1959

Design and construction of an automatic antenna pattern plotter and design of a microwave absorbent material

Norval D. Wallace

DESIGN AND CONSTRUCTION OF AN AUTOMATIC ANTENNA PATTERN PLOTTER AND DESIGN OF A MICROWAVE ABSORBENT MATERIAL

BY

NORVAL DALE WALLACE

A
THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

Rolla, Missouri

1959

Approved by

Roger E. Nolte (advisor) G. G. Skitek

R. M. Rankin

ACKNOWLEDGEMENT

The author wishes to acknowledge the cooperation of Bob Stebbins and Buehl John in the construction work involved, Dr. Roger E. Nolte for his helpful suggestions on the servo design of the proposed system, and especially of Professor G. G. Skitek for his guidance and many helpful suggestions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT.)

INTRODUCTION

The following study consisted of two problems. One was the design and construction of an automatic antenna pattern plotter, and the other was the design of a microwave absorbing material for use in a darkroom.

Before any antenna design can be accomplished, the designer must have adequate testing facilities available. The theoretical design must be validated by appropriate experimental results. One of the most important testing facilities to an antenna designer is one which will enable him to obtain a plot of the antenna field pattern. The field pattern is a plot of relative field intensity versus azimuth angle. The pattern can be taken at various elevation angles of the antenna to obtain a three-dimensional pattern. The pattern may be obtained by use of an antenna range or a radiation darkroom. Of course, the darkroom may be used for other measurements for which it is necessary to keep reflections from nearby bodies to a minimum.

An antenna range is an outside testing facility for obtaining field patterns. It is adaptable to about any range of frequency.

A darkroom is an inside resting facility. It is most adaptable to higher frequencies because of the shorter wavelengths and smaller size of associated components. The radiation at these higher frequencies is much easier to absorb, which means less costly design of the darkroom. The darkroom is very convenient to use because it is an inside testing facility.

A complete testing facility should include both an antenna range and a darkroom. Antenna ranges and darkrooms are commercially available, but the cost is prohibitive. Therefore, this thesis project was undertaken in which an attempt was made to design an automatic antenna pattern plotter and design a darkroom, keeping the cost in both cases to a minimum.

The following pages show the development of the pattern plotter and the darkroom. Since the study consists of two parts, the design, experimental data, and conclusions of each part are discussed separately. No theoretical design is involved. All the work is experimental. In the case of the pattern plotter, equipment was used that was already available to keep the cost to a minimum. The problem was adapting the equipment to the system.

Naturally, a system such as this will have its limitations. Therefore, suggestions for additional development of the pattern plotter are included in the thesis. These suggestions are in the form of a preliminary design of a more elaborate pattern plotter. If at some later date the need for a better pattern plotter is needed, this design will form the basis for the construction of one.

It is felt that with the darkroom and pattern plotters available, the Electrical Engineering Department will be equipped to carry out research in the antenna field. Also, the new facilities may be used as additional laboratory equipment for undergraduate and graduate courses in antennas and UHF techniques.

REVIEW OF LITERATURE

Much has been written on the measurement of antenna patterns and very little on the microwave absorbers that are used in darkrooms. Almost any good book on antenna theory will have a section on antenna pattern measurements, and several fine articles have been published on the subject. This section will discuss some of the theory and problems associated with antenna pattern measurements as found in some of the leading textbooks and articles. Also, a part of this section will be devoted to a discussion of the few articles that have been written about microwave absorbers and darkrooms.

ANTENNA PATTERN MEASUREMENTS

The far-field pattern of an antenna is one of its most important characteristics. If the test antenna is not at a sufficient distance from the antenna under test, the near-field pattern will be measured. The near-field pattern is relatively unimportant, and is, in general, a function of the distance from the antenna. The shape of the far-field pattern is independent of the distance from the antenna.

Due to the reciprocity theorem, the field of an antenna is the same whether it is operated as a transmitting antenna or a receiving antenna. However, in pattern measurements, operating the antenna under test as a receiver is usually better.(1) The transmitting antenna is fixed, and the antenna

---

[1] All references are in bibliography.

under test is rotated about its axis.

An equation has been derived which will insure the pattern measurements to be in the far-field and to have negligible error due to the wave striking the antenna not being a plane wave.[1,2]

Consider Figure 1. D is the aperture distance of the antenna under test. The aperture in question is the physical aperture which is defined as the cross section of the antenna in square wavelengths when oriented perpendicular to the direction of propogation. It is desired that a plane wave be present at this antenna. R is the distance from the transmitting antenna which has an aperture of dimension d.

Applying the pythagorean theorem to the upper triangle in the figure

$$R^2 + \left(\frac{D}{2}\right)^2 = (R + \Delta R)^2$$

If

$$\Delta R << R$$

$$2 \Delta R R = D^2/2$$

or

$$R = \frac{D^2}{8 \Delta R}$$

Some people[3] have stated that the maximum ΔR that can be tolerated is

$$\Delta R \leq \lambda/16$$

The phase difference in the case of

$$\Delta R \leq \lambda/16$$

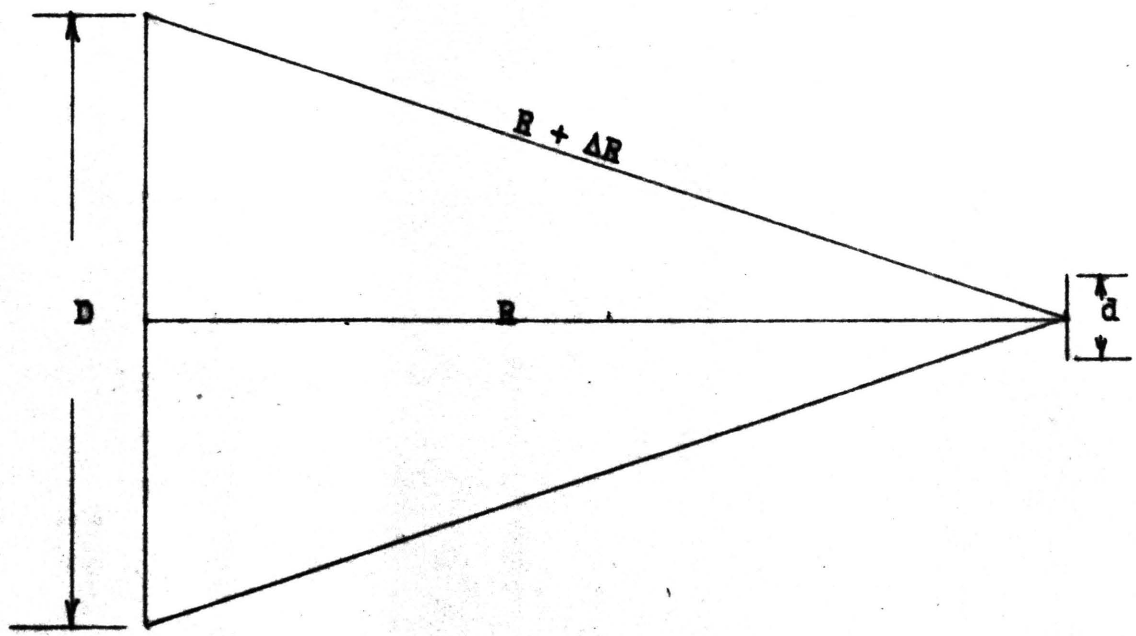


Figure 1. Figure for determining phase error.

would be

$$\frac{360}{\lambda}\frac{\lambda}{16} = 22.5°$$

In most cases this much phase difference can be tolerated. This would yield

$$R \geq \frac{2D^2}{\lambda}$$

That the minimum distance of measurement is a function of antenna aperture and wavelength λ can be seen. In some cases of high frequencies and large antennas this distance may be quite large.

Another consideration when choosing a testing site is the reflections of surrounding objects and the ground. The best site for two antennas is between two high points. This can be achieved by situating the antennas at the edges of two tall buildings or on towers.

Consider Figure 2. The first minimum in the transmitting beam will occur at approximately λ/d radians from the peak.[2] Therefore,

$$h/R/_2 \cong \lambda/d$$

or

$$h = \frac{R\lambda}{2d}$$

If

$$R \geq \frac{2D^2}{\lambda}$$

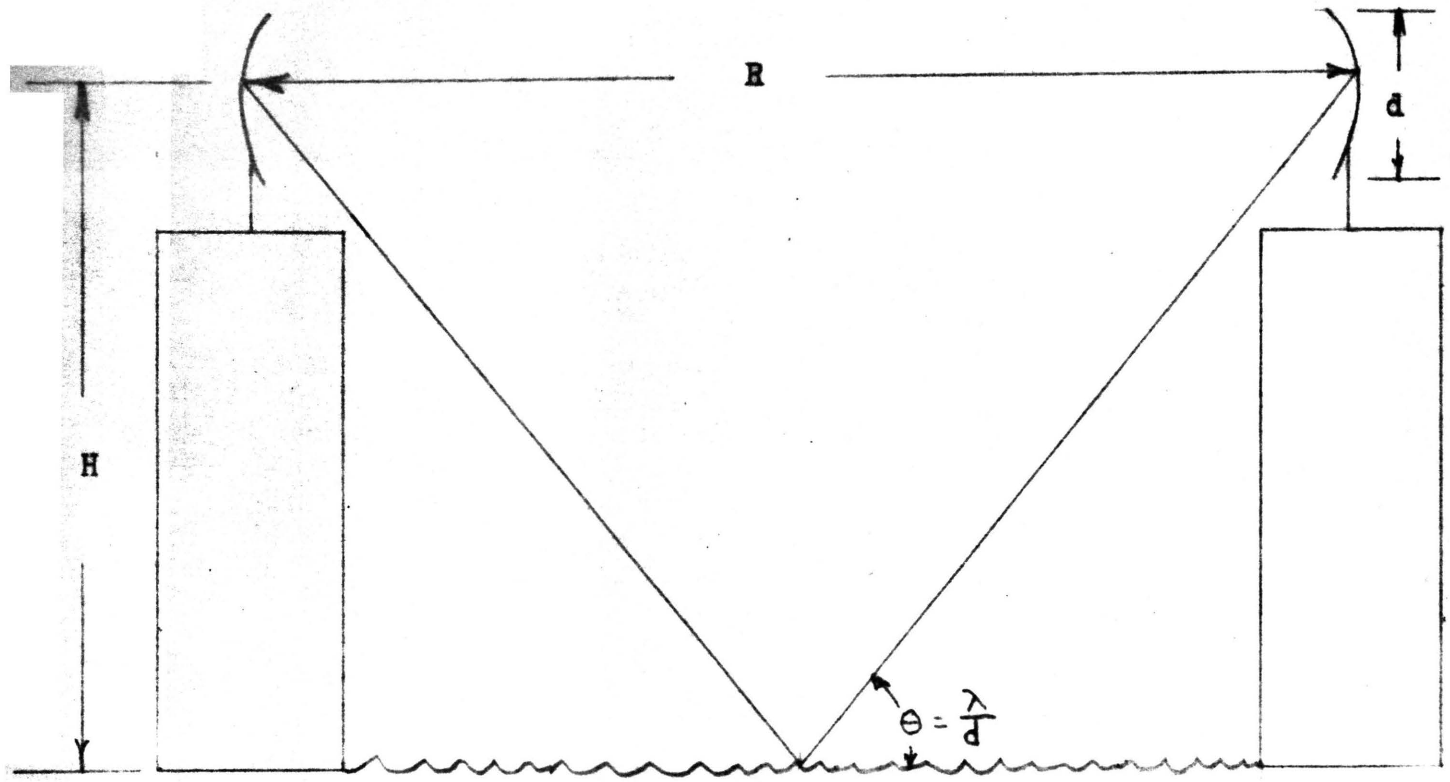


Figure 2. Figure to illustrate error due to ground reflections

as prescribed before,

$$h \geq \frac{D^2}{d}$$

This is the height requirement to minimize ground reflections.

The use of absorber screens placed on the ground halfway between antennas can help minimize the effect of the reflected ground beam.

The antenna under test should be placed on a rotating mount. The mount should have two rotation axes, an azimuth axis and an elevation axis. With the two rotational axes, complete space patterns can be obtained.

The antenna mount should be aligned properly so that the vertical axis is perpendicular to the line of sight between the transmitter and the test antenna. This insures that the antenna will rotate horizontally or in the proper azimuth cut. The transmitting antenna should be aligned properly with the test antenna so that peak transmitted power is being received. The antenna is then rotated in azimuth, and the power received is a function of the angle of azimuth recorded.

One procedure for obtaining complete coverage is to take the pattern in normal azimuth; then rotate the antenna under test through Θ° in elevation and obtain the Θ cut. This can be done for any number of cuts that are of interest.

A certain amount of equipment is necessary for each testing site.[3,4] Usually an automatic pattern recorder is used to facilitate antenna measurements because patterns can be taken in a short period of time. This is of great value when changing characteristics of the antenna under test to see the effect on the pattern.

Any good transmitter with the proper power requirements will do as a power source. At UHF frequencies reflex klystrons are good power sources for several reasons. They are easily adjusted and can be tuned over a wide frequency range with precision. They and their associated power supply for low power applications are small and lightweight. They are easily cooled by air blowers.

Bolometers and crystals are most frequently used as detectors in microwave antenna measurements. The law of behavior of a bolometer stays at two over a wide range of power, while the law of behavior of a crystal varies. However, crystals are more sensitive than bolometers.

After a signal is detected, it must be amplified before it is recorded. Depending upon whether or not the signal is modulated, the amplifier must be an audio or d-c amplifier with the following characteristics. It must have good stability, have a good signal to noise ratio, and be free from influence of outside fields. There are many amplifiers with these characteristics available, although the good stability is hard to realize when using a d-c amplifier.

The simplest type of recorder is merely a recording ammeter. The recorder is fed by the audio or d-c amplifier, depending on which is used. If the recording paper of the meter is synchronized to the turning of the antenna, a rectangular plot can be obtained.

Figure 3 shows a more elaborate system for an automatic antenna pattern recorder.[2] It works as follows:

The azimuth position of the antenna is transmitted to the selsyn motor by the selsyn generator. This causes the recording drum to be synchronized with the antenna rotation. The signal, after being detected, is fed to the signal amplifier. The output of this amplifier is felt across the potentiometer. This voltage is fed to the potentiometer amplifier and is compared with a reference voltage. The difference between the two voltages is fed to the servo amplifier, and this amplified voltage drives the servo motor which moves the potentiometer arm in such a way as to reduce the difference between the potentiometer voltage and the reference voltage to zero. The stylus is connected to the same mechanism that drives the potentiometer arm so that it is moved proportional to the input signal. This gives a rectangular plot of relative power versus azimuth. Of course, a polar plotter could be substituted for the rectangular plotter and a polar diagram obtained directly.

MICROWAVE ABSORBERS

With many small microwave antennas, obtaining the far-field pattern at fairly short distances is possible; therefore, working indoors is convenient. Of course, when working indoors there is the possibility of getting reflections from the walls, floor, ceiling, or any other reflecting object in the vicinity. These reflections must be minimized.

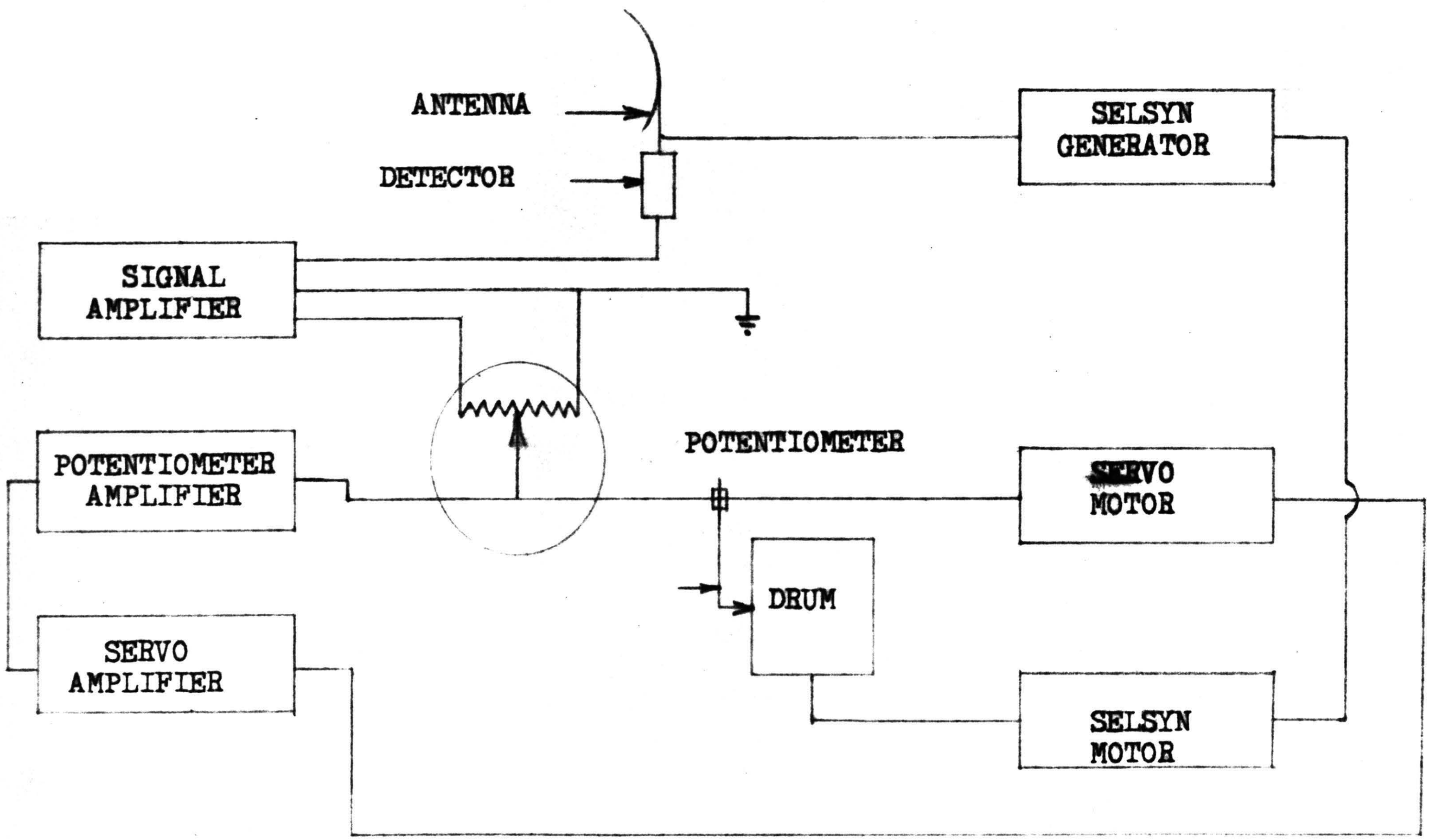


Figure 3. A typical automatic antenna pattern recorder.

An anechoic chamber or darkroom - as it has been called - is a special chamber designed to keep these reflections to a minimum. The construction of such a darkroom is dependent upon having a suitable absorbing material with which to line the insides of the room. This material must effectively absorb a good percentage of the incident power over the range of frequencies for which the darkroom is to be used. At the same time it should be lightweight and low in cost.

The ideal absorbing material would be a lossy material that has a low dielectric constant in order that it may be a better match to free space and at the same time have a high enough attenuation so that the material must not be too thick.

One very effective way of doing this is to impregnate a mat of curled animal hair with a lossy mixture of conducting carbon black and neoprene rubber. The hair is lightweight, tough, and resilient. It is excellent for this purpose. The hair is widely used for upholstering and packing and is readily available commercially.

The secret of keeping the absorber width to a minimum while retaining high efficiency lies in the manufacturing process. The absorbing mixture is applied to the hair in varying amounts from the front to the back to get a more effective match to air. This reduces the surface reflections. Experiments have shown[5,6] that geometric shaping of the front face of the absorbing material may minimize air-material interface reflections over a wide frequency range. One method is to shape the material in pyramids. This is only necessary for wide-band absorbers, and for this to be effective the material must be relatively thick. These methods are similar to using tapered waveguide sections to make an impedance transformation. The pyramid-type material was found to be[5] better at lower frequencies, but at 3000 mc and above there was essentially no difference.

Figure 4 is a typical test apparatus for testing microwave absorbers.[5] The arch is mounted on two tables. On the middle table a metal plate and piece of microwave absorber are placed. Transmitted energy from one horn is reflected from the metal plate to a receiving horn. A comparison of the amount of energy reflected from the metal plate with that reflected from the plate when covered by a microwave absorber allows a determination of the percentage of incident power reflected by the absorbing material. The two horns are mounted on the arch which has the various angles of incidence marked off on it. This allows a convenient variation of the angle of incidence. Figure 5 is a typical curve of percentage reflection versus angle of incidence.[5]

The absorbing material may be backed by a conducting sheet or by some non-conducting material such as wood. Above 2500 mc, tests have shown[5] that the performance is about the same in either case.

Measurements have been made to determine the upper limit of power-handling ability of these materials.[5] It

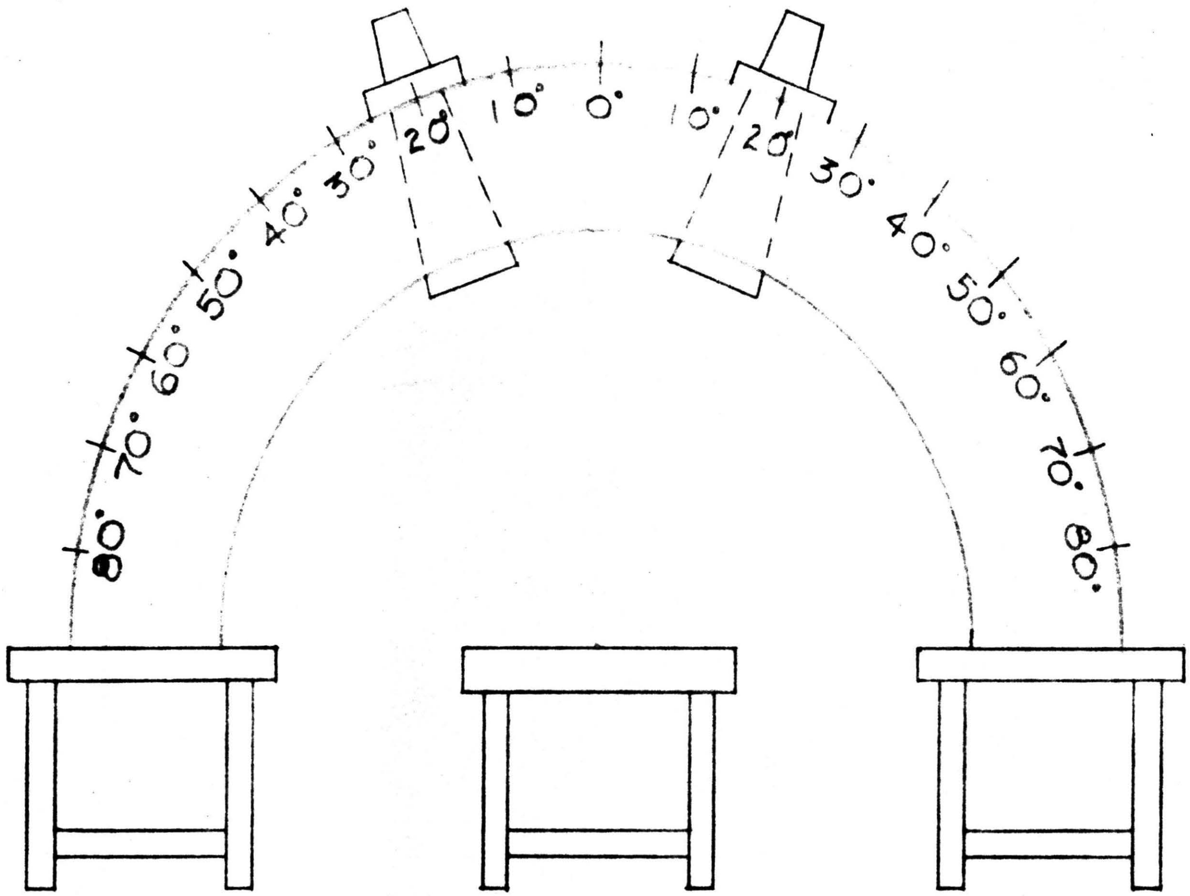


Figure 4. Apparatus for testing microwave absorbers.

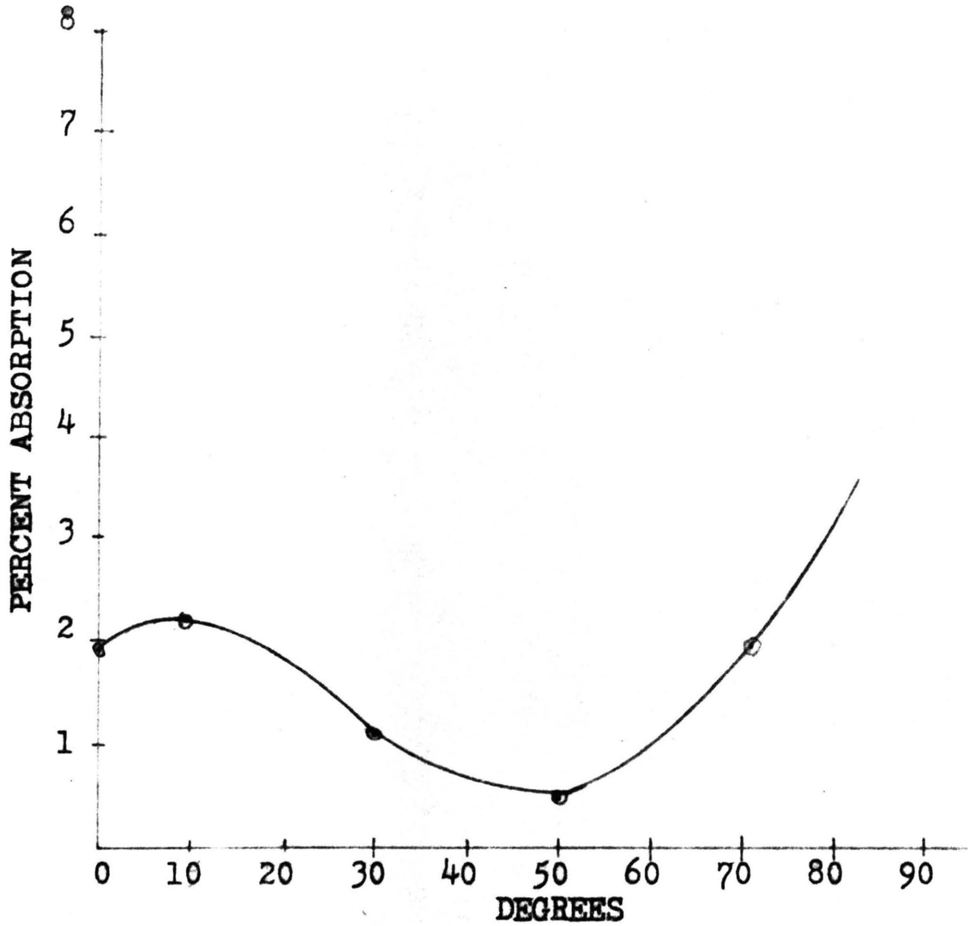


Figure 5. Typical absorption curve for a microwave absorber

was found that at 1300 mc both flat and pyramid types of materials could dissipate as much as one watt per square inch, and at this power level the temperature of the hair was around 200 degrees F.

The greatest error in pattern measurement in a dark-room will occur when the antennas are oriented such that the transmitting antenna is pointed to a spot on the wall halfway between the transmitting and receiving antenna. This angle is best for reflection off the wall.

If the angle of rotation is , and the effect of the reflection is represented by an image antenna behind the wall, then the ratio of undesired signal to desired signal strength is[5]

$$\left| \frac{E_u}{E_d} \right| = \frac{R_1}{R_2} \sqrt{\frac{P_1 G_T(\theta) G_R(\theta_r)}{P_T G_T(\theta_r) G_R(\theta)}}$$

where

R_1 is the distance between transmitting and receiving antennas.

R_2 is the distance between image and receiving antennas.

P_t is the total power radiated by the transmitting antenna.

$G_T(\theta)$ is the gain of the transmitting antenna.

$G_R(\theta)$ is the gain of the receiving antenna.

If

$$\frac{P_1}{P_T} = \alpha(\theta_r)$$

the power reflection coefficient at the angle θ_r , and if

$$G_T(\theta) = G_R(\theta)$$

or the transmitting and receiving antennas are identical, then

$$\left|\frac{E_u}{E_d}\right| = \frac{R_1}{R_2}\sqrt{\alpha(\theta_r)}$$

If

$$\frac{R_1}{R_2} = 1/2$$

(which is the case for the transmitting antenna pointed to a spot halfway between the transmitting and receiving antennas) and

$$\alpha(\theta_r) = 1\%$$

then

$$\left|\frac{E_u}{E_d}\right| = .05$$

and the pattern would be off by .5 db at this angle. This much error can usually be tolerated.

Measurements to determine the relative effectiveness of darkrooms as compared with outside antenna ranges have been made.[5] In cases where the absorbing material has been properly designed, it has been found that the darkroom was at least as effective and in some cases more effective than the outside range.

The absorbent material is usually designed for a maximum of two percent reflection for normal incidence at the operating frequency. A room using absorber so designed would actually measure much better.[6] This is due to most of the absorber being better than the two percent figure and the possibility of multiple reflections.

The absorbing material is most effective at higher frequencies; therefore, if it is operating well at the x-band of frequencies, which is around 10,000 mc, there would be no difficulty in extending the frequency range higher. There would be difficulty at lower frequencies, however.

Perhaps some shape of room other than rectangular would seem feasible. It is possible that reflections could be minimized better with a better-shaped room, but the results with a rectangular room are satisfactory enough that the additional effort and time required to design a better-shaped room is impractical.

These absorbing materials are primarily designed for indoor use, but they can withstand considerable exposure to rain and sun. One sample was kept under water in the Potomac River for ten weeks.[5] Upon removal and drying, the reflection from it was found to have changed by less than 3 db. Other samples showed less than 4 db variation in reflection after having been exposed to the weather for eleven weeks.

This suggests that the material could be used on outside ranges for covering troublesome reflecting bodies that are nearby.

DESIGN OF ANTENNA RANGE

Since the design of the antenna range was to be done with equipment that was available on the campus at as low cost as possible, there was very little theoretical design work involved. The problem consisted of finding equipment that would do the job and adapting it to the system. A block diagram of the antenna range is shown in Figure 6. The turntable has for its base a surplus radar antenna mount which was adapted for use with the system. Figure 7 is a picture of the turntable that was built for the system with an antenna in place. All parts were made out of wood to minimize reflections. All connections were made with wooden pins. The cradle was made so that it could be rotated in elevation in steps of fifteen degrees up to sixty degrees. Holes were bored in a wheel at the side of the cradle, and plugs were provided so that the cradle can be held in position at the different angles. Other elevation angles can be obtained by clamping the cradle in position. The base on which the cradle sits is on wheels. The wheels ride on another base which will be supported by the tower eventually. The shaft fits into the base and is clamped by three screws. The shaft was made only three feet long, but it can be made as long as desired in the final installation.

The transmitting and receiving synchros are high torque General Electric synchros. The transmitting synchro has a handle on the shaft which is used to control the rotation of the turntable and the recording ammeter. One of the

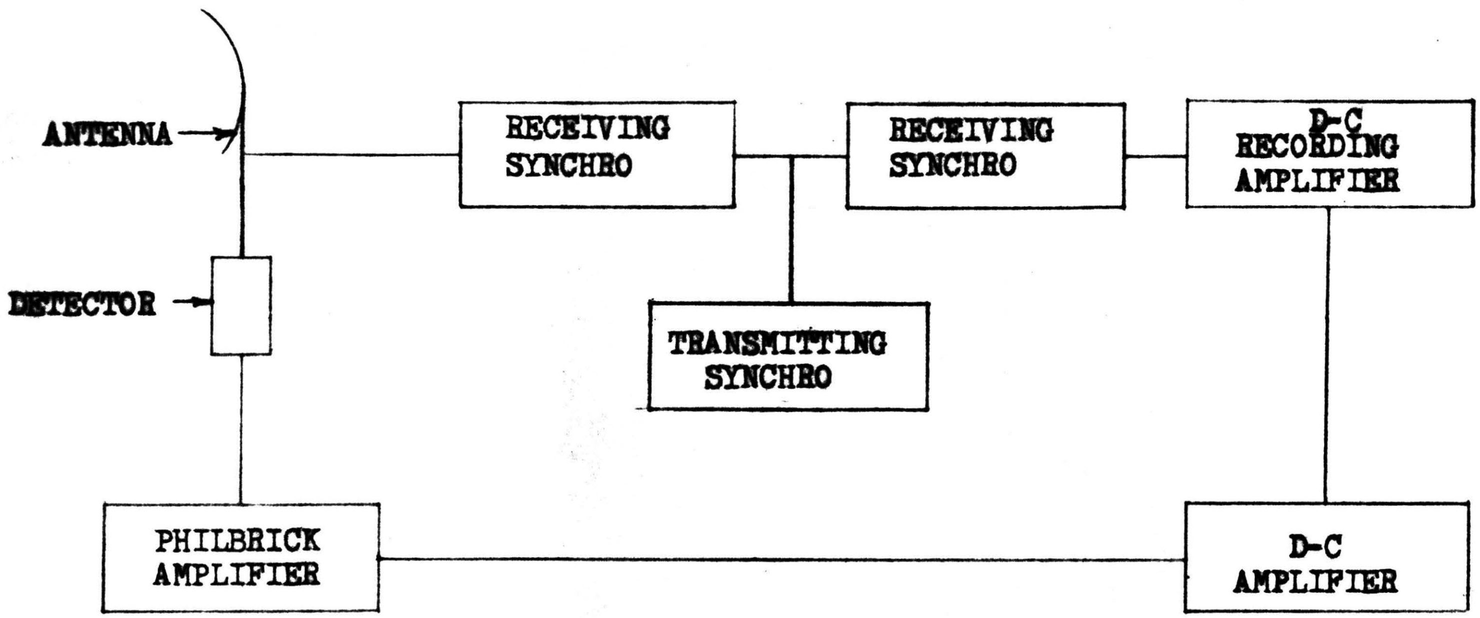


Figure 6. Block diagram of automatic antenna pattern plotter

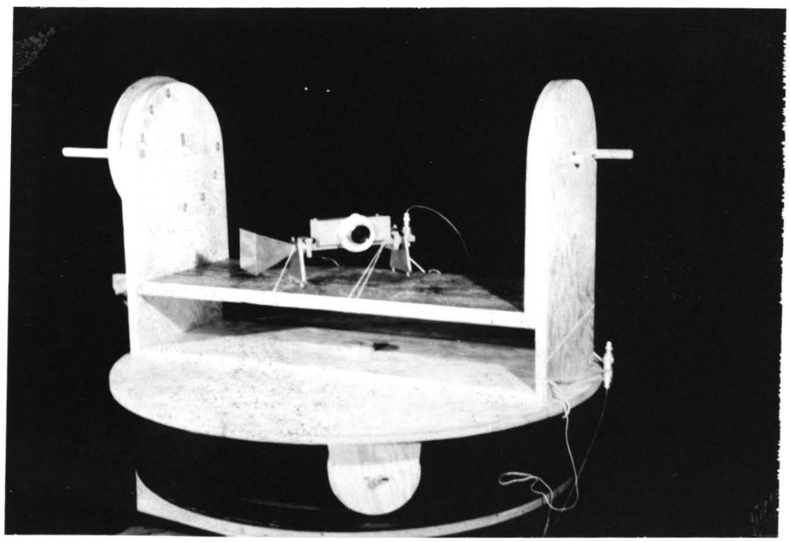


Figure 7. Antenna turntable.

receiving synchros is mounted on the turntable base through a large step-down gear ratio. The other receiving synchro is mounted in the control box and is attached to the shaft of the recording ammeter through a step-down gear ratio. The transmitting synchro is also mounted in the control box. A switch is provided on the control box to switch the power to the synchro control windings on and off.

Since no slip rings were provided, only one complete rotation of the turntable in any one direction is allowed. The synchros will turn in both directions, but the recording ammeter can only turn in one direction. Therefore, provision had to be made to switch directions of the turntable rotation of the recorder. This was done by providing a switch to switch two of the stator leads of the turntable synchro. This switch was placed on the control box.

The d-c amplifier is made by the General Radio Company and is designed for use with the five milliampere Esterline-Angus recording ammeter which is used in the system. The instrument is a three-stage, direct-coupled amplifier. On the most sensitive adjustment, 100 millivolts input gives full-scale output of five milliamperes.

The Esterline-Angus recording ammeter is normally run by a clock, but that mechanism was taken loose in order that the meter could be driven by a synchro. The paper winds around a reroll stick that operates something like a window shade. The paper can be pulled out for ready inspection, and when released, it snaps back into place. Figure 8 is a

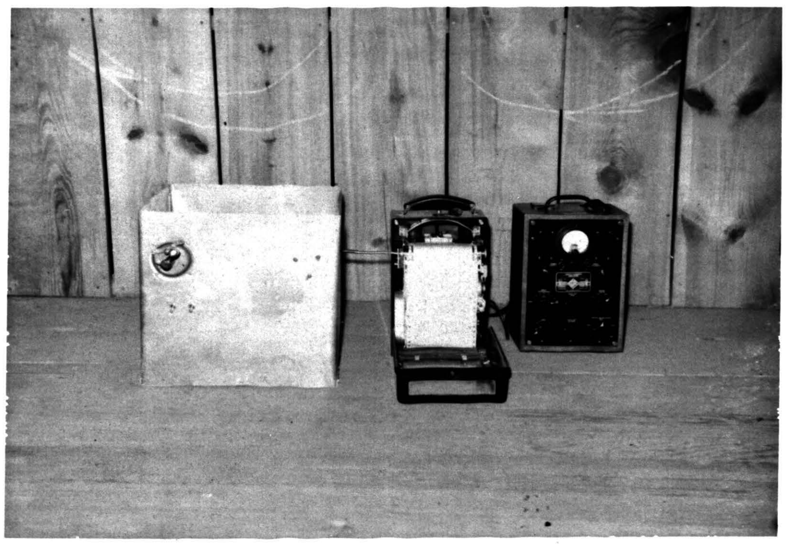


Figure 8. Amplifier, recorder, and control box.

picture of the amplifier, recorder, and control box.

It was obvious from some preliminary tests that the one d-c amplifier would not give enough sensitivity. Therefore, some more d-c amplification had to be provided. The Electrical Engineering Department has a console of ten operational amplifiers manufactured by George A. Philbrick Researchers, Incorporated. One of these amplifiers was used in this system. A feedback resistor of 1,000,000 ohms was used with an input resistor of 10,000 ohms. This gives an additional stage of amplification of 100. This additional amplification gives the system very good sensitivity. Figure 9 is a picture of this amplifier.

The detector used in the system is a crystal detector.

EXPERIMENTAL DATA

The only antennas that were available and were suitable for making patterns were two microwave horns. The pattern of the horn is narrow and not very spectacular, but it does give an indication of the operation of the system.

Figure 10 is a picture of the setup for a plot of the horn pattern. The horn in the cradle is the test antenna and is used as the receiving antenna.

Before the pattern is run, all equipment must be turned on and allowed about fifteen minutes to warm up. The d-c amplifiers must then be zeroed. The Philbrick amplifier is zeroed in the following manner. The output is shorted to the negative input. The positive input is grounded. A voltmeter is connected between the output and ground. The potentiometer

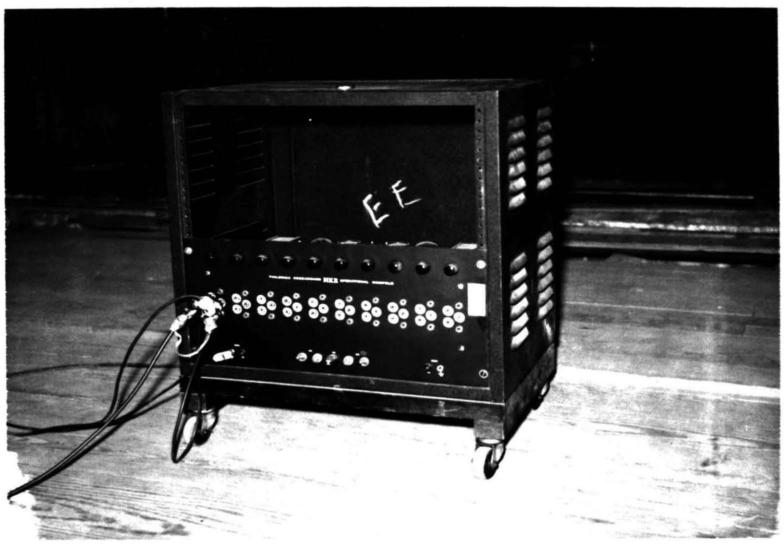


Figure 9. Philbrick Amplifier.

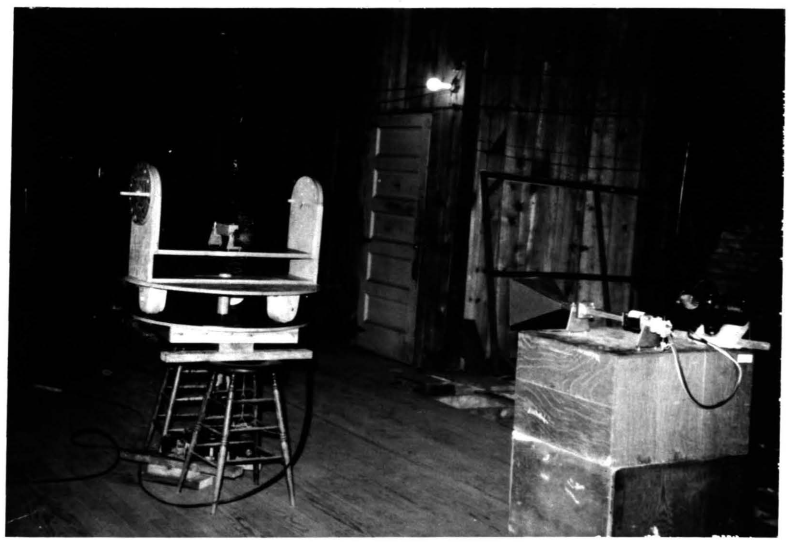


Figure 10. Antenna test setup.

on the front of the console directly above the amplifier is then adjusted until the voltmeter reads zero on its lowest scale. The General Radio amplifier has two zero adjust controls on the front of the case. One is a course control, and the other is a fine control. These are adjusted until the amplifier reads zero.

Next the transmitter is turned on, and the antennas oriented for maximum deflection of the ammeter. The amplified gain is then adjusted to give full-scale deflection of the ammeter. The pattern may then be started at zero degrees or at any other angle desired. In the case of the horns, a better picture of the pattern is obtained by start-at 180 degrees.

The horn patterns were run for elevations of 0°, 5°, 10°, and 15°. Figures 11 through 14 show these patterns. Due to the nature of the pen movement, the plots are not linear. However, these plots are not too useful in visualizing the pattern of the antenna. The useful pattern is the polar plot which can be obtained easily from the rectangular plot. Figure 15 is a composite picture of the polar plots for each elevation. From this plot the three-dimensional shape of the pattern can be visualized.

To show any effect the cradle of the turntable might have on the antenna pattern, the test horn was oriented at forty-five degrees off center as shown in Figure 7. The rectangular pattern is shown in Figure 16. Comparing this to the previous pattern, it can be seen that the cradle has no

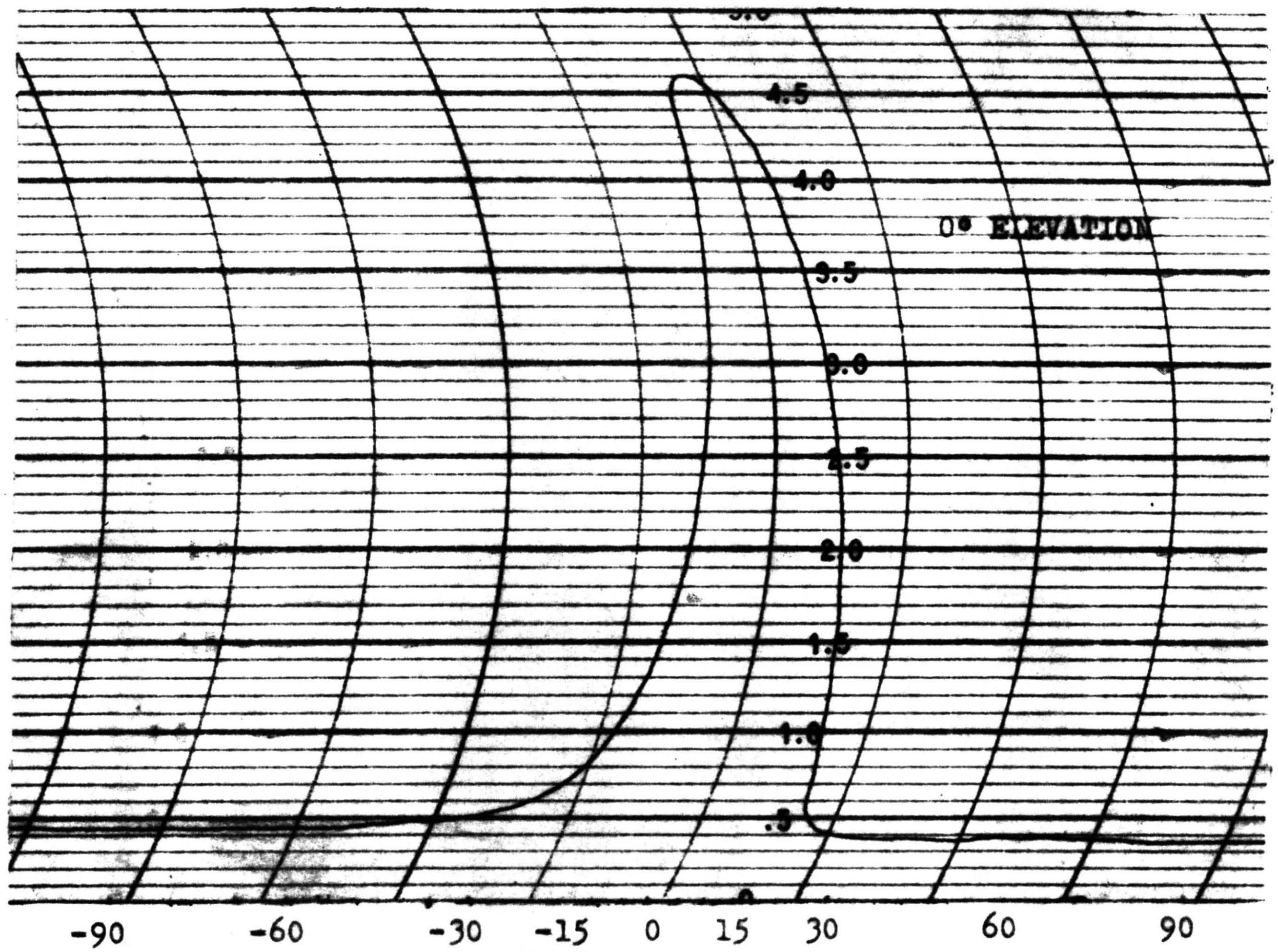


Figure 11. Rectangular presentations of the antenna pattern
for a 3 cm horn at zero degrees elevation.

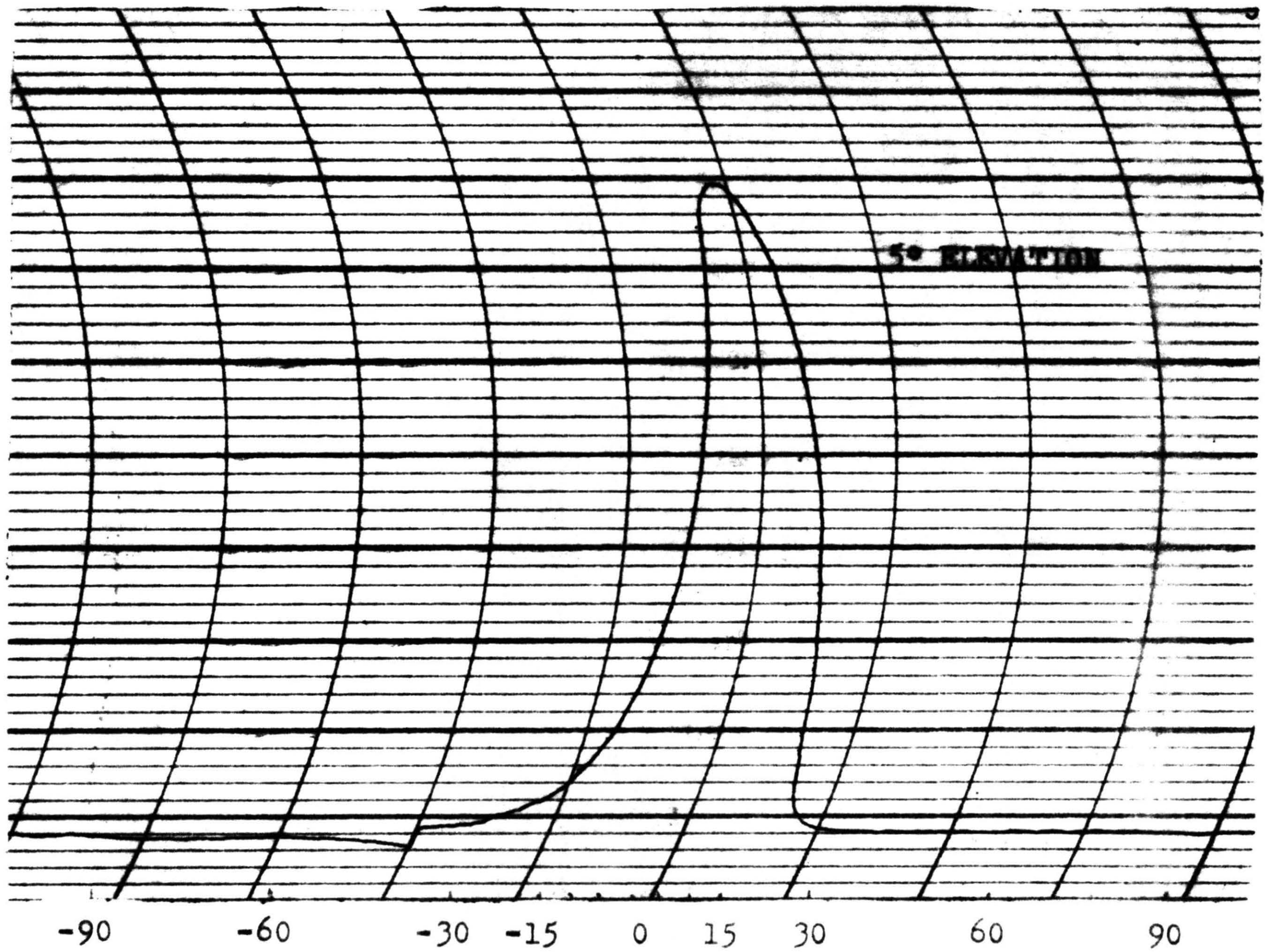


Figure 12. Rectangular presentations of the antenna pattern for a 3 cm horn at five degrees elevation.

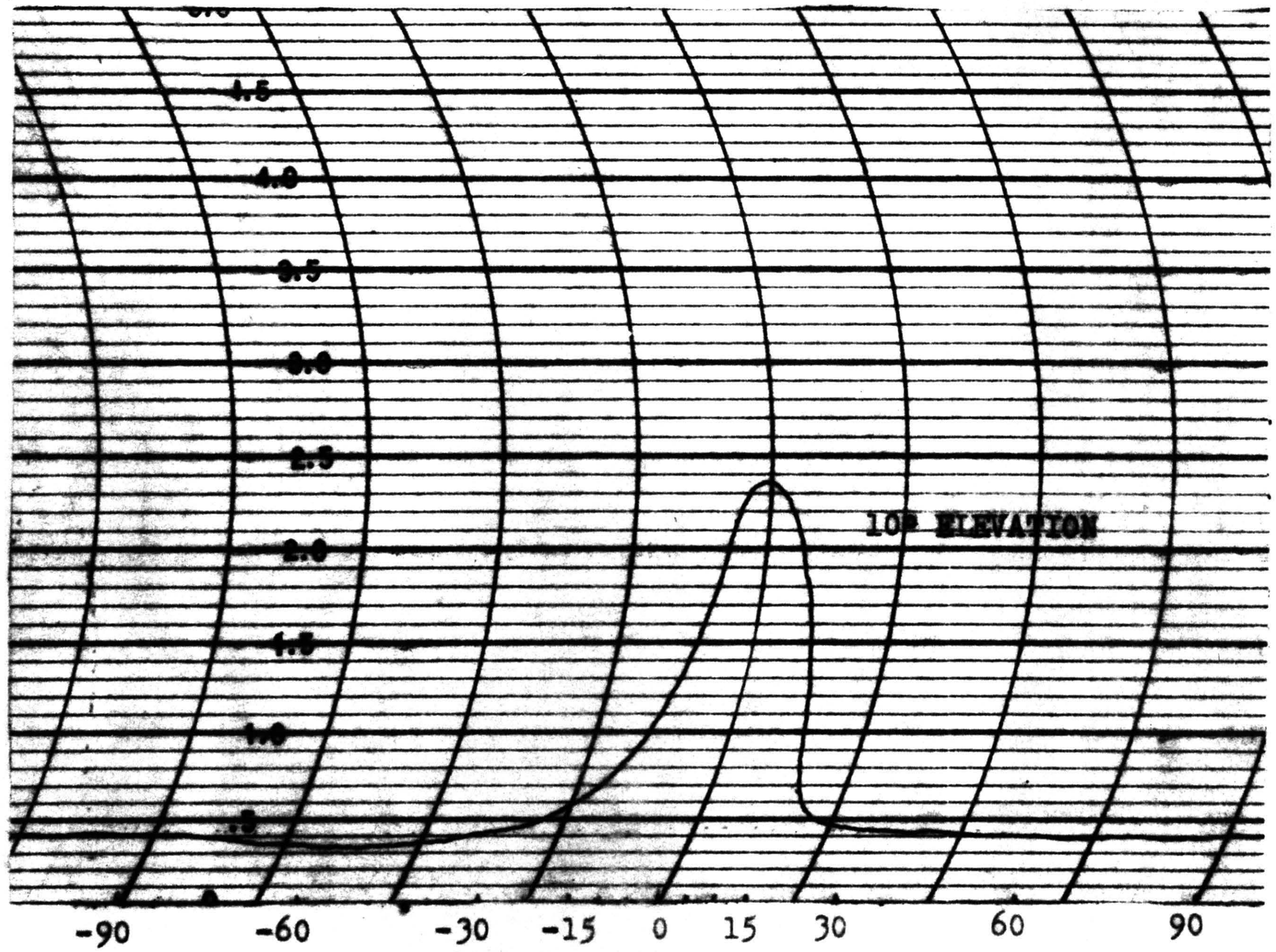


Figure 13. Rectangular presentation of the antenna pattern for a 3 cm horn at ten degrees elevation.

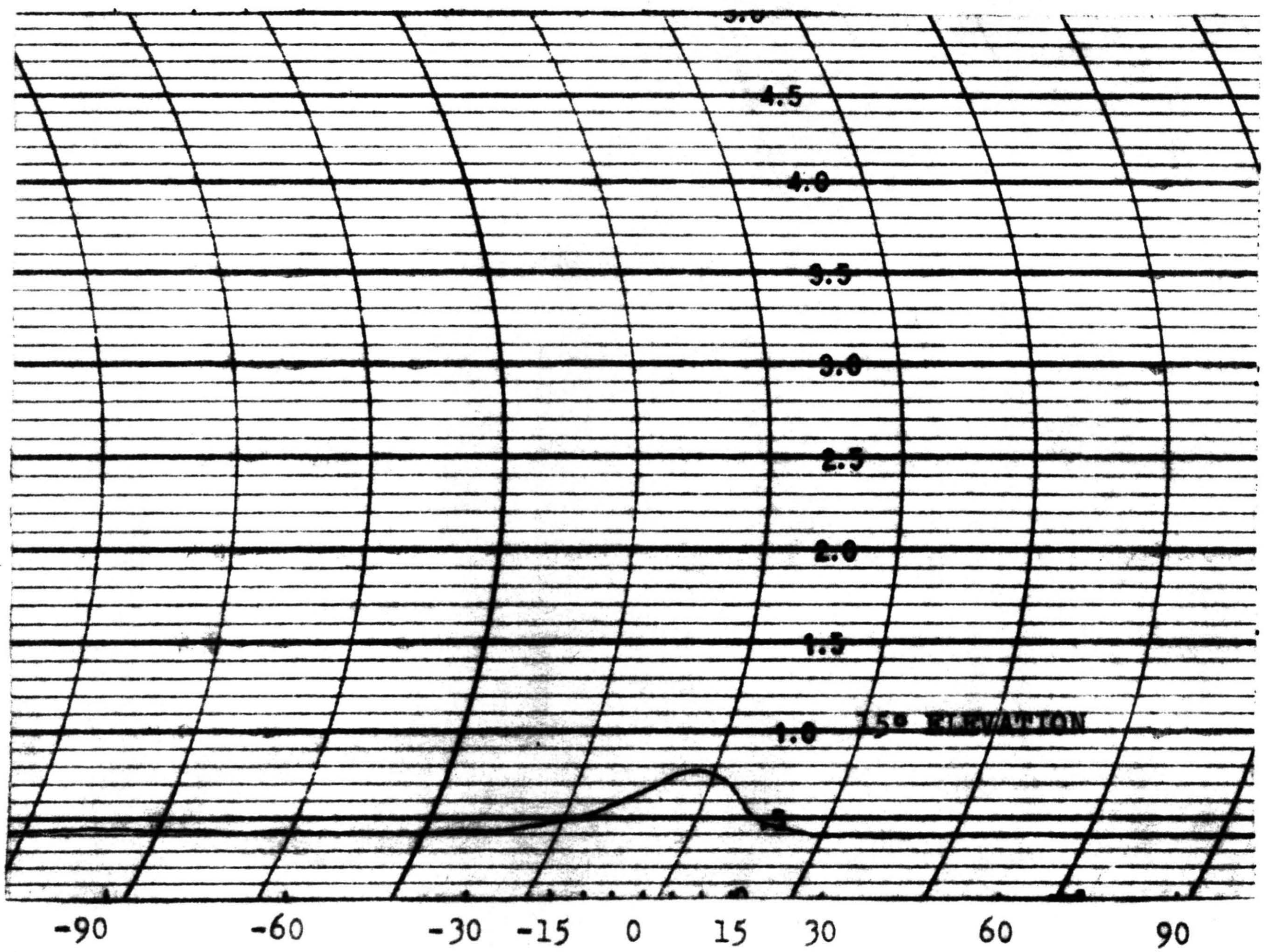


Figure 14. Rectangular presentation of the antenna pattern for a 3 cm horn at fifteen degrees of elevation.

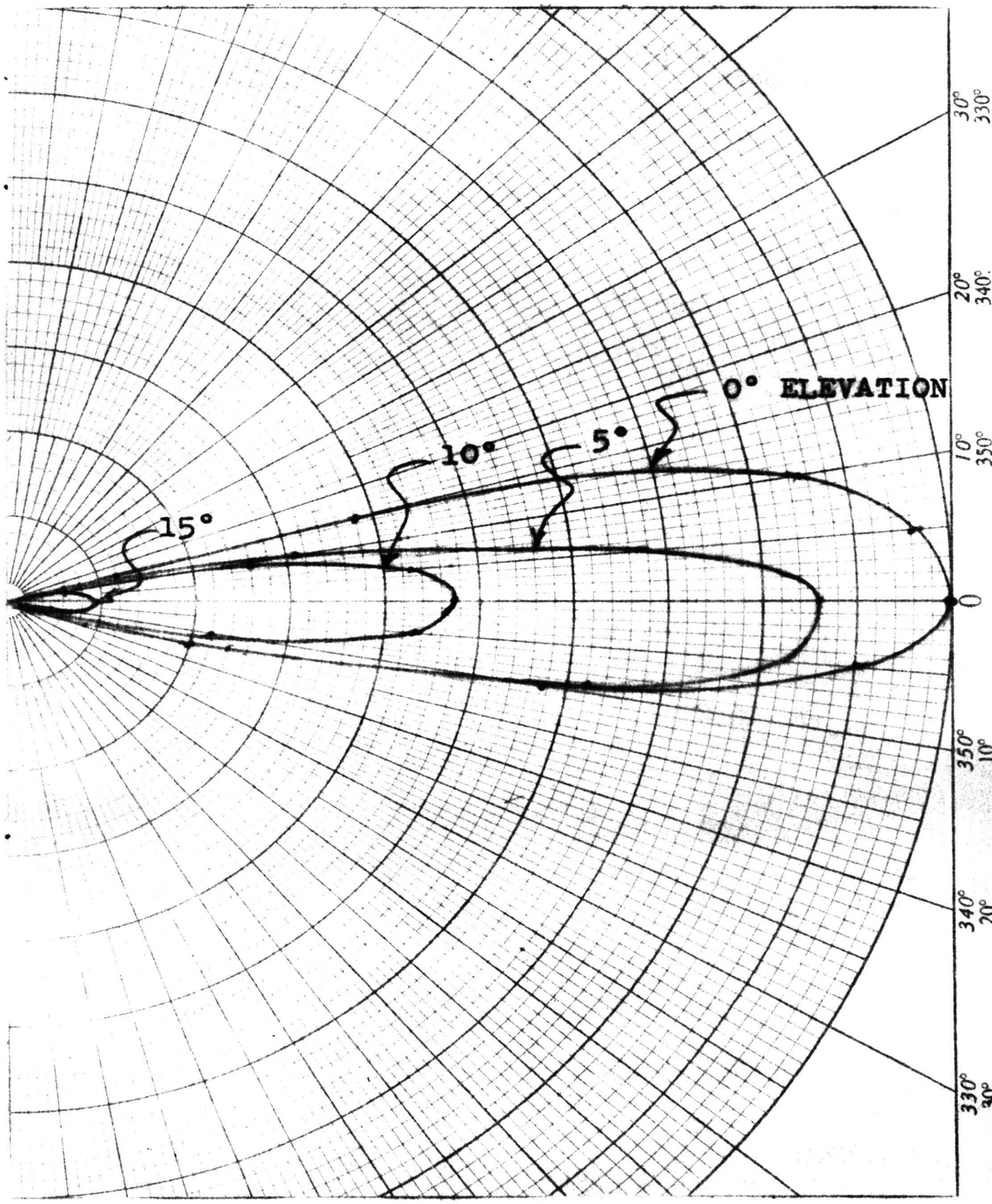


Figure 15. Composite polar presentation of the antenna patterns from Figures 11 through 14.

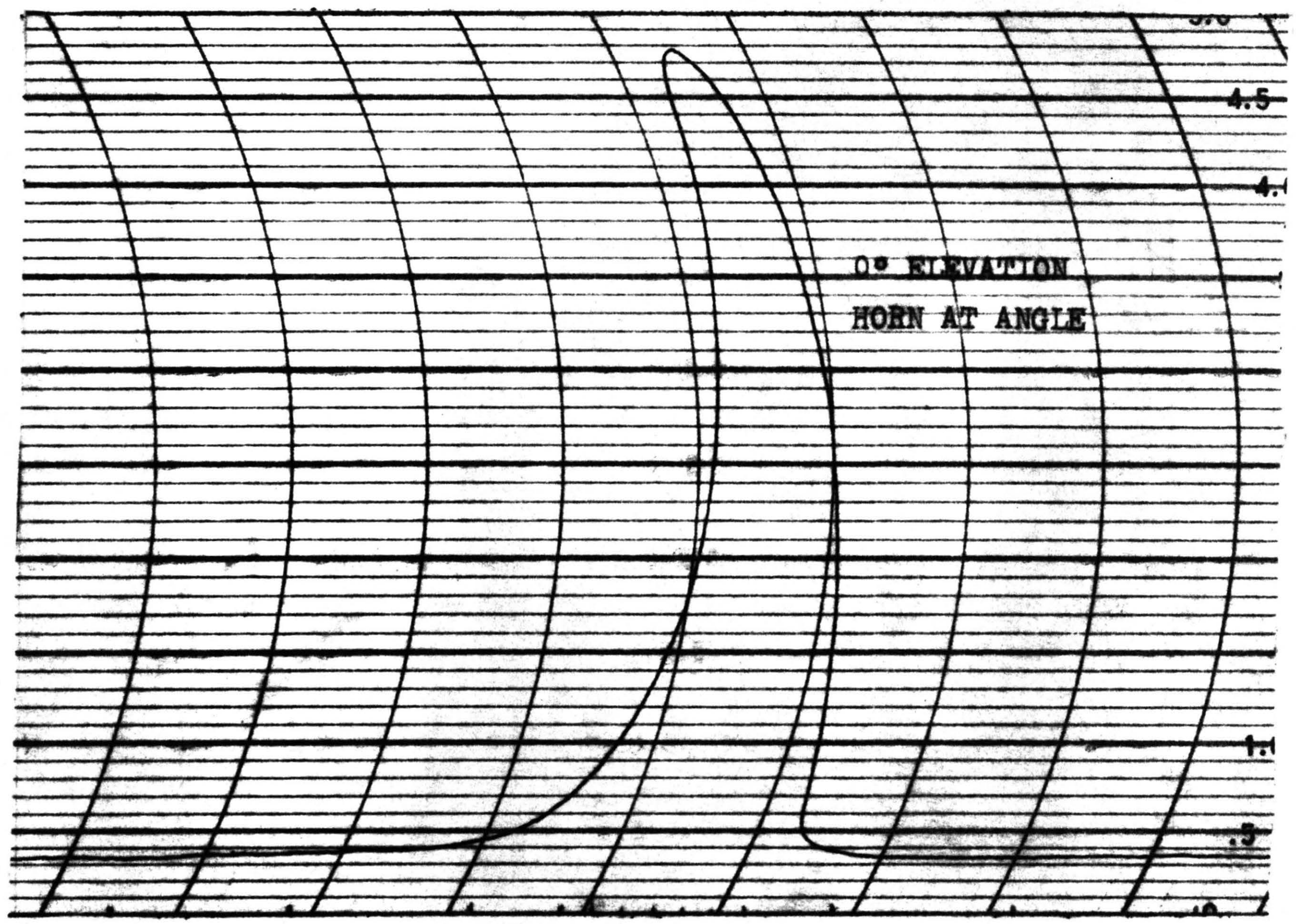


Figure 16. Antenna pattern for a 3 cm horn at zero degrees elevation, but turned 45 degrees in the turntable cradle.

effect on the pattern.

CONCLUSIONS AND SOURCES OF ERROR

The antenna plotter gave good results when plotting the horn patterns, and there is no reason why it will not do so on other types of antennas if the site is chosen properly as explained before. However, there are certain limitations to this type of system.

Use of a d-c system necessitates use of d-c amplifiers. It is well known that d-c amplifiers are unstable. They tend to drift with temperature variations and power fluctuations. This causes errors in the antenna pattern. Use of a rectangular plotter requires that the pattern be transferred to polar paper to get a good picture of the pattern. Also, the type recorder used in the system makes it a little inconvenient to transfer the pattern to polar paper. Since the transmitted energy is unmodulated, there could be interference problems from other sources in the area.

Regardless of the above limitations, the original goal has been achieved. An automatic pattern plotter has been built using equipment and materials already available, and it works satisfactorily.

DESIGN OF MICROWAVE ABSORBER

When the design of the microwave absorber was first started, it was decided to mix the absorbing compound and optomize the compound as to absorbing qualities and cost. However, considerable difficulty was found in trying to obtain the necessary materials. After much time was spent trying to obtain the materials, it was finally decided to buy the completed compound from the B. F. Goodrich Company which manufactures microwave absorbers.

The problems left were to decide what kind of hair was best or possibly necessary for obtaining the proper absorption qualities and to find a method for treating the hair with the absorbing compound such that the absorption qualities were sufficient, and the amount of absorbing material necessary was optimum.

Since this hair is used as packing material for packing delicate instruments, several kinds of hair were available in the department. Two kinds of hair were used in the experiments. One kind is a mat of coarse, very dense hair in thicknesses of two inches and 1 5/8 inches. Another kind is softer hair in a mat that is a little less dense than the first kind. This softer hair was available in only one thickness of 1 5/8 inches. All samples were 16" X 16" in surface area.

One of the first methods used to apply the absorbing compound was to spray it on. It was soon discovered that the absorber did not penetrate well enough to take full advantage of the thickness of the hair. Therefore, it was decided that the absorber must be dipped.

As discussed in the Review of Literature, an important attribute of a good absorber is that the dielectric constant varies from a small number at the front to a large number at the back. Thus, the absorber must be tapered from a heavy coating at the back to a light coating at the front. An attempt at doing this was made in the first two samples. The samples were dipped in the absorber about half of the thickness. Then they were turned over and allowed to drip dry. It was thought that in this manner the absorber would gradually diffuse from the back to the front of the hair mat. The absorbers were allowed to dry and then tested for absorption.

Figure 17 is a picture of the test setup used. The transmitting and receiving horns were placed about ten feet from a metal plate. A semicircle was then drawn at this distance from the plate, and angles of 15°, 30°, 45°, and 60° were marked off on it.

The transmitted energy, which was transmitted at 9300 mc and modulated at 1000 cycles, was aimed at the center of the metal plate. The energy which was reflected from the plate was picked up by the receiver horn, sent through a calibrated attenuator, detected, and sent to a Hewlett Packard Model 415B VSWR meter. An amount of attenuation believed to be more than that produced by the absorber was then introduced by the attenuator. Next a piece of the absorber was placed in front of the metal plate. The attenuator was varied

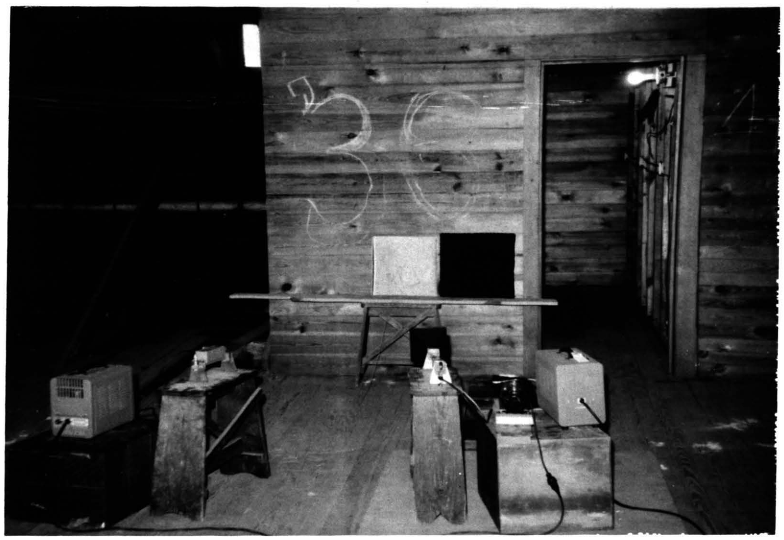


Figure 17. Absorber test setup.

until the previous reading of the VSWR meter was restored. The absorption of db could then be read from the attenuator. The attenuator only had a range from zero to 20 db; therefore, in the cases where the attenuation was more than twenty db, a combination of the attenuator reading and meter reading could be used.

This procedure was repeated for all of the angles of incidence which were mentioned above. The two horns were lined up at each angle of incidence by means of a cord which was run from the bottom center of the metal plate.

The results of runs on the first two samples are given in Figure 18 and 19. Specimen "A" is the thick hair and specimen "B" is the thin-textured hair. Specimen "A" weighed 232 grams and specimen "B" weighed 228 grams before treatment. The db readings have been changed to percent reflection readings. These results were not very satisfactory. About eighty grams of absorbing compound was applied to each sample, but the reflection coefficient was only four percent at normal incidence in both cases. The thinner-textured hair appears to have a slight edge in absorbtion qualities over the range of angles.

It was decided to see what would happen if the absorbing compound were put on the hair in heavy amounts without tapering it. This was done by completely immersing the same two samples in the absorbing compound and letting them soak for about one minute. Runs were made on these samples, and the results are shown in Figures 20 and 21. These results were

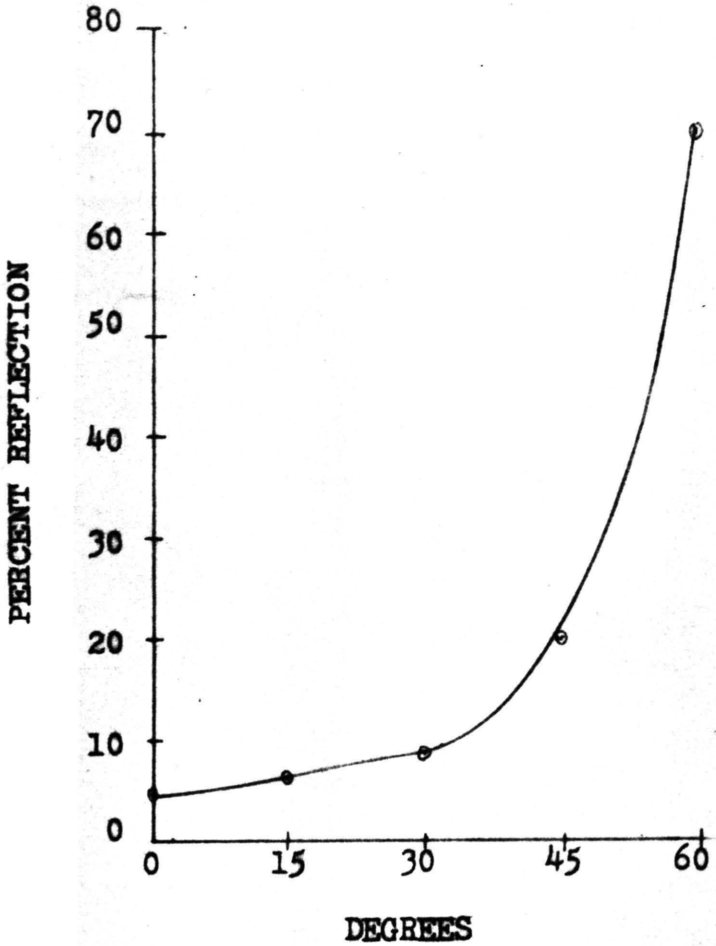


Figure 18. Absorption characteristics of specimen "A."

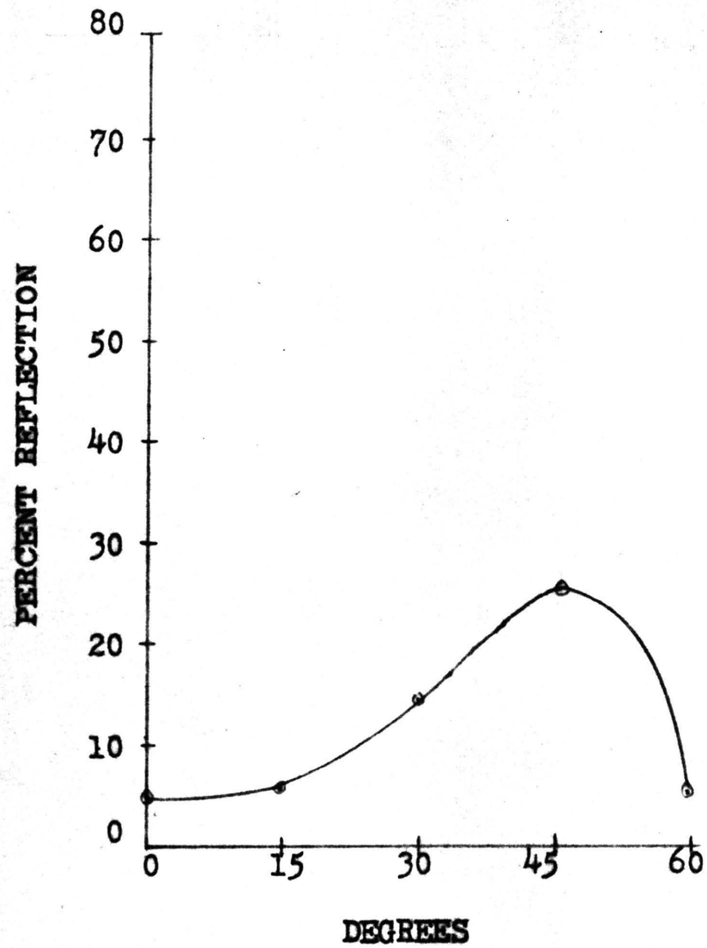


Figure 19. Absorption characteristics of specimen "B."

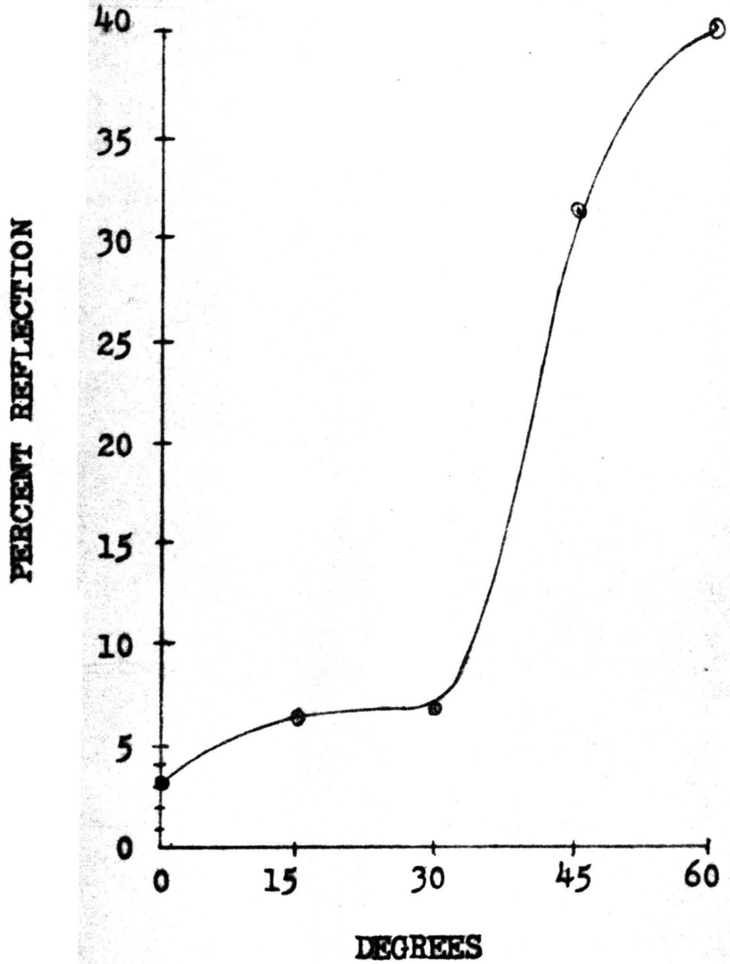


Figure 20. Absorption characteristics of specimen "A," after heavy soaking.

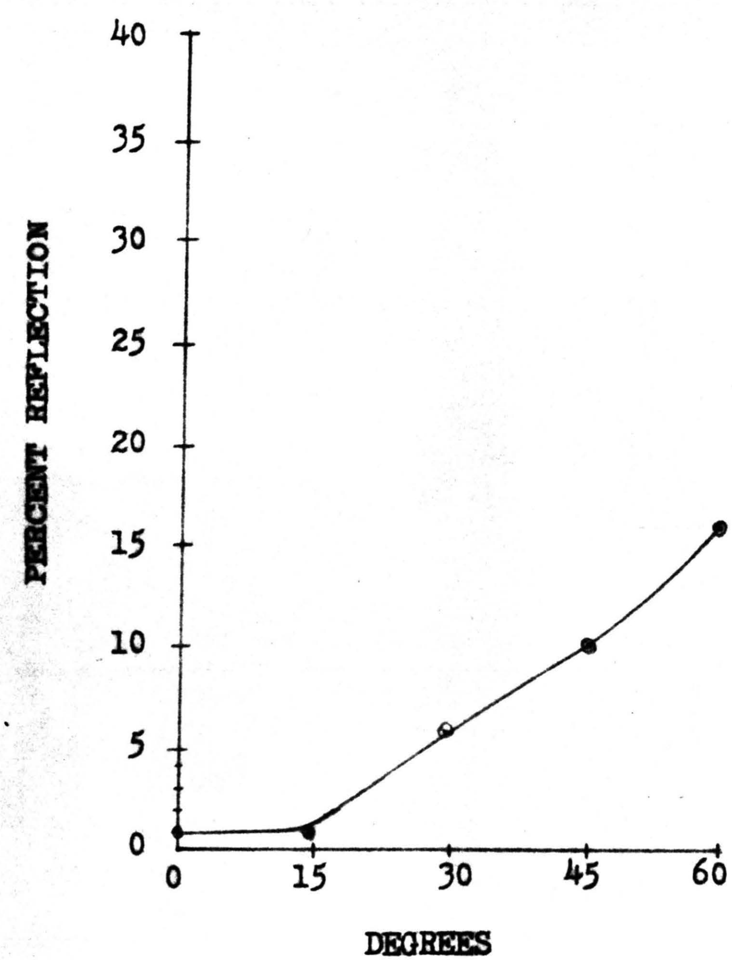


Figure 21. Absorption characteristics of specimen "B" after heavy soaking.

good, but not what was expected considering the amount of absorbing compound used. 129 grams of absorbing compound was added to the thin-textured hair, and 122 grams was added to the thick-textured hair. The small increase in absorption was probably due to the large surface reflections caused by not tapering the absorbing compound from back to front. Although the absorption qualities are much better than the previous samples, the surface reflections are worse. It also should be noticed that in both cases the thin-textured hair has the best absorption qualities.

One piece of hair matting was available which was two inches thick. It was the coarse hair, very dense type and weighed 317 grams before treatment. It was decided to try the same procedure on this hair to see if the additional thickness helped much. Figure 22 gives the results of the first run in which it was attempted to taper the absorbing compound. The results give satisfactory absorption qualities, since the reflection is less than two percent at normal incidence. However, it was noticed that, as before, the absorbing compound did not diffuse very readily through the hair. Instead, it dripped through the hair in spots. Only the additional thickness and the amount of absorber used--147.5 grams--gave the better absorption qualities over previous samples.

To see if much could be gained by thoroughly soaking this thicker hair with absorbing compound, the specimen was

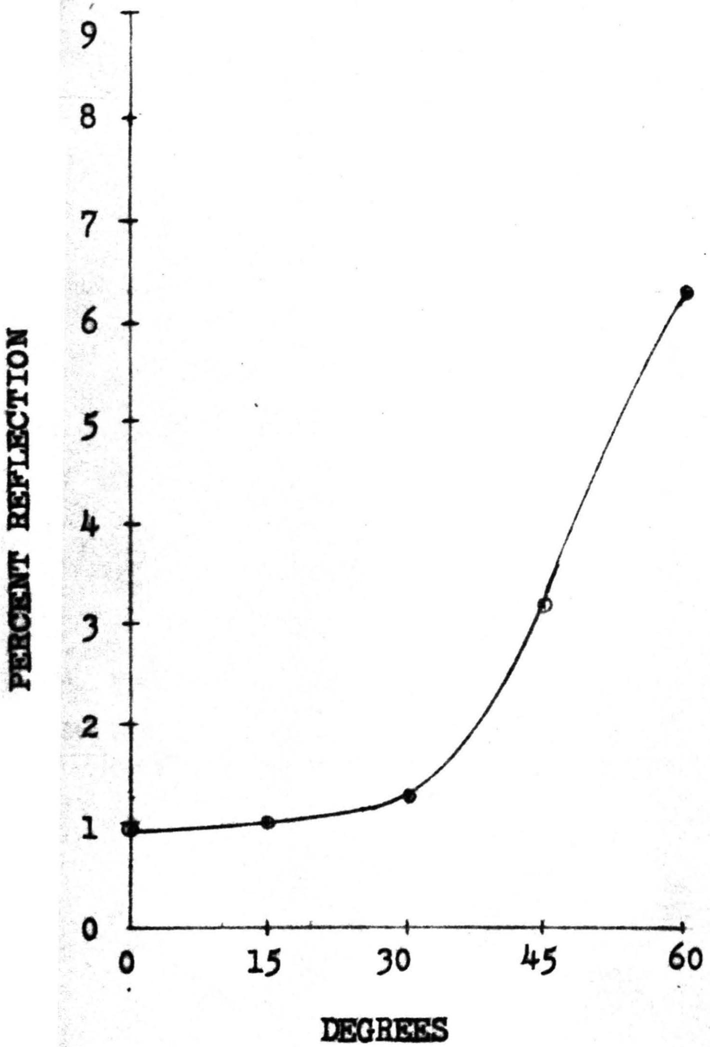


Figure 22. Absorption characteristics of a two-inch thick mat of hair after light soaking.

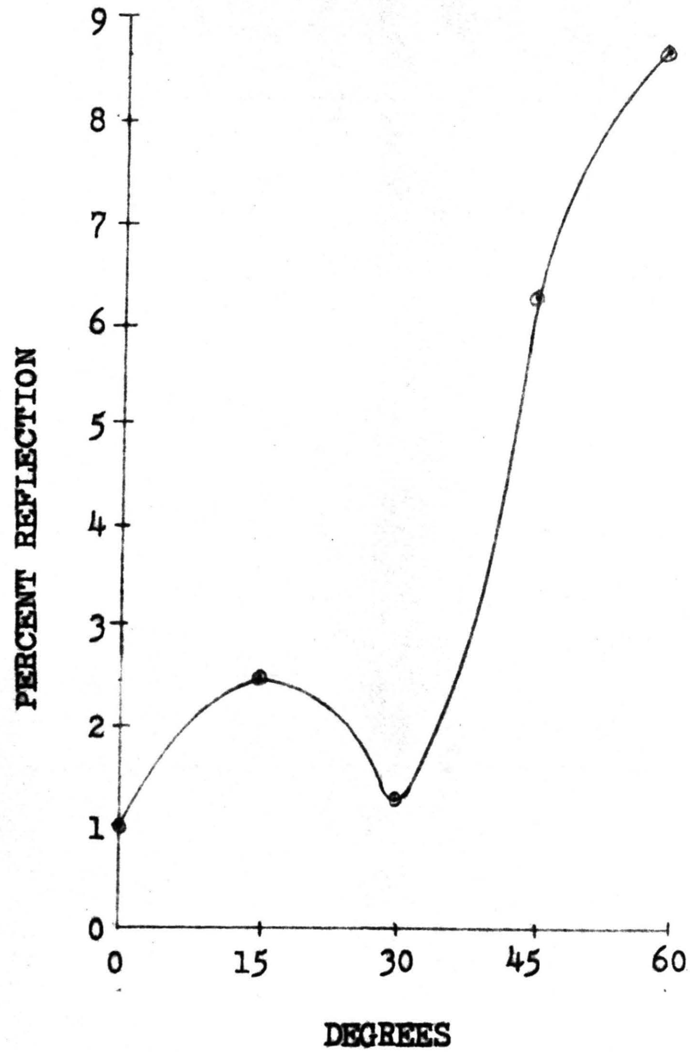


Figure 23. Absorption characteristics of a two-inch thick mat of hair after heavy coating.

completely immersed in the absorber and allowed to soak for a minute. After drying, the hair was tested. The results are shown in Figure 23. It can be seen that, although 352 grams of absorbing compound was added, the absorption qualities are worse. This is undoubtedly due to the large amount of surface reflections present.

One sample of hair matting was available which is lighter and thinner-textured than any previously used. It is 1 5/8 inches thick and the same type of hair as specimen "B", and it only weighed 189.5 grams before treatment. It was dipped as before about two-thirds of the way down into the absorber and then turned over to dry. The absorber diffused through this thinner-textured hair much better. The results of the absorption tests are shown in Figure 24. It can be seen that by adding only 74.5 grams of absorbing compound, a satisfactory absorber has been made.

It was decided to try spraying a light coating of absorbing compound on the undipped side of the test specimen. It was believed that in this manner more absorbing compound could be added and still maintain the tapering effect. The results of absorption tests after this was done are shown in Figure 25. The results show increased absorption with only twenty grams additional absorbing compound.

CONCLUSIONS AND SOURCES OF ERROR

All tests showed the thinner-textured hair to have better absorption qualities than the thick hair. This was probably due to the ability of the absorbing compound to diffuse through the thinner hair more readily. The last sample

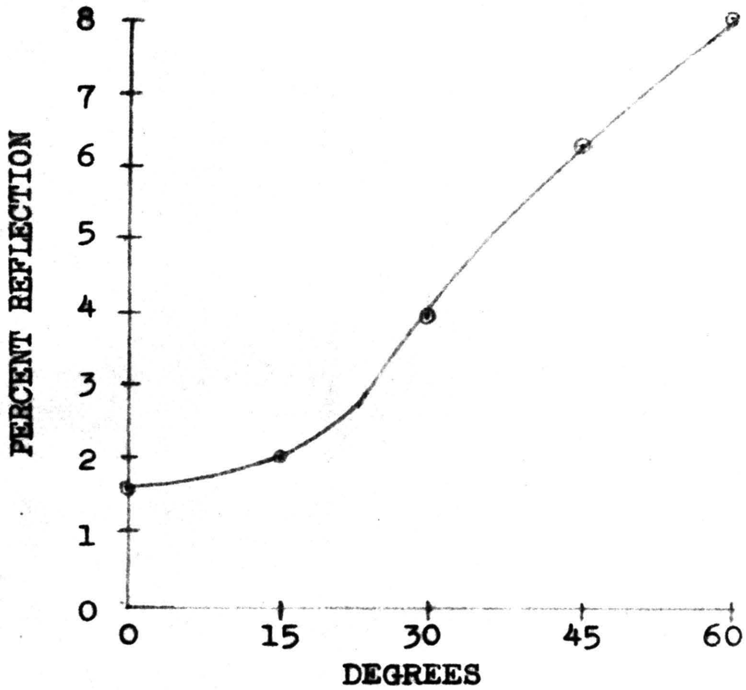


Figure 24. Absorption characteristics of a mat of very thin-textured hair, lightly coated.

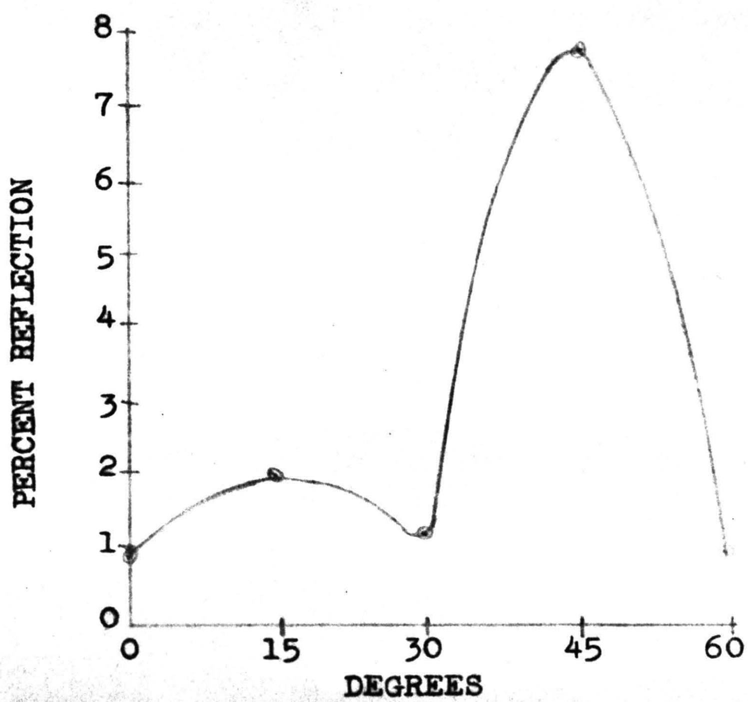


Figure 25. Absorption characteristics of the same hair as in Figure 24, but with additional compound sprayed on the face.

provided the most satisfactory results for the amount of absorbing compound used. Therefore, the recommended procedure for applying the compound is as follows:

The hair is dipped into the absorbing compound about two-thirds of the way down. It is allowed to soak about fifteen seconds. Then it is turned over and laid on a wire screen or something else that will give it support and still allow the compound to drip through. It should be allowed to drip dry. After it is dry, the undipped side is sprayed with a light coat of the absorbing compound and allowed to dry again. A fly sprayer can be used for this purpose, or, if one is available, a paint sprayer. It is recommended that whatever is used be cleaned thoroughly after using.

Although 1 5/8 inch-thick hair gave good results, it is recommended that two-inch thick hair be used to insure better results. This would insure that most of the hair would have much better than 98 % absorbtion at normal incidence.

There are several possible errors in the experimental data. One possible error is coupling between antennas. Interference between test antennas can provide a direct coupling path varying with the angle of incidence at which the sample is being tested. This would make the absorber appear much worse than it is, especially at grazing incidence.

A corrective measure for this error is to limit the direct transmission path between the antennas by staggering their distances from the absorber. This was done when running the tests, and tests showed there was little error due to coupling.

Since crystals were used, there could be some error due to the law of the crystal changing. However, since a calibrated attenuator was used, the power reaching the crystal was about the same level at each reading. Therefore there was no error due to the law of the crystal changing.

The absorbing compound was not evenly distributed throughout the hair. These anisotropic qualities caused the absorption to change some with orientation of the absorber. However, an average reading was taken which is representative of the overall absorption qualities of the absorber.

DARKROOM SPECIFICATIONS

The size of the darkroom should be 10 x 10 x 10 cubic feet. This would be small enough to put in a laboratory but be plenty large enough for measurements at the X-band of frequencies. It can be made of wood, since it is not necessary to back the absorber with metal. If it is desired to screen out undesired signals, the room may be made of wire screen or wood, backed by wire screen. All that is needed in the basic darkroom, however, is a frame to which the absorber is attached.

The absorber may be tied on with twine, stuck on nails, or cemented on. For the walls, it is convenient to drive nails into the wood and stick the absorber on them. The reflection from the nails is negligible if they are well imbedded in the absorber. Ceiling mounting is best done by cementing the absorber on or by tying. Loose pieces of absorber may be placed on the floor where needed and shifted around as desired.

The method of applying the absorber to the hair has already been described. The hair can be obtained from Armour Cushioning Products Division, North Benton Road, Alliance, Ohio. The type recommended is Packaging Hairflex in the medium density. The price quoted was twenty-nine cents per square foot, in quantities of 100 pounds per shipment or more. The price includes transportation costs. The absorbing compound can be obtained from the B. F. Goodrich Sponge Products Division in Shelton, Connecticut. The name of the product is Microwave Absorber Compound #13450, and it sells for two dollars per gallon.

At least five pieces of absorber 2 x 2 square feet can be made from one gallon of absorbing compound. Since 600 square feet of absorber is needed for the room, thirty gallons of absorbing compound is needed. The cost of the hair and compound combined for the complete room is thus $234. This combined with the cost of the lumber will provide an inexpensive darkroom, considering that commercial darkrooms cost several thousand dollars. The darkroom described will give excellent results at the x-band of frequencies and higher, but would be of questionable efficiency at lower frequencies.

SUGGESTIONS FOR ADDITIONAL DEVELOPMENT

Sometime in the future the need might be felt for an automatic pattern plotter that is more elaborate and does not have the limitations of the present system. Therefore, a proposal that would form the basis for the development of a better system is submitted. Then, if at some later date there is justification for the added expense, the following proposal may be carried through to a completed system.

Figure 26 is a block diagram of the system. The system works as follows:

The recorder is a polar recorder synchronized to the antenna by means of two synchros. A portion of the transmitted energy which is modulated at 1000 cycles is picked up at the transmitter and used as a reference. Both the received and transmitted energy are detected and amplified. Both signals pass through a potentiometer system and are compared out of phase in a mixer. Phase shifters are provided to obtain the proper phase relationship between signals. If the signals are unequal, there is an output from the mixer which is amplified, and this output drives the control motor.

The motor drives the attenuator arms in such a manner as to balance out the voltages. At the same time, the pen moves on the plotter proportional to the difference in the voltages. In this manner the pattern of the antenna is plotted as the antenna is turned.

The reference phase of the motor is supplied by the same source that supplies the modulation. A phase trimmer is

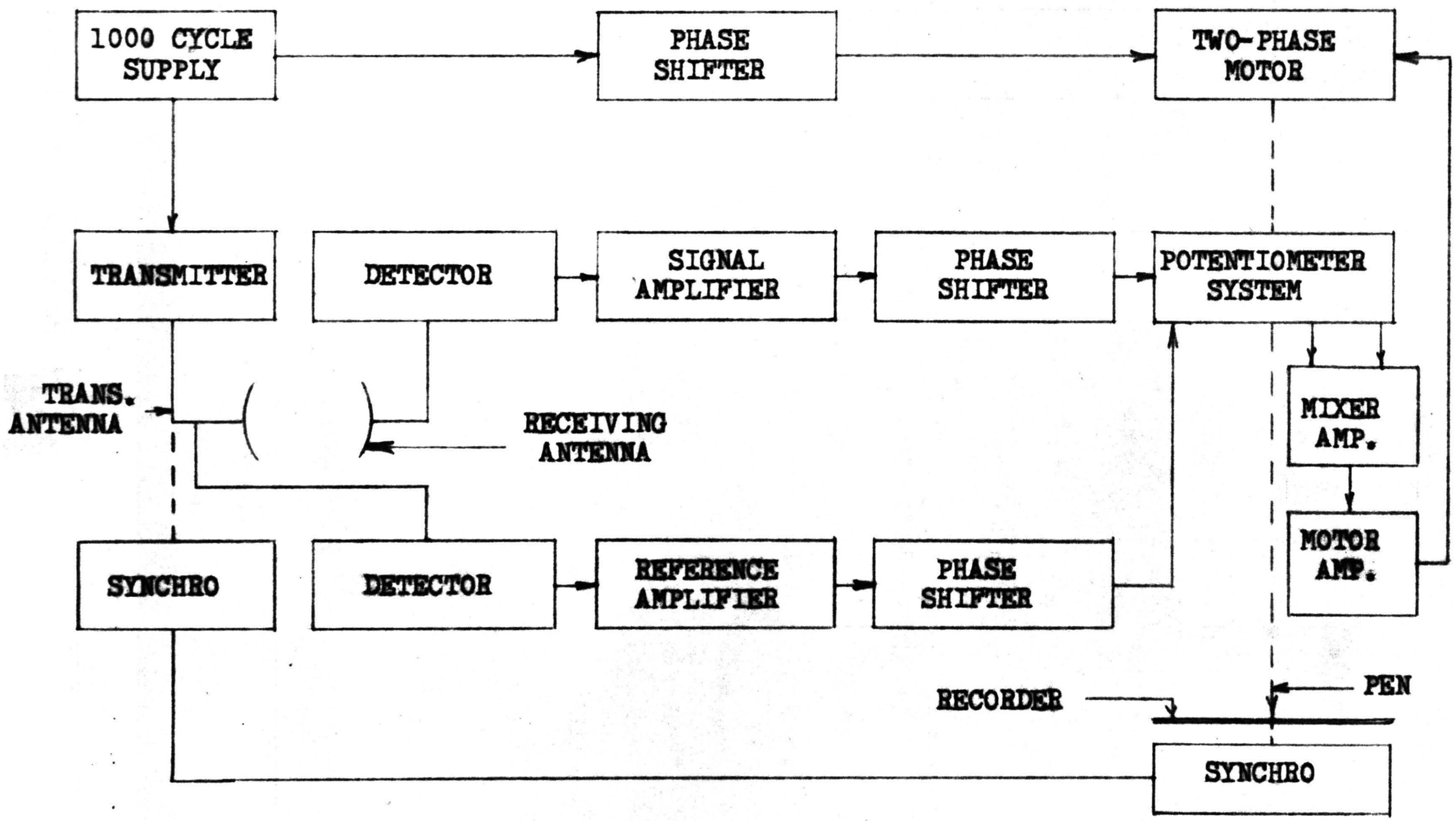


Figure 26. Block diagram of a proposed automatic antenna pattern plotter.

provided to obtain the proper phase relationship between the control and reference voltages. Each of the blocks will be discussed separately.

The detector can be a crystal or bolometer. Because of the bolometer's constant square-law detection over wide ranges of power, it is usually preferred, but a crystal will give satisfactory results.

The feedback amplifier should be linear over a wide range of input voltages and have good sensitivity. The Hewlett Packard Model 400Ab vacuum tube voltmeter has an amplifier that fits this description. The amplifier is linear with forty db amplification over the frequency range ten cps to 600 kc. On the most sensitive range it is sensitive to signals much less than one millivolt.

Figure 27 shows a diagram of the signal phase-shifter and its equivalent circuit. The transfer function is derived as follows:

$$E_{IN} = I\,\frac{\left(rR + 1/j\omega C\right)}{2n}$$

$$E_0 = I\left(\frac{1}{j\omega C}\right) - nE_{IN}$$

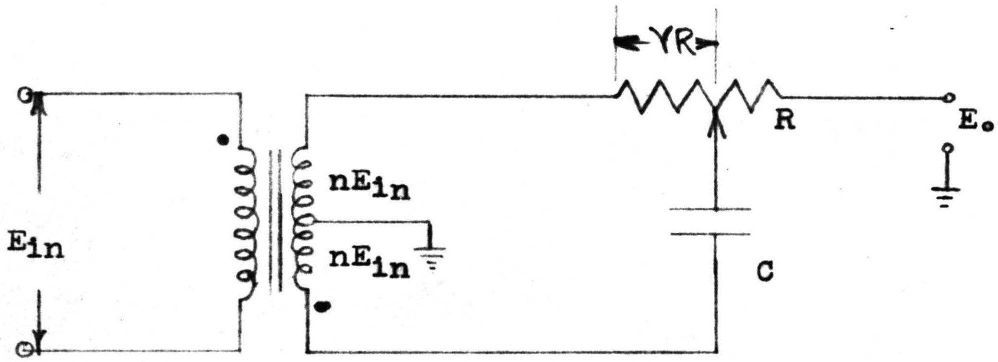
$$= I\left(\frac{\frac{1}{j\omega C} - rR}{2}\right)$$

$$\frac{E_0}{E_{IN}} = \frac{n(1 - j\omega\tau r)}{(1 + j\omega\tau r)}$$

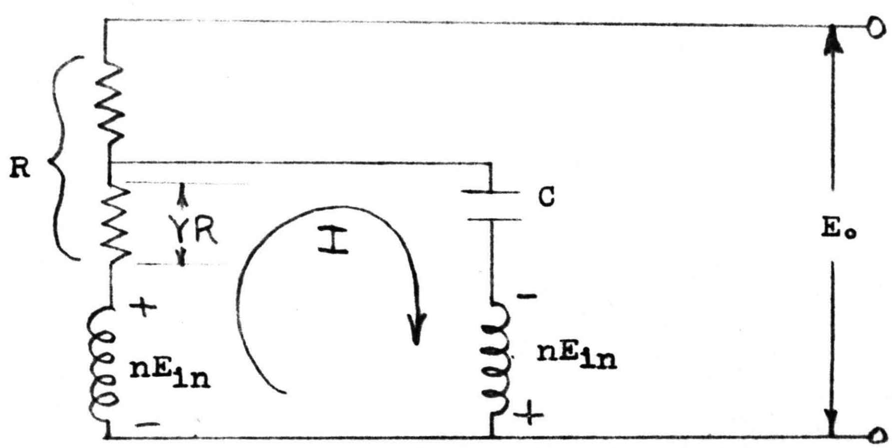
$$= n\,\angle -2\tan^{-1}(\omega\tau r)$$

where

$$\tau = RC$$



PHASE-SHIFTING NETWORK



EQUIVALENT CIRCUIT

Figure 27. The phase-shifting network and its equivalent circuit.

Use $\tau = .001$ with $f = 1000$ cycles. Two suitable values of R and C are $R = 100K$ and $C = .01 \mu f$. Use a step-up turns ratio of 1:2. A phase shift of 180 degrees is obtained by use of the transformer. Using $\tau = .001$ gives a variable phase shift of zero to about 172 degrees.

The reference voltage phase-shifter is identical except that there is no phase shift in the transformer. The settings of the phase-shifters will have to be made when the pattern plotter is first adjusted and when major component changes are made. Except for aging of parts, there should not be any need for adjustment otherwise. This same phase-shifter may be used in the motor reference phase to obtain the proper phase relationship between reference and control voltages.

Figure 28 is a diagram of the potentiometer system. The output of the signal potentiometer is

$$\frac{2000\, E_s}{\gamma \times 200{,}000 + 2000}$$

where γ is the fraction of total displacement of the potentiometer arm.

The output of the monitor potentiometer is $E_m \gamma$. For best operation it is desired to compare one-tenth of the monitor output to ten times the signal output. This is done in the mixer.

Therefore, at zero position

$$\frac{E_m \gamma}{10} = \frac{10 \times 2000\, E_s}{\gamma \times 200{,}000 + 2000}$$

$$E_m \gamma = \frac{E_s}{\gamma + .01}$$

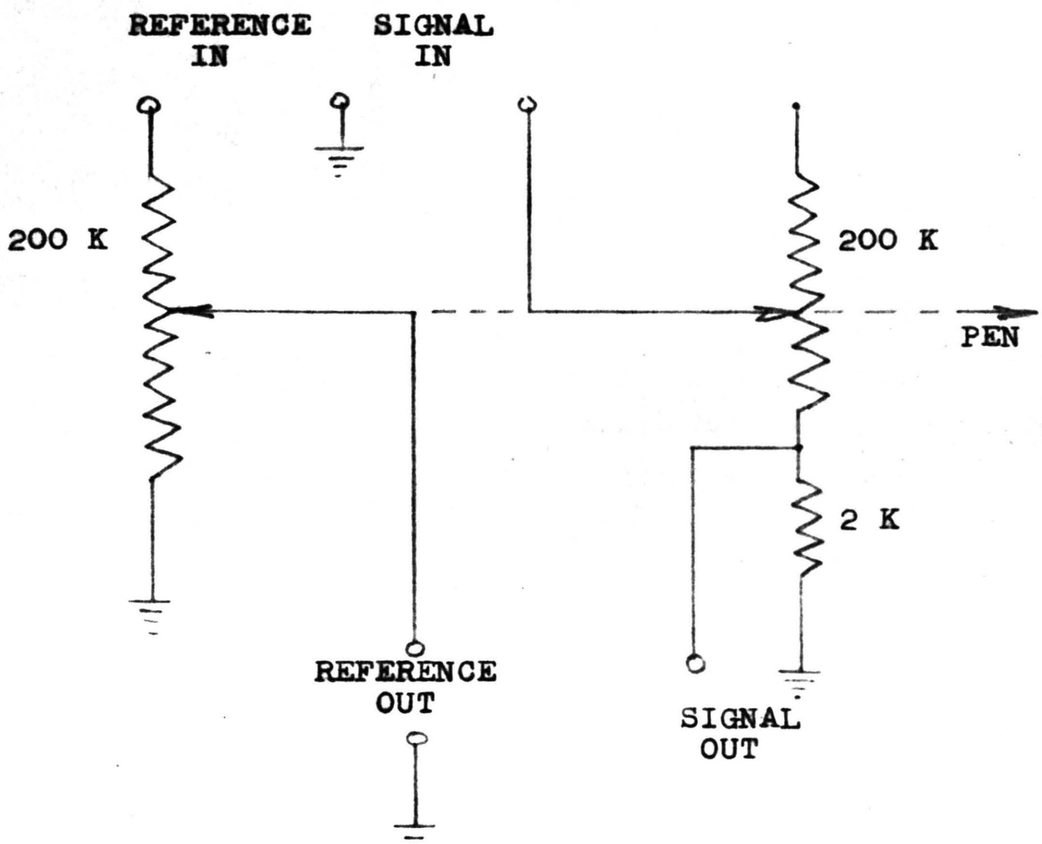


Figure 28. The potentiometer system.

or

$$\frac{E_s}{E_m} = r(r+.01)$$

Therefore,

$$r \cong \left(\frac{E_s}{E_m}\right)^{1/2}$$

Thus the position of the potentiometer arm is made independent of any fluctuations in the transmitted signal. Therefore, the pen position does not vary with fluctuations in the transmitted output, and this source of error is eliminated.

Figure 29 is a diagram of the mixer amplifier. As mentioned before, ten times the output of the signal potentiometer is compared with one-tenth the output of the monitor potentiometer. This can be done very easily by using an operational amplifier. The output of the operational amplifier is

$$e_o = -\left(\frac{R'}{R_s}e_s + \frac{R'}{R_m}e_m\right)$$

where e_m = output of monitor potentiometer, e_s = output of signal potentiometer. If e_m is opposite in phase to e_s then

$$e_o = -\left(\frac{R'}{R_s}e_s - \frac{R'}{R_m}e_m\right)$$

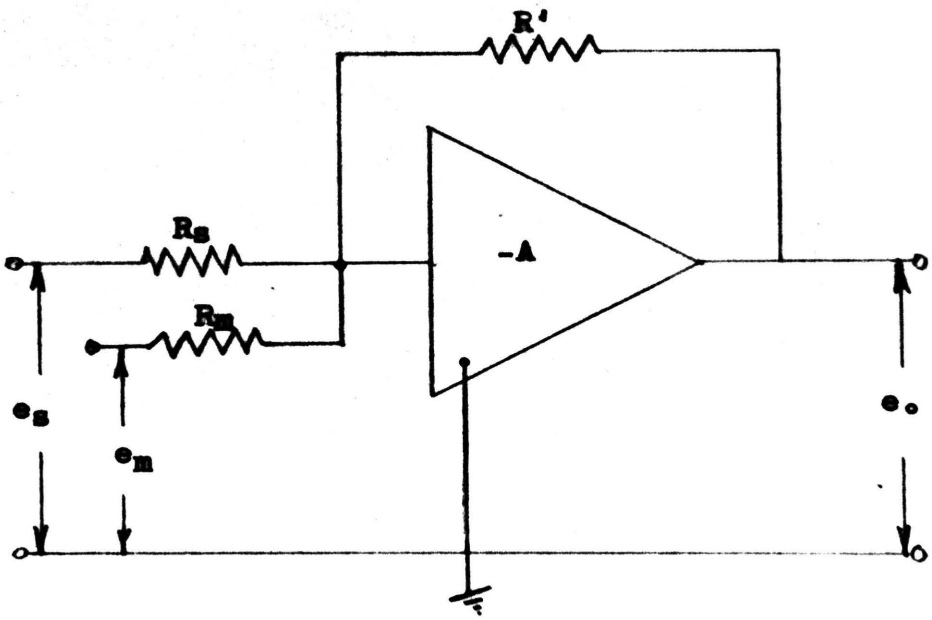


Figure 29. The mixer amplifier.

Make R' one megohm with $R_s = 100K$ and $R_m = 10$ megohm

Then

$$e_o = -(10e_s - .1e_m)$$

The amplifier should be a high-gain amplifier. The analysis for the operational amplifier is no different whether the signal is a-c or d-c unless the a-c signal is a high frequency signal. At very high frequencies stray capacitive effects become important and must be taken into consideration. However, at 1000 cycles it is doubtful that stray capacities will affect the analysis. Therefore, one of the Philbrick amplifiers that was used in the present system may be adapted for use as the mixing amplifier for this system.

Figure 30 is a diagram of the motor amplifier and phase inverter. The phase inverter is of the split-load type. Since it uses only one tube, any changes in tube characteristics affect both voltage outputs in a similar manner. If $R_1 = R_2$ both outputs are the same.

$$E_1 = E_2 = \frac{\mu R E_s}{r_p + R + (\mu+1)R}$$

For the circuit shown

$$E_1 = E_2 = .877\,E_s$$

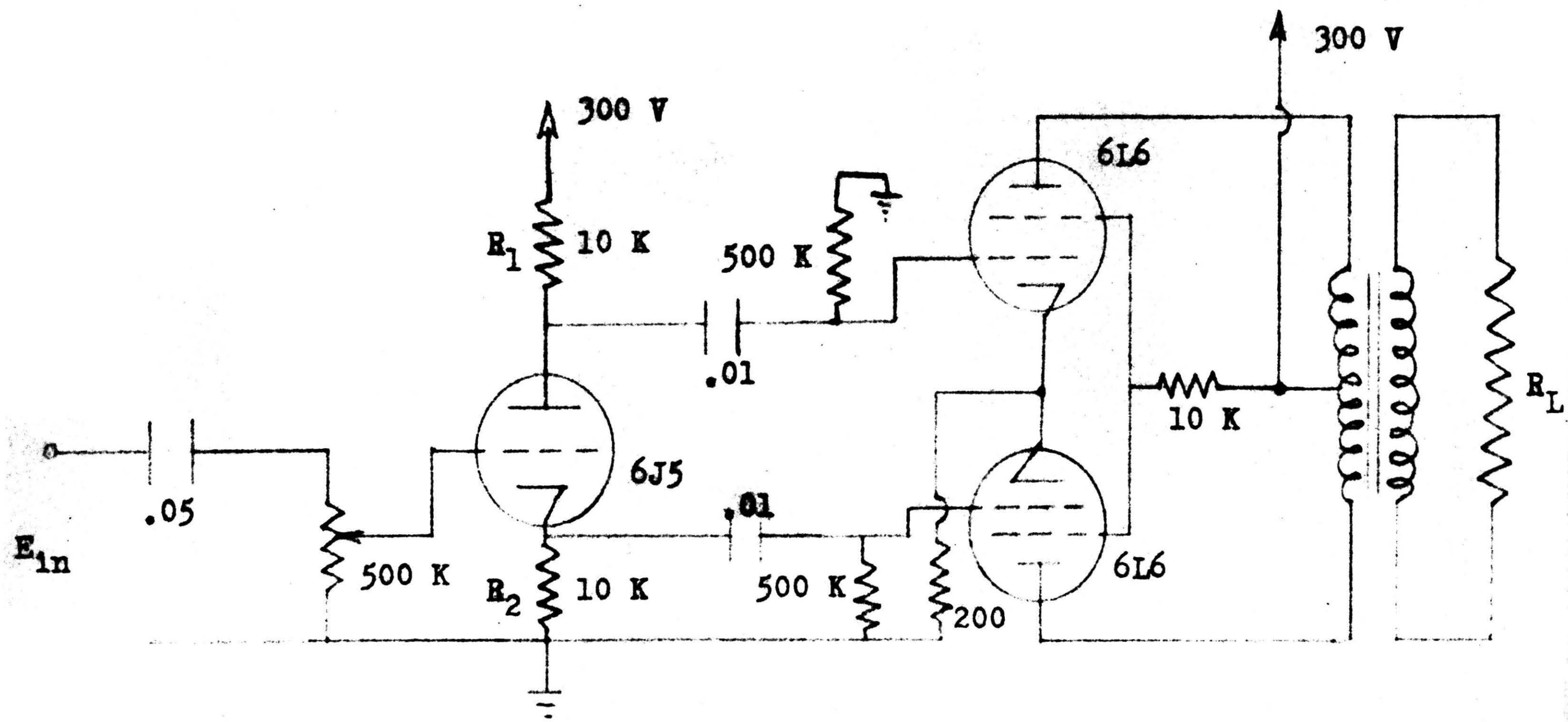


Figure 30. The phase-inverter and motor amplifier.

It is apparent that degenerative feedback is present in this circuit, and consequently, its distortion is low.

The push-pull amplifier has a load that will be the control winding of the servo motor. It is not known exactly what this load is, but 3000 ohms is a reasonable value for this type of motor. The gain can be derived from an equivalent circuit analysis as

$$A = \frac{\mu \left(\frac{N}{N_2}\right)^2 R_L}{\left(\frac{N}{N_2}\right)^2 R_L + r_p/2}$$

It can be shown that for maximum power transfer

$$\left(\frac{N}{N_2}\right)^2 R_L = r_p/2$$

Let

$$\frac{N}{N_2} = 2$$

Then

$$2^2 \times 3000 = 12{,}000$$

Therefore,

$$A = \frac{120(12{,}000)}{24{,}000} = 60$$

for the amplifier shown.

The motor used is a typical servo motor. It is a Type ck-5 Drag-Cup Low-Inertia Servo Motor manufactured by Eclipse-Pioneer. It is designed for two phase, twenty-six volt, 400 cycle operation. Stall torque is 0.5 inch-ounces. Speed at no-load is 3460 rpm. The motor transfer function

$$\frac{\theta}{E} = \frac{K_M}{P(\tau P + 1)}$$

can be derived from the stall torque and no-load speed characteristics.

$$m = \frac{1}{2}\,\frac{\text{STALL TORQUE}}{\text{no-load speed}} = \frac{1}{2}\cdot\frac{.5(60)}{3420(2\pi)}$$

$$= .69 \times 10^{-3}\ \frac{\text{IN-OZ}}{\text{SEC}}$$

$$K = \frac{\text{STALL TORQUE}}{\text{RATED CONTROL VOLTAGE}} = 1.92 \times 10^{-2}\ \frac{\text{IN-OZ}}{\text{VOLT}}$$

$$J = 1.4\ \text{gm-cm}^2 = \frac{1.4 \times .39}{980} = .558 \times 10^{-3}\ \frac{\text{IN-OZ}}{\text{SEC}^2}$$

$$\tau = \frac{J}{M} = .794\ \text{sec}^{-1}$$

$$K_M = K/M = 27.8\ \text{SEC}/\text{VOLT}$$

$$\theta/E = 27.8/P(.794P + 1)$$

The overall block diagram of the servo system in terms of the transfer functions is shown in Figure 31. By using block diagram identities, Figure 32 is derived. An analysis of this system will be made using root-locus techniques.

$$KGH = \frac{K K_2 K_M}{P(\tau P + 1)}$$

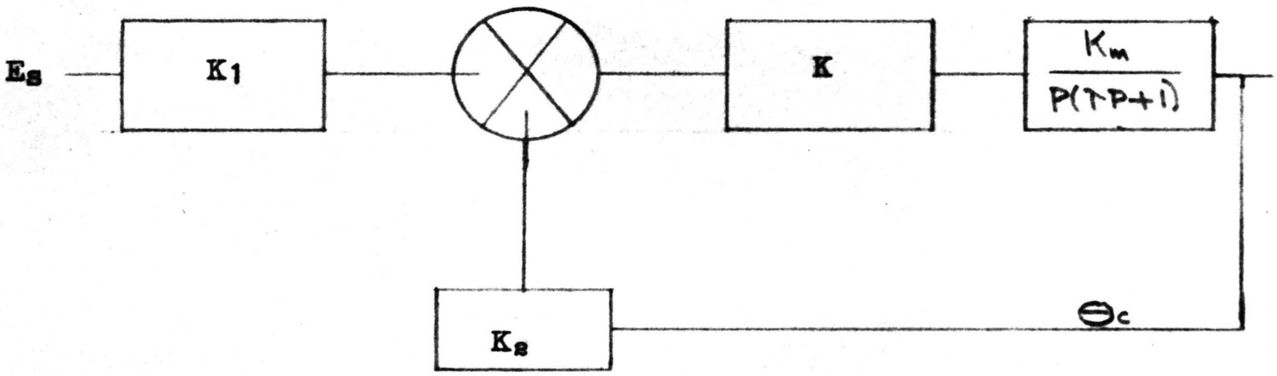


Figure 31. The servo system.

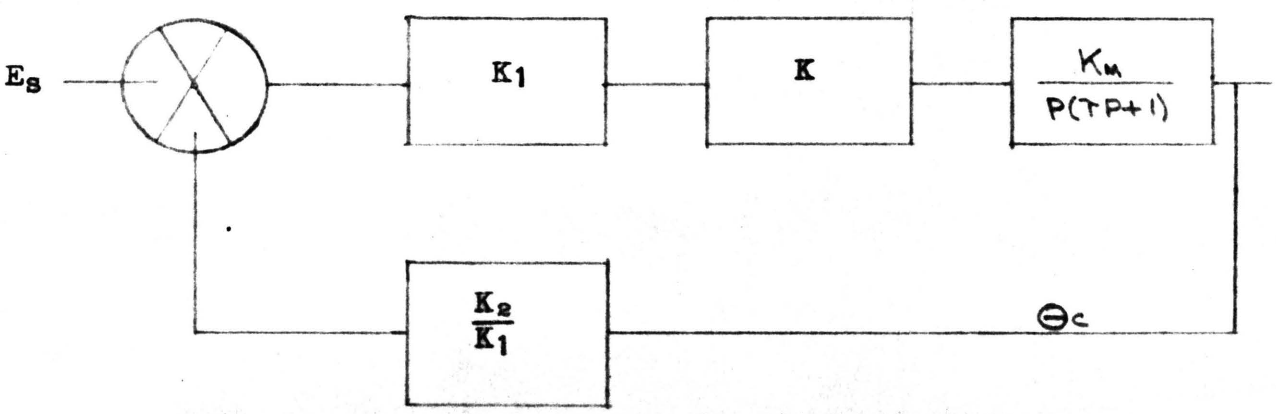


Figure 32. Different form of the servo system block diagram.

Where

K = gain of phase inverter and push-pull amplifier
= 52.6
K_2 = potentiometer constant = 726×15^3
K_m = motor gain constant = 27.8
τ = motor time constant = .794

In numbers

$$KGH = \frac{1.335}{P(P+1.26)}$$

The root-locus plot of this transfer function is shown in Figure 33. With a value of δ of 55 the percent overshoot is ten percent. For an ω_n of 1.18 the rise-time is about two seconds. These values are only approximations because all gains and time constants are theoretical. An experimental adjustment of the gain would be necessary to get the proper value of δ and rise-time.

For an idea of how fast the pen should respond, consider the following analysis. Let the time of one revolution of the polar plotter be one minute. Let the signal amplitude go from zero to maximum in twenty degrees. This would be for a very narrow beam antenna. Twenty degrees corresponds to one-eighth of a revolution. This means the pen would have to go from zero to maximum in 3.33 seconds. Thus, a rise-time of 2.0 seconds seems reasonable.

If the diameter of the polar plotter is six inches, and if the diameter of the pulley on which the pen movement turns is one inch, then the maximum angular displacement from center is 344 degrees. A one-turn potentiometer should thus be used in the potentiometer system. The sixteen degrees would

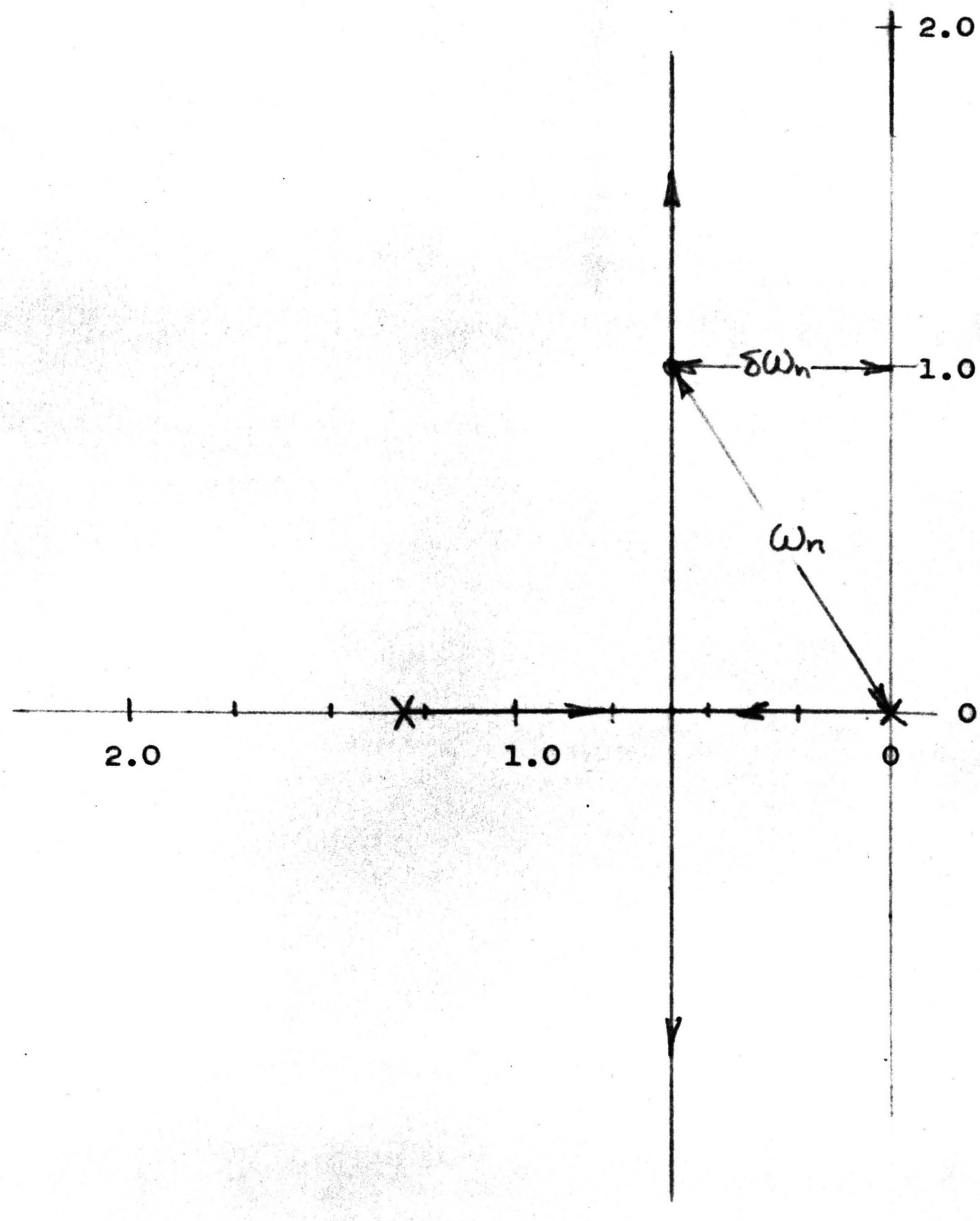


Figure 33. A root-locus plot of the KGH function

be taken up in end effects, since one-turn potentiometers have a useable range less than 260 degrees.

The synchro system for the new plotter will be the same as the synchro system for the present system. The proper gear ratio will have to be determined experimentally.

The 1000 cycle signal for the transmitter and the control phase of the motor may be obtained from any 1000 cycle generator with the proper power requirements. There are many available commercially which will do the job.

The power requirements for the system can be supplied by a commercial power supply, or, if necessary, one can be built.

It is realized that the above analysis is merely a preliminary design. Much laboratory work is required before the system will become a finished product. In the process of putting the system together and testing it, some discrepancies in the above analysis may become evident that are not now. However, it is believed that the above described system is workable and will provide a much better means of recording antenna patterns than the present system. Whenever possible in the design, use was made of equipment already available in order to cut down on the labor and additional outlay of money required.

BIBLIOGRAPHY

1. Silver, S. Microwave Antenna Theory and Design. McGraw-Hill Book Company Inc., New York, 1949, pp. 593-613.

2. Kraus, John D. Antennas. McGraw-Hill Book Company Inc., New York, 1950, pp. 444-487.

3. Cutler, C. C. Microwave Antenna Measurements, Proc. I.R.E., Vol. 35 (1947), pp. 1462-1471.

4. Caine, H. L., Katchky, M. "Microwave Antenna Beam Evaluator," Electronics, Vol. 20, (August, 1947), pp. 116-120.

5. Simmons, A. J., Emerson, W. H. "Anechoic Chamber for Microwaves," Tele-Tech, Vol. 12, (July, 1953), pp. 44-47, 100-107

6. Emerson, W. H., "Broadband Absorbing Materials," Tele-Tech, Vol. 14, (November, 1955), pp. 74-75, 137-137.

7. Skifter, H. R., Prichard, J. S. "Antenna Pattern Measurements," Communications, Vol. 28, (March, 1948), pp. 26-28, 41-43.

8. Schmitt, O. H., Peyser, W. P. "Aircraft Antenna Pattern Plotter," Electronics, Vol. 20. (May, 1947), pp. 85-88.

9. Newman, D. J., Radiation Absorbers -- Their Selection and Use, Canton, Massachusetts, Emerson and Cuming, Inc., 4 pp.

VITA

Norval Dale Wallace was born on July 27, 1932, in Branson, Missouri. He attended the public schools in Branson until 1942. He moved to Aurora, Missouri, in 1943 and lived there two years during which he attended Franklin Grade School. In 1945 he returned to Branson where he continued his education, graduating from Branson High School in 1950.

On July 13, 1950, he entered the Air Force. He went to Radar Maintenance School in the Air Force and served until July 12, 1954, as a radar mechanic.

After being discharged from the Air Force in 1954, he entered Drury College in Springfield, Missouri. In the fall of 1955 he transferred to the University of Missouri School of Mines and Metallurgy from which he was graduated in the spring of 1958.

In September of 1959 he entered the University of Missouri School of Mines and Metallurgy as a graduate student with an assistantship in electrical engineering.

He is a member of IRE, Eta Kappa Nu, Tau Beta Pi, and Phi Kappa Phi.