_3 Z_{33}$$

where V is the driving voltage in element #1.

Solving for I_2 and I_3 in terms of I_1, we have

$$\frac{I_2}{I_1} = - \frac{Z_{12}Z_{33} - Z_{13}Z_{23}}{Z_{22}Z_{33} - Z_{23}^2}$$

$$\frac{I_3}{I_1} = - \frac{Z_{13}Z_{22} - Z_{12}Z_{23}}{Z_{22}Z_{33} - Z_{23}^2}$$

If we now consider the symmetrical case as used to plot Fig. 5, the following simplifications can be made:

$$Z_{12} = Z_{13} = Z_m$$

$$Z_{23} = Z_m'$$

$$Z_{22} = Z_{33} = Z_s$$

The equations for the currents I_2 and I_3 reduce to

$$i = \frac{I_2}{I_1} = \frac{I_3}{I_1} = -\left(\frac{Z_m}{Z_s}\right)\left(\frac{1}{1 + Z_m'/Z_s}\right)$$

The first factor gives the current induced when a single scatterer is present and the second factor is a correction brought on by the presence of the second scatterer. If the second scatterer is absent ($Z_m' = 0$), the expression reduces to $-Z_m/Z_s$ as it should.

Having calculated the current in each scatterer, account must now be taken of the fact that there are two of them forming an array. Only one direction, that of the broadcast array null, will be examined here as this is the only azimuth at which the scatter signal can be measured by itself.

Two elements each with a current i and spaced a distance d apart have an array factor of

$$2i \cos \frac{\pi d}{\lambda} \quad \text{in the end fire}$$

direction. The final scatter signal relative to the maximum of the broadcast array will then be given by the following expression.

$$-\frac{Z_m}{Z_s}\left(\frac{1}{1 + Z_m'/Z_s}\right) 2 \cos \frac{\pi d}{\lambda}$$

Values for Z_m and Z_m' were obtained from Antennas - J.D. Kraus, page 266. These values are for antennas much thinner than the scatterers in use, however, they are probably adequate for the purpose at hand which is to come to some understanding of how actual measured values come about. In this respect, the simple analysis outlined here appears to be adequate.

APPENDIX B

Calculation of the Radiation Pattern in the Presence of Two Buildings

It has been shown in Appendix A that in the symmetrical case under discussion the normalized currents induced in each of the buildings is given by

$$- \frac{Z_m}{Z_s} \left(\frac{1}{1 + Z_m'/Z_s} \right)$$

Since the two buildings form an array, their radiated field relative to their mid-point will be given by

$$- \frac{Z_m}{Z_s} \left(\frac{1}{1 + Z_m'/Z_s} \right) 2 \cos \left(\frac{\pi d}{\lambda} \cos \phi \right)$$

where d is the center-to-center spacing of the buildings.

The normalized field produced by the two elements in the scale model broadcast array will be equal to

$$\cos \left(\frac{\pi}{2} \cos \phi \right)$$

relative to the mid-point of this array.

The mid-point of the buildings is a distance s from the mid-point of the broadcast array and at an angle $\phi = 90$. The total radiated field relative to the center of the broadcast array is then equal to

$$\cos \left(\frac{\pi}{2} \cos \phi \right) - \frac{Z_m}{Z_s} \left(\frac{1}{1 + Z_m'/Z_s} \right) 2 \cos \left(\frac{\pi d}{\lambda} \cos \phi \right) \exp \left(j \frac{2\pi s}{\lambda} \sin \phi \right)$$

This is the expression used to calculate the points shown on Fig. 7.

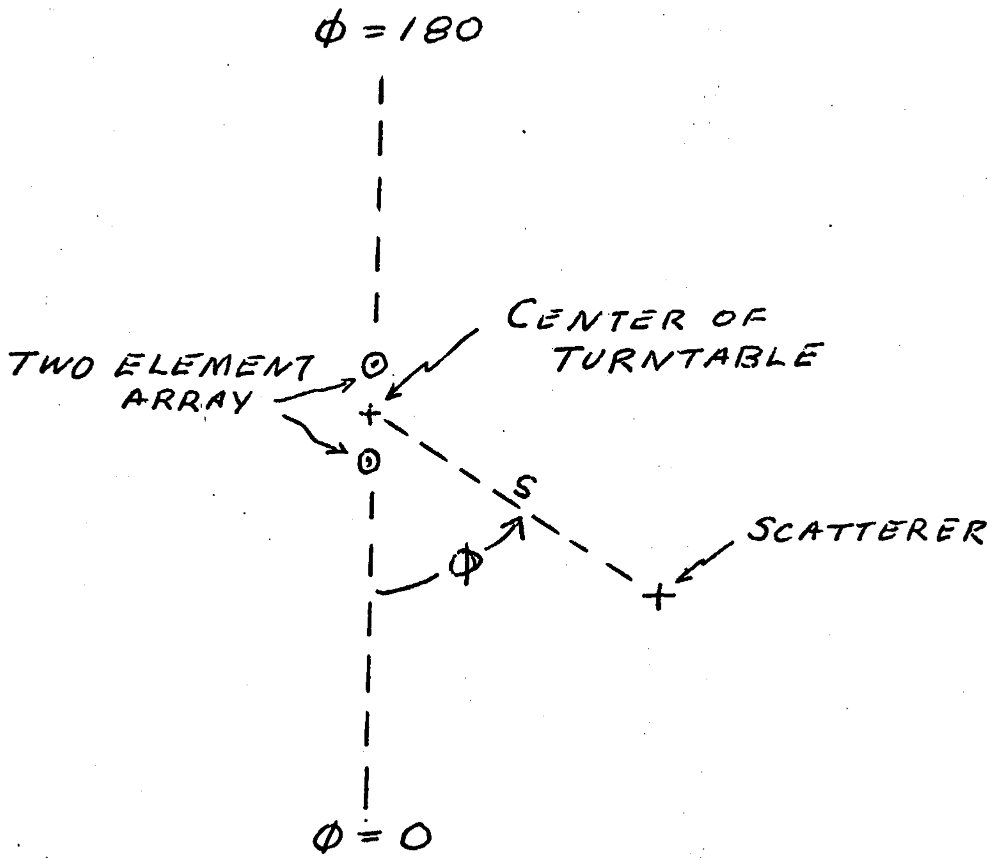


FIG. 1
LOCATION OF SCATTERER
UNDER TEST

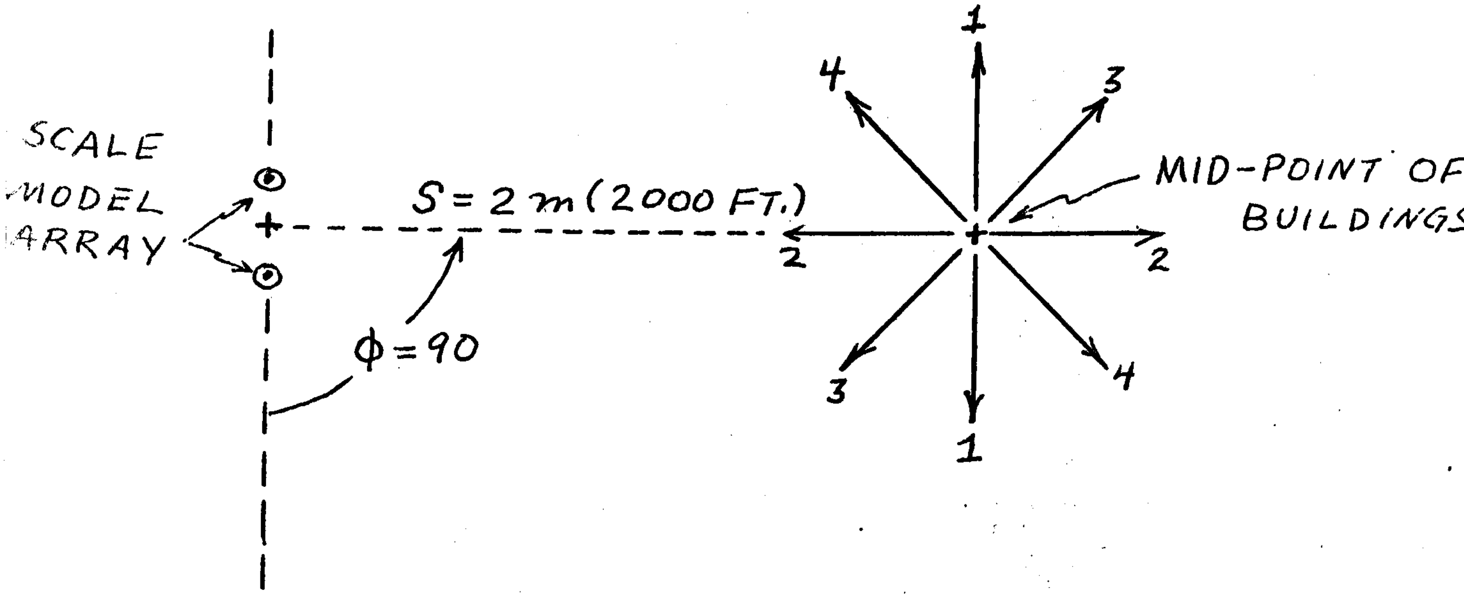


FIG. 2

LOCATION OF TWO BUILDINGS

FOR RE-RADIATION TESTS

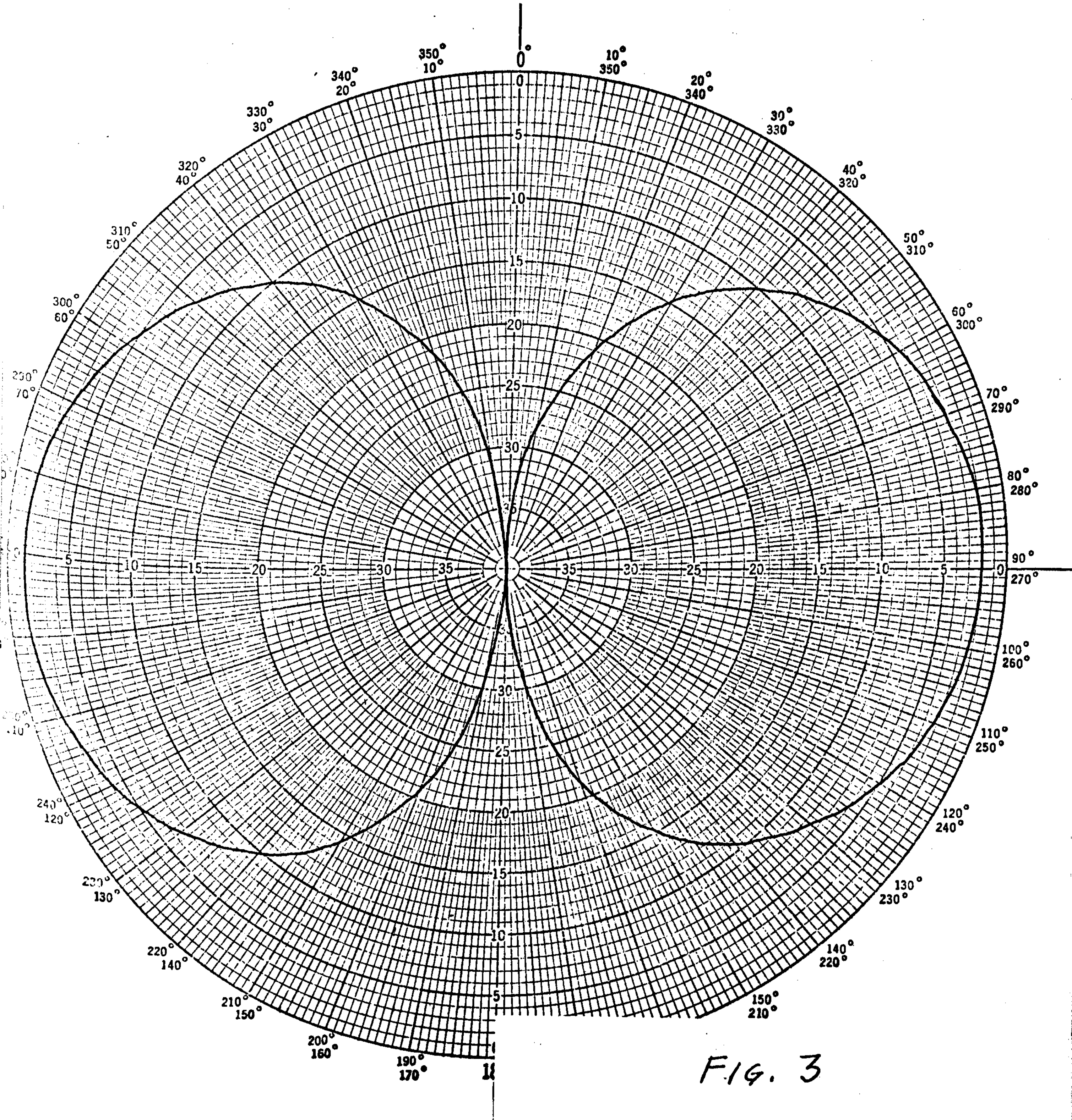


FIG. 3

PATTERN OF ARRAY ONLY

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SCIENTIFIC-ATLANTA, INC.
ATLANTA, GEORGIA

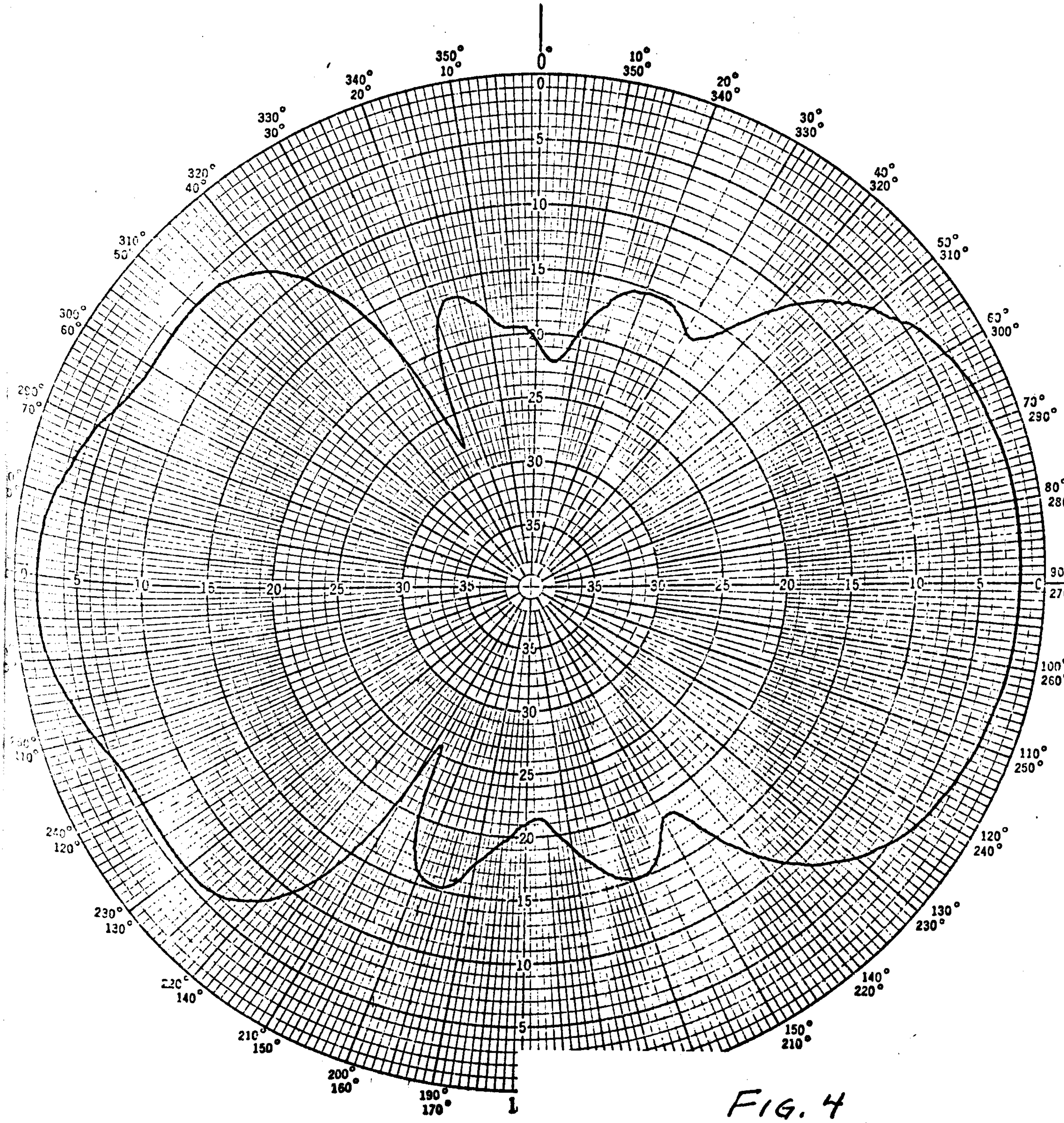

FIG. 4

SCATTER FROM SINGLE BUILDING

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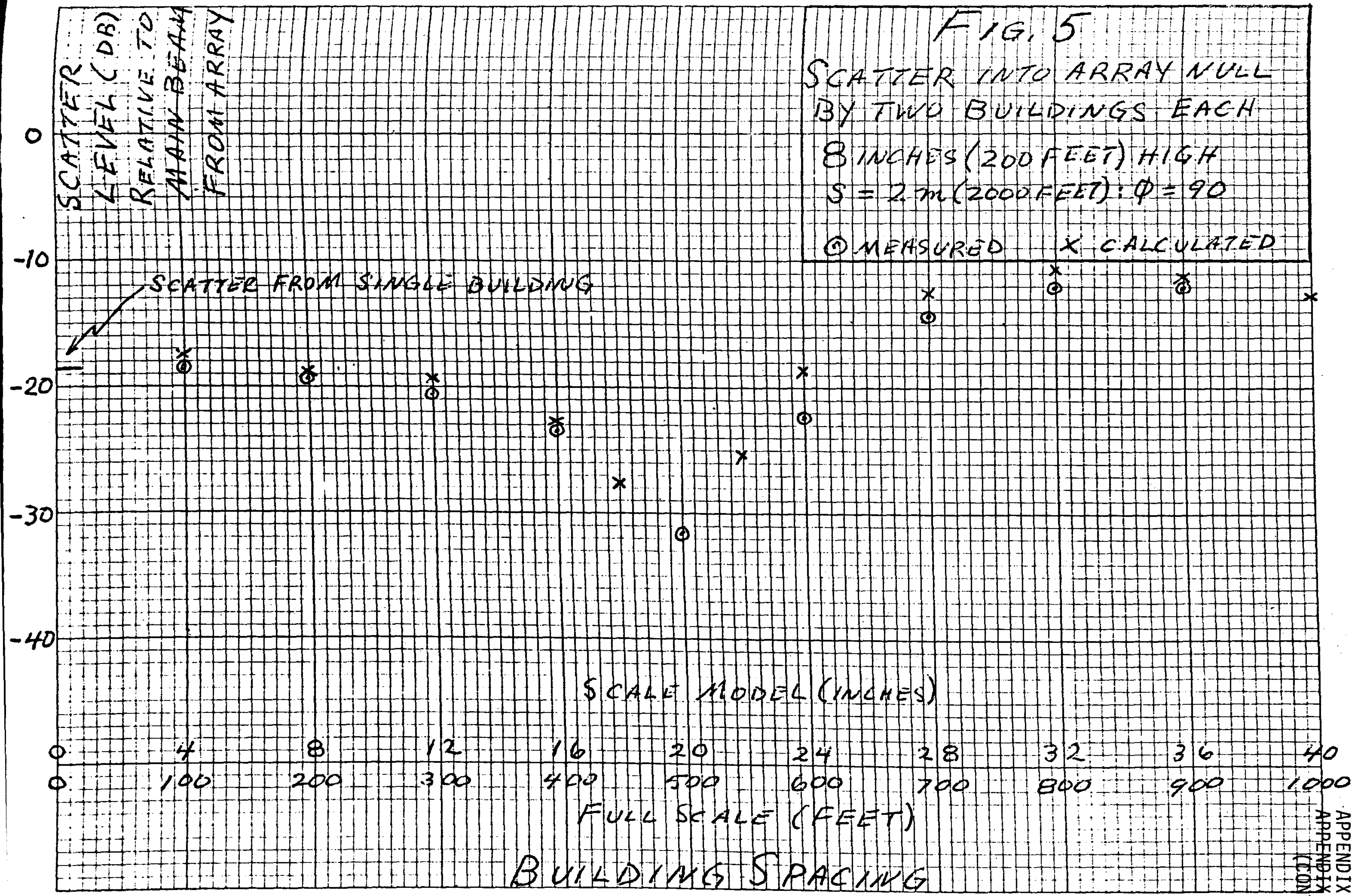


FIG. 5
SCATTER INTO ARRAY NULL BY TWO BUILDINGS EACH 8 INCHES (200 FEET) HIGH
S = 2 m (2000 FEET): Φ = 90
⊙ MEASURED   X CALCULATED
SCATTER LEVEL (DB) RELATIVE TO MAIN BEAM FROM ARRAY
SCATTER FROM SINGLE BUILDING
0
-10
-20
-30
-40
SCALE MODEL (INCHES)
0 4 8 12 16 20 24 28 32 36 40
0 100 200 300 400 500 600 700 800 900 1,000
FULL SCALE (FEET)
BUILDING SPACING

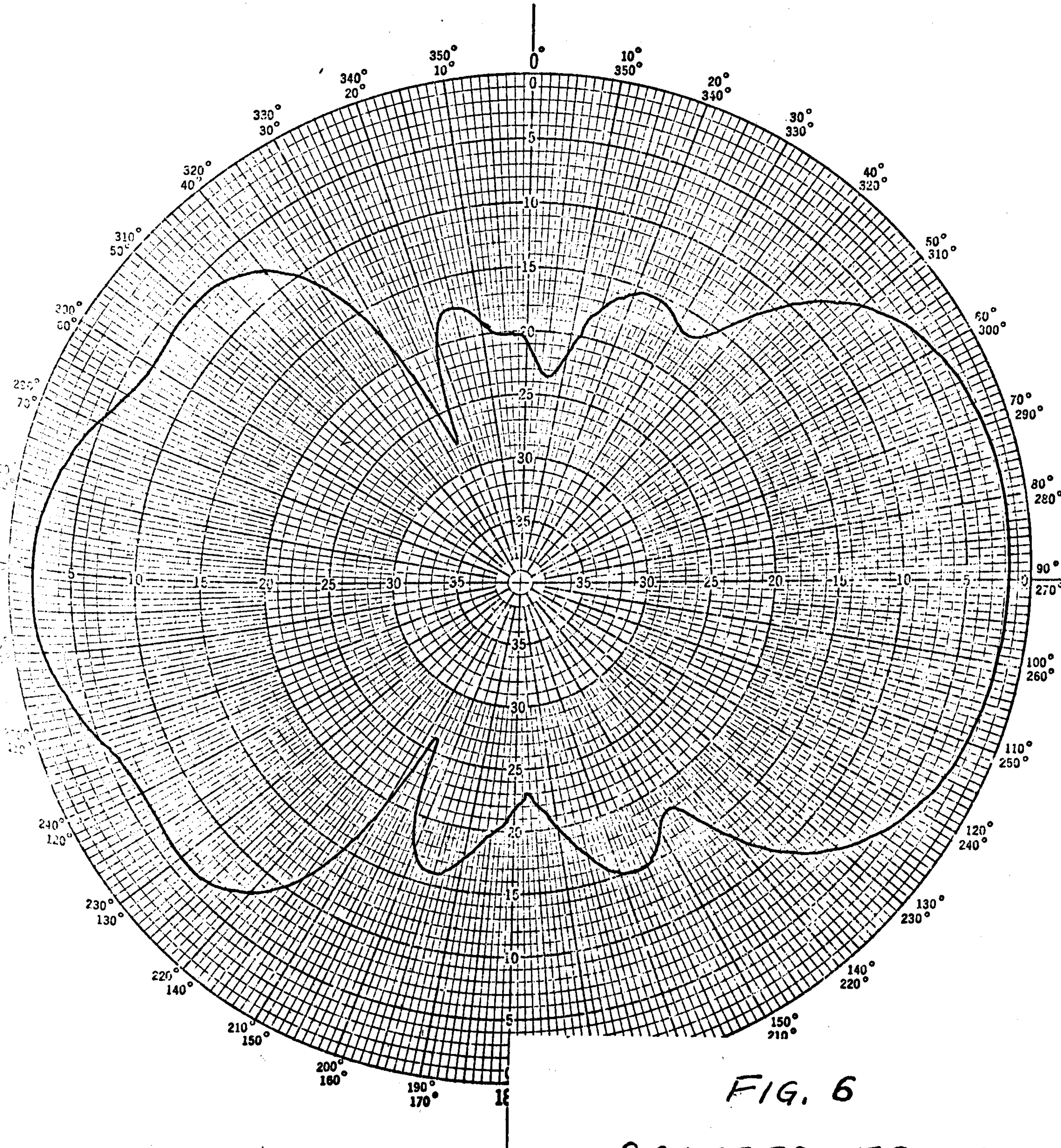
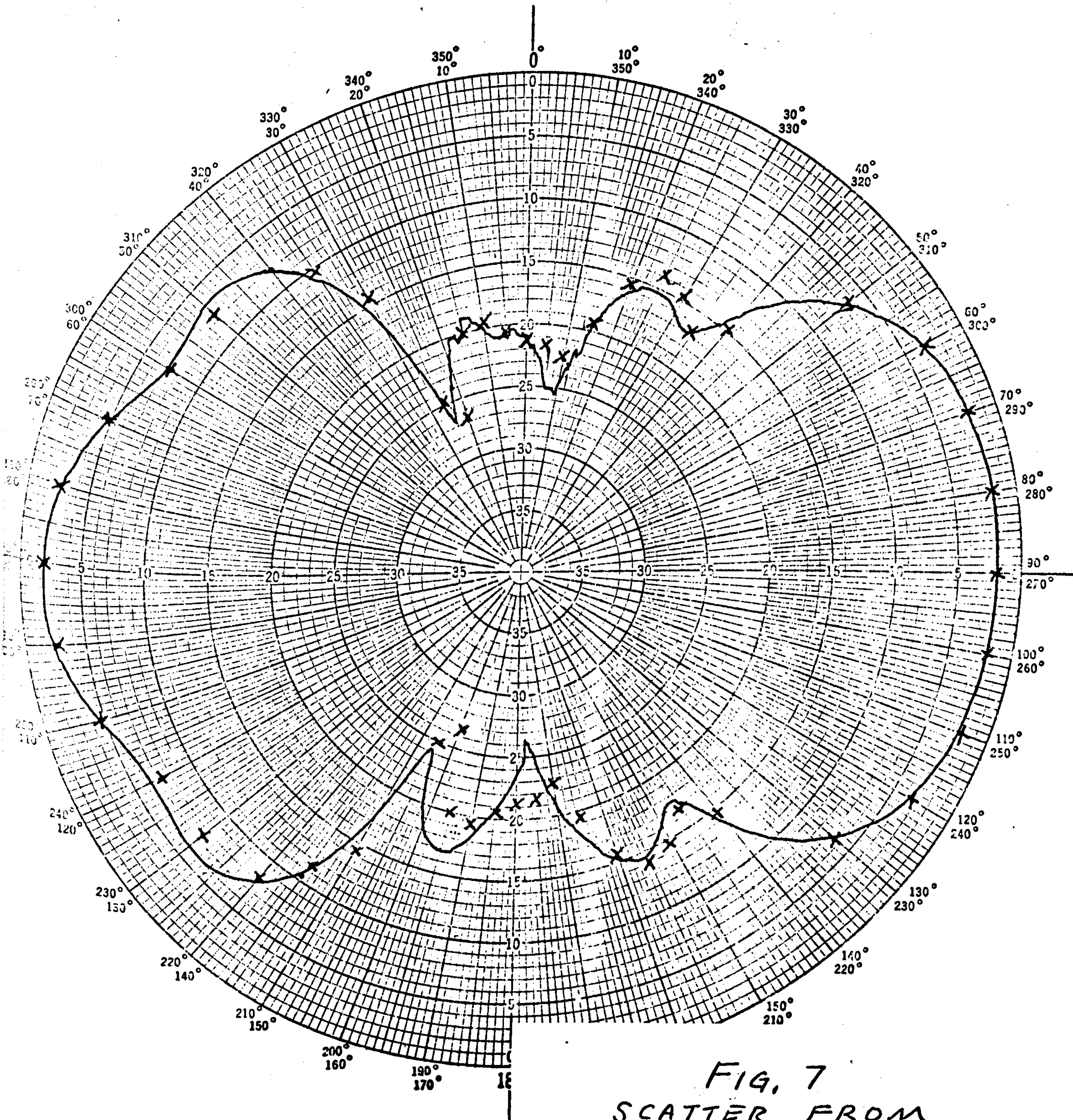


FIG. 6

SCATTER FROM TWO BUILDINGS

C-C SPACING = 8 INCHES (200 FEET)



Polar Chart No. 127D
SCIENTIFIC-ATLANTA, INC.
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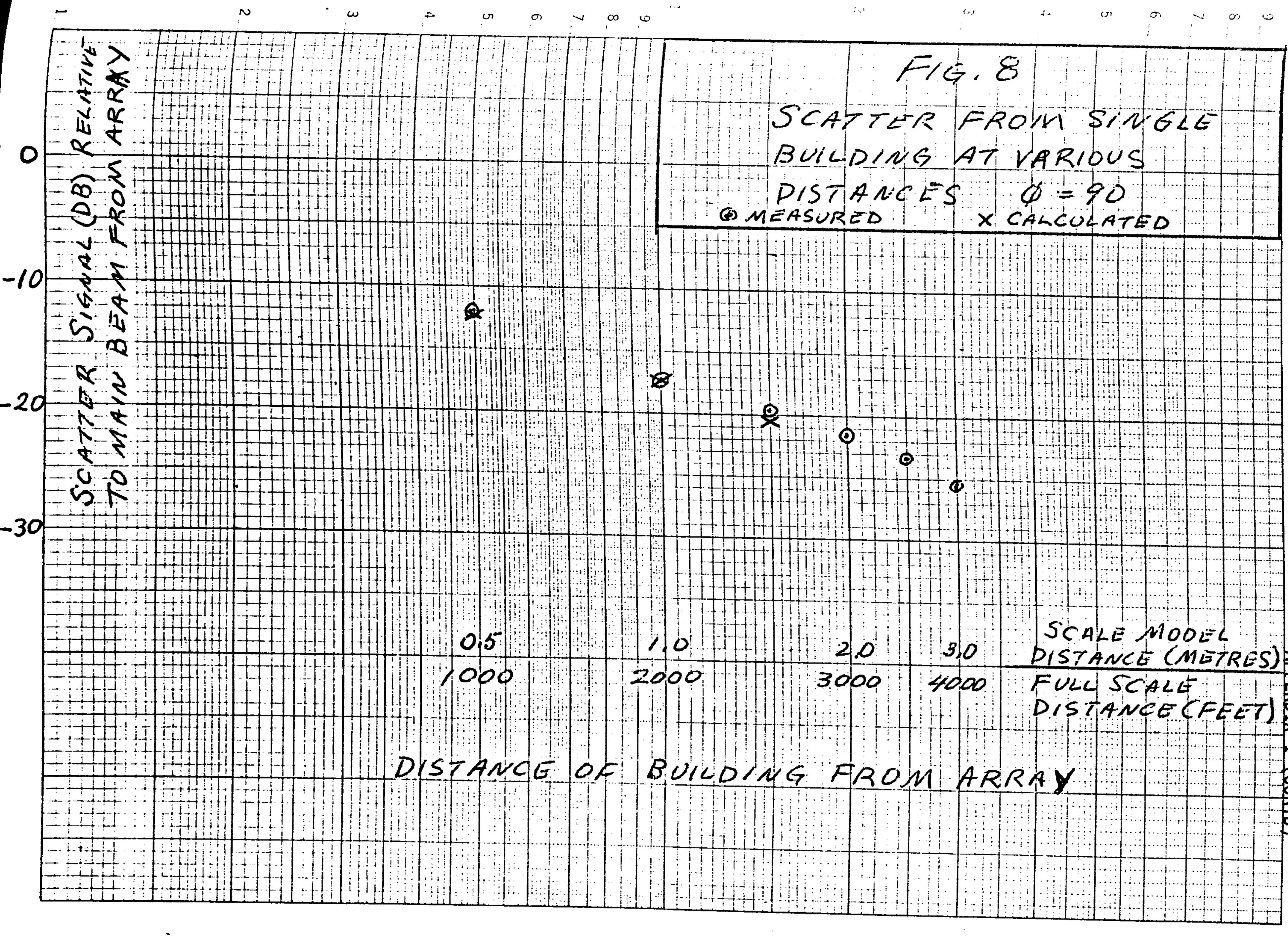

APPENDIX B TO
APPENDIX I (CONTD)

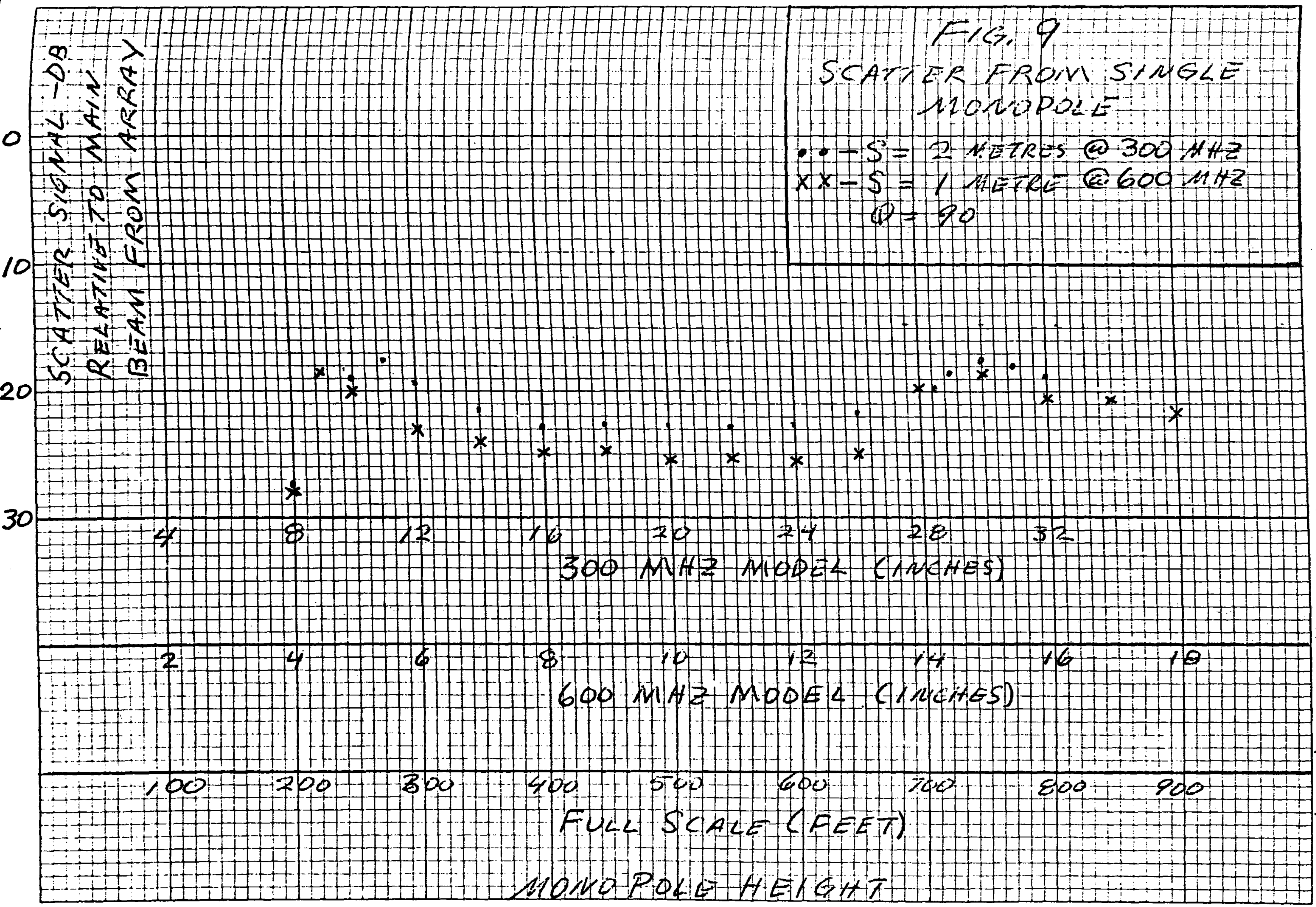
FIG. 9
SCATTER FROM SINGLE MONOPOLE
• • — S = 2 METRES @ 300 MHZ
X X — S = 1 METRE @ 600 MHZ
Φ = 90
SCATTER SIGNAL - DB RELATIVE TO MAIN BEAM FROM ARRAY
0
10
20
30
4
8
12
16
20
24
28
32
300 MHZ MODEL (INCHES)
2
4
6
8
10
12
14
16
18
600 MHZ MODEL (INCHES)
100
200
300
400
500
600
700
800
900
FULL SCALE (FEET)
MONOPOLE HEIGHT

Interim Report on University of Toronto Work

1. STATUS

November and early December 1977 were spent making extensive improvements to the anechoic chamber, the transmitting antenna and the associated instruments. The results of this are improved accuracy, dependability and speed in making re-radiation measurements. From early December 1977 an intensive experimental test program has been carried out and is continuing.

2. PERSONNEL

K.G. Balmain, Professor and Principal Investigator.

P.C. Kremer, Engineering Technologist IV.

J.-F. Laroye, Engineering Assistant.

3. EXPERIMENTAL RESULTS

3.1 Re-Radiation from Power Lines

The basic experimental arrangement involves a model power transmission line near a transmitting antenna along with a distant receiving antenna, as shown in Fig. 1. In the same figure is shown the basic 5-tower model line with dimensions chosen to be approximately 1/1000 of the EHV power line adjacent to the CBC transmitting antenna at Hornby, Ont. The nominal scale factor of 1000 is especially convenient because experimental millimetres, metres and megahertz transform respectively at full scale into metres, kilometres and kilohertz. Thus the available frequency sweep of 450 to 1050 MHz scales to cover the lower-frequency half of the broadcast band. In addition to the 5-tower arrangement, a 9-tower arrangement was also used to bring the lowest-frequency resonance of the system into the middle of the available range of test frequencies.

The model power line in the anechoic chamber is shown in Fig. 2, in which the newly-constructed transmitting antenna is visible to the left of the line. It must be kept in mind that such a model includes the electrical image of a power line over ground and therefore a perfectly conducting ground surface is implicitly assumed. In Fig. 3 can be seen the low-capacitance Teflon supports which hold the wire at a distance of 1 mm from the model tower, as well as the skywire "grounding" wires fastened under a screw in the top of each tower.

The case of one skywire connected to the tops of all towers in a 9-tower configuration is considered first. Transmission of a swept-frequency signal straight through the power line reveals the lowest frequency resonance as the sharp dip shown in the top curve in Fig. 4. Also shown in the same figure (bottom curve) is the arrangement to give specular or "mirror-like" reflection for the ray path drawn from the transmitting antenna to the center of the power line and from there to the receiving antenna.

Figure 5 shows radiation patterns with and without the power line, the top curve showing strong front lobe notching and back-lobe null-filling at the apparent resonance frequency deduced from the foregoing figure. If the receiving antenna were far away the re-radiated signal level at ± 180 deg. would be approximately 3.7 dB higher relative to the front lobe. Also shown in Fig. 5 in the bottom curve is clear evidence of the specular reflection already referred to.

Isolation of towers from the skywire has been discussed as a possible remedy for re-radiation problems. Figure 6 shows the effect of isolating the tower nearest to the transmitting antenna and in its main lobe. The low-frequency pattern perturbation has been reduced very little, while an additional perturbation has been introduced at another frequency. Examples of the associated radiation patterns are shown in Fig. 7.

The question of how many wires are needed to model (experimentally or theoretically) a power line with two skywires and six power-carrying wires is a very important one because the answer to it will determine to a considerable degree how much work will be needed to complete the power-line part of the project. The use of two skywires instead of one as shown in Fig. 8 increases slightly the perturbations at both resonant frequencies (compare with the bottom curve in Fig. 6). The addition of two power-carrying wires is modelled by resistively terminating two wires isolated from all towers; the result in the bottom curve of Fig. 8 is that both resonant pattern perturbations are spread and shifted slightly in frequency, and reduced in magnitude by from 1 to 2 dB.

In order to investigate further the influence of the power-carrying wires, a four-wire, five-tower configuration was tried with towers #2 and #4 isolated from the skywires. The two power-carrying wires (located below the skywires at a distance from them equal to the skywire separation) were terminated in their characteristic impedances with resistors. With the resistors removed (open-circuit termination) very little current flows in these wires except at their resonant frequencies, at which small irregularities appear in swept-frequency measurements; however no such irregularities are visible in the top curve of Fig. 9 so this can be taken approximately to represent the case of no power-carrying wires. The bottom curve in the same figure shows that resistive terminations on the power-carrying wires cause a 3 dB diminution in the resonant perturbation caused by isolating the two towers. Corresponding radiation patterns in Figs. 10 and 11 show that the power-carrying wires have no effect at 488 MHz, while at 680 MHz their presence diminishes the front-lobe perturbation by 3 dB and reduces the back-lobe null-fill field by 4 dB. Therefore it appears that important cases do exist in which it will be necessary in future work to take into account the presence of power-carrying wires, or at least the ones closest to the skywires. These important cases are the ones in which a few towers have been isolated (or possibly detuned).

In the next interval it would be useful to study the effects of varying the distance d between the power line and the transmitting antenna. The distance d = 900 mm chosen for the experiments described above is somewhat large to represent the CBC-Hornby site, for which the value d = 500 mm would be better for small values of the angle α. In addition, correction factors need to be devised to make results of the types described more easily comparable to cases with isotropic transmitting antennas, or ones with very deep nulls.

3.2 Re-Radiation from Buildings

A pair of high-rise buildings has been shown to comprise a very useful basic re-radiator. If the buildings are irradiated with in-phase fields, the scattered field is very much like that of a single double-sized building, with a very low - Q resonance at a height of about a quarter wavelength. With out-of-phase irradiation, a much higher - Q resonance is excited at more or less the same height, accompanied by much greater re-radiation and consequently greater perturbation of the transmitting antenna radiation pattern.

The basic arrangement used for studying re-radiation from buildings is shown in Fig. 12, along with the dimensions of the model high-rise buildings referred to in this report. Figure 13 shows the actual arrangement of the buildings and antennas inside the anechoic chamber. Figure 14 shows close-up views of the model buildings in both open-ended and metal-capped (roofed) versions. The only noticeable effect of simulating a metal roof was found to be a 5% reduction in resonant frequency, so all measurements referred to in this report were taken using the open-ended models.

Typical swept-frequency measurements are shown in Fig. 15, from which it is clear that maximum perturbation of the radiation pattern for this case occurs probably near the values α = 90 deg., θ = 15 to 30 deg., and f = 677. This was found to be the case and the maximally perturbed radiation pattern is shown in Fig. 16. The maximum perturbation for α = 90 deg. occurs at θ = 26 deg. and results in a 6.8 dB notch in the pattern. The maximum perturbation for α = 0 deg. occurs at θ = 28 deg. and results in a 2 dB notch in the pattern.

Consider a procedure for calculating the null-fill level from the measured main-lobe notch level, with reference to the α = 90 deg. case shown in Fig. 16. The notch level is at -6.8 dB relative to the unperturbed radiation pattern which in turn is at -1.0 dB relative to the main lobe. The re-radiation relative to the main lobe is then given by the following relation (all in dB):

$$\text{null-fill} = 20 \log \left[1 - 10^{\text{notch}/20} \right] + \text{reference}$$

$$= -6.3 \text{ dB}$$

Adding to this the distance compensation of -3.7 dB, we get a calculated value of -10 dB which can be compared with the value of -11 dB actually measured at θ = 180 deg. and shown in Fig. 16. The calculated figure is probably more accurate than the measured one because of various difficulties connected with making measurements in the back lobe of the transmitting antenna.

An important quantity to be considered is the variation with distance of the maximum perturbation in the radiation pattern. Measurements similar to Figs. 15 and 16 were taken at eight different distances and for various orientations and frequencies. The results are compiled in Table 1 for which the "worst case" frequencies have been selected. A graph of the results is given in Fig. 17; these results are preliminary in the sense that some corrections will have to be made, because of the finite distance to the receiving antenna.

			Far-field Levels (dB)					
			α = 90 deg.			α = 0 deg.		
d(m)	d'(m)	f(MHz)	Ref.	Notch	Null-fill	Ref.	Notch	Null-fill
0.500	0.400	679	-1.4	-17.7	-2.6	-2.0	-3.0	-12.7
0.700	0.600	680	-1.1	- 9.8	-4.5	-1.5	-2.3	-14.2
0.900	0.800	677	-1.0	- 6.8	-6.3	-1.2	-1.9	-15.3
1.125	1.025	682	- .6	- 4.6	-8.3	- .8	-1.5	-16.8
1.325	1.225	681	- .4	- 4.1	-8.9	- .5	-1.4	-17.0
1.525	1.425	683	0	- 3.6	-9.4	- .1	-1.1	-18.6
1.725	1.625	684	- .1	- 3.3	-10.1	- .1	-1.1	-18.6
1.925	1.825	689	- .1	- 2.7	-11.6	0	- .9	-20.1

Table 1. Maximum perturbation of the radiation pattern under resonance conditions. The pattern notch is the one at the lowest positive value of θ. "Reference" is the unperturbed radiation pattern level relative to the main lobe, and "notch" is the notch level relative to the unperturbed pattern at the same angle. "Null-fill" is the level of re-radiation relative to the main lobe and is the value calculated from the reference and notch levels. The distance d' is measured from the estimated phase center of the transmitting antenna.

4. THEORY AND COMPUTATION

The possibility that a multiwire analysis of power lines may be necessary raises serious questions about the economics of applying moment-method techniques to the solution of the power-line re-radiation problem. Currently we have under development a transmission-line theory of power-line re-radiation which ultimately will be applicable to the multiwire case. In the development of theories of this type, a particularly useful reference is the book by Uchida (1967). For future work involving finite ground conductivity, useful current references are the works by Wait (1972), Olsen and Chang (1976), and Chang (1977). On the same subject, one should not overlook the fundamental work by Carson (1926) and its extension by Kikuchi (1973). The latter paper shows how a wire over ground changes from a lossy transmission line into a surface waveguide as the frequency is raised from 1 MHz to 200 MHz.

Re-radiation from groups of buildings is being examined from the point of view of multiple thin-wire scatterers, but as yet there are no results to report.

The remainder of the contract period will be spent mainly in work on the above theories, as well as in processing the experimental data already acquired.

5. CONCLUSIONS

Re-radiation from power lines can be very strong and highly directive near the resonant frequencies of the system. Isolation of one or two towers from their skywires introduces strong new resonances while reducing somewhat the strength of existing resonances. The power-carrying wires serve to conduct power away from localized resonances, so such wires would have to be taken into account when analyzing detuning techniques. However the question remains as to whether this latter effect would be noticeable with ground conductivity taken into account.

Re-radiation from a single quarter-wave, high-rise building at 2 km from a transmitting antenna is about 20 dB below the level of the signal incident upon it. Resonant re-radiation from a pair of such buildings is about 8 dB higher in level. It is clear that groups of high-rise buildings could have a profound effect on the radiation patterns of nearby antennas.

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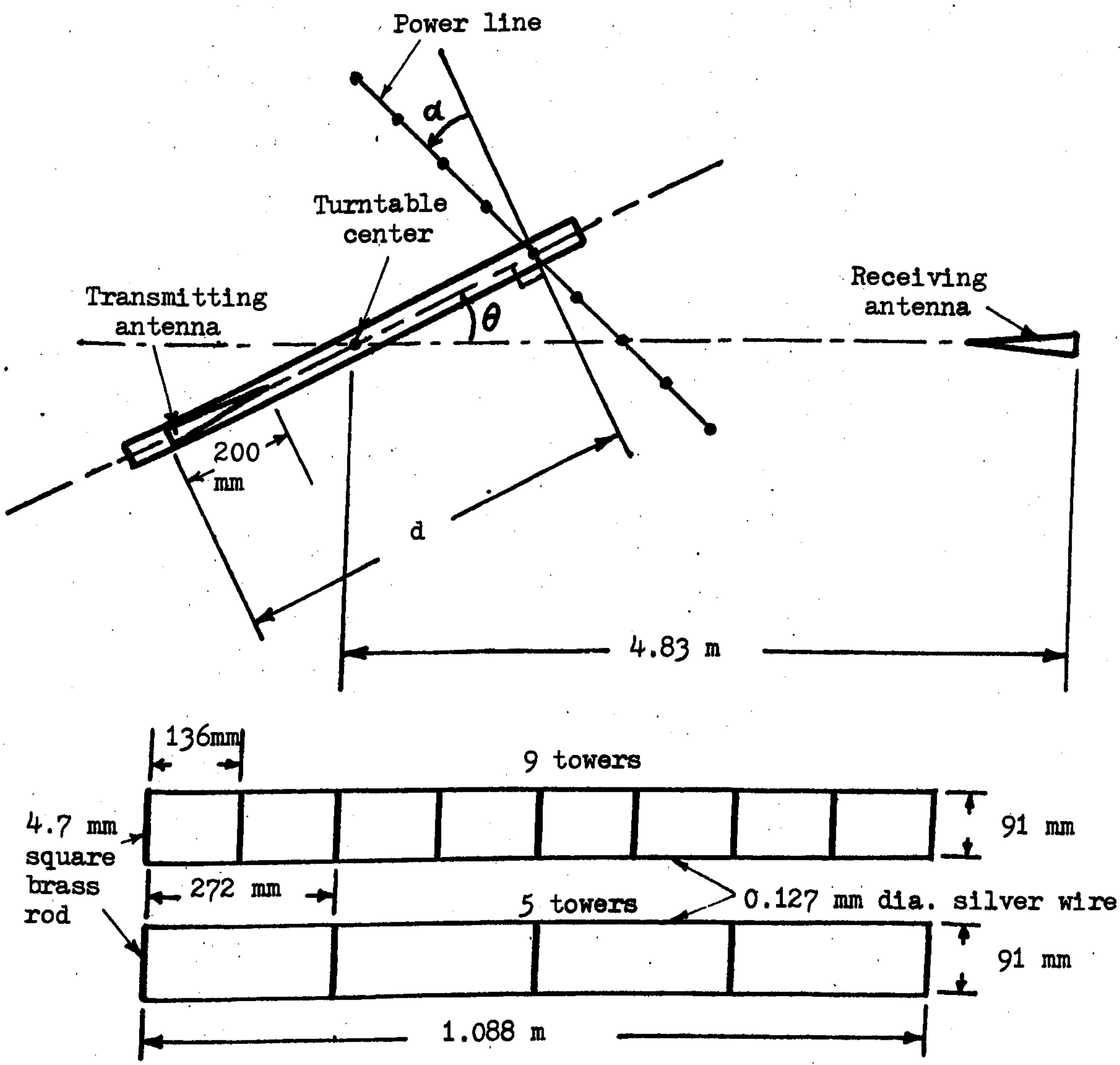

Fig. 1. Power line model test arrangement, with power line dimensions for 9-tower and 5-tower cases. Note that the 5-tower case simulates the EHV line adjacent to the CBC antenna at Hornby.

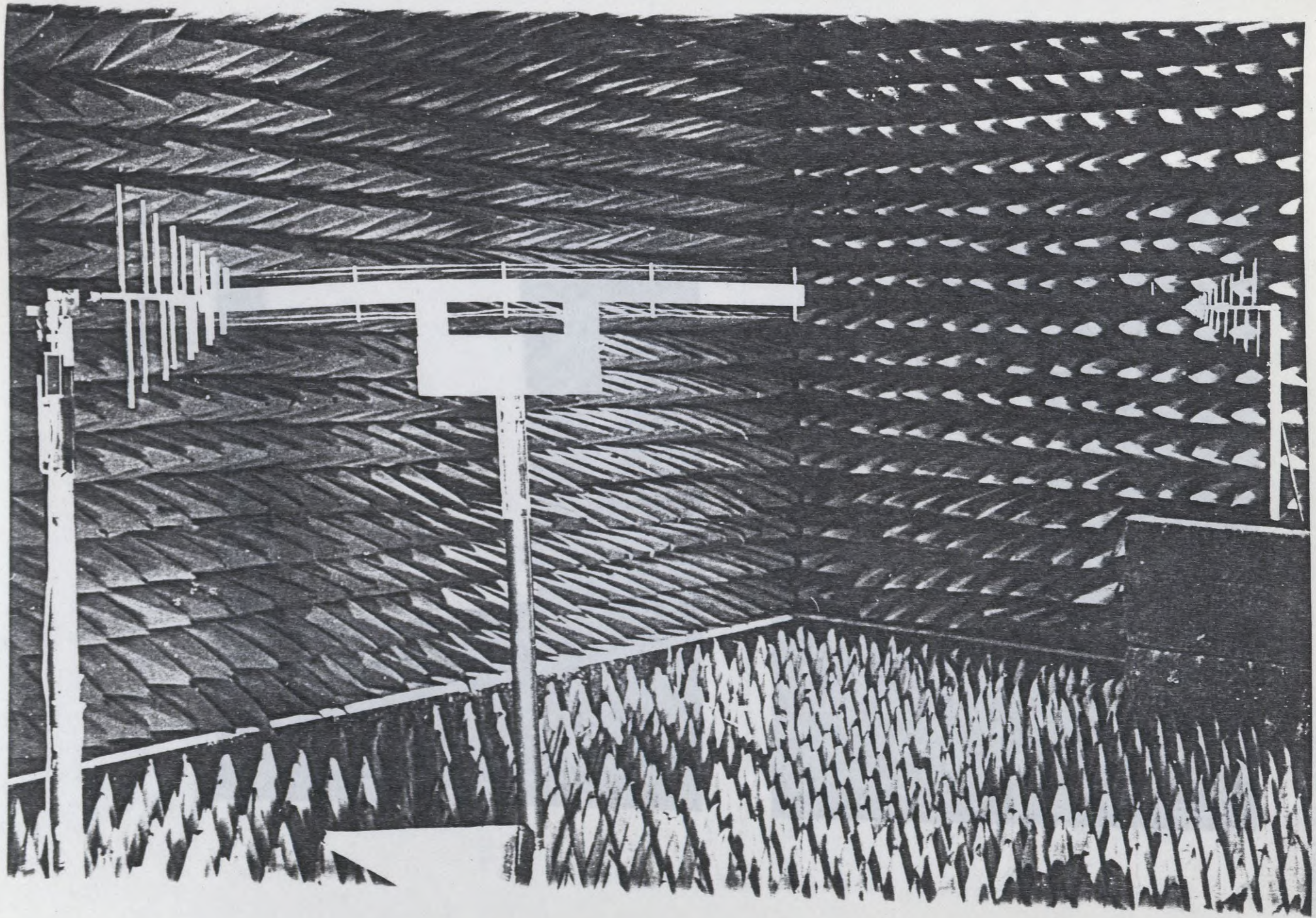

Fig. 2. Model power line test facility in anechoic chamber.

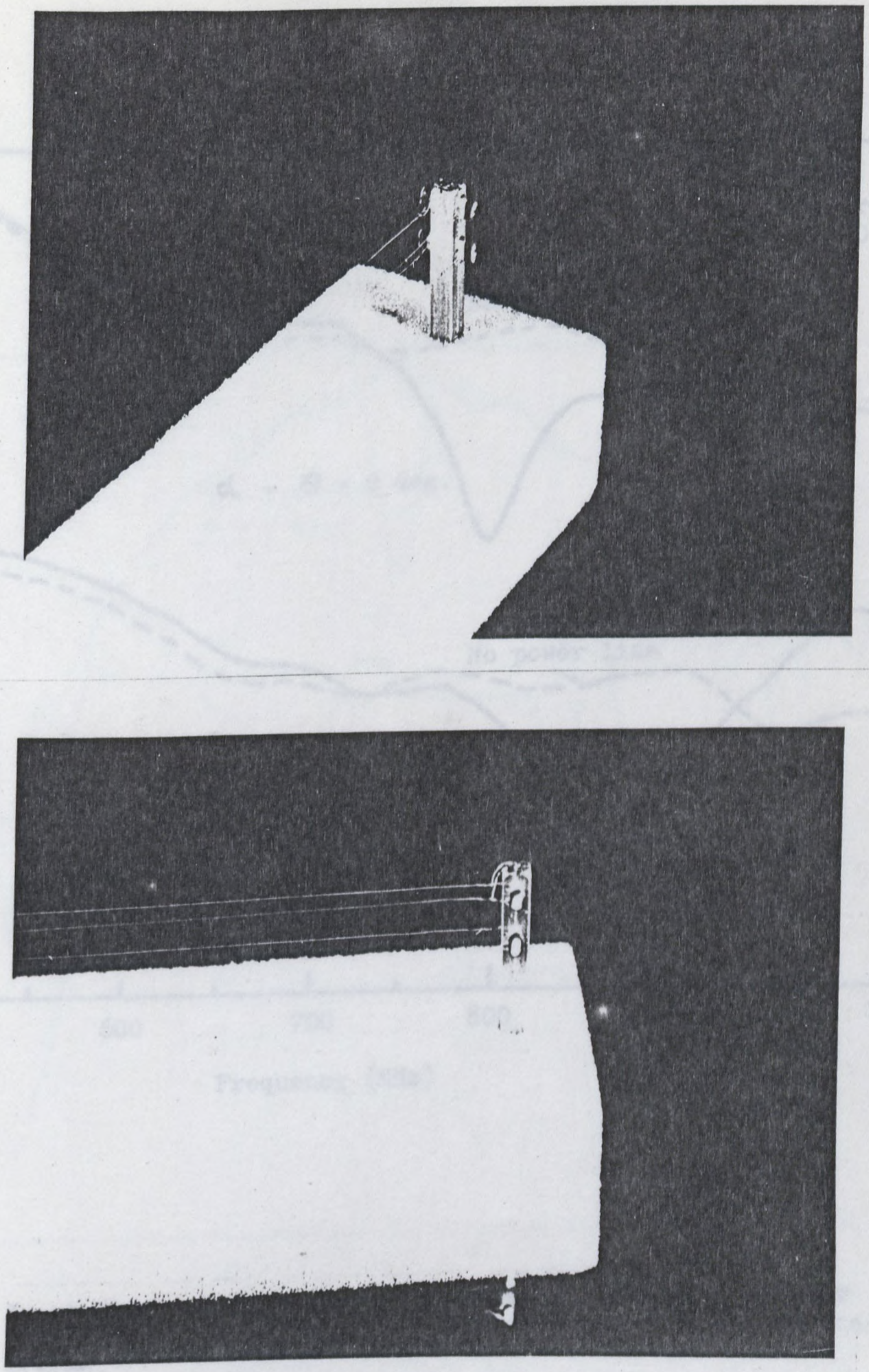

Fig. 3. Detail of wire attachment to top of tower.

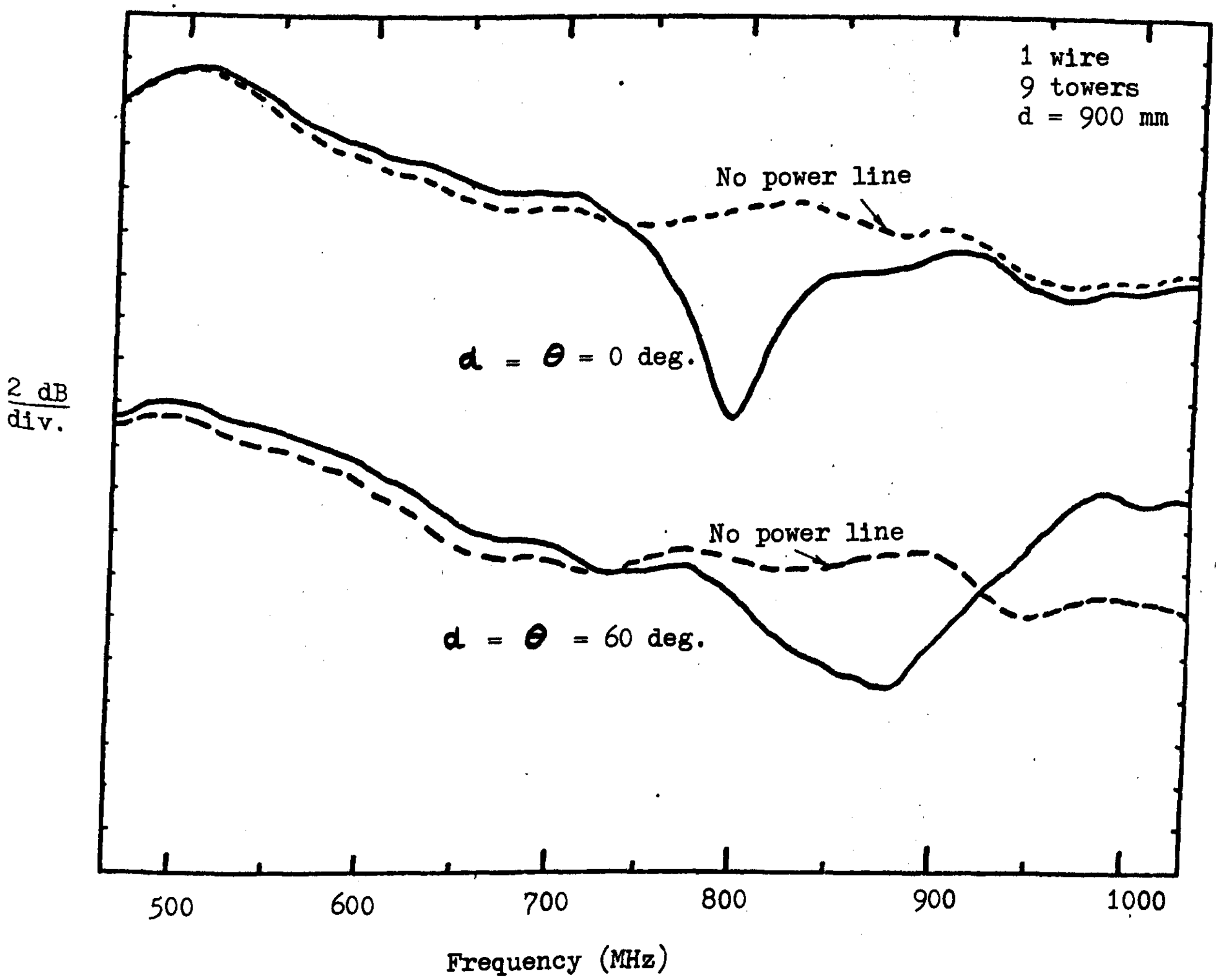

Fig. 4. Swept-frequency measurement of reradiation from a 9-tower line. The bottom curve is for the specular reflection condition.

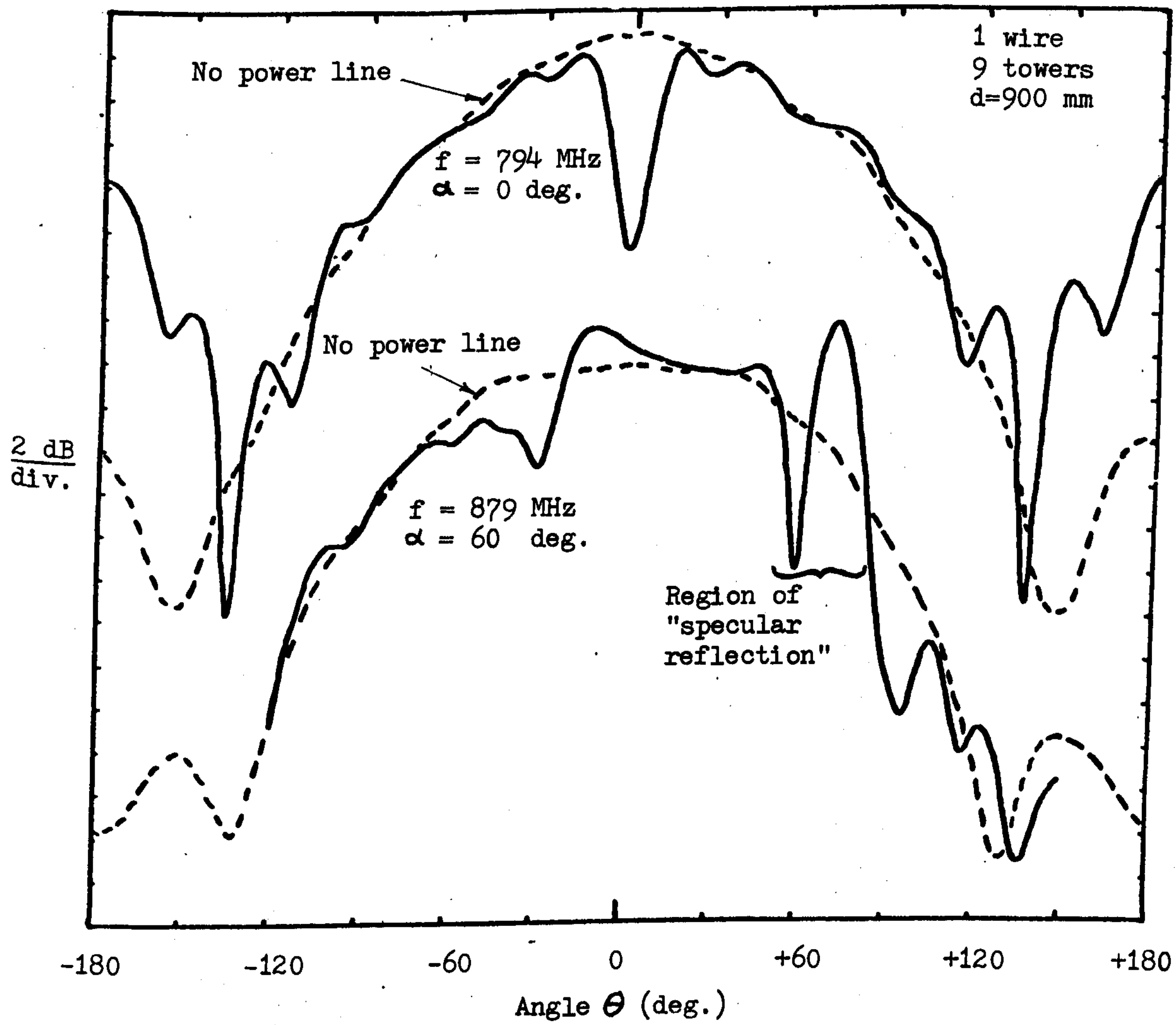

Fig. 5. Radiation patterns relating to Fig. 4 and showing severe notching and null-filling (top), and specular reflection off the side of the power line (bottom).

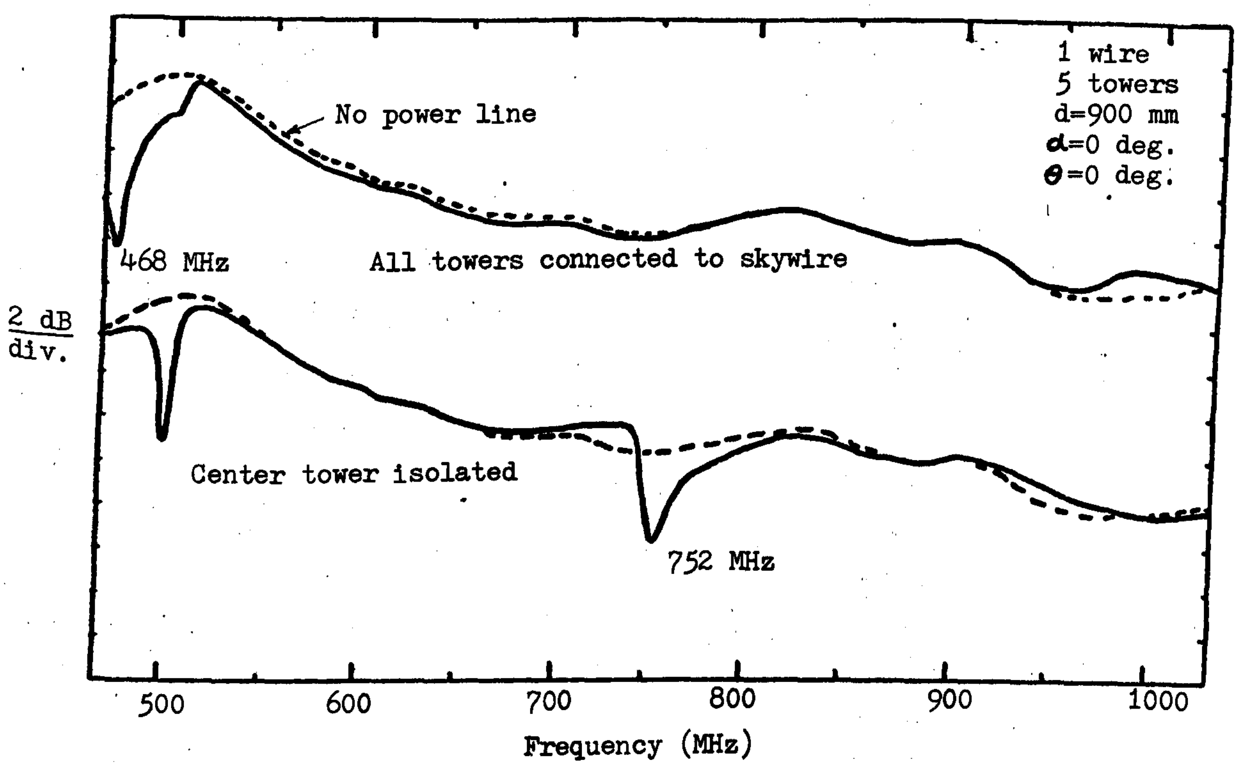

Fig. 6. The effect on swept-frequency measurements of isolating one tower from the skywire, for the 5-tower line.

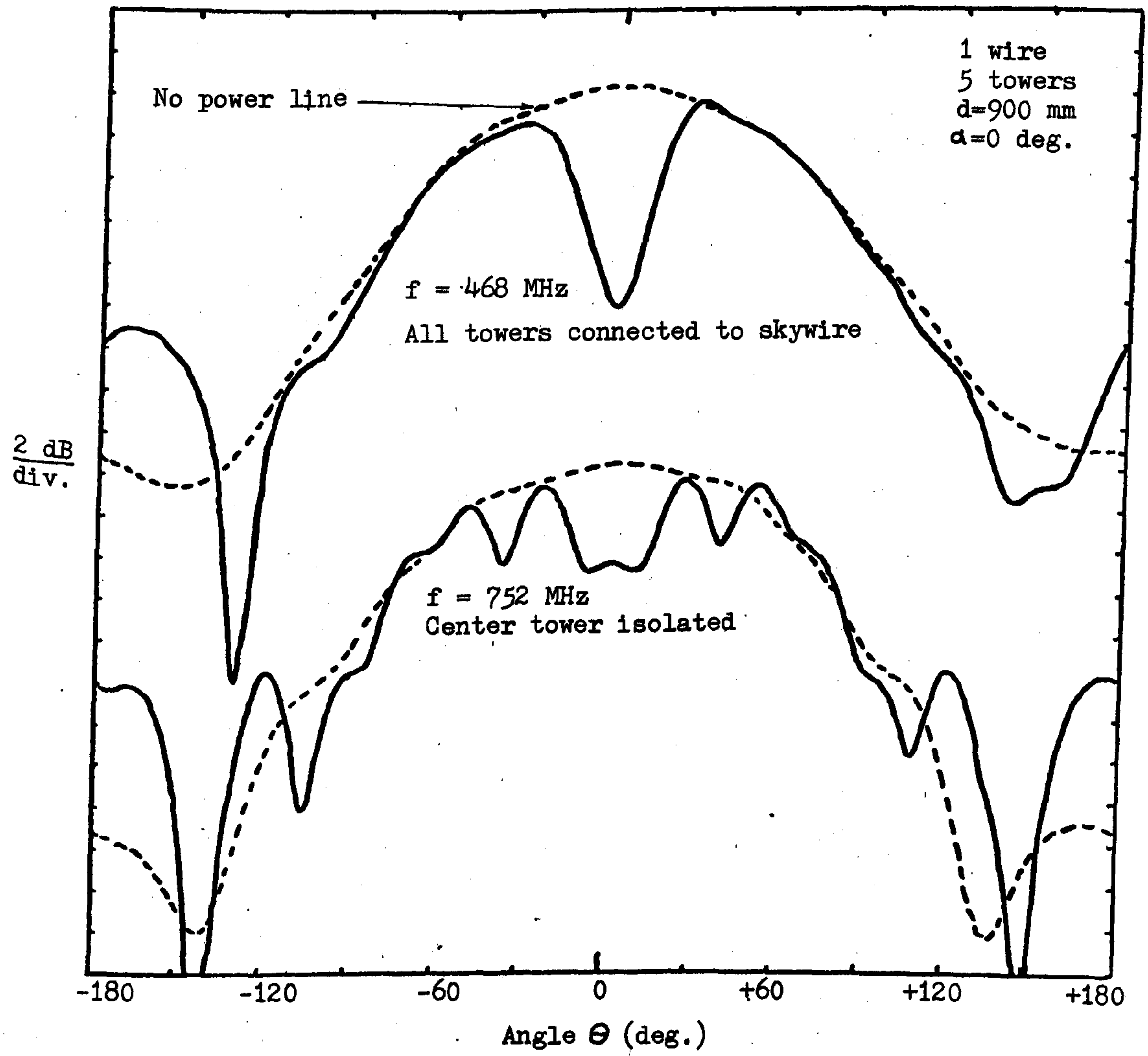

Fig. 7. Radiation patterns relating to Fig. 6 and showing the effect of the low frequency resonance (top), and the additional resonance introduced by isolating one tower (bottom).

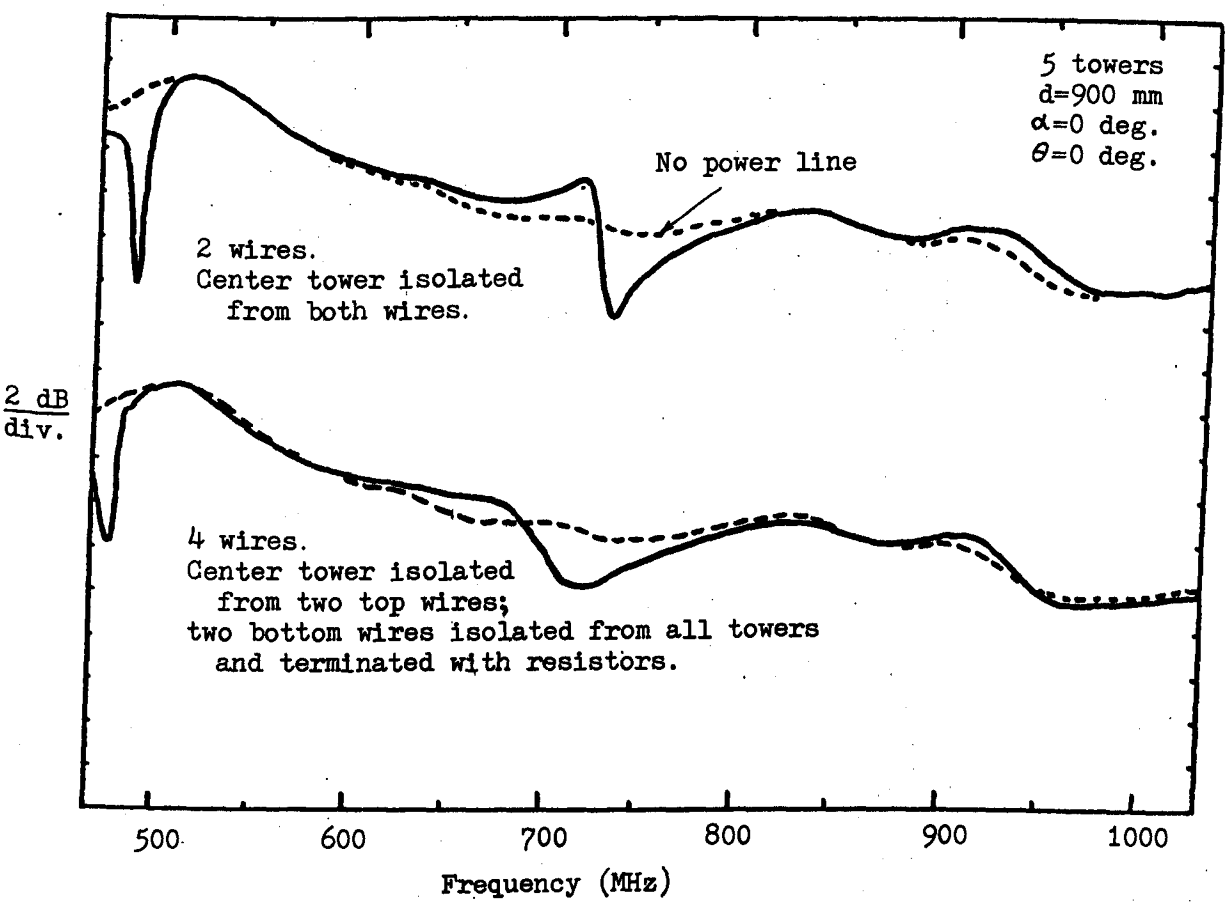

Fig. 8. Swept-frequency measurements showing the effect of adding two power-carrying wires to a configuration having two skywires and one isolated tower.

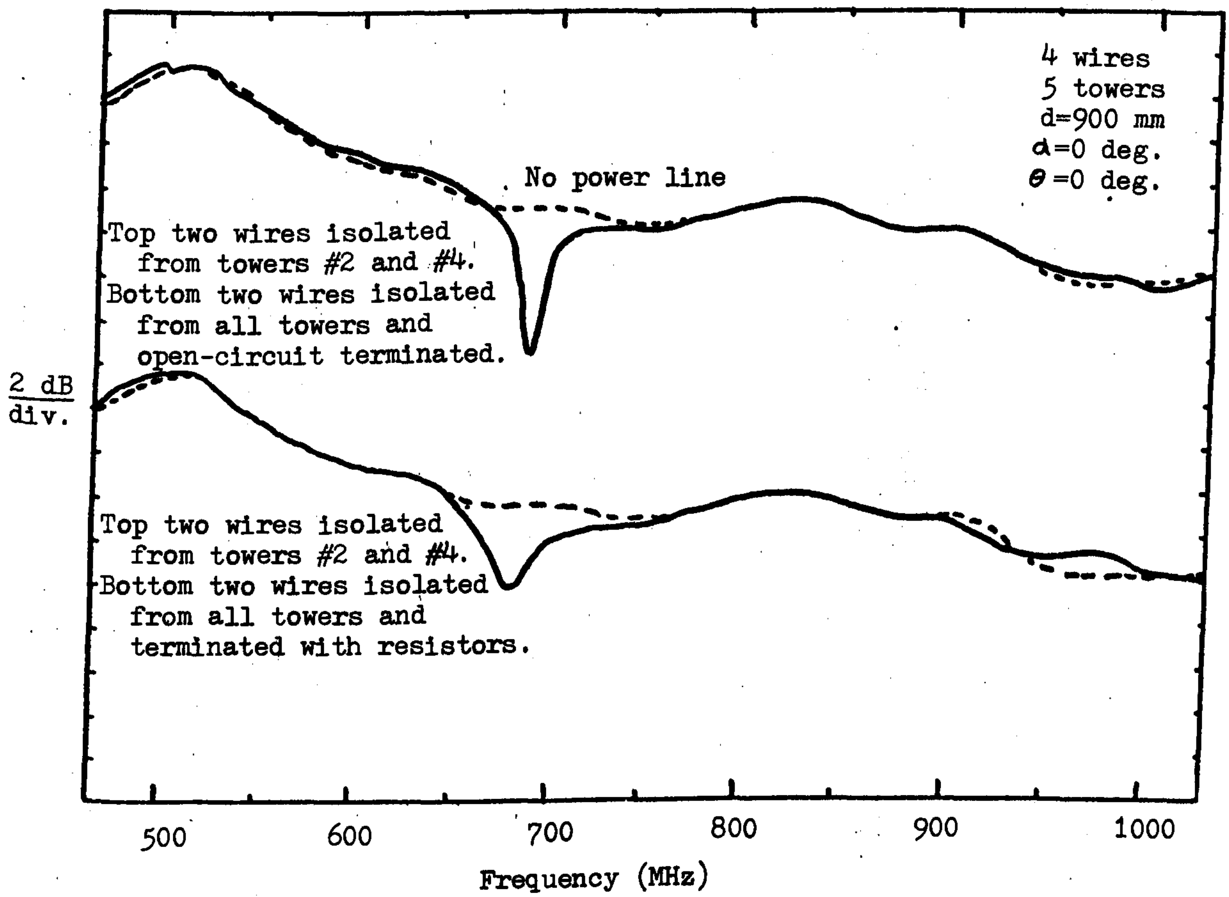

Fig. 9. The effect of two power-carrying wires on the resonance caused by isolation of skywires from two non-adjacent towers.

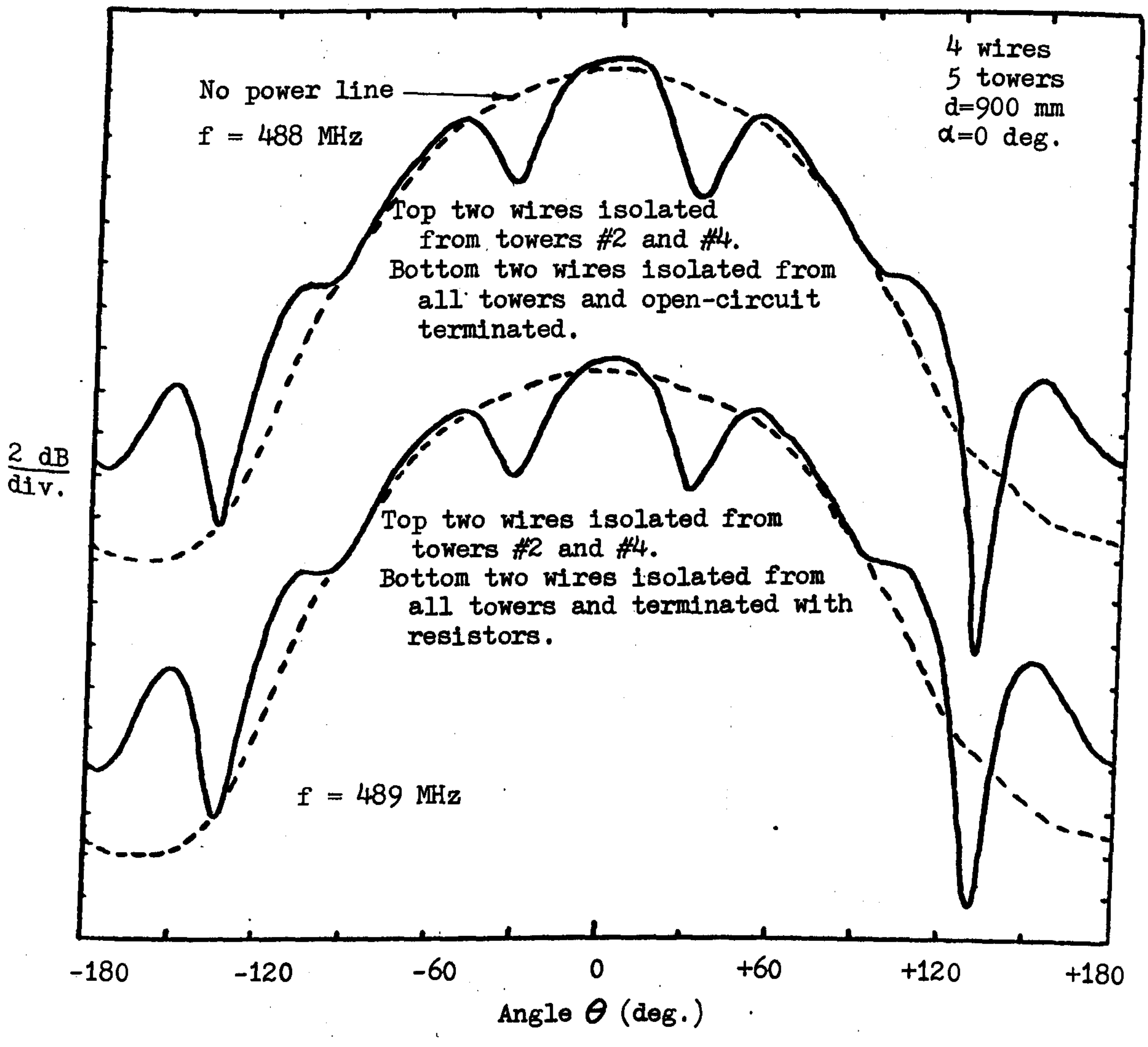

Fig. 10. Demonstration that the power-carrying wires do not affect re-radiation at the low-frequency resonance, for the same conditions as in Fig. 9.

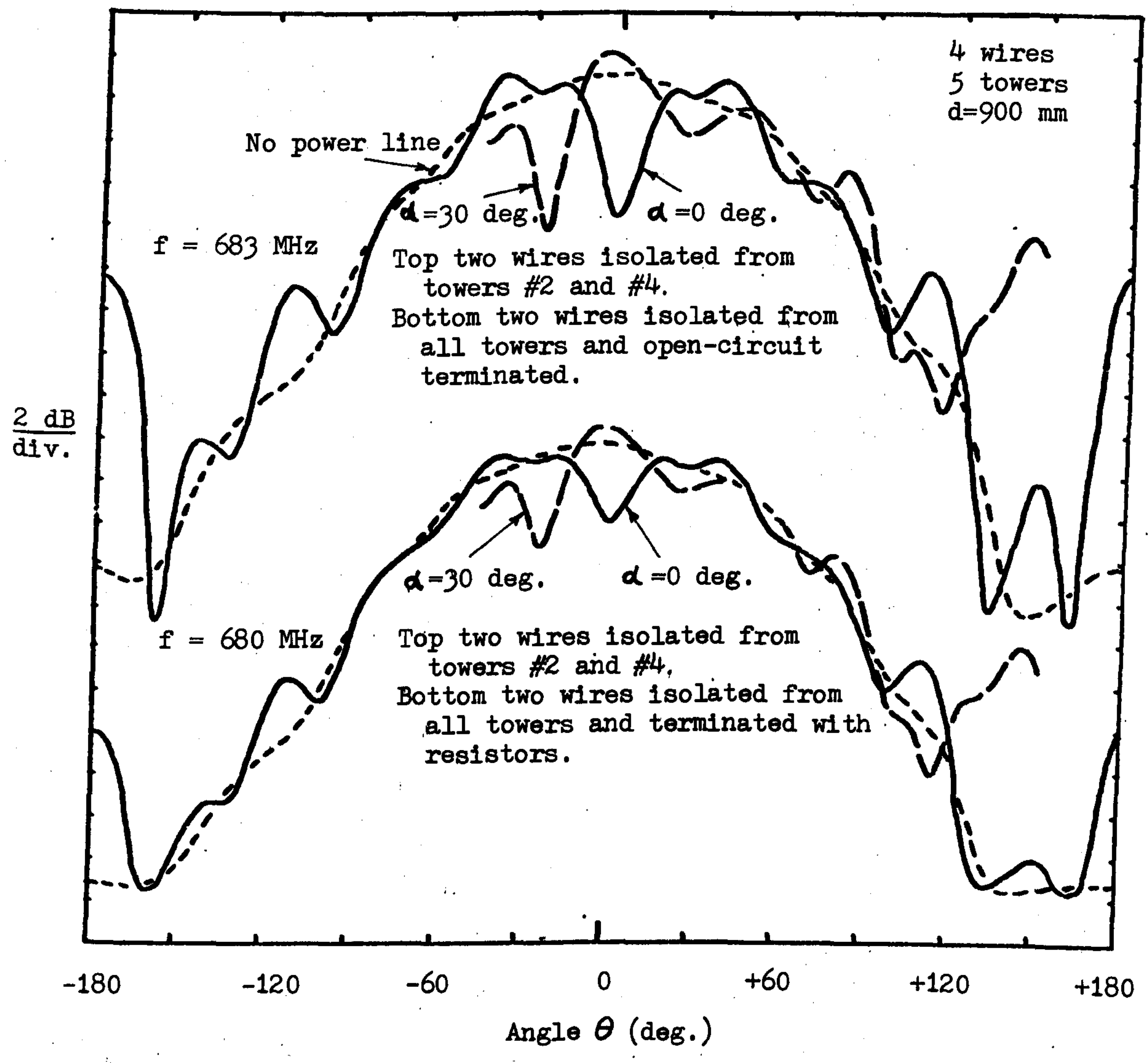

Fig. 11. Demonstration of a significant mid-frequency pattern perturbation reduction caused by the power-carrying wires, for the same conditions as in Fig. 9.

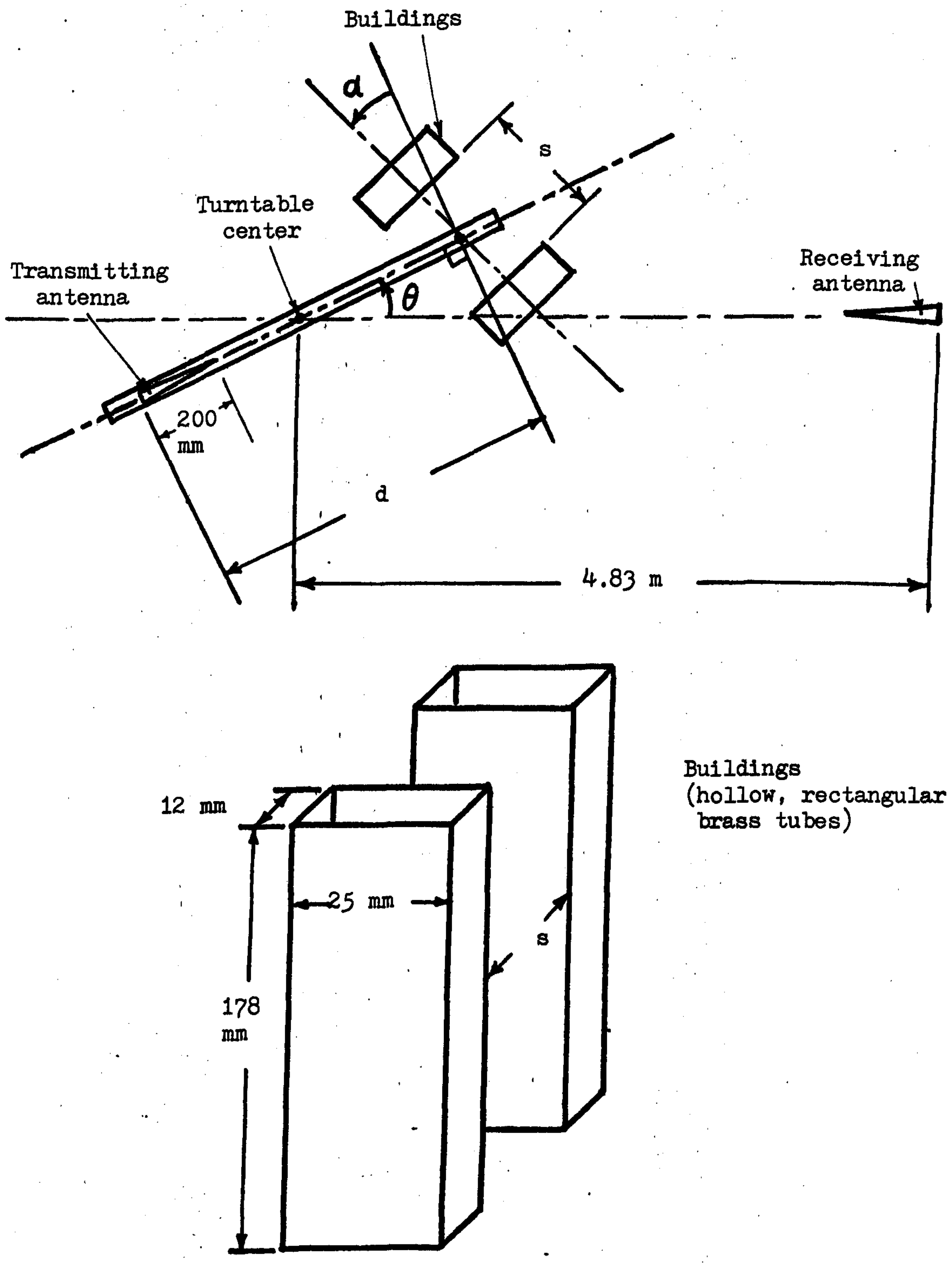

Fig. 12. Test arrangement for model of two high-rise buildings.

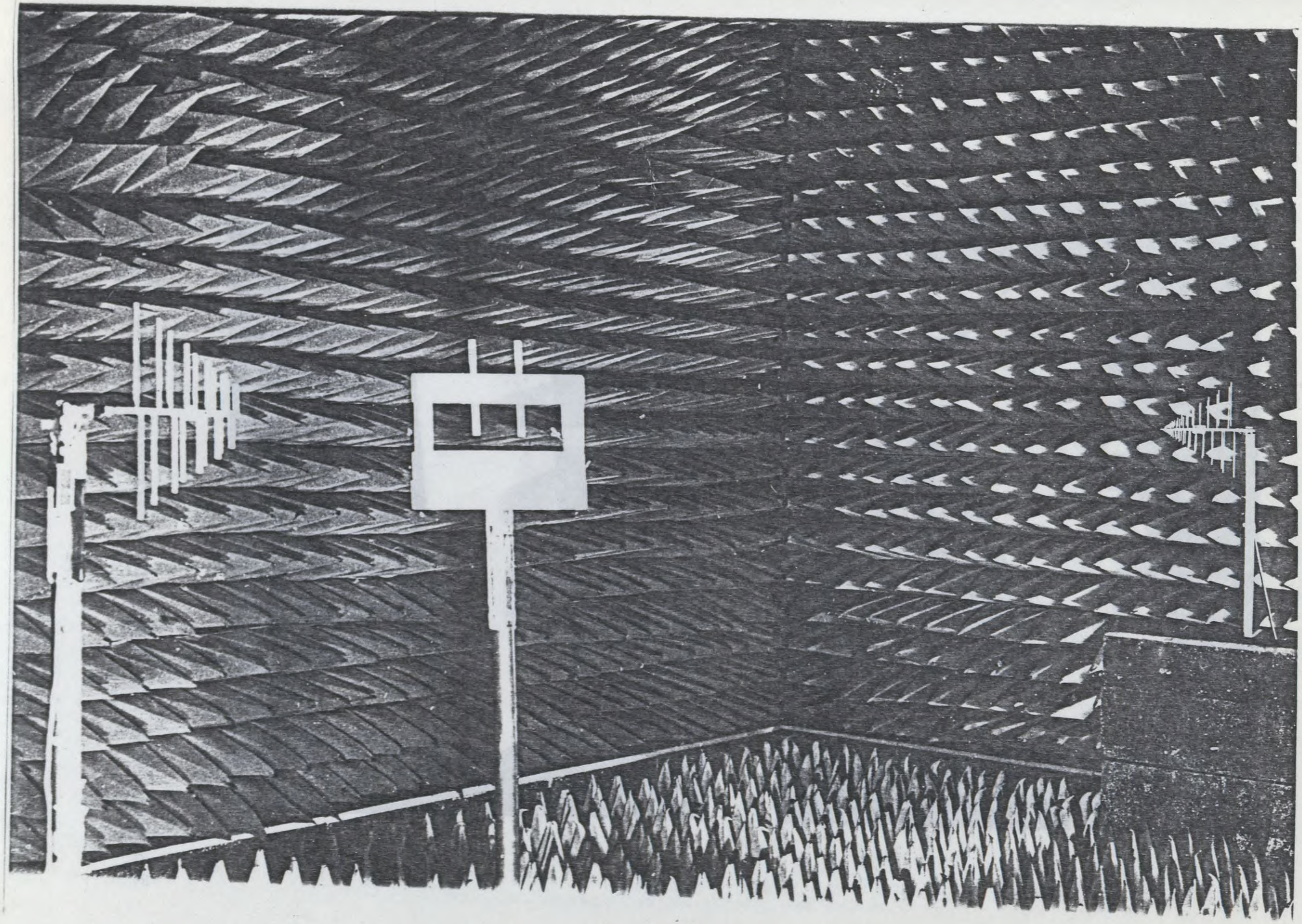

Fig. 13. Model high-rise building test facility in anechoic chamber.

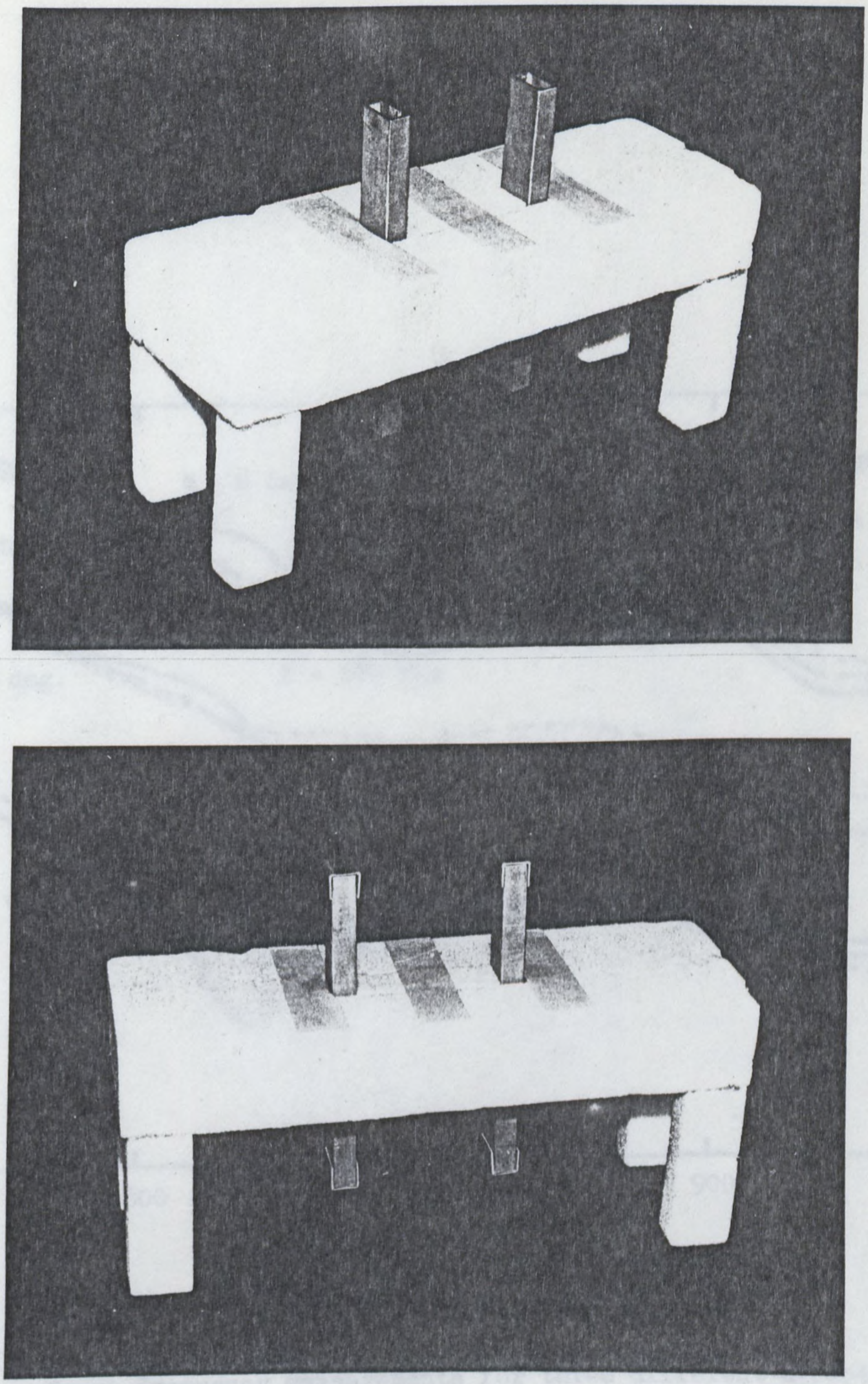

Fig. 14. Detail of model high-rise buildings (top), and metal-roof version (bottom).

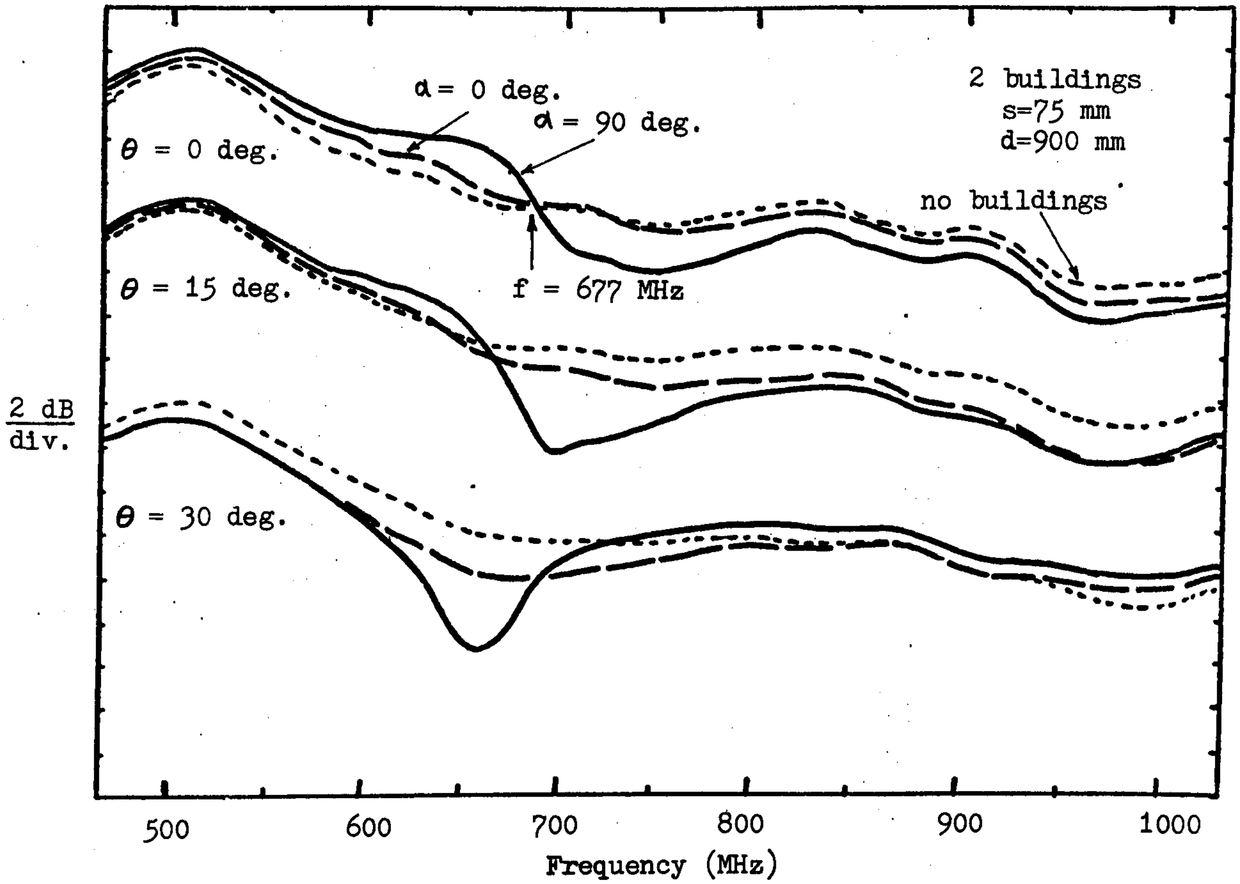

Fig. 15. Swept-frequency measurements for three different directions.

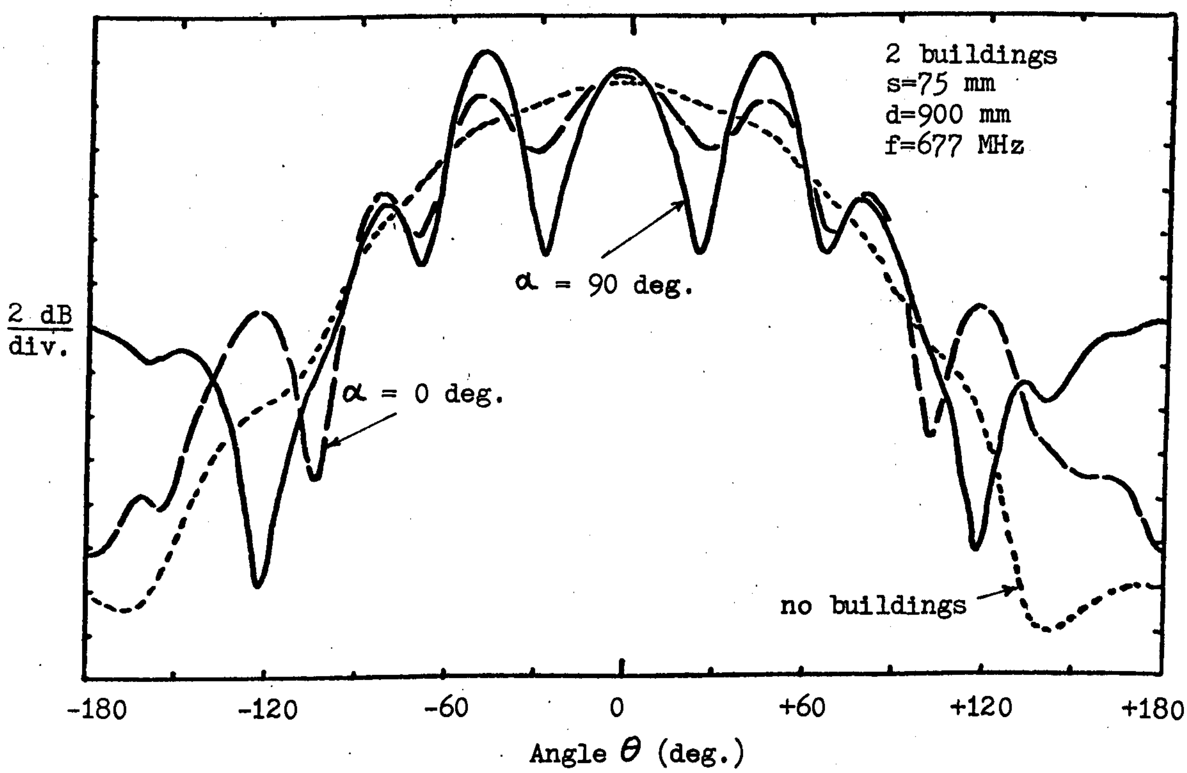

Fig. 16. Radiation pattern perturbation by two buildings under non-resonant conditions (α = 0 deg.), and under worst-case resonant conditions (α = 90 deg.).

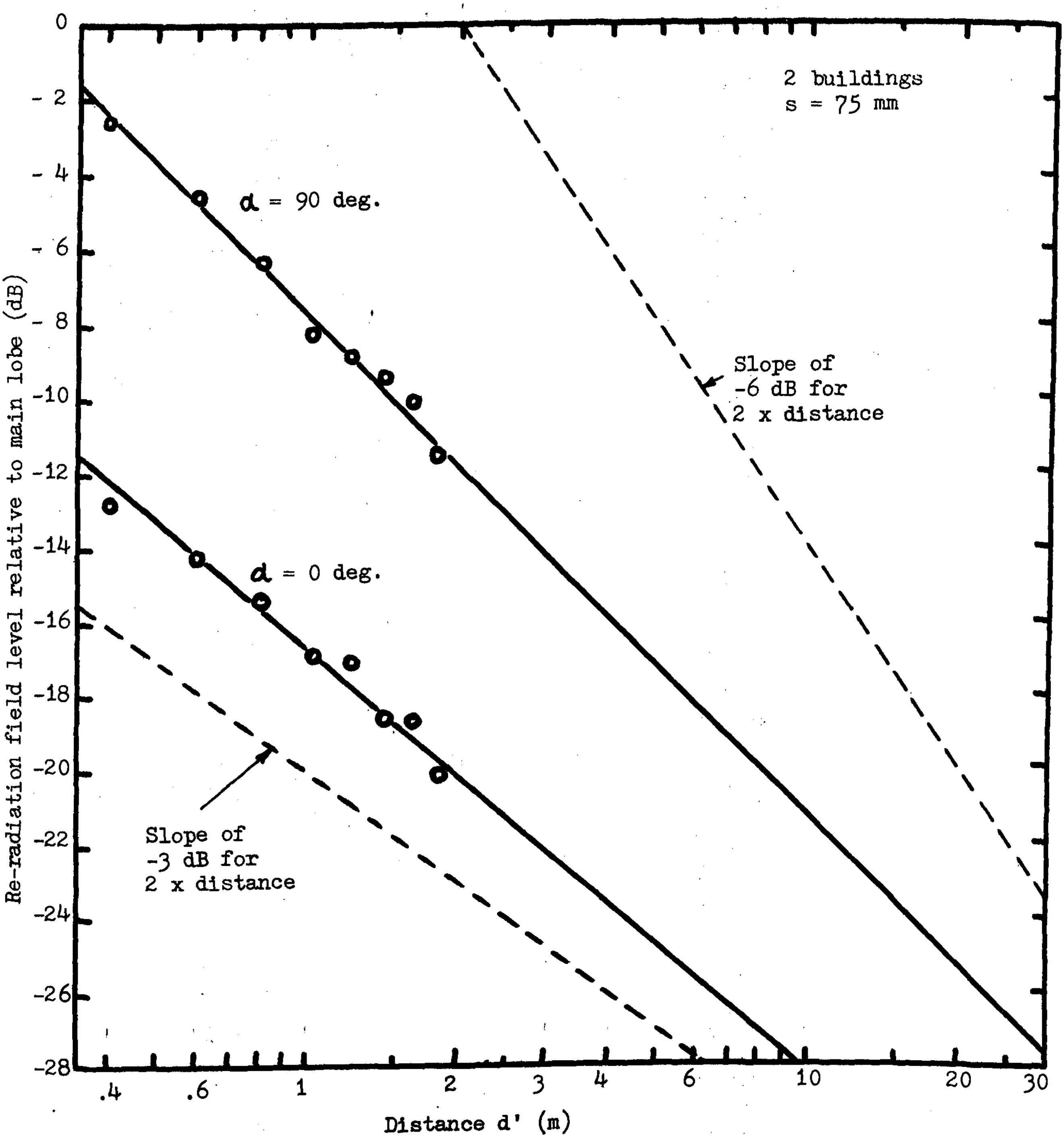

Fig. 17. Variation with distance of the re-radiated signal levels for two different orientations of a pair of model high-rise buildings. Note that at full scale the distance units would be km.

ANALYTICAL MODEL FOR THE RE-RADIATION FROM THIN TOWERS

ABSTRACT

This report summarizes the progress made in developing an analytical model for the re-radiation from thin towers due to an incident field from a two-element broadcast array. The results obtained by using this analytical model are compared with the measurements made on the NRC antenna modelling range, and as indicated in the various figures, the theoretical results provide a good agreement with the measured values. The analytical model has also been used to calculate the electric field in the null direction for varying distances of the tower from the broadcast array. On the basis of these calculations, it is found that the tower distance for a tower of any height should be more than 24 wavelengths from the broadcast array in order to have a null field of less than -40 dB.

INTRODUCTION

The determination of the re-radiation from thin towers requires a knowledge of the induced currents on the towers. These currents are induced on the towers due to the radiated field from the broadcast antenna array. These induced currents are then used to calculate the modified radiation pattern of the broadcast array.

Quite accurate but complicated expressions for the induced currents were derived by iterative methods [1, see Ch. 4, pp. 503, Eqs. (17a) and (17b)], and by superposition of direct and reflected waves [2]. These induced currents, in general, require a numerical integration to determine the modified radiation pattern of the broadcast array. Therefore, during the past few years, with the availability of high speed digital computers, the induced currents are more practically determined using numerical methods [3, 4]. The numerical methods have the advantages of being useful to analyze thin towers of an arbitrary height and at any distance from the broadcast array. The numerical method used is outlined in the following paragraphs, to determine the modified radiation pattern of the broadcast array along with a tower in the near vicinity.

It should be noted that the broadcast array in this analytical model is assumed to consist of a two-element dipole array. These elements are fed by inphase currents and are separated from each other by a half wavelength. The analysis can easily be extended, however, to include any number of elements in the broadcast array.

The second section of the report gives the formulation for the re-radiation calculations from towers located at arbitrary distances from the broadcast array. This is followed by a comparison of the theoretical results with the measurements performed by the NRC. Finally, the last section, presents the conclusions drawn from the present investigation.

FORMULATION FOR RE-RADIATION CALCULATIONS

The towers for the re-radiation calculations can be approximated as thin wires since the diameter of the tower is much smaller than the wavelength corresponding to the frequency of the AM broadcast station, as well as the height of the tower. The induced current on the tower or a thin wire is proportional to the incident field on the tower due to the broadcast array. Since the tower is assumed to be located close to the broadcast array, it is necessary to use the electric field expressions corresponding to a finite distance from the antenna. The field of most interest is the component of the electric field strength parallel to the antenna, that is E_z. The electric field E_z at any point P with coordinates (ρ,ϕ,z) due to a dipole of length 2H is given by [5] (reference pp. 336, eq. (10-74)).

$$E_z = -j\,30\,I_m \left[\frac{e^{-jkR_1}}{R_1} + \frac{e^{-jkR_2}}{R_2} - 2\cos kH\,\frac{e^{-jkr}}{r}\right] \qquad (1)$$

where as shown in Figure 1

$$R_1 = \sqrt{\rho^2 + (z-H)^2}\ ; \qquad R_2 = \sqrt{\rho^2 + (z+H)^2}$$

$$r = \sqrt{\rho^2 + z^2}$$

and $k = 2\pi/\lambda$

Without any loss in generality, the elements of the broadcast array can be assumed to be lying along the x-axis. Then, the total field incident at any point on the wire due to two dipoles is given by

$$E_z^i(\rho,\phi,z) = -j\,30\,I_m \left[\frac{e^{-jkR_{11}}}{R_{11}} + \frac{e^{-jkR_{12}}}{R_{12}} + \frac{e^{-jkR_{21}}}{R_{21}} + \frac{e^{-jkR_{22}}}{R_{22}} - 2\cos kH\,\frac{e^{-jkr_1}}{r_1} - 2\cos kH\,\frac{e^{-jkr_2}}{r_2}\right] \qquad (2)$$

where as shown in Figure 2

$$R_{11} = \sqrt{\rho_1^2 + (z-H)^2}\ ; \qquad R_{12} = \sqrt{\rho_1^2 + (z+H)^2}$$

$$R_{21} = \sqrt{\rho_2^2 + (z-H)^2}\ ; \qquad R_{22} = \sqrt{\rho_2^2 + (z+H)^2}$$

$$r_1 = \sqrt{\rho_1^2 + z^2} \qquad r_2 = \sqrt{\rho_2^2 + z^2}$$

$$\rho_1 = \sqrt{\rho^2 + d^2 - 2\rho d\cos\phi}$$

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and $\rho_2 = \sqrt{\rho^2 + d^2 + 2\rho d \cos \phi}$

Since the wire radius is assumed to be much smaller than the wavelength, the surface current on the wire can be considered to have only the axial component. With this form of current distribution, the incident field on the wire can be written as [3]

$$E_z^i (\rho,\phi,z) = j \frac{15\lambda}{\pi} \int_{-L}^{L} I(z^1) \frac{e^{-jkr}}{r}$$

$$\cdot \left[(1 + jkr) (2r^2 - 3a^2) + k^2a^2r^2\right] dz^1 \qquad (3)$$

where L = height of the wire;

$r = \sqrt{a^2 + (z^1 - z)^2}$;

and I(z) is the current distribution on the wire.

Knowing the incident field from the broadcast array, Equations (2) and (3) can be solved for the current distribution on the wire by using the method of moments. For the present analysis, the integral equation was reduced to matrix equations by using pulse and Direc delta functions as the basis and testing functions, respectively [4].

The electric field strength at any observation point with coordinates (r_0,θ_s,ϕ_s) is a sum of the fields radiated by the wire and the dipole array. The fields radiated by the wire has only a θ component and is found to be given by

$$E_\omega^S(r_0,\theta_s,\phi_s) = j \frac{60\pi}{\lambda r_0} e^{-jkr_0} \sin \theta_s \; e^{jk\rho \sin\theta_s \cos(\phi_s - \phi)}$$

$$\cdot \int_{-L}^{L} I(z^1) \, e^{jkz^1\cos\theta_s} \, dz^1 \qquad (4)$$

where (r_0,θ_s,ϕ_s) are the coordinates of the observation point;

and (ρ,ϕ,z) are the coordinates of the source point on the wire.

The distant radiated field from the dipole array also has only a θ component which after some far field approximations in Equation (2) is found to be

$$E_D^S (r_0,\theta_s,\phi_s) = j\, 120\, I_m \frac{\cos (kH \cos\theta_s)}{\sin\theta_s} \cos\left[kd \sin\theta_s \cos\phi_s\right]$$

$$\cdot \frac{e^{-jkr_0}}{r_0} \qquad (5)$$

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where d is the distance of the array elements from the origin.

Equations (4) and (5) have been used to calculate the modified radiation patterns of the broadcast array. These theoretical results along with the measured radiation patterns employing the NRC antenna modelling range are shown in Figures 3-5. In general, the difference between the theoretical and experimental results is not very appreciable.

RESULTS AND DISCUSSION

The amount of re-radiation from any tower, for a constant incident field, is a function of the tower height and its distance from the broadcast array. The analytical model of the preceding section has been used to analyze the effect of both these parameters.

The theoretical and experimental radiation patterns for towers of scaled heights 10", 20" and 30" are shown in Figures 3-5, respectively. These heights correspond to 0.254, 0.508 and 0.762 wavelengths at a frequency of 300 MHz. The towers for these patterns were located at a distance of two meters or two wavelengths from the broadcast array. As shown in Figures 3-5, the difference between the theoretical and experimental patterns is not very significant.

The broadcaster, in general, is mainly interested in knowing the electric field strength in the null direction due to the presence of a tower. The analytical model has also been used to study the effect of tower height and its distance from the broadcast array on the electric field in the null direction. The results for this analysis are plotted in Figure 6.

The electric field strength in the null direction has two peaks corresponding to heights of about 0.225 and 0.770 wavelengths for any distance from the broadcast array. The second peak is usually higher than the first peak by about 1.5 to 2.0 dB depending upon the distance of the tower. The electric field strength decreases with an increase in distance of the tower from the broadcast array. In order to have a field of less than -40 dB in the null direction, a tower of any height should be located at a distance of more than 24 wavelengths from the broadcast array.

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CONCLUSIONS AND DIRECTION OF FURTHER WORK

Conclusions drawn from the present investigation for the re-radiation from a tower are as follows:

(1) The scattered field from a tower is dependent upon the tower height and its distance from the broadcast array.

(2) The scattered field has two peaks corresponding to tower heights of about 0.225 and 0.770 wavelengths.

(3) The re-radiation from the tower decreases with an increase in distance of the tower from the broadcast array.

(4) The tower should be located at a distance of more than 24 wavelengths in order to have a field of less than -40 dB in the null direction.

The direction of future work will be to extend the numerical analysis to include the effect of more than one tower and to consider thick towers; i.e., towers having an appreciable diameter in terms of the wavelength, since single buildings undoubtedly radiate as thick monopoles.

6 January 1978

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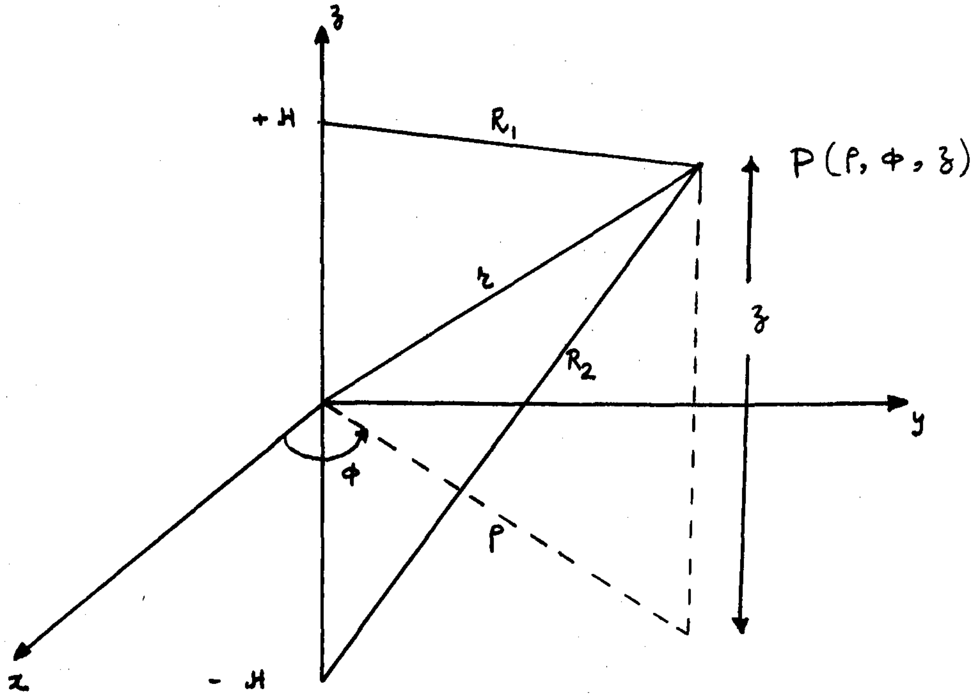


FIGURE 1. Geometry for fields near the antenna.

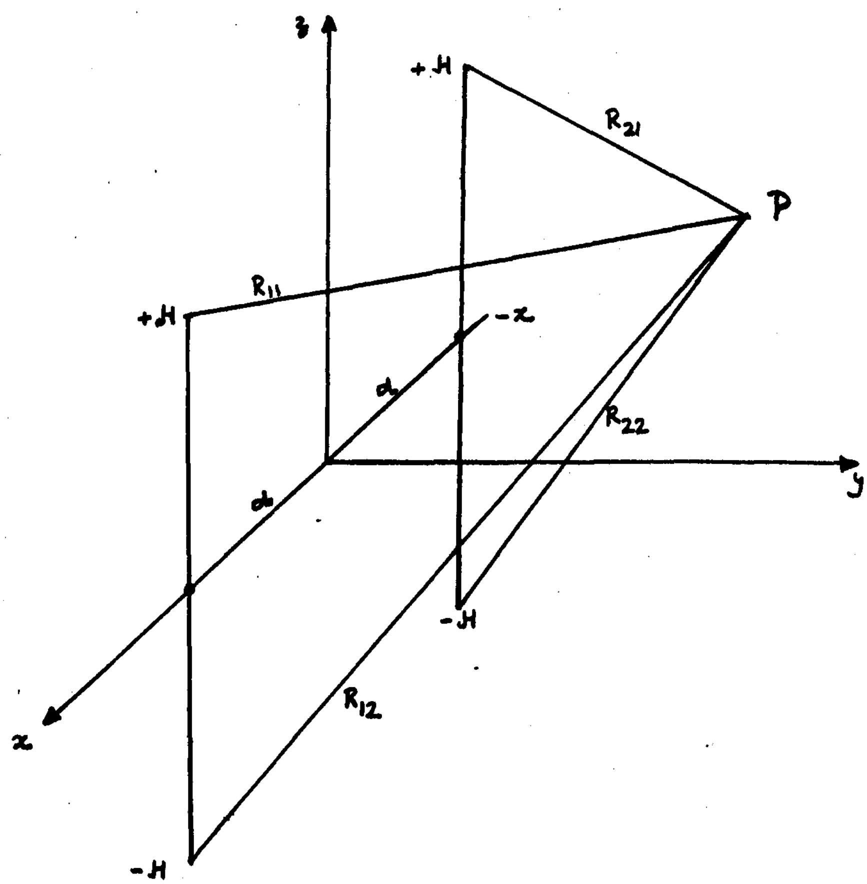
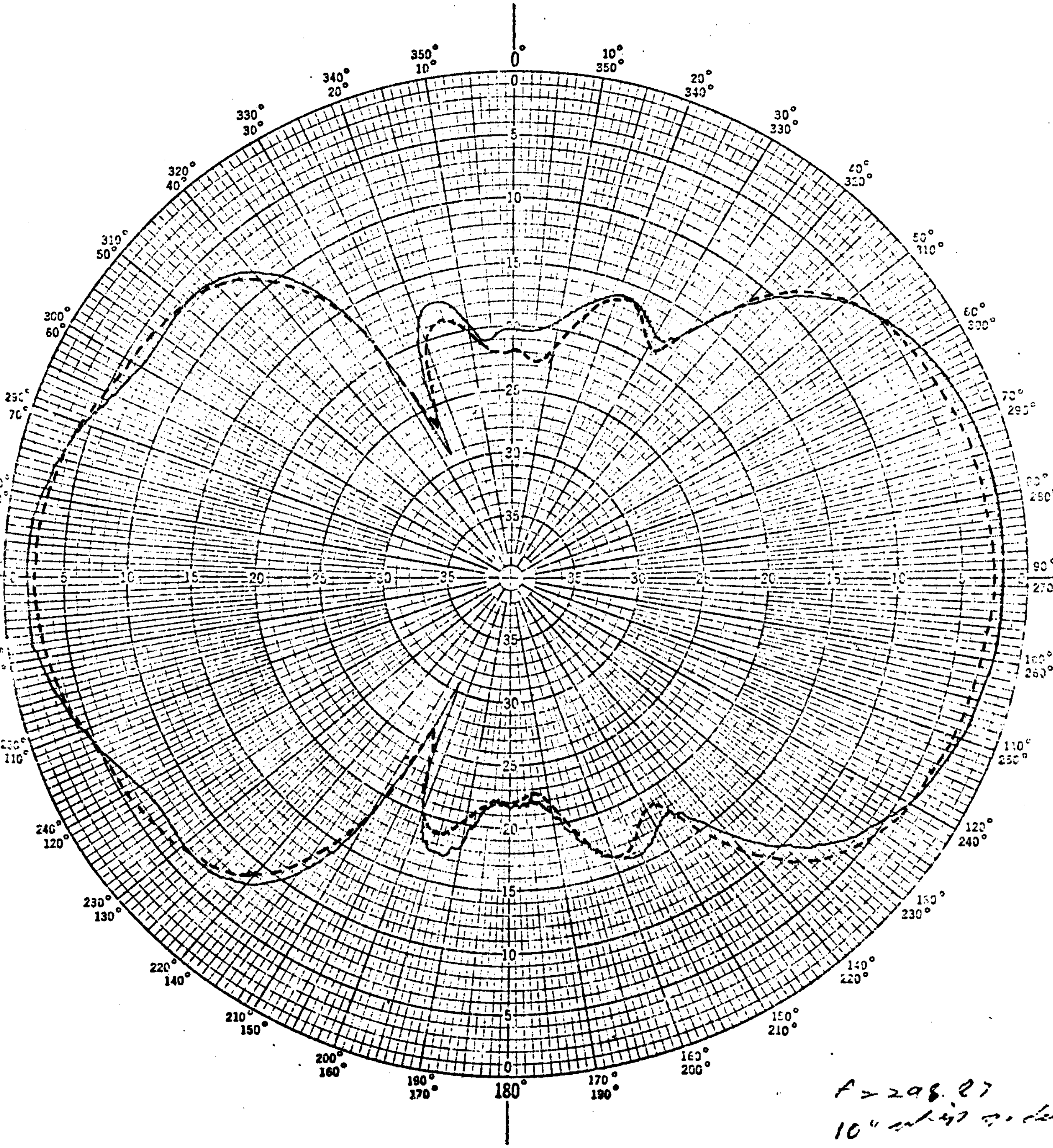


FIGURE 2. Geometry of the incident field on the wire due to two element broadcast array.

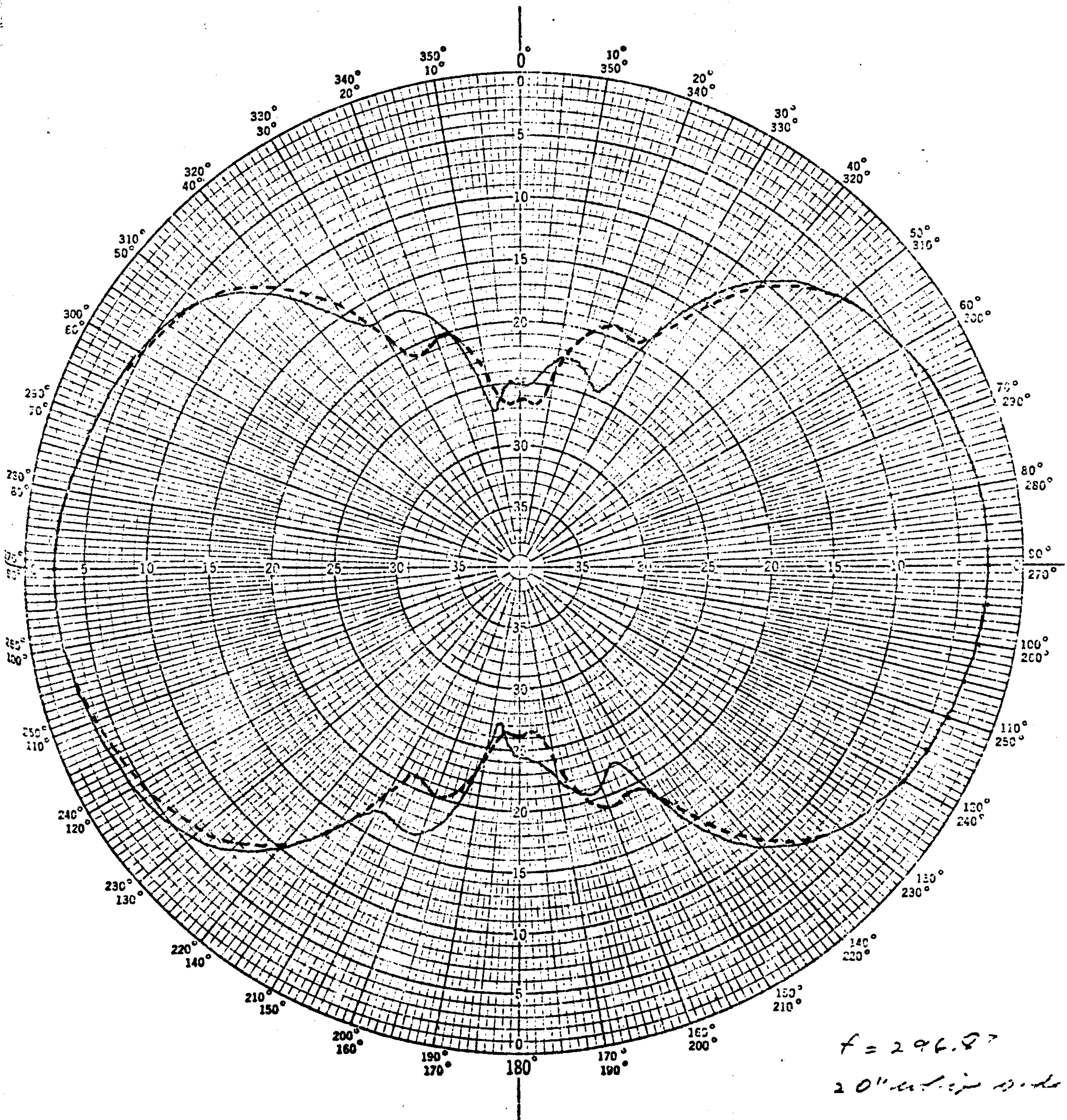


19.5

FIGURE 3

- - - Theoretical
—— Measured.

d = 0.4"



22

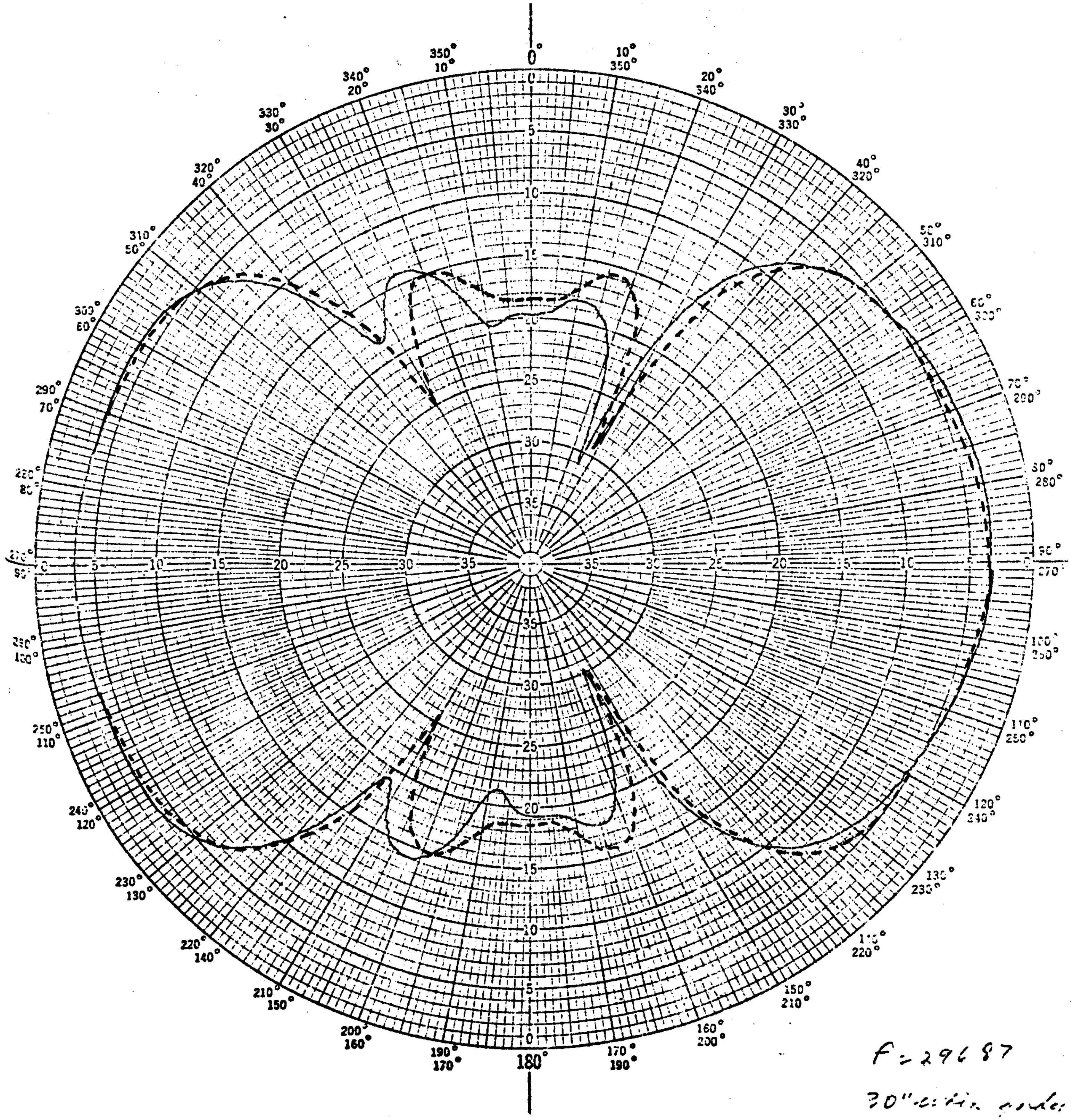
Polar Chart No. 127D
SCIENTIFIC-ATLANTA, INC.
ATLANTA, GEORGIA

FIGURE 4

——— Measured

- - - Theoretical

d = 0.4"



17

Polar Chart No. 127D
SCIENTIFIC-ATLANTA, INC.
ATLANTA, GEORGIA

FIGURE 5

—— Measured
---- Theoretical

d = 0.4"

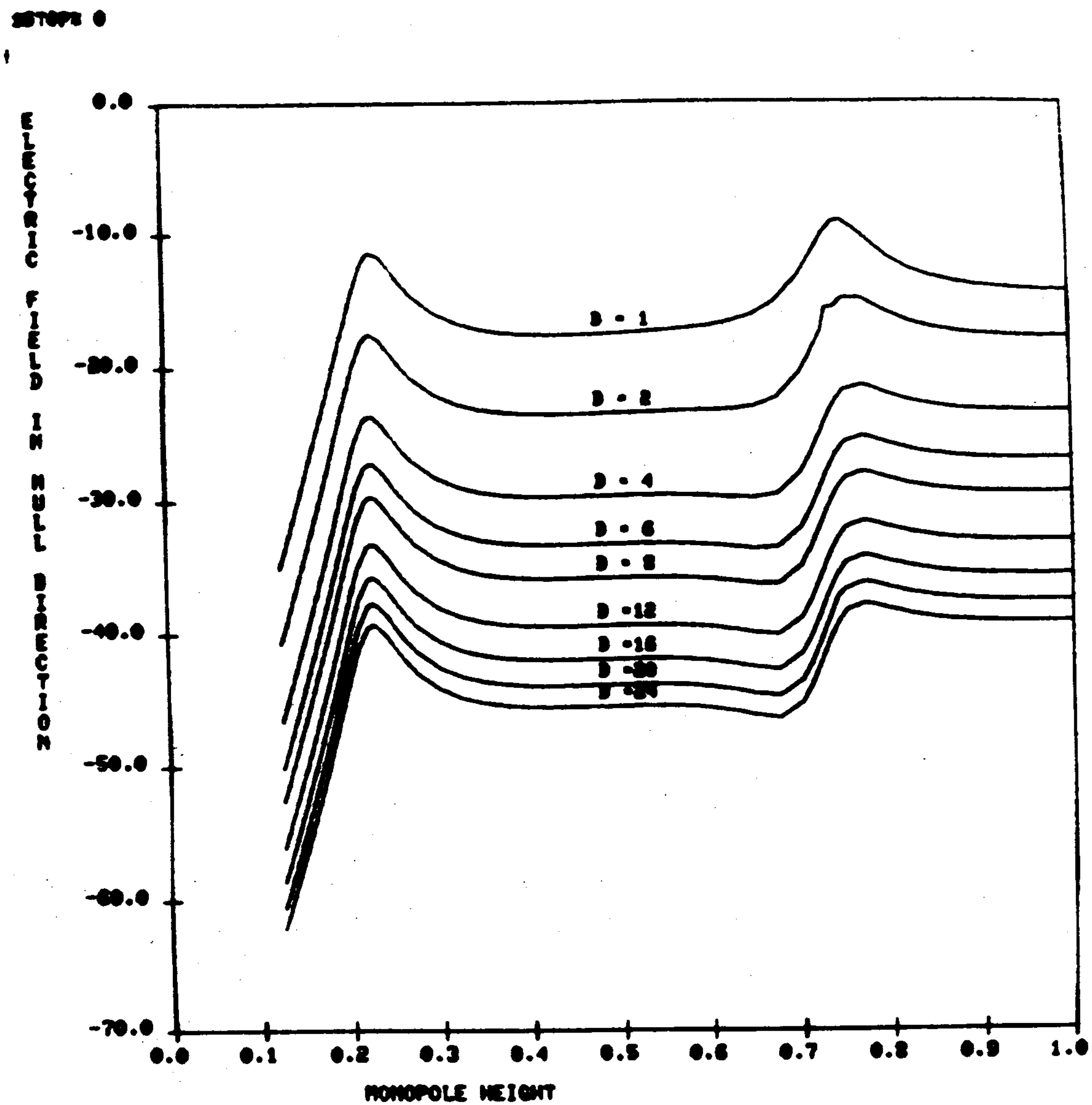

ELECTRIC FIELD IN NULL DIRECTION
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
D = 1
D = 2
D = 4
D = 6
D = 8
D =12
D =16
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
MONOPOLE HEIGHT

FIGURE 6