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An experimental investigation of receiver system sensitivity

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AN EXPERIMENTAL INVESTIGATION OF RECEIVER SYSTEM SENSITIVITY

BY

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SUMMARY

A method of determining the minimum detectable power density incident at the receiving antenna of a UHF receiver is proposed. The minimum detectable power density is the power density required to produce a signal-to-noise ratio of unity in the output of the receiver. The proposed method includes the receiving antenna impedance, the necessary connecting transmission lines, and the receiver impedance.

It is shown that an error in the antenna directivity will produce a significant error in the overall sensitivity of a receiving system. Since the directivity is the most difficult system variable to determine experimentally, it is probably the limiting factor in the proposed method.

It is shown that the methods presently used to evaluate the receiver system sensitivity are a function of antenna directivity, effective temperature of the receiving antenna, and a term called noise factor. All of these parameters produce considerable error in the experimental evaluation of the sensitivity. It is for this reason that a better method of determining the overall receiving system sensitivity is desirable.

The proposed method includes the receiving antenna directivity but does not include the effective temperature

of the antenna or the noise factor of the receiver. Elimination of these two variables should improve the accuracy of determining the overall sensitivity. The sensitivity is evaluated in terms of the receiving system variables including the receiving antenna and the receiver. These variables can be measured with greater accuracy than those of the methods presently used. The method is straightforward and can be accomplished in the field by technicians with reasonable accuracy and within a reasonable length of time.

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LIST OF SYMBOLS

Symbol	Description
f	Frequency
mc	Megacycle
c	Speed of light
λ	Wavelength
L	Length of antenna
ℓ	Length of transmission line
VSWR	Voltage standing wave ratio
S	Voltage standing wave ratio
R_a	Resistive component of the input impedance of the antenna
X_a	Reactive component of the input impedance of the antenna
R_t	Resistive component of input impedance of transmission line
X_t	Reactive component of input impedance of transmission line
Z_o	Characteristic impedance of a transmission line.
W_a	Power absorbed in the receiver
W_i	Available power input to transmission line used to feed the receiver
W_{in}	Available power input to transmission line used to feed the transmitting antenna
D	Antenna directivity
η_a	Antenna efficiency
η	Efficiency of transmission line
dbm	Decibel

LIST OF SYMBOLS (CON'T)

Symbol	Description
α	Attenuation factor
β	Phase constant
r	Distance between the transmitting and receiving antennas
S_l	VSWR looking into a transmission line
S_t	VSWR of the transmitting antenna
S_a	VSWR of the receiving antenna
S_r	VSWR of receiver

I INTRODUCTION

The design and development of receiver systems has progressed very rapidly within the last few years. The limit of these receivers is the distance beyond the transmitter, where the field strength at the receiving antenna falls below a value incapable of producing a satisfactory receiver output signal. The definition of receiver system sensitivity, including the antenna and the receiver, is the minimum detectable power density at the receiving antenna required to produce a signal-to-noise ratio of unity, in the output of the receiver. The term receiver system shall be interpreted to include the receiving antenna and the receiver throughout this thesis.

In rating a receiving system the problem of interest is how large must the power density be at the receiving antenna in order to override the noise induced in the antenna and the noise generated within the receiver. A portion of the noise generated within the receiver consists of shot noise, thermal noise, and noise generated in the mixer. These terms are commonly used in current literature. The antenna noise is the noise received by the antenna from external sources such as the noise from the sky.

If a signal is to be heard over a communication receiver it must be larger than the noise within the

the receiving system. This is very important in both military and commercial applications. For example in the complex problem of air traffic control it is essential that the signal be discernible above the noise in order that the pilot can receive the proper instructions and thereby avoid serious accidents.

Since the output of the receiver is dependent upon the signal strength at the receiving antenna, the system should be evaluated upon the minimum detectable signal at the receiving antenna. This minimum detectable signal should be expressed in terms of the power density, as mentioned above, at the receiving antenna. The power density incident at the receiving antenna is expressed in watts per square meter. This would be the sensitivity of the receiving system and maybe referred to as the sensitivity or the minimum detectable power density.

An accurate account of the receiver system sensitivity would include all the noise induced within the antenna and that generated within the receiver. Since the sensitivity is a function of the antenna impedance, the receiver impedance, transmission lines, frequency, antenna directivity, antenna efficiency, and other parameters, these receiving system parameters should be included in any evaluation of the overall receiver system sensitivity.

In order that the overall sensitivity of any receiving system be evaluated accurately the system should be operating within its normal environment. That is, for example, if the antenna is a ground plane antenna it should be operating over a ground plane when it is to be a part of the receiving system under test.

D. O. North[1] has developed a formula for absolute receiver system sensitivity which shows how the minimum usable signal field strength is related to the operating wave length, the antenna directivity, the local noise field strength, the receiver bandwidth, the effective temperature of the antenna, and a number called noise factor. This method has the disadvantages of determining, (1) the effective temperature of the antenna, (2) the noise factor of the receiver, and (3) the antenna directivity.

Smith[2], while employed with the Boeing Airplane Company, developed a mathematical means of interpreting the overall system sensitivity, including the receiving antenna, in terms of a minimum detectable incident power density, at the receiving antenna, required to produce a detectable signal at the output of the receiver. This development does not involve the effective temperature of the antenna or the term called noise factor. Because of these two advantages and because the parameters of the receiving system, including the receiving antenna, are included, the latter method was chosen for this experimental thesis.

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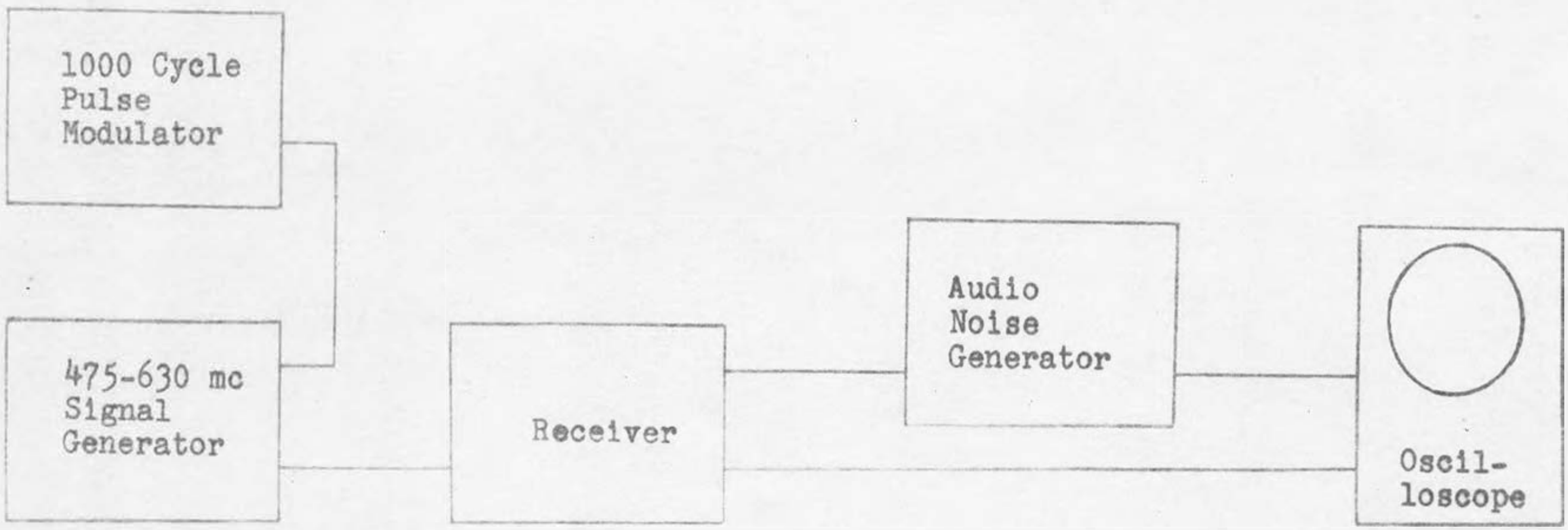
1. All references are listed in the bibliography

The objectives of this investigation were, (1) to set forth an experimental method for determining the overall receiver system sensitivity, including the receiving antenna and the receiver, in terms of the minimum detectable power density at the receiving antenna, (2) to determine the effects of impedance mismatch of the antenna and the receiver, upon the overall sensitivity of the receiving system.

The following is a proposed method of determining the minimum detectable power density at the receiving antenna: (1) connect the receiving antenna to the receiver through a transmission line, (2) observe the magnitude of the output noise, this is the total noise in the antenna and the receiver, (3) disconnect the antenna and connect the signal generator to the receiver, (4) connect a noise generator in series with the output of the receiver, (5) adjust the noise generator until the noise is equal to that of step 2, adjust the signal generator to produce the desired signal-to-noise ratio of unity, and record W_i from the calibrated dial of the signal generator, the term W_i is the available power input to the receiver, (6) evaluate the impedance of the receiving antenna and the receiver, (7) evaluate the antenna directivity and other parameters of equation (29) and (8) determine the minimum detectable power density by the use of equation (32).

This method, therefore, provides a way for evaluating the receiver system sensitivity in terms of the receiving system variables. The method is readily adaptable to field applications. The accuracy of this method should be better than some of the methods presently being used. A block diagram of the test circuit is shown in Figure 1.



BLOCK DIAGRAM OF CIRCUIT FOR DETERMINING W_1

FIGURE 1

II REVIEW OF LITERATURE

Much has been written in regard to the noise generated within receivers and for methods to determine the noise figure of a receiver. These problems are directly related to the receiver system sensitivity in the report of this investigation.

The method of determining the sensitivity, as proposed by Smith[2], is presented in the following pages. There are a few modifications in the mathematical presentation, which were emphasized by the experimental results. These are noted in the experimental results.

The time rate of energy flow per unit area from a point source is known as the Poynting vector[3], or power density. Since the Poynting vector of a point source has only a radial component, it follows that the power density consists only of a radial component. The radiation intensity is the product of power density and the square of the radius at which it is measured. Thus the power per unit solid angle, or radiation intensity is

$$U = Pr^2$$

Since all antennas exhibit directional properties it is convenient to normalize the radiation intensity in terms of the maximum radiation intensity thus producing a relative radiation intensity rather than an absolute radiation intensity[3].

Antenna directivity has been defined as the ratio of the maximum radiation intensity to the average radiation intensity. Expressed mathematically the directivity (D) is

$$D = \frac{Um}{Uo} = \frac{\text{Maximum radiation intensity}}{\text{Average radiation intensity}} \quad \text{---------1}$$

where U_m and U_o apply to the antenna under consideration.

The radiation-intensity pattern can be expressed as

$$U = U_a f(\theta, \emptyset) \quad \text{---------2}$$

and its maximum value by

$$U_m = U_a f(\theta, \emptyset)\max \quad \text{---------3}$$

The average radiation intensity is

$$U_o = \frac{W}{4\pi} = \frac{U_a f(\theta, \emptyset) d\Omega}{4\pi} \quad \text{---------4}$$

where W = total power radiated

U_a = constant

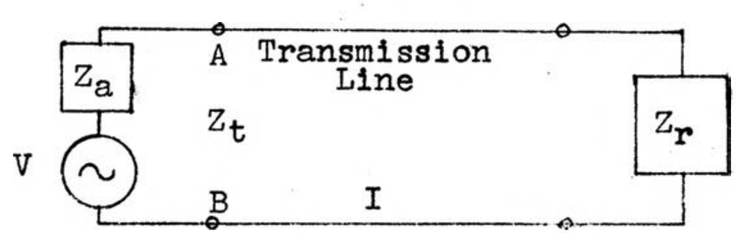
$d\Omega = \sin\theta d\theta d\emptyset$ = element of solid angle.

The antenna directivity is therefore

$$D_{max} = \frac{4\pi f(\theta, \emptyset)\max}{f(\theta, \emptyset) d\Omega} = \frac{Um}{Uo} \quad \text{---------5}$$

Complete derivations are found in reference (3).

The receiving antenna collects power from the field of a passing electromagnetic wave and delivers it to the terminating or load impedance. The antenna can be replaced by the equivalent circuit shown in Figure (2).



ANTENNA EQUIVALENT CIRCUIT

FIGURE 2

The voltage V induced in the antenna produces a current

$$I = \frac{V}{Z_a + Z_t} \quad \text{---------------6}$$

where Z_a and Z_t are in general complex impedances as shown below.

$Z_a = R_a + jX_a$ = antenna impedance

$Z_t = R_t + jX_t$ = load impedance looking into the transmission line

$R_a = R_r + R_L$ = radiation resistance + loss resistance

The receiver impedance Z_R referred to the input terminals (A, B) of the antenna in Figure 2 is computed from the transmission line formula.

$$Z_t = Z_o \frac{Z_R \operatorname{Cosh}(\gamma\ \ell) + Z_o \operatorname{Sinh}(\gamma\ \ell)}{Z_R \operatorname{Sinh}(\gamma\ \ell) + Z_o \operatorname{Cosh}(\gamma\ \ell)} \quad \text{-----------7}$$

where Z_o = characteristic impedance of the transmission line.

$Z_R = R_R + jX_R$ = receiver input impedance

$\gamma = \alpha + jB$

where α is the attenuation constant

and B is the phase constant

ℓ = length of transmission line

The power delivered to the terminating impedance is given by $W = I^2 R_t$.

Substituting for Z_a and Z_t equation 6 becomes

$$|I| = \frac{V}{\left[(R_a + R_t)^2 + (X_a + X_t)^2\right]^{1/2}} \qquad \text{---------8}$$

and the power is therefore

$$W = \frac{V^2 R_t}{(R_a + R_t)^2 + (X_a + X_t)^2} \qquad \text{---------9}$$

The effective antenna aperture is defined by

$$A_e = \frac{W}{P} \qquad \text{------------------10}$$

Where W is the power absorbed by the load and P is incident power density at the receiving antenna.

The power W from equation 9 is substituted into equation 10 yielding

$$A_e = \frac{1}{P}\left[\frac{V^2 R_t}{(R_a + R_t)^2 + (X_a + X_t)^2}\right] \qquad \text{--------11}$$

This equation includes any mismatch between the antenna impedance and the input impedance of the transmission line, which is connected between the antenna and the receiver as shown in Figure 2.

The definition of the maximum effective aperture follows from equation 10.

$$A_{em} = \frac{W'}{P} = \frac{\text{Maximum power absorbed by the load}}{\text{Power density incident at the antenna}} \qquad \text{--12}$$

Assuming $R_t = R_a = R_r$, $R_L = 0$, and $X_t = -X_a$, the maximum power absorbed by the load is

$$W' = \frac{V^2}{4R_t} = \frac{V^2}{4R_r} \qquad \text{-------------13}$$

Substituting W' into equation 12 yields

$$A_{em} = \frac{1}{P} \frac{V^2}{4R_r} \qquad \text{-------------14}$$

The effectiveness ratio is defined as

$$\sigma = \frac{A_e}{A_{em}} = \frac{\frac{W}{P}}{\frac{W'}{P}} = \frac{W}{W'} \qquad \text{-------------15}$$

$$\sigma = \frac{\dfrac{V^2 R_t}{(R_a + R_t)^2 + (X_a + X_t)^2}}{\dfrac{V^2}{4R_r}}$$

$$\sigma = \frac{4R_r R_t}{(R_a + R_t)^2 + (X_a + X_t)^2} \qquad \text{-------------16}$$

The ratio of the directivity of two antennas is expressed as

$$\frac{D_1}{D_2} = \frac{KA_{em1}}{KA_{em2}} = \frac{A_{em1}}{A_{em2}} \qquad \text{-------------17}$$

The directivity of an isotropic source is

$$D_1 = \frac{U_m}{U_o} = 1$$

since the radiation intensity is the same in all directions at a fixed distance away.

Recalling that $D_1 = 1$ for an isotropic source equation 17 reduces to

$$\frac{1}{D_2} = \frac{A_{em1}}{A_{em2}} \qquad \text{or}$$

$$A_{em1} = \frac{A_{em2}}{D_2} \qquad \text{------------------18}$$

The maximum effective aperture and directivity of a short thin dipole antenna are $\frac{3\lambda^2}{8\pi}$ and $\frac{3}{2}$ respectively. By substituting these quantities into equation 18 it becomes

$$A_{em1} = \frac{\frac{3\lambda^2}{8\pi}}{\frac{3}{2}} = \frac{\lambda^2}{4\pi}$$

It follows from equation 18 that

$$D = \frac{4\pi}{\lambda^2} A_{em} \qquad \text{------------------19}$$

Where λ is the wavelength in the medium where the antenna is immersed.

From equation 15 $A_e = \sigma A_{em}$ substituting this into equation 19 yields

$$D = \frac{4\pi}{\lambda^2} \frac{A_e}{\sigma} \qquad \text{------------------20}$$

From which

$$A_e = \frac{D\lambda^2 \sigma}{4\pi} \qquad \text{------------------21}$$

Substituting equation 16 for σ we have

$$A_e = \frac{D\lambda^2}{4\pi} \left[\frac{4R_r R_t}{(R_a + R_t)^2 + (X_a + X_t)^2} \right]$$

$$A_e = \frac{1}{\pi} \left[\frac{D\lambda^2 R_r R_t}{(R_a + R_t)^2 + (X_a + X_t)^2} \right] \qquad \text{----------22}$$

The power input to the transmission line connecting the antenna to the receiver is

$$W = PA_e = P\frac{1}{\pi}\left[\frac{D\lambda^2 R_r R_t}{(R_a + R_t)^2 + (X_a + X_t)^2}\right] \qquad \text{----23}$$

where A_e is given by equation 22.

The power delivered to the receiver is somewhat less than that given in equation 23 if the transmission line has losses. If the transmission line has losses the power delivered to the load is

$$W' = PA_e 10^{-0.001(db)\ell} \qquad \text{-------------24}$$

where db - db attenuation per 100 feet

ℓ - transmission line length in feet

If the receiver impedance is matched to the transmission line of Z_o characteristic impedance, the power (W_a) absorbed by the receiver is the incident power W_i at the input of the transmission line, minus the reflected power W_r. Stated mathematically the power absorbed in the receiver is

$$W_a = W_i - W_r \qquad \text{------------------25}$$

and the ratio of W_a to W_i is

$$\frac{W_a}{W_i} = \frac{W_i - W_r}{W_i} \qquad \text{------------------26}$$

Since power is proportional to the square of the magnitude of the voltage this ratio can be expressed as

$$\frac{W_a}{W_i} = \frac{|V_i|^2 - |V_r|^2}{|V_i|^2} = 1 - |K|^2 \qquad \text{-------------27}$$

where K is the ratio of V_r to V_i and

V_r ——— the reflected voltage

V_i ——— the incident voltage of the input of the transmission line.

The VSWR is

$$S = \frac{1 + |K|}{1 - |K|} \text{ —— voltage standing wave ratio --------28}$$

From equation 28 we have

$$|K| = \frac{S - 1}{S + 1} \quad \text{-----------------29}$$

Substituting the value of K, from equation 29, into equation 27 yields

$$\frac{W_a}{W_i} = \frac{4S}{(S + 1)^2} \quad \text{------------------30}$$

Solving equation 30 for W_a and equating the resulting equation to equation 24, and recalling that A_e is given by equation 22, we have

$$W_i \frac{4S}{(S + 1)^2} = \frac{1}{\pi} \frac{P\lambda^2 D R_r R_t 10^{-0.001(db)\ell}}{\left[(R_a + R_t)^2 + (X_a + X_t)^2\right]} \quad \text{---31}$$

$$P = \frac{4\pi W_i S \left[(R_a + R_t)^2 + (X_a + X_t)^2\right] 10^{-0.001(db)\ell}}{D\eta_a (S + 1)^2 R_a R_t \lambda^2} \quad \text{----32}$$

where R_r is assumed to be $\eta_a R_a$. The term η_a is the antenna efficiency. Equation 32 represents the minimum detectable power density at the receiving antenna.

All of the variables of equation 32 can be determined experimentally. The limitation of equation 32 is the accuracy in the experimental determination of the system variables.

The power density can also be calculated from the transmitting parameters. Assumming the signal generator to be matched to the transmission line, the only reflection in the transmitting system is caused by mismatch of the transmitting antenna. This mismatch will produce a VSWR S_t. The power delivered to the antenna is

$$W_a' = W_{in} \frac{4S_t}{(S_t + 1)^2} \qquad \text{------------------------33}$$

where W_{in} is the available power into the transmission line.

The power density at the receiving antenna is

$$P' = W_{in} \frac{S_t}{(S_t + 1)^2} \frac{D_t}{\pi r^2} \qquad \text{------------------34}$$

where D_t —— transmitting antenna directivity

r —— distance between the transmitting and receiving antennas.

The minimum detectable power density can be determined from equations 32 and 34. All of the system variables can be determined in the field with reasonable speed and accuracy.

III EXPERIMENTAL PROCEDURES

1. Experimental Results:

Most of the equipment used in this investigation was furnished by the electrical engineering department and the Boeing Airplane Company under Boeing's Purchase Order No. 295336. Part of the equipment was constructed and modified as the work progressed.

Two circular ground planes six feet in diameter were constructed. The ground planes were constructed of plywood covered with bronze mesh wire. These ground planes and part of the experimental equipment are shown in Figure 3. The ground planes were constructed to accomodate the vertical stub antennas used in the experimental work. These antennas were chosen because of their simplicity.

A Hewlett Packard UHF signal generator was used as the power source for the transmitting antenna. A Nems Clarke 1501A commercial receiver was used in conjunction with the receiving antenna.

Type N connectors were used to attach the coaxial transmission line to the antennas.

The original antennas were the adjustable automobile receiving type. Each antenna was adjusted to a fixed length of six inches. The transmitting antenna was mounted vertically in the center of one of the ground planes, and the receiving antenna was mounted vertically in the center of the second ground plane. One of these antennas is shown in Figure 4.

The input impedance of the antenna and receiver were determined by utilizing the experimental circuit in Figure 5. A sinusoidal frequency of 1000 cycles was used as the modulating signal.

The receiver was tuned to produce a maximum output for each frequency under consideration. The probe in the slotted line was then adjusted along the slotted line until the maximum VSWR reading was obtained. The VSWR and null location were recorded for each frequency under consideration. The impedance was determined as shown in the sample calculations in the appendix.

The video output of the receiver was monitored with a 514D Tektronix oscilloscope. A general radio unit pulser was used to amplitude modulate the UHF generator signal at a frequency of 1000 cycles per second.

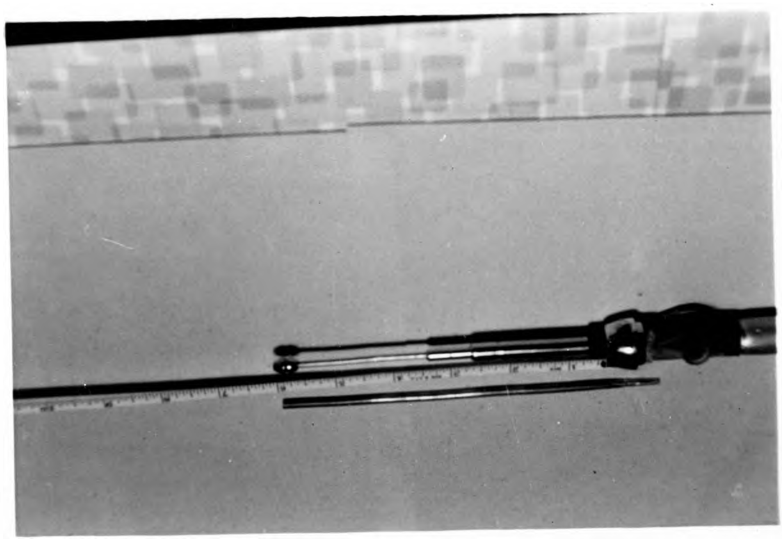
Calibrated dials on the signal generator provide an easy method for determining the power input to the transmission line and the frequency of operation.

The signal power was increased until a signal-to-noise ratio of unity was obtained in the video output. A block diagram of the circuit for determining this signal-to-noise is shown in Figure 6. The receiver was adjusted for a maximum output for each frequency. The value of frequency and power (-dbm) was recorded for each frequency.

The signal generator and receiver were then connected

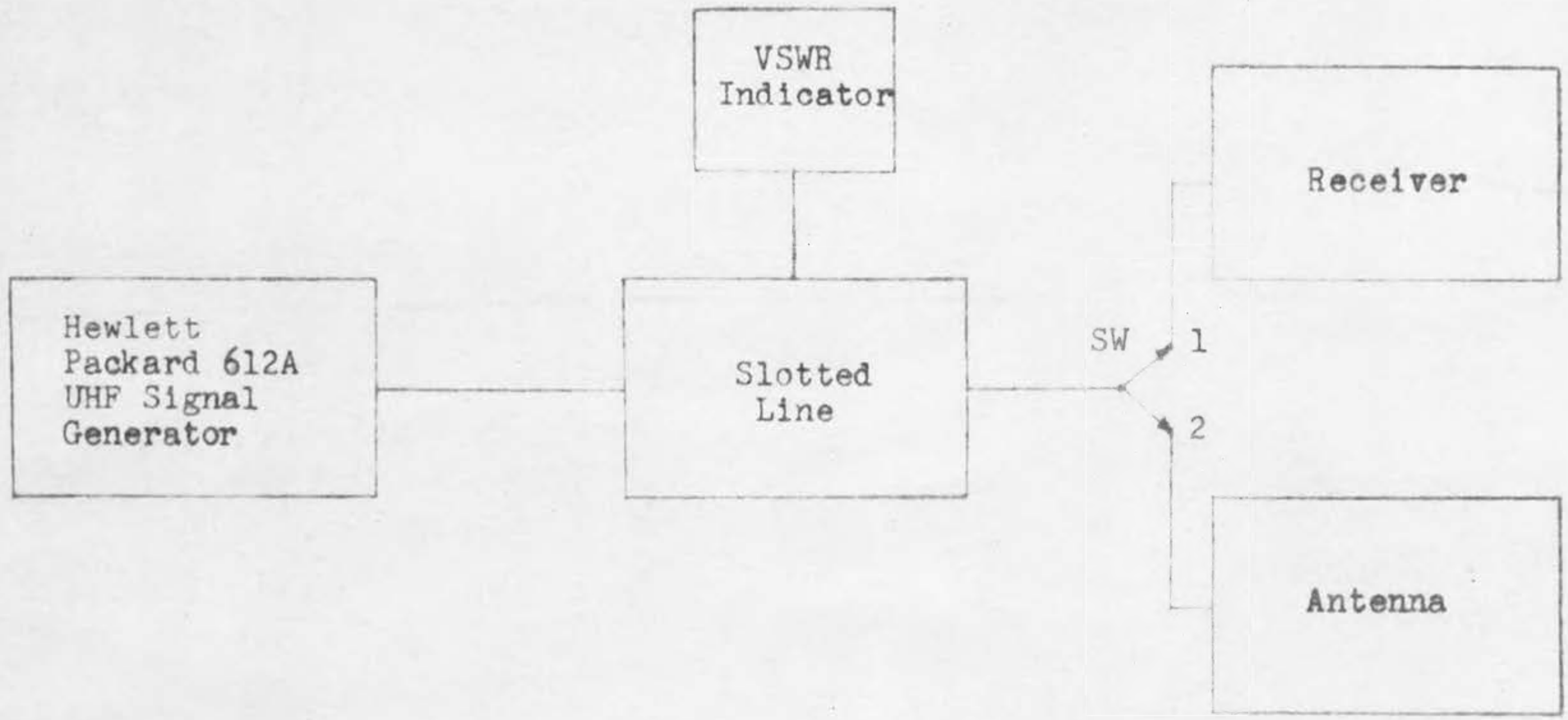
EXPERIMENTAL EQUIPMENT

FIGURE 3



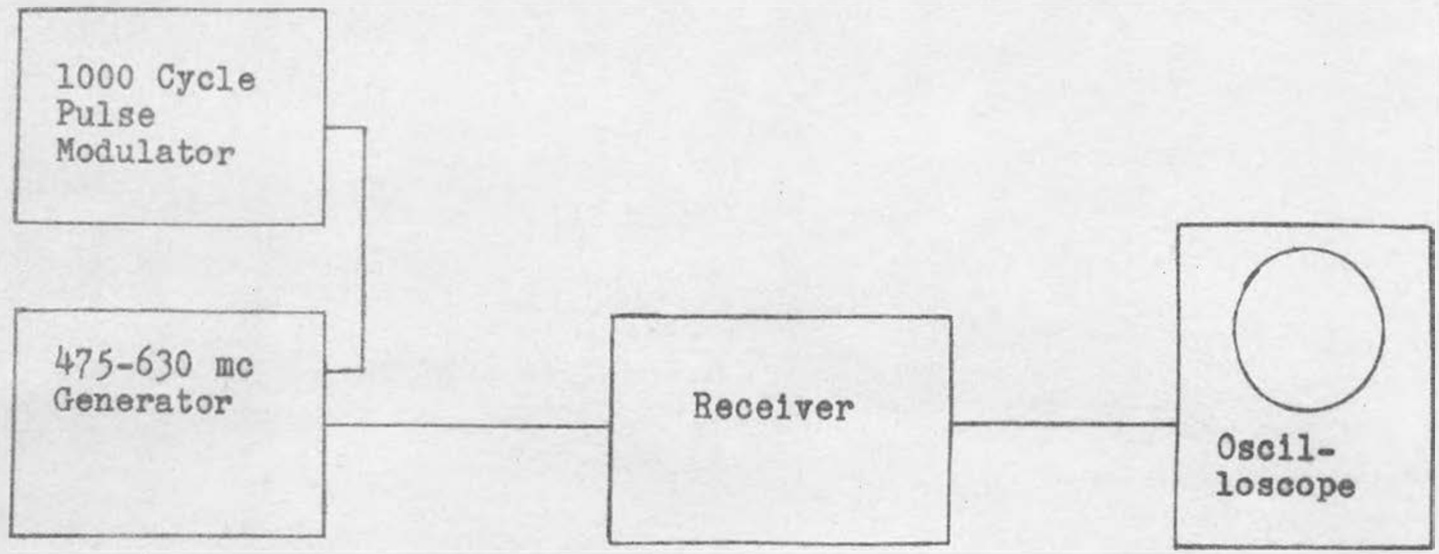
EXPERIMENTAL ANTENNAS

FIGURE 4



BLOCK DIAGRAM OF CIRCUIT FOR DETERMINING THE
INPUT IMPEDANCE OF THE ANTENNA AND RECEIVER

FIGURE 5



BLOCK DIAGRAM OF THE CIRCUIT USED
TO DETERMINE TANGENTIAL SENSITIVITY

FIGURE 6

by the same transmission line used in the above case. The adjustments were made in the same manner. The frequency and power were recorded as above.

The VSWR (S_r) of the receiver was determined for each frequency. The VSWR (S_1) looking into the transmission line connected between the signal generator and receiver was also determined by the use of a slotted line and a VSWR indicator.

Unfortunately the data obtained using the two circular ground planes was very inconsistent. The data could not be repeated. It appeared that reflections from the edges of the ground plane caused the data to be inconsistent. This data was not included in this report.

A transmission line has increased losses when the VSWR is increased. If the VSWR is large the efficiency of transmission may be reduced considerably.

Macalpine[4] has shown that the efficiency of a transmission line can be represented as follows,

$$\eta = \frac{S_1^2 - 1}{S_r^2 - 1} \frac{S_r}{S_1} \qquad \text{------------------------} 35$$

where

S_r _______ VSWR at the load

S_1 _______ VSWR at the input end of the transmission line

These values are determined experimentally. The VSWR at the input can also be predicted from the equation,

$$S_1 = \left[\frac{1}{\tanh(0.115A_o) + \tanh\frac{1}{S_r}} \right]$$

where $A_o = 8.686\alpha' \ell$ ______ matched attenuation of a length of line in decibels

α' ______ attenuation constant in nepers per unit length

Since large VSWR's are present equation 32 should be modified to include the transmission line efficiency. Equation 32 then becomes,

$$P = \frac{4\pi W_i}{\eta D \lambda^2} \frac{S}{\eta_a (S + 1)^2} \frac{\left[(R_a + R_t)^2 + (X_a + X_t)^2\right]}{R_a R_t} \quad \text{--36}$$

Another ground plane was constructed. This ground plane was connected between the two original ground planes. Triangular metal wedges were installed around the extreme ends of the ground plane.

The data obtained with the modified ground plane also proved to be unsatisfactory. The results are plotted in Figure 7. There is very little correlation between the two curves of minimum detectable power density calculated from transmitting and receiving system variables. This may have been caused by a variation in directivity from the theoretical value. An attempt was made to measure the directivity. This measurement was very difficult since the presence of a person near the antenna would vary the signal strength considerably. A probe was then attached to a transmission line and placed in the field of the antenna. Because of the standing waves which were present along the transmission line, and the difficulty in determining the exact position of the probe the idea of determining directivity was discontinued to explore the possibilities of reflections.

Small serrated strips of metal were attached along both sides of the ground plane as shown in Figure 3. A noticeable change occurred in the signal-to-noise ratio when these metal strips were placed on the ground plane.

The minimum detectable power density from transmitting and receiving variables plotted in Figure 8 has virtually no correlation. A change in directivity, antenna impedance, or reflections could possibly produce this condition.

The original antennas were not designed for UHF frequencies. The impedance and VSWR of the antennas changed from day to day. As a result of these effects two new antennas, (Number 4 and 5), were constructed of a solid copper conductor.

A type N connector was attached to the ground plane for inserting the antenna and connecting the transmission line.

Repeated measurements of VSWR and null location indicated that the impedance of these antennas, (Number 4 and 5), did not change appreciably. These antennas were used for the remaining part of the experimental work.

It should be noted that the VSWR of the receiver alone was very small, usually less than 2:1. A 700 ohm carbon resistor was connected in series with the input to

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING
ANTENNA USING A FIXED LENGTH OF TRANSMISSION LINE
AND THE ORIGINAL GROUND PLANE

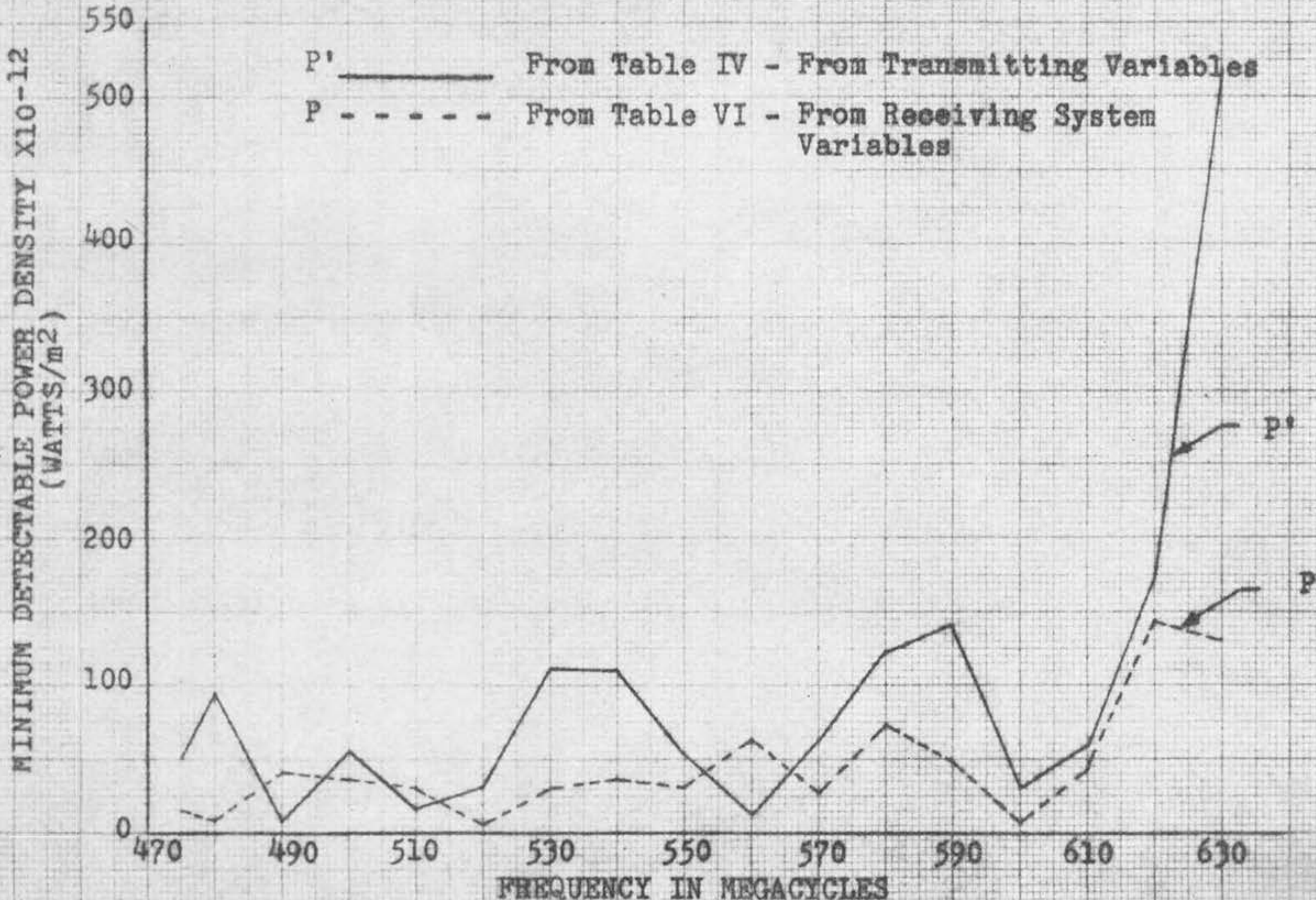


FIGURE 7

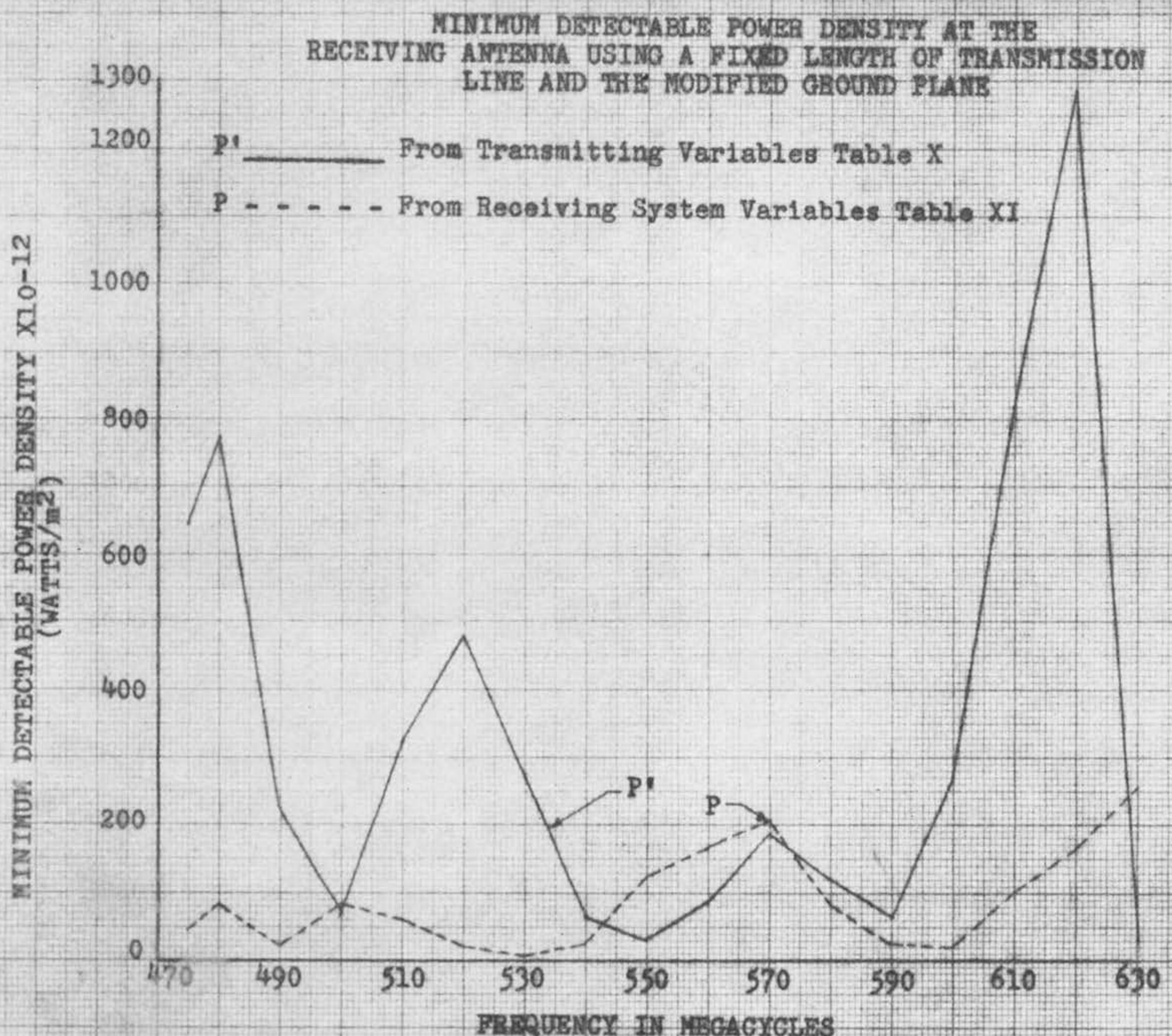

MINIMUM DETECTABLE POWER DENSITY AT THE
RECEIVING ANTENNA USING A FIXED LENGTH OF TRANSMISSION
LINE AND THE MODIFIED GROUND PLANE
P' ________ From Transmitting Variables Table X
P - - - - - From Receiving System Variables Table XI
MINIMUM DETECTABLE POWER DENSITY X10-12
(WATTS/m2)
1300
1200
1000
800
600
400
200
0
P'
P
470
490
510
530
550
570
590
610
630
FREQUENCY IN MEGACYCLES

FIGURE 8

the receiver. This produced an impedance mismatch and increased the VSWR (S_r) to approximately 10:1. This increased mismatch causes the curves of power density versus frequency to have the high peaks indicated in Figures 7, 8, 9, and 10.

Difficulty in determining the directivity led to checking the impedance variations. The impedance did not vary from the previous data. Another check for reflections was made. Large sheets of copper were spaced around the periphery of the ground plane. The locations were changed while observing the receiver output on the oscilloscope. Reflections were reaching the antenna from both sides of the ground plane. No reflections were detected from the extreme ends.

If the ground plane was not a perfect conductor there would be a variation in the directivity from the theoretical value. A solid sheet of copper was placed over the wire mesh, between the antennas. No change was observed in the receiver output with the copper plate installed. Therefore, the wire mesh was considered to be a good conductor.

Since the input resistor was made of carbon the possibility of a change in the input resistance existed, when a change in temperature occured. The temperture was increased to 114^{o}F and then reduced to approximately 30^{o}F with no appreciable change in the VSWR or null location. These data are tabulated in Table XVII in the appendix.

Microwave absorbent material was then placed on the ground plane in positions to absorb the reflected energy.

The curves of minimum detectable power density versus frequency, plotted in Figure 9, were obtained without the absorbent material on the ground plane and a different carbon resistor in the input. The curves of minimum detectable power density versus frequency, plotted in Figure 10, were obtained with the absorbent material. There is a definite correlation in the latter curves. In the calculation of the minimum detectable power density for Figure 10, both antennas were assumed to be 95% efficient.

The maximum and minimum deviation between the two curves occured at 500 mc and 590 mc respectively. Observation of Figure 10 and equations (32) and (36) reveals that an error of only 36.4% in directivity would give the values of power density shown at 500 mc. Similarly an error of 13% in the directivity would give the results shown at 590 mc. This is not unreasonable since the theoretical directivity used here was for an antenna above a perfect conducting ground plane.

A large cardboard crescent having an outer radius of 5 feet was placed perpendicular to the ground plane in the plane of the antenna. The 5 foot radius was measured from the base of the antenna. The crescent extended through an arc of 90°. This covered one quadrant from the ground plane to a point 5 feet directly above the antenna. Notches

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA USING A FIXED LENGTH OF TRANSMISSION LINE, ANTENNAS THREE AND FOUR, AND MODIFIED GROUND PLANE

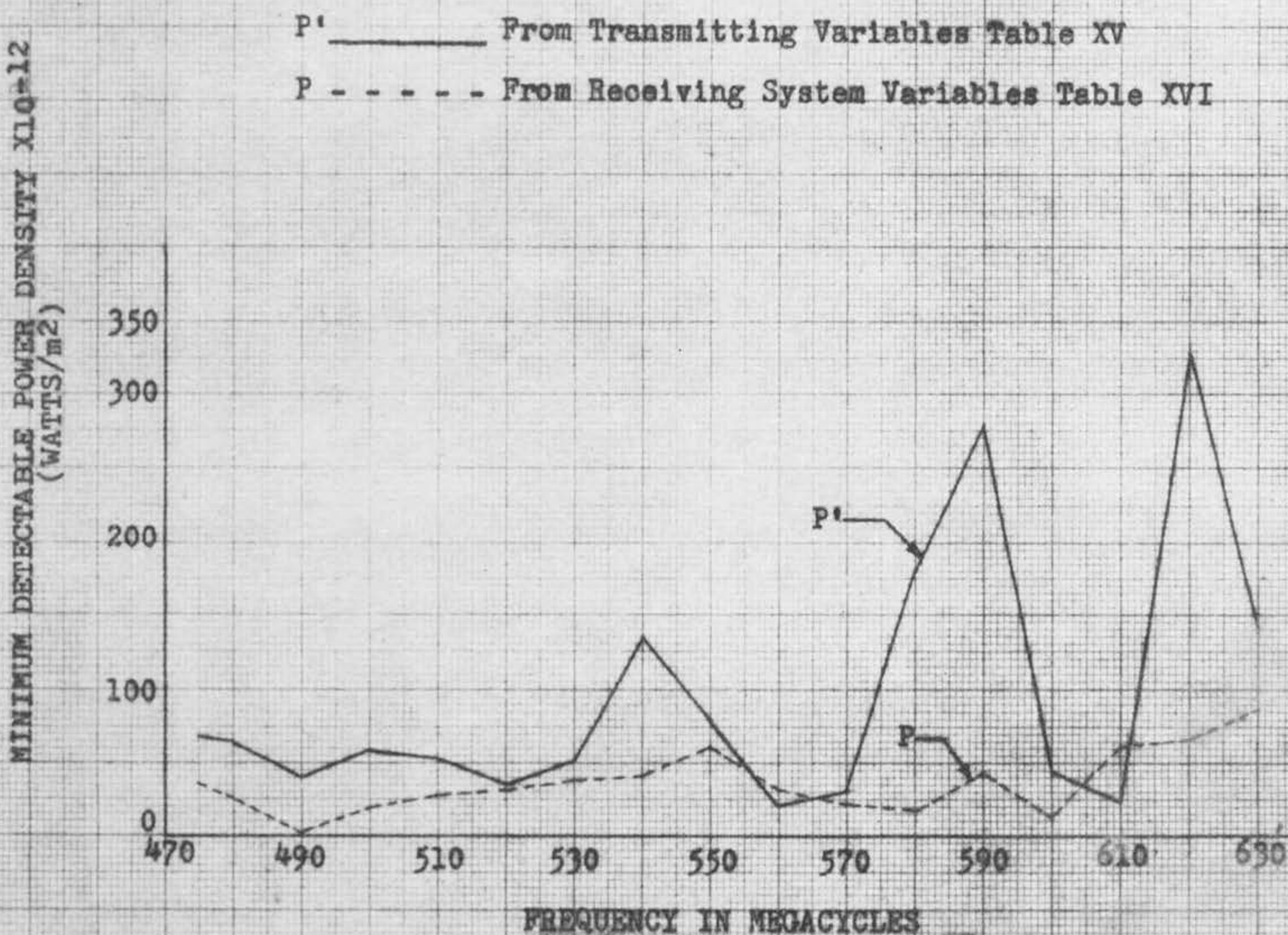


FIGURE 9

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA USING A FIXED LENGTH OF TRANSMISSION LINE AND MODIFIED GROUND PLANE WITH MICROWAVE ABSORBENT ON THE GROUND PLANE TO REDUCE REFLECTIONS

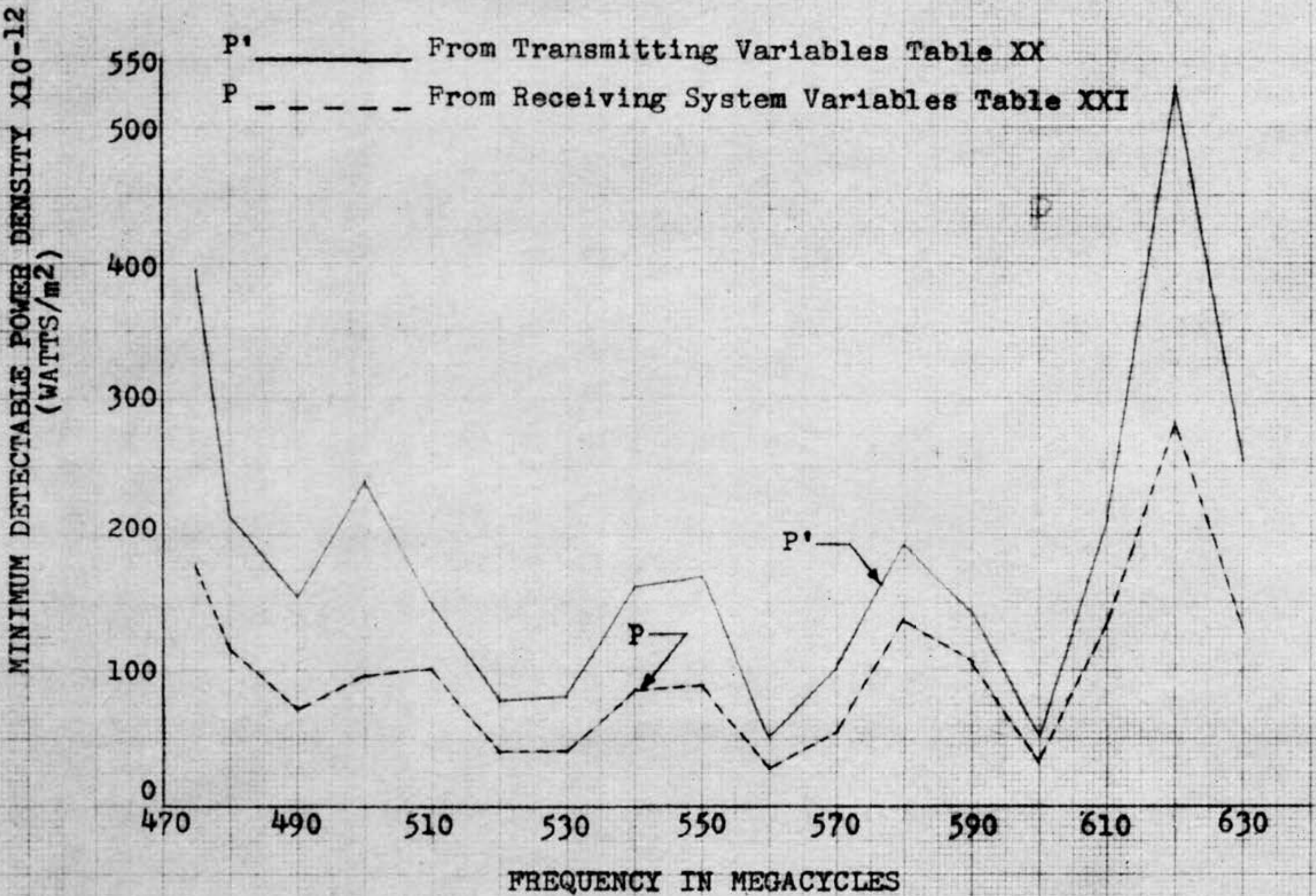


FIGURE 10

were cut in the cardboard every 10°. A microammeter with a crystal detector was attached to a long wood probe. The probe was placed in the slots at 10° intervals and rotated until a maximum current was indicated. The magnitude of the current and the location were recorded. This was repeated for several frequencies.

The data obtained did not produce sufficient information for determining the directivity. It was difficult to read the meter accurately and even at a distance of 6 feet the presence of a person affected the meter reading.

The procedure used to determine the complete receiver system sensitivity in terms of receiver parameters as indicated above is; (1) determine the impedance and VSWR of the receiver and the receiving antenna, for the desired frequencies of operation, (2) determine the efficiency of any transmission lines being used, (3) determine the available power (W_i) input to the receiver to produce a signal-to-noise ratio of unity, (4) calculate the operating wavelength, (5) measure antenna directivity, and (6) calculate the minimum incident power density by the use of equation (36).

The minimum detectable power density from transmitter parameters is found as follows; (1) determine the VSWR of the transmitting antenna, (2) determine the transmitting antenna directivity, (3) determine the distance between the transmitting and receiving antennas, (4) determine the transmitter power required to produce a signal-to-noise ratio of unity in the receiver output, and (5) calculate the minimum detectable power density by the use of equation (32), modified to consider the antenna efficiency.

If a noise generator were used as a signal generator the circuits in the receiver would respond to only random noise frequencies. The receiver of the system used responded to a sinusoidal carrier and to the receiver noise. The output then was a comparison of the noise power to a sinusoidal power. The noise generator method would compare noise power to noise power.

It should be noted that the noise generator was not used as indicated in the introduction.

2. Errors:

A. Tangential Sensitivity: Observation of Figure 6 indicates that it is impossible to define tangential sensitivity independently of the operator. Such measurements have been reported using a radar receiver and an A-scope as an indicating device.[5] It was found that of seven observers each could report tangential-signal measurements with a standard deviation from the mean of less than 1 db for a variety of receiver-gain settings and intensities of the oscilloscope trace. The standard deviation in the mean was less than 2 db for the same conditions. The mean absolute of the peak pulse power for the tangential signal was 9.2 db above the c-w power required to equal the rms noise power output as measured by a wattmeter connected to the output terminals of the receiver. It is believed that the error caused by adjusting the tangential sensitivity visually was very small. To insure a minimum error, two readings of W_i were obtained for each frequency. The value used in the calculations was the average of the two readings.

B. Receiver: The receiver was tuned very carefully. A very slight deviation from the peak output caused an error of several db. This was minimized by providing a very large signal while the receiver was being tuned to a maximum, and observing the output on an oscilloscope.

C. VSWR Indicator: Since the VSWR indicator is a square law detector there is a possibility of an error when measuring large VSWR. The accuracy of the VSWR indicator was checked by the equation and found to be very accurate for a VSWR up to thirteen. It is believed that this VSWR meter did not contribute an appreciable error in the results.

D. Slotted Line: The pick up probe was extracted out of the slotted line as far as possible to avoid distortion in the electric field. Repeated measurements on the same equipment indicated that the error in reading the null position was very small.

E. Ground Plane: Reflections from the edges of the ground plane were reduced by the installation of the triangular wedges and absorbent material. Since the ground plane was not infinite in extent the impedance of the antenna may have been changed. It is very difficult to determine the magnitude of this error since an infinite ground plane could not be constructed. It is believed to be small.

F. Antenna Efficiency: The antennas were assumed to be one hundred percent efficient for the data plotted in Figures 7, 8, and 9. This error could not be avoided since there was no equipment available to measure the efficiency. The efficiency of a vertical dipole antenna approaches 100%. The curves of Figures 7, 8, and 9 would approach each other by the efficiency factor if it deviated from 100%. This is shown in Figure 10 where the antenna efficiency is assumed to be 95%.

G. Frequency: The frequency of the signal generator was checked with a resonant cavity indicating device. The frequency tracked sufficiently accurate throughout the range of frequencies used.

A vernier is available on the frequency indicator. This vernier reading was recorded for each frequency setting to insure that the same frequency adjustment could be repeated.

The error introduced here is believed to be very small.

H. Antenna Directivity: The antenna directivity is very difficult to determine. An error in directivity, using the receiver parameters and equation (36) produces a considerable error. This error is one of the limiting factors in any method used for the determination of overall receiver system sensitivity.

IV CONCLUSIONS

This study presents a method of evaluating the minimum detectable power density, at the receiving antenna, of a UHF receiver. The method includes the entire receiving system including the antenna and the receiver.

The most difficult quantity to determine is the antenna directivity. An error in the antenna directivity will cause a significant error in the minimum detectable power density. This quantity is probably the limiting factor in determining the receiver system sensitivity.

Even though there is a significant error in the antenna directivity the method has advantages over the method proposed by North[1] since it does not include the effective temperature of the antenna or the receiver noise factor as numerical quantities. The other variables in the equations can be determined with reasonable accuracy.

The curves of minimum detectable power density versus frequency plotted in Figure 10 verifies that the power density determined from the receiving system variables follows the same pattern as that found by using the transmitting variables. An error in directivity could exaggerate the difference between the two curves.

Special pieces of equipment are necessary to determine the actual antenna efficiency. It is felt that more research on methods of determining actual antenna efficiency and directivity could improve the results of the proposed method for determining overall system sensitivity.

BIBLIOGRAPHY

1. North, D. O. "The Absolute Sensitivity of Radio Receivers", RCA Review.

2. Smith, J. G. "Receiver System Sensitivity Study Interim Report", Unpublished Report, (December 1959), pp. 1-13.

3. Kraus, John D. "Antennas", McGraw-Hill Book Company Inc., New York, (1950), pp. 11-56.

4. Macalpine, W. W. "Computation of Impedance and Efficiency of Transmission Line with High Standing Wave Ratio", AIEE Transactions, Vol. 72, Part I. Communications and Electronics, (1953), pp. 336-339.

5. Montgomery, G. G. "Technique of Microwave Measurements", Vol. 11., Massachusetts Institute of Technology Radiation Series", 28 Vol., Edited by Louis Ridenour, New York and London, McGraw-Hill Book Company, (1947), pp. 228-229.

APPENDIX

TABLES OF VARIABLES FOR DETERMINING THE MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA OF A UHF RECEIVER.

SAMPLE CALCULATIONS OF MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA OF A UHF RECEIVER.

TABLE I

IMPEDANCE OF RECEIVING ANTENNA

NUMBER ONE WITH ORIGINAL GROUND PLANE

f Frequency in Megacycles	S_a VSWR of Antenna	R_a Resistance of Antenna (Ohms)	X_a Reactance of Antenna (Ohms)
475	9.0	8.0	34.0
480	7.2	11.2	38.0
490	6.5	14.0	44.8
500	5.8	19.0	53.0
510	5.3	25.0	59.0
520	5.0	30.0	67.0
530	4.7	40.5	75.0
540	4.8	59.0	93.0
550	5.1	75.0	108.0
560	5.6	97.0	126.0
570	6.2	109.0	139.0
580	6.5	315.0	56.0
590	7.6	350.0	-80.0
600	8.2	145.0	-195.0
610	9.0	51.0	-138.0
620	9.8	33.0	-112.0
630	9.5	22.0	-88.0

TABLE II

IMPEDANCE OF RECEIVER LOOKING INTO A

50-OHM, COAXIAL CABLE

f Frequency in Megacycles	S_1 VSWR Looking into the Transmission Line	R_t Resistance of Load (Ohms)	X_t Reactance of Load (Ohms)	W_i Available Power into Coaxial Cable(-dbm)
475	7.7	12.5	-57.0	89.0
480	7.6	9.0	-31.0	88.5
490	7.3	6.7	4.2	90.2
500	7.3	14.0	50.5	92.0
510	7.3	305.0	140.0	89.5
520	7.3	22.0	-73.0	90.5
530	6.8	8.2	-16.0	90.5
540	6.5	9.0	14.5	92.0
550	6.6	28.0	77.0	90.9
560	6.8	120.0	-160.0	91.0
570	6.8	12.0	-46.0	90.8
580	6.5	8.0	-5.1	90.9
590	6.2	14.0	42.7	90.9
600	6.2	82.0	130.0	90.8
610	6.3	44.0	-100.0	90.2
620	6.2	10.0	-26.8	90.6
630	5.8	9.0	9.0	89.0

TABLE III

TRANSMITTING PARAMETERS WITH ANTENNA NUMBER TWO AS THE TRANSMITTING ANTENNA ABOVE GROUND PLANE

f Frequency in Megacycles	S_t VSWR of Transmitting Antenna	W_{in} Available Power (-dbm)	λ Wave-length (cm)
475	6.9	52.0	63.1
480	6.9	49.4	62.5
490	6.9	50.1	61.2
500	6.1	52.1	60.0
510	5.4	57.7	58.8
520	5.2	55.1	57.7
530	5.0	49.8	56.6
540	5.8	49.4	55.6
550	6.5	52.2	54.6
560	7.3	57.6	53.6
570	8.3	50.8	52.7
580	8.7	47.7	51.8
590	10.1	46.6	50.9
600	10.8	53.0	50.0
610	12.0	44.8	49.2
620	13.3	40.9	48.4
630	13.2	44.9	47.6

TABLE IV

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA FROM TRANSMITTER PARAMETERS

f Frequency in Megacycles	$\frac{S_t}{(S_t + 1)^2}$	$W_{in} x 10^{-7}$ Available Power (Watts)	$\frac{D_t x 10^{-12}}{\pi r^2}$	$P' x 10^{-12}$ Minimum Detectable Power Density (Watts/m^2)
475	0.111	0.063	7.39	51.6
480	0.111	0.114	7.42	94.0
490	0.111	0.010	7.46	8.3
500	0.121	0.062	7.51	56.3
510	0.132	0.017	7.56	17.0
520	0.136	0.031	7.61	32.0
530	0.139	0.104	7.65	110.5
540	0.126	0.114	7.71	110.0
550	0.116	0.060	7.76	54.0
560	0.106	0.017	7.80	14.1
570	0.096	0.084	7.84	63.2
580	0.092	0.169	7.88	123.0
590	0.082	0.216	7.93	140.0
600	0.078	0.050	7.97	30.9
610	0.071	0.104	8.01	59.1
620	0.065	0.330	8.05	173.0
630	0.066	0.979	8.10	519.0

TABLE V

TRANSMISSION LINE EFFICIENCY

f Frequency in Megacycles	S_i VSWR Looking into Transmission Line	S_r VSWR of Receiver	η Transmission Line Efficiency
475	7.7	10.9	0.762
480	7.6	10.8	0.756
490	7.3	10.8	0.659
500	7.3	10.7	0.721
510	7.3	10.5	0.721
520	7.3	10.3	0.737
530	6.8	10.2	0.674
540	6.5	10.2	0.640
550	6.6	10.1	0.650
560	6.8	10.1	0.680
570	6.8	10.0	0.672
580	6.5	9.8	0.653
590	6.2	9.4	0.650
600	6.2	9.1	0.671
610	6.3	8.9	0.687
620	6.2	8.8	0.698
630	5.8	8.1	0.710

TABLE VI

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA FROM RECEIVING SYSTEM PARAMETERS

f Frequency in Megacycles	$W_{in} \times 10^{-10}$ Available Power (Watts)	$P \times 10^{-12}$ Minimum Detectable Power Density (Watts/m^2)
475	0.0126	16.75
480	0.0140	9.86
490	0.0095	42.40
500	0.0063	38.10
510	0.0112	35.50
520	0.0089	6.26
530	0.0089	30.60
540	0.0063	38.00
550	0.0081	32.42
560	0.0079	63.70
570	0.0083	29.10
580	0.0081	73.20
590	0.0081	50.00
600	0.0083	9.25
610	0.0095	68.90
620	0.0087	144.50
630	0.0126	131.00

TABLE VII

IMPEDANCE OF RECEIVING ANTENNA

(ANTENNA NUMBER 1)

f Frequency in Megacycles	S_a VSWR of Antenna	R_a Resistance of Antenna (Ohms)	X_a Reactance of Antenna (Ohms)
475	8.40	8.7	+32.7
480	7.20	10.3	+35.3
490	6.00	14.5	+42.0
500	5.40	17.6	+47.0
510	4.95	22.6	+53.4
520	4.80	26.5	+59.2
530	4.90	34.0	+71.0
540	5.20	35.0	+77.0
550	5.60	47.0	+94.5
560	6.25	75.0	+125.0
570	7.00	111.0	+155.0
580	7.60	212.0	+180.0
590	8.40	400.0	+80.0
600	8.90	211.0	-218.0
610	10.20	108.0	-205.0
620	11.00	46.0	-148.0
630	11.60	28.0	-116.0

TABLE VIII

IMPEDANCE OF RECEIVER LOOKING INTO A

50-OHM, COAXIAL CABLE

f Frequency in Megacycles	S_r VSWR of Receiver	S_l VSWR Looking into Coaxial Cable	R_t Resistance of Load (Ohms)	X_t Reactance of Load (Ohms)
475	12.4	8.4	17.5	-68.0
480	12.0	8.3	102.0	-174.0
490	11.8	8.1	111.0	+178.0
500	11.6	7.8	12.0	+45.0
510	11.4	7.6	6.7	+6.7
520	11.7	7.7	7.9	-22.8
530	11.9	8.0	21.7	-74.3
540	12.2	8.2	340.0	-62.0
550	12.1	7.9	23.0	+77.0
560	11.8	7.7	7.7	+21.2
570	11.4	7.4	7.0	-10.0
580	11.1	7.5	14.0	-51.5
590	10.8	7.5	127.0	-171.0
600	10.5	7.3	59.5	+129.0
610	10.2	6.9	10.8	+33.8
620	10.1	6.7	7.6	+1.0
630	10.0	6.8	10.4	-31.8

TABLE IX

TRANSMITTING PARAMETERS WITH ANTENNA NUMBER TWO AS THE TRANSMITTING ANTENNA ABOVE GROUND PLANE

f Frequency in Megacycles	S_t VSWR of Transmitting Antenna	W_{in} Available Power (-dbm)
475	5.00	42.00
480	5.30	41.10
490	5.40	46.40
500	5.00	51.55
510	4.70	46.45
520	4.55	43.75
530	4.40	46.25
540	4.80	52.10
550	5.10	55.15
560	5.80	50.50
570	7.10	47.00
580	9.60	47.45
590	10.70	49.65
600	11.80	43.35
610	13.20	38.05
620	14.60	35.75
630	15.20	41.40

TABLE X

MINIMUM DETECTABLE POWER DENSITY

AT THE RECEIVING ANTENNA FROM TRANSMITTER

PARAMETERS USING ANTENNA NUMBER TWO

f Frequency in Megacycles	$\frac{S_t}{(S_t + 1)^2}$	$W_{in} \times 10^{-6}$ Available Power (Watts)	$\frac{D_t \times 10^{-2}}{\pi r^2}$	$P' \times 10^{-12}$ Minimum Detectable Power Density (Watts/m^2)
475	0.1390	0.0630	0.0739	647.00
480	0.1340	0.0776	0.0742	772.00
490	0.1320	0.0229	0.0746	225.50
500	0.1390	0.0070	0.0751	73.00
510	0.1445	0.0226	0.0756	326.70
520	0.1480	0.0420	0.0761	473.00
530	0.1510	0.0237	0.0765	274.00
540	0.1430	0.0062	0.0771	68.40
550	0.1370	0.0032	0.0776	34.00
560	0.1250	0.0089	0.0780	86.80
570	0.1184	0.0200	0.0784	186.00
580	0.0854	0.0180	0.0788	121.40
590	0.0782	0.0108	0.0793	67.00
600	0.0720	0.0462	0.0797	265.00
610	0.0654	0.1566	0.0801	820.00
620	0.0600	0.2660	0.0805	1285.00
630	0.0563	0.0725	0.0810	33.02

TABLE XI

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA FROM RECEIVING SYSTEM PARAMETERS

f Frequency in Megacycles	W_i Available Power (-dbm)	$W_i \times 10^{-10}$ Available Power into Transmission Line (Watts)	$P \times 10^{-12}$ Minimum Detectable Power Density (Watts/m^2)
475	87.00	0.0200	46.60
480	88.50	0.0141	81.75
490	91.05	0.0025	20.05
500	90.70	0.0085	80.90
510	90.50	0.0089	60.84
520	91.05	0.0078	21.96
530	90.75	0.0084	8.31
540	90.10	0.0098	26.44
550	88.00	0.0158	126.13
560	88.90	0.0128	165.60
570	88.00	0.0158	204.47
580	89.00	0.0126	81.90
590	87.55	0.0176	28.88
600	90.10	0.0098	20.63
610	90.75	0.0084	101.26
620	91.90	0.0065	164.92
630	90.55	0.0088	254.25

TABLE XII

IMPEDANCE OF RECEIVING ANTENNA

NUMBER FOUR WITH MODIFIED GROUND PLANE

f Frequency in Megacycles	S_a VSWR of Antenna	R_a Resistance of Antenna (Ohms)	X_a Reactance of Antenna (Ohms)
475	1.30	50.0	+13.0
480	1.36	58.0	+14.0
490	1.53	76.0	+3.5
500	1.73	82.0	-16.0
510	1.95	63.0	-36.0
520	2.15	43.0	-35.5
530	2.32	29.0	-26.0
540	2.50	22.4	-16.2
550	2.70	18.3	-5.0
560	2.80	18.0	+6.0
570	3.00	19.0	+17.6
580	3.25	24.2	+36.0
590	3.52	34.0	+53.0
600	3.88	59.0	+79.0
610	4.30	147.0	+95.0
620	4.62	230.0	-15.0
630	4.90	79.0	-106.0

TABLE XIII

IMPEDANCE OF RECEIVER LOOKING INTO A

50-OHM, COAXIAL CABLE

f Frequency in Megacycles	S_r VSWR of Receiver	S_1 VSWR of Receiver Looking into a Transmission Line	R_t Resistance Looking into a Transmission Line (Ohms)	X_t Reactance Looking into a Transmission Line (Ohms)
475	12.4	8.4	17.5	-68.0
480	12.0	8.3	102.0	-174.0
490	11.8	8.1	111.0	+178.0
500	11.6	7.8	12.0	+45.0
510	11.4	7.6	6.7	+6.7
520	11.7	7.7	7.9	-22.8
530	11.9	8.0	21.7	-74.3
540	12.2	8.2	340.0	-62.0
550	12.1	7.9	23.0	+77.0
560	11.8	7.7	7.7	+21.2
570	11.4	7.4	7.0	-10.0
580	11.1	7.5	14.0	-51.5
590	11.8	7.5	127.0	-171.0
600	10.5	7.3	59.5	+129.0
610	10.2	6.9	10.8	+33.8
620	10.1	6.7	7.6	+1.0
630	10.0	6.8	10.4	-31.8

TABLE XIV

TRANSMITTING PARAMETERS USING ANTENNA NUMBER THREE AS THE TRANSMITTING ANTENNA ABOVE THE MODIFIED GROUND PLANE

f Frequency in Megacycles	S_t VSWR of Transmitting Antenna	D_t Directivity of Transmitting Antenna	W_{in} Available Power (-dbm)
475	1.39	1.54	54.65
480	1.45	1.57	54.90
490	1.56	1.64	57.15
500	1.72	1.68	55.50
510	1.91	1.73	56.00
520	2.10	1.77	57.55
530	2.50	1.81	55.85
540	2.75	1.84	51.60
550	2.81	1.88	53.75
560	3.08	1.91	59.80
570	3.37	1.94	57.75
580	3.62	1.96	50.10
590	3.77	1.98	47.95
600	4.04	2.00	55.85
610	4.37	2.15	48.55
620	4.55	2.20	47.30
630	4.70	2.30	51.20

TABLE XV

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA IN TERMS OF TRANSMITTING PARAMETERS WITH ANTENNA NUMBER THREE AS THE TRANSMITTING ANTENNA

f Frequency in Megacycles	$\frac{S_t}{(S_t + 1)^2}$	$W_{in} \times 10^{-7}$ Available Power (Watts)	$\frac{D_t \times 10^{-2}}{\pi r^2}$	$P' \times 10^{-12}$ Minimum Detectable Power Density (Watts/m^2)
475	0.2433	0.0340	8.37	69.22
480	0.2416	0.0322	8.54	66.42
490	0.2381	0.0192	8.89	40.63
500	0.2324	0.0280	9.13	59.41
510	0.2255	0.0250	9.41	53.04
520	0.2185	0.0175	9.63	36.82
530	0.2040	0.0259	9.84	51.99
540	0.1955	0.0690	10.00	135.00
550	0.1935	0.0420	10.22	83.03
560	0.1850	0.0105	10.39	20.18
570	0.1765	0.0167	10.55	31.09
580	0.1696	0.0975	10.67	176.48
590	0.1656	0.1560	10.78	278.49
600	0.1590	0.0260	10.88	44.97
610	0.1516	0.0140	11.69	24.80
620	0.1477	0.1850	11.96	328.00
630	0.1446	0.0760	12.51	137.47

TABLE XVI

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA IN TERMS OF RECEIVER PARAMETERS

f Frequency in Megacycles	W_i Available Power (-dbm)	$W_i \times 10^{-10}$ Available Power (Watts)	$P \times 10^{-12}$ Minimum Detectable Power Den. (Watts/m^2)
475	87.00	0.0200	35.10
480	88.50	0.0141	25.82
490	91.05	0.0025	4.31
500	90.70	0.0085	19.00
510	90.50	0.0189	28.60
520	91.05	0.0078	32.63
530	90.75	0.0084	39.19
540	90.10	0.0098	42.20
550	88.00	0.0158	63.41
560	88.90	0.0128	33.11
570	88.00	0.0158	23.87
580	89.00	0.0126	17.45
590	87.55	0.0176	44.90
600	90.10	0.0098	13.77
610	90.75	0.0084	62.90
620	91.90	0.0065	65.55
630	90.55	0.0088	86.86

TABLE XVII

IMPEDANCE OF RECEIVER LOOKING INTO

A 50-OHM, COAXIAL CABLE

f Frequency in Megacycles	S_l VSWR Looking into a Transmission Line	S_r VSWR of Receiver	R_t Resistance of Load (Ohms)	X_t Reactance of Load (Ohms)
475	7.8	12.4	20.0	+72.0
480	7.8	12.0	60.0	+132.0
490	7.8	11.8	82.0	-152.0
500	7.4	11.6	11.5	-42.2
510	6.3	11.4	8.0	-6.0
520	7.3	11.7	8.6	+25.0
530	7.5	11.9	24.5	+78.0
540	7.4	12.2	350.0	-65.0
550	7.0	12.1	21.8	-68.0
560	6.8	11.8	8.5	-20.0
570	6.8	11.4	7.6	+10.2
580	7.2	11.1	14.0	+50.1
590	7.2	11.8	118.0	+164.0
600	6.9	10.5	47.0	-110.0
610	6.6	10.2	11.0	-33.2
620	6.3	10.1	8.0	0
630	6.4	10.0	11.6	+33.2

TABLE XVIII

TRANSMITTING PARAMETERS WITH ANTENNA

NUMBER THREE AS THE TRANSMITTING ANTENNA

ABOVE MODIFIED GROUND PLANE WITH ABSORBENT MATERIAL

f Frequency in Megacycles	S_t VSWR of Transmitting Antenna	D_t Directivity of Transmitting Antenna	W_{in} Available Power (-dbm)
475	1.34	1.54	46.90
480	1.36	1.57	49.65
490	1.44	1.64	51.15
500	1.60	1.68	49.25
510	1.76	1.73	51.30
520	1.95	1.77	54.10
530	2.15	1.81	53.65
540	2.35	1.84	50.60
550	2.60	1.88	50.45
560	2.80	1.91	55.50
570	3.00	1.94	52.40
580	3.25	1.96	49.50
590	3.50	1.98	50.75
600	3.75	2.00	55.00
610	4.00	2.15	49.00
620	4.10	2.20	45.00
630	4.30	2.30	48.60

TABLE XVIX

IMPEDANCE OF RECEIVING ANTENNA

NUMBER FOUR, WITH ABSORBENT MATERIAL

AND MODIFIED GROUND PLANE

f Frequency in Megacycles	S_a VSWR of Antenna	R_a Resistance of Antenna (Ohms)	X_a Reactance of Antenna (Ohms)
475	1.28	50.0	+13.0
480	1.34	58.0	+14.0
490	1.52	76.0	+3.5
500	1.75	82.0	-16.0
510	1.98	63.0	-36.0
520	2.15	43.0	-35.5
530	2.35	29.0	-26.0
540	2.50	22.9	-16.2
550	2.65	18.3	-5.0
560	2.80	18.0	+6.0
570	2.95	19.0	+17.6
580	3.10	24.2	+36.0
590	3.46	34.0	+53.0
600	3.72	59.0	+79.0
610	4.15	147.0	+95.0
620	4.35	230.0	-15.0
630	4.70	79.0	-100.0

TABLE XX

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA IN TERMS OF TRANSMITTING PARAMETERS WITH ANTENNA NUMBER THREE AS THE TRANSMITTING ANTENNA ABOVE THE GROUND PLANE AND ABSORBENT MATERIAL. ASSUMED ANTENNA EFFICIENCY OF 95%

f Frequency in Megacycles	$\frac{S_t}{(S_t + 1)^2}$	W_{in}x10^{-7} Available Power (Watts)	$\frac{D_t \text{x} 10^{-2}}{\pi r^2}$	P'x10^{-12} Minimum Detectable Power Density (Watts/m^2)
475	0.2430	0.2040	8.37	396.0
480	0.2416	0.1082	8.54	214.0
490	0.2381	0.0710	8.89	154.2
500	0.2324	0.1190	9.13	240.0
510	0.2255	0.0740	9.41	149.0
520	0.2185	0.0390	9.63	78.0
530	0.2040	0.0430	9.84	82.0
540	0.1955	0.0870	10.00	161.5
550	0.1935	0.0900	10.22	169.0
560	0.1850	0.0262	10.39	51.0
570	0.1765	0.0575	10.55	102.0
580	0.1696	0.1120	10.67	192.0
590	0.1656	0.0840	10.78	142.0
600	0.1590	0.0302	10.88	51.9
610	0.1516	0.1260	11.69	212.0
620	0.1477	0.3160	11.96	530.0
630	0.1466	0.1380	12.51	254.0

TABLE XXI

MINIMUM DETECTABLE POWER DENSITY AT THE RECEIVING ANTENNA IN TERMS OF RECEIVER PARAMETERS WITH ANTENNA NUMBER FOUR AS THE RECEIVING ANTENNA. ASSUMED ANTENNA EFFICIENCY OF 95%.

f Frequency in Megacycles	W_i Available Power (-dbm)	$W_i \times 10^{-10}$ Available Power (Watts)	$P \times 10^{-12}$ Minimum Detectable Power Den. (Watts/m^2)
475	82.5	0.0560	178.0
480	83.2	0.0447	117.5
490	84.2	0.0380	73.0
500	85.2	0.0280	97.0
510	86.5	0.0224	102.0
520	87.1	0.0190	41.9
530	87.8	0.0166	41.7
540	88.0	0.0158	85.4
550	88.0	0.0158	88.1
560	88.0	0.0158	31.2
570	88.0	0.0158	55.0
580	88.0	0.0158	136.5
590	87.8	0.0165	107.0
600	87.1	0.0195	29.5
610	86.8	0.0204	134.0
620	86.0	0.0250	278.0
630	85.5	0.0280	133.0

TABLE XXII

EFFECT OF CHANGING TEMPERATURE ON INPUT RESISTANCE

TO RECEIVER

f Frequency in Megacycles	VSWR at Ambient Temperature	Null at Ambient Temperature	VSWR at 114° F.	Null at 114° F.	VSWR at 30° F.	Null at 30° F.
490	12.20	274.5	12.0	274.0	11.9	276.0
560	11.10	216.2	11.1	217.4	11.2	220.0
590	10.95	197.0	11.2	194.2	11.1	196.8
600	10.80	189.4	11.0	189.7	10.9	189.4
620	10.40	177.8	10.4	177.7	10.4	177.8

SAMPLE CALCULATIONS

1. Calculations of Receiving Antenna Impedance:

Frequency 580 mc

Location of null, with the antenna as the termination, was 62.0 millimeters.

Location of the short circuit null was 119.3 millimeters.

VSWR was 3.25.

The wavelength at 580 mc is $\frac{3 \times 10^8}{5.80 \times 10^8}$ = 0.518 meters.

With the antenna as the termination, the null is located -0.1106λ from the short circuit null. This was determined as follows:

$$d = \frac{\text{Loaded Null - Short Circuit Null}}{\text{Operating Wavelength}}$$

$$= \frac{0.62 - 1.193}{.518} = -0.1106\lambda$$

Enter the Smith chart, Figure 11, at point A. Follow a constant VSWR circle of 3.25 a distance of -0.1106λ toward the generator. The impedance at 580 mc as indicated at point B is 24.2 + j36.0 Ohms. The impedance was calculated for each frequency and tabulated in Table XII, page 60 of the appendix.

2. Calculation of Load Impedance:

Frequency -580 mc.

The location of loaded null with the transmission line connected to the receiver, as the termination, was

336.0 millimeters.

The location of the short circuit null was 268.3 millimeters.

The impedance was found by following the constant VSWR circle a distance (d) of 0.1285λ as shown in Figure 12 where,

$$d = \frac{3.360 - 2.683}{0.518} = 0.1285\lambda$$

Enter the Smith chart at point A. The impedance at point B is 14.0 + j50.1 ohms.

The impedance was determined for each frequency and tabulated in Table XIII, page 61 of the appendix.

3. <u>Antenna Directivity</u>:

The theoretical value of directivity was determined by the use of the expression $E^2 = \frac{[1.18(1 - \cos L)]^2}{R_r}$.

The value of this expression was plotted on polar co-ordinate paper. The area under the curve was determined with a planimeter. A circle representing an isotropic source and having the same area as that determined by the planimeter was constructed. The directivity was determined by taking the ratio of the maximum of the above expression to the maximum value of the isotropic source. The value of directivity used was taken from the smooth curve of directivity versus frequency.

4. <u>Available Power</u>:

The available power was read from a calibrated dial on the signal generator in -dbm. The power in watts was calculated as follows:

$$-dbm = 10 \log \frac{W_{in}}{0.001}$$

from which

$$W_{in} = 10^{-(3 + 0.1dbm)}$$

$$= 10^{-(3 + 4.95)} = 10^{-7} \times 10^{-0.95}$$

$$= 0.1120 \times 10^{-7} \text{ Watts}$$

5. Power Density:

The VSWR of the transmitting antenna was 3.62 at 580 mc.

The minimum detectable power density at the receiving antenna was determined from equation 34, page 25.

$$P' = \eta_a W_{in} \frac{S_t}{(S_t + 1)^2} \cdot \frac{D_t}{\pi r^2}$$

$$= (0.95)(0.1120 \times 10^{-7})(0.1696)(10.67) = 192.00$$

watts per square meter.

The efficiency of the antenna was assumed to be 95%. This data is tabulated in Table XX, page 68 of the appendix.

The minimum detectable power density, in terms of receiver parameters, was determined from equation 36, page 32, and the experimental data. Equation 36 is repeated here for convenience.

$$P = \frac{4 W_i \pi S_r}{D_r (S_r + 1)^2 \lambda^2 \eta \eta_a} \left[\frac{(R_a + R_t)^2 + (X_a + X_t)^2}{R_a R_t} \right]$$

The transmission line efficiency is found by using the values given in Table XVII, page 65 of the appendix.

$$\eta = \frac{S_1^2 - 1}{S_r^2 - 1} \cdot \frac{S_r}{S_1} \quad \frac{7.2^2 - 1}{11.1^2 - 1} \cdot \frac{11.1}{7.2} = 0.643$$

and

$$\eta_a = 0.95$$

W_i from Table XXI, page 69 of the appendix, was 0.0158 watts.

$$\lambda = 0.518 \text{ meters.}$$

The efficiency of a two foot coaxial cable connected to the receiving antenna was assumed to be 90%.

$$P = \left[(0.0158) \frac{11.1}{(11.1 + 1)^2} \cdot \frac{1}{0.518^2} \cdot \frac{1}{0.90} \cdot \frac{1}{0.95} \cdot \frac{6.4016}{} \right] \left[\frac{(24.2 + 14)^2 + (36 + 50.1)^2}{(24.2)(14.0)} \right]$$

$$= 136.5 \text{ Watts/m}^2$$

TITLE DATE

IMPEDANCE COORDINATES—50-OHM CHARACTERISTIC IMPEDANCE
IMPEDANCE OF RECEIVING ANTENNA

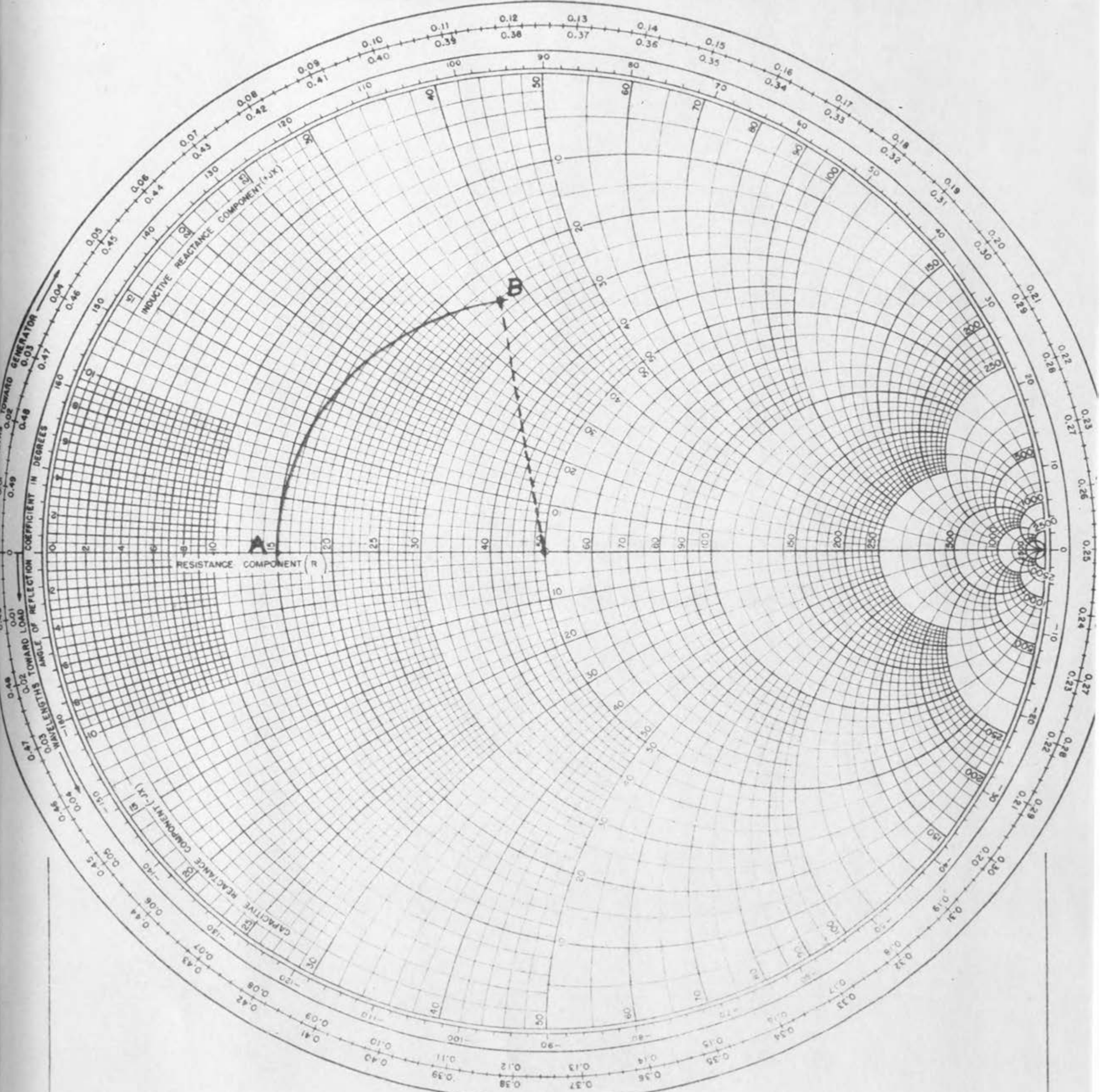
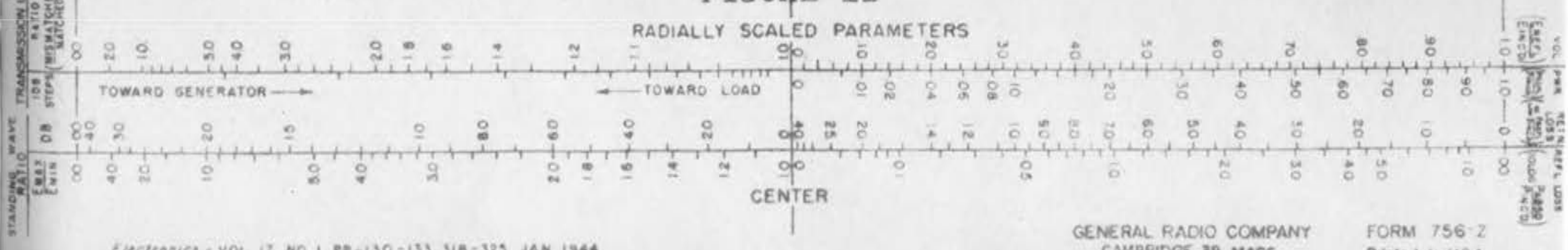


FIGURE 11



GENERAL RADIO COMPANY
CAMBRIDGE 39, MASS

FORM 756-Z
Printed in USA

TITLE DATE

IMPEDANCE COORDINATES—50-OHM CHARACTERISTIC IMPEDANCE

IMPEDANCE OF LOAD LOOKING INTO A COAXIAL CABLE

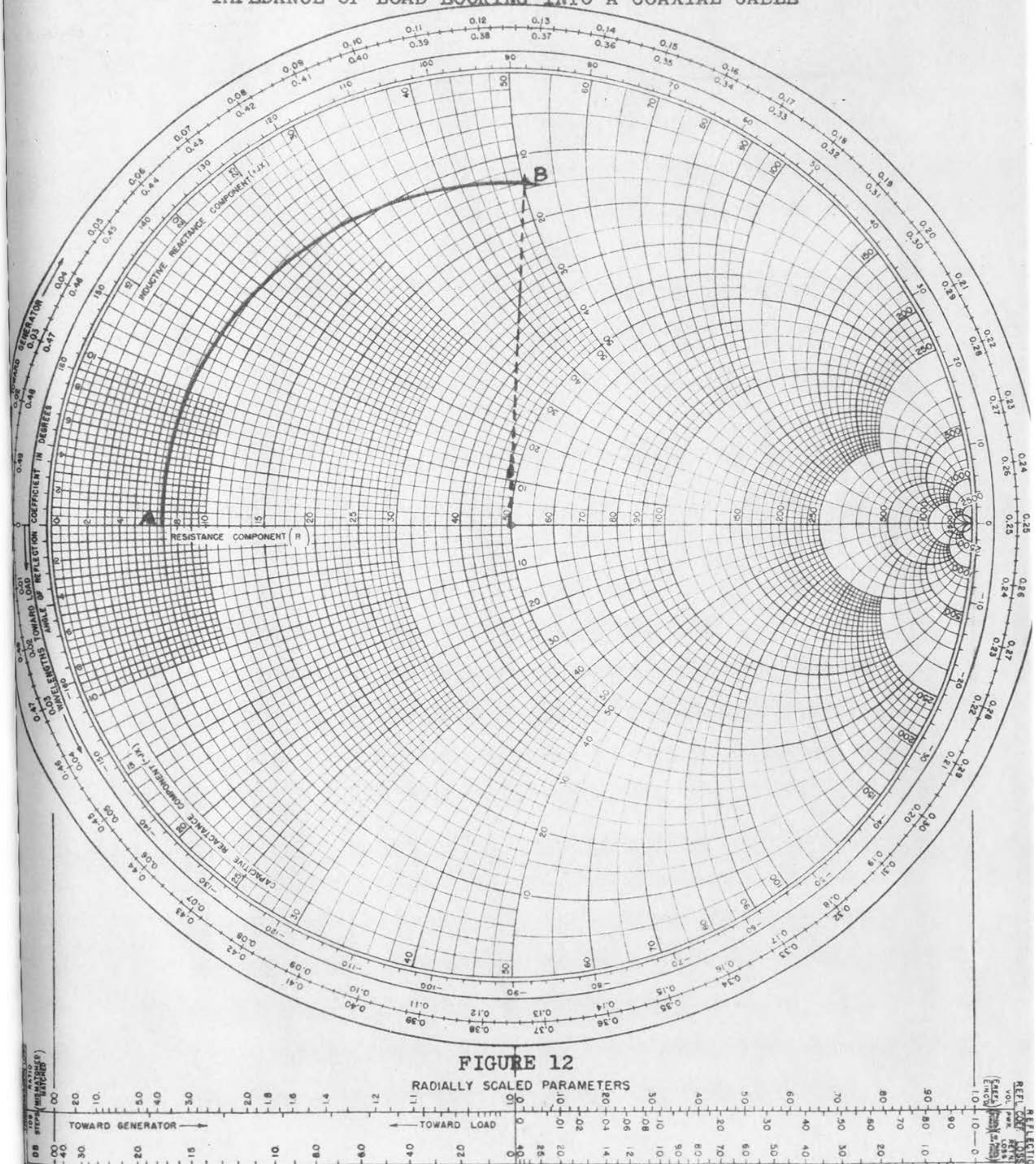


FIGURE 12

RADIALLY SCALED PARAMETERS

GENERAL RADIO COMPANY
CAMBRIDGE 39, MASS

FORM 756-Z
Printed in USA

VITA

James H. Johnson, the son of Mr. and Mrs. Joseph F. Johnson, was born at Hornersville, Missouri, on March 21, 1929. He received his elementary and high school education in the public schools of Braggadocio, Missouri between the years of 1936 and 1946.

After the tragic death of his father, and marriage of the older brothers, his formal educational training was interrupted. He enrolled in a high school correspondence course with the American School.

In May, 1948, he entered the United States Navy, serving as an aircraft electrician. Twelve months were spent in the Hawaiian Islands, three months in Alaska and the final twelve weeks of the enlistment in an aircraft electrician's school in Memphis, Tennessee.

Immediately following his discharge from the service he became engaged in a small electrical contracting business. He was later employed by the Arkansas-Missouri Power Company of Blytheville, Arkansas, as a groundsman and was promoted to a linesman on a line crew, and later to senior stores clerk. He served in this capacity until September 1953. He entered the Missouri School of Mines and Metallurgy in September 1953 and received a Bachelor of Science Degree in Electrical Engineering in June 1957.

During the summer of 1957 the author was employed by the Radio Corporation of America. In September of that year he entered the Missouri School of Mines and Metallurgy for graduate study, and carried an appointment as full time instructor simultaneously. During the summers of 1958 and 1959 he was employed in the liaison engineering group of the Boeing Airplane Company of Wichita, Kansas.

He is a member of the American Institute of Electrical Engineers, the Institute of Radio Engineers, Eta Kappa Nu, and the American Society for Engineering Education. He has served as the counselor for the student branch of AIEE for the last two years.