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Determination of the Residual VSWR [Voltage Standing Wave Ratio] of a Slotted Line.

Michael C. Robel

THE RESIDUAL VSWR — ROBEL

DETERMINATION OF THE RESIDUAL VSWR
OF A SLOTTED LINE

By

Michael C. Robel

A Thesis
In partial fulfillment of the
Requirements for the Degree of
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MASTER OF SCIENCE

E. F. Castetter
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1/23/1956
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CHAPTER I

THE PROBLEM AND REVIEW OF THE LITERATURE

I. THE PROBLEM

Impedance can be determined at microwave frequencies by the use of a slotted line. In determining the impedance, a quantity termed Voltage Standing Wave Ratio, VSWR, is measured. The VSWR of a load is in itself a very useful quantity, since it indicates the degree of mismatch between a load and the transmission line.

Statement of the Problem. Idealistically, a slotted line should be designed so that, when it is terminated in its characteristic impedance, the VSWR as determined by a movable probe in the slotted line will be 1.0. However, in practice this is not possible, particularly in the case of coaxial slotted lines where matching elements, adapters and connectors are utilized. The devices mentioned above have physical discontinuities which give rise to reflections, which cause a standing wave to be produced even though the line is terminated in its characteristic impedance.

The effect of the physical discontinuities can be minimized, at least over a band of frequencies, by standard techniques, such as: stepping or tapering inner and outer conductors, use of matching beads, use of cancellation principles and minimization of discontinuities. However, the standing wave is never entirely eliminated;

in fact, it usually has a value between 1.02 and 1.20 for coaxial slotted lines and about 1.01 or 1.02 for waveguide slotted lines. In waveguide the major discontinuities, which usually are insignificant, are due to the slot and the coupling junction.

This VSWR produced by the discontinuities discussed is commonly termed "residual VSWR", ρ_R, or "cable to rigid line VSWR". The value of the residual VSWR usually increases with usage of the slotted line due to center pin wear, sprung finger contacts, damaged dielectric beads, marred center conductor, accumulation of dirt, improper soldering procedures and rough handling. Thus, it is of importance to be able to measure this residual VSWR to insure proper operation of the slotted line when measuring the impedance or VSWR of a load.

Importance of the Study. In industry, where a quality control organization maintains an inspection over products, such as coaxial cables, antennas and other microwave components, a problem often arises where the manufacturer and the customer disagree on the compliance of the product with the specifications set up by the customer in regard to maximum and/or minimum VSWR. In some instances there is disagreement between organizations within the manufacturer, such as engineering and the quality control groups. This disagreement can usually be traced to the fact that each group used a different commercial slotted line and/or the slotted lines were not in

in fact, it usually has a value between 1.02 and 1.05 for coaxial slotted lines and about 1.01 or 1.02 for waveguide slotted lines. In waveguide the major discontinuities, which usually are insignificant, are due to the slot and the coupling junction.

This VSWR produced by the discontinuities discussed is commonly termed "residual VSWR", ρ_o, or "slotted line VSWR". The value of the residual VSWR usually increases with usage of the slotted line due to center pin wear, worn fingers contacts, damaged dielectric beads, marred center conductor, accumulation of dirt, improper soldering procedures and rough handling. Thus, it is of importance to be able to measure this residual VSWR to insure proper operation of the slotted line when measuring the impedance or VSWR of a load.

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proper condition. In other words, the residual VSWR was different in each case and thus the VSWR of the load appeared different. This problem can be minimized to some extent by specifying limits which take these differences into account, but in the case where a tight specification is needed the only solution is to have available a method of measuring the residual VSWR.

General Solutions of the Problem. This difference in residual VSWR between slotted lines, or due to wear on one slotted line, can be measured on either a relative or an absolute basis. A stable load could be used to evaluate a slotted line over a period of time to detect a change, or it could be used to detect a difference between various slotted lines. This would be a relative measurement and with the accumulation of data would suffice to evaluate the worth of a slotted line. However, in practice a stable load is difficult to obtain due to the effects of temperature and humidity. Thus an absolute method would be more useful. The desirable features of an absolute method would be as follows:

1. Independent of temperature and humidity.
2. Independent of slotted line termination.
3. Repeatable over a period of time.
4. As simple and non-time-consuming as possible.
5. As accurate as possible.

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2. Independent of slotted line [illegible].
3. Repeatable over a period of time.
4. As simple and non-[illegible] as possible.
5. As accurate as possible.

Main Objective of Thesis. The main objective of this project was to develop an absolute method of measuring the residual VSWR of a slotted line with the above requirements. Since the problem exists mainly with coaxial slotted lines, the discussion will be limited to them; however, it applies equally well to waveguide. The frequency of operation is limited to the range of 1000 mcps to 10,000 mcps.

II. REVIEW OF THE LITERATURE

In the course of the project several available methods were experimentally evaluated and theoretically analyzed in regard to accuracy. Of these the more important methods evaluated were as follows:

1. Null Shift
2. Frequency Variation
3. Variable Short Circuit
4. Perfect Load
5. Movable Coaxial Load

Null Shift.[1] This method utilizes various lengths of open circuited transmission line. The displacement of a voltage node in the slotted line is plotted against movement of the open circuited line. If the residual VSWR is equal to zero the relationship is linear

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[1] Hunton, J. K. and Wholey, W. B., "The Perfect Load and the Null Shift", Hewlett-Packard Journal, Vol. 3, No. 5-6, Jan.-Feb. 1952

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depending upon the velocity of propagation in the line extensions. With a residual VSWR present the relationship is sinusodial, the maximum variation depending upon the magnitude of the residual VSWR. From the data the residual VSWR is calculated.

The method has the disadvantage of poor repeatability due to the fact that each line extension has a slightly different residual VSWR. This could be alleviated by careful machining of each extension, but this is time consuming and expensive.

Frequency Variation.[2] The basic principle of this method is that if two reflections are present on a transmission line a maximum and minimum VSWR can be obtained with correct phasing of the two reflections, the two reflections here being the reflections from the residual discontinuities considered as one resultant reflection, and the reflection from the coaxial load. The method utilizes a 50 wavelength cable between the slotted line and a coaxial load. With a 5% variation in frequency, the 50 wavelength line produces sufficient phase shift to obtain a maximum and minimum VSWR. From the data the residual VSWR is calculated.

The major disadvantage of the method is the poor repeatability between different 50 wavelength transmission lines. This is due to the

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[2]Griemsmann, John W., Handbook of Design Data on Cable Connectors for Microwave Use, Polytechnic Institute of Brooklyn, Report No. R-158-47, PIB 107, July 1947, pp. 61-62.

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[2] [illegible], John W., Methods of [illegible] for Microwave Use, Polytechnic Institute of Brooklyn, [illegible] PIB 107, July 1947, pp. 61-62.

difficulty of assembling cable connectors to the line. It is especially noticeable at frequencies beyond 3500 mcps. The method is also very time consuming.

Variable Short Circuit.[3] The principles involved here are very similiar to the Frequency Variation Method. The major difference is the substitution of a movable short circuit at the termination of the 50 wavelength transmission line. Then the movable short circuit is positioned over a half a wavelength and again a maximum and minimum VSWR are obtained. This eliminates the necessity for the variation of the frequency. The transmission line here serves as an attenuator to reduce the large VSWR of the short circuit, so that it does not mask out the residual VSWR.

The disadvantage again is the poor repeatability due to the assembly of the coaxial connectors on the transmission line. Also the construction of a movable short circuit which maintains a constant pressure on the sliding fingers is difficult to obtain. If this requirement is not met, the magnitude of the load impedance is not constant, which invalidates the calculation of the residual VSWR. This difficulty could be alleviated by the construction of a non-contacting shorting plunger, but this would not solve the problem of poor repeatibility due to the assembly of the connector to the cable.

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[3]Griemsmann, John W., and Caltun, Louis, Variable Short Circuit Method For Measuring Cable-to-Rigid Line VSWR, Polytechnic Institute of Brooklyn, Report No. R-297-52, PIB-236, Dec. 12, 1952

Perfect Load.[4] The major component necessary for this method is a movable coaxial load with a VSWR close to unity. The movable load is connected directly to the slotted line and positioned for predetermined values of VSWR. From the data the residual VSWR is calculated. It can be shown that this method is an approximation, but a very good one. The formulas for calculating the residual VSWR are based upon the assumption that if two discontinuities are present on a transmission line the resultant reflection coefficient is the summation of the two individual complex reflection coefficients, which means that only two reflections are set up in the line. This is not correct since there are theoretically an infinite number of reflections due to multiple reflections between the two discontinuities. It has been proven previously that the overall reflection coefficient under the above conditions is much more complicated than a simple summation.[5]

However, the errors introduced by the assumption are of second order effect or higher, and thus the method is capable of good accuracy. The method meets the majority of the requirements determined previously. The calculation of the residual VSWR is somewhat laborious, although not prohibitively so. This method, although not the most accurate studied, was retained as a second method. Experimental results of

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[4]See footnote 3, loc. cit.

[5]Montgomery, C. G., Dicke, R. H., and Purcell, E. M., Principles of Microwave Circuits, M.I.T., Rad. Lab. Series, McGraw-Hill Book Co., Inc., New York, 1948, pp. 70-71.

Perfect load.[4] The major amount of measuring was performed is a movable coaxial load with a VSWR fixed at unity. The movable load is connected directly to the slotted line and positioned for predetermined values of VSWR. From the data the reflection coefficient is calculated. It can be shown that this method is not exact, but a very good one. The formulas for calculating the reflection coefficient are based upon the assumption that if two discontinuities are present on a transmission line the resultant reflection coefficient is the summation of the two individual complex reflection coefficients, which means that only two reflections are taken into account. This is not correct since there are theoretically an infinite number of reflections due to multiple reflections between the two discontinuities. It has been proven previously that the overall reflection coefficient under the above conditions is much more complicated than a simple summation.[5]

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of this method are presented in Chapter VI and an experimental procedure for its use is presented in Chapter V.

Movable Coaxial Load. The movable coaxial load method is an original adaptation of the frequency variation method and the movable short circuit method. The method to be discussed complies to a large extent to all of the requirements determined previously.

The method is similiar to the movable short circuit method, but differs from it in that a movable coaxial load is substituted for the 50 wavelength cable and movable short circuit. It was reasoned that a movable coaxial load with a VSWR of approximately 1.05 presents a VSWR in the slotted line of the same magnitude as the reflection from the movable short circuit after traversing the 50 wavelength cable with its associated attenuation. Thus here also a maximum and minimum VSWR can be obtained and the residual VSWR calculated.

The major advantage is the elimination of the necessity for a long coaxial cable with associated connectors. Also the experimental procedure is not as time consuming. Since this method was the one decided upon by the writer it will be presented in detail in the next chapter. Although the theory of the method is similiar to those of the two other methods mentioned, the underlying theory will be developed completely, since the derivations in the references cited are vague and limited. The derivation which follows utilizes the well-known Smith Transmission Line Calculator, since the writer believes it allows the solution of the problem in the most understandable manner. The derivations in references 2 and 3 do not use this approach.

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The remainder of the thesis consists of the presentation of the theory for the movable coaxial load method, design and construction of a suitable movable coaxial load, laboratory procedure for using method, experimental results, and summary and conclusions.

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CHAPTER II

DEFINITION OF RESIDUAL VSWR

AND TRANSMISSION LINE CALCULATORS

I. DEFINITION OF RESIDUAL VSWR

Figure IA represents a typical setup for measuring the impedance of a coaxial load. Included is an equivalent two-wire representation. Since the diameters of coaxial slotted lines are generally larger than standard connectors, matching elements must be incorporated internally in the slotted lines. Also, since some slotted lines are equipped with only one type of connector, adapters are needed to convert to other types of connectors. All of these elements produce reflections due to physical discontinuities and changes in characteristic impedance.

Calculation of Theoretical Residual VSWR. It can be proven that a change in the inner and/or outer radius of a coaxial line produces two effects. These two effects are a change in the characteristic impedance and the addition of a shunt capacitance. The change in characteristic impedance, Z_o, can be calculated readily by well known formulas. The value of the shunt capacitance can also be calculated.[6,7] Thus the theoretical residual VSWR of

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[6]Whinnery, J. R., and Jamieson, H. W., "Equivalent Circuits for Discontinuities in Transmission Lines", Proc. I.R.E., vol. 32, February 1944, pp. 98-115.

[7]Whinnery, J. R., Jamieson, H. W., and Robbins, Theo., "Coaxial-Line Discontinuities", Proc. I.R.E., November 1944, pp. 695-709.

CHAPTER III

DETECTION OF [illegible]

AND TRANSMISSION LINE [illegible]

1. [illegible]

Figure 1A represents a typical curve for measuring the impedance of a coaxial lead. Included is a schematic [illegible] representation. Since the diameters of coaxial slotted lines are generally larger than standard connectors, [illegible] incorporated internally in the slotted line. [illegible] slotted lines are equipped with only one type of connector, adapters are needed to convert to other types of connectors. All of these elements produce reflections due to physical discontinuities and changes in characteristic impedance.

<u>Calculation of Theoretical Residual</u> [illegible]. It can be shown[6] that a change in the inner and/or outer radius of a coaxial line produces two effects. These two effects are a change in the characteristic impedance and the addition of a shunt capacitance. The change in characteristic impedance, Z_0, can be calculated readily by well known formulas. The value of the shunt capacitance can also be calculated.[6,7] Thus the total [illegible]

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[6] Whinnery, J. R., and Jamieson, H. W., "Equivalent Circuits for Discontinuities in Transmission Lines", *Proc. I.R.E.*, [illegible] February 1944, pp. 98-11[illegible].

[7] Whinnery, J. R., Jamieson, H. W., and Robbins, T. E., "Coaxial Line Discontinuities", *Proc. I.R.E.*, November [illegible]

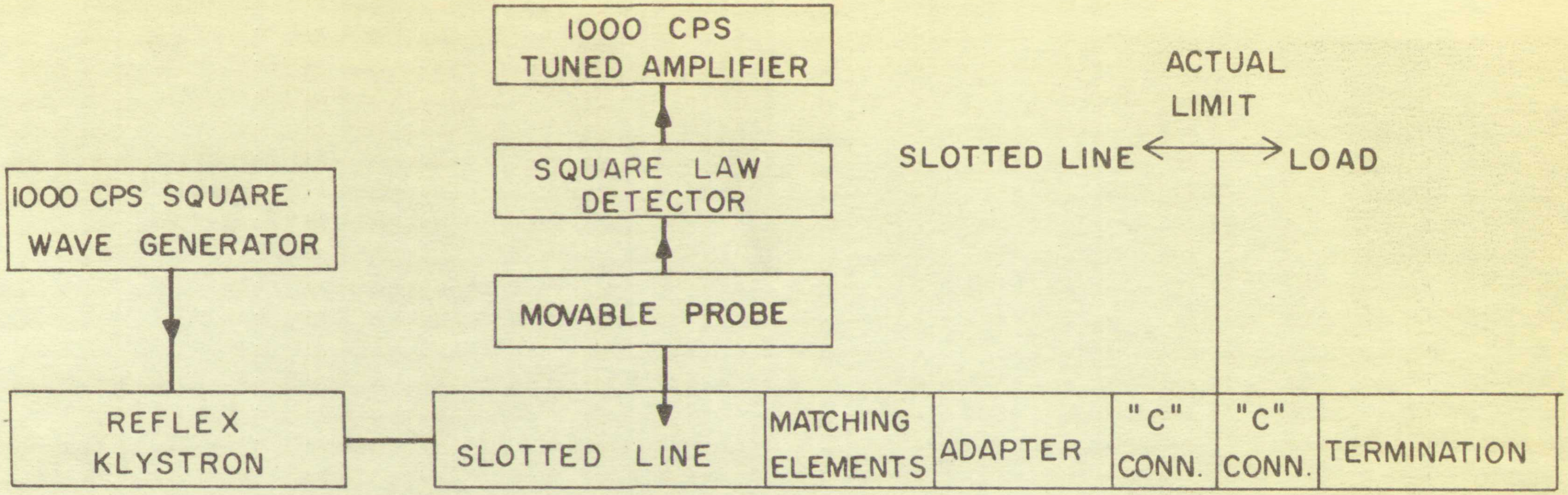

FIG. IA - TYPICAL SET-UP FOR MEASURING IMPEDANCE

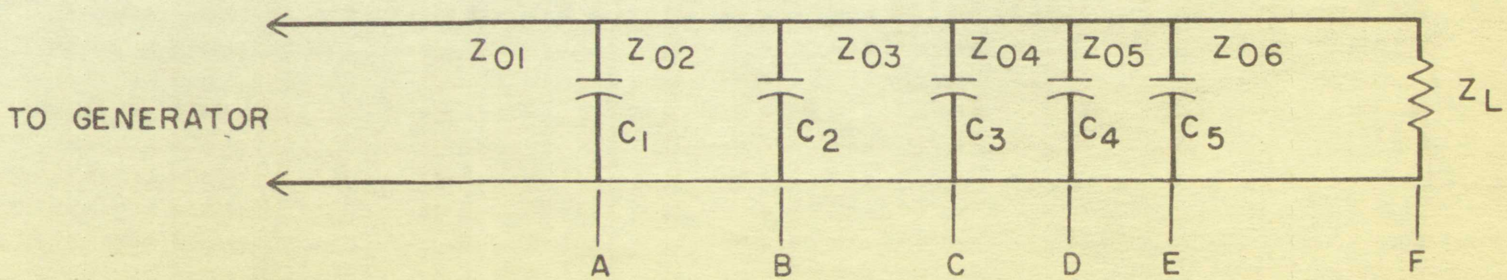

FIG. IB - EQUIVALENT TWO-WIRE REPRESENTATION

the slotted line can be calculated by assuming a perfect termination and transforming this impedance down the transmission line, taking into account each change in Z_0 and additional capacitance.

This method of calculation was undertaken and compared to experimental results. The correlation was fair, but not entirely dependable. This was thought to be due to contact resistance of center pins and spring finger contacts. This theoretical calculation was not pursued further and is not included in the thesis. It is very laborious even when using a Smith Chart Transmission Line Calculator. It is hoped that the discussion of this approach clarifies the definition of the residual VSWR given in the next paragraph.

Definition of Residual VSWR. Referring to Figure IB the residual VSWR, ρ_R, is defined as the VSWR produced by the summation of all reflections due to the discontinuities between and including planes E and A, when the terminating impedance, Z_L, is equal to the characteristic impedance, Z_{06}, of the terminating line.

II. TRANSMISSION LINE CALCULATORS

Two charts used for transmission line calculations are "Rectangular Charts" and "Smith Charts".

Rectangular Charts. The Rectangular Chart is a plot of impedance having coordinates Z = R + jX. Superimposed is the quantity

the slotted line can be calculated by assuming a [illegible] and transforming this impedance down the transmission line, taking into account each change in Z_o and additional [illegible].

This method of calculation was undertaken and [illegible] experimental results. The correlation was fair, but not entirely dependable. This was thought to be due to [illegible] of center pins and spring finger contacts. This theoretical calculation was not pursued further and is not included in this thesis. It is very laborious even when using [illegible] Calculator. It is hoped that [illegible] clarifies the definition of residual [illegible] the next paragraph.

Definition of Residual ρ_R. [illegible] in Figure 2 the residual VSWR, ρ_R, is defined as the [illegible] produced by the summation of all reflections due to [illegible] between and including planes X and Y, when the terminating impedance, Z_T, is equal to the characteristic impedance, Z_{oL}, of the terminating line.

II. [illegible]

Two charts used for transmission line calculations are "Rectangular Charts" and "Smith Charts".

Rectangular Charts. The Rectangular Chart is a plot of impedance having coordinates $Z = R + jX$. [illegible]

$2\beta d$ where β is the phase propagation constant of the line and d is the distance from the load to a point on the line. It is indicated on the chart as βd, which is the electrical length of the portion of the line in question. The quantity βd is given in degrees. Circles of constant VSWR are also plotted. The Rectangular Chart is discussed in many textbooks.[8]

Smith Charts. The Smith Chart is a bilinear transformation of the Rectangular Chart and has coordinates $K = u + jv$ where K is the complex reflection coefficient. On the chart, the K coordinates are not indicated, but instead circles of constant resistance and reactance. The quantity d is given in the ratio to wavelength. Smith Charts are also discussed in many textbooks.[9,10]

The Smith Chart is generally used for the solution of transmission line problems, since it is more convenient to use than the Rectangular Chart. The Smith Chart contains all values of impedance from zero to infinity, while the Rectangular Chart contains values of impedance only in the neighborhood of zero for a chart of finite size. Circles of constant VSWR are concentric on a Smith Chart while on the Rectangular Chart they are not. Also on the Smith Chart the βd scale is uniform in terms of the arc traversed on a given VSWR circle

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[8] See for example, Ryder, John D., Network, Lines and Fields, Prentice-Hall, Inc., 1949, pp. 258-264.

[9] Smith, P. H., "Transmission Line Calculator", Electronics, Vol. 12, Jan. 1939, pp. 65-71.

[10] See for example, Ragan, G. L., Microwave Transmission Circuits, M.I.T., Rad. Lab. Series, McGraw-Hill Book Co., Inc. New York, 1948, pp. 60-67.

$2\beta d$ where β is the phase propagation constant of the line and d is the distance from the load to a point on the line. It is indicated on the chart as βd, which is the electrical length of the portion of the line in question. The quantity βd is given in degrees. Circles of constant VSWR are also plotted. The Rectangular Chart is discussed in many textbooks.[8]

<u>Smith Charts.</u> The Smith Chart is a bilinear transformation of the Rectangular Chart and has coordinates $u + jv = \Gamma$ where Γ is the complex reflection coefficient. On the charts the Γ coordinates are not indicated, but instead circles of constant resistance and reactance. The quantity d is given in the rotation as wavelength. Smith Charts are also discussed in many textbooks.[9,10]

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[8] See for example, Ryder, John D., Networks, Lines and Fields, Prentice-Hall, Inc., 1949, pp. 253-275.

[9] Smith, P. H., "Transmission Line Calculator", Electronics, Vol. 12, Jan. 1939, pp. 29-31.

[10] See for example, Ragan, G. L., Microwave Transmission Circuits, M.I.T., Rad. Lab. Series, McGraw-Hill Book Co., Inc., New York, 1948, pp. 60-67.

while on the Rectangular Chart this is not true. The Rectangular Chart has an advantage in that the magnitude and phase angle of a given impedance can be visualized as a vector drawn from the origin, whereas no such simple relationship exists in the Smith Chart. However, most of the advantages remain with the Smith Chart when solving the majority of transmission line problems.

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CHAPTER III

THEORY OF MOVABLE COAXIAL LOAD METHOD

I. ADMITTANCE LOCUS WITH ρ_R EQUAL TO ZERO

Locus on a Rectangular Chart. The normalized admittance at any point d on a transmission line is given by:[11]

$$\frac{Y_d}{Y_o} = g_a - jb_a = \frac{1 - |K| \angle \phi - 2\beta d}{1 + |K| \angle \phi - 2\beta d} \qquad (1)$$

where

Y_o = characteristic admittance of line

β = $\frac{2\pi}{\lambda}$ = phase constant where λ equals wavelength

d = distance from load

$K\angle\phi$ = reflection coefficient

Substituting[12]

$$|K| = \frac{\rho_L - 1}{\rho_L + 1} \qquad (2)$$

where ρ_L = VSWR of load

[11] See footnote 8, loc. cit., p. 263

[12] See footnote 8, loc. cit., p. 235

the following equation can be obtained by complex variable theory

$$\left[g_a - \left(\frac{\rho_L^2 - 1}{2\rho_L}\right)\right]^2 + b_a^2 = \left[\frac{\rho_L^2 - 1}{2\rho_L}\right]^2 \qquad (3)$$

Equation (3) is recognized as a circle with radius

$$R = \frac{\rho_L^2 - 1}{2\rho_L} \qquad (4)$$

and center coordinates

$$\frac{\rho_L^2 - 1}{2\rho_L}, \; o \quad = g_o, b_o \,. \qquad (5)$$

It can further be proven that if β d is increased or decreased π radians the admittance locus of a load with a VSWR of ρ_L will lie on such a circle.[13] Equation (3) could be plotted on a rectangular chart with a change of coordinates of R to g_a and +jX to + jb_a.

Locus on a Smith Chart. To transform this admittance circle to a Smith Chart the following transformation equations are utilized:[14]

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[13] See for example, Ware, L. A. and Reed, H. R., Communications Circuits, John Wiley and Sons, Inc., 1949, Chap. II, Section 98-101.

[14] See for example, Reich, Ardung, Krauss and Skalink, Microwave Theory and Techniques, Van Nostrand Co., Inc., New York, 1953, pp. 860-861

$$u_o = \frac{g_o{}^2 - 1 - R + b_o{}^2}{(g_o + 1)^2 - R^2 + b_o{}^2} \qquad (6)$$

$$v_o = \frac{-2b_o}{(g_o + 1)^2 - R^2 + b_o{}^2} \qquad (7)$$

$$R_p = \frac{2R}{(g_o + 1)^2 - R^2 + b_o{}^2} \qquad (8)$$

where g_o, b_o and R are as previously defined and

(u_o, v_o) = coordinates of the center of the circle on the Smith Chart

R_p = radius of the circle on the Smith Chart

Therefore, by substitution of equations (4) and (5) into equations (6), (7) and (8), the following result can be obtained

$u_o = 0$

$v_o = 0$

$R_p = |K|$

The admittance locus of $\rho_L = 2$ is plotted in Figure 2 on a Smith Chart.

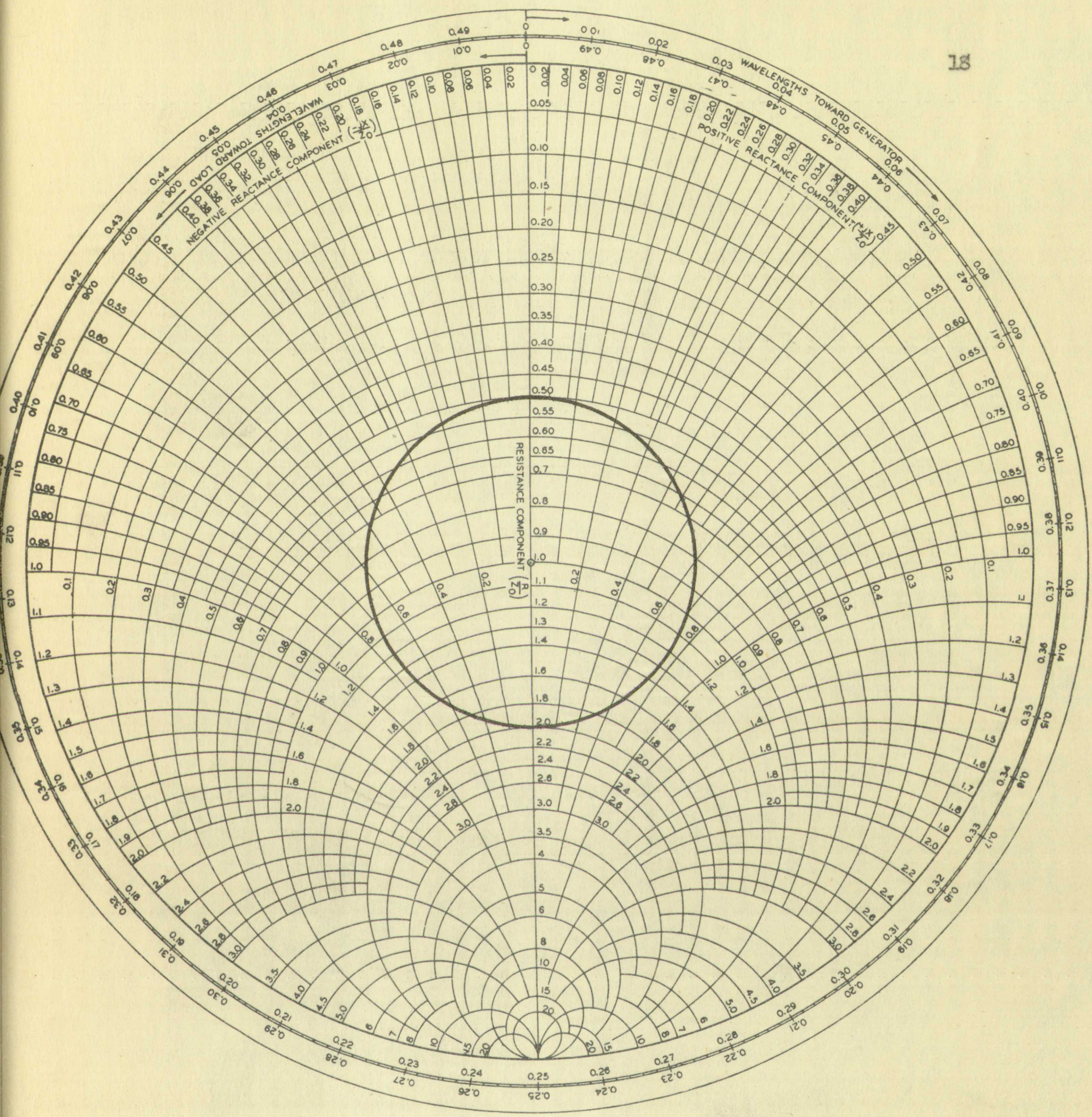

FIG. 2. SMITH CHART, ADMITTANCE LOCUS $\rho_L = 2$, B = 0

II. ADMITTANCE LOCUS WITH ρ_R

NOT EQUAL TO ZERO

Locus on a Rectangular Chart. If ρ_R is not equal to zero the admittance locus remains a circle, but with the center transformed. For the rectangular chart this center transformation can be shown by the following analysis:

The combined admittance of all the discontinuities can be replaced by a single susceptance placed in shunt with the line at some point toward the generator from plane A. This can be seen by referring to Figure 3 where two reflections E_{R1} and E_{R2} produced by two discontinuities are represented by vectors. The resultant of these two vectors is equal to E_T which is obtained by constructing a parallelogram as indicated.

Thus any number of reflections could be reduced to one vector. A susceptance could be placed on the line to give the required magnitude of reflected signal with proper phase.

Let

$-jB$ = normalized susceptance of discontinuities.

Following the previous procedure

$$\frac{Y_d}{Y_o} = g_a - j(b_a + B) = \frac{1 - |K|\underline{/\phi - 2\beta d}}{1 + |K|\underline{/\phi - 2\beta d}} \qquad (10)$$

E. ADMITTANCE [illegible]

[illegible]

Locus on a Rectangular Chart. If ρ_L is not equal to zero the admittance locus remains a circle, but with the center transferred. For the rectangular chart this center transformation can be shown by the following analysis:

The combined admittance of all the discontinuities can be replaced by a single susceptance placed in shunt with the line at some point toward the generator from plane L. This can be seen by referring to Figure 3 where the reflections Γ_d and Γ_L produced by the discontinuities are represented by vectors. The resultant of these two vectors is equal to Γ_t which is obtained by constructing a parallelogram as indicated.

Thus any number of reflections could be reduced to one vector. A susceptance could be placed on the line to give the required magnitude of reflected signal with proper phase.

Let

$-jB$ = normalized reactance of discontinuities.

Following the previous procedure

$$\frac{Y_d}{Y_o} = (g_d - jb_d + j\beta) = \frac{1 - [illegible]}{1 + [illegible]} \qquad (30)$$

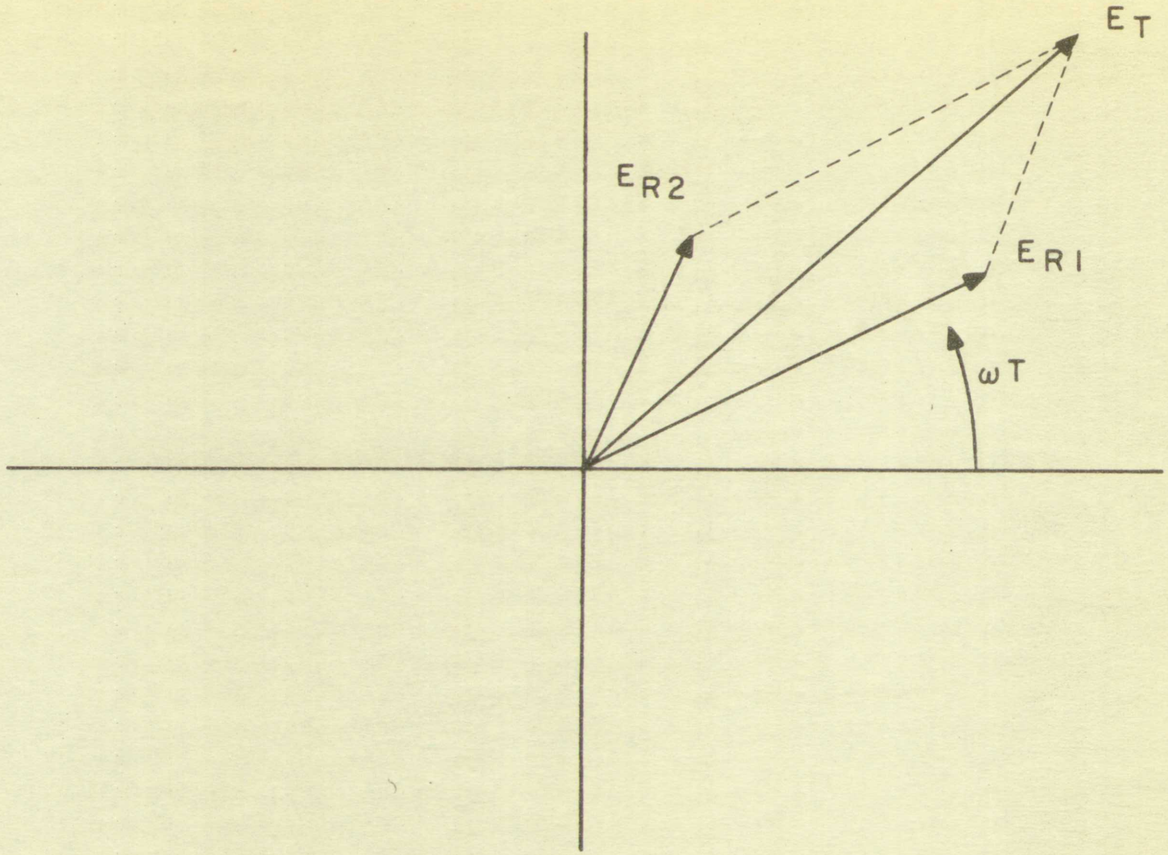

FIG. 3 - EQUIVALENT SUSCEPTANCE VECTOR RELATIONS

and as before the following admittance locus is obtained

$$\left[g_a - \left(\frac{\rho_L^2 - 1}{2\rho_L}\right)\right]^2 + (b_a + B)^2 = \left[\frac{\rho_L^2 - 1}{2\rho_L}\right]^2 \quad (11)$$

This is recognized as a circle with

$$R = \frac{\rho_L^2 - 1}{2\rho_L} \quad (12)$$

and center coordinates of

$$\frac{\rho_L^2 - 1}{2\rho_L}, -B = (g_o, b_o) \quad (13)$$

Locus on a Smith Chart. Using the transformation equations, the following relationships are established on the Smith Chart.

$$u_o = \frac{B^2\rho_L}{(\rho_L + 1)^2 + \rho_L B^2} \quad (14)$$

$$v_o = \frac{-2B\rho_L}{(\rho_L + 1)^2 + \rho_L B^2} \quad (15)$$

$$R_p = \frac{\rho_L^2 - 1}{(\rho_L + 1)^2 + \rho_L B^2} \quad (16)$$

Refer to Figure 4 for $\rho_L = 2$, $B = -1$.

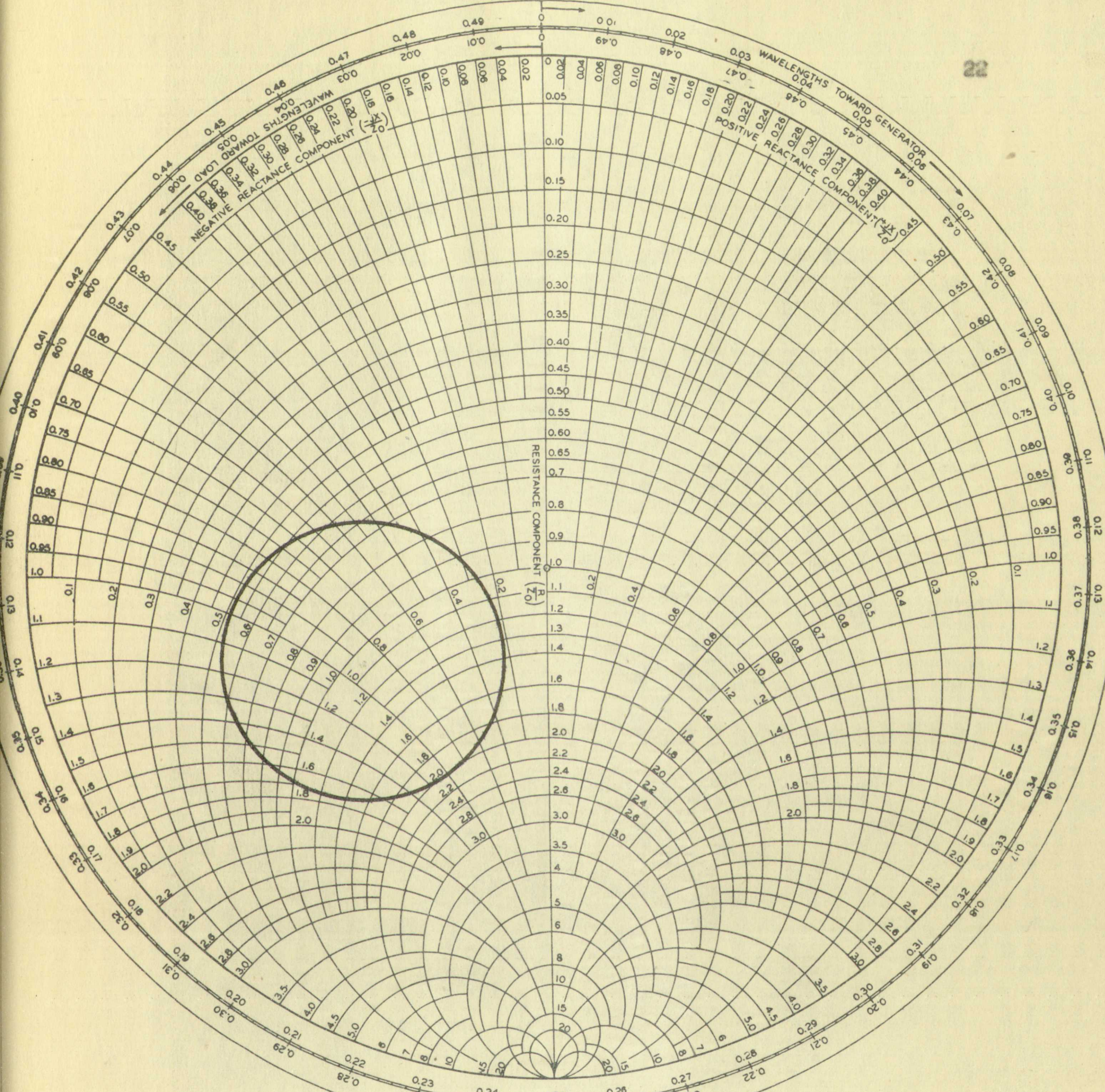

FIG. 4. SMITH CHART, ADMITTANCE LOCUS $\rho_L = 2$, B = - 1

By referring to Figure 4 it can be seen that as βd varies π radians a maximum and minimum VSWR will be obtained in the slotted line. By determining this maximum and minimum VSWR the value of ρ_R and ρ_L can be calculated. The equations needed for this calculation are derived in the following sections. Before deriving these equations further discussion of the preceding results are in order. Equation (1) gives the admittance at any point (d) on a transmission line knowing the complex reflection coefficient of the load. Equation (1) at all points on the line is equal to $g_a - jb_a$. This same equation can be used to give the admittance at any one point as the distance between the point and the load is changed. The admittance locus was shown to be a circle.

If a susceptance (-jB) is added at some point on the line then the admittance at that point is equal to $g_a - jb_a$ as before plus -jB. Therefore, equation (10) equates $g_a - j\ (b_a + B)$ to the standard transmission line equation and gives an expression for the admittance when a residual reflection is present.

Therefore, an expression could be derived for the maximum and minimum VSWR obtained in the $g_a - jb_a$ plane, but a VSWR or reflection coefficient is not expressed simply on an admittance plot of this type. However, a Smith Chart relates the reflection coefficient and thus the VSWR quite easily to the known parameters, that is, the radius and circle coordinates on the Smith Chart. Therefore, the admittance

By referring to figure 4 it can be seen that as θ varies π radians a maximum and minimum VSWR will be obtained in the slotted line. By determining this maximum and minimum VSWR the value of ρ_R and ρ_L can be calculated. The equations necessary for this calculation are derived in the following section. Before deriving these equations first a discussion of the preceding results are in order. Equation (1) gives the admittance at any point of the transmission line knowing the complex reflection coefficient of the load. Equation (1) still holds [illegible] $g_1 - jb_1$. This same equation can be used to give the admittance at various points as the distance between the point and the load is changed. The admittance locus was shown to be a circle.

If a susceptance $(-jB)$ is added at some point on the line then the admittance at that point is equal to $g_1 - jb_1$ as before plus $-jB$. Therefore, equation (10) [illegible] $g_1 - j(b_1 + B)$ and the standard transmission line equation and gives an expression for the admittance when a residual reflection is present.

Therefore, an expression could be derived for the maximum and minimum VSWR obtained in the $g_1 - jb_1$ plane, but a VSWR or reflection coefficient is not expressed simply on a [illegible] of this type. However, a Smith Chart relates the reflection coefficient and thus the VSWR quite easily to the above parameters. [illegible], the center and circle coordinates on the Smith Chart, [illegible] admittance

locus was transformed to the Smith Chart where expressions will be derived for the maximum and minimum VSWR in terms of the circle radius and center coordinates.

A Smith Chart was not used to begin with because two reflection coefficients cannot be added as simply as two admittances. Thus an expression for the complex reflection coefficient at the resultant susceptance could not be obtained as easily as was equation (10) where B was just added to b_a.

Calculation of ρ_R by obtaining a ρ_{max} and ρ_{min}. Referring to Figure 5, which indicates general relationships on the Smith Chart, the following equations are obtained:

$$|\rho_o| = \sqrt{u_o^2 + v_o^2} \tag{17}$$

by substitution of equations (14) and (15) into equation (17)

$$|\rho_o| = \frac{\rho_L B \sqrt{B^2 + 4}}{(\rho_L + 1)^2 + \rho_L B^2} \tag{18}$$

A vector from the origin to a point is equal to a reflection coefficient. Thus, as one traverses the admittance locus, a maximum and minimum $|K|$ will be obtained.

$$|K_{max}| = |\rho_o| + R_p \tag{19}$$

$$|K_{min}| = |\rho_o| - R_p \tag{20}$$

Substitution of equations (16) and (18) into equations (19) and (20) gives

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A Smith Chart was not used to begin with because two reflection coefficients cannot be added as simply as two admittances. Thus an expression for the complex reflection coefficient at the resultant susceptance could not be obtained as easily as was equation (10) where B was just added to b_s.

<u>Calculation of ρ_p by obtaining a ρ_{max} and ρ_{min}.</u> Referring to Figure 5, which indicates general relationships on the Smith Chart, the following equations are obtained:

$$|\rho_o| = \sqrt{u_o^2 + v_o^2} \qquad (17)$$

by substitution of equations (14) and (15) into equation (17)

$$|\rho_o| = \frac{\rho_L B \sqrt{B^2 + 4}}{(\rho_L + 1)^2 + \rho_L B^2} \qquad (18)$$

A vector from the origin to a point is equal to a reflection coefficient. Thus, as one traverses the admittance locus, a maximum and minimum $|K|$ will be obtained.

$$|K_{max}| = |\rho_o| + R_p \qquad (19)$$

$$|K_{min}| = |\rho_o| - R_p \qquad (20)$$

Substitution of equations (16) and (18) into equations (19) and (20) gives

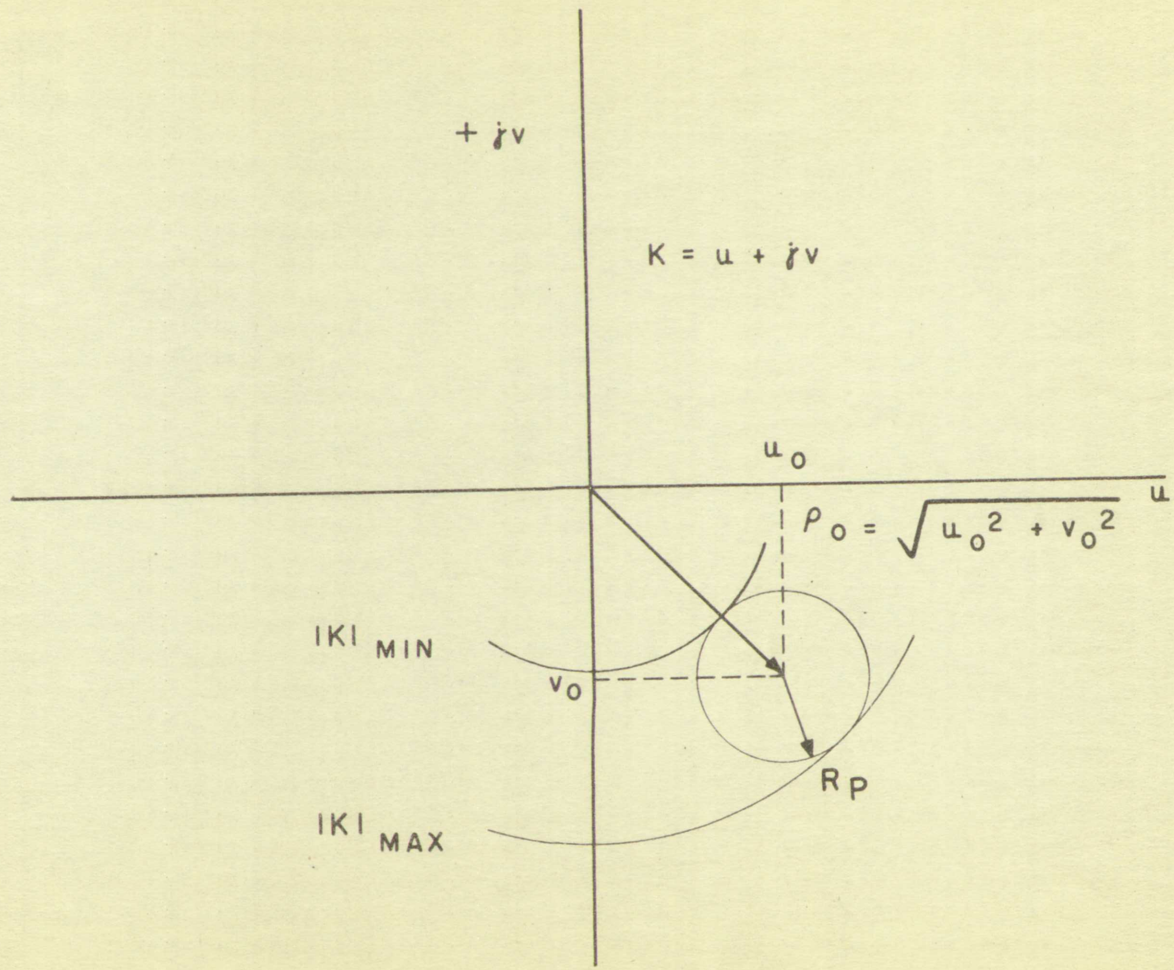

FIG. 5 - SMITH CHART, GENERAL RELATIONS

$$|K_{max}| = \frac{\rho_L B \sqrt{B^2 + 4} + (\rho_L^2 - 1)}{(\rho_L + 1)^2 + \rho_L B^2} \qquad (21)$$

$$|K_{min}| = \frac{\rho_L B \sqrt{B^2 + 4} - (\rho_L^2 - 1)}{(\rho_L + 1)^2 + \rho_L B^2} \qquad (22)$$

The $|K_{max}|$ and $|K_{min}|$ can be converted to a ρ_{max} and ρ_{min} by equation (2).

By obtaining the quotient of ρ_{max}/ρ_{min} the following relationship is established

$$\sqrt{\frac{\rho_{max}}{\rho_{min}}} = \rho_L \qquad (23)$$

and likewise the product of $\rho_{max}\ \rho_{min}$ yields the following

$$\sqrt{\rho_{max}\,\rho_{min}} = \frac{2 + B^2 + B\sqrt{B^2 + 4}}{2 + B^2 - B\sqrt{B^2 + 4}} \qquad (24)$$

To realize the significance of equation (24) an expression for the VSWR of a normalized susceptance (B) inserted into a line, which is terminated in its characteristic impedance will be derived.

Let

$$\frac{Y_R}{Y_o} = 1 - jB \tag{25}$$

where

Y_R = residual admittance

but[15]

$$K = \frac{1 - \frac{Y_R}{Y_o}}{1 + \frac{Y_R}{Y_o}} \tag{26}$$

then

$$K = \frac{-B^2 + 2jB}{4 + B^2} \tag{27}$$

then

$$|K| = \frac{B\sqrt{B^2 + 4}}{4 + B^2} \tag{28}$$

Since

$$\rho_R = \frac{1 + |K|}{1 - |K|} \tag{29}$$

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[15]See footnote 8, loc. cit., p. 205

where

ρ_R = VSWR of added susceptance when line is terminated in Y_o.

= residual VSWR

$$\rho_R = \frac{4 + B^2 + B\sqrt{B^2 + 4}}{4 + B^2 - B\sqrt{B^2 - 4}} \tag{30}$$

If equation (24) is multiplied by $\sqrt{\frac{8 + 2B^2}{8 + 2B^2}}$ the following results

$$\sqrt{\rho_{max}\,\rho_{min}} = \frac{4 + B^2 + B\sqrt{B^2 + 4}}{4 + B^2 - B\sqrt{B^2 - 4}} \tag{31}$$

$$= \rho_R$$

This result is equal to equation (30). Thus the square root of the product $\rho_{max}\,\rho_{min}$ is equal to the residual VSWR of the line as defined previously.

<u>Conditions Effecting Calculations</u>. The above analysis is correct if

$$\rho_L < \rho_R \tag{32}$$

Under this condition, the admittance locus does not encircle the origin. Refer to Figure 4.

If $\rho_L > \rho_R$ the admittance locus will encircle the origin. Refer to Figure 6. Then the following changes in $|K_{max}|$ and $|K_{min}|$ have to be made:

$$|K_{max}| = |\rho_o| - R_p \tag{33}$$

$$|K_{min}| = R_p - |\rho_o| \tag{34}$$

By substitution of equations (16) and (18) into equations (33) and (34) and by following the same procedure as previously done the following equations are obtained. These equations are the opposite of equations (23) and (31).

$$\sqrt{\frac{\rho_{max}}{\rho_{min}}} = \rho_R \tag{35}$$

$$\sqrt{\rho_{max}\,\rho_{min}} = \rho_L \tag{36}$$

When $\rho_R = \rho_L$ the admittance locus intercepts the origin and

$$\sqrt{\rho_{max}\;\rho_{min}} = \sqrt{\frac{\rho_{max}}{\rho_{min}}} \tag{37}$$

since $\rho_{min} = 1.0$ in that case.

In general it will not be known before the measurement of ρ_{min} and ρ_{max} if $\rho_L \gtrless \rho_R$. Therefore, one would not know by which equations to calculate ρ_L or ρ_R. A method is available for determining if $\rho_L \gtrless \rho_R$. The following discussion indicates the method.

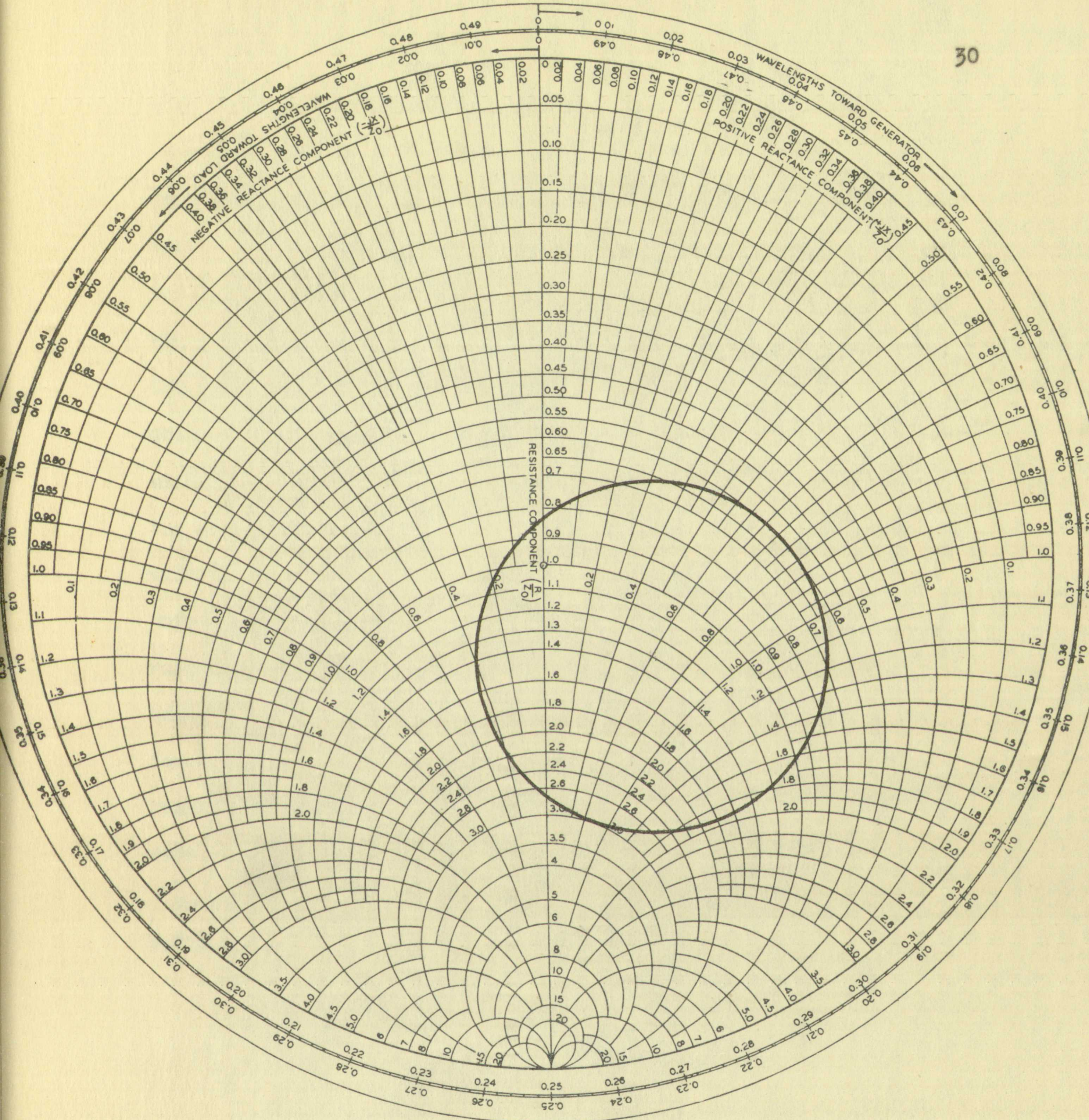


FIG. 6. SMITH CHART, $\rho_L > \rho_R$

<u>Method of Determining if $\rho_L \gtrless \rho_R$.</u> If a load is connected to a slotted line which has a residual VSWR two reflections will take place, one at the residual discontinuity and another at the load. When the distance between load and discontinuity is correct, the two reflected voltages will be in phase and give a maximum VSWR. When a minimum VSWR is obtained the two reflections are out of phase. If the magnitude of $\rho_L < \rho_R$ the resultant reflected voltage when in phase and when out of phase will produce standing wave voltage minimums at the same points in the slotted line. If $\rho_L > \rho_R$ the resultant reflected voltage when in phase and when out of phase will produce standing wave voltage minimums separated by $1/4\,\lambda$. Referring to Figure 7 this can be seen by noting that when the two reflections are out of phase the resultant voltage will have the phase angle of the larger reflection. Thus if $\rho_L < \rho_R$ the resultant voltage for both ρ_{max} and ρ_{min} will have the same phase angle and the resultant reflection coefficient for ρ_{max} and ρ_{min} will have the same phase angle. However, if $\rho_L > \rho_R$ the resultant voltage for ρ_{max} and ρ_{min} will be 180° out of phase, and the resultant reflection will differ by 180°.

These relationships are summarized as follows:

If $\rho_L < \rho_R$

$$\phi_{max} = \phi_{min}$$

Difference in nulls for ρ_{max} and ρ_{min} equals zero or multiples of half wavelength

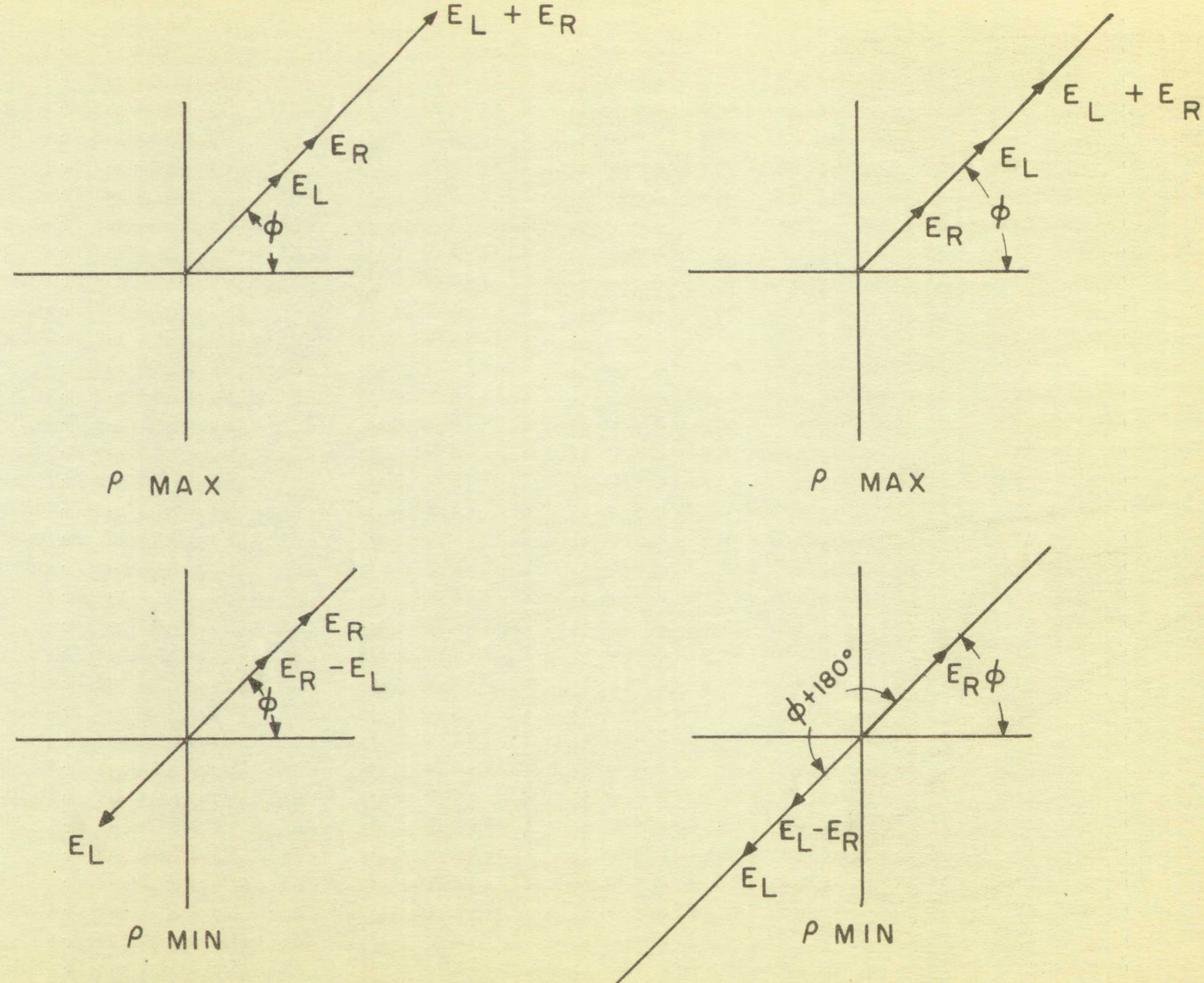
Method of Determining the Phase [illegible]. If a load is connected to a slotted line which has a residual VSWR, two reflections will take place, one at the residual discontinuity and one at the load. When the distance between load and discontinuity is varied, the two reflected voltages will be in phase and give a maximum VSWR. When a minimum VSWR is obtained the two reflections are out of phase. If the magnitude of $\rho_L < \rho_R$ the resultant reflected voltage when in phase and when out of phase will produce standing wave voltage minimums at the same points on the slotted line. If $\rho_L > \rho_R$ the resultant reflected voltage when in phase and when out of phase will produce standing wave voltage minimums separated by $\lambda/4$. Referring to Figure 7, this can be seen by noting that when the reflections are out of phase the resultant voltage will have the phase angle of the larger reflection. Thus if $\rho_L < \rho_R$ the resultant voltage for both ρ_{max} and ρ_{min} will have the same phase angle and the resultant reflection coefficient for ρ_{max} and ρ_{min} will have the same phase angle. However, if $\rho_L > \rho_R$ the resultant voltage for ρ_{max} and ρ_{min} will be 180° out of phase, and the resultant reflection will differ by 180°.

These relationships are summarized as follows:

If $\rho_L < \rho_R$

$\rho_{max} = \rho_{min}$

Difference in nulls for ρ_{max} and ρ_{min} would be an odd multiple of half wavelength.



A. $\rho_L < \rho_R$ B. $\rho_L > \rho_R$

FIG. 7 – VECTOR RELATIONS WHEN $\rho L \gtrless \rho R$

If $\rho_L > \rho_R$

$$\phi_{max} = \phi_{min} + 180°$$

Difference in nulls for ρ_{max} and ρ_{min} equals one quarter of wavelength or an odd multiple thereof.

where

ϕ_{max} = resultant reflection coefficient angle for ρ_{max}

ϕ_{min} = resultant reflection coefficient angle for ρ_{min}

CHAPTER IV

DESIGN AND CONSTRUCTION OF

MOVABLE COAXIAL LOAD

As mentioned previously a movable load is necessary to evaluate a slotted line by either the Perfect Load Method or the Movable Coaxial Load Method. Since a movable coaxial load was not available commercially one had to be designed and constructed.

Theory of Low VSWR Load. In the literature several coaxial load designs are described. Most of them involve inserting lossy material into the line. The physical configuration of the lossy material, in general, determines the VSWR of the load. The most common termination is one which inserts a tapered section of lossy material. The taper can either be an inside or an outside taper. The taper should be logarithmic, that is, the physical shape of the taper should be such that the material is introduced logarithmically.[16] Any physical configuration which introduces the lossy material at an increased rate as one approaches the end of the line will suffice; in fact, a linear taper is generally satisfactory.

Other factors influencing the VSWR of the load are the total length of the taper, loss tangent of lossy material and smoothness of

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[16] Montgomery, C. G., Technique of Microwave Measurements, M.I.T., Rad. Lab. Series, Vol. 11, McGraw-Hill Book Co., Inc., New York, 1947, pp. 720-735.

tip of taper. The taper should never be less than one half wavelength long and preferably several half wavelengths. Since the lossy material is followed by a short circuit all of the energy incident upon the short is reflected towards the generator. Therefore, the loss tangent of the material should be such that the total two way loss of the material should be equal to at least 20 db. A loss of 20 db will reduce a VSWR of infinity to 1.01. The tip of the taper should be finished to as fine a point as possible. The actual fineness is determined by the type of material used due to physical strength.

Selection of Lossy Material. Many types of lossy materials were available. Of these the more important types tested for suitability for this project were synthane, commercial polyiron and aquadag coated tissue. None of these produced a satisfactory load due to various factors, respectively, machining difficulties, not available in suitable lengths, and too fragile.

Further experimentation proved that the material most suitable for such a load was a mixture by weight of 60 parts "Powdered Iron", 40 parts "Epoxy Resin Epon 828" and 5 parts "Hardner D. E. A.". This material has a dielectric constant of 3.6 and a loss tangent of 0.3 at a frequency of 8.6 KMC.

Construction of Load. The load was constructed by casting the material in a glass tube 7/8" in diameter and approximately 12" in length. The load was cast in a vacuum to draw out air bubbles, and

tip of taper. The taper should [illegible] be [illegible] wave-length long and preferably several half wave-lengths. Since the lossy material is followed by a short-circuit [illegible] of the energy incident upon the short is reflected towards the [illegible]. Therefore, the loss tangent of the material should be such that [illegible] of the material should be equal to [illegible]. A [illegible] will reduce [illegible] VSWR of infinity to 1.01. The tip of the taper should be finished to as fine a point as possible. The [illegible] fineness is determined by the type of material used and mechanical strength.

<u>Selection of Lossy Material</u>. [illegible] lossy materials were available. Of these the more important types tested for suitability for this project were [illegible], [illegible] and aquadag coated tissue. None of these proved satisfactory [illegible] due to various factors, respectively, [illegible] difficulties, not available in suitable lengths, and too fragile.

Further experimentation proved that the material most suitable for such a load was a mixture by weight of [illegible] parts [illegible] and 40 parts "Epoxy Resin Type [illegible]" and [illegible]. This material has a dielectric constant of [illegible] and a loss tangent of 0.5 at a frequency of [illegible].

<u>Construction of Load</u>. The load was constructed by [illegible] material in a glass tube [illegible] diameter [illegible] length. The load was [illegible]

thus produce a more homogeneous material. After curing in an oven at 80° C for 15 hours the glass was broken away from the lossy material. The cylindrical material was then machined on a lathe to correct taper and a hole for the center conductor was drilled. The back portion of the load was connected to a section of brass rod containing a rack gear. The entire load was fitted into a section of brass tubing having a center conductor. Figure 8 is a photograph of the movable load in disassembled form and should clarify the explanation. The ratio of the inner and outer diameter of the barrel and center conductor was such as to have a characteristic impedance of 50 ohms, and the diameters were chosen to physically match the dimensions of a type "C" connector. A front section was pressed onto the brass tube which allowed any type "C" connector to be used. A pinion gear was mounted on the barrel which engaged the rack gear of the brass section of the load through a slot in the barrel. Thus the load could be positioned in the brass barrel by turning the pinion gear.

<u>Electrical Properties of Movable Load</u>.

Nominal Characteristic Impedance---50 ohms.

Frequency---1000 to 6000 mcps.

VSWR Tapered Section---1.03 to 1.05.

Connectors---Cable type "C".

Movable---One half wavelength at 1000 mcps, other frequencies proportionately more.

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Electrical Properties of Movable Load.

Nominal Characteristic Impedance—50 ohms.

Frequency—1000 to 6000 mcps.

VSWR Tapered Section—1.03 to 1.05.

Connectors—Cable type "C".

Movable—One half wavelength at 1000 mcps, other frequencies proportionately more.

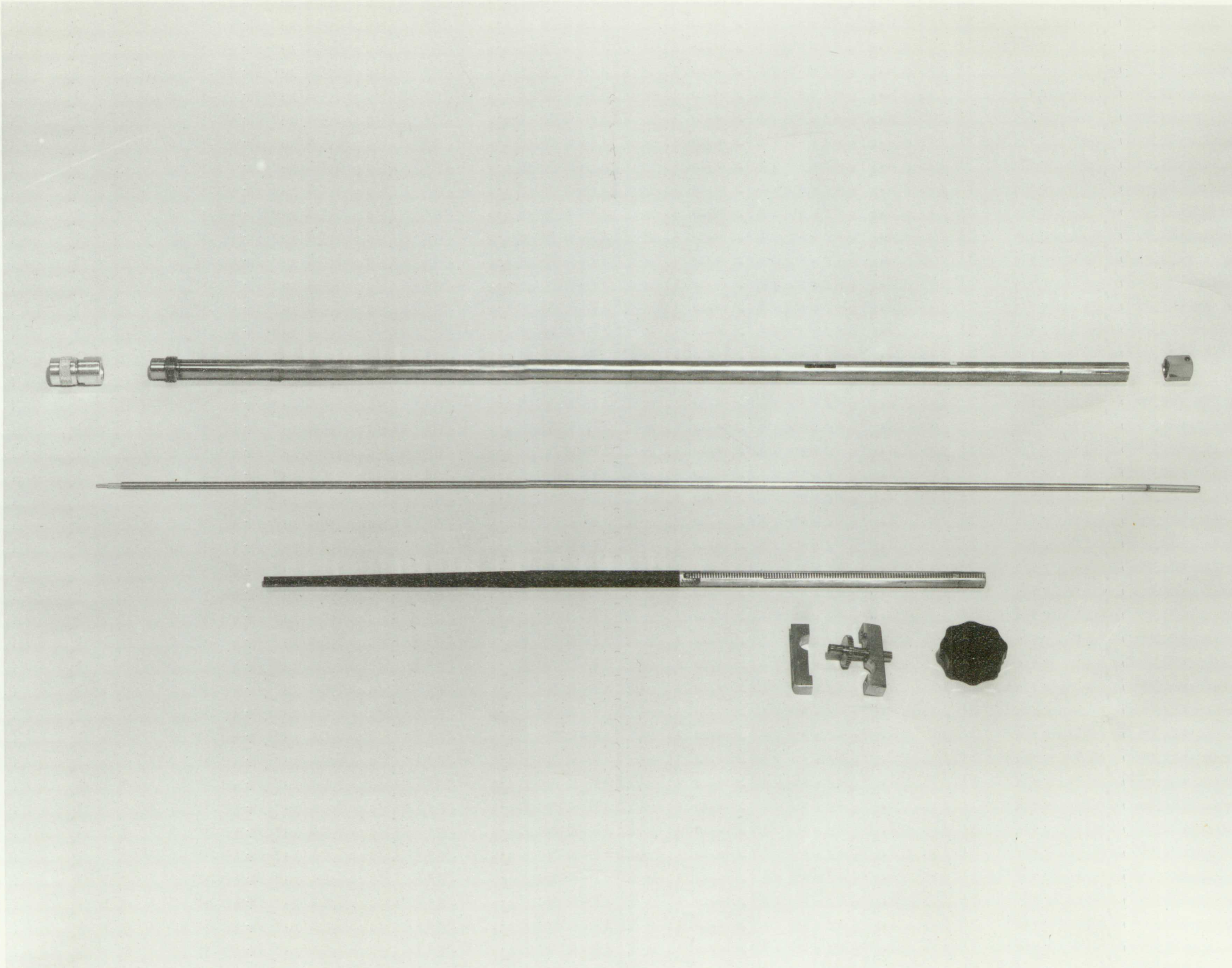

FIG. 8 - MOVABLE COAXIAL LOAD

Mechanical Dimensions.

Length--25 inches.

Diameter (Outer)--1/2 inch (approx.).

Length of Lossy Section--10 inches.

Length of Taper--7 inches.

CHAPTER V

LABORATORY PROCEDURE FOR

DETERMINING ρ_R OF SLOTTED LINE

The equipment setup necessary to determine the residual VSWR of a slotted line is shown in block diagram form in Figure 9. A brief summary of the equipment is given below:

1. RF Source. In the frequency range of 1 to 10 kilomegacycles a reflex klystron is generally used for a source of RF power. Many commercial units are available complete with power supply, modulation facilities and one direct reading frequency dial. Commercial klystrons can also be used with any acceptable power supply and modulator. Such tubes as Sperry 2K41, 2K42, 2K43 and 2K39 are readily usable for coaxial systems. In this particular case Hewlett-Packard Signal Generators 614, 616 and 618 were used due to the simplicity of tuning the direct reading frequency dial.
2. Modulator. The modulator in this case was a 1000 cycle square wave generator. When a reflex klystron is square wave modulated properly the RF output is a series of pulses. The modulation frequency was chosen to correspond with the frequency of the tuned amplifier used as an indicator.

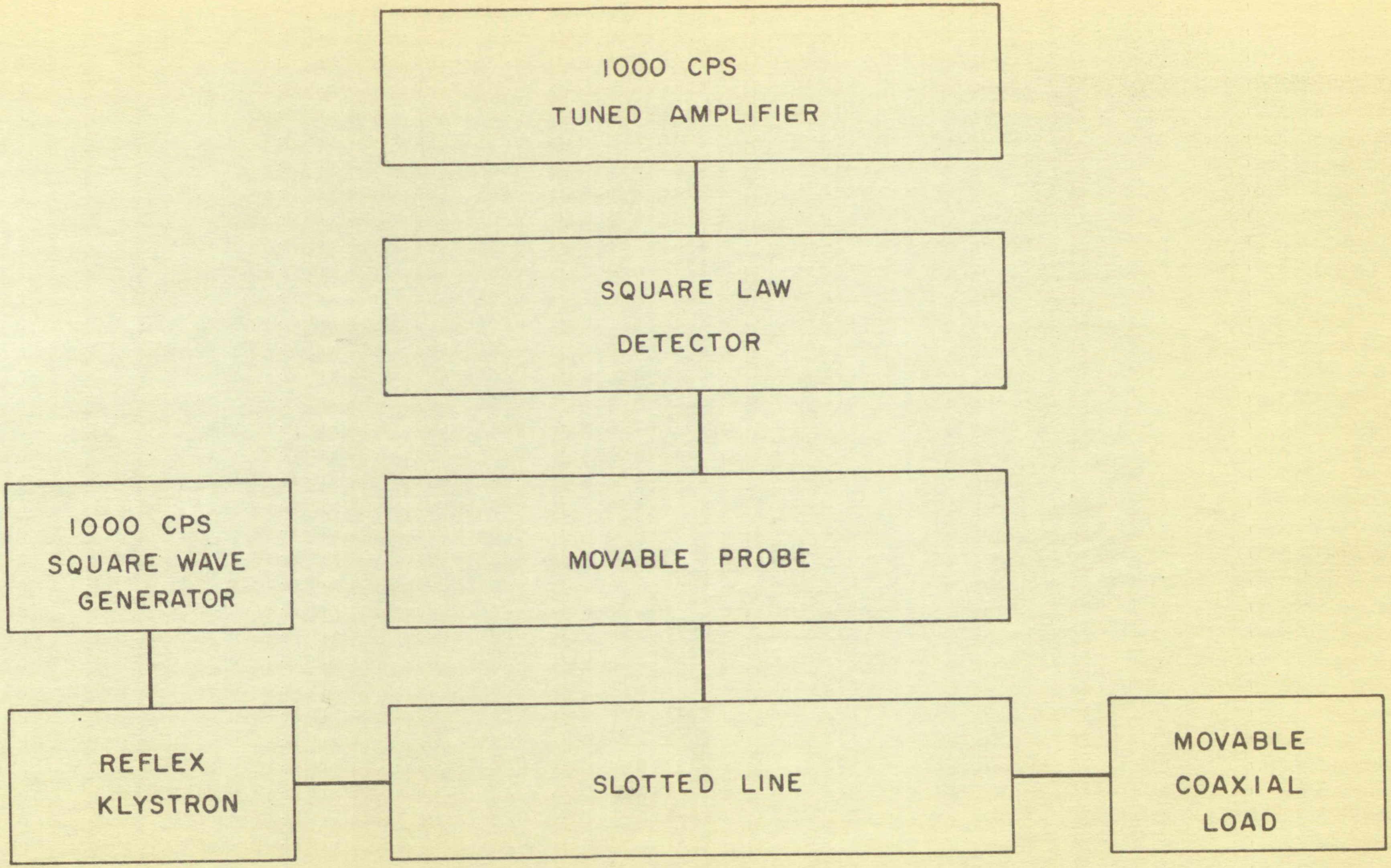

FIG. 9- EQUIPMENT SET-UP

3. Slotted Line. The slotted line used is the one which is to be evaluated with respect to residual VSWR.

4. Detector. A barretter or a crystal is used for a detecting element. Both of these elements are square law detectors. A barretter is an element which changes resistance when subjected to RF power. A DC bias current is required to bring it up to its operating range. Since the RF is modulated at an audio rate the barretter undergoes a resistance change at this same rate. Thus the product of the constant DC current and the changing resistance produces an AC voltage at the terminals of the indicator.

   A crystal demodulates the RF signal in the usual manner producing an AC signal voltage.

   A barretter conforms to square law over a wider range than does a crystal but a crystal produces less noise and does not require a DC bias current. A crystal is also more sensitive.

5. Indicator. An amplifier is necessary in order to amplify the small AC voltage available from the detector. Almost any AC amplifier would suffice for this purpose, but many commercial units are available with a gain of

3. Slotted Line. The slotted line must be the one which is to be evaluated with respect to residual VSWR.

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A barretter conforms to square law over a wider range than does a crystal but a crystal produces less noise and does not require a DC bias current. A crystal is also more sensitive.

5. Indicator. An amplifier is necessary in order to amplify the small AC voltage available at the detector. Almost any AC amplifier would suffice for this purpose, but many commercial units are available, typical of

60 to 70 db. Also a constant DC bias current is supplied for operation of barretters with these amplifiers.

Most VSWR amplifiers have a meter which is calibrated directly in VSWR. Thus to measure the VSWR in a slotted section the probe is positioned for a maximum indication on the indicator. The indicator gain is adjusted so that the meter reads 1.0 which is full scale. The probe is then positioned for a minimum indication and the meter indicates the ratio of the maximum to the minimum voltage directly.

In this case a Hewlett-Packard 415 tuned amplifier was used.

6. Movable Load. To use the method described in Chapter III a movable load is necessary. The load used is described in Chapter IV.

If one arbitrarily adjusts the movable load for a maximum and minimum VSWR considerable time is spent in determining the position of the load for the correct phasing. By noting the relationship between the incident wave and the two reflected waves the length of time necessary to complete both the Movable Load Method and the Perfect Load Method can be greatly reduced.

Briefly this is seen by the following:

Assume three waves

E_i = Incident wave

E_R = Reflected wave from residual discontinuities

E_L = Reflected wave from movable load

Note that the phase of E_L can be varied with respect to E_R due to the fact that the load is movable.

Assume that one adjusts the position of the load for a maximum VSWR in the slotted section, then

$$\rho_{max} = \frac{E_i + (E_R + E_L)}{E_i - (E_R + E_L)}$$

After this ρ_{max} has been recorded, reposition probe in slotted section for maximum voltage indication. Then the following relationship is fulfilled

$$\text{MAXIMUM VOLTAGE INDICATION} = E_i + (E_R + E_L)$$

Set indicator to read 1.0. Then adjust position of load (not moving probe) for minimum signal indication. The relationship between the waves at this time is

$$\text{INDICATION} = (E_i + E_R) - E_L$$

The reading on the indicator at this time is recorded as a VSWR used in the calculation of ρ_R by the Perfect Load Method. The probe is

not moved to obtain this VSWR, but only the load. The indication recorded as a VSWR is

$$\text{INDICATION} = \frac{(E_i + E_R) + E_L}{(E_i + E_R) - E_L}$$

This reading must be smaller than ρ_{max} but is not the minimum VSWR obtainable in slotted line. This VSWR is approximately equal to the VSWR of movable load, since E_R is normally small.[17]

With movable load positioned for minimum reading from above procedure determine VSWR in slotted line by usual procedure, that is, by moving the sliding probe on the slotted line. The following minimum VSWR will be outlined

$$\text{MINIMUM VSWR} = \frac{E_i + (E_R - E_L)}{E_i - (E_R - E_L)}$$

Thus one need only to determine ρ_{max} by trial and error, and then other VSWR's are found by simple manipulations as discussed.

A step-by-step procedure for determining the residual VSWR of a slotted line by the Movable Load Method is presented below, and as mentioned above the Perfect Load Method is incorporated in the procedure, since it requires no additional manipulations.

Laboratory Procedure.

1. Connect equipment as shown in Figure 9.
2. Tune equipment as in normal VSWR measurements.
3. Position movable load until maximum VSWR has been obtained. Record ρ_{max} and position of null d_N.

[17] See footnote 1, loc. cit.

not moved to obtain this VSWR, but only the load. The indication recorded as a VSWR is

$$\text{INDICATION} = \frac{(E_1 + E_2) + [illegible]}{(E_1 + E_2) - E_1}$$

This reading must be smaller than ρ_{max}, that is the maximum VSWR obtainable in slotted line. This VSWR is approximately equal to the VSWR of movable load, since the load is perfectly matched.[17]

With movable load positioned for maximum reading from above procedure determine VSWR in slotted line by usual procedure, that is, by moving the sliding probe on the slotted line. The following minimum VSWR will be outlined

$$\text{MINIMUM VSWR} = \frac{E_1 + (E_2 - E_1)}{E_1 - (E_2 - E_1)}$$

Thus one need only to determine ρ_{max} by trial and error, and then other VSWR's are found by simple [illegible] as [illegible].

A step-by-step procedure for determining the residual VSWR of a slotted line by the Movable Load Method is presented below, and as mentioned above the Perfect Load Method is [illegible] in the procedure, since it requires no additional [illegible].

Laboratory Procedure.

1. Connect equipment as shown in Figure [illegible].
2. Tune equipment as in normal VSWR measurements.
3. Position movable load until maximum VSWR [illegible] is obtained. Record ρ_{max} and position of [illegible].

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[17] See footnote 1, loc. cit.

4. Position probe for maximum signal under above condition, that is, load still positioned for maximum VSWR.
5. Adjust gain on indicator to 1.0 on VSWR scale.
6. Move sliding load until minimum signal is obtained.
7. With sliding load in position for minimum signal adjust probe carriage and record ρ_{min} for slotted section. Record position of null d_m.
8. Subtract position of nulls d_M and d_m.
9. If difference $d_M - d_m$ equals zero or multiple of half wavelengths calculate

$$\rho_{residual} = \sqrt{\rho_{max} \rho_{min}}$$

$$\rho_{tapered\ load} = \sqrt{\rho_{max} / \rho_{min}}$$

If $d_M - d_m$ equals one quarter of a wavelength or an odd multiple thereof, calculate

$$\rho_{residual} = \sqrt{\rho_{max} / \rho_{min}}$$

$$\rho_{tapered\ load} = \sqrt{\rho_{max} \rho_{min}}$$

If it is desired to check results, record minimum signal (as a VSWR) obtained in step 6. Using this and the ρ_{max} obtained in step 3, calculate:

$$\rho_{residual} = \frac{\rho_6 + 1}{\rho_6 - 1 + 2 \frac{\rho_6}{\rho_{max}}}$$

CHAPTER VI

EXPERIMENTAL RESULTS

All of the methods discussed in Chapter I were experimentally evaluated. The major disadvantages and advantages of each of these methods were discussed to a limited extent in Chapter I. In general, it was found that Methods 1, 2, and 3 were not suitable due to poor repeatability. Since this thesis is primarily concerned with the Movable Coaxial Load Method the experimental results of these methods will not be presented. The references listed for these methods present a considerable amount of experimental data.

As a laboratory procedure the movable load method was found to be very simple in operation. The positioning of the load for maximum VSWR was not critical, and with increased familiarity with the equipment, required but a few moments. It was found that a moving load with a VSWR in the neighborhood of 1.05 was easier to manipulate than one with a VSWR of 1.02. This was due to the fact that a near-to-perfect moving load has a very small effect when positioned in the brass barrel. Also if the residual VSWR is small and if the load has a small VSWR the null is not very well defined, which increases the difficulty of obtaining the correct phase relationships.

Several commercial slotted lines were evaluated for residual VSWR. All of the slotted lines evaluated were originally supplied with type "N" connectors. Since this project was primarily concerned with type "C" connectors all of the slotted lines were either equipped with adapters or refitted with type "C" connectors: therefore, the residual VSWR obtained is not indicative of the residual VSWR as stated by the manufacturer. Supplementary data taken with type "N" connectors indicate a lower residual VSWR.

The experimental curves for three commercial slotted lines are presented in Figures 10, 11 and 12. From the curves it can be seen that phase relationships in the connectors and adapters cause the residual VSWR to maximize and minimize as the frequency is varied. The Hewlett-Packard line had the smoothest curve; however, it was the slotted line which was refitted with type "C" connectors. The other lines utilized adapters, since they were not readily converted to type "C".

To double check the accuracy of the "Movable Load Method" the "Perfect Load Method" was also used. The results of the two methods are plotted together for comparison purposes. The two methods agree very closely considering the type of measurement involved. As stated previously the Perfect Load Method is an approximate method, but a very good one. The close agreement between the two methods indicates that the Movable Coaxial Load Method is a valid method of

Several commercial slotted lines were evaluated for residual VSWR. All of the slotted lines available were originally supplied with type "N" connectors. Since this project was primarily concerned with type "C" connectors all of the slotted lines were either equipped with adapters or refitted with type "C" connectors; therefore, the residual VSWR obtained is not indicative of the residual VSWR as stated by the manufacturer. Supplementary data taken with type "N" connectors indicate a lower residual VSWR.

The experimental curves for three commercial slotted lines are presented in Figures 10, 11 and 12. From these curves it can be seen that phase relationships in the connectors and the line cause the residual VSWR to maximize and minimize as the frequency is varied. The Hewlett-Packard line had the lowest output; however, it was the slotted line which was refitted with type "C" connectors. The other lines utilized adapters since they were not readily converted to type "C".

To double check the accuracy of the "Movable Load Method" the "Perfect Load Method" was also used. The results of the two methods are plotted together for comparison purposes. The two methods agree very closely considering the type of measurements involved. As stated previously the Perfect Load Method is not an absolute method, but a very good one. The close agreement between the two methods indicates that the Movable Load Method is a valid method.

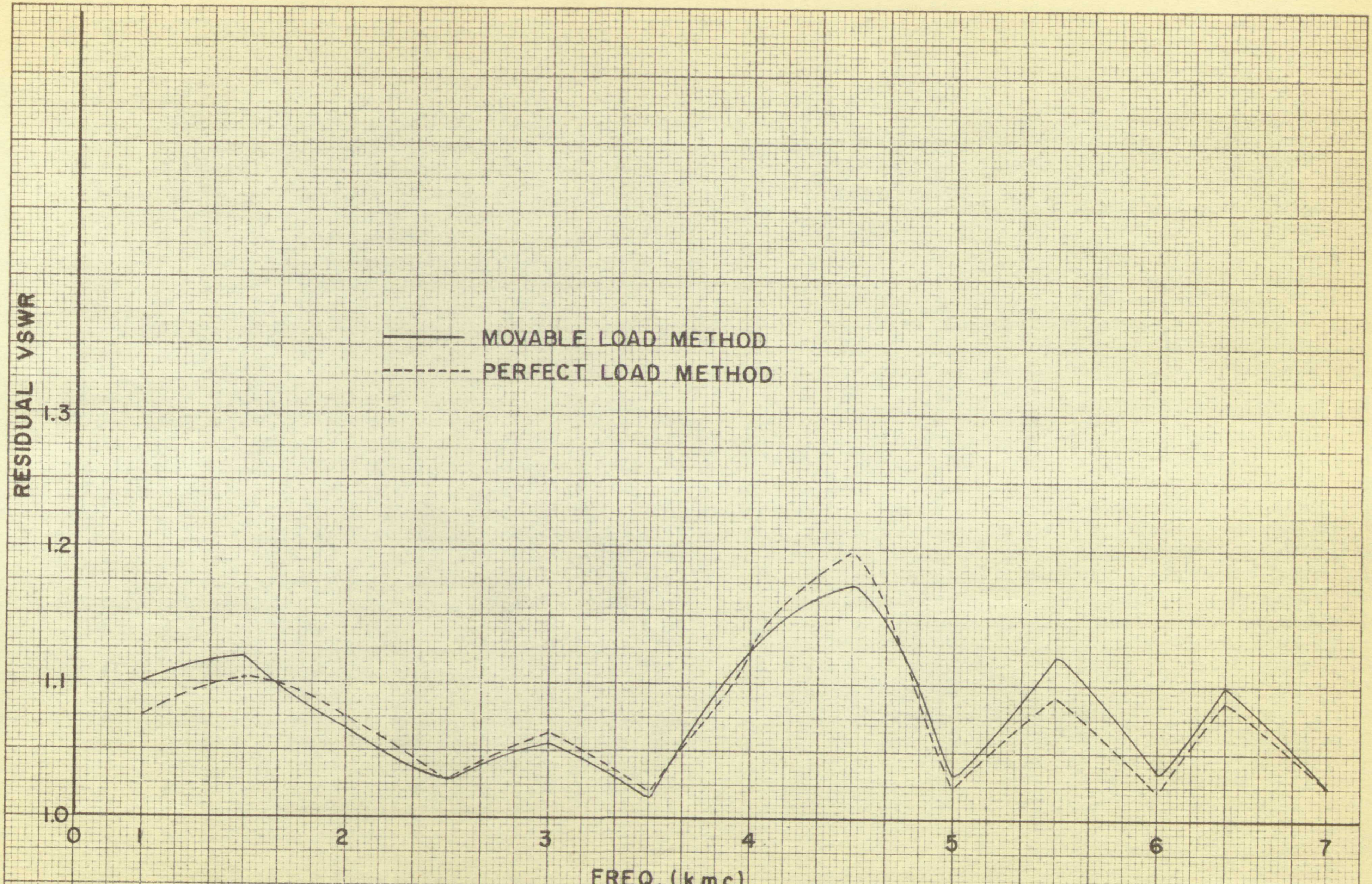

FIG. 10 – RESIDUAL VSWR PRD-215 SLOTTED LINE, SERIAL NO. 175.

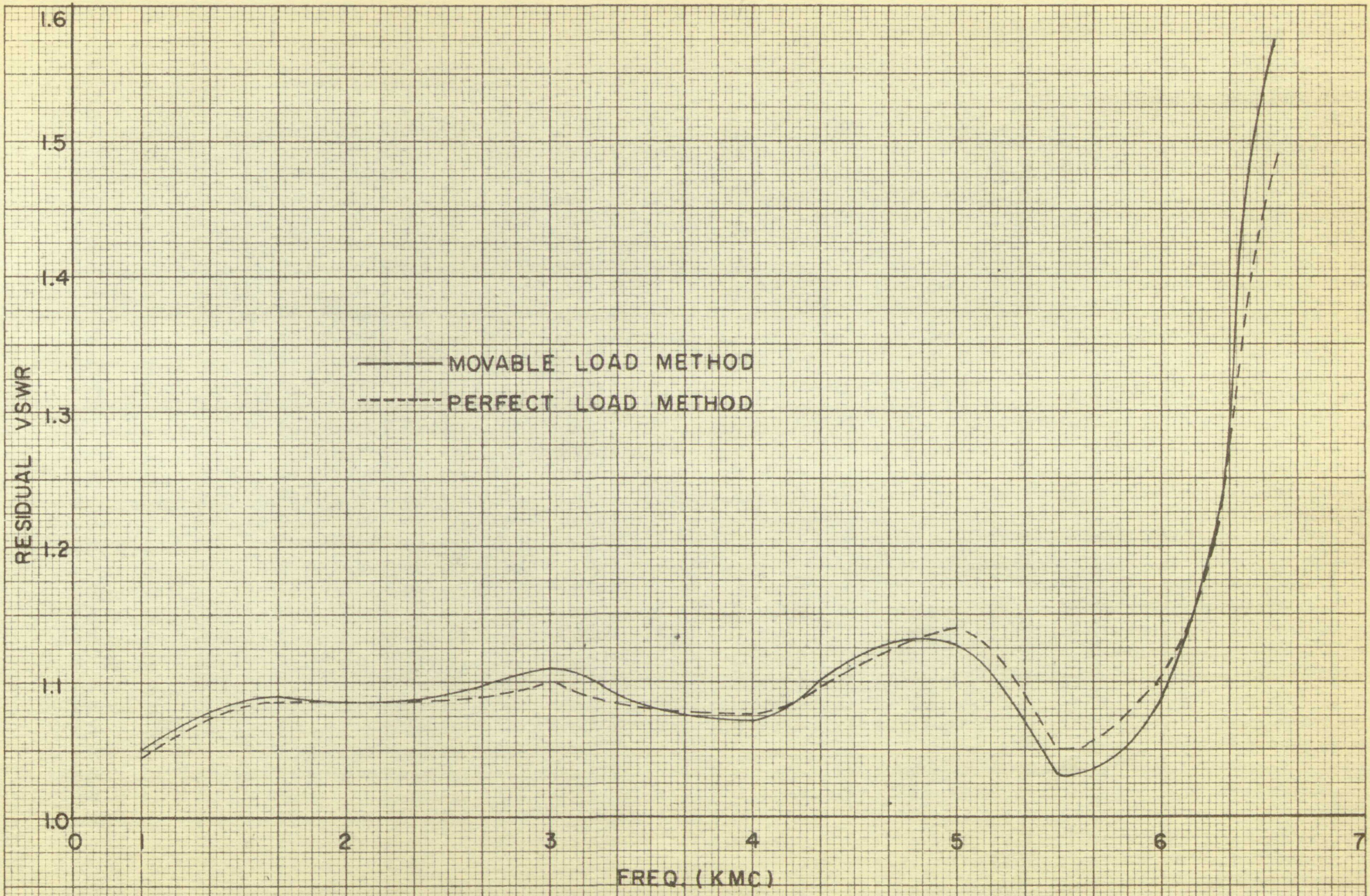

FIG. 11 - RESIDUAL VSWR HEWLETT-PACKARD 805 SLOTTED LINE, SERIAL NO 898.

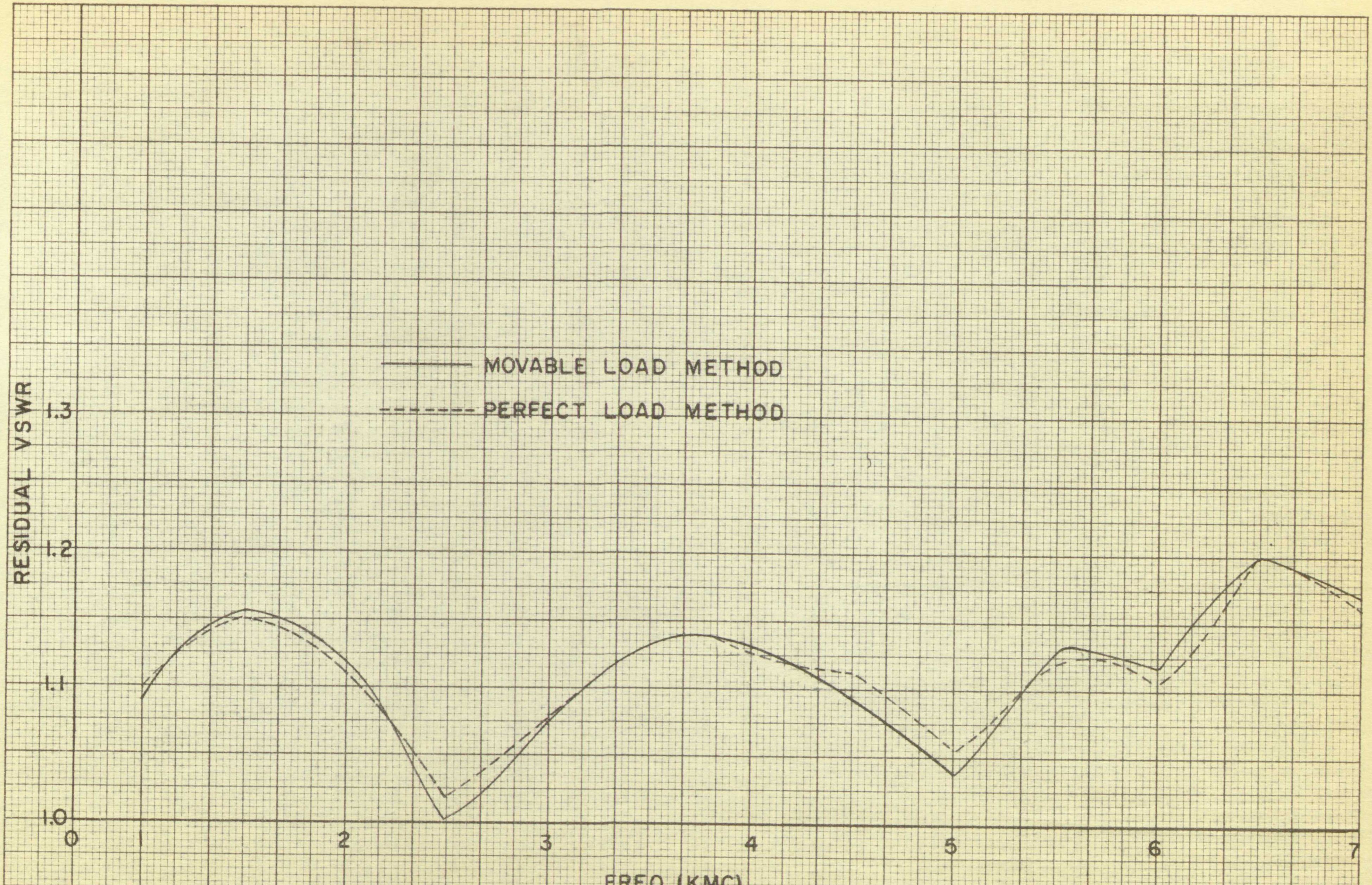

FIG 12 - RESIDUAL VSWR FR N 101A SLOTTED LINE, SERIAL NO. 111

determining the residual VSWR of a slotted line. Therefore, the main objective of the thesis was fulfilled.

More exhaustive tests were run in an effort to determine repeatability and sensitivity of the method to connector or adapter deterioration. From these tests it was found that the repeatability of the method when using the same movable load was very good. Also the method was sensitive enough to detect a separation of .010" of the centerpin from the connector body.

As the theory predicted the VSWR of the movable load did not effect the residual VSWR of the slotted line. Although one would not use a movable load having an extremely large or small VSWR, since either one of these conditions tends to increase the time required for determining the maximum VSWR.

determining the residual VSWR of the slotted lines. Therefore, the main objective of the thesis was fulfilled.

More exhaustive tests were run in an effort to determine the repeatability and sensitivity of the method to connector or line deterioration. From these tests it was found that the repeatability of the method when using the same [illegible] was very good. Also the method was sensitive enough to [illegible] of the centerpin from its [illegible].

As the theory predicted the VSWR of the movable load did not effect the residual VSWR of the slotted line. Although one would not use a movable load having [illegible], since either one of these conditions would [illegible] for determining the [illegible] VSWR.

CHAPTER VII

SUMMARY AND CONCLUSIONS

I. SUMMARY

The residual VSWR of a slotted line is caused by reflections from imperfect matching elements, adapters or connectors fitted to a slotted line. Therefore, when the line is terminated in its characteristic impedance a residual VSWR is present in the slotted section. It was proven that a movable coaxial load terminating the slotted section could be positioned to obtain a maximum and minimum VSWR. This was due to the fact that the reflection from the load could be adjusted to be in or out of phase with the residual reflection from the discontinuities.

It was further proven that the maximum and minimum VSWR obtained allowed one to calculate the residual VSWR of the slotted section independent of the VSWR of the moving load. In effect, the calculated residual VSWR would be the VSWR present in the line if it could be terminated in its exact characteristic impedance.

The Movable Coaxial Load Method is an original adaptation of current methods described in the literature. Most of the current methods that are theoretically exact utilize a long length of coaxial cable, which contributes to the poor repeatability obtainable by such methods.

Since the Movable Coaxial Load Method requires a movable coaxial load, one had to be designed and constructed, due to the fact that one is not manufactured commercially. The movable load constructed was described in detail. A method commonly known as the Perfect Load also utilizes a moving load and is described in the reference given; however, this method was primarily applied to waveguide slotted sections since the author of the article is employed by a firm manufacturing a waveguide movable load.

To verify the validity of the Movable Load Method it was compared to the Perfect Load Method, since the same movable load suffices for both methods. The results indicated very good agreement.

II. CONCLUSIONS

The project provided a very simple method for determining the residual VSWR of a slotted line. It proved to be the least time consuming and the most accurate of all the methods investigated.

One important point should be brought out at this time, and that is that the residual VSWR as determined by any of the methods is somewhat arbitrary. This is brought about by the fact that all the methods theoretically determine the residual VSWR independent of the <u>load</u> terminating the slotted section. However, none of the methods determine the residual VSWR independent of the <u>terminating line</u>. Thus one is left the choice of specifying the dimensions of the terminating

50 ohm transmission line, whether it be a coaxial cable for the current methods, or a brass barrel for the Movable Load Method. Several brass barrels housing a movable load could all be 50 ohms but differ in diameters, since it is the ratio of the inner and outer conductor that determines the characteristic impedance, and not the individual diameters. Therefore, it is arbitrary as to what these diameters should be, other than their ratio. The brass barrel designed for the movable load used in this project was designed to fit a type "C" connector with the smallest physical discontinuity; however, it is feasible to expect that a brass barrel could be designed which would give a smaller residual VSWR for the slotted section.

This rather arbitrary point is not of too much importance in many applications, where one is mainly interested in determining the difference between two identical slotted lines, or the deterioration of one slotted line.

The important feature of the Movable Coaxial Method is that it is entirely independent of the movable load, and thus it is independent of any change in the VSWR of the load, such as, due to temperature, humidity or physical damage. The advantages over the current methods are simplicity, ease of operation and accuracy.

The method is also useful in the testing and designing of coaxial connectors and adapters, and in the design of slotted lines.

CHAPTER VIII

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