MICROWAVE ANTENNAS ADJACENT TO
METAL SURFACES.

BY

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From: Commanding Officer, Naval Training Schools.
To: Superintendent, U. S. Naval Postgraduate School.

OR

Subj: Thesis entitled "Microwave Antennas Adjacent to Metal Surfaces", prepared by LCDR H. H. Montgomery, Jr. and LCDR M. W. Whitaker, Jr., as a partial fulfillment for the requirements of a Master's degree.

1. The thesis supervisor, Professor H. J. Zimmermann, assigned a grade of "C" to this work, with the following comment:

"On this project the work was shared fairly equally by the two students. A large quantity of data was obtained but the thesis was somewhat lacking in interpretation and evaluation of the results."

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ADJACENT TO METAL SURFACES

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STATEMENT OF THE DIVISION OF WORK

Since the measuring equipment used required two operators for best results, all measurements were made jointly. The responsibility for the preparation of the paper was divided as follows:

Chapters I, V, and VI by H. H. Montgomery, Jr.

Chapters II, III, and IV by M. W. Whitaker, Jr.

Chapter VII was prepared jointly.

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MICROWAVE ANTENNAS ADJACENT TO METAL SURFACES

Abstract

Radiation patterns of three general types of microwave antennas adjacent to plane metal surfaces are studied to determine which is most suitable for use in a new type navigational system for high speed aircraft. The antenna types investigated are: (1) rectangular wave guides cut off at an angle and adjacent to a metal plane, (2) these same antennas filled with a solid dielectric (polystyrene), and (3) slotted wave guide antennas of the end-fire type. A preliminary investigation was made of the radiation of wave guides cut off at an angle, but with the metal plane absent, to determine the effects of variations of the angle of cut on the radiation patterns.

Of the antennas tested of types (1) and (2) above, several have radiation patterns with reasonably small side lobes, but the main beam widths and position of the centers of the main beams are not suitable for the particular application for which a low drag antenna is sought. The results presented show what may be expected from these antennas for different orientations with respect to the metal plane. Some of these may be useful where their radiation characteristics are needed.

The slotted wave guide antennas with four slots have a radiation pattern which is close to the preliminary

estimates of the requirements of the navigational equipment. It should be possible to meet the final specifications very satisfactorily with this type antenna. The radiation pattern has very small side lobes and a main beam of approximately the desired width and orientation with respect to the metal plane. It is also of the zero aerodynamic drag type, making it more applicable to high speed aircraft.

Measuring equipment designed and built by the authors to facilitate measurements of the radiation patterns is recommended for use in antenna design by an experimental method. The equipment used gave three cathode ray tube presentations of the radiation pattern. One cathode ray tube was used to present a polar plot, while the other was used to present either a 360-degree rectangular coordinate plot, or a 60-degree rectangular coordinate plot with markers at 10-degree intervals. The center of the 60-degree plot could be manually selected at any point on the polar plot.

CHAPTER I

INTRODUCTION

Microwave antennas suitable for high speed aircraft should be small and should contribute little or no aerodynamic drag. As the supersonic region is approached, the drag consideration becomes increasingly important. Ideally, an antenna should be flush with the fuselage surface, or should be an integral part of the wing surface. A few zero drag microwave antennas[8] have been built. In general, these have radiation patterns with the main beam approximately normal to the plane of the fuselage at the antenna.

An antenna is desired for a new type navigational equipment for high speed aircraft, using 3 centimeter wave length. Since the equipment is yet in the design stage, rigorous specifications for the antenna radiation characteristics have not been set. Preliminary estimates are that the radiation pattern should have a main beam about 60 degrees wide in both vertical and horizontal planes. If the antenna is to be located in the fuselage, it is desired that one half-power point of the main beam be near the plane of the fuselage surface at the antenna. If the antenna is to be located at the wing tips, it is desired that the center of the main beam lie in the direction of flight.

In attempting to obtain an antenna which would satisfy these requirements, a study was made of the radiation patterns of three general types of antennas:

(1) Open wave guides cut off at an angle and projecting through, or adjacent to, a plane metal

surface.

(2) Same as (1), but filled with a solid dielectric.

(3) End-fire slotted wave guide antennas.

Preliminary investigations were made into open wave guide radiators, with the metal plane absent. Measurements were made of the radiation patterns of these wave guides, cut off at various angles in either the broad or narrow dimension, and with or without solid dielectric filling. This was done to establish what radiation patterns could be expected from such antennas.

The effect of various orientations of the metal surface in (1) and (2) above, were measured, although all arrangements did not give zero drag antennas. All of the antennas tested were made of standard 3 centimeter wave guides. Polystyrene was used as the dielectric filling in the wave guide. The preliminary measurements of end-fire slotted guides were discouraging, because of the low percentage of power radiated, but later designs made this type antenna seem most promising for application in the navigational equipment.

All of the experimental results for the three types of antennas are given, although many are entirely unsuited for application in the navigational equipment. Some will have other applications in high speed aircraft, and, collectively, they present a factual report of what may be expected from various microwave antennas near metal surfaces.

The experimental, rather than the analytical approach was chosen, because it seemed more practical. Several approximate solutions have been made for the relatively simple case of the open-end rectangular wave guide radiator (cut off at an angle of 90 degrees).[1,3,5] Some of these agree fairly closely with experimental results, while others do not, depending upon what assumptions were made in the attempt to satisfy the boundary conditions at the aperture. With more complex wave guide antenna constructions, the theoretical solution is made more difficult. Considerable time was spent in the design and construction of equipment which would automatically plot the antenna radiation patterns. This equipment is described in the following chapter.

Solid dielectric use in antennas has been restricted to those of the end-fire type in radar systems requiring small beam angles. Since fairly broad beams are desired here, the dielectric will either be terminated flush with the edge of the radiating aperture of the wave guide or will project only a short distance beyond.

Slotted wave guide antennas of both the end-fire and broadside array type have been used previously. However, the type studied here is a new one, since the slots are oriented transversely in the broad side of the wave guide.

CHAPTER II

ANTENNA RADIATION PATTERN MEASURING EQUIPMENT

In order to avoid the slow process of plotting a large number of antenna radiation patterns point-by-point, equipment was constructed which would rapidly and accurately present the radiation pattern on the screen of a cathode ray tube. Three types of presentation were chosen: (1) a 360-degree polar plot, (2) a 360-degree rectangular plot, and (3) a 60-degree rectangular coordinate plot. These patterns were photographed and the time required to obtain the radiation pattern of a test antenna was reduced to about ten seconds.

Briefly, the measuring equipment consisted of the following: a Shepherd-Pierce tube with square-wave modulation of its repeller voltage was used as the transmitter for the test antenna, which was rotated at six revolutions per minute. A receiving antenna and crystal detector were placed about 30 feet from the test antenna (Figs. 48 and 49). The video signal from the crystal detector was amplified and fed to the two driver stages which supplied current to the magnetic deflection coils of two cathode ray tubes. One of these tubes had a rotating deflection coil which was driven in synchronism with the test antenna rotation and which presented a polar plot of the power radiated by the test antenna. The other tube had both horizontal and vertical deflection coils. The amplified video signal was applied to the vertical deflection coils, while the horizontal deflection coils received a sweep voltage controlled by the test antenna rotation. This tube presented a 360 degree or a 60 degree rectangular coordinate plot of the power radiated, depending upon which of two sweep voltages was selected for the horizontal deflection coils. A block diagram of the equipment is shown in fig. 1 . The physical arrangement of the measuring equipment is shown in figs. 52, and 54.

The test antenna and its rotating equipment (Fig. 51) are located inside the radome (Figs. 48 and 49). The test antenna was mounted on the turntable driven by a d.c. motor at about six revolutions per minute. Voltages for the Shepherd-Pierce tube were supplied through slip rings. The turntable was geared to a one-to-one speed synchro transmitter and to a thirty-six-to-one speed synchro transmitter, both of which were used to supply bearing data to a servomechanism which positioned the rotating deflection coil on one of the cathode ray tubes. The modulation-frequency of the transmitter was about 330 cycles per second. This frequency was chosen because it gave the best current wave form in the deflection coils of the cathode ray tubes. The turntable was also geared to a potentiometer which controlled the horizontal sweep voltage on one of the cathode ray tubes.

The receiving antenna used was a high-gain electromagnetic horn. An absorption type wavemeter was inserted between the horn and the crystal detector. The receiving antenna assembly is shown in fig. 50.

The crystal detector output was fed through a coaxial

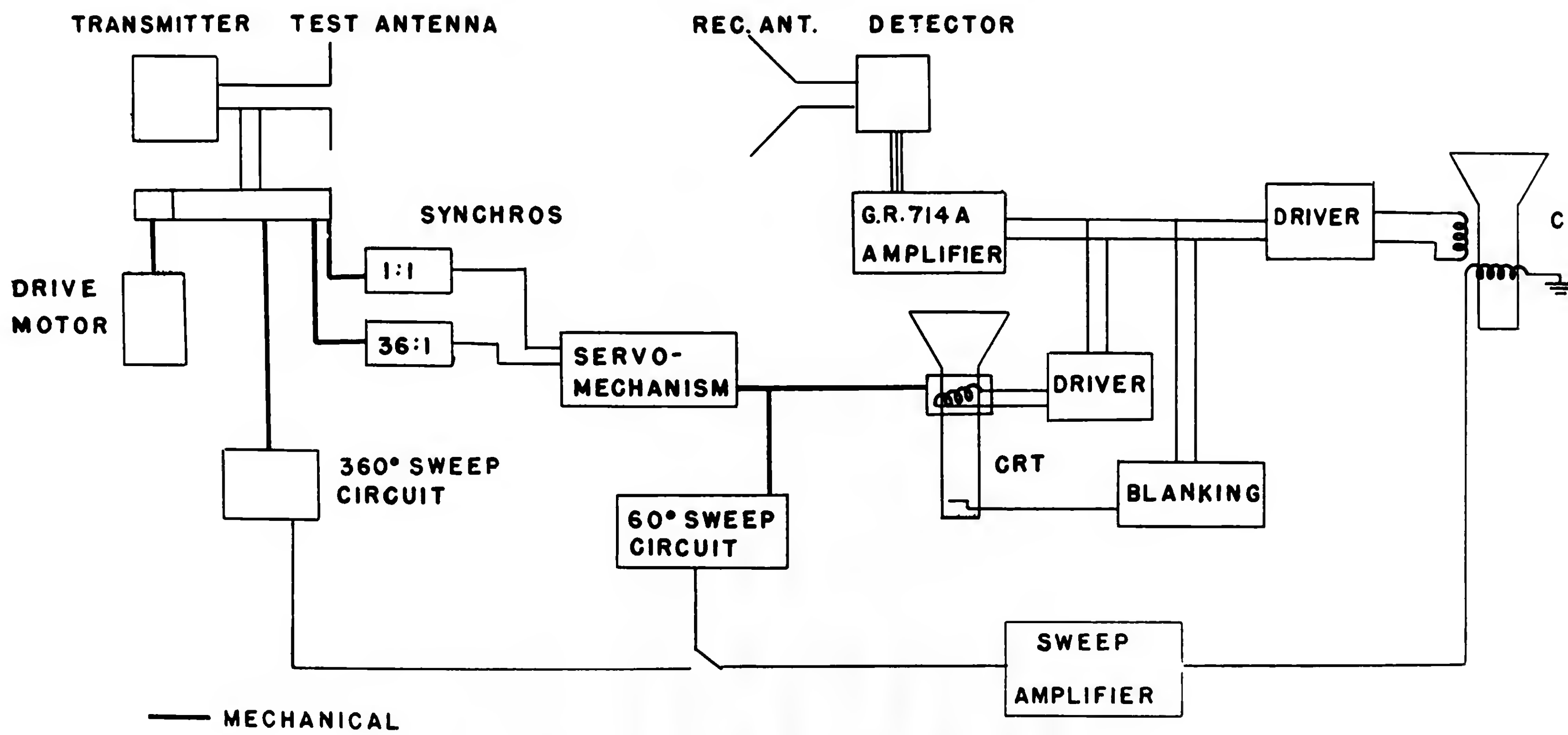


FIG. I. BLOCK DIAGRAM OF ANTENNA RADIATION PATTERN MEASURING EQUIPMENT line and a shielded plug to a General Radio type 714-A amplifier. This amplifier was chosen because of its high gain (0 - 80 db.), and because of its flat frequency response over a sufficiently wide band for amplification of a 330 cycles per second square-wave. Even with 80 db. gain, the square-wave signal maintained its wave form and had very little noise added to it by the amplifier.

A surplus radar indicator having two cathode ray tubes was modified extensively and used to complete the measuring equipment. The "P.P.I." scope was modified to present the polar plot, and the "B" scope was used for the other presentations. The signal from the General Radio 714-A amplifier was fed to two driver stages for the deflection coils. The circuits for these stages are shown in figs. 2 and 3 . They are designed to produce beam deflections that are linear functions of the input square-wave voltage amplitude over a reasonable region, and then to limit the deflection coil current to a safe value to prevent burning out the deflection coils with large signals.

The 60-degree sweep voltage for the rectangular coordinate plot was already provided in the radar indicator and was used unchanged. The center of this 60-degree pattern could be selected by setting an index marker to the desired bearing on a bearing dial surrounding the polar plot cathode ray tube. The 60-degree sweep circuit also provided bearing markers at 10 degree intervals, one marker appearing at the center of the 60-degree sweep. A photograph of a 60-degree pattern is shown in fig. 47. The markers provided an easy means for obtaining beam angles, positions of maxima, etc.

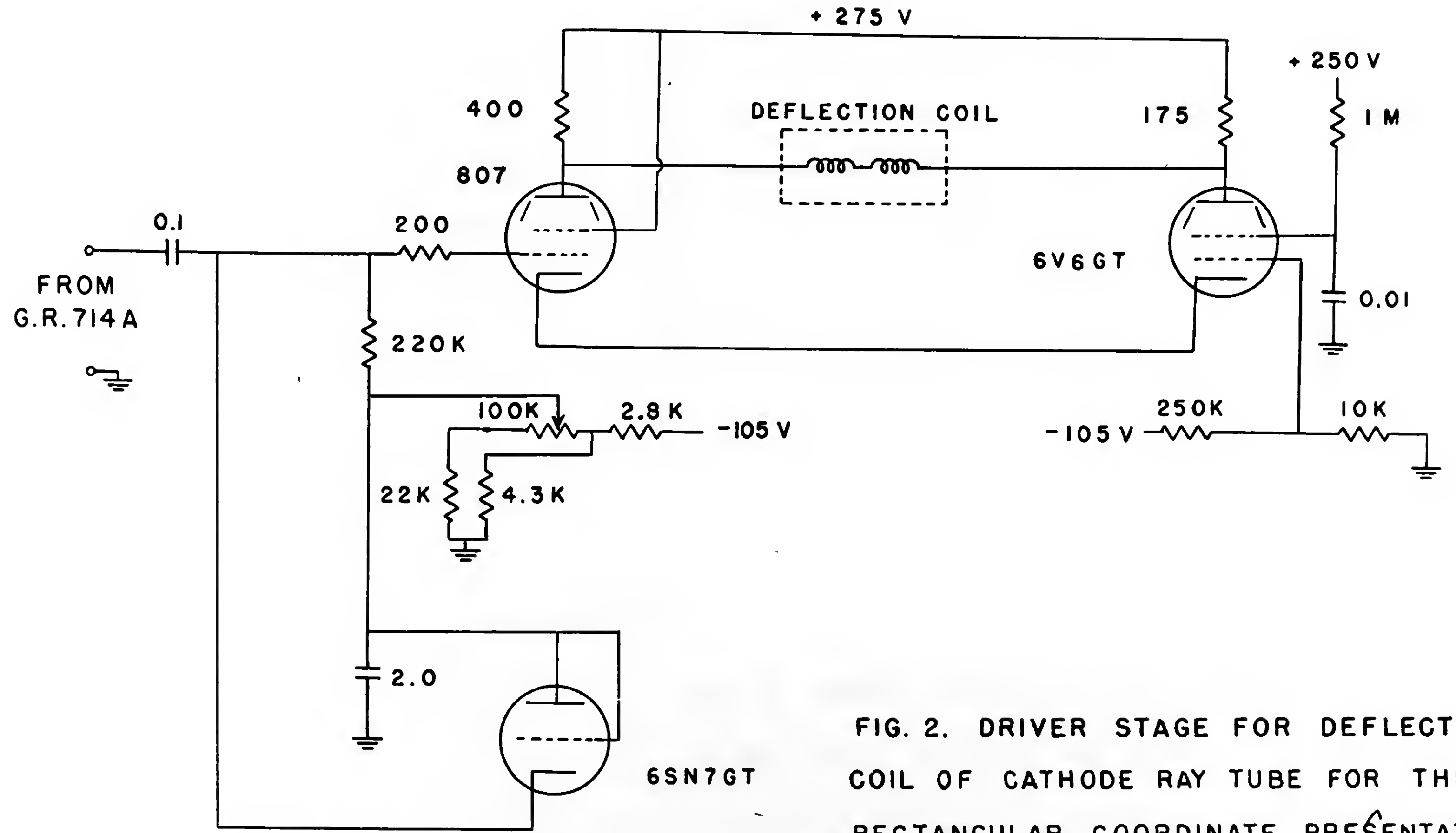


FIG. 2. DRIVER STAGE FOR DEFLECTION COIL OF CATHODE RAY TUBE FOR THE RECTANGULAR COORDINATE PRESENTATION

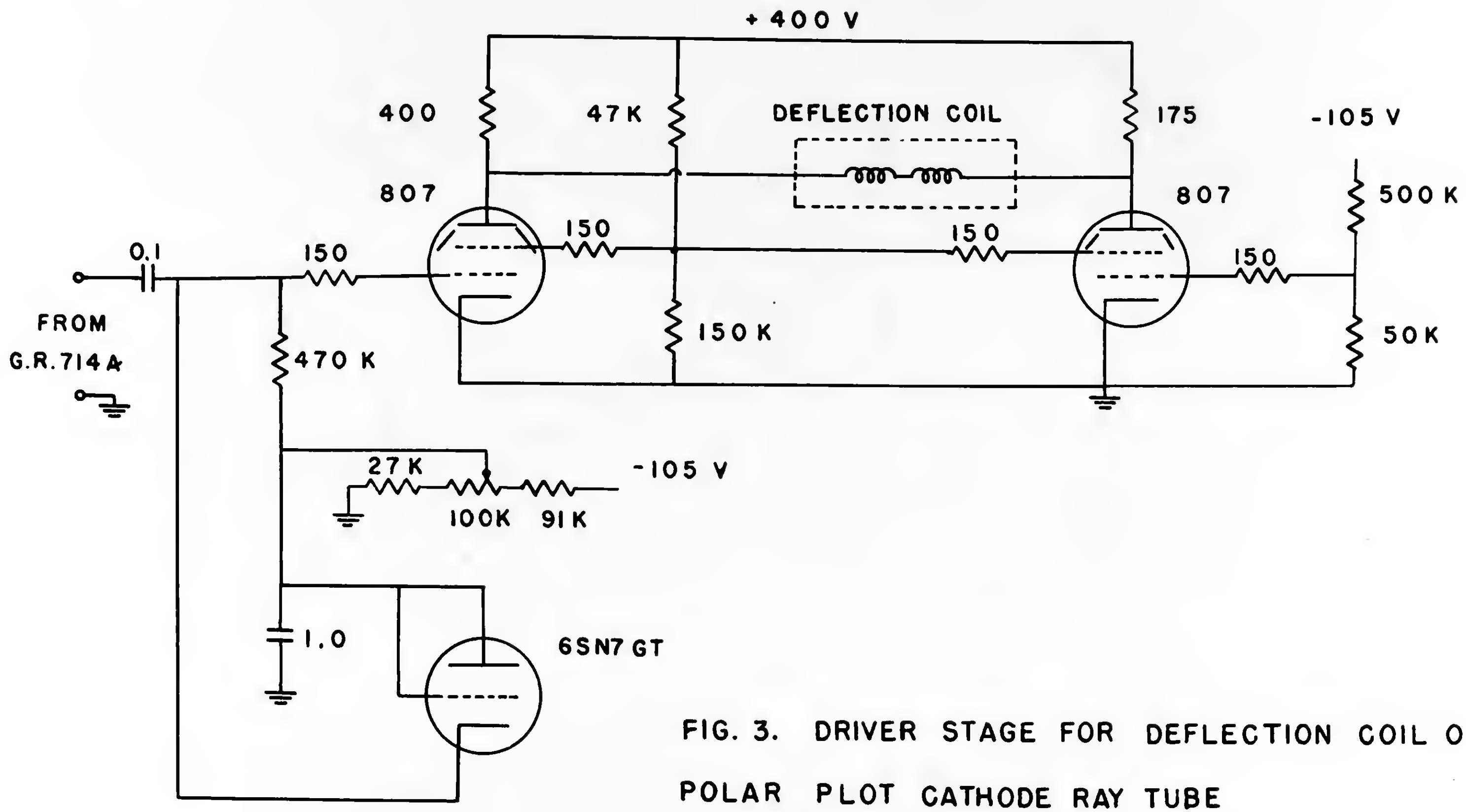


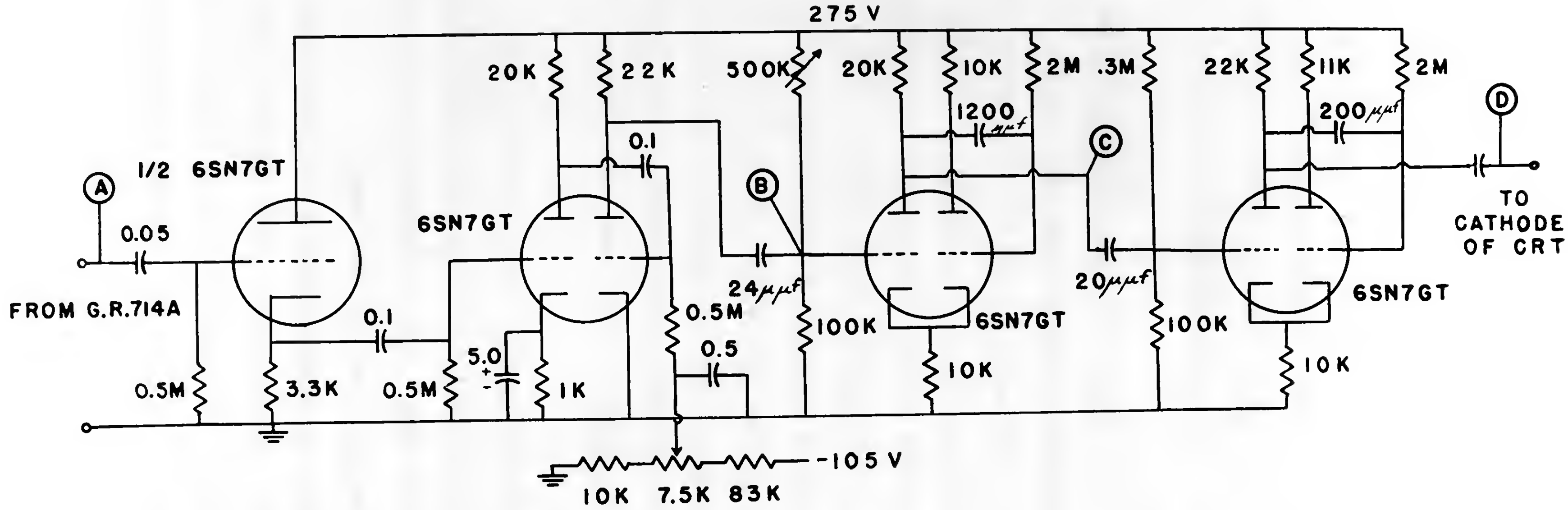
FIG. 3. DRIVER STAGE FOR DEFLECTION COIL OF POLAR PLOT CATHODE RAY TUBE

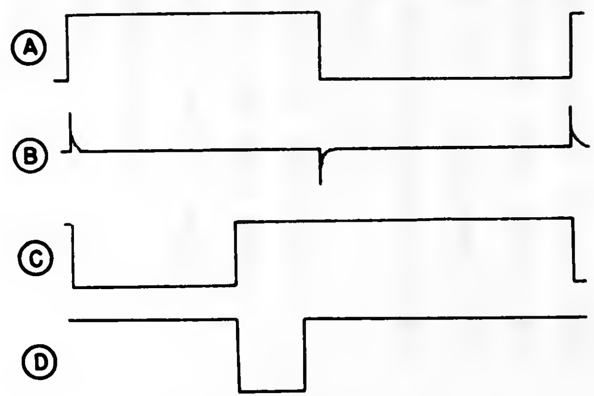
The 360-degree sweep voltage circuit is shown in fig. 6 . The sweep potentiometer was rotated by the antenna turntable, and the saw-tooth voltage produced was applied to the horizontal deflection coils through a sweep amplifier stage. A selector switch was provided in the input grid circuit of the sweep amplifier stage so that either the 360-degree or the 60-degree sweep could be chosen.

The appearance of the polar plot was greatly improved by the addition of the blanking circuit shown in fig. 4. The current wave form in the deflection coil of the polar plot cathode ray tube is shown in fig. 5 . Because of fairly slow rise time and the curvature of the leading edge of wave form, the result was a scope presentation with a broad line trace of the antenna pattern with too much "clutter" inside the trace, which would not photograph well. Because each null point in an antenna pattern left the sweep in the center of the scope, this resulted in the center becoming too bright for photographs. The blanking circuit was designed to have the following effects:

(1) To unblank the cathode ray tube only during a portion of the time when the deflection coil current wave form had a flat top. This resulted in a fine line trace of the antenna pattern on the scope.

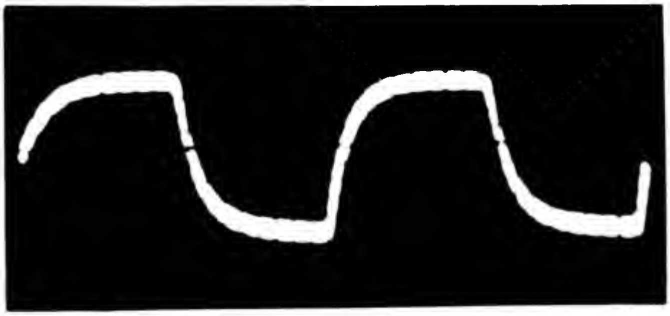
(2) To unblank the cathode ray tube during the time in (1) above, only when the video signal amplitude is larger than a pre-selected small value. This eliminated the bright spot in the center of the scope. The minimum video signal which would appear on the scope was adjustable.



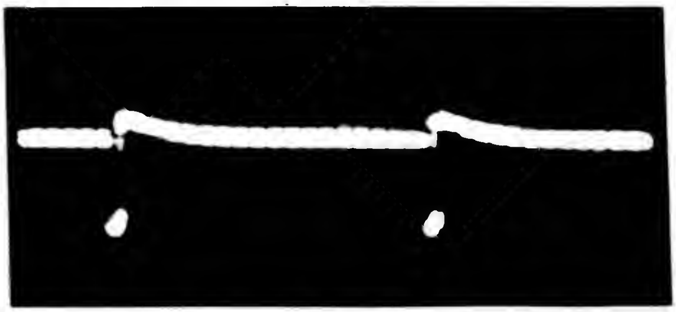


VOLTAGE WAVE FORMS

FIG. 4. BLANKING CIRCUIT FOR POLAR PLOT CATHODE RAY TUBE



DEFLECTION COIL CURRENT



BLANKING VOLTAGE TO CATHODE OF CRT

FIG. 5. WAVE FORMS SHOWING TIMING OF THE UNBLANKING PULSE

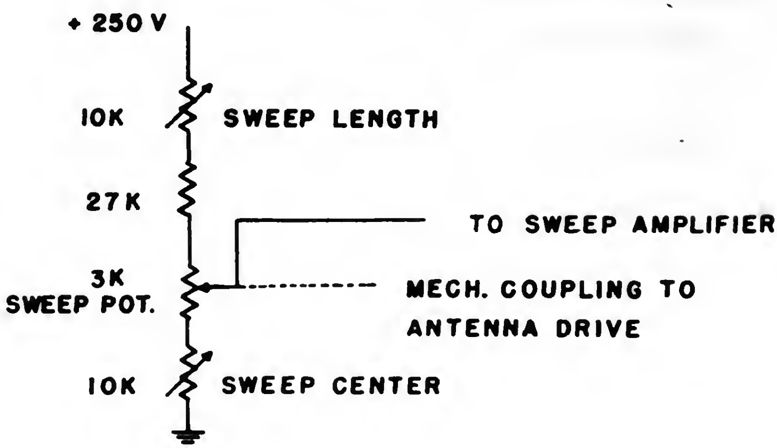


FIG. 6. 360° SWEEP CIRCUIT

The operation of the blanking circuit may be seen from the voltage wave forms shown in fig. 4 . The cathode follower was used as the input stage for decoupling. The first amplifier stage amplifies the video signal and the second amplifier passes only those signals above a pre-selected level, which is determined by the adjustable bias of that stage. The first triggered multi-vibrator provides a square-wave output which is then peaked to provide a delayed positive trigger for the second multi-vibrator. This delay is sufficient to make the trigger to the second multi-vibrator occur during the time when the deflection coil current wave form has a flat top. It should be noted that only positive triggers affect the operation of either of the multi-vibrators. The output of the second multi-vibrator is a negative square pulse of about 200 microseconds duration used to unblank the cathode ray tube. This signal is applied to the cathode of the cathode ray tube. The time at which this unblanking pulse occurs during the deflection coil current wave form cycle is shown in fig. 5 .

The measuring equipment was designed to produce accurate plots, to a linear scale, of the power radiated by the test antenna in the plane in which the measurements were made. The assumption was made that the crystal detector (IN23) would have square-law characteristics. The law of the crystal was measured at various power levels by the method of H. Krutter,[+] and was found to vary between 1.54 and 2.63 for the power levels considered, the crystal law increasing for decreasing power levels. This departure from the square-law characteristics would cause some distortion of the antenna pattern presentation. However, R. Beringer[2] has investigated crystal detector characteristics in the microwatt power range and found that they adhere rigidly to the square-law characteristic at this power level. Since the power received from a Shepherd-Pierce tube transmitter at 30 feet is in the microwatt range, it is assumed that the square-law crystal response was obtained.

The deflection coils should produce beam deflections proportional to the video signal amplitude. Curves of the deflections obtained plotted against video signal amplitude to the driver stage were prepared (fig. 7). When each of the antenna patterns was measured, the video gain was adjusted so that the peak deflections remained in the linear range.

Before measurements were made of the radiation patterns of each group of antennas, the bearing alignment of the measuring equipment was checked. This was done by using as a test antenna a high gain electromagnetic horn having a beam angle of about 5 degrees. The center of this beam on the cathode ray tube screens was taken as the reference zero degree bearing. It represented the direction of the receiving antenna from the test antenna and could be accurately set. The transmitter frequency was checked before and after each group of measurements.

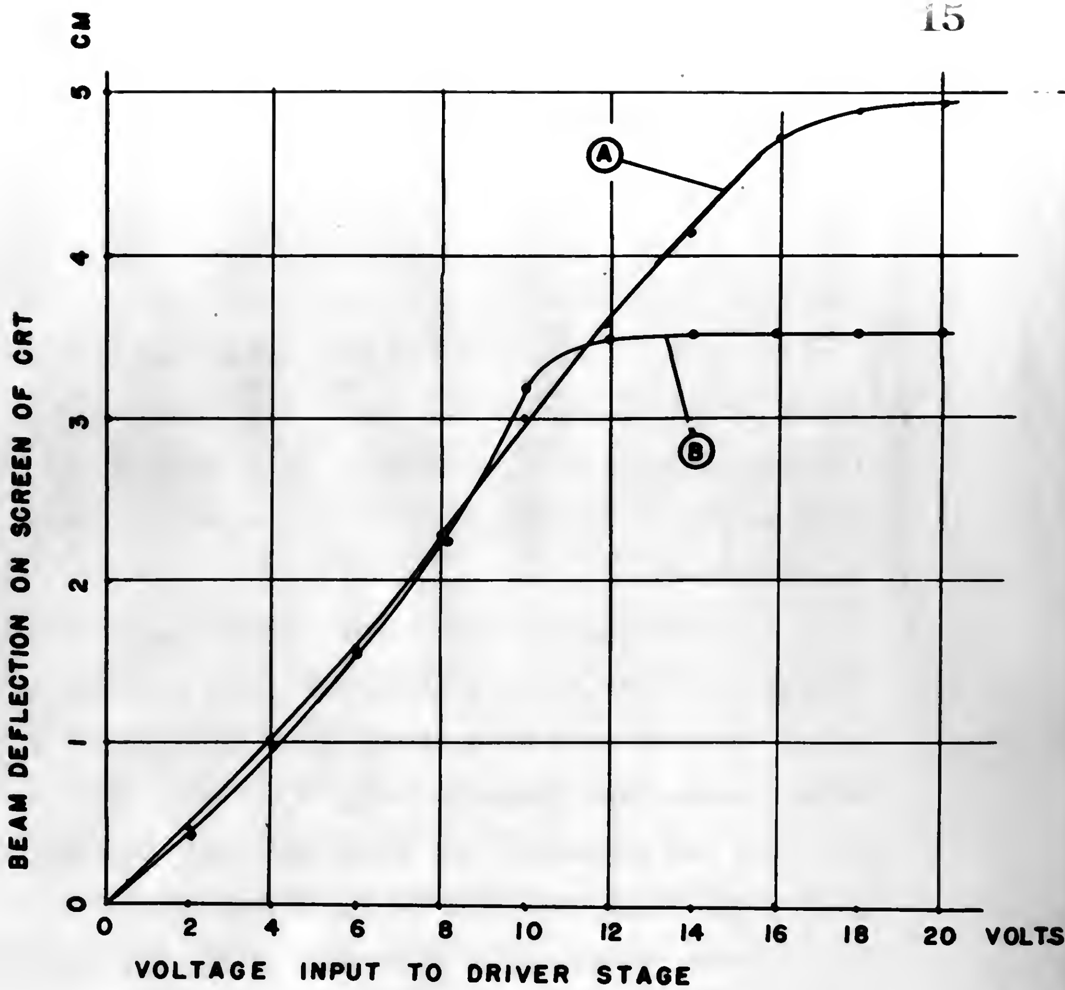


FIG. 7. DEFLECTION CHARACTERISTICS OF DRIVER STAGES AND DEFLECTION COILS

(A) POLAR PLOT CRT

(B) RECTANGULAR COORDINATE PLOT CRT

7855

CHAPTER III

THE RADIATION PATTERNS OF RECTANGULAR WAVE GUIDES CUT OFF AT AN ANGLE

The radiation pattern of a wave guide cut off at an angle of 90 degrees has been calculated and measured by others.[1,3,5] When the wave guide is cut off at an acute angle, as shown in fig. 8 or in fig. 9, the equivalent current distribution over the aperture may not be accurately predicted and calculation of the radiation pattern is more difficult. An attempt was made to calculate the radiation pattern for the type of antenna shown in fig. 8, assuming that the field over the aperture was the same as if the wave guide had extended infinitely. The results were that the pattern had a main beam that was fairly broad (100 degrees between half-power points for a wave guide cut off at 45 degrees) and was symmetrical about the normal to the plane of the aperture. These results did not at all agree with experimental results, and it was concluded that the assumptions made for the field over the aperture were greatly in error.

For antennas of the type shown in figs. 8 and 9, the radiation pattern will, in general, be expected to have a main lobe deflected toward the normal to the plane of the aperture. This effect will be caused by the phase velocity in the wave guide being greater than in air. Also, the main beam will be narrower for sharper angles of cut because of the increase in the area of the aperture. The actual beam deflections and beam widths which will be obtained with these types of antennas

FIG. 8. WAVE GUIDE ANTENNA CUT OFF AT AN ANGLE IN THE BROAD DIMENSION

FIG. 9 WAVE GUIDE ANTENNA CUT OFF AT AN ANGLE IN THE NARROW DIMENSION

are not known and need to be measured.

The measurements of all patterns presented in this report were made at 9500 megacycles, except for a few cases in which the frequency was the variable under observation and is specifically noted on those patterns. On each antenna pattern a reference line has been drawn which represents the axis of the wave guide, or the X-direction, or which represents the projection of the X-axis on the plane of the pattern.

Figs. 10 and 11 show the radiation patterns of antennas of the type shown in fig. 8. The following characteristics are noted in these patterns:

(1) The beam angle (between half power points) is narrower for the sharper angles of cut and becomes progressively wider as the angle of cut approaches 90 degrees. The beam angle has a width of 17 degrees for the 10-degree cut and 57 degrees for the 90-degree cut.

(2) The power in the side lobes is relatively higher for the sharper angles of cut. The largest side lobe for the 10-degree cut is down only 4 db. from the main lobe amplitude, but side lobes are more suppressed as the angle of cut is increased. The radiation pattern for the 75-degree cut has unexplained large side lobes.

(3) The center of the main lobe (half-way between half-power points) is deflected an almost constant amount, 26 to 28 degrees, for all angles of cut from 10 degrees through 45 degrees. For larger angles of cut, the beam deflection is reduced.

(A) α = 10°

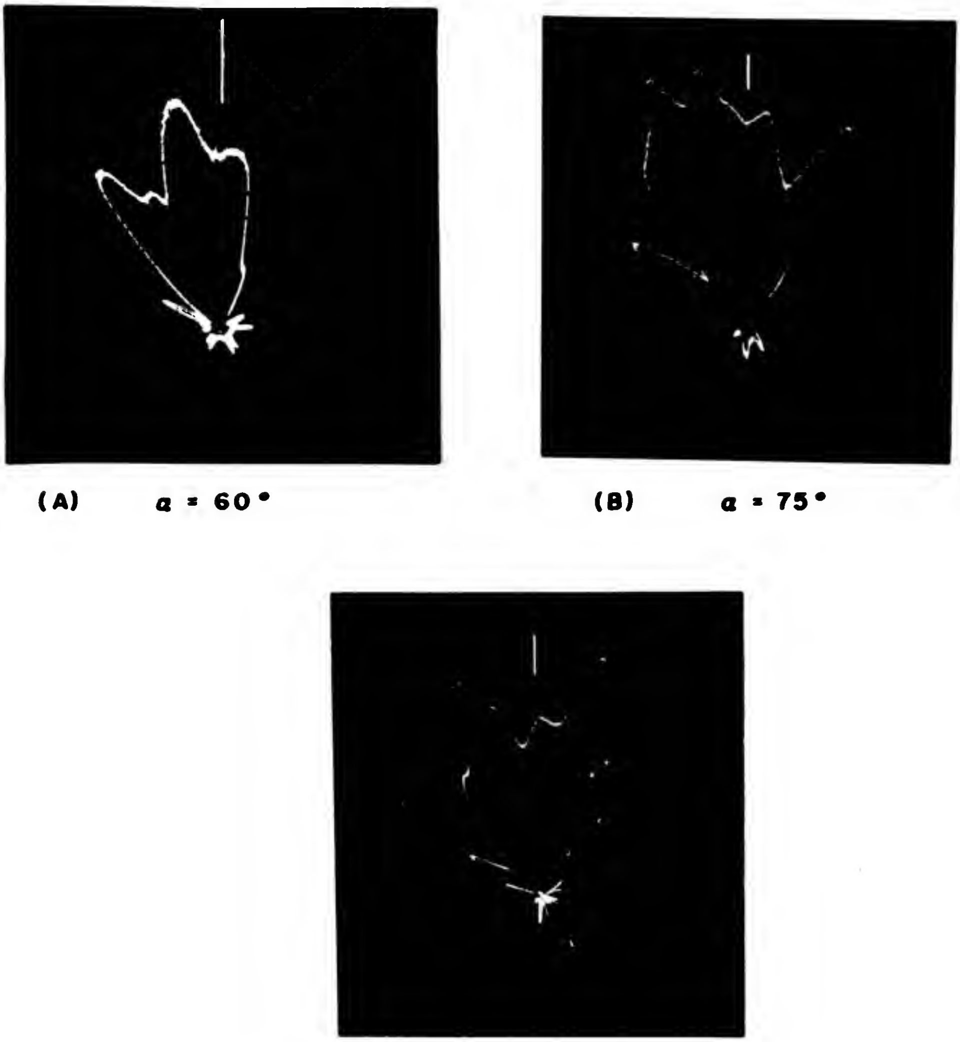
(B) α = 15°

(C) α = 20°

(D) α = 30°

(E) α = 45°

FIG. 10. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 8.



(A) $\alpha = 60°$ (B) $\alpha = 75°$

(C) $\alpha = 90°$

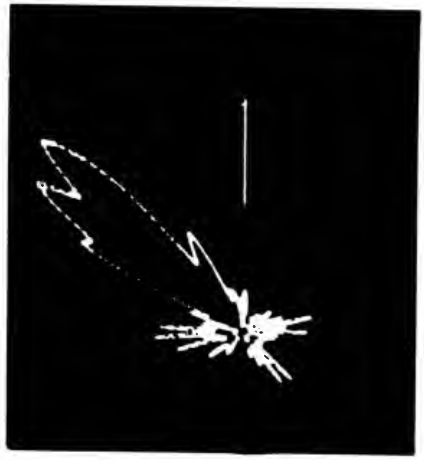
FIG. 11. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 8. (CONT'D.)

The radiation patterns of some of these same wave guides filled with a solid dielectric (polystyrene) are shown in fig. 12. The deflection of the center of the main lobe seems to have a maximum near an angle of cut of 20 degrees, where the deflection is 56 degrees from the axis of the wave guide. The main beams are narrower, since the effect of the dielectric filling should be, to a first approximation, the same as the effect of a slight increase in the wave guide dimensions. The peculiar split beam for the 30 degree angle of cut was investigated further, using dielectric fillings of several lengths, but the same pattern recurred.

Fig. 13 shown the patterns obtained for wave guides cut off as in fig. 9, and patterns for these same wave guides filled with solid dielectric are shown in fig. 14. Except for the patterns for the 15-degree angle of cut, none of the patterns have any value in any application requiring directivity, because of the numerous large side lobes. The dielectric filling has a negligible effect on the pattern in the plane of observation (XZ-plane). Fig. 15 shows the patterns of some of these antennas in the plane of the main lobe normal to the XZ-plane, and again the dielectric filling is shown to have negligible effect. The beam angle for the 15-degree cut is 70 degrees for no dielectric filling and 68 degrees when filled with the solid dielectric.

The practical use of these type antennas as circuit elements would require impedance matching for maximum power transfer. The dielectric filling used was in each case a carefully fitted polystyrene plug extending several wave

(A) α = 10°



(B) α = 15°

(C) α = 20°

(D) α = 30°

(E) α = 45°

FIG. 12 RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 8.

DIELECTRIC FILLED

(A) β = 15°

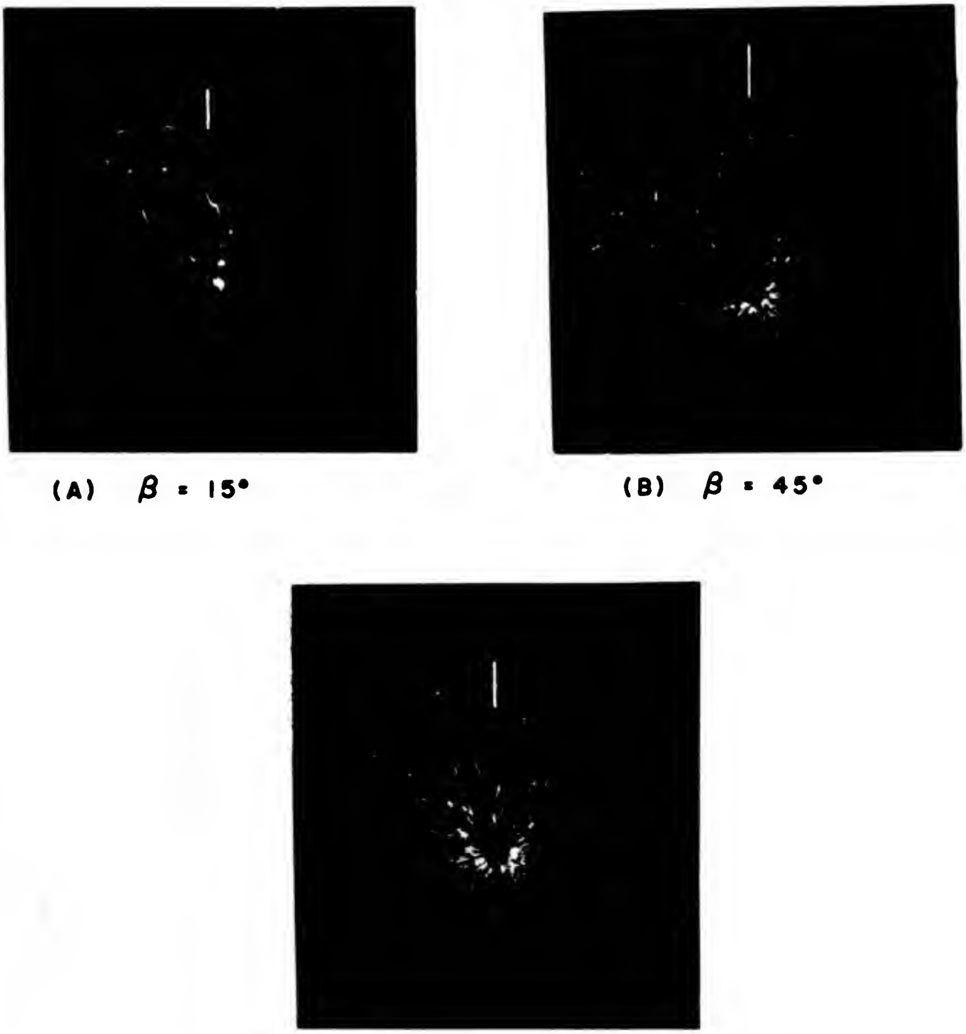
(B) β = 30°

(C) β = 45°

(D) β = 60°

(E) β = 75°

FIG.13. RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 9.



(A) $\beta = 15°$

(B) $\beta = 45°$

(C) $\beta = 75°$

FIG. 14. RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 9.

DIELECTRIC FILLED

(A) $\beta = 15°$

(B) $\beta = 75°$

(C) $\beta = 15°$
DIELECTRIC FILLED

(D) $\beta = 75°$
DIELECTRIC FILLED

FIG.15. RADIATION PATTERNS IN PLANE OF MAIN LOBE NORMAL TO XZ-PLANE OF ANTENNA IN FIG.9.

lengths, usually about 5 inches, into the wave guide. A matched load was then obtained by carefully notching the rear end of the dielectric plug. The notch was made in the broad dimension of the plug, and voltage standing wave ratios as low as 1.03 were measured in wave guides terminated by the notched plug. Also, a sufficient number of these plugs were notched in this manner to indicate that this is a reliable method for impedance matching.

Without the dielectric filling, the impedance mismatch caused by the antennas produced standing wave ratios of 1.7 to 2.5 for the various angles of cut, which would not be serious for most applications. However, the open wave guide will require a dielectric window over its aperture if it is to be used in high speed aircraft. The effect of dielectric windows of various thicknesses was investigated. Four windows whose thicknesses varied from about one-quarter guide wave length to one-half guide wave length were used in an antenna of the type shown in fig. 8. Each of these caused a marked increase in side lobes amplitudes, but caused no serious distortion of the main lobe. However, the impedance mismatch produced was serious, except when a thickness of nearly one-half guide wave length was used. Since the thicker windows increased the side lobes, it was decided to use thinner ones. R. M. Walker[6] has shown that for thin windows introduced across a wave guide ahead of a matched load, the voltage standing wave ratio produced is a linear function of the window thickness. For a frequency of 9500 megacycles, a polystyrene window in the guide adds about 0.01 to the voltage standing wave ratio, per mil thickness. Fig. 16 shows that a window 0.060 inches thick had negligible effect on one antenna pattern. From the above considerations, it was concluded that the window to be used in such antennas should be as thin as the particular application would allow.

(A) WITH WINDOW

(B) NO WINDOW

FIG. 16. EFFECT OF DIELECTRIC WINDOW ON RADIATION PATTERN IN XY-PLANE OF ANTENNA IN FIG. 8.

$a = 30°$

WINDOW THICKNESS = 0.060 IN.

CHAPTER IV

RECTANGULAR WAVE GUIDE ANTENNAS ADJACENT TO A METAL PLANE

Since a small area of the fuselage of an aircraft is essentially a plane surface, the radiation characteristics of wave guide antennas projecting through, or adjacent to, a plane surface were investigated. The assumption that the curvature of the fuselage could be neglected greatly simplified construction of the test antennas. This assumption is not seriously in error, for in the three centimeter wave length band, surface currents at a distance of about ten wave lengths from the antenna become very small compared with those adjacent to the antenna, and contribute little to the radiation pattern. At first, a metal plane three feet square with an antenna projecting through the plane, as shown in fig. 17, was used as a test antenna. When the large plane was replaced by one only eight inches square, the radiation pattern was unchanged, within the accuracy of the measuring equipment. This test was conducted on several antennas of the type shown in fig. 17, with the same results. It was concluded that the smaller plane was sufficiently large to represent the surface of an aircraft fuselage, and that the effect of the curvature of the fuselage may be neglected.

Fig. 18 shows the radiation patterns of antennas of the type shown in fig. 17, for various angles α. These patterns are very similar to those of the wave guide without the plane (fig. 10). Only in the case of an angle α of 45 degrees is

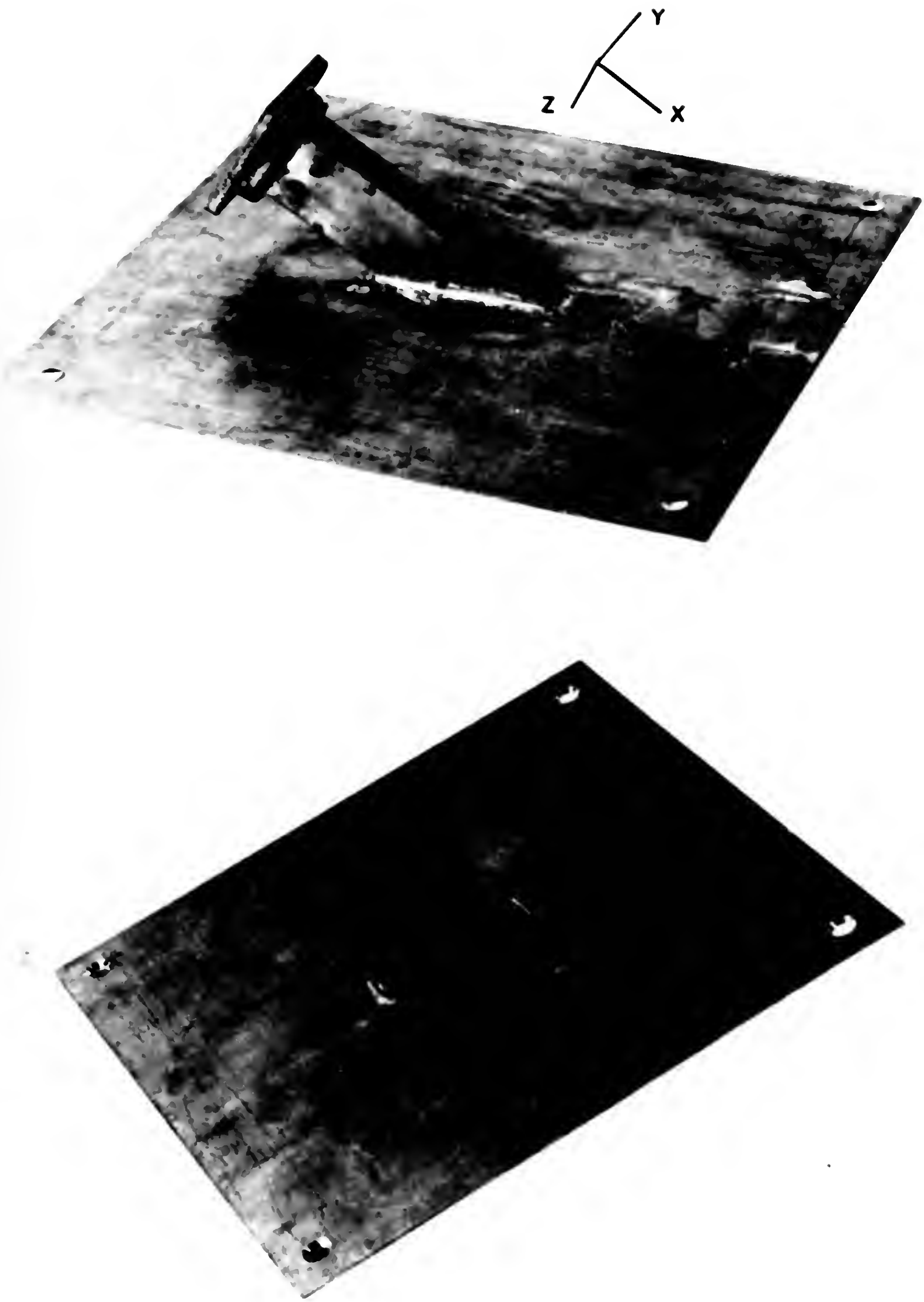


FIG. 17 WAVE GUIDE ANTENNA MOUNTED WITH APERTURE FLUSH WITH METAL PLANE

(A) a = 10°

(B) a = 15°

(C) a = 20°

(D) a = 30°

(E) a = 45°

FIG. 18. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 17.

there a great difference. Here the beam angle is increased from 32 to 57 degrees. In both cases (i.e., with and without the shield) the center of the main beam is deflected from the axis of the wave guide by an almost constant amount, 25 to 31 degrees. However, when the metal plane is used as the reference plane, the deflection of the main lobe from this plane is seen to increase as the angle α increases. None of the half-power points of the main lobes lie closer than 33 degrees to the metal plane, and none lie farther than 45 degrees. The beam angle increases from 20 degrees width for an α of 10 degrees to 57 degrees width for an α of 45 degrees.

Using an antenna of the type shown in fig. 17 with an angle of 20 degrees, a series of antenna patterns were measured (fig. 19) to show the effect of frequency variations on the shape of the pattern. The results show that the deflection of the center of the beam remained unchanged for the 10 percent variation in frequency (from 8695 to 9485 megacycles). The beam width, however, varied from 37 degrees width for the lowest frequency, to 19 degrees width for middle frequencies, and to 24 degrees for the highest frequency considered. The phasing of the excitation over the aperture, as well as the relative amplitudes of higher modes of propagation in the wave guide in the vicinity of the aperture, change when the frequency is changed, and necessarily alter the radiation pattern.

The variations of the main lobe patterns in a plane normal to the x-y plane are shown in fig. 20. The beam widths decrease as α is decreased. It would seem that the width of

(A) 9483 MCPS

(B) 9390 MCPS

(C) 9265 MCPS

(D) 9062 MCPS

(E) 8695 MCPS

FIG. 19. RADIATION PATTERNS IN XY-PLANE OF ANTENNA SHOWN IN FIG. 17.
FREQUENCY VARIABLE

(A) $\alpha = 10°$

(B) $\alpha = 20°$

(C) $\alpha = 30°$

(D) $\alpha = 45°$

FIG. 20. RADIATION PATTERNS OF ANTENNA IN FIG. 17 IN PLANE OF MAIN LOBE NORMAL TO XY-PLANE.

the wave guide would be the controlling factor in the width of the beam in this plane. However, there is a longitudinal component of the magnetic field in a wave guide excited in the dominant mode ($TE_{1,0}$), and that component becomes increasingly important as the angle α is decreased.

Fig. 23 shows the radiation patterns of wave guides mounted on the surface of the metal plate (fig. 21). The width of the main lobe and the side lobe amplitudes are practically unchanged when the angle of cut of the wave guide is varied. The main lobe width is 30 degrees for all antennas measured in this group. The deflection of the center of the main beam from the axis of the wave guide varies from 28 degrees for the 20-degree antenna to 35 degrees for the 60-degree antenna. This is opposite to the effect noted in fig. 10 for these wave guides with no shield present. This effect can be attributed to the surface currents on the metal plane and to the image effect of the metal plane.

For a wave guide cut in the narrow dimension and mounted on a plate, the radiation patterns are as shown in fig. 24. These are in great contrast with those of the same wave guides without the metal plate present (fig. 13). The width of the main lobe varies from 23 to 28 degrees. Side lobes show a definite tendency to increase as the angle of cut is decreased. For the 15-degree antenna, the "side lobes" have apparently increased to become the main lobe of radiation.

The radiation patterns of these antennas in the plane of the main lobe normal to the X-Z plane are shown in fig. 25. These have progressively wider beams as the angle of cut increases, provided that the large side lobe for the 15-degree

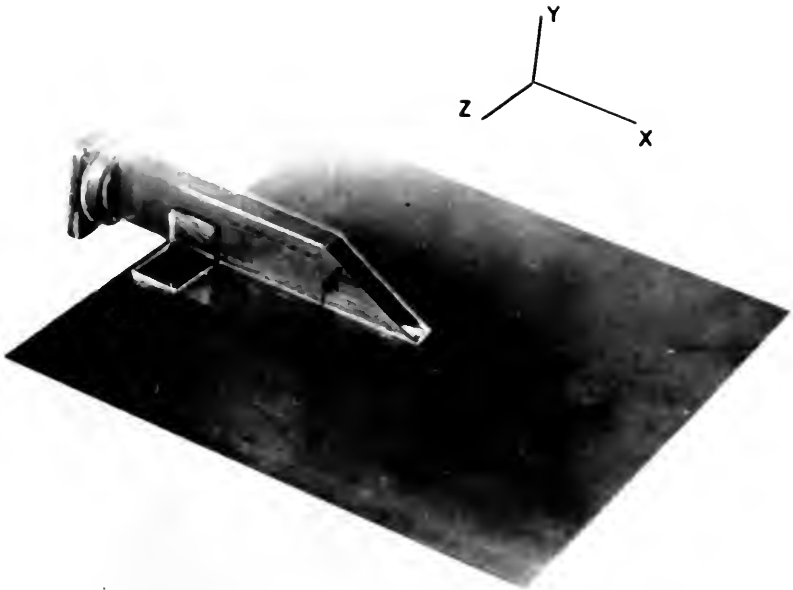


FIG. 21. WAVE GUIDE ANTENNA ADJACENT TO A METAL PLANE

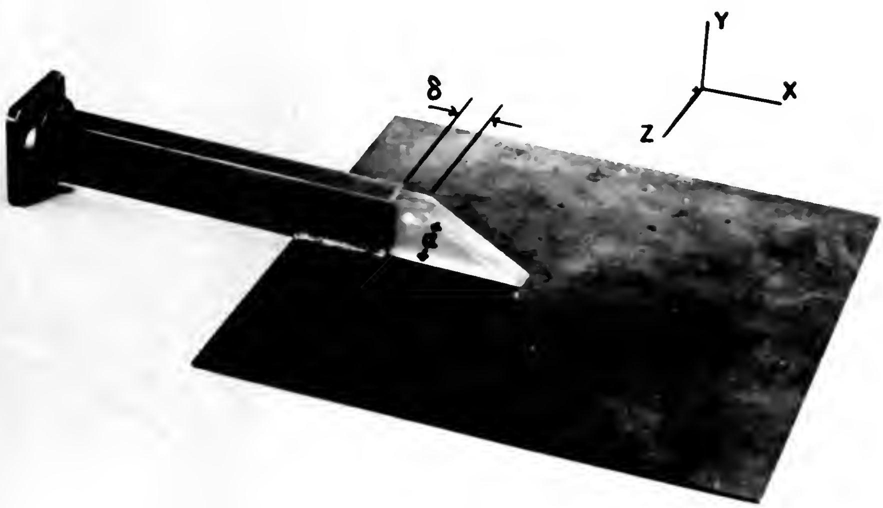


FIG. 22. WAVE GUIDE ANTENNA WITH PROJECTING DIELECTRIC ADJACENT TO A METAL PLANE

(A) $\beta = 30°$ (F) $\beta = 15°$ (B) $\beta = 45°$

(C) $\beta = 60°$

(D) $\beta = 75°$

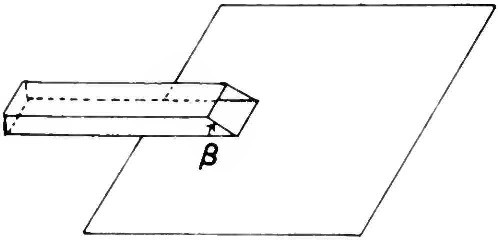


FIG.24 RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 24 (E)

(E) ANTENNA

(A) β = 15°

(B) β = 30°

(C) β = 45°

(D) β = 60°

(E) β = 75°

FIG. 25 RADIATION PATTERNS IN THE PLANE OF THE MAIN LOBE NORMAL TO XZ-PLANE OF ANTENNA IN FIG. 24(E).

antenna is not considered a part of its main beam. For the same antennas with the shield absent, the effect of the angle of cut on the beam angle is reversed. It must again be attributed to the skin currents on the metal plate and to the image effect.

None of these antennas mounted externally on the surface of the aircraft will have zero aerodynamic drag. They could be streamlined to reduce the drag and might find use where their particular radiation patterns are desirable.

Another type of antenna was considered, (fig. 27), one which is a compromise between the flush mounted type in fig. 17 and the externally mounted type in fig. 21. Although zero drag is not achieved, the drag produced will be less than for an externally mounted antenna. The resulting patterns (fig. 28), are, in general, undesirable, since side lobes are greatly increased. These patterns should be compared with those in fig. 18.

None of these antennas fulfill the requirements for the antenna for the aircraft navigational equipment. The antenna in fig. 24 (E) most nearly meets the requirement of a half-power point near the metal plane, having half-power points within 9 degrees of the plane when the side lobes are small. However, the beam angle in the XZ-plane is only 25 degrees wide, less than half that desired for the navigational equipment. The beam width in the plane of the main lobe normal to the XZ-plane is sufficiently broad, about sixty degrees. The zero drag antennas in fig. 17 offer little possibilities for use in this application, since the beam angle is too small and the main beam lies too far from the metal plane. If the

FIG. 26. SLOTTED WAVE GUIDE ANTENNA

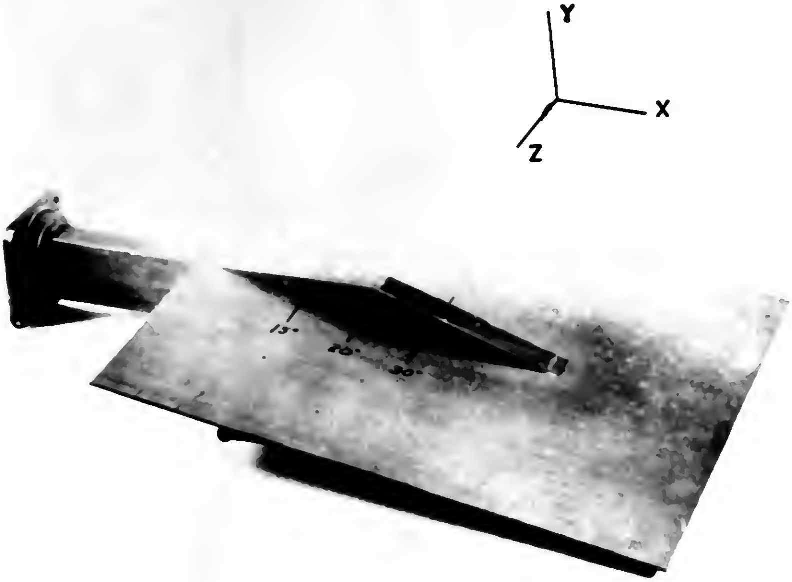


FIG. 27 OPEN END WAVE GUIDE PROJECTING THROUGH A METAL PLANE AT AN ANGLE

(A) α = 60° γ = 30°

(B) α = 30° γ = 15°

(C) α = 30° γ = 20°

(D) α = 20° γ = 10°

(E) α = 20° γ = 15°

FIG. 28. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 27.

radiation patterns are to be computed for the antennas discussed, the field distributions over the apertures must be measured. Otherwise serious errors are introduced.

CHAPTER V

DIELECTRIC FILLED RECTANGULAR WAVE GUIDE ANTENNAS ADJACENT TO METAL SURFACES

The addition of a solid dielectric filling to the antennas described in the previous chapter causes a considerable alteration of the radiation patterns. The change is caused primarily by the decrease in phase velocity in the dielectric filled wave guide, which changes the amplitude and phase distribution of the equivalent current distribution over the aperture of the antenna. This corresponds roughly to the effect of a slight increase in the wave guide dimensions.

For a dielectric filled antenna of the type shown in fig. 17, the radiation patterns (Fig. 29) have the same general shape as for the same antenna without the metal plate, and have beam deflections nearly identical with those in fig. 12. The 20-degree and 45-degree antennas do have much larger side lobes. In general it may be concluded that the effect of a metal plane oriented as in fig. 17 has little effect on the radiation patterns of wave guide radiators with or without dielectric filling.

The effect of frequency variation on the pattern of a 20-degree dielectric filled antenna of the type shown in fig. 17 was measured (Fig. 30). It would seem that if the effect of the dielectric filling is the same as that for a slight increase in wave guide dimensions, the same pattern obtained without the dielectric filling could be reproduced with the dielectric filled antenna if the frequency is lowered a sufficient amount. However, when the frequency was lowered 500

(A) α = 10°

(B) α = 15°

(C) α = 20°

(D) α = 30°

(E) α = 45°

FIG.29 RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG.17.
DIELECTRIC FILLED

(A) 9308 MCPS

(B) 9483 MCPS

(C) 9390 MCPS

(D) 9265 MCPS

(E) 9062 MCPS

FIG. 30. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 17 . FREQUENCY VARIED. DIELECTRIC FILLED

$a = 20°$

megacycles, there did not seem to be any tendency for the beam to assume the form of the patterns in fig. 19. The pattern remained broken into two large lobes of nearly the same amplitude, the centers of where were separated by 40 degrees.

The radiation patterns for this same type of antenna in the plane of the main lobe, normal to the XY-plane, are shown in fig. 31. The beam angles varied widely, from 18 degrees for the 15-degree antenna to 75 degrees for the 45-degree antenna. The large beam width, 70 degrees, obtained with the 10-degree antenna is unexplained.

Since the beams so far obtained in the XY-plane are generally too narrow for application in the high speed aircraft navigational system, an effort was made to increase the beam width by closing off a portion of the aperture of the antenna, as shown in fig. 32 (E). The resulting patterns are shown in figs. 32 and 33. Side lobes are increased and the main beam width changes very little, much less than was expected. Decreasing the length of the aperture, for the same current distribution, should increase the beam width by a greater amount than was observed. Hence the current distribution across the aperture must have changed considerably. The metal over the aperture produced a serious impedance mismatch, but no effort was made to secure a matched termination since the radiation patterns did not seem to warrant it.

The next type of dielectric filled antenna considered was the one shown in fig. 21, with the dielectric flush with the aperture of the wave guide. Main beam widths in the radiation

(A) $a = 10°$

(B) $a = 15°$

(C) $a = 20°$

(D) $a = 30°$

(E) $a = 45°$

FIG. 31. RADIATION PATTERNS IN PLANE OF MAIN LOBE NORMAL TO XY-PLANE OF ANTENNA IN FIG. 17.

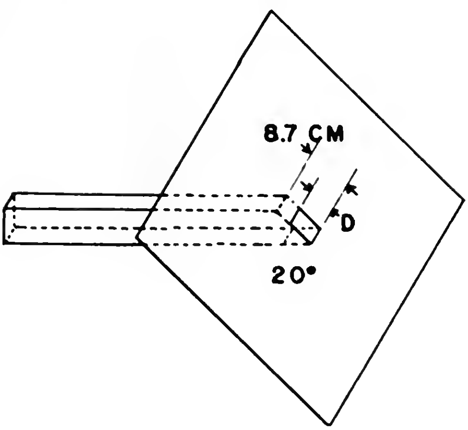
DIELECTRIC FILLED

(A) D = 8.7 CM

(B) D = 7.0 CM

(C) D = 6.0 CM

(D) D = 5.5 CM



(E) ANTENNA

FIG. 32. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG.(E) WITH PORTION OF APERTURE CLOSED WITH METAL.

$a = 20°$
DIELECTRIC FILLED

(A) D = 5.0 CM

(B) D = 4.5 CM

(C) D = 4.0 CM

(D) D' = 7.0 CM
(LOWER END CLOSED)

FIG. 33. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG.32 WITH PORTION OF APERTURE CLOSED. (CONT'D.)
DIELECTRIC FILLED

patterns (Fig. 34) varied from 16 degrees for the 30-degree antenna to 32 degrees for the 60-degree antenna. The amplitude of the side lobes is larger than for the same antennas without dielectric (Fig. 23). The half-power point of the main beam for the 30-degree antenna lies within 7 degrees of the metal plane.

For antennas of the type shown in fig. 24 (E), with the wave guide cut off at an angle in the narrow dimension, the dielectric filling greatly improves the radiation patterns, reducing the side lobes, but making the main lobe slightly narrower. The main beam widths for the antennas tested were each 22 degrees, and deflection of the center of the main beam above the metal plate was 20 to 25 degrees.

The radiation patterns of these same antennas in the plane of the main lobe are shown in fig. 36. The beam widths in this plane, normal to the XZ-plane, are from 60 to 80 degrees. The dielectric filling again improves the patterns. (Compare figs. 36 and 25).

When solid dielectric plugs are placed in the antenna shown in fig. 22, the resulting patterns have only small side lobes and main beam angles between 20 and 33 degrees between half-power points (Figs. 37 and 38). For all the angles of cut of the dielectric plugs used, the centers of the main beams were deflected about 25 degrees from the metal plate. The half-power point of the main lobe is never nearer than 12 degrees to the metal plate. When the dielectric was removed from the guide, the main beam was 19 degrees wide with its center 31 degrees above the plate.

(A) $\alpha = 20°$

(B) $\alpha = 30°$

(C) $\alpha = 60°$

FIG. 34. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG. 21.

DIELECTRIC FILLED

(A) β = 15°

(B) β = 45°

(C) β = 75°

FIG.35 RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 24(E).

DIELECTRIC FILLED

(A) β = 15°

(B) β = 45°

(C) β = 75°

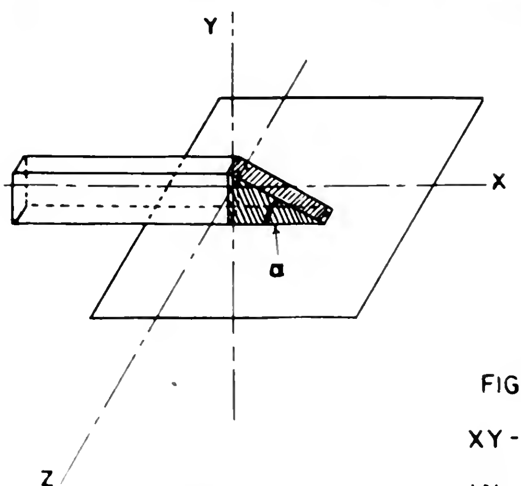
FIG. 36. RADIATION PATTERNS IN PLANE OF MAIN LOBE NORMAL TO XZ-PLANE OF ANTENNA IN FIG. 24(E).

(A) α = 10°

(B) α = 15°

(C) α = 20°

(D) α = 30°



(E) ANTENNA

FIG.37. RADIATION PATTERNS IN XY-PLANE OF ANTENNA SHOWN IN FIG. 22.

δ = 0

(A) a = 45°

(B) a = 75°

(C) NO DIELECTRIC

FIG.38. RADIATION PATTERNS IN XY-PLANE OF ANTENNA SHOWN IN FIG.22. (CONT'D.)

$\delta = 0$

The 20-degree dielectric for the antenna just discussed was withdrawn various distances from the wave guide (Fig. 39 E), and the effect on the radiation pattern measured. The beam width of the main lobe (Figs. 39 and 40) remained constant at 21 degrees until the dielectric was withdrawn four centimeters, and then the beam narrowed to 17 degrees when the dielectric was withdrawn further to seven centimeters. The center of the main beam moved slowly toward the plane as the length of the protruding dielectric was increased. The deflection of the center of the main beam from the metal plane decreased from 25 degrees to 15 degrees. Both of these effects, the narrowing of the main beam and the decrease in the deflection from the axis of the wave guide, are caused by the end-fire effect of the dielectric. This type of antenna could undoubtedly be further lengthened and would produce a beam which would lie nearer the metal plate, but the beam also becomes narrower and the side lobes seem to increase in amplitude as the length of the dielectric is increased.

Radiation patterns were measured for the antenna shown in fig. 27 filled with dielectric. These patterns (Fig. 41) have numerous large side lobes which make them unsuitable for most applications.

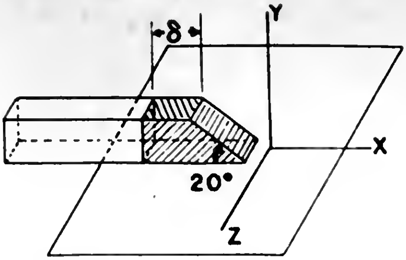
In general the wave guide antennas with dielectric filling are not satisfactory since they have large side lobes. However for antennas of the type shown in fig. 24 (E), the dielectric filling greatly improves the radiation patterns. This antenna has too small a beam angle for use in the navigational equipment.

(A) δ = 0 CM.

(B) δ = 1 CM.

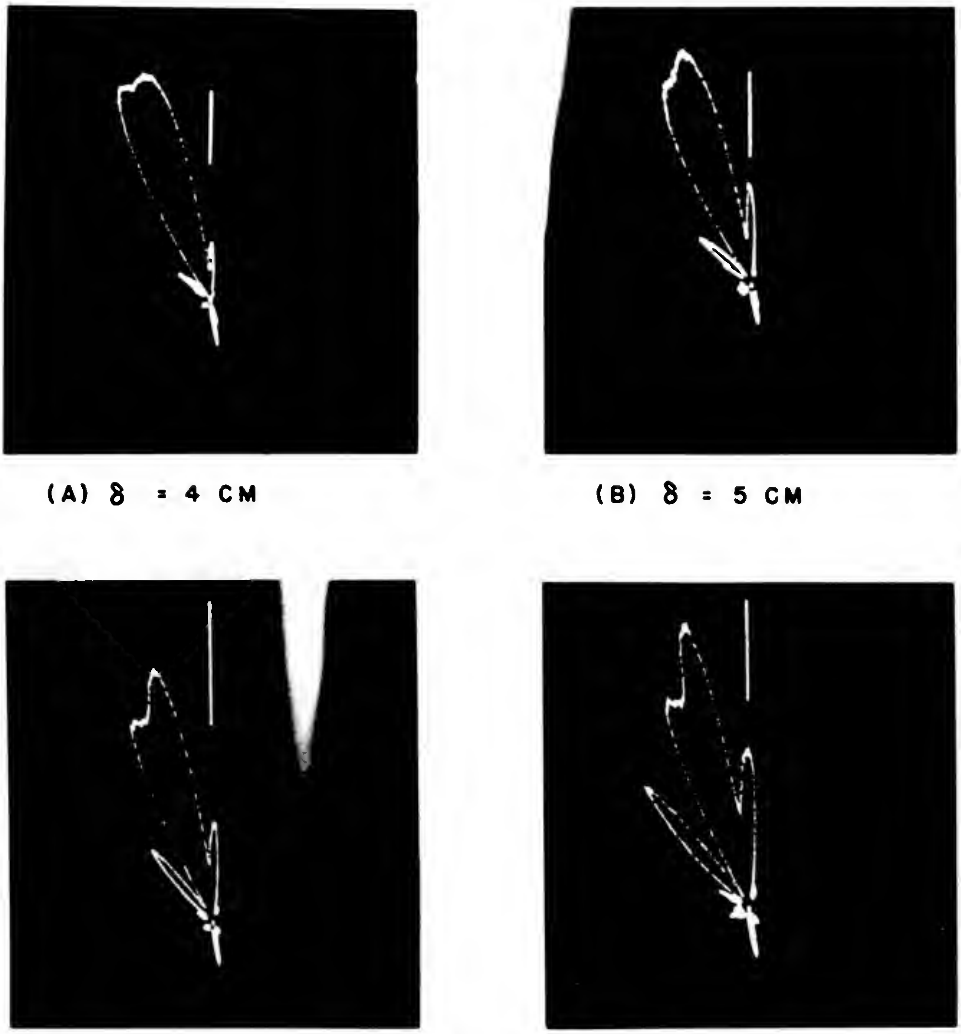
(C) δ = 2 CM

(D) δ = 3 CM



(E) ANTENNA

FIG.39. RADIATION PATTERNS IN XY-PLANE OF ANTENNA SHOWN IN FIG. 22.



(A) δ = 4 CM

(B) δ = 5 CM

(C) δ = 6 CM

(D) δ = 7 CM

FIG. 40. RADIATION PATTERNS IN XY-PLANE OF ANTENNA SHOWN IN FIG.22. (CONT'D)

(A) $\alpha = 60°$ $\gamma = 15°$

(B) $\alpha = 60°$ $\gamma = 20°$

(C) $\alpha = 60°$ $\gamma = 30°$

(D) $\alpha = 30°$ $\gamma = 15°$

(E) $\alpha = 30°$ $\gamma = 20°$

FIG.41. RADIATION PATTERNS IN XY-PLANE OF ANTENNA IN FIG.27.

DIELECTRIC FILLED

CHAPTER VI

SLOTTED WAVE GUIDE ANTENNAS

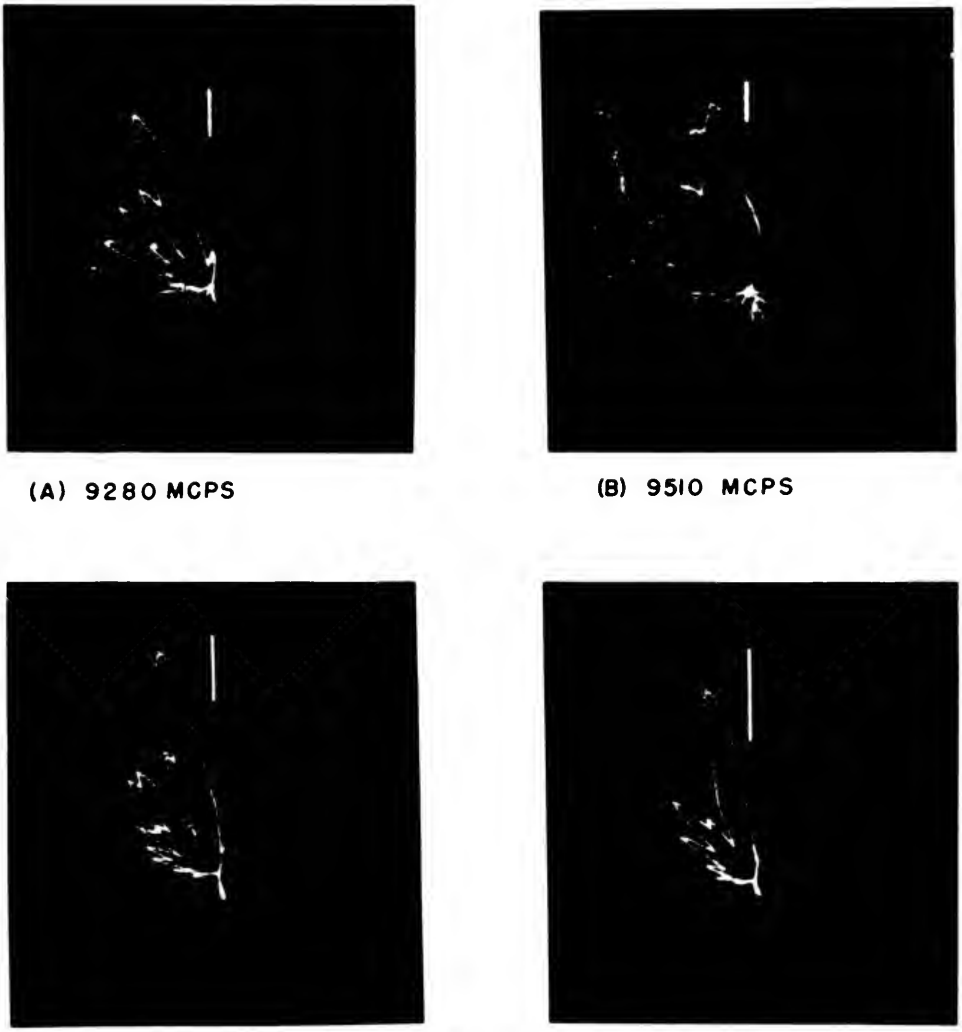
The preliminary work on slotted wave guide antennas of the type shown in fig. 26 was not promising because the slots used were only one-sixteenth inches wide and did not radiate sufficient power. Since it was assumed that this antenna would be of the end-fire type, the addition of a large number of slots to obtain more radiated power would have the undesirable effect of making the main beam very narrow. This type of antenna was temporarily set aside and the open wave guide antennas were investigated. When the slotted wave guides were again considered, the slots were widened, first to one-eighth inches, and finally to three-sixteenths inches, and a much greater percentage of the power was radiated. The patterns obtained were close to the requirements of the navigational equipment, and these antennas deserve further study.

For the slotted wave guide antennas considered by Watson,[7] the slots were either longitudinal on the broad dimension of the wave, or transverse on the narrow dimension. In the former arrangement, the slots were spaced to give a broadside array. The latter type can be made into an end-fire or Yagi type of antenna, if one slot is inclined to act as the excited element, while the others act as parasitic elements.

It was decided to cut the slots across the broad dimension of the wave guide (Fig. 26) in order to intercept the surface currents which flow longitudinally on the inside surface of that wall of the guide. The amplitude of this surface current has a half-sinusoidal distribution across the guide, with a maximum at the center of the guide (for the dominant mode of propagation, $TE_{1,0}$). The final antenna designs were for both two and four slots. Each slot was centered in the broad side of the guide, was three-sixteenths inches wide, and had an overall length of 0.4875 inches. Since the slots were made with a vertical milling machine, the ends were semicircular in shape. The distance between the centers of these semicircles was made 0.300 inches, which accounts for the odd value of the overall length. A matched load was used to terminate the guide, making the antenna a traveling wave type.

The slots were spaced 0.366 inches longitudinally (center to center). This spacing was computed by assuming that, for two slots, the backward traveling radiation emerging from the first slot should be cancelled by the backward traveling radiation from the second slot, in order that an end-fire effect would result. Also, the radiation traveling forward along the direction of the guide should add from the two slots. A consideration of the phase velocity of a 9400 megacycle wave in air and inside the guide showed that 0.366 inches was the theoretical value of the proper slot spacing.

The radiation patterns for the two-slot antenna are shown in fig. 42 for various frequencies. The beam width, between half-power points, in the XZ-plane is 15 to 20 degrees for the upper and lower frequencies considered, but is 56 degrees for 9510 megacycles per second, and the half-power point then lies only three degrees from the axis of the guide. The beam angle in the plane of the main lobe, normal to the XZ-plane is 40 to



(A) 9280 MCPS

(B) 9510 MCPS

(C) 9700 MCPS

(D) 9750 MCPS

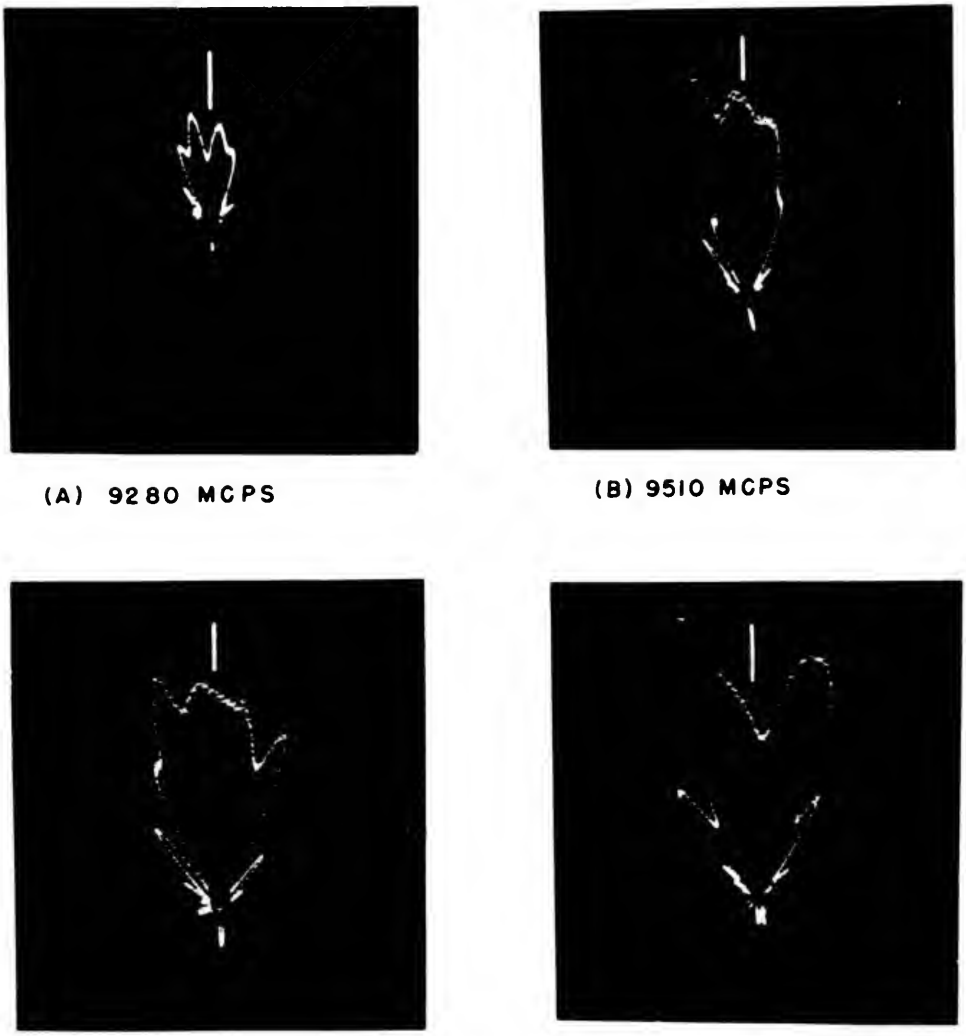
FIG. 42. RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 26.

2 SLOTS 3/16 IN WIDE

60 degrees, being broadest at 9600 megacycles. Since this type of antenna is desired to be mounted flush with the fuselage of an aircraft, metal planes were added on either side, as shown in fig. 42, to represent the effect of the fuselage. In the plane of the main lobe (Fig. 43) the beam width was increased to 47 degrees. This type of antenna seems quite frequency sensitive and has large side lobes in the XZ-plane.

The radiation patterns for the four-slot antenna are shown in fig. 44. If the main beam is considered to have only a dip (the dip does not drop below the quarter-power point), the side lobes present are negligible. Proper spacing of the slots longitudinally might eliminate this dip in the main lobe and make this type of antenna more useful. For the four per cent frequency variation observed, the beam angle, in the XZ-plane, varied from 48 to 58 degrees between half-power points. The half-power point of the main beam lies on the axis of the wave guide at the frequency of 9545 megacycles per second. This antenna has come the nearest to fulfilling the requirements in the XZ-plane for the antenna for the navigational equipment. In the plane of the main lobe, normal to the XZ-plane (Fig. 45), the beam width is only 30 degrees. When a shield is added to each side of the wave guide, this beam angle is increased to 58 degrees (Fig. 47), but in the XZ-plane the beam angle is reduced to 32 degrees, and the half-power point is moved to 12 degrees above the axis of the guide. Moving one or more of the slots longitudinally a small distance might produce a favorable change in the beam width.

These slotted wave guide antennas can be constructed to



(A) 9280 MCPS

(B) 9510 MCPS

(C) 9595 MCPS

(D) 9510 MCPS
WITH SHIELD

FIG. 43. RADIATION PATTERNS IN PLANE OF MAIN LOBE NORMAL TO XZ-PLANE OF ANTENNA IN FIG.26.

2 SLOTS 3/16 IN WIDE

(A) 9610 MCPS

(B) 9545 MCPS

(C) 9412 MCPS

(D) 9350 MCPS

(E) 9265 MCPS

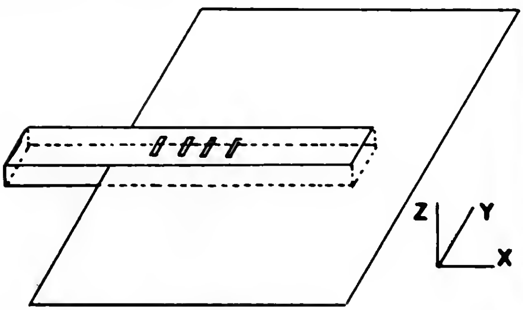
FIG.44. RADIATION PATTERNS IN XZ-PLANE OF ANTENNA IN FIG. 26.

4 SLOTS 3/16" WIDE
FREQUENCY VARIABLE

(A) 9550 MCPS

(B) 9610 MCPS

FIG. 45. RADIATION PATTERNS IN PLANE OF MAIN LOBE – NORMAL TO XZ-PLANE OF ANTENNA IN FIG. 26.

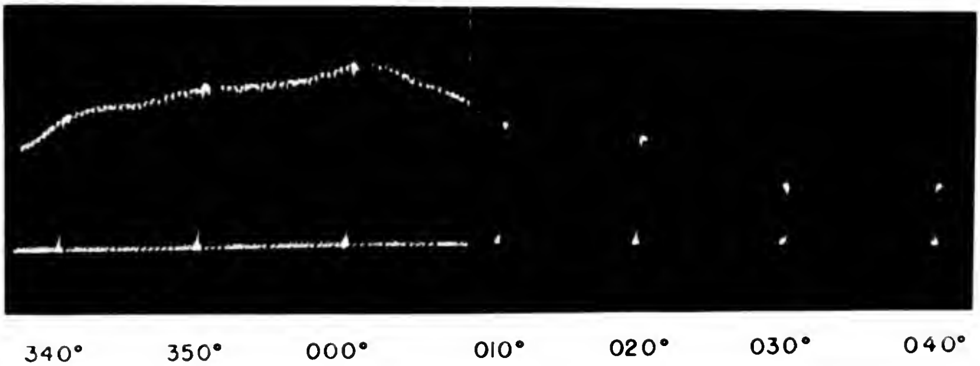


(A) ANTENNA

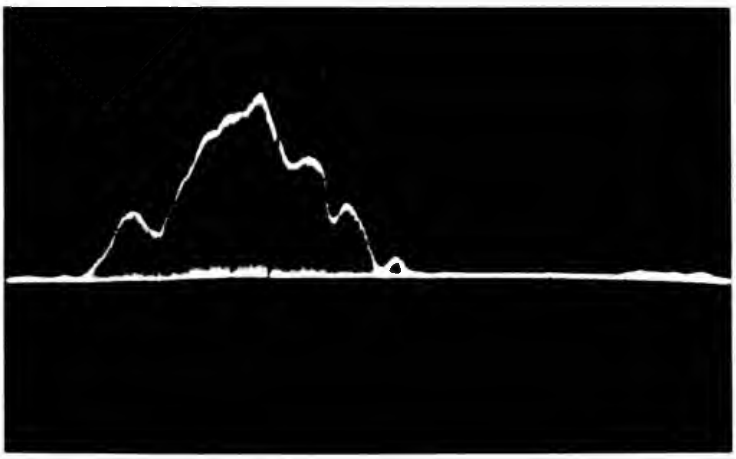
(B) 9390 MCPS

FIG. 46. RADIATION PATTERN IN XZ-PLANE OF ANTENNA IN FIG. 26. ATTACHED TO METAL SHIELD.

(A) POLAR PLOT



(B) 60° PLOT



(C) 360° PLOT

FIG.47 RADIATION PATTERN IN PLANE OF MAIN LOBE NORMAL TO XZ-PLANE OF ANTENNA IN FIG.46 (A).
4 SLOTS 3/16 IN. WIDE 9390 MCPS

give zero aerodynamic drag. There are no significant side lobes present, and it is believed that careful design will produce an antenna with a radiation pattern fitted to the specifications given in Chapter I.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Of the three general types of antennas considered, the slotted wave guide antenna will be most suited to the requirements of the high speed aircraft navigational system. This antenna can be constructed with thin dielectric windows in the slots, and will contribute no additional aerodynamic drag when mounted flush with the surface of the aircraft. When the beam requirements of the radiation pattern of the antenna for the navigational system are rigidly set, experiments with various slot widths, lengths, and longitudinal spacing should produce the desired radiation pattern. With proper design, this type antenna should have a high efficiency, and the matched load used to terminate the wave guide in the experimental models could be replaced by a shorting plunger. This type antenna would occupy little space and could be installed flush with the surface of the fuselage or wings, or at the wing tips. Either vertical or horizontal polarization could be obtained by proper selection of the location of the antenna on the aircraft.

Of the other types of antennas investigated, only the one shown in fig. 17 will give zero aerodynamic drag. The radiation patterns of this antenna, without solid dielectric filling, but with a thin dielectric window over the aperture, should be useful in some installations where the main beam is not required to lie so closely to the surface of the aircraft at the antenna.

When some drag can be tolerated in the antenna design, several of the other types could be chosen. The one shown in fig. 21, with a dielectric window, or the one in fig. 22, have radiation patterns without large side lobes, and the position and width of the main beam has some flexibility with design so that certain beam specifications might be met. If the location of the antenna is restricted and the other polarization is desired, the antenna in fig. 24 (E), with solid dielectric filling, could be adopted. This latter type would contribute even less drag than the two mentioned above.

The measuring equipment used in this research would be invaluable in the design of antennas for specific purposes. The antenna to be tested can be mounted with the desired orientation with respect to the receiving antenna and its radiation pattern rapidly obtained. By changing some of the variables in the antenna design, such as the width of the slots for the slotted type antenna, this experimental method of design should quickly produce the desired results.

It is recommended that the measuring equipment be improved by increasing the linearity of the patterns obtained on the cathode ray tubes so that they are more truly linear plots of the power radiated by the antennas. This can be done by proper adjustment of the driver stages for the deflection coils, or by a re-design of these stages. In an earlier design of an antenna radiation pattern plotting system, one of the tubes in the driver stage was replaced by resistors, and better overall linearity characteristics were obtained. However, for the purpose of this research, the distortion of the radiation patterns obtained was not serious, and no time was spent in attempting to improve the driver stages.

There was considerable interference from 3-centimeter radars in the vicinity and measurements could be made only when this interference was absent. To eliminate this troublesome factor, a transmitter with higher power output than for a Shepherd-Pierce tube should be used. The receiving system should be made frequency selective, possibly by the use of a superheterodyne receiver having a sharply tuned I.F. stage of about 30 megacycles.

APPENDIX A

PHOTOGRAPHS OF THE MEASURING EQUIPMENT

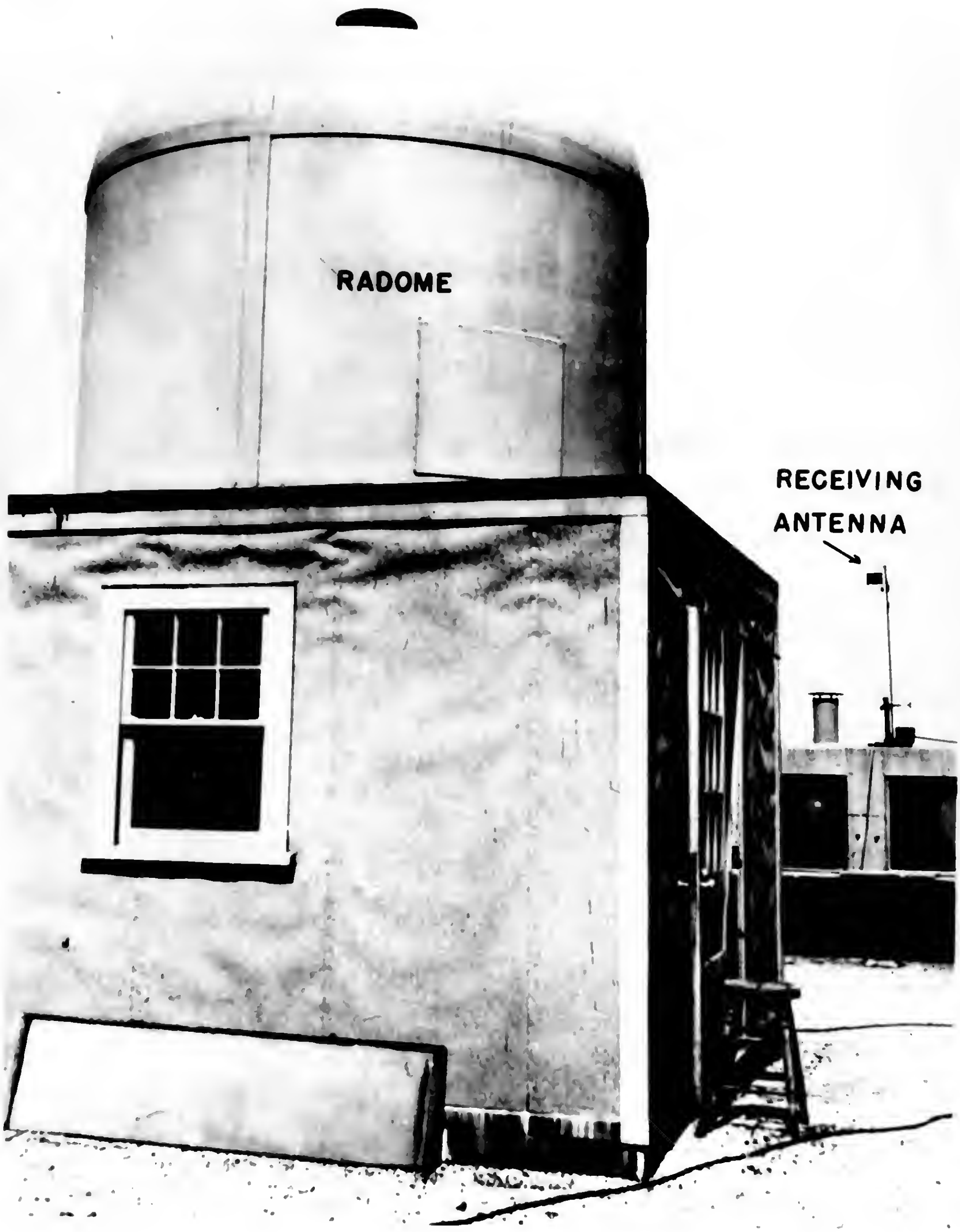


FIG. 48. RADOME AND RECEIVING ANTENNA

FIG. 49. RADOME AND RECEIVING ANTENNA

FIG 50 RECEIVING ANTENNA

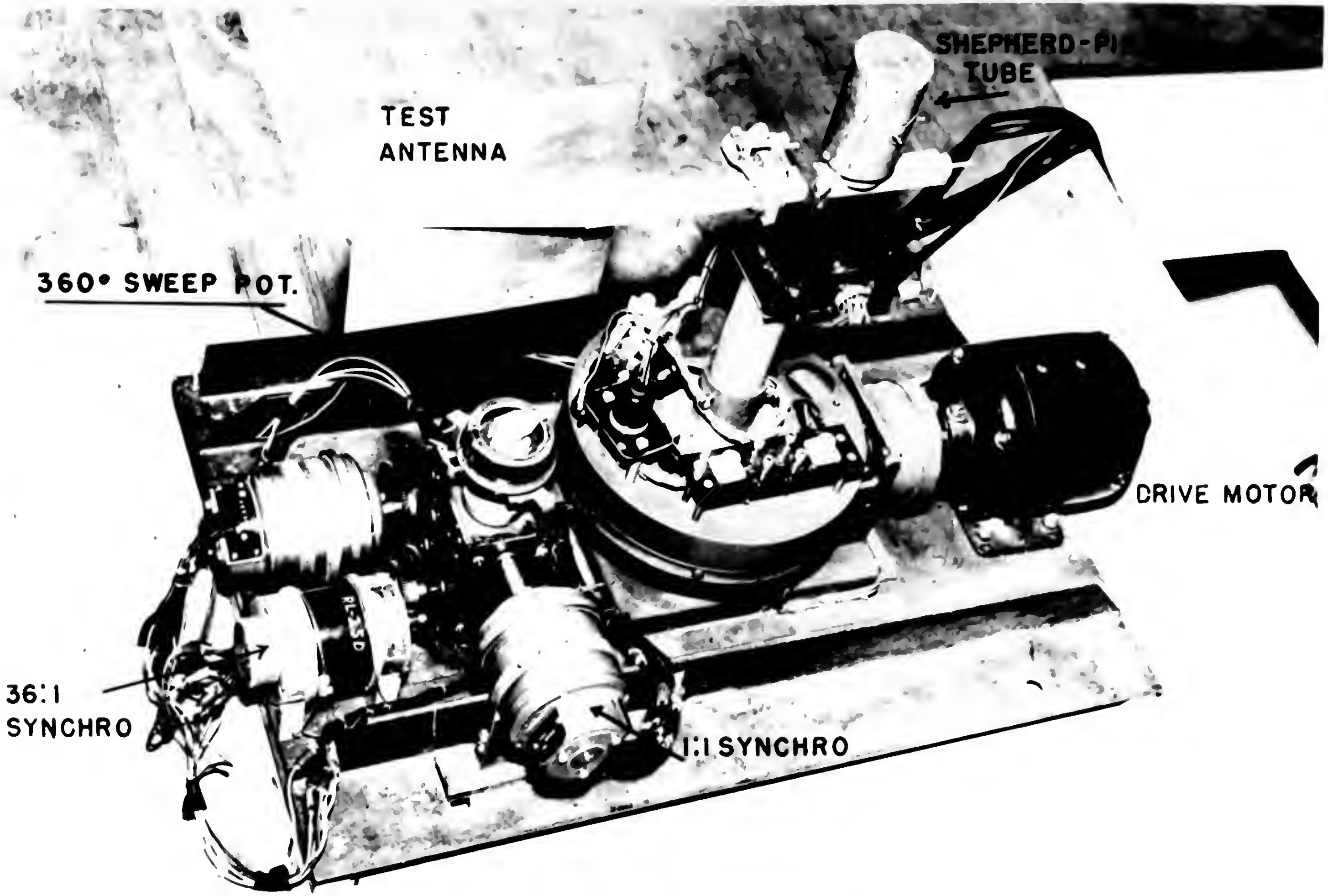


FIG. 51. TEST ANTENNA ROTATION EQUIPMENT

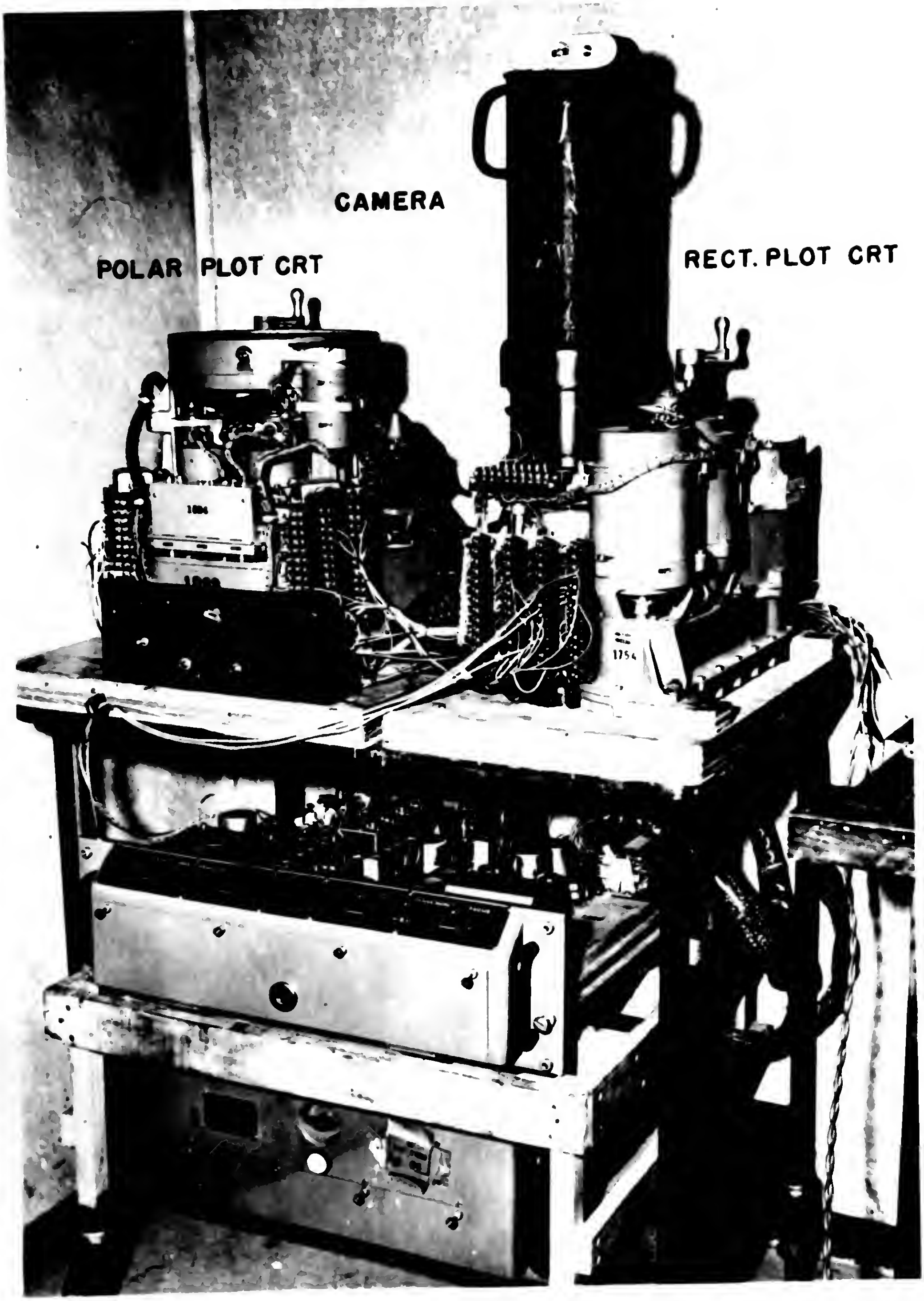


FIG. 52. PATTERN PLOTTER

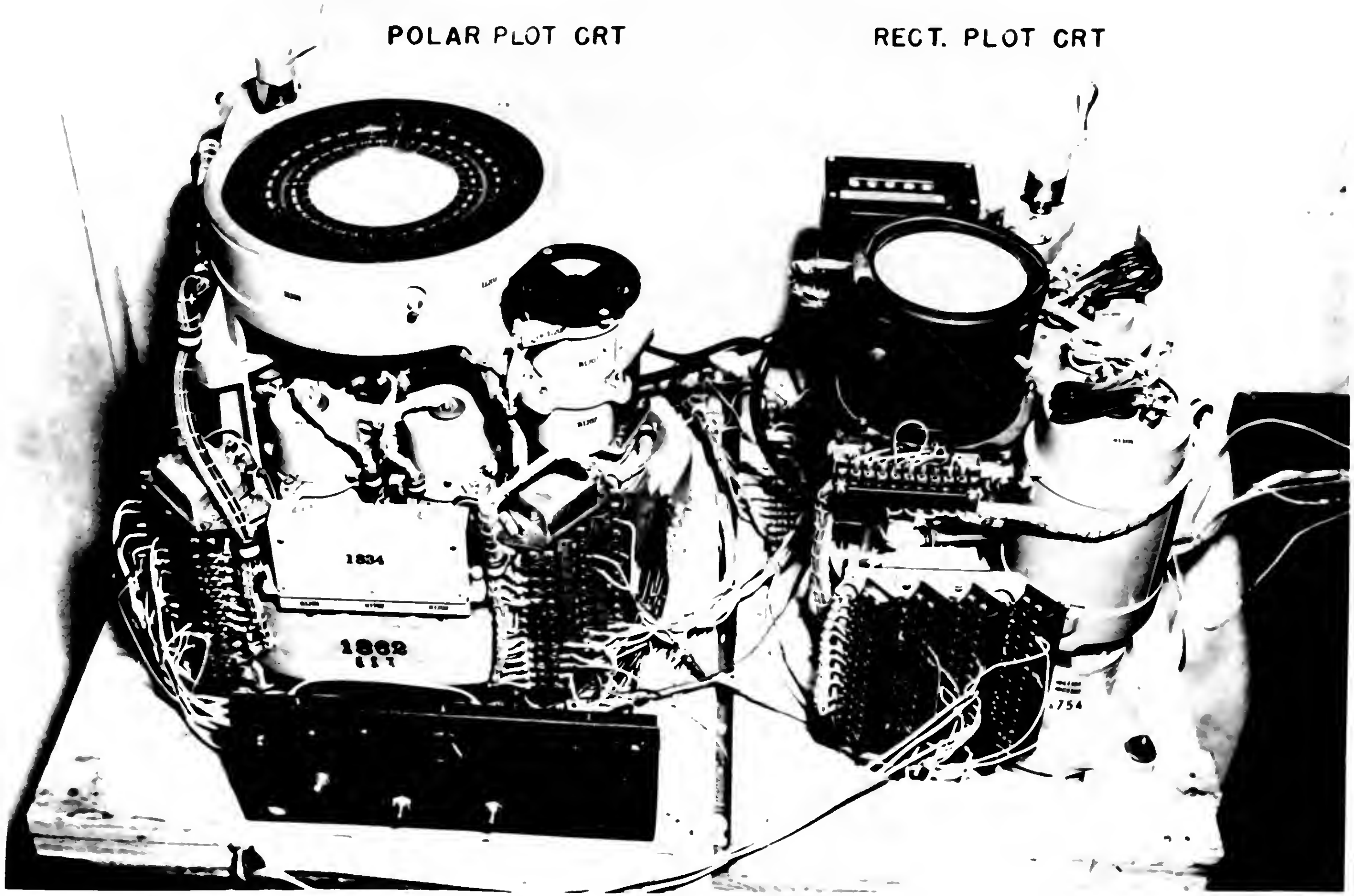


FIG. 53. PATTERN PLOTTER

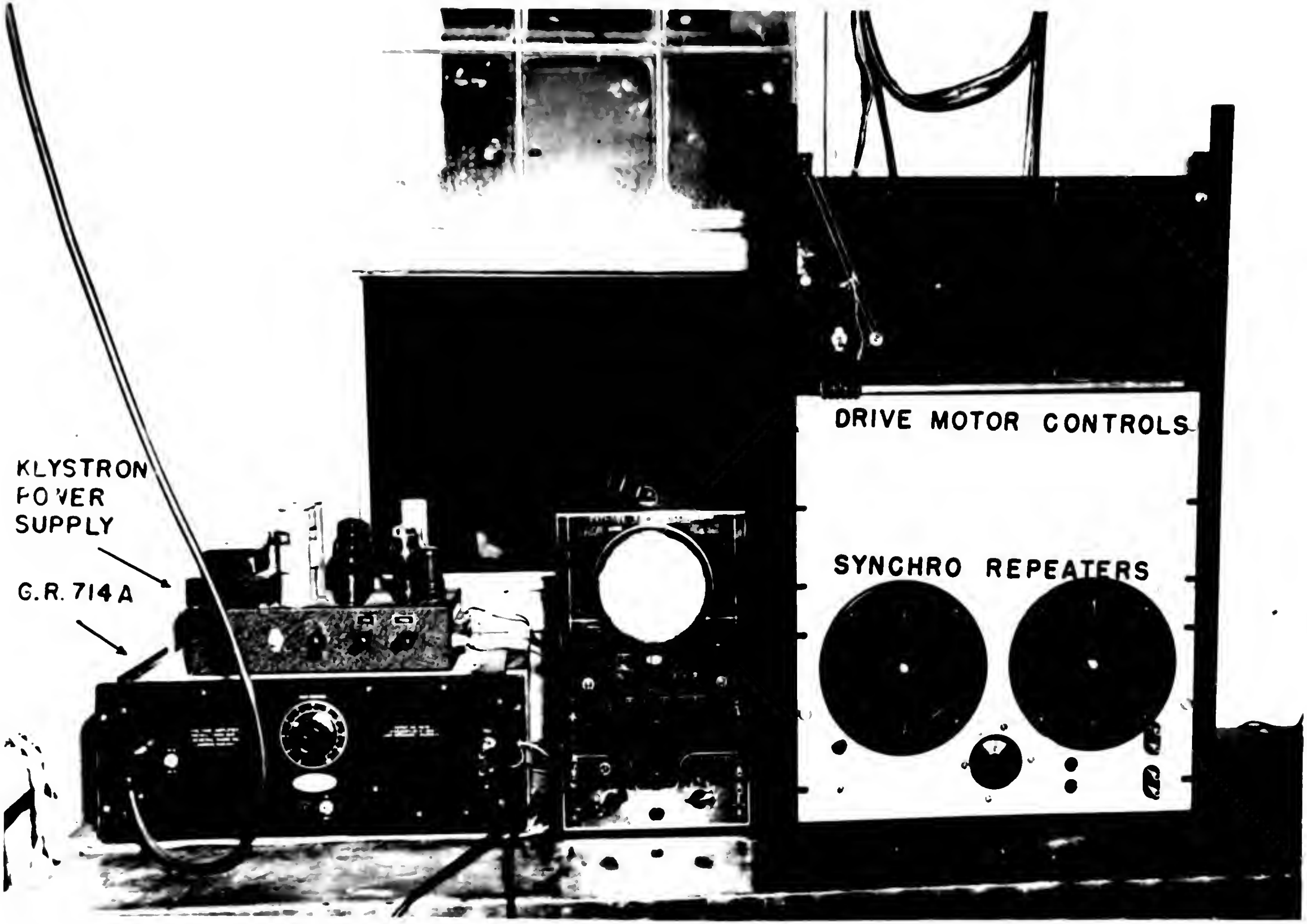


FIG.54. COMPONENTS OF MEASURING EQUIPMENT

BIBLIOGRAPHY

1. Barrow, W. L. and Greene, F. M. — "Rectangular Hollow Pipe Radiators." Proc. I.R.E. 26, 1498-1519 (1938).

2. Beringer, R. — "Low Level Crystal Detectors." Rad. Lab. Report 61-15 (3/16/43)

3. Chu, L. J. — "Calculation of the Radiation Properties of Hollow Pipes and Horns." Jour. Appl. Phys. 11, 603-610 (1940)

4. Krutter, H. — "Determining the Law of a Crystal." Radiation Lab. Rep. 54-22 (4/29/43)

5. Schelkunoff, S. A. — "On Diffraction and Radiation of Electromagnetic Waves." Phys. Rev. 56, 308-316 (1939)

6. Walker, R. M. — "Dielectric Windows in Wave Guides." Radiation Lab. Rep. 587 (6/29/44)

7. Watson, W. H. — "Resonant Slots." Jour. I.E.E. 93 IIIA, 747-777 (1946)

8. Wehner, R. S. — "A Zero Drag Aircraft Antenna for U.H.F." N.D.R.C. Rep. 895-35 (R.C.A.)

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Microwave antennas adjacent to metal surfaces.