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MICROWAVE INTERACTION WITH LABORATORY PLASMA CONFINED IN A DIPOLAR MAGNETIC FIELD

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ABSTRACT

An experimental technique has been devised to measure the scattering of microwave radiation from a plasma coated magnetized sphere. A review of the relevant literature is given and the experimental apparatus and techniques are described. Preliminary results of attenuation and phase shift are presented which indicate that the plasma properties can be determined using this technique.

In addition the results provide the radar cross section of a sphere clad with plasma having configurations varying from a spherical shell to a disc.

INTRODUCTION

In earlier publications,[1,2] the author has described a technique for establishing and maintaining a stable plasma belt trapped in the field of a permanent spherical, dipole magnet. The experimental apparatus is essentially a glow discharge with the magnet serving as the cathode. The plasma properties and configuration are dependent upon the residual gas pressure, the size of the sphere, the applied voltage and various other physical parameters.

These properties have been studied using Langmuir probes. The results of these studies will be briefly reviewed to familiarize the reader with the experimental situation. For a comprehensive and complete discussion, the reader is referred to the references cited above.

The applicability of microwave scattering techniques as a diagnostic tool for the plasma will then be discussed. First the general experimental and theoretical background will be reviewed. Next, the experimental apparatus which has been constructed will be described. Finally, preliminary results of phase and amplitude measurements will be presented.

PLASMA PROPERTIES

The experimental arrangement is essentially a glow discharge. A spherical permanent magnet which produces a dipole field to an excellent approximation is placed in a vacuum system and made the cathode of a d.c. discharge. The residual gas pressure is typically of the order of tens of microns. Two basic types of plasma configurations occur when the gas breaks down. One is a stable luminous plasma belt which surrounds the sphere. The second is the onset of instabilities in the plasma in which brilliant arcs occur which emanate in the belt and traverse a magnetic field line, terminating on the sphere. These instabilities last for a few milliseconds. Both the stable belt and the instabilities have been studied and discussed in the works mentioned earlier.

Spheres of various size have been used, namely 1.25, 3.0, 6.0 and 12.0 inches in diameter. The shape of the stable belt varies with the size of sphere used as well as the applied voltage. In the case of the 1.25 inch diameter sphere, the visible plasma essentially surrounds the sphere with the exception of small areas near the pole. As the sphere size is increased, the belt becomes more flat, approaching a disc in the equatorial plane. In addition, the plasma around the larger spheres is more unstable than that around the small sphere.

A time exposure, color photograph of all of the plasma configurations is shown in Figure 1. The size of the sphere in this case is 12.0 inches. Shown in Figures 2 and 3, are photographs of some of the types of instabilities which occur. The size of the sphere in this case is 6 inches. A plot of plasma density vs distance in the equatorial plane is shown in Figure 4. In general, it may be said that for all sphere sizes the plasma density is of the order of 10^7 particles/cc, exhibits a maximum, and extends to a few radii. For the smallest sphere, the plasma almost completely surrounds the sphere, while for the largest sphere, the plasma is essentially a disc in the equatorial plane. It is this stable belt which is the subject of this investigation, rather than the arc instabilities.

It has been determined that the plasma is gyrating about the field lines, and drifting in the equatorial plane under the combined influence of the magnetic field radial gradient and the radial electric field.

The use of Langmuir probes has certain inherent difficulties and limitations which have been pointed out in the references cited. In addition, the plasma offers an excellent geometry for investigation using microwave scattering techniques. The problem may be categorized as the interaction of microwave radiation with a conducting sphere surrounded by a gyrotropic plasma having a configuration which varies from a non-uniform spherical shell to a disc of varying density.

It is well then to review the theoretical and experimental background for such a study before proceeding with the description of the experiment. The next two sections then are intended to provide the reader with a fairly extensive literature review as well as discuss the general aspects of the problem.

REVIEW OF THEORETICAL AND EXPERIMENTAL BACKGROUND

A. Scattering of Electromagnetic Waves

The scattering of electromagnetic waves from objects is, historically speaking, quite old and well formulated. The basic differential equations and general boundary conditions are known. However, except for the most simple geometries, the theoretical derivation of scattering patterns is quite complex. Experimentally, the problem is also quite complicated. An excellent review, is the text by King and Wu.[3]

In considering the ideal scattering problem, that is, one in which all interactions between transmitter, receiver and spurious reflections can be neglected, there are two important features which determine the scattering pattern, the geometry and physical properties of the scatterer. Perhaps the most simple scattering problem from the standpoint of geometry is the case of the infinite cylinder. Theoretical calculations and experimental results have been obtained by numerous investigations of the various cases of perfectly conducting, dielectric, and dielectric-clad, conducting cylinders.[4,6] The scattering of electromagnetic radiation from another geometrically simple body, the sphere, has also been the subject of a number of studies, including the cases of concentric spheres and dielectric spheres.[7,8] The text by Van de Hulst[9] is an excellent treatise on the subject of scattering by conducting and dielectric spheres.

The following general statements might be made concerning the present state of the scattering problem. Theoretical solutions of the scattering pattern are available for simple geometries such as the thin wire, cylinders, and spheres and various simple arrays of these bodies. In most cases computer evaluations are necessary. There have been a few experimental studies of a number of various shapes to verify the theoretical calculations. Usually, the best method of obtaining the scattering pattern of a complicated object is to actually measure it, or a suitable model, experimentally.

B. Scattering of Electromagnetic Waves from Plasma

We now turn to the question of scattering from plasma and plasma-clad bodies. In considering the propagation of electromagnetic waves through a plasma one observes that the plasma is a dielectric mainly because of the presence of free electrons. The collisions between electrons and ions cause energy dissipation which makes the dielectric lossy. Further, in the presence of a steady magnetic field, the plasma becomes anisotropic so that the dielectric constant is a tensor. Thus, when an electromagnetic wave traverses a plasma one might generally expect attenuation as well as non-reciprocal propagation. Wait[10] has examined the general case of boundary conditions in such a plasma giving explicit results for reflection coefficients of stratified plasma in planar and cylindrical geometry. Unz[11] has made a study of boundary conditions and reflections for general gyrotropic media.

In general, the dielectric tensor, neglecting ion motion, is a function of the electron plasma frequency, the electron gyro frequency and the electron collision frequency. Thus, the wave scattered by a body of plasma contains, in general, information concerning these three quantities. The particular form of the information is, of course, dependent upon the physical conditions involved. For example, Nagelberg[12] has studied theoretically the interaction of microwaves with gyroelectric plasmas of finite extent having cylindrical and spherical boundaries. One of the important effects of the anisotropy is to induce changes in the polarization of the scattered wave. In addition, if the plasma is in thermal equilibrium, there is a relation between the scattered radiation and the noise emitted from the plasma.

The scattering of microwaves from cylindrical plasmas has been the subject of a number of studies.[13,14] The normal modes of oscillation of a cylindrically symmetric, magnetically confined plasma have been studied. The scattering of microwaves from an infinitely long magnetized plasma column has been studied by Platzman and Ozaki.[16] Midzuno[17] has attacked the same problem by a different technique eliminating some of the assumptions using the Born approximation. Shmoys[18] has shown for a cylindrical column whose density distribution is a slowly varying, monotonically decreasing function of radius, that the diffraction pattern can be calculated directly from the knowledge of the density function and vice versa. Easley[19] has made an excellent review of the problem of scattering of microwaves from plasma cylinders and has performed a number of experiments on a plasma jet at 35 and 72 kmc/s. He has concluded on the basis of his results a number of important things, among which are: that the concept of matching experimental scattering measurements with plasma microscopic parameters is a useful laboratory technique; and, that quite accurate measurements can be made using relatively simple techniques.

In concluding this review, it may be said that considerable experimental and theoretical results concerning the scattering of microwaves from various bodies exists. However, there have been no measurements of the scattering of microwaves from a plasma coated sphere. We may thus say that apart from the possible geophysical applications of such measurements we may obtain in addition the scattering patterns of a physically important and simple plasma-conductor configuration.

We now turn to a discussion of the experimental apparatus which has been constructed and the results which have been obtained.

EXPERIMENTAL APPARATUS

The microwave source used was an X-13 klystron capable of generating frequencies in the range 8-12 gc. Standard X band equipment was used throughout. The transmitting and receiving horns were the standard gain type. The transmitting horn was fixed in a given position while the receiving horn was mounted on a lucite stand. The receiving horn assembly slides on a lucite table top in a circular direction. The angular position can be measured to within 0.1^{o}. A schematic of the entire assembly as viewed from the vertical direction is shown in Figure 5. The glass bell jar is 18" in diameter and has 1/4" walls. The magnetized sphere is placed in the center of the bell jar. The top of the bell jar and the table are sufficiently far from the sphere so that they do not effect the measured scattering patterns.

Phase shift measurements were made using a rotary vane phase shifter as shown in the schematic in Figure 6. Mechanical motion of the receiver was accomplished using suitable flexible wave guide.

EXPERIMENTAL RESULTS

The radiation pattern of the transmitting horn was first measured and is shown in Figure 7. It can be seen that the received power drops 40 db within 60°. All scattering measurements at a given angle have been referred to this curve by arbitrarily designating the same zero level for all patterns at zero degrees. Figure 8 shows the effect of the bell jar. A new feature is a side lobe at approximately 42° and 20 db down. Numerous other side lobes also occur at larger angles which are of the order of 30 db down. Figure 8 also shows the effect of the sphere alone. A broad side lobe occurs between 10° and 30°, a more pronounced lobe at 42° and a pronounced minimum at approximately 65°. The pattern for greater than 80° is essentially flat at 20 db down.

The combined effect of the bell jar and sphere are shown in Figure 9. This pattern shows numerous maxima and minima.

This pattern indicates that a simple addition of the various curves is not valid due to phase differences. In view of this fact, the following procedure was used to observe the effect of the plasma.

At each particular angle the received power was measured first, then the plasma discharge was established and the difference in the received power measured. A curve of this power difference is presented in Figure 10. The missing segment from 50°-140° is due to lack of sufficient power received in this range as seen from Figure 9.

Measurements of phase shift caused by the plasma as a function of angle were also made. A plot of this phase shift is shown in Figure 11.

An alternate procedure to observe the effects of the plasma was to transmit the microwave signal unmodulated. The plasma discharge was then initiated and quenched at a 1000 cps in an essentially square waveform. The oscillating plasma thus serves to modulate the microwave signal. The percent modulation is sufficient to make a detectable signal at 1000 cps. The resultant pattern is shown in Figure 12.

In this case, 20 db down represents a condition of being in noise.

CONCLUSION

The change in power received and the phase shift caused by the plasma show definite periodic effects. No exact analysis of these patterns can be made without the use of a computer. In general, however, the position and depth of the minima as well as the position and height of the maxima will yield the maximum plasma density as well as its spatial distribution. Such calculations will be made in the future comparing the theory with experimental results. The plasma density and temperature will also be varied to observe their affects on the scattering cross section.

The technique of modulating the plasma offers some other advantages. The fact that the percent modulation has been found proportional to the discharge current indicates that the power detected at the receiver will be proportional to the electron density.

Thus, these preliminary results indicate that the microwave techniques described herein provide an excellent means of measuring the properties of the trapped plasma and will also give the radar cross section of a plasma clad sphere in which the configuration of the plasma with respect to the sphere as well as its density are easily variable.

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FIGURE CAPTIONS

FIGURE 1. Fully developed plasma belt with accompanying arcs. Radius of sphere is 6 inches. Pressure = 50 microns.

FIGURE 2. Fully developed plasma belt with one arc and one streamer. Radius of sphere is 3 inches. Pressure = 42 microns.

FIGURE 3. Fully developed plasma belt with two arcs. Radius of sphere is 3 inches. Pressure = 42 microns.

FIGURE 4. Plasma density, curve a is electron density; curve b is ion density; curve c is total density. Radius of sphere is 6 inches. Pressure = 42 microns. Discharge current = .44 ma at 540 volts.

FIGURE 5. Schematic diagram of scattering assembly; vertical view.

FIGURE 6. Schematic diagram of interferometer.

FIGURE 7. Power received vs. angle for the configuration of no bell jar or sphere.

FIGURE 8. Power received vs. angle for the configuration of: (a) sphere, no bell jar, (b) bell jar, no sphere.

FIGURE 9. Power received vs. angle for the configuration of sphere and bell jar combined.

FIGURE 10. Change in power received due to plasma as a function of angle.

FIGURE 11. Change in phase of received signal due to plasma as a function of angle.

FIGURE 12. Power received vs. angle with unmodulated klystron and 1000 cps square wave plasma discharge.

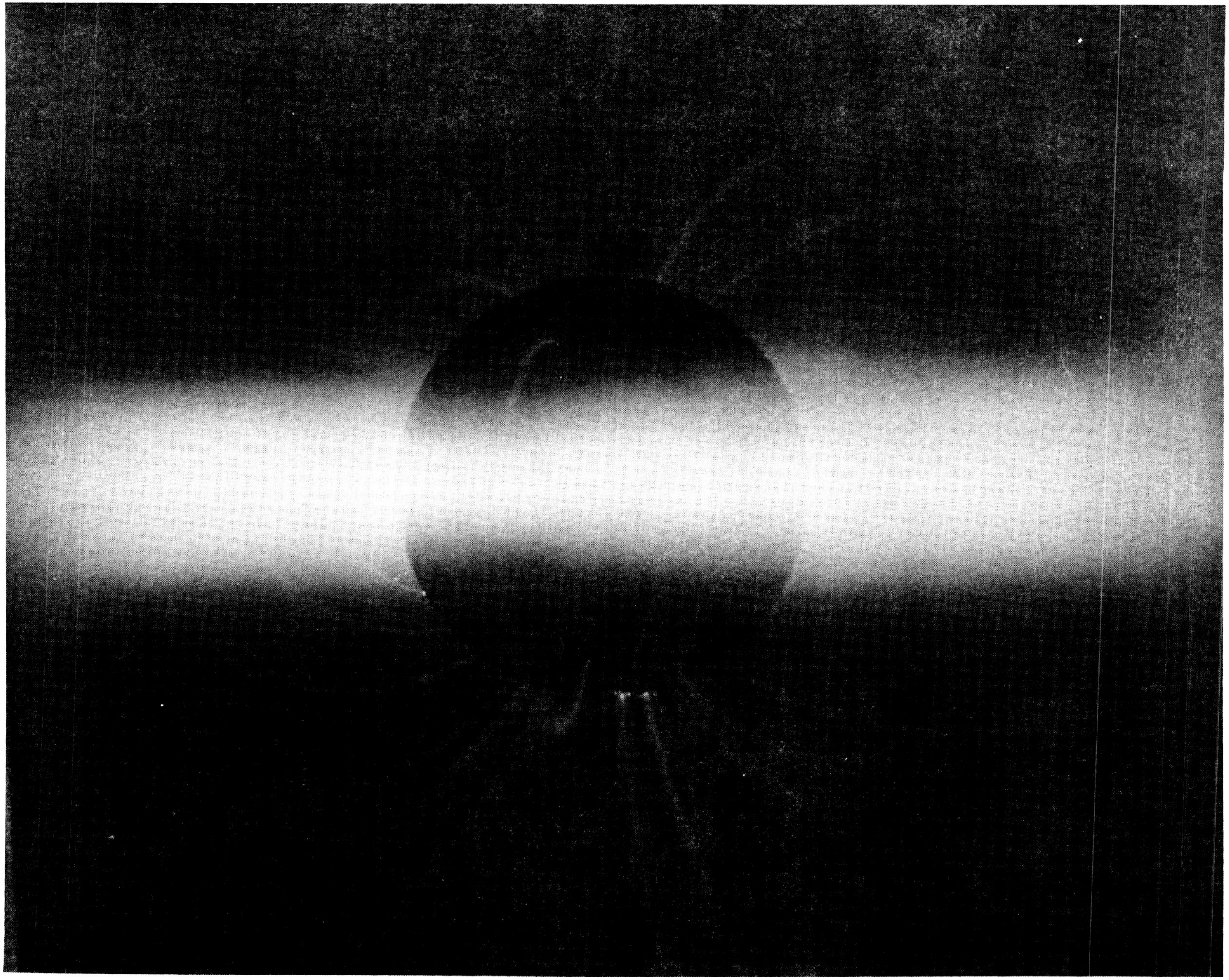


FIGURE 1.

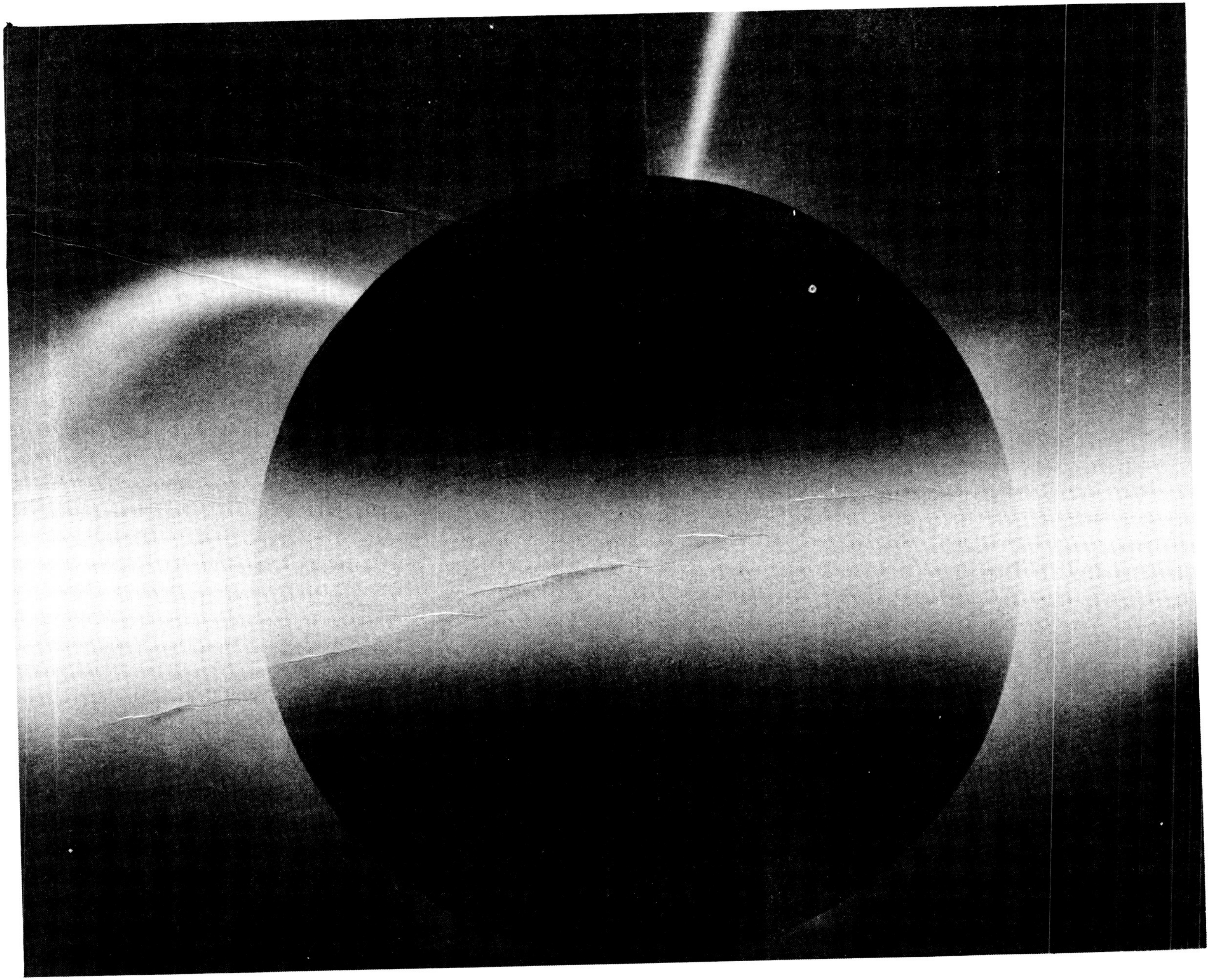


FIGURE 2.

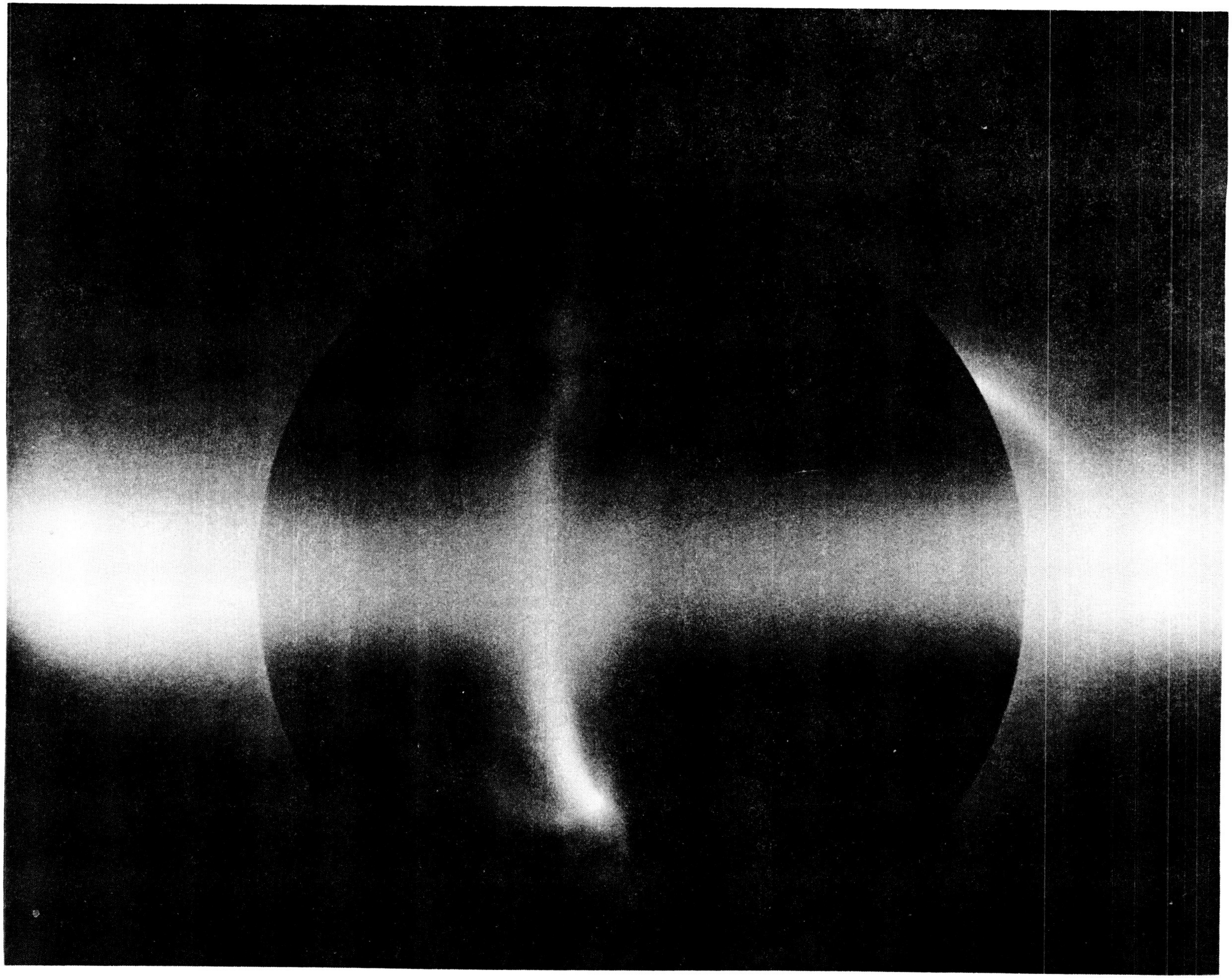
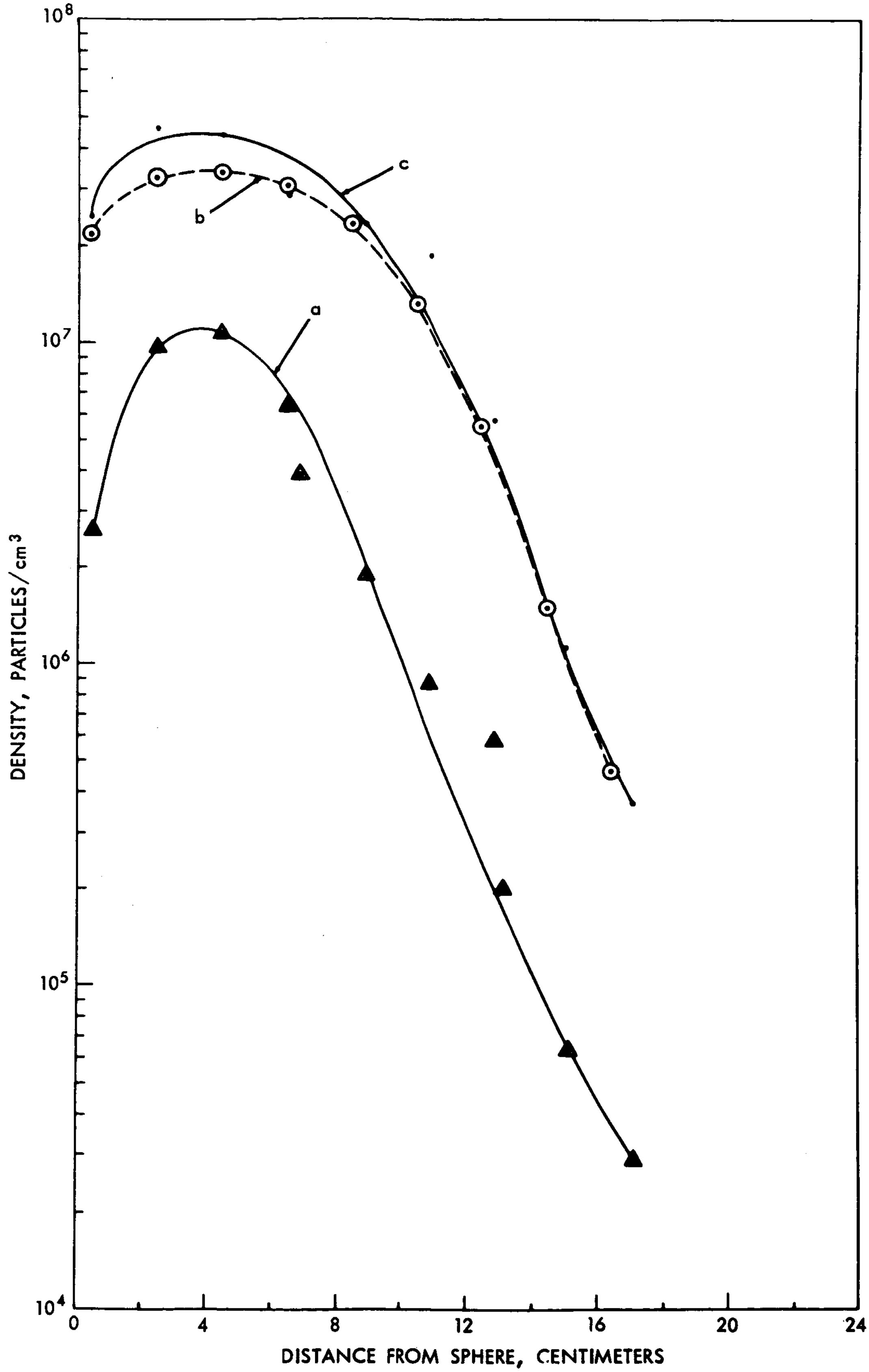


FIGURE 3.



10^8
10^7
10^6
10^5
10^4
c
b
a
DENSITY, PARTICLES/cm³
0
4
8
12
16
20
24
DISTANCE FROM SPHERE, CENTIMETERS

FIGURE 4.

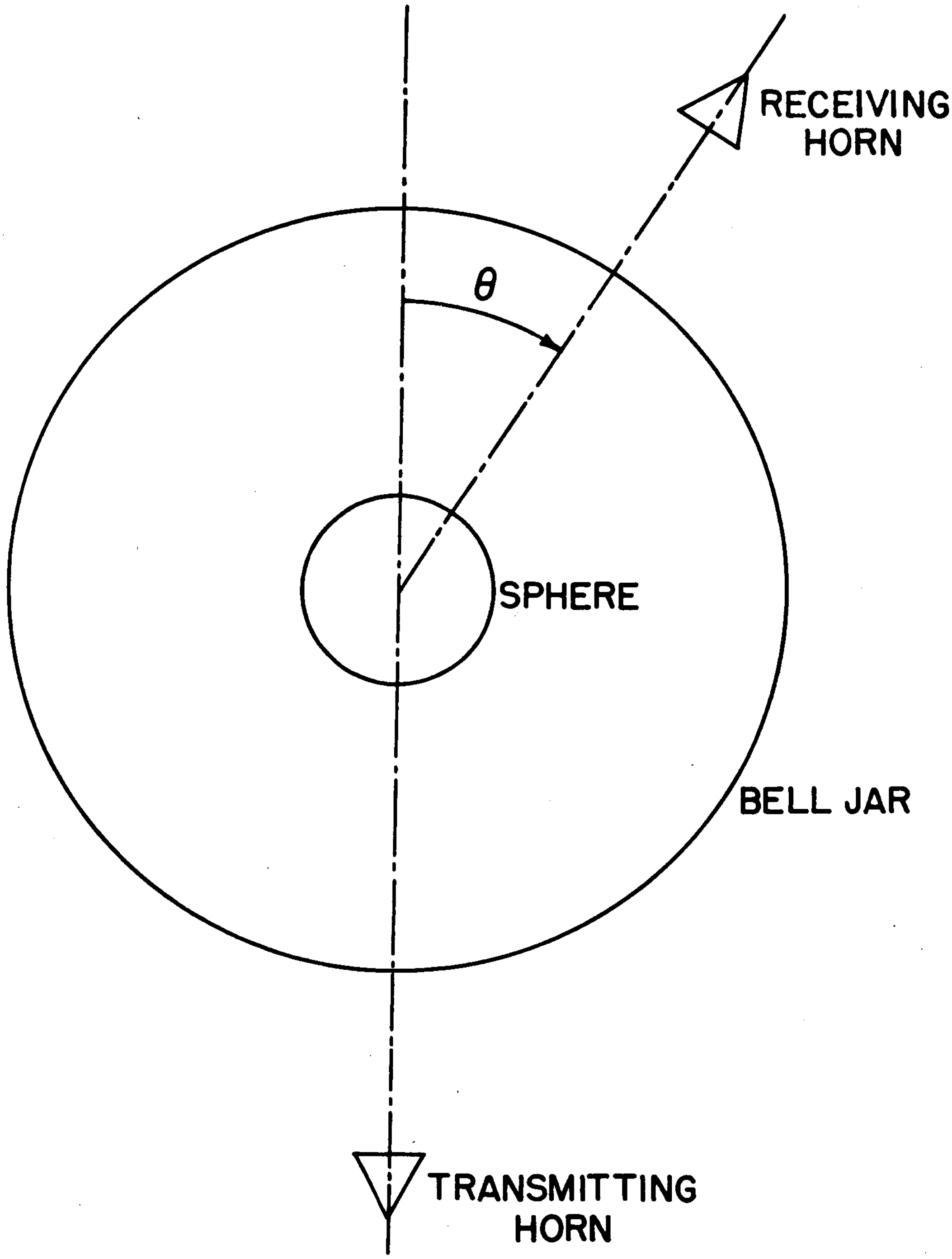


FIGURE 5.

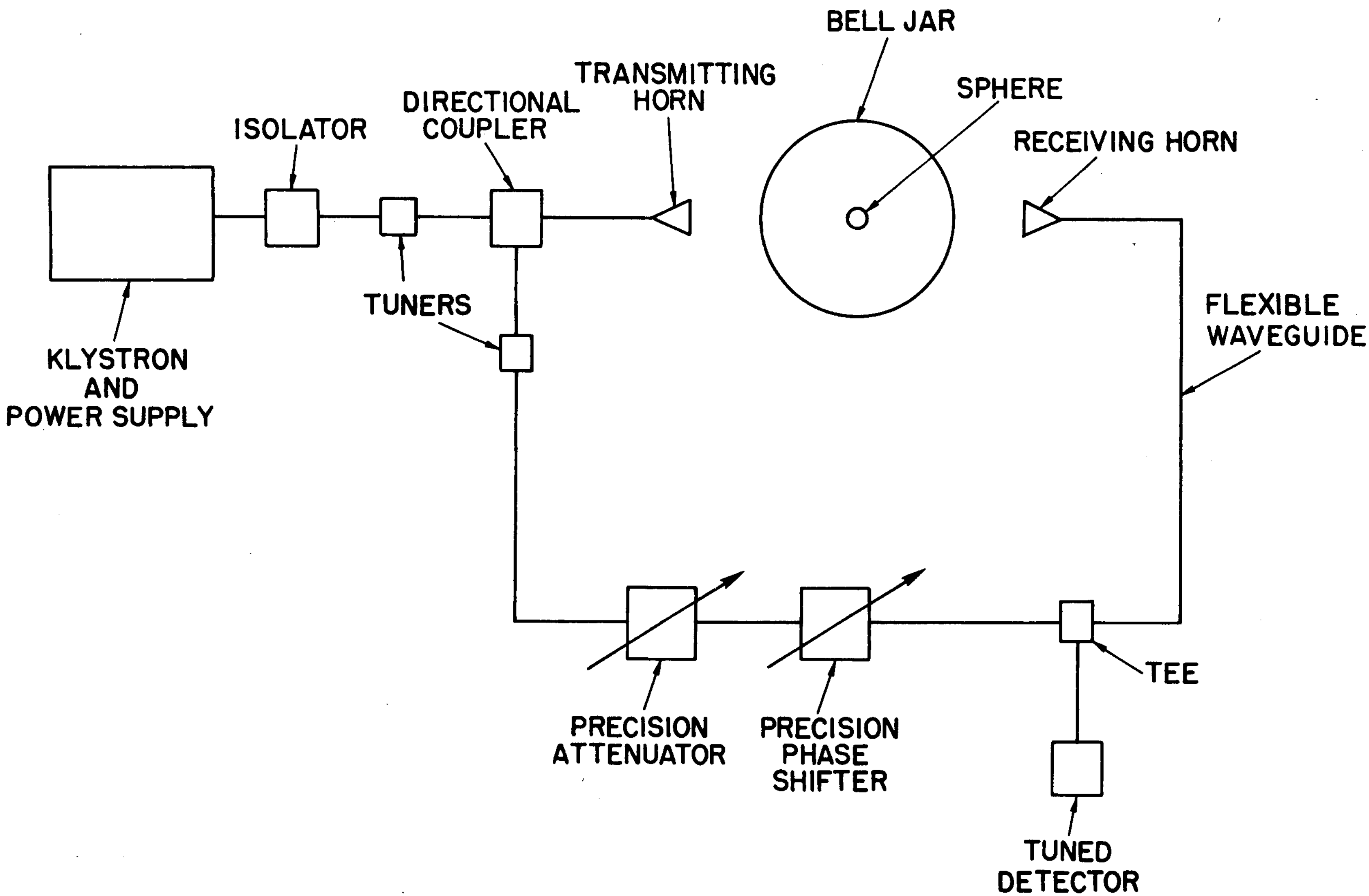
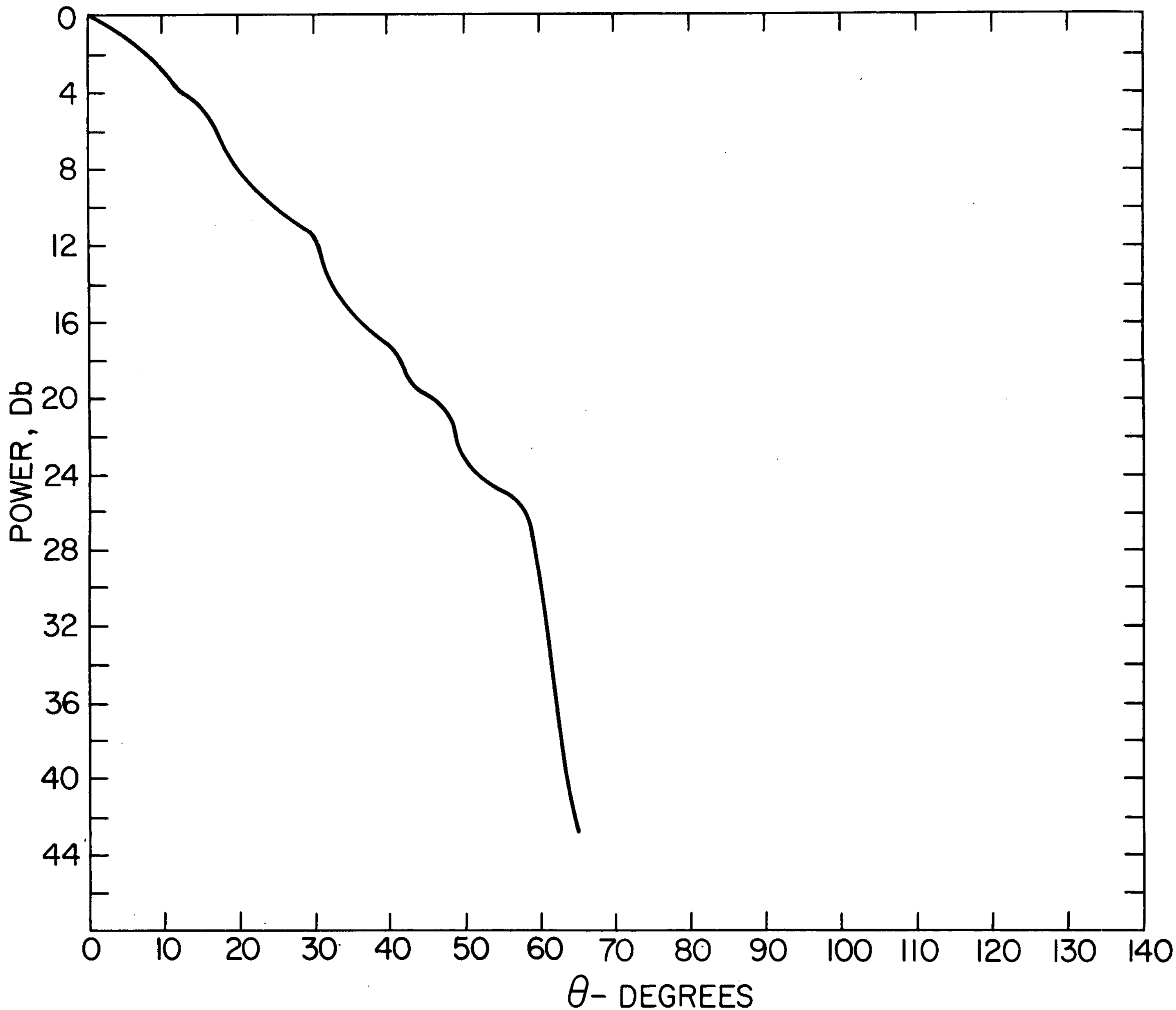

BELL JAR
TRANSMITTING HORN
SPHERE
DIRECTIONAL COUPLER
ISOLATOR
RECEIVING HORN
TUNERS
KLYSTRON AND POWER SUPPLY
FLEXIBLE WAVEGUIDE
TEE
PRECISION ATTENUATOR
PRECISION PHASE SHIFTER
TUNED DETECTOR

FIGURE 6.


POWER, Db
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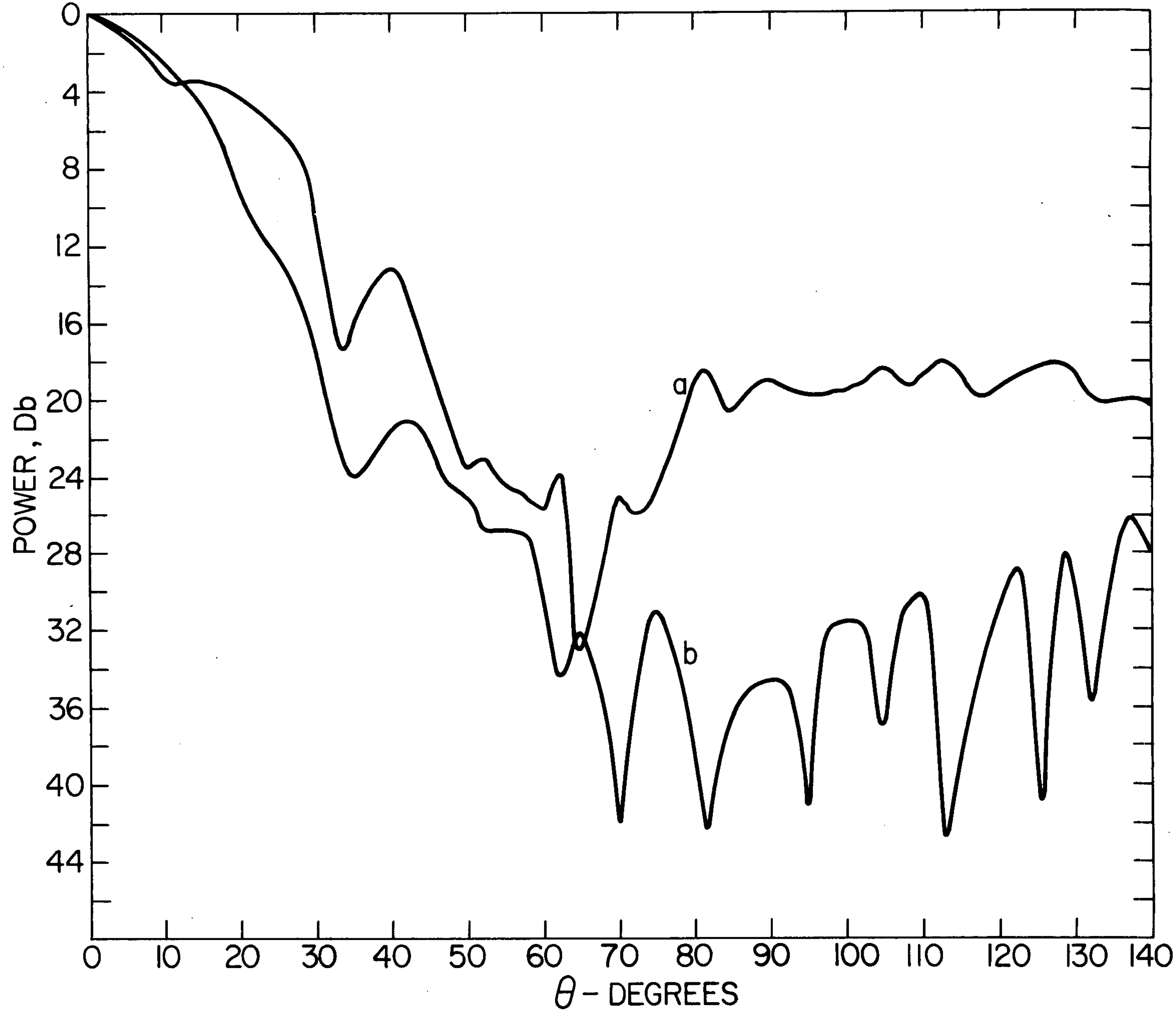
θ- DEGREES

FIGURE 7.



POWER, Db
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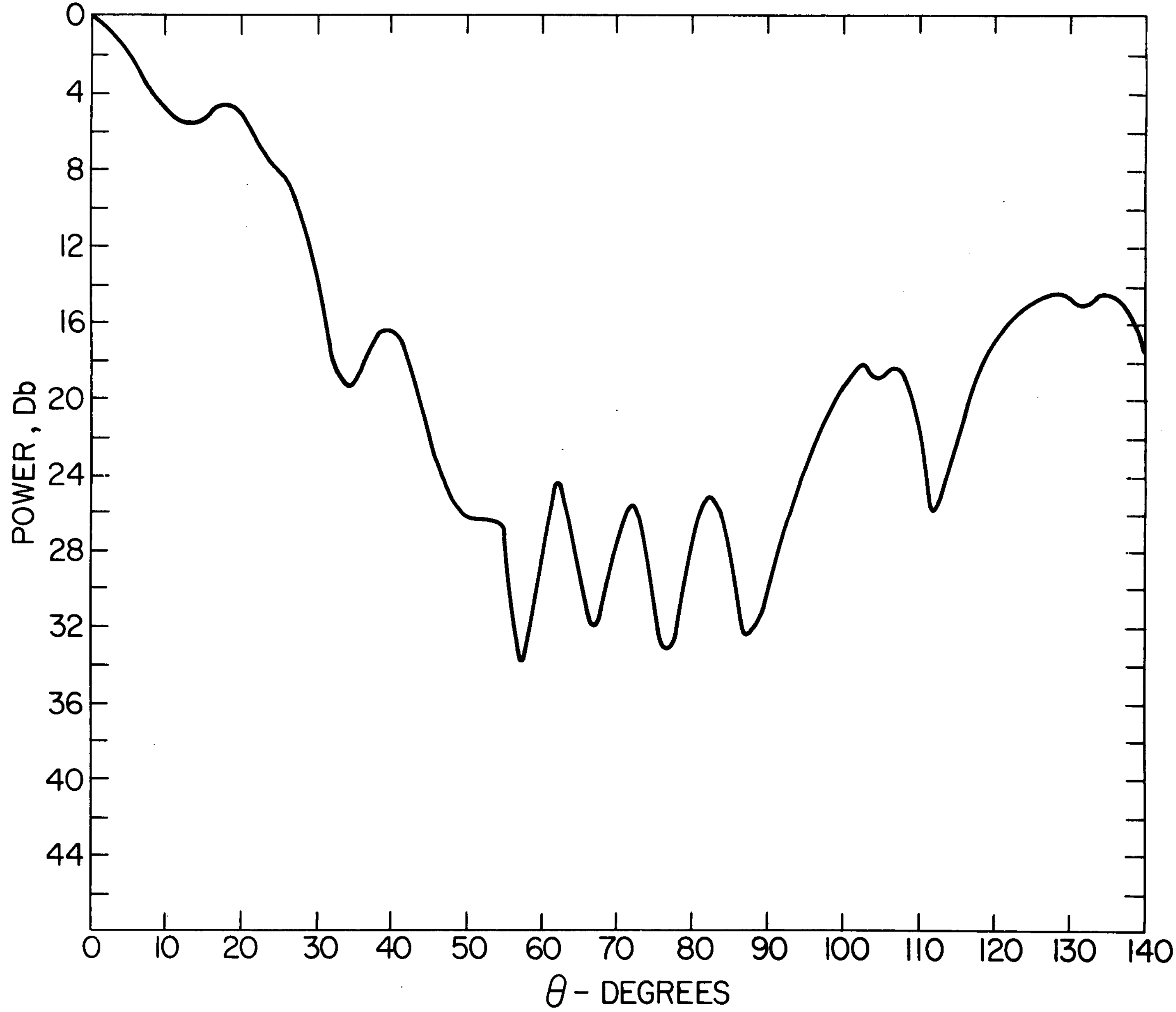
θ - DEGREES
a
b

FIGURE 8.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POWER , Db
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140
θ - DEGREES

FIGURE 9.

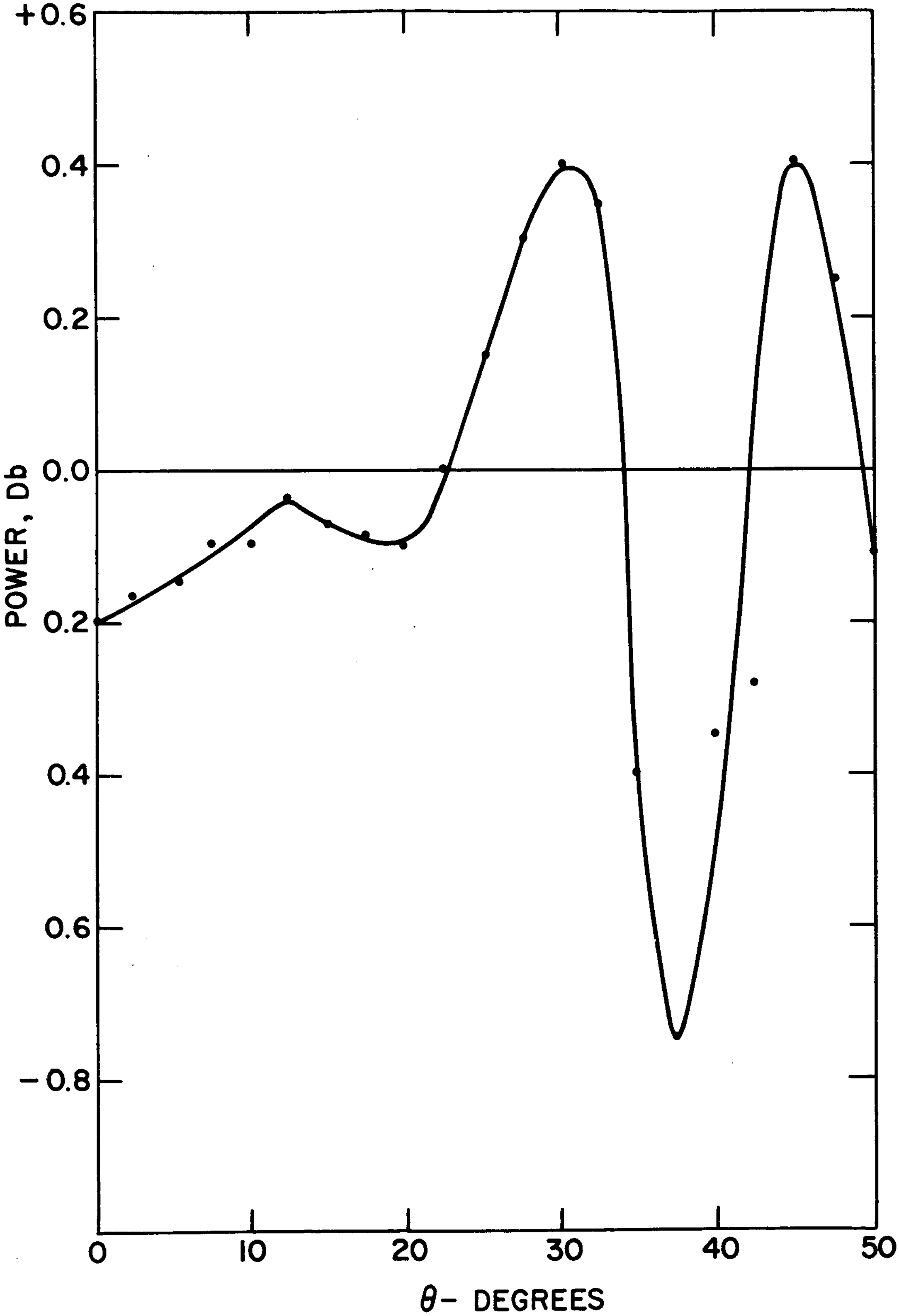
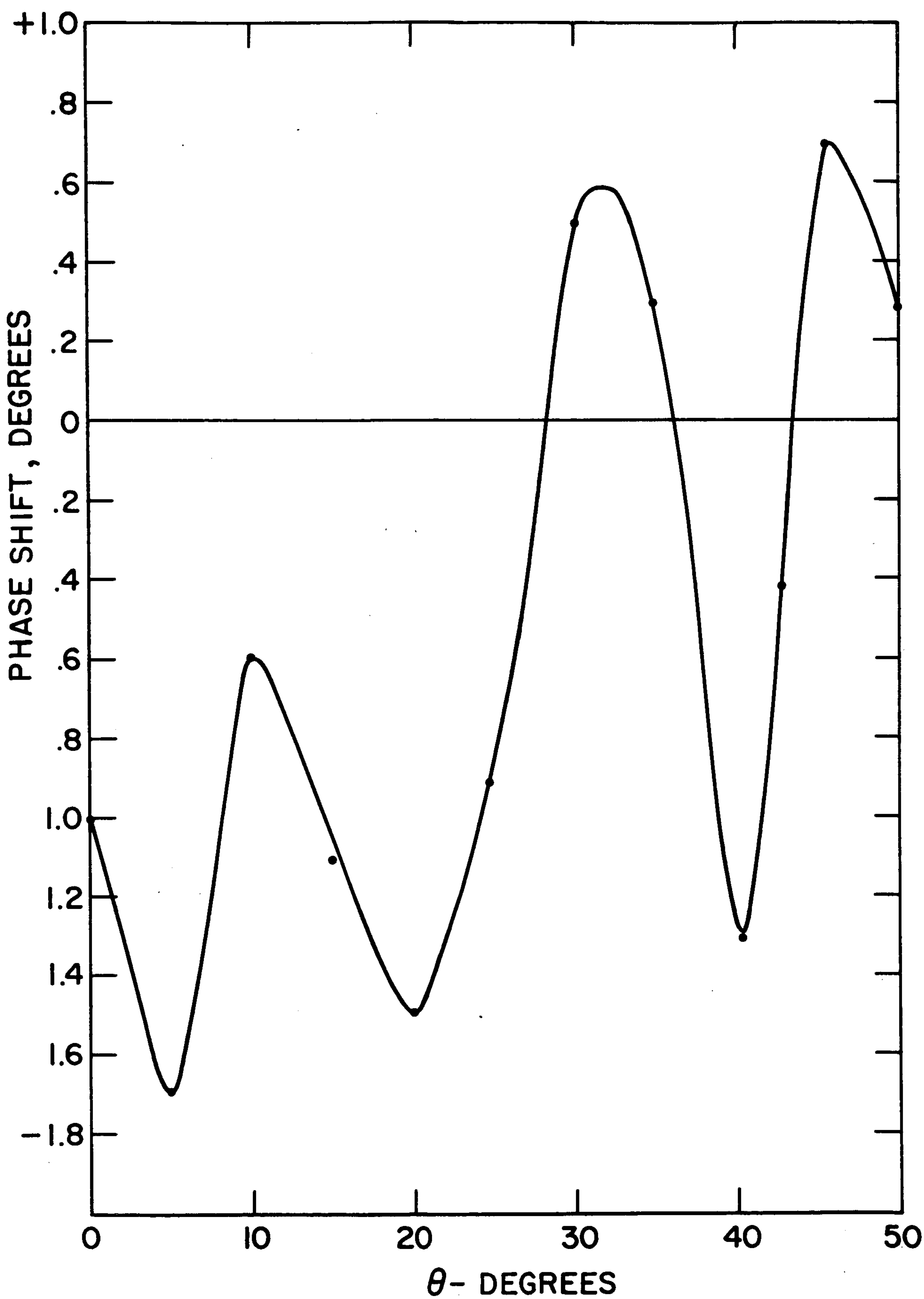


FIGURE 10.



+1.0
.8
.6
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.2
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
−1.8
PHASE SHIFT, DEGREES
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θ- DEGREES

FIGURE 11.

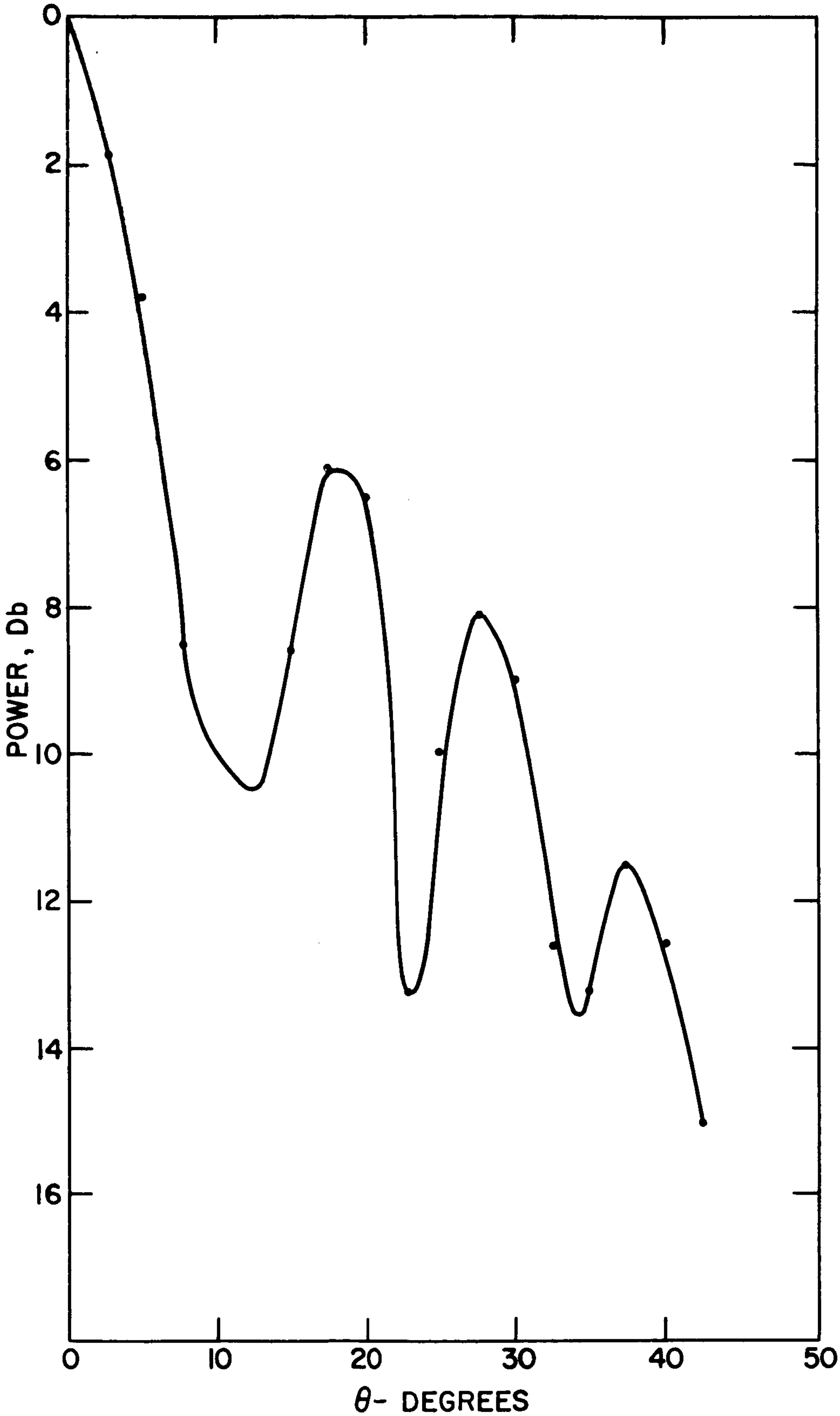

FIGURE 12.