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PERATING INSTRUCTIONS

TYPE 874-LBA

SLOTTED LINE

NERAL RADIO COMPANY

SPECIFICATIONS

Characteristic Impedance:	50 ohms, ±1%.
Probe Travel:	50 cm, scale calibrated in mm.
Scale Accuracy:	±(0.1 mm +0.05%).
Frequency Range:	300 to 5000 Mc. Operation below 300 Mc possible by use of Type 874 Air Lines. Can be used with reduced accuracy to 7000 Mc.
Accuracy:	Constancy of probe penetration, ±1½%.
Residual VSWR:	Less than 1.025 at 1000 Mc, less than 1.07 at 4000 Mc.
Accessories Supplied:	Storage box and spare drive cable.
Accessories Required:	Adjustable Stub (Type 874-D20) for tuning the crystal rectifier when audio-frequency detector or microammeter is used; suitable detector and generator; one each Type 874-R22 Flexible Line and Type 874-R34 Patch Cord for generator and detector connections.
Other Accessories Available:	See List of Type 874 Components at the rear of this manual.
Dimensions:	26 by 4½ by 3½ in., over-all.
Weight:	8 lb.

U.S. Patent No. 2,548,457.

Several copies of Smith Charts are supplied with the Slotted Line. Additional copies can be obtained from General Radio at the following prices:

Quantity	Price	Quantity	Price
50	$2.00	500	$14.00
100	3.75	1000	25.00
250	7.00	2000	47.00

When ordering, please specify Impedance Coordinates (Form 756-Z), Admittance Coordinates (Form 756-Y), Normalized Coordinates (Form 756-N), or Normalized Coordinates with Expanded Center (Form 756-NE).

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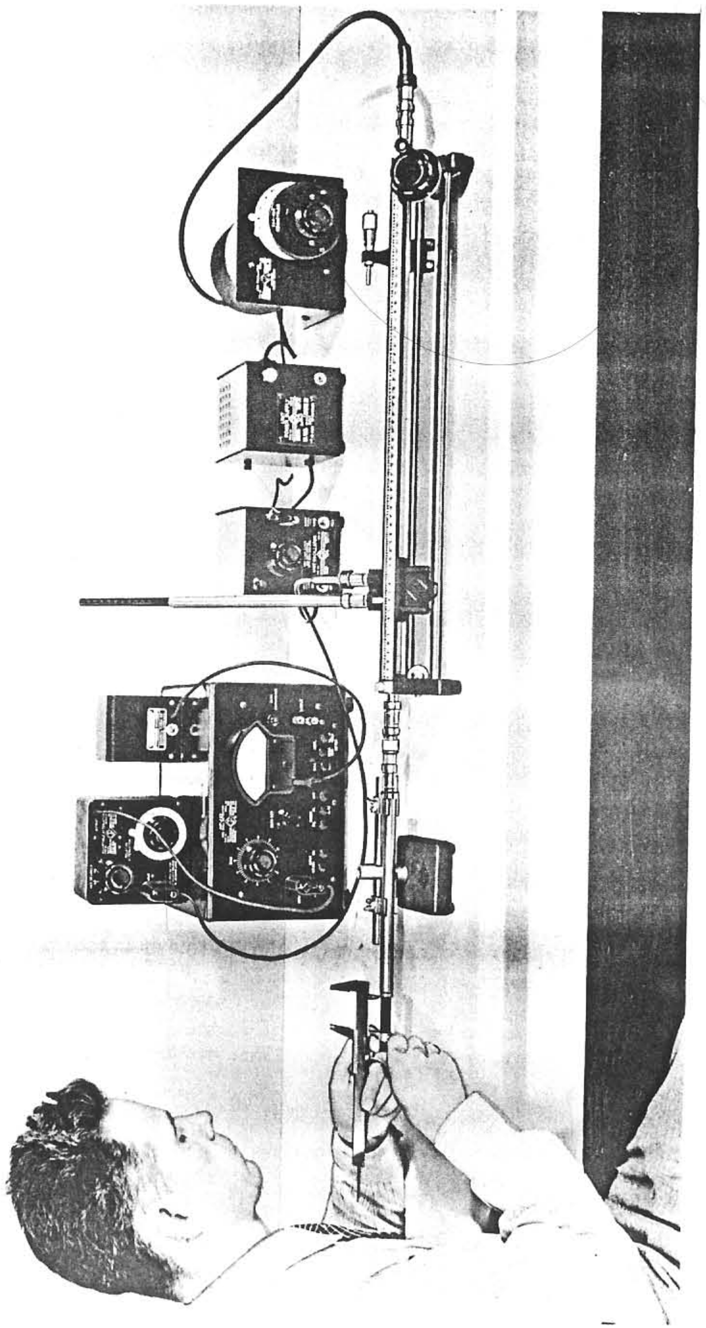


View of set-up with the Type 874-LBA Slotted Line for measurement of the VSWR of Type 874-QN Adaptors, using the sliding short-circuit method. The Type 874-QN Adaptors are used for connecting components fitted with Type N Connectors to devices fitted with Type 874 Connectors.

OPERATING INSTRUCTIONS

for

TYPE 874-LBA SLOTTED LINE

Section 1.0 General Description

One of the important basic measuring instruments used at ultra-high frequencies is the slotted line. With it, the standing-wave pattern of the electric field in a coaxial transmission line having a known characteristic impedance can be accurately determined. From a knowledge of the standing-wave pattern several characteristics of the circuit connected to the load end of the slotted line can be obtained. For instance, the degree of mismatch between the load and the transmission line can be calculated from the ratio of the amplitude of the maximum of the wave to the amplitude of the minimum of the wave, which is called the voltage standing-wave ratio, VSWR. The load impedance can be calculated from the standing-wave ratio and the position of a minimum point on the line with respect to the load. The wavelength of the exciting wave can be measured by obtaining the distance between minima, preferably with a lossless load to obtain the greatest resolution, as successive minima or maxima are spaced by one-half wavelengths. The properties outlined above make the slotted line valuable for many different types of measurements on antennas, components, coaxial elements, and networks.

The Type 874-LBA Slotted Line is designed to measure the standing-wave pattern on a coaxial transmission line having a 50-ohm characteristic impedance over a frequency range from about 300 to 5000 Mc. A small probe mounted on a sliding carriage extends through a slot into the region between the inner and outer conductors of a coaxial line and samples the electric field in the line. The probe is connected to a detector, and the variation in electric field intensity, and hence the voltage along the line, can be determined by sliding the carriage along the line while noting the output of the detector.

Section 2.0 Theory

2.1 CHARACTERISTIC IMPEDANCE AND VELOCITY OF PROPAGATION

A transmission line has uniformly distributed inductance and capacitance, as shown in Figure 1. The series resistance due to conductor losses and shunt resistance due to dielectric losses are also uniformly distributed, but will be

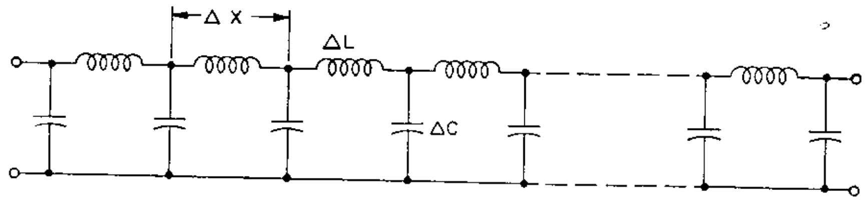


Figure 1. Circuit showing the distribution of inductance and capacitance along a transmission line.

neglected for the present. The square root of the ratio of the inductance per unit length, L, to the capacitance per unit length, C, is defined as the characteristic impedance, Z_0, of the line.[1]

$$Z_0 = \sqrt{\frac{L}{C}} \quad (1)$$

In the next paragraph, transmission-line behavior will be discussed in terms of electromagnetic waves traveling along the line. The waves travel with a velocity, v, which depends on L and C in the following manner:

$$v = \frac{1}{\sqrt{LC}} \quad (2)$$

If the dielectric used in the line is air and the permeability is unity, the product of L and C for any uniform line is always the same and results in a velocity equal to the velocity of light, c, (3×10^{10} cm/sec). If the dielectric has an effective dielectric constant, K, greater than unity, the velocity of propagation will be the velocity of light divided by the square root of the effective dielectric constant.

$$v = \frac{c}{\sqrt{K}} \quad (3)$$

The relationship between frequency, f, and wavelength, λ, in the transmission line is

$$\lambda f = v \quad (4a)$$

$$f = \frac{v}{\lambda} \quad (4b)$$

$$\lambda = \frac{v}{f} \quad (4c)$$

1 As indicated in footnote 2, this is an approximation which is valid if line losses are low. The approximation gives satisfactory results for most practical applications at high frequencies.

If the dielectric is air and the permeability is unity,

$$\lambda f = 3 \times 10^{10} \text{ cm./sec.} \quad (4d)$$

if λ is in centimeters and f is in cycles per second.

2.2 TRAVELING AND STANDING WAVES

The performance of a transmission line having a uniform characteristic impedance can be explained using a wave approach in which an electromagnetic wave is considered which travels along the line from the generator to the load where all or a portion of it may be reflected with or without a change in phase, as shown in Figure 2a. The reflected wave travels in the opposite direction along the line back toward the generator. The phases of these waves are retarded linearly 360° for each wavelength traveled.

The wave traveling from the generator is called the incident wave, and the wave traveling toward the generator is called the reflected wave. The combination of these two traveling waves produces a stationary interference pattern on the line which is called a standing wave, as shown in Figure 2b. The maximum amplitude of the standing wave occurs when the incident and reflected waves are in phase, or an integer multiple of 360° out of phase. The minimum amplitude occurs when the two waves are 180°, or an odd integer multiple thereof, out of phase. The amplitude of the standing wave at other points along the line is the vector sum of incident and reflected waves at each other point. Successive minima and maxima are spaced, respectively, a half-wavelength along the line, as shown in the figure.

The magnitude and phase of the reflected wave at the load relative to the incident wave are functions of the load impedance. For instance, if the load impedance is the same as the characteristic impedance of the transmission line, the incident wave is totally absorbed in the load and there is no reflected wave. On the other hand, if the load is lossless, the incident wave is always completely reflected with no change in amplitude but with a change in phase.

A traveling electromagnetic wave actually consists of two component waves, a voltage wave and a current wave. The ratio of the magnitude and phase of the incident voltage wave, E_i, to the magnitude and phase of the incident current wave, I_i, is always equal to the characteristic impedance, Z_0. The reflected waves travel in the opposite direction from the incident waves, and consequently the ratio of the reflected voltage wave, E_r, to the reflected current wave, I_r, is $-Z_0$. Since the characteristic impedance in most cases is practi-

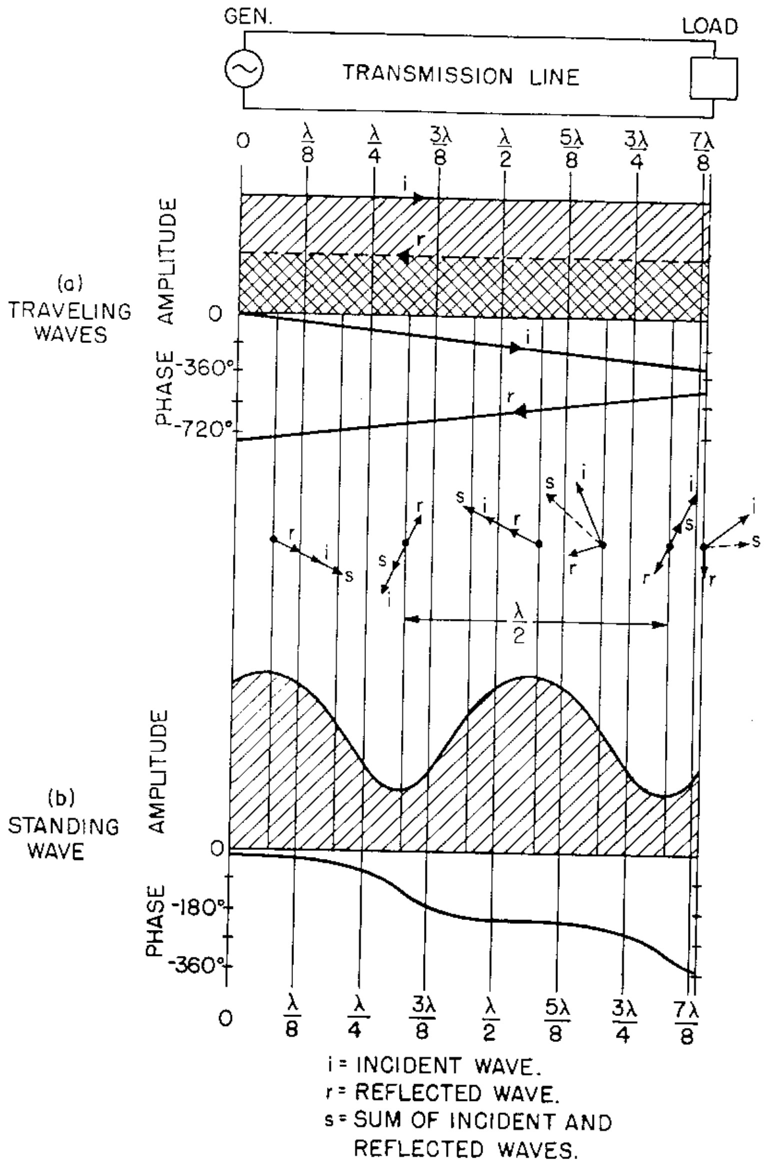


Figure 2. (a) Chart showing the variations in the amplitude and phase of incident and reflected waves along a transmission line. (b) The vector combination of the incident and reflected waves at various points along the line is illustrated and the resultant standing wave produced by the combination of the two waves is plotted.

cally a pure resistance,[2] the incident voltage and current waves are in phase with each other and the reflected voltage and current waves are 180° out of phase.

$$\frac{E_i}{I_i} = Z_o \quad (5a)$$

$$\frac{E_r}{I_r} = -Z_o \quad (5b)$$

Equations (5a) and (5b) are valid at all points along the line.

The magnitude and phase of the reflected voltage wave, E_r, relative to incident wave, E_i, at the load is called the reflection coefficient, Γ, which can be calculated from the expression

$$\Gamma = \frac{Z_x - Z_o}{Z_x + Z_o} = \frac{Y_o - Y_x}{Y_o + Y_x} \quad (6)$$

$$E_r = E_i \Gamma \quad \text{at the load} \quad (7a)$$

$$I_r = -I_i \Gamma \quad \text{at the load} \quad (7b)$$

where Z_x and Y_x are the complex load impedance and admittance, and Z_o and Y_o are the characteristic impedance and admittance of the line. ($Y_o = \frac{1}{Z_o}$).

2.3 LINE IMPEDANCE

If the line is terminated in an impedance equal to the characteristic impedance of the line, there will be no reflected wave, and $\Gamma = 0$, as indicated by Equation (6). The voltage and current distributions along the line for this case are shown in Figure 3.

If the line is open-circuited at the load, the voltage wave will be completely reflected and will undergo no phase shift on reflection, as indicated by

2

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{L}{C} x \frac{1 - j\frac{R}{\omega L}}{1 - j\frac{G}{\omega C}}} \cong \sqrt{\frac{L}{C}}$$

where L is the inductance per unit length in henries, C is the capacitance per unit length in farads, R is the series resistance per unit length in ohms, and G is the shunt conductance per unit length in mhos. The approximation is valid when the line losses are low, or when $\frac{R}{L} = \frac{G}{C}$.

Equation (6), ($Z_x = \infty$), while the current wave will also be completely reflected but will undergo a 180° phase shift on reflection, as shown in Figure 4. If the line is short-circuited, the current and voltage roles are interchanged and the impedance pattern is shifted $\lambda/4$ along the line. The phase shifts of the voltage and current waves on reflection always differ by 180° as the reflected wave travels in the opposite direction from the incident wave. A current maximum, therefore, always occurs at a voltage minimum, and vice versa.

The voltage at a maximum of the standing-wave pattern is $|E_i| + |E_r|$ or $|E_i|(1 + |\Gamma|)$ and at a minimum is $|E_i| - |E_r|$ or $|E_i| \times (1 - |\Gamma|)$. The ratio of the maximum to minimum voltages, which is called the voltage standing-wave ratio, VSWR, is

$$\text{VSWR} = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (8a)$$

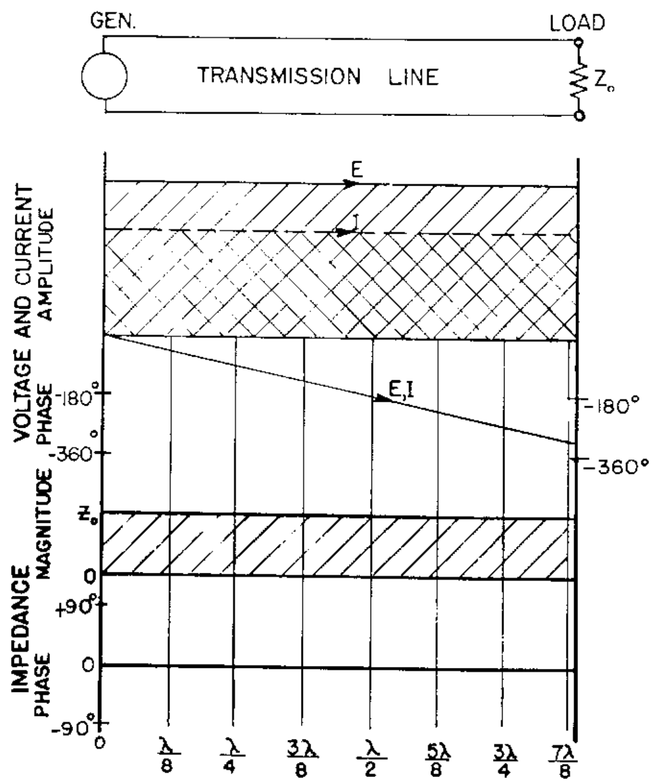


Figure 3. Chart showing voltage and current waves along a transmission line terminated in its characteristic impedance. Note the absence of reflected waves and that the impedance is constant and equal to the characteristic impedance at all points along the line.

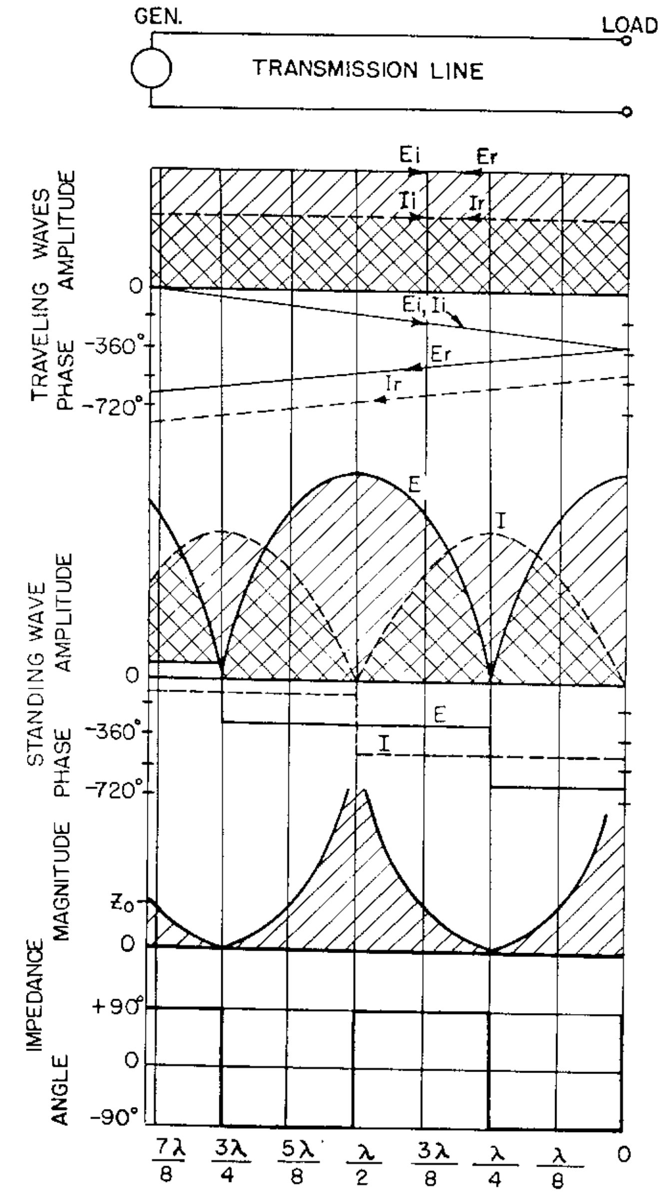


Figure 4. Chart showing voltage and current waves along a transmission line terminated in an open-circuit. Note that the minima of the voltage waves occur at the maxima of the current waves, and vice versa, and that the separation of adjacent minima for each wave is a half-wavelength. The variation in the magnitude and phase angle of the impedance is also shown.

The standing-wave ratio is frequently expressed in decibels, in which case it is referred to as SWR.

$$SWR = 20\log_{10}\frac{E_{max}}{E_{min}} \quad (8b)$$

The impedance, Z_p, seen looking towards the load at various points along a uniform lossless line, is the ratio of the magnitude and phase of the effective voltage at the point in question to that of the effective current at the same point and varies along the line in a cyclical manner, repeating each half-wavelength of the line, as shown in Figure 4.

At a voltage maximum on the line, the incident and reflected voltage waves are in phase, and the incident and reflected current waves are 180° out of phase with each other. Since the incident voltage and incident current waves are always in phase (assuming Z_o is a pure resistance), the effective voltage and current at that point are in phase, and the effective impedance at that point is pure resistance. At a voltage minimum, the two voltage waves are opposing and the two current waves aiding, and again the effective impedance is a pure resistance. At a voltage minimum, the resistance is equal to the characteristic impedance of the line divided by the VSWR, and, at a voltage maximum, it is equal to the characteristic impedance multiplied by the VSWR.

$$R_{p\,max} = Z_o \times (VSWR) \quad (9a)$$

$$R_{p\,min} = \frac{Z_o}{VSWR} \quad (9b)$$

The impedance, Z_p, at any point along the line is related to the load impedance by the expression

$$Z_p = Z_o \times \frac{Z_x + jZ_o\tan\theta}{Z_o + jZ_x\tan\theta} \quad (10a)$$

$$Y_p = Y_o \times \frac{Y_x + jY_o\tan\theta}{Y_o + jY_x\tan\theta} \quad (10b)$$

where Z_x and Y_x are the complex load impedance and admittance, Z_o and Y_o are the characteristic impedance and admittance of the line, and θ is the electrical length of line between the load and the point along the line at which the impedance is measured. (See Figure 5.)[3] The effective length, ℓ_e, is proportional to the physical length, ℓ, multiplied by the square root of the effective dielectric constant, K, of the insulating material between the inner and outer conductors.

$$\ell_e = \ell\sqrt{K} \quad (11a)$$

$$\theta = \frac{\ell_e}{\lambda} \text{ wavelengths} \quad (11b)$$

$$\theta = \frac{2\pi\ell}{\lambda}\sqrt{K} \text{ radians} \quad (11c)$$

$$\theta = \frac{360\ell}{\lambda}\sqrt{K} \text{ degrees} \quad (11d)$$

If ℓ is in centimeters,

$$\theta = 0.012 f_{mc}\ell\sqrt{K} \text{ degrees} \quad (11e)$$

2.31 Determination of the Load Impedance from the Impedance at Another Point on the Line: The load impedance, Z_x, or admittance, Y_x, can be determined if the impedance, Z_p, at any point along a lossless line is known. The expressions relating the impedances are:

$$Z_x = Z_o \times \frac{Z_p - jZ_o\tan\theta}{Z_o - jZ_p\tan\theta} \quad (12a)$$

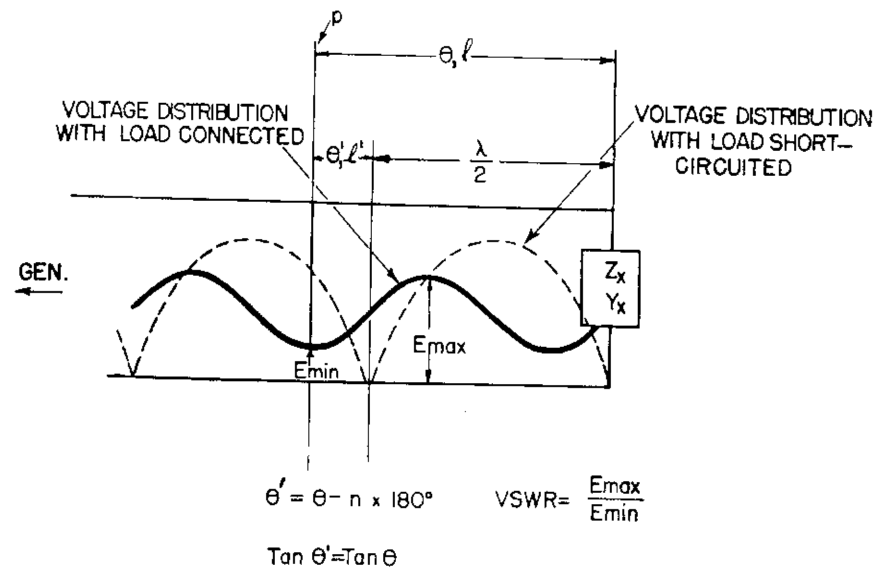


Figure 5. Voltage variation along a transmission line with a load connected and with the line short-circuited at the load.

3 In Figure 5, point 'p' is shown at a voltage minimum. However, Equations (10a) and (10b) are valid for any location of point 'p' on the line.

$$Y_x = Y_o \times \frac{Y_p - jY_o \tan\theta}{Y_o - jY_p \tan\theta} \qquad (12b)$$

If the line loss cannot be neglected, the equations are:

$$Z_x = Z_o \times \frac{Z_p - Z_o \tanh \gamma \ell}{Z_o - Z_p \tanh \gamma \ell} \qquad (13a)$$

$$Y_x = Y_o \times \frac{Y_p - Y_o \tanh \gamma \ell}{Y_o - Y_p \tanh \gamma \ell} \qquad (13b)$$

where $\gamma = \alpha + j\beta$, and
α = attenuation constant in nepers/cm. $= \frac{\text{att. in db/100 ft.}}{26490}$

β = phase constant in radians/cm. $= 2\pi f \sqrt{LC} = \frac{2\pi\sqrt{K}}{\lambda}$

2.32 Determination of the Load Impedance from the Standing-Wave Pattern: The load impedance can be calculated from a knowledge of the VSWR present on the line and the position of a voltage minimum with respect to the load, since the impedance at a voltage minimum is related to the VSWR as indicated by Equation (9b). Equation (9b) can be combined with Equation (12a) to obtain an expression for the load impedance in terms of the VSWR and the electrical distance, θ, between the voltage minimum and the load.

$$Z_x = Z_o \times \frac{1 - j(\text{VSWR}) \tan\theta}{\text{VSWR} - j\tan\theta} \qquad (14a)$$

$$= Z_o \times \frac{2(\text{VSWR}) - j\left[(\text{VSWR})^2 - 1\right] \sin 2\theta}{\left[(\text{VSWR})^2 + 1\right] + \left[(\text{VSWR})^2 - 1\right] \cos 2\theta} \qquad (14b)$$

Since in a lossless line the impedance is the same at half-wavelength intervals along the line, θ can be the electrical distance between a voltage minimum and any multiple of a half-wavelength from the load (see Figure 5). Of course, if the half-wavelength point used is on the generator side of the voltage minimum located with the load connected, θ will be negative. The points corresponding to half-wavelength distances from the load can be determined by short-circuiting the line at the load and noting the positions of the voltage minima on the line. The voltage minima will occur at multiples of a half-wavelength from the load.

If the VSWR is greater than 10 and $\frac{\tan\theta}{\text{VSWR}} < 0.1$, the following approximation of Equation (14b) gives good results.

$$R_x \cong \frac{Z_o}{\text{VSWR} \cos^2\theta} \qquad (15a)$$

$$X_x \cong -Z_o \tan\theta \qquad (15b)$$

2.33 Smith Chart: The calculation of the impedance transformation produced by a length of transmission line using the equations previously presented can be time consuming. Mr. P. H. Smith[4] has devised a chart, shown in Figure 6, which simplifies these calculations. In this chart the circles whose centers lie on the resistance component axis correspond to constant values of resistance and the arcs of circles whose centers lie on an axis perpendicular to the resistance axis correspond to constant values of reactance. The chart covers all values of impedance from zero to infinity and the position of a point corresponding to any given complex impedance can be found from the intersection of the resistance and reactance coordinates corresponding to the resistive and reactive components of the unknown impedance.

The impedance seen looking along the line toward a fixed unknown will travel around a circle with its center at the center of the chart as the distance from the load is increased or decreased. The angular movement around the circle is proportional to the electrical displacement along the line. One complete traverse of the circle will be made for each half-wavelength of travel. The radius of the circle is a function of the VSWR.

2.331 Calculation of Impedance at One Point from the Impedance at Another Point on a Line: If the impedance at one point on a line, say at a point "p," is known, and the impedance at another point a known electrical distance away (for instance, at the load) is desired, the problem can be solved using the Smith Chart in the following manner. First, locate the point on the chart corresponding to the known impedance, as shown in Figure 6. (For example, assume that $Z_p = 20 + j25$ ohms.) Then, draw a line from the center of the chart through Z_p to the outside edge of the chart. If the point at which the impedance is desired is on the load side of the point at which the impedance is known, travel along the WAVELENGTHS TOWARD LOAD scale, from the intersection of the line previously drawn, a distance equal to the electrical distance in wavelengths between the point at which the impedance is known and the point at which it is desired. If the point at which the impedance is desired is on the generator side of the point at which the impedance is known, use the WAVELENGTHS TOWARD GENERATOR scale. (In this example, assume that the electrical distance is 0.11 wavelength toward the load.) Next, draw a circle through Z_p with its center at the center of the chart, or lay out, on the last radial line drawn, a dis-

[4] Smith, P.H., Electronics, Vol. 17, No. 1, pp. 130-133, 318-325, January 1944.

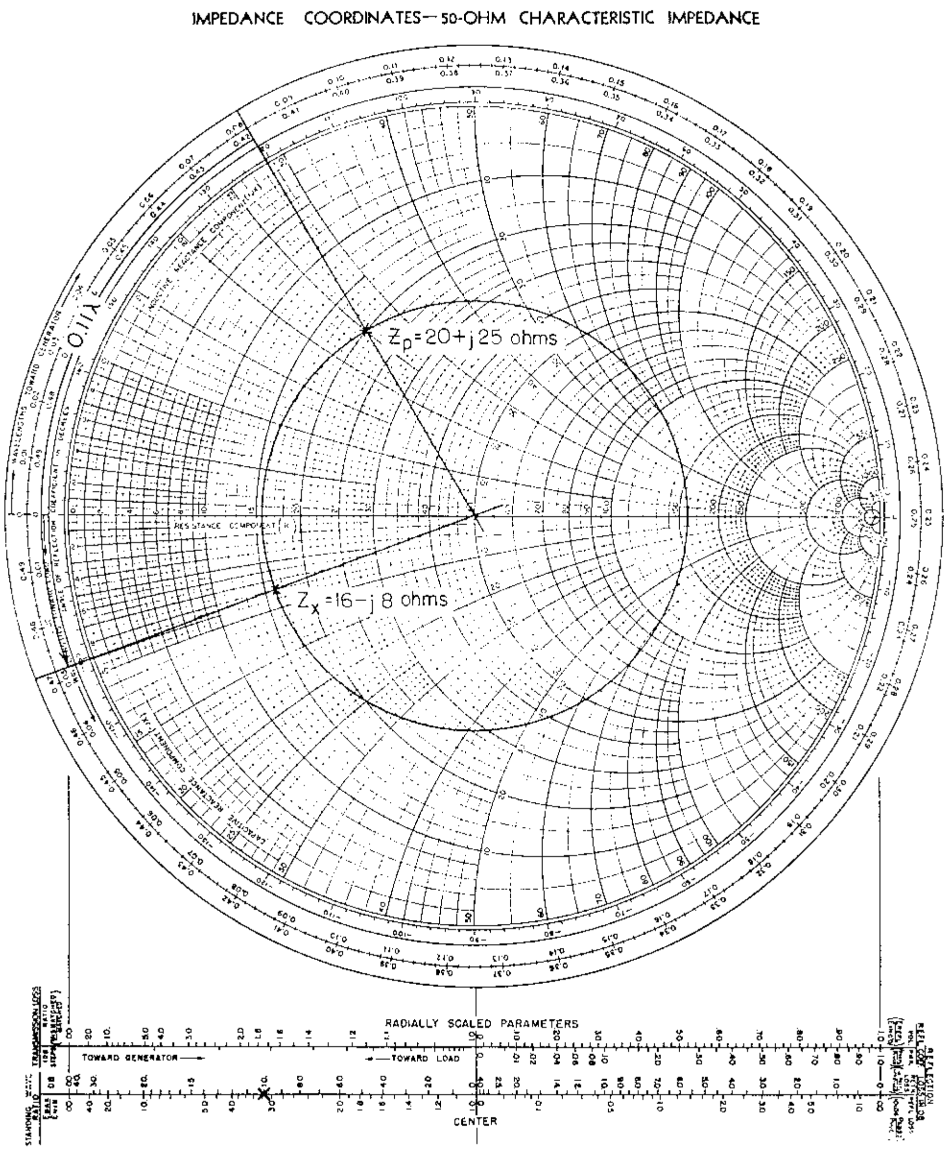


Figure 6. Illustration of the use of the Smith Chart for determining the impedance at a certain point along a line when the impedance a specified electrical distance away is known. In the example plotted, the known impedance, Z_p, is 20 + j25 ohms and the impedance, Z_x, is desired at a point 0.11 wavelength toward the load from the point at which the impedance is known.

tance equal to the distance between Z_p and the center of the chart. The coordinates of the point found are the resistive and reactive components of the desired impedance. (In the example chosen, the impedance is 16 - j8 ohms.)

The VSWR on the line is a function of the distance which the point, corresponding to the impedance, is from the center of the chart. To find the VSWR, lay out the distance on the STANDING WAVE RATIO scale located at the bottom of the chart, and read the VSWR as a ratio, $\frac{E_{max}}{E_{min}}$, or SWR in db off the appropriate scale. (In the example, the VSWR is 3.2 or the SWR is 10.1 db.)

2.332 <u>Calculation of Impedance at the Load from the VSWR and Position of a Voltage Minimum</u>: In impedance measurements in which the voltage standing-wave pattern is measured, the impedance at a voltage minimum is a pure resistance having a magnitude of $\frac{Z_o}{VSWR}$. This point can be plotted on the resistance component axis and a circle having its center at the center of the chart drawn through the point. The impedance at any point along the transmission line must lie on this circle. The load impedance can be determined by traveling around the circle from the original point an angular distance indicated on the WAVELENGTHS TOWARD LOAD scale equal to the electrical distance, expressed as a fraction of a wavelength, between the voltage minimum and the load (or a point a half-wavelength away from the load, as explained in Paragraph 2.32.) If the half-wave point chosen lies on the generator side of the minimum found with the load connected, travel around the chart in the opposite direction, using the WAVELENGTHS TOWARD GENERATOR scale. The radius of the circle can be determined directly from the VSWR expressed as a ratio or the SWR in decibels, if desired, using the scales labeled STANDING WAVE RATIO located at the bottom of the chart.

The example plotted on the chart in Figure 7 shows the procedure for determining the load impedance when the VSWR is 5 to 1, and the electrical distance between the load or a half-wavelength point and a voltage minimum is 0.14 wavelength. The unknown impedance read from the chart is 23 - j55 ohms.

The Smith Chart can also be used when the line between the load and the measuring point is not lossless. The procedure for correcting for loss is outlined in Paragraph 4.61.

NOTE: Additional copies of the Smith Chart, drawn for a 50-ohm system in either impedance or admittance coordinates, are available. The Impedance Chart, similar to the one shown in Figure 6 but printed on transparent paper, is Form 756-Z, and the Admittance Chart, similar to Figure 8, is Form 756-Y. A normalized chart with an expanded center portion for low VSWR measurements is also available, Form 756-NE.

2.333 <u>Conversion from Impedance to Admittance</u>: The transformation between impedance and admittance can be easily made using the chart by advancing around the circle of constant VSWR exactly 0.25 wavelength from the impedance point and multiplying the coordinates of the point obtained by 0.4 to obtain the conductance and susceptance in millimhos, as illustrated in Figure 7. This conversion property is a result of the inversion of impedance every

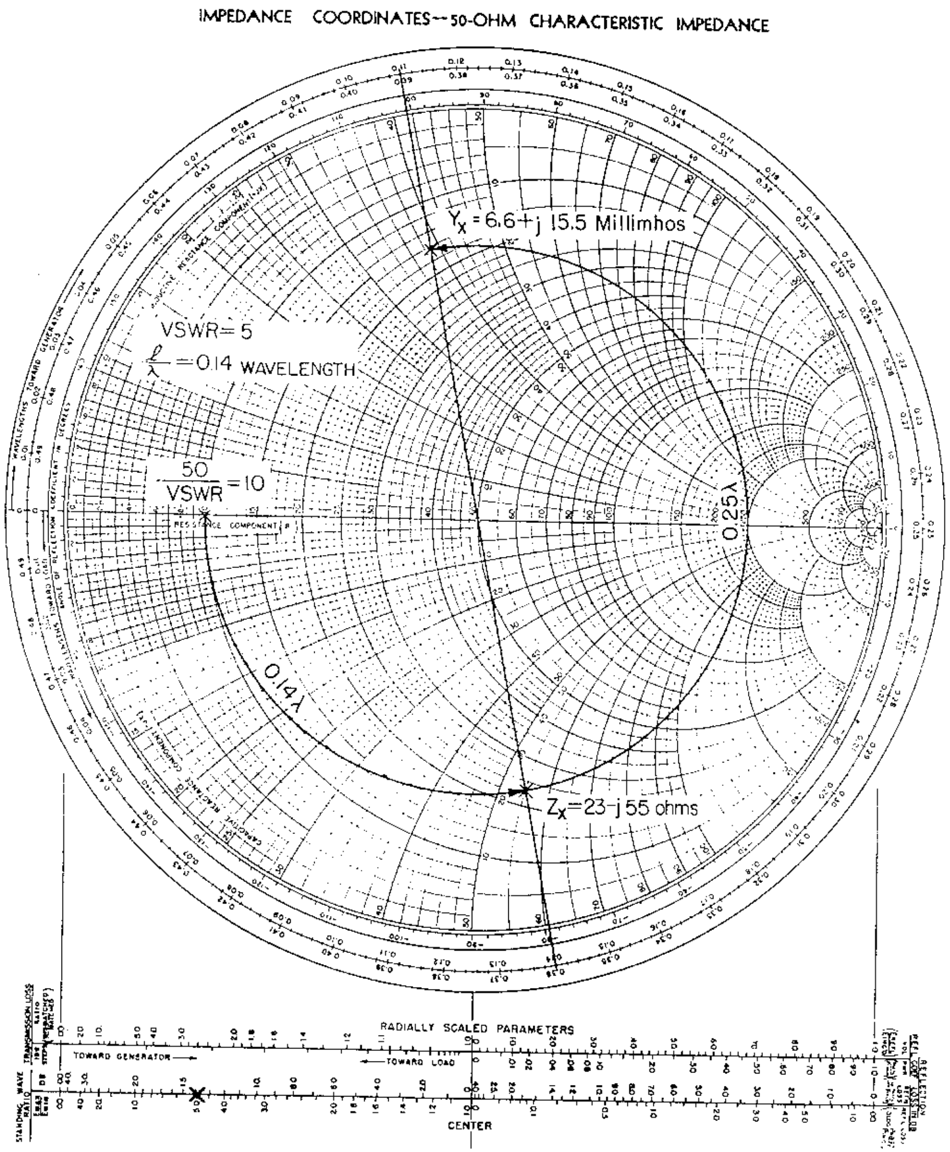


Figure 7. Example of the calculation of the unknown impedance from measurements of the VSWR and position of a voltage minimum, using a Smith Chart. The measured VSWR is 5 and the voltage minimum with the unknown connected is 0.14 wavelength from the effective position of the unknown. A method of determining the admittance of the unknown is also illustrated.

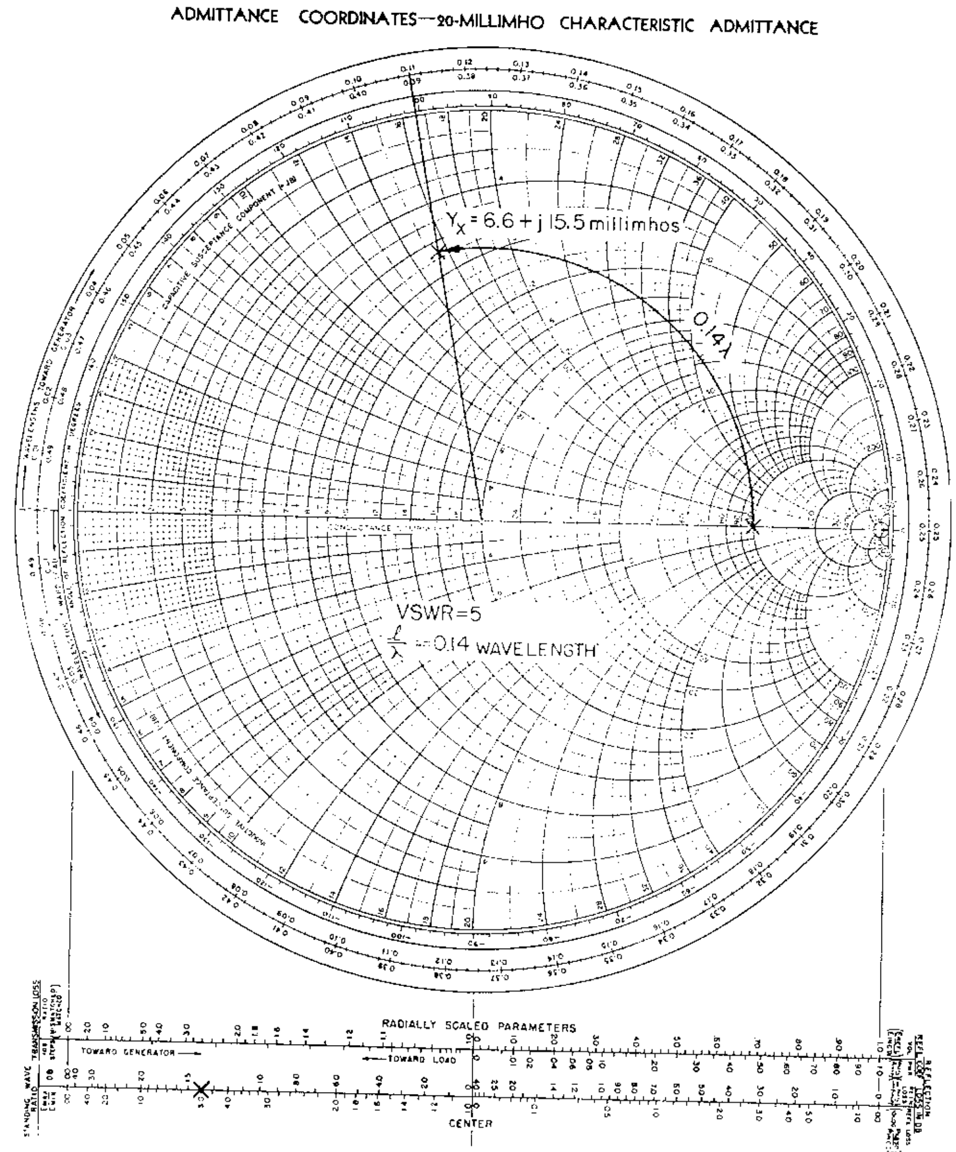


Figure 8. Example of the calculation of the unknown admittance from measurements of the VSWR and the position of a voltage minimum, using the Smith Chart drawn for admittance measurements on lines having characteristic admittances of 20 millimhos (50 ohms).

quarter-wavelength along a uniform transmission line. The impedances at points a quarter-wavelength apart are related by the equation

$$Z_1 = \frac{Z_0^2}{Z_2} \qquad (16a)$$

or

$$Z_1 = Z_0^2 Y_2 \qquad (16b)$$

2.334 Admittance Measurements Using the Smith Chart: The admittance of the unknown can be obtained directly using a normalized Smith Chart, or the chart shown in Figure 8, whose coordinates are admittance components, rather than by the procedure outlined in Paragraph 2.333. When the chart shown in Figure 8 is used, the characteristic admittance, 20 millimhos, is multiplied by the measured VSWR to find the conductance at the voltage minimum and the radius of the corresponding admittance circle on the chart found by plotting the measured conductance directly on the conductance axis. The radius can also be found from the STANDING WAVE RATIO scale located at the bottom of the chart. The electrical distance to the load is found and laid off on the WAVELENGTHS TOWARD LOAD scale, starting at 0.25 wavelength. The coordinates of the point on the VSWR circle corresponding to the angle found on the WAVELENGTHS scale are the conductance and susceptance of the unknown.

The example plotted on the chart is the same as that used for the impedance example of Figure 7.

2.335 Use of Other Forms of the Smith Chart: In some forms of the Smith Chart, all components are normalized with respect to the characteristic impedance to make the chart more adaptable to all values of characteristic impedance lines. **If normalized charts are used, the resistance component value used for the voltage minimum resistance is $\frac{1}{VSWR}$, and the unknown impedance coordinates obtained must be multiplied by the characteristic impedance of the line to obtain the unknown impedance in ohms and, if the admittance is desired, the coordinates corresponding to the admittance should be multiplied by the characteristic admittance.**

The normalized Smith Chart is produced in a slide rule form by the Emeloid Corporation, Hillside, New Jersey.

Section 3.0 Description

3.1 SLOTTED LINE DESIGN

The Type 874-LBA Slotted Line is designed to measure the voltage standing-wave pattern along a coaxial transmission line having a 50-ohm characteristic impedance. The outer conductor is slotted for a length of approximately 50 centimeters, and a small shielded probe extends into the region between the two conductors. The probe is mounted on a carriage which slides along the outside of the outer conductor. The capacitive coupling between the probe and the line can be adjusted over a wide range by varying the penetration of the probe into the inner line. This is accomplished by screwing the probe in or out. Cross-sectional views of the probe arrangement are shown in Figure 9a.

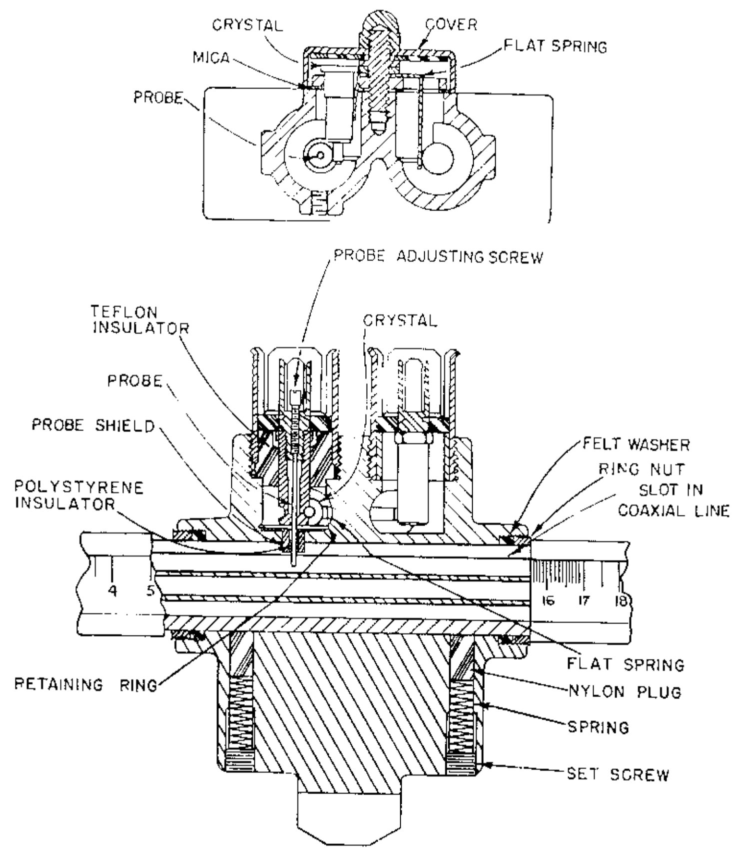


Figure 9a. Cross-sectional views of the carriage on the Type 874-LBA Slotted Line, showing the crystal mount and the adjustable probe.

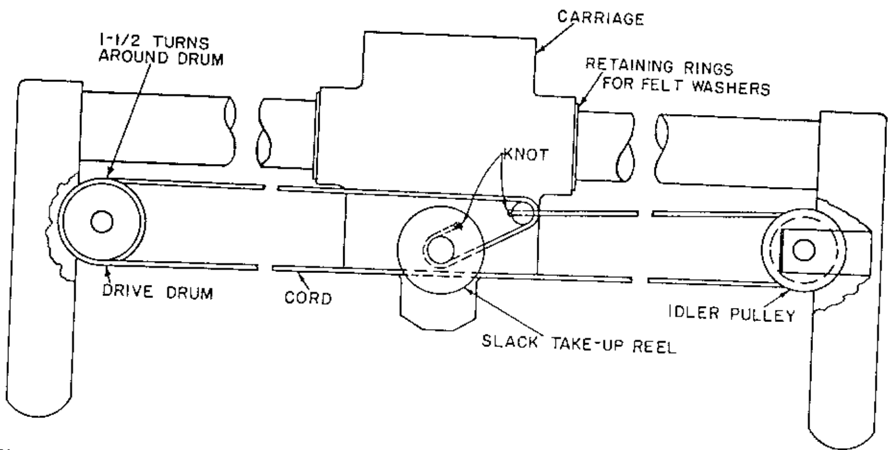


Figure 9b. Backview of drive mechanism showing arrangement of nylon cord.

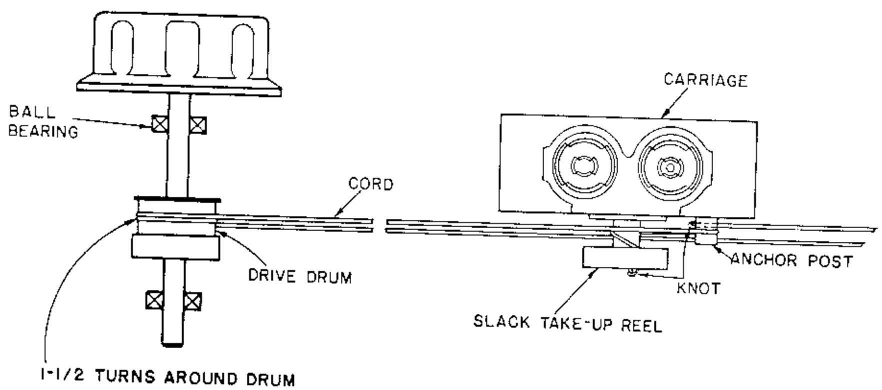


Figure 9c. View from top of carriage of arrangement of nylon cord.

Since the probe is capacitively coupled to the line, the voltage induced in the probe circuit is proportional to the voltage existing between the inner and outer conductors of the line at the probe position.

The carriage is driven by means of a nylon cord which passes around a drum mounted on the casting at one end of the line and around an idler pulley which is mounted on the casting at the other end of the line. The driving knob is attached to the same shaft as the drum. The drive depends upon friction, and one and a half turns of the cord around the drum is sufficient to give a

positive drive. A ratchet-type take-up reel is located on the back of the carriage to permit adjustment of the tension in the cord. Figures 9b and 9c show the cord, drum, and take-up device.

The r-f voltage induced in the probe can be measured by means of a built-in tuned crystal detector and associated indicating equipment as shown in Figures 10 and 11, or by means of an external receiver as shown in Figure 12.

One end of the slotted line is terminated in the circuit under test, usually called the unknown, and the other in the power source. Each end is fitted with a Type 874 Connector which introduces only a very small reflected wave in the line at frequencies up to about 7000 Mc.

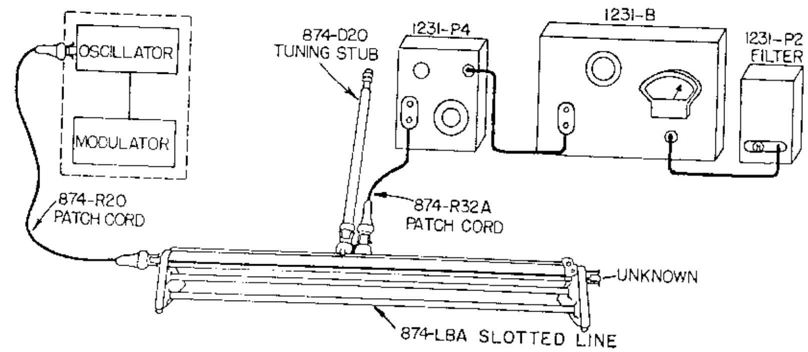


Figure 10. A typical setup for measurements with the Type 874-LBA Slotted Line, using a modulated source. The built-in crystal detector and an external tuned audio amplifier are used to detect the voltage induced in the probe. The probe is tuned by means of the tuning stub shown.

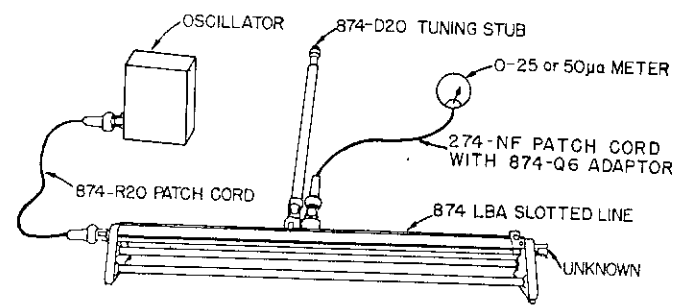


Figure 11. A typical setup for measurements with the Type 874-LBA Slotted Line using an unmodulated source and a microammeter as the indicator.

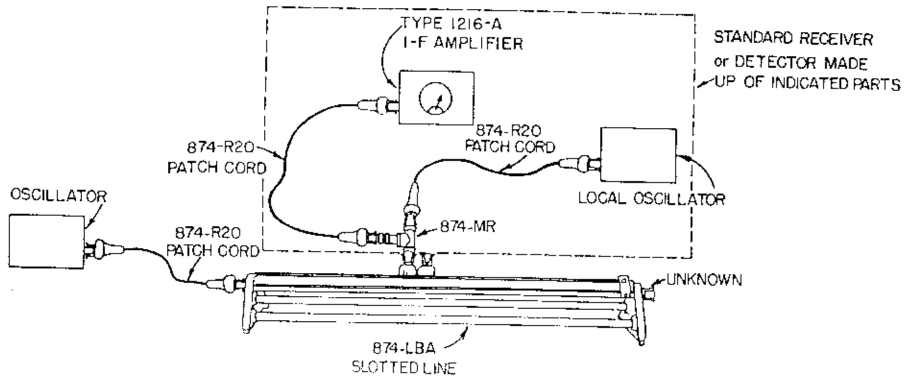


Figure 12. A typical setup for measurements with the Type 874-LBA Slotted Line using an unmodulated source and a superheterodyne detector or receiver.

3.2 GENERATOR

The generator requirements are dependent on the type of detector used and the standing-wave ratio of the load to be measured. Table I is a chart showing several possible combinations of generators and detectors along with advantages and disadvantages of the arrangements. Besides the generators indicated in the table, the Type 1208-A Oscillator can be used from 65 to 500 Mc and the Type 857-A Oscillator from 100 to 500 Mc, although the shielding of the latter is relatively poor and in some cases may cause difficulty.

3.3 DETECTOR

As mentioned previously, either the built-in crystal detector[5] or an external receiver may be used as a detector.

3.31 Crystal Rectifier and Audio Amplifier: The most commonly used detector consists of the built-in crystal rectifier with an external audio amplifier and attenuator as shown in Figure 10. In this case, of course, the oscillator driving the line must be modulated, and for best results, the audio amplifier should be tuned to the modulation frequency. The Type 1231-B Amplifier with the Type 1231-P2 Tuned Circuit and the Type 1231-P4 Attenuator is well suited for this application.

At very low levels, the crystal operates in the so-called square-law region, that is, the rectified output is proportional to the square of the r-f input. At high levels the crystal approaches a linear characteristic. In most cases,

[5] If desired, Type 610-A Bolometer elements, manufactured by Polytechnic Research and Development Co., can be inserted in place of the crystal.

Table I Detector Characteristics

DETECTOR	OSCILLATOR SIGNAL	EQUIPMENT	ADVANTAGES	DISADVANTAGES
Crystal (Built in)	Modulated For frequency range of 250 to 920 Mc, use Type 1209 Oscillator modulated by Type 1214-A Oscillator; Type 1021-AU Standard-Signal Generator can also be used. For frequency range of 900 to 2000 Mc, use Type 1218-A Oscillator square-wave modulated by Type 1210 Oscillator or by Type 1217-A Pulser with Type 1218-A Pulse Amplifier; Type 1021-AW Standard-Signal Generator can also be used.[1]	Audio amplifier with indicating meter (Type 1231-B Amplifier with Type 1231-P2 Filter and preferably Type 1231-P4 Calibrated Attenuator).	1. Good sensitivity if audio amplifier gain adequate. 2. Simple. 3. Well shielded. Leakage in measurement of high SWR's rarely a problem. 4. Performance when used with Type 874-F500 and Type 874-F1000 Low-Pass Filters satisfactory for most measurements. 5. Covers a very wide frequency range.	1. Harmonic rejection poor. May cause trouble in measurement of high SWR's. Can be cured by low-pass filter. 2. If sine-wave modulation is used, frequency modulation usually produced at upper end of oscillator frequency range may cause trouble in measurement of very high SWR's. Square-wave modulation eliminates difficulty.
Crystal (Built in)	CW For frequency range of 250 to 920 Mc, use Type 1209 Oscillator or Type 1021-AU Standard-Signal Generator; For frequency range of 900 to 2000 Mc, use Type 1218-A Oscillator or Type 1021-AW Standard-Signal Generator.[1]	Microammeter with sensitivity of 50 μa or better.	1. Simple. 2. Covers a very wide frequency range.	1. Insensitive, requires large oscillator power. Oscillators referred to do not have adequate output even for moderately high SWR measurements.
Receiver (Type 874-MR Mixer Rectifier)	CW Same as above.	Type DNT-3 or Type DNT-4 Detector Assembly (See Paragraph 3.33.)	1. Good sensitivity. 2. Very well shielded against leakage. 3. Covers a wide frequency range. 4. Good selectivity.	1. Requires several pieces of equipment. However, much of this is usually available in the laboratory.
Receiver (Such as AN/APR4, AN/APR1, etc.)	CW Same as above.	Receiver.	1. Good sensitivity. 2. Good selectivity.	1. Some receivers are not sufficiently well shielded for use at very high frequencies.

[1] Above 2700 Mc, the Type 1220-A Unit Klystron Oscillator can be used.

the crystal is operated in the square-law range. When the Type 1231-B Amplifier and associated filter and attenuator are used, the square-law region[6] with typical crystals extends to r-f inputs with 50% modulation, which produce full-scale deflection of the meter on the amplifier with the amplifier gain set at maximum and the Type 1231-P4 Attenuator set at 30 db. At inputs less than this value, the deviation from the square-law characteristic is less than 1/2 db.

For most accurate results, the ratio of the outputs obtained at a maximum and at a minimum on the line should be measured on the Type 1231-P4 Attenuator, rather than on the meter scale, by measuring the difference in attenuation required to produce the same meter reading for a voltage minimum as for a voltage maximum. If the crystal is operating in the square-law region, the actual db difference in r-f voltage is half the db difference measured by the attenuator or meter.

3.32 Crystal Rectifier and Microammeter: An even simpler detector system consists of the built-in crystal rectifier used with an external microammeter, as shown in Figure 11. In this case, the rectified d-c output of the crystal is measured by connecting a sensitive microammeter between the inner and outer terminals of the right-hand connector on the probe carriage. In most cases, the rectified d-c output is closely proportional to the square of the r-f input at currents up to roughly 50 microamperes. The limit of the square-law region is greatly affected by the resistance of the microammeter since the r-f crystal impedance varies with the d-c bias voltage developed across the meter, and, therefore, for the most accurate results, the law of the detector should be checked at the operating frequency using an r-f attenuator.

The sensitivity of this system is poor, and difficulties are usually encountered in measuring even moderately high VSWR's unless the oscillator output is large, as the probe coupling required may be excessive (see Paragraph 4.3). The simplicity of the system makes it attractive in many cases when low VSWR's are to be measured.

The detector can be used beyond its square-law range by calibrating it, using an r-f attenuator to control accurately the relative input to the line, or actually to adjust the r-f input at the voltage maximum and at the voltage minimum to produce the same meter indication. In the second method, the VSWR can be read from the r-f attenuator and all dependence on the detector response eliminated.

3.33 The Type 874-MR Mixer Rectifier as a Detector: The combination of the Type 874-MR Mixer Rectifier, a local oscillator or signal generator such

[6] The actual response of a crystal can be determined by applying known amounts of r-f power to the slotted line from a signal generator or an oscillator equipped with an accurately calibrated attenuator such as the Type 874-GA Adjustable Attenuator, or by measuring the standing-wave pattern with the line open-circuited and determining the deviation from the theoretical half-sine-wave characteristic.

as a Type 1208 or 1209 Unit Oscillator, and a communications-type receiver or i-f amplifier strip, such as the Type 1216-A I-F Amplifier,[7] shown in Figure 12, comprises an excellent detector, particularly for measuring circuits with high VSWR's, as the sensitivity and harmonic rejection are very good (see Paragraph 4.63). The communications receiver used should have a bandwidth of at least 20 kc to minimize difficulties arising from small drifts of the r-f oscillators. Bandwidths of the order of a megacycle or so, such as are obtained using high-frequency amplifiers, are very desirable for this application. The shielding of this detector is excellent, a property which is useful when measuring radiating systems. Harmonics of the local oscillator frequency can be used to beat with the signal from the slotted line and, hence, the upper frequency limit may be several times the upper frequency limit of the oscillator.

In order to measure VSWR accurately, the output meter, or S meter, on the receiver must be accurately calibrated for relative input, or the receiver output measured. The Type 1216-A Unit I-F Amplifier contains a calibrated attenuator and meter, and differences in signal levels up to 80 db can be accurately measured.

The calibration of the S meter on a receiver used as an i-f amplifier can be checked using a low-frequency signal generator. The indicating meter on an APR-1 or APR-4 i-f amplifier (complete receiver without tuning units) used with the Type 874-MR Mixer Rectifier and an appropriate oscillator provides a much better measurement means, as the indication is closely directly proportional to the i-f input voltage at indications above 1/4 of full scale. The i-f gain control can be calibrated to measure VSWRs too large to be directly measurable on the meter. The step switch on the APR-4 unit is better suited to accurate calibration than the continuously variable control found on the APR-1. The shielding of the combination of the mixer rectifier and the i-f

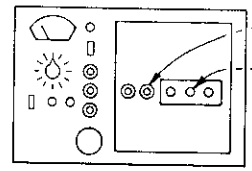


Figure 13. Method of connecting the 30-Mc output of a Type 874-MR Mixer Rectifier to the i-f amplifier in an AN/APR-1 or AN/APR-4 Receiver. The receiver tuning unit is removed for this application.

[7] The Type 1216-A Unit I-F Amplifier, the Type 874-MR Mixer Rectifier, and the Type 1209 Unit Oscillator are available as the Type DNT-3 Detector for a fundamental frequency range from 220 to 950 Mc. The Type DNT-4 Detector, which uses a Type 1218-A Unit Oscillator, has a fundamental frequency range from 870 to 2030 Mc.

section of the receiver is much superior to that of either the APR-1 or APR-4 used with their regular tuning units. The method of making the connection to the i-f amplifier in these receivers is indicated in Figure 13.

The mixer-rectifier output-vs-input variation is closely linear for signal input voltages up to about 50 mv when the rectified d-c crystal current produced by the local oscillator alone is at least 200 μa. The rectified crystal current can be checked by disconnecting the i-f amplifier and connecting a milliammeter between the inner and outer conductors. To prevent damage to the crystal, the current should not exceed 10 milliamperes.

3.34 High-Frequency Receiver as a Detector: Various high-frequency receivers such as the AN/APR-1 and AN/APR-4 Radar Search Receivers can be used as highly selective detectors and have the advantages for high VSWR measurements mentioned in Paragraph 4.63. The operation is similar to that obtained using the Type 874-MR Mixer Rectifier with the i-f amplifier of one of these receivers, as described in the previous paragraph, with the exception that the shielding is much poorer, particularly at the higher frequencies, and difficulties with leakage are frequently encountered, particularly when measuring radiating systems.

Section 4.0 Operation

4.1 CONNECTIONS AND ADJUSTMENTS

In use, the slotted line is fed from an oscillator which is connected to one end of the line, and the circuit to be measured is connected to the other end. If a Type 874-MR Mixer Rectifier (see Paragraph 3.33) is to be used as the detector, it is mounted directly on the left-hand connector on the probe carriage, as indicated in Figure 12. No connection is made to the other connector on the carriage. If a receiver (see Paragraph 3.34) is to be used as a detector, a length of double-shielded cable fitted with coaxial connectors should be used to connect the left-hand connector on the carriage to the receiver input. A Type 874-R20 or R22 Patch Cord is suitable.

If the built-in crystal detector (see Paragraphs 3.31 or 3.32) is to be used, a Type 874-D20 Adjustable Stub should be inserted in the left-hand connector on the carriage and the shielded connection to the amplifier, attenuator, or microammeter made from the other connector using a Type 874-R32A Patch Cord, as shown in Figure 10, or a Type 274-NF Patch Cord with a Type 874-Q6 Adaptor, as shown in Figure 11.

4.11 Coaxial Adaptors: If the unknown, the generator, or the detector is fitted with connectors other than the Type 874 Connectors, adaptors can be used to make the necessary transition to the Type 874 Connector. A large number of Adaptors are available (see list at the rear of this manual), permitting use of the Slotted Line with most standard connectors. The low standing-wave ratios of the Type 874-Q Adaptors assure a minimum of reflection, and the Adaptors will have no significant effect on the measurements. Any of the connectors listed in the table of adaptors may be used. It should be remembered, however, that Type UHF Connectors do not have a constant impedance, and may introduce appreciable reflection in the line at higher frequencies.

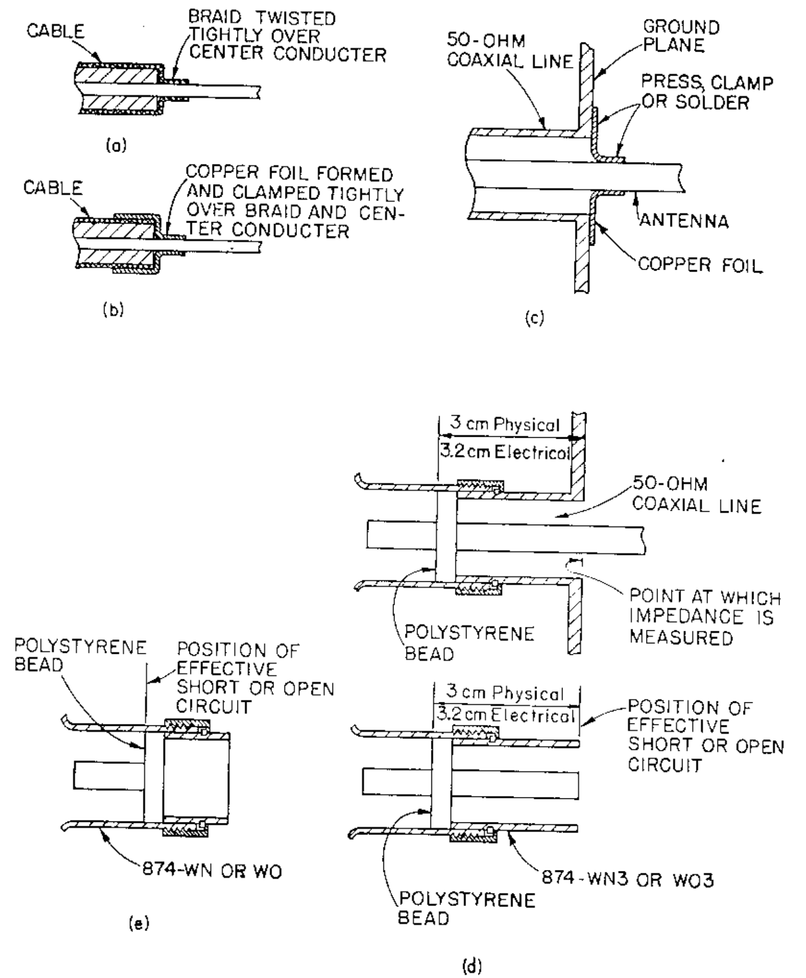
In addition to the adaptors, there are available Type 874 tees, ells, rotary joints, and other accessories for convenience of connection. Refer to the list at the rear of this manual or, for full description, to the latest General Radio Catalog.

4.12. Methods of Short- and Open-Circuiting a Line: The method of producing the short-circuit for the line-length measurement or adjustment is important. In cases in which an antenna or other element terminating a line is being measured, the short-circuit may be made by wrapping a piece of copper foil around the inner conductor and binding it to the outer conductor of the outer conductor of the feed line at its end, as shown in Figure 14c.

It is more difficult to obtain an accurate open-circuit on a line than a short-circuit, as the fringing capacitance at the end of the center conductor will effectively make the line appear to be longer than it really is, and hence will cause errors, unless compensated for. The fringing capacitance is compensated for in the open-circuit termination units mentioned below.

A more satisfactory method of producing a short-circuit or open-circuit is to use a Type 874-WN or WN3 Short-Circuit Termination or Type 874-WO or WO3 Open-Circuit Termination Unit. The Type WN3 and WO3 units produce a short- or open-circuit a physical distance of 3 cm (3.2 cm electrical distance) from the front face,[8] the measuring instrument side, of the insulating

8 The front face of the bead is located at the bottom of the slots between the contacts on the outer connector. Hence, its position can be easily determined from the outside of the connector.



(a) Short-circuiting a cable with its own braid.
(b) Short-circuiting a cable with copper foil.
(c) Short-circuiting an air line with copper foil.
(d) Use of Type 874-WN3 Short-Circuit Termination Unit or Type 874-WO3 Open-Circuit Termination Unit to make a short circuit or open-circuit when measuring point is located 3 cm from front face of bead, as in upper figure. Upper unit is similar to a Type 874-M Component Mount.
(e) Position of the short- or open-circuit when a Type 874-WN Short-Circuit Termination Unit or Type 874-WO Open-Circuit Termination Unit is used.

Figure 14. Methods of Short- and Open-Circuiting Cables and Air Lines.

bead as shown in Figure 14. Hence, if the device under test is fitted with a Type 874-B Connector and a length of 50-ohm Air Line[9] in which the physical distance between the front face of the insulating bead and the point at which the measurement is desired is exactly 3 cm, the circuit under test can be disconnected and a Type 874-WN3 or Type 874-WO3 Short- or Open-Circuit Termination Unit connected for the line-length measurement. This arrangement produces very accurate results.

The Type 874-WN or -WO Termination Units produce a short- or open-circuit directly at the front face of the insulating bead. These units can be used even if the impedance is desired at a point on the line, other than at the face of the bead, if the electrical distance between the two points is added to or subtracted from the line length measured with the short- or open-circuit termination units connected. The electrical line length for air dielectric line is equal to the physical length. Each bead in the Type 874 Connector effectively adds 0.20 cm to the length in addition to its physical length.

If the impedance is desired at the input to a coaxial circuit connected to the slotted line, a Type 874-WN Short-Circuit can be used to produce a short-circuit directly at the front face of the insulating bead in the Type 874 Connector on the circuit under test. (The front face of the bead is located at the bottom of the slots in the outer connector.)

4.2 DETECTOR TUNING

4.21 Crystal Rectifier Tuning: The crystal rectifier built into the carriage is tuned by means of the adjustable stub, which is effectively connected in parallel with it in order to increase the sensitivity and to provide selectivity. In operation, the stub is adjusted until maximum output is indicated by the detector.

In tuning the stub, one must be careful not to tune it to a harmonic of the desired signal rather than to the fundamental. Confusion may result in some cases if the tuning is done with a high VSWR on the line, as the minima of the harmonics may not be coincident with the minima of the fundamental and, consequently, the harmonic content of the signal picked up by the probe may be several orders of magnitude greater than that present in the local oscillator output. To minimize the possibility of mistuning, the probe should be tuned with a low VSWR on the line, for instance, with the line terminated in a Type 874-WM Termination Unit or with the load end of the slotted line open-circuited. In the open-circuit case, the minima of the harmonics fall very close to the fundamental minima and, hence, the possibility of confusion is small even though the VSWR is high. As a check, the distance between two adjacent voltage minima on the line can be measured. If the stub is tuned correctly, the spacing should be half a wavelength.

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9 The coaxial-line section of a Type 874-M Component Mount can be used for this purpose, or a Type 874-WN3 Short Circuit or a Type 874-L10 Air Line can be modified to be suitable.

With the Type 874-D20 Adjustable Stub, the crystal can be tuned to frequencies from about 275 Mc to above 5000 Mc. In the vicinity of 3000 Mc the crystal is self-resonant, and the effective Q of the probe circuit is low and the tuning rather broad. For operation at frequencies below 275 Mc, a Type 874-D50 Adjustable Stub can be used down to 150 Mc or various lengths of Type 874-L Air Lines can be inserted in series with the adjustable stub. Smoother carriage operation is obtained when the low-frequency stub is used if the line is tilted forward slightly, making the stub stand more nearly vertical.

4.22 Mixer Rectifier Tuning: When a mixer rectifier is used as a detector (and also when a superheterodyne receiver is used), care must be taken to tune the local oscillator to beat with the desired signal and not with one of its harmonics. Harmonics of the oscillator signal will beat with harmonics of the signal picked up from the slotted line and produce an output at the intermediate frequency if the local oscillator is mistuned from the proper frequency. Proper settings of the local oscillator are given by the following expression, assuming that the intermediate frequency is 30 Mc.

$$f_{LO} = \frac{f_s \pm 30}{n} \qquad (17)$$

where f_{LO} is the frequency of the local oscillator, f_s is the signal frequency and n is an integer corresponding to the harmonic of the local oscillator signal used. For best results, the lowest possible harmonic of the oscillator should be used.

If $n = 1$, there are two possible settings of the local oscillator separated by 60 megacycles and centered about the signal frequency. If $n = 2$, the two possibly settings are separated by 30 Mc and centered about $f_s/2$. In the general case, the two possible settings are separated by 60/n and centered about the frequency f_s/n.

The second harmonic of the desired signal frequency will produce a beat frequency of 30 Mc when the local oscillator frequency is

$$f_{LO} = \frac{2f_s \pm 30}{n} = \frac{f_s \pm 15}{n/2} \qquad (18)$$

or, in general,

$$f_{LO} = \frac{f_s \pm \frac{30}{h}}{\frac{n}{h}} \qquad (19)$$

where h is the harmonic of the signal frequency. It can be seen from the above equation that some of the harmonic responses may be located reasonably close to the frequency at which the fundamental is detected. The higher the harmonic of the local oscillator used, the closer will be the spurious responses.

In general, spurious responses do not cause much difficulty, as the frequency to which the detector is tuned can be easily checked by measuring the distance between two voltage minima on the line, which should be half a wavelength at the operating frequency.

At some frequencies it is necessary to insert a Type 874-L10 10 cm Air Line between the connector on the carriage and the mixer rectifier in order to obtain sufficient local-oscillator voltage developed across the crystal.

4.3 PROBE PENETRATION ADJUSTMENT

The probe penetration should be adjusted to give adequate sensitivity and yet not have a significant effect on the measured VSWR. The presence of the probe affects the VSWR because it is a small capacitance in shunt with the line. It has the greatest effect at a voltage maximum where the line impedance is high.

The probe penetration can be adjusted by removing the tuning stub connected to the left-hand connector and turning the small screw found inside the inner connector. (See Figure 9.) Clockwise rotation of the screw increases the coupling. In most cases in which moderate VSWR's are measured, a penetration of about 30% of the distance between the two conductors gives satisfactory results. The coupling can be adjusted to 30% by increasing the coupling until the probe strikes the center conductor of the slotted line and then backing it off six full turns of the screw. The point of contact between the probe and the center conductor is most easily measured by connecting an ohmmeter between the inner and outer conductors of the line and noting when the resistance suddenly drops from a very high value to a reasonably low value. The crystal is in series with this circuit so the resistance will not drop to zero. No indication will be obtained if the crystal has been removed. Do not screw the probe down tight against the center conductor, as it will damage the probe.

The amount of probe penetration can be visually checked by looking through the slot from one end of the line at the probe.

The effect of the probe coupling on the VSWR can be determined by measuring the VSWR with one probe coupling and then increasing the coupling and remeasuring the VSWR. If the measured VSWR is the same in both cases, the probe coupling used has no significant effect on the measurement. If the measured VSWR's are different, additional measurements should be made with decreasing amounts of probe penetration until two similar measurements are obtained. However, as pointed out in the previous paragraph, a 30% coupling usually gives satisfactory results except when the VSWR is high and a larger coupling is usually required.

The probe coupling or the oscillator output should be adjusted until the output from the detector is in a satisfactory range. If the crystal detector is used, this means the maximum output to be measured should not correspond to an input beyond the square-law range if the square-law characteristic is to be depended upon (see Paragraph 3.31), and the probe coupling should not be large enough to affect the measurements appreciably.

The variation in probe coupling along the line is affected by the depth of penetration. At large penetrations the variation tends to increase. The specified ±1-1/2% holds for penetrations of 30%.

4.4 MEASUREMENT OF WAVELENGTH

The wavelength of the exciting wave in air can be measured using the slotted line by observing the separation between adjacent voltage minima when the line is short- or open-circuited. As explained in Paragraph 2.2, the spacing between adjacent minima, d, is one-half wavelength or

$$\lambda = 2d \qquad (20)$$

For greater accuracy at the higher frequencies, the distance over a span of several minima can be measured. If the number of minima spanned, not counting the starting point, is n, then

$$\lambda = \frac{2d}{n} \qquad (21)$$

4.5 MEASUREMENT OF CIRCUITS HAVING LOW VSWR'S

If the standing-wave ratio on the line is less than 10 to 1, the VSWR is usually determined by actually measuring the relative amplitudes of a voltage maximum and a voltage minimum (see Paragraph 3.3). To do this, the carriage containing the probe can be moved along the line by turning the knob mounted on the end casting, or by grasping the body of the carriage at the base of the knob with the thumb and forefinger and pushing in the desired direction of motion. The relative amplitudes of the voltage maximum and minimum and the position of the voltage minimum can be determined in this manner.

The probe coupling can vary a maximum of ±1-1/2% along the line, and the VSWR measured is in error by the difference in coupling coefficients at the maximum and minimum voltage points. This error can be avoided by calibrating the variation of coupling with probe position, as outlined in Paragraph 5.2, or can be reduced greatly by measuring several minima and several maxima and averaging the results. The coupling usually changes the most near the ends of the line and, hence, better accuracy usually can be obtained if measurements close to either end are avoided.

For a particular setup, a check must be made to determine whether the crystal is operating in the square-law range and whether the sensitivity is adequate. This is done by connecting the circuit to be tested and setting the probe to a voltage maximum. If the meter and the Type 1231-B Amplifier can be brought on scale with the amplifier set at maximum sensitivity and with an attenuation of less than 30 db in the Type 1231-P4 Attenuator, the crystal will

be operating in the square-law range (assuming 50% modulation). The probe is then moved to a voltage minimum, and if the meter reading under these conditions is greater than about one-fourth of full scale with any setting of the Type 1231-P4 Attenuator, the r-f input to the line is adequate. If a one-fourth full-scale meter reading cannot be obtained, even with the attenuator set at zero, the r-f input to the line should be increased. If the r-f input cannot be increased, the probe coupling should be increased. (See Paragraph 4.3.) If either the r-f input or the probe coupling are increased, the voltage maximum point should be rechecked to make sure that the crystal is still operating in the square-law range. If the meter indication at the voltage maximum is greater than full scale with the attenuator set at 30 db, and the meter indication at the voltage minimum is less than one-third of full scale with the attenuator set at zero, the VSWR on the line is greater than 20 db and the width-of-minimum method, described in Paragraphs 4.6 and 4.722, should be used.

If the impedance of the unknown is desired, the VSWR and the electrical distance between a voltage minimum on the line and the unknown must be determined and the unknown impedance calculated, as outlined in Paragraphs 2.32 or 2.33.

The effective distance to the unknown can be measured by short-circuiting the line with a very low inductance short at the unknown (see Paragraph 4.12) and measuring the position of a voltage minimum on the line. This minimum is an integer number of half-wavelengths from the unknown. Since the impedance along a lossless line is the same every half-wavelength, the position of the voltage minimum found with the line short-circuited is the effective position of the unknown. If the line is very long, oscillator frequency shifts (discussed in Paragraph 4.62) may be serious.

If a series of measurements are to be made on the same circuit, it may be desirable to determine the actual effective length of the line in centimeters between a reference point on the scale on the slotted line and the unknown and thus eliminate the necessity of short-circuiting the unknown for each frequency. If the position of the minimum with the line short-circuited at the unknown is measured at one frequency, the point at which the minimum is found on the line must be $n\lambda/2$ wavelengths from the unknown. If the line is not too many wavelengths long, the effective length can be estimated from the physical length of the line, multiplied by the square root of the dielectric constant of the line insulation, with an accuracy of better than a quarter-wavelength. The value of the integer n can then be determined by comparing the estimated length with the possible values of $n\lambda/2$. At other frequencies, the electrical distance between the measured position of the minimum on the slotted line and the unknown can then be determined from the sum of (1) the distance between the unknown and the reference point on the line, and (2) the distance between the reference point and voltage minimum, all divided by the wavelength at the operating frequency. If the line is many wavelengths long, the frequency must be known very accurately if the electrical distance to the unknown is to be determined from the frequency and the physical length.

When the VSWR is very low, the minima will be very broad, and it may be difficult to locate their positions accurately. In this case, better results

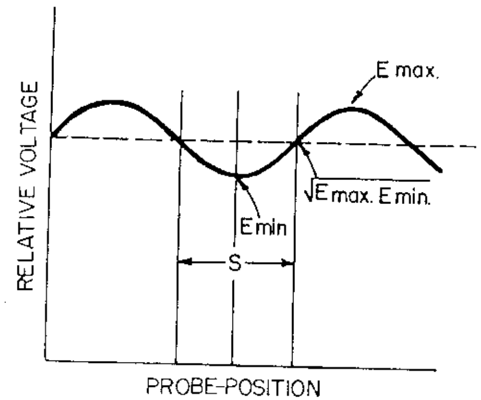

Figure 15. Method of improving the accuracy of the determination of the position of a voltage minimum on the line when the VSWR is low.

usually can be obtained by measuring the positions of points on either side of a voltage minimum at which the voltage is roughly the mean of the minimum and maximum voltages, as shown in Figure 15. The minimum is located midway between these two points.

If the line between the unknown and the slotted line has a significant amount of loss, the effect of the loss on the unknown impedance can be corrected for, as outlined in Paragraph 4.61.

Harmonics of the oscillator frequency may also cause trouble, as discussed in Paragraph 4.63. The effect will tend to be most serious when the VSWR at the harmonic frequencies is high.

4.6 MEASUREMENT OF CIRCUITS HAVING HIGH VSWR'S

When the VSWR on the line is 10 to 1 or more, direct accurate measurements of a voltage maximum and a voltage minimum are difficult because of the following reasons:

(1) The effect of a fixed probe-coupling coefficient on the measurement increases as the VSWR increases because the line impedance at the voltage maximum increases, and the shunt impedance produced by the probe has greater effect.

(2) As the VSWR increases, the voltage at the voltage minimum usually decreases and, hence, a greater probe-coupling coefficient is required to obtain adequate sensitivity. The increased probe coupling may cause errors as outlined in (1).

(3) The accuracy of the measurement of the relative voltage decreases as the VSWR increases. The voltage range becomes too great to permit operation entirely in the square-law region. With the Type 1231-B Amplifier, Type 1231-P2 Tuned Circuit, and the Type 1231-P4 Adjustable Attenuator, an r-f

input voltage range of about 10 to 1, or 20 db, is obtainable with the 50% modulation in the square-law region when, at a voltage minimum, the input level is adjusted to produce a 10-db reading on the amplifier meter, with the amplifier set to maximum sensitivity and the adjustable attenuator set to zero attenuation.

Accurate measurements of VSWR's greater than 10 can be made using the width-of-minimum method. This is essentially a resonance method and is similar to measuring the Q of a circuit by measuring the frequency increment between the two half-power points. In the slotted line case, the spacing, Δ, between points on the line at which the r-f voltage is $\sqrt{2}$ times the voltage at the minimum is measured, as shown in Figure 16. The VSWR is related to the spacing, Δ, and the wavelength, λ, by the expression

$$\text{VSWR} \cong \frac{\lambda}{\pi\Delta} \qquad (22)$$

If the detector is operating in the square-law region, $\sqrt{2}$ times the r-f voltage corresponds to twice the minimum rectified output or a 6-db change in output.

For very sharp minima, the width of the minimum can be measured to a much greater accuracy by using the Type 874-LV Micrometer Vernier, than by means of the centimeter scale on the slotted line. The vernier can be read to $\pm$ 0.002 cm. When the vernier is used, the probe is moved slightly to the right of the minimum and the vernier adjusted to have its plunger strike the carriage on the unpainted surface below the output connector. The position of the vernier is adjusted by loosening the thumb screw which clamps the vernier to a reinforcing rod, sliding it along to the proper position, and relocking it.

The probe is then driven through the minimum and the twice-power points by turning the micrometer screw. The output meter reading corresponding to the minimum is determined and then the Type 1231-P4 Attenuator set for 6 db more attenuation.

The micrometer is then backed off again and the probe returned to the right side of the minimum. The probe is then driven through the minimum and twice-power points again and the two micrometer readings corresponding to the original output meter reading noted. The difference between these readings is equal to Δ.

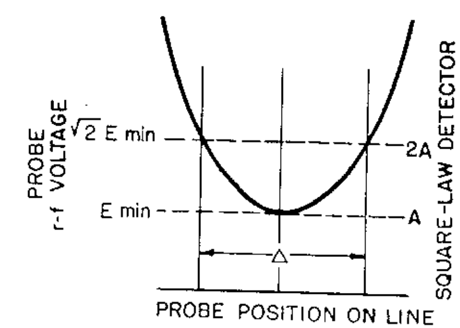

Figure 16. Method of measuring the width of the voltage minimum for VSWR determinations when the VSWR is high.

If the minimum is too close to the right-hand end of the line to permit the vernier being used in the usual manner, the vernier can be moved to the left-hand side of the carriage and the other end of the plunger used to drive the carriage.

The electrical distance between the unknown and the minimum found on the line can be determined as outlined in Paragraph 4.5.

At very high standing-wave ratios, the losses in the slotted line and in any connecting line or cable used may have an appreciable effect on the measurements. To keep this error as low as possible, the voltage minimum nearest the load should be measured. The effect of the loss in the line can be corrected for as outlined in Paragraph 4.61.

4.61 Correction for Loss in Line Between Measuring Point and Unknown: When a load is connected to the slotted line through a length of air line or cable, the loss in the air line or cable may appreciably affect the measurements. Loss in the cable tends to make the measured VSWR less than the true VSWR produced by the load.

The amount of loss in a length of cable can be estimated from published data or measured using a slotted line. The loss can be measured by determining the VSWR with the load end of the line open-circuited and shielded to prevent radiation losses. An open-circuited line is used for this measurement to eliminate the significant losses present in most short-circuiting devices. A Type 874-WO Open Circuit Termination is useful for this purpose. The total attenuation, $\alpha \ell$, in the length of cable is:

$$\tanh \alpha\ell = \frac{1}{(VSWR)_{oc}} \qquad (23a)$$

$$\alpha\ell = \tanh^{-1} \frac{1}{(VSWR)_{oc}} \text{ nepers} \qquad (23b)$$

$$= 8.686 \tanh^{-1} \frac{1}{(VSWR)_{oc}} \text{ db.} \qquad (23c)$$

where VSWR is expressed as a ratio, not in db.

If VSWR is greater than 10,

$$\alpha\ell \cong \frac{1}{(VSWR)_{oc}} \text{ nepers} = \frac{8.686}{(VSWR)_{oc}} \text{ db.} \qquad (24)$$

The attenuation can also be determined from the open-circuited VSWR using the TRANSMISSION LOSS and STANDING WAVE RATIO scales located below the Smith Chart, shown in Figure 17b. The point corresponding to the open circuit VSWR is located on the $\frac{E_{max}}{E_{min}}$ or DB scales under STANDING WAVE RATIO. At the same distance from the center, find a corresponding point on the TRANSMISSION LOSS scale. Attenuation of the line is equal to the number of decibels between the left-hand end of the scale labeled 1 DB STEPS and this latter point. The scale is marked off in 1-db steps.

In most cases the loss in the slotted line itself can be neglected, but the loss in the line or cable used to connect the slotted line and the load is of importance. The unknown impedance can then be calculated in the same manner as for the lossless case by first correcting the measured voltage standing-wave ratio, $(VSWR)_m$, for the effect of the loss in the line. The effective voltage standing-wave ratio, $(VSWR)_e$, is then

$$(VSWR)_e = \frac{(VSWR)_m - \frac{1}{(VSWR)_{oc}}}{1 - \frac{(VSWR)_m}{(VSWR)_{oc}}} \qquad (25)$$

In measurements of very high VSWRs, the lumped resistance loss at the Type 874 Connector on the slotted line can have an important effect. The magnitude of this resistance for a typical line is plotted in Figure 17a. If a current

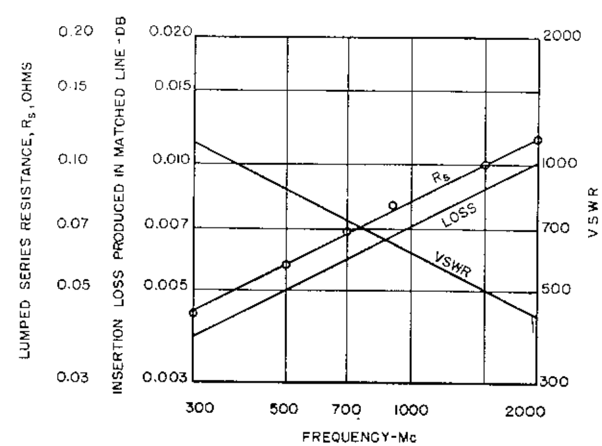

Figure 17a. Plot of the effective lumped series resistance at the connector measured on a typical Type 874-LBA Slotted Line. The insertion-loss produced in a matched line by the measured value of lumped resistance is also indicated, as well as the VSWR which would be produced by the measured lumped resistance located at a current maximum in an open- or short-circuited 50-ohm line that has no other losses.

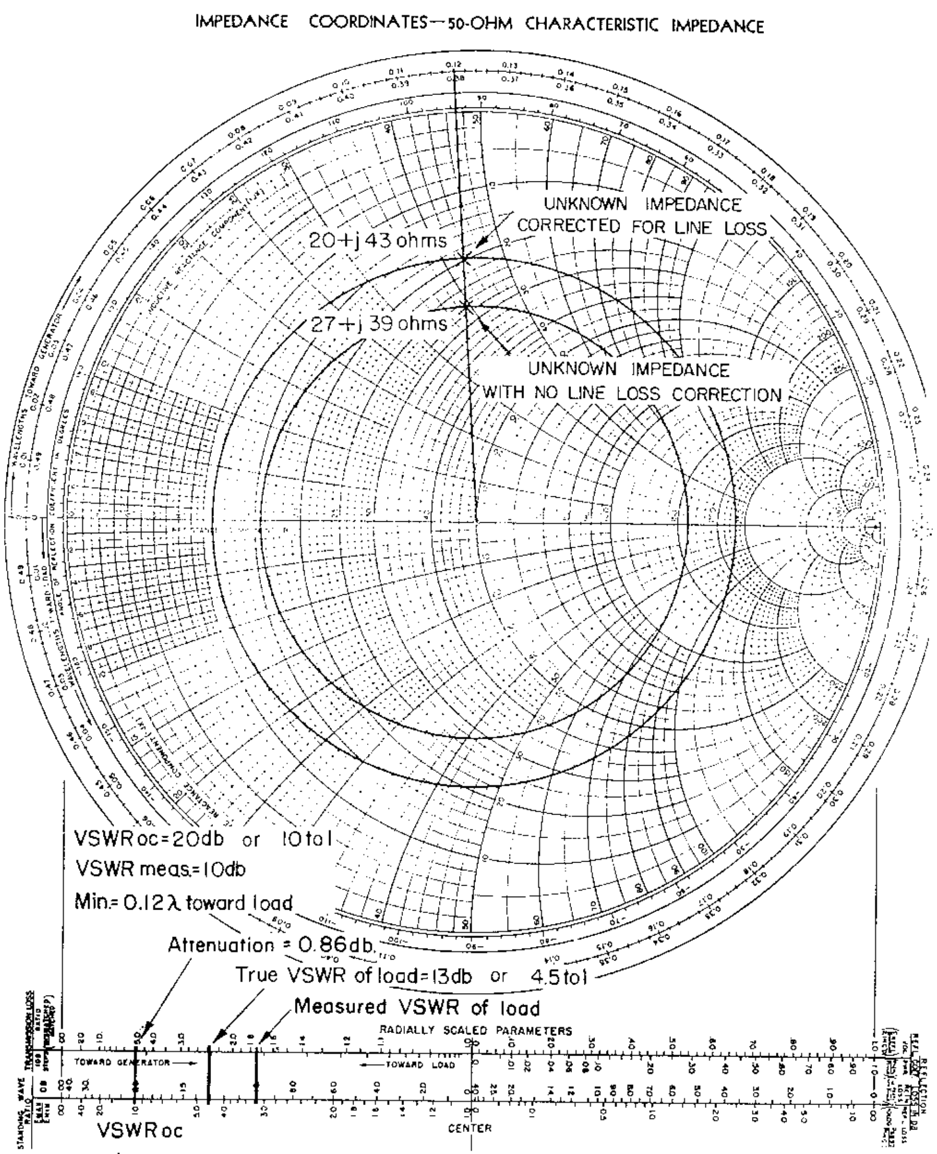

Figure 17b. Example of the use of the Smith Chart for line length corrections when the line has an appreciable amount of loss. (See Paragraph 4.61.)

maximum occurs at the resistance, the VSWR will be reduced the maximum amount. If a current minimum occurs at the resistance, the VSWR will be unaffected. Therefore, if circuits are measured whose VSWRs are high enough to be affected by the losses in the slotted line itself, and these losses are measured by making a measurement with the unknown disconnected, the figure obtained for the line loss may be different than that actually obtained when the unknown is connected. The reason for this is that the standing wave may be shifted along the line and thus the lumped resistance loss may be different in the two measurements.

This type of error can be avoided by using the substitution method of measurement. In this method, the reactance at the end of the line is adjusted with the unknown disconnected to produce a voltage minimum at exactly the same position on the slotted line as produced with the unknown connected. The effective loss produced by the lumped resistance is the same in both cases; hence Equation 26 can be used to obtain the true value of the VSWR produced by the unknown alone.

$$\frac{1}{(VSWR)_e} \cong \frac{1}{(VSWR)_m} - \frac{1}{(VSWR)_{oc}}$$

$$(VSWR)_e \cong \frac{(VSWR)_m}{1 - \frac{(VSWR)_m}{(VSWR)_{oc}}} \qquad (26)$$

The impedance of an unknown connected to the slotted line by a line or cable having an appreciable loss can be calculated from the slotted-line measurements, using the Smith Chart exactly as outlined in Paragraph 2.332 if the measured VSWR is corrected as indicated in Equation (25); or the complete correction procedure can be carried out on the Smith Chart and the need for the solution of Equation (25) eliminated, if desired, in the following manner. First, the point corresponding to the measured VSWR is determined on the scale marked STANDING WAVE RATIO, located below the chart, and the corresponding point on the TRANSMISSION LOSS, 1 DB STEPS scale is found. A new point is found on this scale by traveling outward, TOWARD LOAD, a distance corresponding to the db attenuation in the line. The radius of the circle drawn on the Smith Chart is the distance from this point to the center of the scale. The unknown impedance is found on this new circle at an angle from the resistance axis corresponding to the electrical distance to the load, as outlined in Paragraph 2.332.

For example, suppose the measured open-circuit SWR is 20 db, the SWR with the load connected is 10 db, and the minimum with the load connected is 0.12 wavelength on the load side of the short-circuit minimum. The attenuation, $\alpha\ell$, in the length of cable is 0.86 db. The point on the STANDING WAVE RATIO scale for a SWR of 10 db is located as shown on Figure 17b, and the corresponding point is found on the TRANSMISSION LOSS 1-DB STEPS scale. A new point on the TRANSMISSION LOSS scale 0.86 db (0.86 division) toward the left-hand end of the scale is found and a line is drawn from this point to the STANDING WAVE RATIO scale. The reading of the scale at this point is 4.5 or 13 db, which is the true VSWR.

Corrections can also be made using the following transmission-line equations (from Equations (14a) and (14b)):

$$R_X = Z_O \times \frac{2(VSWR)_e}{\left[(VSWR)_e^2 + 1\right] + \left[(VSWR)_e^2 - 1\right]\cos 2\theta} \quad (27)$$

$$X_X = -Z_O \times \frac{\left[(VSWR)_e^2 - 1\right]\sin 2\theta}{\left[(VSWR)_e^2 + 1\right] + \left[(VSWR)_e^2 - 1\right]\cos 2\theta} \quad (28)$$

where θ is the electrical distance between the minima with the line short-circuited and with the load connected. It is positive when the load minimum is on the generator side of the short-circuit minimum. When both VSWR's are greater than 10, and θ is not approximately $n \times 90°$, where n is an odd integer, $\left(\frac{\tan\theta}{VSWR} < 0.1\right)$, the following approximation is valid:

$$R_X \cong \frac{Z_O}{(VSWR)_e \cos^2\theta} \quad (29)$$

$$X_X \cong -Z_O \tan\theta \quad (30)$$

The equations are much more accurate than the Smith Chart, particularly when the VSWR is high.

As an example, suppose the open-circuit standing-wave ratio is 30 db, or 31.6 to 1, the VSWR with the unknown connected is 25 db or 17.77 to 1, and the minimum with the unknown connected is located 0.17 wavelength on the generator side of the short-circuit minimum. Then,

$$R_X \cong \frac{50}{40.5\cos^2(360° \times 0.17)} = 5.32 \text{ ohms}$$

$$X_X \cong -50 \tan 61.2° = -90.9 \text{ ohms}$$

4.62 Oscillator Frequency Shifts: If the effective position of the unknown is determined by short-circuiting the unknown and measuring the position of a voltage minimum, errors may be caused in some cases by shifts in the oscillator frequency with the change in the load impedance between the short-circuit and loaded conditions. The effect can become more serious as the length of line between the load and the slotted line is increased. Oscillators which are tightly coupled to the line can have relatively large frequency shifts. The effect can be greatly reduced by inserting a pad, such as a Type 874-G10 10-DB Pad, between the oscillator and the slotted line. If the resultant decrease in input cannot be tolerated, the oscillator tuning can be adjusted to compensate for the frequency shift. The oscillator frequency can be checked using a receiver or a heterodyne frequency meter such as a General Radio Type 720-A. Signal generators, in general, are loosely coupled, and the frequency shift is usually small.

4.63 Harmonics: Another possible source of error in the measurement of high standing-wave ratios is the presence of harmonics in the wave traveling along the line. Harmonics can be generated by the driving oscillator or by a non-linear unknown such as a crystal rectifier. The minima for the harmonics will not necessarily appear at the same points along the line or have the same relative amplitudes as the fundamental minima, and, hence, a small harmonic content in the signal may produce a harmonic signal many times that of the fundamental at a minimum point. Therefore, if the detector will respond at all to harmonics, difficulty may be encountered. Superheterodyne receivers and the mixer rectifier detector, in general, have excellent harmonic rejection; but the tuned crystal detector may not have a large amount of rejection for various harmonics because the tuning stub has higher order resonances. When the crystal detector is used for measurements of high VSWR's, and preferably even when a receiver is used, a good low-pass filter, such as the Type 874-F500 or F1000 Low-Pass Filter, is required between the oscillator and the line to reduce the harmonics to an insignificant value. A good superheterodyne receiver or a mixer rectifier is recommended when the VSWR is very high.

4.64 Frequency Modulation: The presence of appreciable frequency modulation on the applied signal may also have a serious effect on the results when the high standing-wave ratio is very high. Frequency modulation is usually produced when a high-frequency oscillator is amplitude-modulated; but, in oscillators using filament-type tubes, frequency modulation can also be caused by the filaments when heated with a-c power. The amount of frequency modulation for a given degree of amplitude modulation usually increases as the oscillator frequency approaches its upper limit. The Type 1209- Unit Oscillator and Type 1021-AU Signal Generator are satisfactory for modulated signal measurements on very high VSWR's at 50% modulation up to about 750 Mc. At the higher frequencies, reasonably large errors are produced in measurements of standing-wave ratios of the order of 500 or 1000. At standing-wave ratios below 50, the error is usually negligible if the over-all line length is short. Square-wave modulation should be used on the Type 1218-A U-H-F Oscillator to minimize frequency modulation.

4.7 MEASUREMENT OF 50-OHM COAXIAL LINE CIRCUITS

In coaxial-line measurements, the VSWR on the line, the impedance seen looking into an unknown line, or the impedance at the far end of a line may be desired. For instance, in measurements on antennas, either the VSWR on a line terminated in the antenna or the actual antenna impedance is desired. However, in most cases it is not possible to connect the antenna directly to the slotted line and an intermediate length of cable or air line must be used. The line or cable used should have a 50-ohm characteristic impedance. Lengths of Type 874-A2 Cable can be used for this purpose. The connecting cable has no effect on the VSWR if it is a lossless uniform line, and hence the VSWR produced by the load is the same as that measured on the slotted line. In practice, however, the connecting cable and connectors will not be absolutely uniform but will have small discontinuities which will have some effect on the VSWR. The uniformity of lengths of Type 874-L Air Line is much better than that of coaxial cable and should be used if possible when the most accurate results are desired. There is, also, always some loss in the connecting cable. If it is significant, it can be corrected for as outlined in Paragraph 4.61.

4.71 Measurement of VSWR on a 50-Ohm Line: When the VSWR setup on a 50-ohm line terminated in the unknown is desired, the following procedure can be used.

(1) Set up the equipment and the tune detector, as outlined in Paragraphs 4.1, 4.2, and 4.3.

(2) Connect the unknown directly to the slotted line, if possible, or use lengths of 50-ohm air lines or cable provided with constant-impedance connectors, such as the Type 874 Connectors. If the unknown is fitted with connectors other than Type 874 Connectors, use one of the adaptors listed in Paragraph 4.11.

(3) Check the output from the detector at a voltage minimum and maximum and determine whether the probe coupling and generator outputs are satisfactory, as outlined in Paragraphs 3.3 and 4.3. If the indicated SWR is greater than 20 db, only the voltage minimum need be measured, as the width-of-minimum method can be used.

(4) If the SWR is less than 20 db, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but, due to the variations in probe coupling along the line, greater accuracy can be obtained by averaging several minima and maxima or by calibrating the probe coupling, as outlined in Paragraph 5.2. For maximum accuracy using the crystal detector and the Type 1231-B Amplifier with the Type 1231-P4 Attenuator, the difference in the attenuator settings producing the same meter indications at the minima and maxima should be recorded, rather than the difference in the meter readings obtained with a constant attenuator setting.[10] The SWR is half the average db difference in the outputs if the detector is square law, and equal to the average difference if the detector is linear. If the SWR is greater than 20 db, use the width-of-minimum method, outlined in Paragraph 4.6, to determine the SWR.

4.72 Unknown Impedance Connected at the End of a 50-Ohm Line: When the actual load impedance is desired, the following procedure can be used.

(1) Set up the equipment and tune the detector, as outlined in Paragraphs 4.1, 4.2, and 4.3.

(2) Connect the unknown to the slotted line. If the unknown is fitted with connectors other than Type 874 Connectors, use one of the adaptors listed in Paragraph 4.11.

(3) Check the output from the detector at a voltage minimum and maximum and determine whether the probe coupling and generator output are satisfactory, as outlined in Paragraphs 3.3 and 4.3. If the indicated SWR is greater than 20 db, only the voltage minimum need be measured, as the width-of-minimum method can be used.

(4) If the SWR is less than 20 db, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but, due to the variations in probe coupling along the line, greater accuracy can be obtained by averaging several minima and maxima or by calibrating the probe coupling, as outlined in Paragraph 5.2. For maximum accuracy using the crystal detector and the Type 1231-B Amplifier with the Type 1231-P4 Attenuator, the attenuator settings producing the same meter indications at the minima and maxima should be recorded, rather than the difference in meter readings.[10] The SWR is half the average db difference in the outputs if the detector is square law, and equal to the average difference if the detector is linear. If the SWR is greater than 20 db, use the width-of-minimum method, outlined in Paragraph 4.6, to determine the SWR.

(5) Measure the position of the voltage minimum nearest the load end of the line.

(6) Short-circuit the end of the line at the point of connection to the unknown, using a very low inductance metal sheet or strap, or a Type 874-WN3 or WN

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10 If the SWR is low, the attenuator can be adjusted to give slightly less than a full-scale meter deflection at a voltage maximum and the meter readings for the other voltage maxima and minima recorded. The average maximum and average minimum readings are calculated, and the change in setting of the attenuator required to produce a shift in the meter reading from the average maximum to the average minimum is recorded. This procedure may save time when many measurements are to be made.

Short Circuit, as described in Paragraph 4.12. Then, find the position of a voltage minimum on the line with the line shorted and record the scale reading corresponding to the probe position (see Paragraph 4.5).

(7) Determine the difference in position, ℓ, between the minimum measured with the line shorted, or the unknown itself,[11] and the minimum measured with the unknown connected, and divide the result by the wavelength to obtain $\frac{\ell}{\lambda}$.

(8) Determine on the Smith Chart the radius of the circle on which the impedance must lie from the scale labeled STANDING WAVE RATIO, located at the bottom of the chart, and draw a circle having this radius on the chart, with its center at the center of the chart. (See Paragraph 2.332.) If desired, the transmission-line equations presented in Paragraph 2.32 can be used in place of the Smith Chart. (The 50-ohm impedance version is considered here.)

(9) Note whether the minimum found with the line shorted lies on the generator side or on the load side of the minimum found with the load connected. If the short-circuit minimum lies on the load side, travel around the circle along the WAVELENGTHS TOWARD LOAD scale the number of wavelengths from zero found in Step 8. If the minimum lies on the generator side, travel in the opposite direction along the WAVELENGTHS TOWARD GENERATOR scale. Draw a line from this point to the center of the chart.

(10) Find the impedance in ohms of the unknown from the coordinates of the intersection of the line drawn in Step 9 and the circle drawn in Step 8. If the admittance is desired, travel around the chart another 0.25 wavelength and draw another line to the center of the chart, or use the admittance chart as outlined in Paragraph 2.334. The coordinates of the intersection of this line with the circle multiplied by 0.4 are the components of the admittance of the unknown in millimhos.

4.721 Example of Antenna Impedance Measurement, Low VSWR: The antenna under consideration is a stub mounted perpendicular to a ground plane. At the ground plane the stub is connected to the center conductor of a short section of 50-ohm coaxial line which terminates in a Type 874 50-Ohm Connector. Since it is not practical to bring the slotted line close enough to the antenna to make a direct connection between the slotted line and the instrument, a 3-foot length of 50-ohm coaxial cable is used to make the connection. (For the best accuracy, the cable should be as short as possible and, if possible, sections of Type 874-L30 Air Line used in place of the cable.) A Type 1209 Unit Oscillator modulated by a Type 1214-A Unit Oscillator is used as a generator, and a Type 1231-B Amplifier with a Type 1231-P2 Filter and a Type 1231-P4 Attenuator are used with the built-in crystal detector, and a Type

11 If several measurements are to be made at different frequencies on the same circuit, the over-all electrical line length between any point on the slotted line can be determined as outlined in Paragraph 4.5, and the line has to be short-circuited only once.

874-D20 Stub Line as a detector. The oscillator is set to operate at 750 Mc and the stub adjusted for maximum output with the cable disconnected from the slotted line. The probe penetration had been previously set at 30% (6 turns out from the center conductor), at which position it has no appreciable effect on the measurements.

The antenna is then connected and the checks made for square-law operation, as outlined in Paragraph 4.5. In this case, the meter on the amplifier read full scale with an attenuator setting of approximately 16 db at a voltage maximum and read full scale with an attenuator setting of approximately 11 db at a voltage minimum. Therefore, the crystal is operating in the square-law range, and no adjustments of the r-f input or probe coupling are required.

For an accurate measure of the VSWR, the probe is set to the voltage minimum[12] nearest the load, and the attenuator adjusted to produce a meter reading of 1 db. The attenuator reading and probe position at this point are found to be 1.72 db and 35.22 cm. The probe is then moved in one direction until a voltage maximum is found and the attenuator is readjusted to give the same meter reading as obtained at the voltage minimum.

The probe is then moved to each of the voltage minima and maxima found on the line[13] and the attenuator is adjusted to give the reference meter reading. The attenuator readings obtained are 17.2, 22.5, 17.4, 22.7, 17.0, and 22.3 db. The SWR is half the average difference in the attenuator settings[10] or

$$1/2 \left[\frac{22.5 + 22.7 + 22.3}{3} - \frac{17.2 + 17.4 + 17.0}{3}\right] = 2.65 \text{ db}.$$

The effective position of the measured minimum with respect to the load is then measured by short-circuiting the line at the antenna by means of a copper disk with a slot in it. The approximate position of the minimum is found and then the attenuator set to minimum attenuation to improve the resolving power. The minimum is still rather broad. To improve the accuracy, the oscillator input is increased. (The minimum position could also be determined more accurately by measuring the position of the two equal-output points, one on either side of the minimum, or by increasing the probe penetration.) In this case, the minimum occurred at 36.12 cm.

12 With this low VSWR, the minima are relatively broad, and more accurate results could be obtained by finding the positions of points on either side of a minimum at which the voltage is the mean between the maximum and minimum voltage. The true position of the minimum is midway between these points (see Paragraph 4.5).

13 For greater accuracy, the variation in probe coupling could be calibrated, and corrections made, as outlined in Paragraph 5.2.

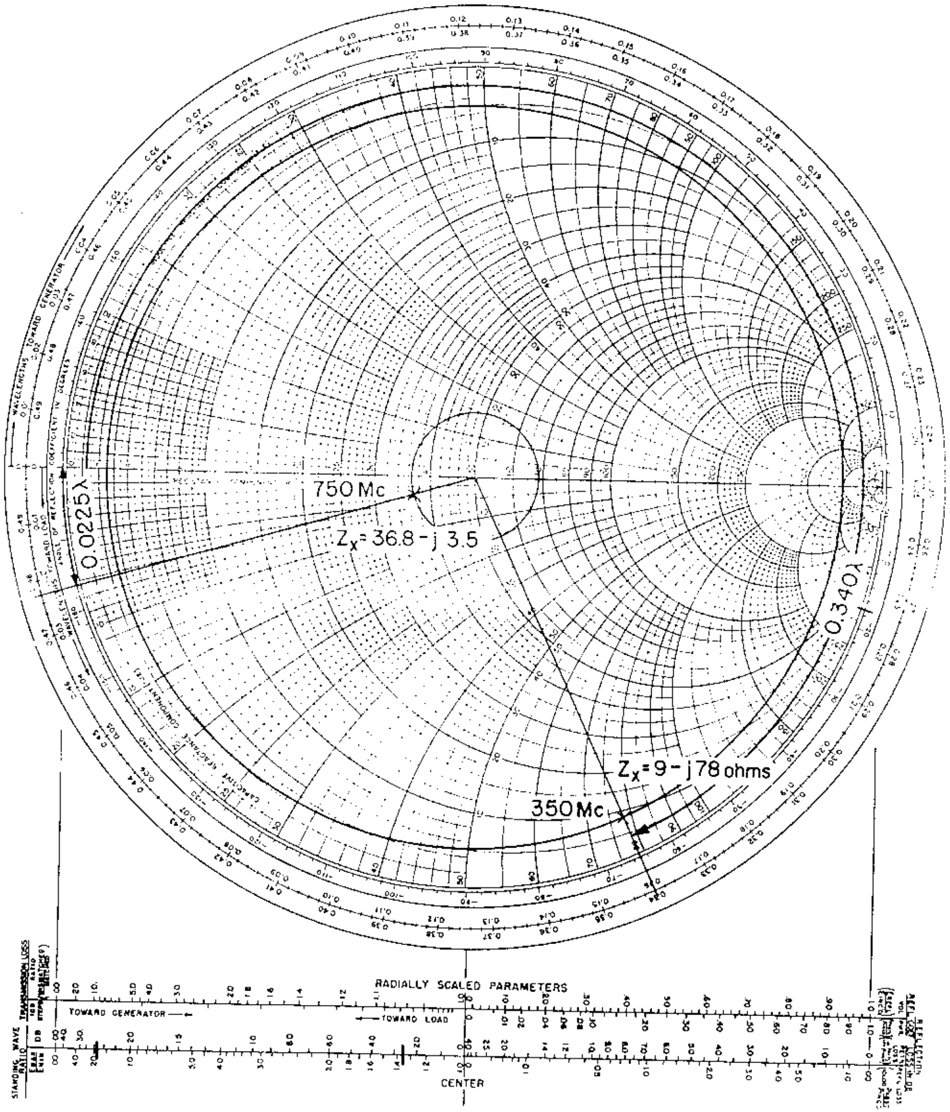


Figure 18. Example of the use of the Smith Chart to calculate antenna impedances. (See Paragraphs 4.721 and 4.722.)

In order to calculate the antenna impedance, the wavelength must be accurately known. It can be determined from the frequency by the equation:

$$\lambda = \frac{3 \times 10^4}{f_{mc}} \quad \text{in cm}$$

where f_{mc} is the frequency in megacycles. It can also be measured on the line by measuring the distance between minima, as outlined in Paragraph 4.4. In the example under consideration, the wavelength was 40.00 cm.

The pertinent information, therefore, is:

SWR = 2.65 db
Position of minima with load connected = 35.22 cm
Position of minima with short-circuit at load = 36.12 cm
λ = 40.00 cm.

The impedance of the antenna is calculated as outlined in Paragraph 2.332. The radius on the Smith Chart, corresponding to 2.65 db, is found from the scales below the chart and the circle drawn on the chart, as shown in Figure 18. The position of the minimum with respect to the short-circuit minimum is $\frac{36.12 - 35.22}{40} = 0.00225$ wavelength toward the load. The antenna impedance is, therefore, 36.8 - j3.5 ohms.

In this case, the loss in the line between the antenna and the slotted line is negligible. In cases in which it is not, the loss can be corrected for as outlined in Paragraph 4.61.

4.722 Measurement of Antenna Impedance Having High VSWR: The same antenna measured in the previous example when measured at 350 Mc shows a high VSWR. The preliminary adjustments are the same as indicated in the previous example, but when the SWR is found to be greater than 20 db the width-of-minimum method is used. The probe is set to a voltage minimum near the load and the generator voltage increased to a maximum. If the meter still does not read at least half-scale at the voltage minimum with the Type 1231-P4 Attenuator at zero, the probe penetration is increased until it does. The input should not be more than required to obtain a half-scale reading with the attenuator set at 30 db. For greatest accuracy, the input or probe coupling should be adjusted to give at least a full-scale indication with the attenuator near zero.

To make the measurement, the probe is set at the voltage minimum and the attenuation is increased until the meter reads about half scale. The probe is then moved to the right of the minimum beyond the point at which the meter reads full scale. If the Type 874-LV Micrometer Vernier is available, it should be adjusted so the plunger contacts the unpainted surface on the edge of the carriage. The carriage is then moved continuously towards the left, using the micrometer vernier, or the knob if a micrometer vernier is not used, and the meter reading at the minimum noted. The attenuation of the Type 1231-P4 Attenuator is decreased to make the minimum read exactly 1 db on the meter, and then the attenuation of the Type 1231-P4 Attenuator is increased exactly 6 db[14] from this setting. The carriage is then slid to the right until the meter reads off scale, and then moved to the left by means of the micrometer vernier, if used, or the knob. The scale or vernier readings corresponding to the 1-db meter readings on each side of the null are recorded. The meter indication at the minimum should be the same as that obtained when the attenuation was originally increased by 6 db. If it is not, the attenuator is readjusted to make it the same.

In the measurement in question, the minimum occurs at a scale reading of 42.40 cm and the micrometer vernier readings for the two 1 db meter readings are 2.111 and 0.632 cm. The distance between the twice-power points, Δ, is then 1.479 cm. The wavelength, λ, at 350 Mc is 85.7 cm. The VSWR from Equation (22) is then

$$\text{VSWR} = \frac{\lambda}{\pi\Delta} = \frac{85.7}{\pi \times 1.479} = 18.46$$

On short-circuiting the antenna, as outlined in Paragraph 4.5, a minimum is found at 13.09 cm. The antenna impedance is then calculated using the Smith Chart or the transmission-line equations, as outlined in Paragraphs 2.32 and 2.332. On the Smith Chart, the radius of the circle corresponding to a VSWR of 18.46 is drawn on the chart, as in Figure 18. The minimum with the antenna shorted is $\frac{42.20 - 13.09}{85.7} = 0.340$ wavelength toward the generator from the minimum found with the antenna unshorted. On traveling around the circle on the Smith Chart 0.340 wavelength toward the generator, the unknown impedand is found to be 9.0 - j78 ohms.

More accurate results can be obtained using the Equations (15a) and (15b) from Paragraph 2.32. Here $\theta = -360° \times 0.340 = -122.4°$, and $\tan\theta = 1.576$. Since $\frac{\tan\theta}{\text{VSWR}} < 0.1$ and the VSWR is greater than 10, the approximate form can be used. Also, θ is negative since it lies on the load side of the short-circuit minimum.

Therefore,

$$R_x = \frac{Z_o}{\text{VSWR}\cos^2\theta} \quad \frac{50}{18.46\cos^2(-122.4°)} = 9.4 \quad \text{ohms}$$

$$X_x = -Z_o\tan(-122.4°) = -78.8 \quad \text{ohms}$$

14 If the sensitivity is not great enough to obtain a 1-db meter reading, any other point on the meter scale can be used. Since the crystal is square law, a 6-db difference in output corresponds to a 3-db change in r-f voltage level.

If the cable is long enough to have appreciable loss, corrections for loss can be made as outlined in Paragraph 4.61.

4.73 Measurement of the Input Impedance to Coaxial-Line Circuits: The input impedance to a coaxial-line circuit can be measured by connecting the circuit directly to the slotted line by means of a coaxial connector and by then using the procedure outlined in Paragraph 4.72. In this measurement, the point in the connector at which the impedance is desired must be specified because the impedance may vary appreciably from one point to another in the connector. In many cases, it is advantageous to measure the impedance at the front face of the polysytrene bead in the unknown connector. (See Paragraph 4.12.) In order to determine the impedance at this point, the electrical distance from the insulator in the connector and the position of a voltage minimum on the slotted line must be found.

The electrical distance can be determined by measuring the physical distance between the two points in question and adding 0.32 cm to the length obtained to account for the lower velocity of propagation in the insulators at the end of the slotted line.

Another more accurate method of determining the effective electrical distance is to short-circuit the end of the slotted line with a Type 874-WN Short Circuit and to determine the position of a voltage minimum on the slotted line, as outlined in Paragraph 2.32. The short-circuit is made at the face of the bead in this unit.

The VSWR is measured and the unknown impedance calculated as outlined in Paragraph 4.72.

4.8 MEASUREMENTS ON COMPONENTS AND LUMPED CIRCUITS

The Type 874-LBA Slotted Line can be used to measure the impedance of components of all types. At high frequencies, this type of measurement is complicated by many factors, the most important of which generally are: (1) the position of the element with respect to ground, leads, and other circuit elements can have a large effect on the impedance of an element, and (2) the reactances of leads used, in addition to any leads which may be part of the component under test, to connect the component to the measuring device and the stray capacitance of the measuring terminals and supplementary leads, may also appreciably affect the measurements.

To minimize the effects of the first difficulty, the component should be measured while mounted in the position in the circuit in which it is to be used, or under as similar conditions as possible. One method of measuring a component in position in a circuit is to connect it to the slotted line by means of a length of flexible cable or rigid coaxial line, as shown in Figure 19. The rigid line is preferred as its characteristic impedance is more uniform. The impedance is measured, as outlined in Paragraph 2.332. The line is short-circuited at its load end by one of the methods shown in Figures 14a and 14b.

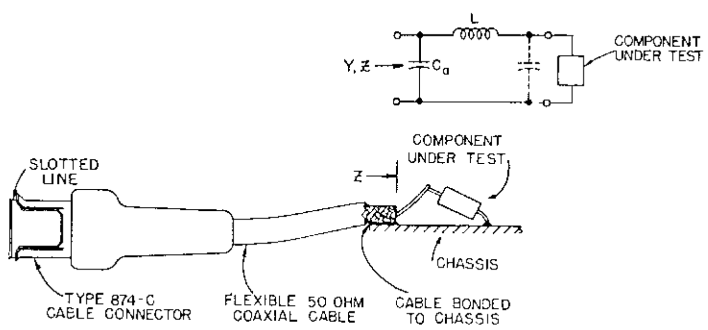


Figure 19. Approximate equivalent circuit of connecting lead reactances encountered when components are measured.

In order to minimize the effects of the lead and terminal reactances, the supplementary leads used to connect the component to the end of the coaxial line should be as short as possible.

The leads referred to do not include those normally used to connect the unknown to the circuit in which it is used. If the supplementary leads are short, the stray reactances can be considered as lumped into two elements: a shunt capacitance across the end of the line from the measuring instrument, and an inductance in series with the line, as shown in Figure 19. The lead and terminal reactances affect the measured impedance, Z_m, as can be seen from the equivalent circuit in the figure. In order to determine the actual impedance of the unknown, the measured impedance should be corrected for the effects of the lead and terminal reactances, using the following equations:[15]

$$R_x = \frac{R_m}{D} \qquad (31)$$

$$X_x = \frac{X_m\left(1 - \frac{X_m}{X_a}\right) - \frac{R_m^2}{X_a}}{D} - X_L \qquad (32)$$

where

$$D = \left(1 - \frac{X_m}{X_a}\right)^2 + \left(\frac{R_m}{X_a}\right)^2 \qquad (33)$$

[15] These will be recognized as the same equations that are used to correct for lead capacitance in the Type 916-A Radio-Frequency Bridge.

$$X_a = -\frac{1}{\omega C_a} \quad \text{ohms} \qquad (34)$$

$$X_L = \omega L \quad \text{ohms} \qquad (35)$$

where L is the magnitude of the lead inductance in henries and C_a is the magnitude of the shunt capacitance in farads.

If the admittance of the unknown is desired, rather than the impedance, the admittance, Y_m, appearing across the end of the line, is calculated from the VSWR and position of a voltage minimum, as outlined in Paragraph 2.334, and the following equations used to correct for the lead reactances:

$$G_x = \frac{G_m}{D} \qquad (36)$$

$$B_x = \frac{B'_m\left(1 - \frac{B'_m}{B_L}\right) - \frac{G_m^2}{B_L}}{D} \qquad (37)$$

where

$$D = \left(1 - \frac{B'_m}{B_L}\right)^2 + \left(\frac{G_m}{B_L}\right)^2 \qquad (38)$$

$$B'_m = B_m - B_a = B_m - \omega C_a \times 10^3 \quad \text{millimhos} \qquad (39)$$

$$B_L = -\frac{10^3}{\omega L} \quad \text{millimhos} \qquad (40)$$

where C_a and L are as defined in the previous paragraph. All admittance components are in millimhos.

The magnitudes of the lead and terminal reactances or susceptances can be determined from measurements of the reactance seen with the leads short-circuited by a low-inductance copper sheet at the point of connection to the unknown, and the reactance seen with the leads open-circuited at the point of connection to the unknown. The inductive reactance is measured when the leads are short-circuited and the capacitive reactance is measured when the leads are open-circuited. For this approximation to hold, the lead-capacitive reactance should be greater than five times the lead-inductive reactance.

A somewhat better approximation can be made by distributing the lead capacitance between the two ends of the leads, as shown by the dotted capacitor. The ratio of the two capacitances can be estimated from the physical configuration of the circuit.

An even better approximation can be made when the leads are reasonably long, if the inductance and capacitance are assumed to be uniformly distributed and the leads treated as a section of transmission line. The characteristic impedance, Z_o, of this line and the tangent of the electrical length, $\tan\theta$, are related to the short- and open-circuit impedances, Z_{oc}, and Z_{sc}, by the expressions:

$$Z_o = \sqrt{Z_{oc} Z_{sc}} \tag{41}$$

$$\tan\theta = \sqrt{\frac{Z_{sc}}{Z_{oc}}} = \frac{X_{sc}}{Z_o} \tag{42}$$

Equation (12) or the Smith Chart can be used to correct the measured impedance for the effect of the equivalent section of transmission line. If a Smith Chart designed for lines having a 50-ohm impedance is used, the measured values should be divided by $\frac{Z_o}{50}$ before entering the chart and the resultant corrected impedance multiplied by $\frac{Z_o}{50}$. In most cases the capacitance is not uniformly distributed but the approximation usually gives reasonably accurate results. A normalized Smith Chart is better suited to this application.

In most cases more accurate measurements can be made by using the Type 874-M Component Mount, shown in Figure 20, on which the component or lumped circuit can be mounted. The end of the center conductor of a section of air line is used as the ungrounded terminal, and the outer conductor is extended in the form of a disk for a ground plane. The line can be short-circuited at the terminal by means of a very low inductance disk supplied, or the mount can be disconnected and replaced by a Type 874-WN3 Short-Circuit Termination Unit. The distance from the front face of the polystyrene bead in the

connector mount is located 3 cm away from the ground plane surface; hence, the termination unit referred to places a short-circuit effectively at the ground plane surface when it is substituted for the component mount.

The reactance of supplementary leads must be corrected for, as previously outlined.

The coaxial-line section can be removed from the ground plate, if desired, by loosening the locking nut, and installed in any other plate if a 3/4-27 tapped hole is provided.

4.81 Example of Measurement of a 200-Ohm Resistor at 600 Mc: In this case, the resistor is mounted on a Type 874-M Component Mount, shown in Figure 20, which is connected to the slotted line. The tuned, built-in crystal, with a Type 1231-P4 Attenuator and a Type 1231-B Audio Amplifier, is used as a detector. A block diagram of the setup is shown in Figure 10. The stub is tuned with the slotted line open-circuited, as indicated in Paragraph 4.2. The unknown is connected and the input power adjusted to keep the maximum excursion of the crystal within the square-law range. The attenuator settings required to give full-scale readings on the meter for several maxima and average of the maxima and the average of the minima are taken as the true readings. Averages of several readings are taken to minimize the effect of the variation probe coupling along the line. The average of the maxima is 21 db, the average of the minima is 1 db, and the minimum is at a scale reading of 40.25 cm.

The component mount is then disconnected, the Type 874-WN3 Short Circuit is connected to the slotted line, and the position of a voltage minimum is measured. The position of the minimum nearest the load is found to be at 51.20 cm. Therefore,

$$\text{SWR} = \frac{21 - 1}{2} = 10.0 \text{ db}$$

$$\frac{\ell}{\lambda} = \frac{51.20 - 40.25}{50} = 0.219 \text{ wavelength}$$

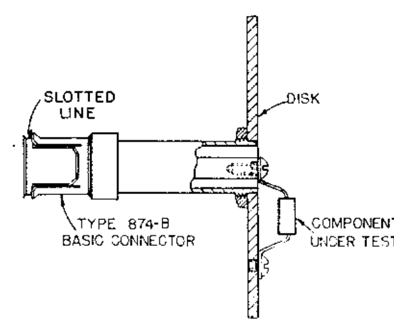


Figure 20. Sketch of the Type 874-M Component Mount.

The measured resistance and reactance calculated using the Smith Chart are: R_m = 118 ohms; X_m = - 66 ohms.

In this case, the impedance directly across the ends of the resistor is desired. However, the resistor is connected to the mount by means of its own leads which, of course, affect the measurements. Since it is not desirable to clip the leads at the ends of the resistor to measure the lead reactances, the resistor is removed and identical leads substituted. The position of the minimum on the line is determined with the leads open-circuited and is found to be 39.90 cm. The ends of the leads are short-circuited by spot-soldering a copper sheet about three inches in diameter to the ends of the leads and the minimum position again found. In this case it is at 32.95 cm.

The short-circuit reactance, X_{sc}, calculated from the Smith Chart, is +57 ohms. The open-circuit reactance, X_{oc}, is -330 ohms. The actual impedance appearing across the resistor terminals is then calculated using Equations (31) and (32).

$$R_m = 118 \text{ ohms}$$

$$X_m = -66.0 \text{ ohms}$$

$$X_L = X_{sc} = +57 \text{ ohms}$$

$$X_a = X_{oc} = -330 \text{ ohms}$$

$$D = \left(1 - \frac{-66}{-330}\right)^2 + \left(\frac{118}{330}\right)^2 = 0.768$$

$$R_x = \frac{118}{0.768} = 154 \text{ ohms}$$

$$X_x = \frac{-66\left(1 - \frac{-66}{-330}\right) - \frac{118^2}{-330}}{0.768} = \frac{-57}{0.768} = -72.2 \text{ ohms}$$

The measured resistance is less than the d-c value of 200 ohms due to the shunt capacitance of the resistor itself.

Section 5.0 Miscellaneous

5.1 OPERATION AT FREQUENCIES BELOW 300 MC

Since the probe travel is only 50 cm, it will not always be possible to measure both a voltage minimum and maximum on the line at frequencies below 300 Mc as the range of travel of the probe is one-half wavelength 300 Mc. At frequencies below 150 Mc, where the line is less than a quarter of a wavelength, it will never be possible to measure both a voltage maximum and minimum on the line directly. If both a voltage minimum and maximum do not appear on the line at frequencies above 150 Mc, additional lengths of Type 874-L30 and L10 Air Lines can be inserted between the line and the load until both a minimum and a maximum do appear. Of course, if the VSWR is greater than 10, only the minimum need appear on the slotted section of line because the measurement can be made by the width-of-minimum method.

At frequencies below 150 Mc, lengths of air line can be inserted between the line and the load until either a minimum or maximum can be measured. Sections of air line are then transferred to the other side of the slotted line, that is, between the line and the generator, until the maximum or minimum appears and can be measured. The sections are transferred rather than removed to keep the load on the oscillator and, hence, the relative voltage amplitude on the line, constant.

A somewhat better solution is to use two slotted lines and add sections of air line between them or between one and the load until a minimum appears on one line and a maximum on the other. The probes are set at the respective maximum and minimum and the outputs from the detector and the position of the probe at the minimum recorded. A Type 874-WM Termination Unit is then connected to the end of the line and the outputs of the two detectors again recorded. Since the voltage is constant all along the line with the termination connected, the probe couplings in this case are proportional to the outputs if the detector is linear. If the detector is square-law, the probe couplings are proportional to the square root of the outputs. The outputs observed with the load connected can then be corrected for any difference in coupling. This calibration corrects for differences in probe penetration, differences in probe couplings, and differences in sensitivity of the detectors.

The Type 874-D20 Stub will tune the crystal rectifier down to 275 Mc. The Type 874-D50 Stub will tune down to 125 Mc. Additional lengths of air line can be inserted in series or in shunt using a Type 874 Tee for operation at lower frequencies. With the long stub in place, smoother operation of the carriage is obtained if the whole slotted line is tilted slightly forward to make the stub almost vertical.

5.2 CALIBRATION OF THE VARIATION IN PROBE COUPLING

The variation in probe coupling along the line can be calibrated and the measurements very easily corrected for the variations. A 1000-cycle signal from the audio oscillator having an output of at least 10 volts is applied to the slotted line whose load end is open-circuited. The tuning stub and crystal are removed and the amplifier input connected directly to the connector normally used for the tuning stub. The variation in indication on the meter on the amplifier is then recorded as a function of probe position. The curve thus obtained can be applied to r-f measurements. In this calibration, the crystal is not used and the output is directly proportional to the coupling. Therefore, the correction factor measured should be applied to r-f measurements after the square-law rectification characteristic has been corrected for.

The variations in probe coupling will change somewhat as the probe penetration is varied. Hence, for the most accurate results, the calibration curve should be made with the same probe penetration as used in the r-f measurements.

Section 6.0 Maintenance

6.1 GENERAL. The two-year warranty given with every General Radio instrument attests the quality of materials and workmanship in our products. When difficulties do occur, our service engineers will assist in anv way possible.

In case of difficulties that cannot be eliminated by the use of these service instructions, please write or phone our Service Department, giving full information of the trouble and of steps taken to remedy it. Be sure to mention the serial and type numbers of the instrument.

Before returning an instrument to General Radio for service, please write to our Service Department or nearest district office (see back cover), requesting a Returned Material Tag. Use of this tag will insure proper handling and identification. For instruments not covered by the warranty, a purchase order should be forwarded to avoid unnecessary delay.

6.2 REPLACEMENT OF CRYSTAL RECTIFIER. The Type 1N23B Crystal Rectifier is mounted in the carriage (see Figure 9a), where it is held in place by a spring. To remove the rectifier, first unscrew the acorn nut on the back of the carriage and remove the cover plates, and then pull the rectifier from its socket.

The crystal can be checked by an ordinary ohmmeter. Measure the resistance with both polarities of applied dc voltage. The resistance should be below 700 ohms in one direction and above 15,000 ohms in the other.

6.3 CLEANING AND LUBRICATION. The Slotted Line should be kept in its storage box or covered when not in use to keep dirt from accumulating on the carriage track. The track should be cleaned and lubricated occasionally for best performance.

The felt washers shown in Figure 9a are lubricated through the oil holes provided. Use a light oil, and keep the oil ports filled so that there is a light oil film on the outer tube. It may occasionally be necessary to tighten the retaining rings to keep the felt washers in contact with the tube. Do not tighten them too much, or they will make it difficult to slide the carriage, causing backlash.

When the track needs cleaning, spread a coat of kerosene or light oil, such as clock oil, over the whole outside of the center conductor, using a pipe cleaner or a cloth. Then slide the carriage back and forth several times to dislodge any dirt caught in the felt rings. Finally, wipe the track dry with a cloth. Repeat this procedure until the wiping cloth does not pick up any dirt.

If the line is very dirty, remove and clean the felt washers. To remove the felt washers, unscrew the retaining washers at both ends of the carriage (see Figure 9a), and pull out the felt. Clean the felt in a solvent. When replacing the felt washers, flatten them out and push them into place. Reload the felt washers with a light oil through the oil holes at the ends of the carriage.

An oil port at the bottom of the carriage permits lubrication at the point of contact with the tie bar. This is especially important if the Slotted Line is motor-driven.

The slot in the center conductor can be cleaned with a pipe cleaner.

If the inside of the tube needs cleaning, remove the connectors at both ends as well as the center conductor, and pass a cloth attached to a string through the tube. Do not perform this operation unless really necessary; it requires care and readjustment of the center conductor after the line is put back together.

6.4 REMOVAL OF CENTER CONDUCTOR. Before or during disassembly of the line, mark the center conductor, both teflon beads, and both end supporting sections, so that they can be reassembled with their original orientations.

To remove the connectors, use gas pliers to unscrew the threaded ring (coupling nut) at the base of the connector, and pull off the outer connector sections. Then carefully pull the inner connector sections and insulators out of the line. (This may be difficult because the inner teflon insulator is a pressed fit.) Then remove the center conductor. (See Figure 21.)

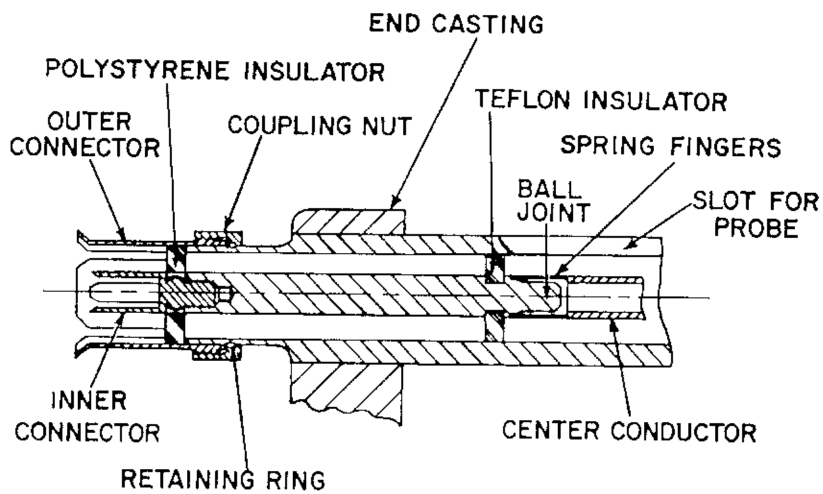


Figure 21. Sketch of end section of the line showing the supporting insulators and ball joint.

If possible, replace the Type 874-70 polystyrene insulators at the base of the inner connectors with new ones before reassembling the line.

Be careful to reassemble the line with the original orientations. Insert the inner conductor part way into the right-hand end of the line, and slip the spring fingers over the ball joint on the right-hand supporting section. Then push the supporting section (with Type 874 Connector on the end) into the tube until the polystyrene insulator is flush with the end of the tube. Align the slots in the insulator and tube, and fasten the outer connector section in place with the coupling nut.

Slide the left-hand supporting section into the other end of the line until its end almost contacts the end of the center conductor, as seen through the large slot. Bend a piece of wire into a shallow hook, insert it through the slot, and hook it around the end of the center conductor. Lift the center conductor so that it will slip onto the shank of the ball joint section, and carefully push the supporting section into place. Be sure that the shank enters the hole in the end of the center conductor without damaging the spring fingers. Then align the slots, replace the outer connector section, and lock in place.

If it is necessary to adjust the center conductor, rotate it until the variation in probe coupling is a minimum. To raise or lower the ends of the center conductor, rotate the teflon beads, which are slightly eccentric. Check the variation in probe coupling at 1000 cycles, as outlined in paragraph 5.2.

To rotate the center conductor, insert a thin blade through the slots between the spring fingers (accessible through the slot in the outer conductor).

A prying motion will rotate the center conductor. Be careful not to damage the spring fingers.

6.5 CENTERING OF PROBE IN SLOT. To check centering of the probe shield, hold the line up to a light and sight from one end along the slot. Move the carriage along the line and observe the centering of the probe shield.

If the probe is not centered, unscrew the large screws that tighten the clamps on the end casting, loosen the outer tube in its mounting, and rotate it slightly. An ell or tee inserted as a handle at one end may make it easier to rotate the line.

6.6 SPRING ADJUSTMENT. If the coupling seems to vary as the direction of the carriage is changed, the springs bearing on the nylon plugs at the bottom of the carriage casting (see Figure 9a) may not be compressed enough. To check this, note if the output returns to its original value when the carriage is rocked sideways (in the direction of the tube) and then released. If the output does not return to the same value under all conditions, the springs are not compressed enough.

To adjust the springs, set the carriage over the hole near the right-hand end of the tie bar. Turn the Slotted Line over, and adjust the carriage so that the heads of the two setscrews in the base of the carriage are lined up with the hole. Adjust the screws with a 1/8 Allen wrench, turning them a half turn at a time, and check the effect of rocking the carriage. Do not compress the springs too far or unevenly, or the carriage will not slide freely.

6.7 ADJUSTMENT OF NYLON CORD TENSION. The nylon cord will stretch slightly with time, causing some backlash. A take-up reel on the back of the carriage can be used to adjust cord tension. The inner flange of the reel has a number of holes around its outer edge; a pin, on the carriage body, enters one of the holes to provide a ratchet-type lock. To turn the reel, first pull it out about 1/16 inch to withdraw the pin from the hole in the flange. Then rotate the reel to produce the desired cord tension, and lock it by pushing it back in so that the pin enters one of the holes.

6.8 REPLACEMENT OF NYLON CORD. The nylon cord is very tough, and should last a long time unless it rubs against a sharp cutting edge. A spare cord is supplied with the Slotted Line, and additional cords can be obtained from General Radio. The cord is 0.045 inch in diameter and 74-1/2 inches long.

Install the cord as shown in Figures 9b and 9c. Knot the cord near one end, and thread the other end through the hole in the anchor post. Then pass the cord around the idler pulley and wrap it 1-1/2 times around the drive drum. Make sure that the end of the first turn is on the knob side of the beginning of the first turn (see Figure 9c) so that the turns travel in the correct direction on the drum. Then pass the cord around the anchor post and thread it through the hole in the outer flange of the take-up reel. Knot the cord near the end to keep it from slipping back through the hole. Then adjust the tension by pulling out the take-up reel, to disengage the pin, and rotating it clockwise until the action of the drive knob feels satisfactory. It may be necessary to slide the cord axially along the driving drum to center it properly and prevent it from riding over the flange at one end.

TYPE 874 ACCESSORIES

ADAPTORS

Type	Contains Type 874 Connector and	Fits
874-QBJ	BNC Jack	BNC Plug
874-QBP	BNC Plug	BNC Jack
874-QCJ	C Jack	C Plug
874-QCP	C Plug	C Jack
874-QHJ	HN Jack	HN Plug
874-QHP	HN Plug	HN Jack
874-QLJ	LC Jack	LC Plug
874-QLP	LC Plug	LC Jack
874-QLTJ	LT Jack	LT Plug
874-QLTP	LT Plug	LT Jack
874-QNJ	N Jack	N Plug
874-QNP	N Plug	N Jack
874-QSCJ	SC Jack	SC Plug
874-QSCP	SC Plug	SC Jack
874-QTNJ	TNC Jack	TNC Plug
874-QTNP	TNC Plug	TNC Jack
874-QUJ	UHF Jack	UHF Plug
874-QUP	UHF Plug	UHF Jack
874-QU1A		7/8" 50Ω UHF rigid air line
874-QU2		1-5/8" 50Ω UHF rigid air line
874-QU3A		3-1/8" 50Ω UHF rigid air line
874-QV2A		1-5/8" 51.5Ω VHF rigid air line
874-QV3		3-1/8" 51.5Ω VHF rigid air line
874-Q2	274 Jack	274 Plug
874-QN6	Pin & Sleeve	274-NO
874-Q7	774 Jack	774 Plug

CABLE (DOUBLE-SHIELDED)

Type	Z	Attenuation/100 ft
874-A2	50Ω ±5%	2.6 db at 100 Mc
874-A3	50Ω ±5%	5.3 db at 100 Mc

CONNECTORS

CABLE CONNECTORS TYPE	FOR CABLE TYPE
874-C	874-A2
874-C8	RG8/U
874-C9	RG9/U, RG116/U
874-C58	874-A3, RG29/U, RG55/U, RG58/U, RG58A/U
874-C62	RG59/U, RG62/U
PANEL CONNECTORS (-P -HEX NUT MTG, -PB -FLANGE MTG)	
874-P, -PB	874-A2
874-P8, -PB8	RG8/U
874-P9, -PB9	RG9/U, RG116/U
874-P58, -PB58	874-A3, RG29/U, RG55/U, RG58/U, RG58A/U
874-P62, -PB62	RG59/U, RG62/U

PATCH CORDS (3 FT)

TYPE	CONNECTOR	CABLE	CONNECTOR
874-R20	874-C	874-A2	874-C
874-R22	874-C58	874-A3	874-C58
874-R33	874-C58	Single-shielded	274-P
874-R34	874-C58	Single-shielded	274-NK

MISCELLANEOUS

TYPE 874-		TYPE 874-		TYPE 874-	
BM	300Ω Balanced Termination	LK	Constant-Z Adjust. Line	UB-P3	300Ω Balun Terminal Pad
D	Adjustable Stubs	LR	Radiating Line	VC	Variable Capacitor
EL	90 ° Ell	LT	Trombone-Constant-Z Line	W100	100Ω Coax. Standard
F	Low-Pass Filter	M	Component Mount	W200	200Ω Coax. Standard
FR	Rejection Filter	MA	Adjustable Coupling Probe	WM	50Ω Termination
G	Fixed Attenuator	MB	Coupling Probe	WN	Short-Circuit Termination
GA	Adjustable Attenuator	T	Tee	WO	Open-Circuit Termination
JR	Rotary Joint	UB	Balun	X	Insertion Unit
K	Coupling Capacitor	UB-P2	200Ω Terminal Unit	XL	Series Inductor
L	Air Line			Y	Cliplock
LA	Adjustable Line			Z	Stand

The above is a partial listing. For complete list and specifications, refer to the General Radio Catalog.

INSTRUCTION MANUAL

Type 874-LBB Slotted Line

B

GENERAL RADIO

Contents

WARRANTY

We warrant that each new instrument manufactured and sold by us is free from defects in material and workmanship and that, properly used, it will perform in full accordance with applicable specifications for a period of two years after original shipment. Any instrument or component that is found within the two-year period not to meet these standards after examination by our factory, District Office, or authorized repair agency personnel will be repaired or, at our option, replaced without charge, except for tubes or batteries that have given normal service.

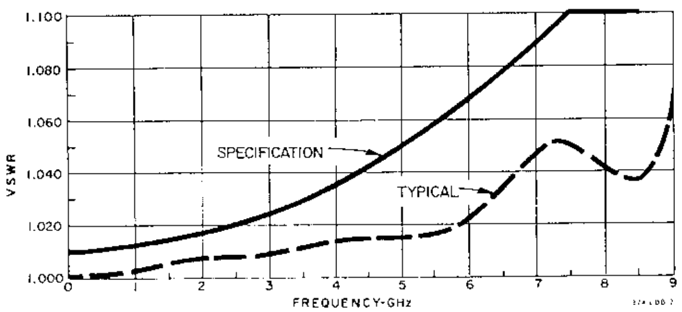
Type 874-LBB
Slotted Line

B

West Concord, Massachusetts, U.S.A. 01781

Form 0874-0205-B
June 1970
ID-B246

SPECIFICATIONS



Type 874-LBB residual VSWR.

NOTE

Type 874-BBL locking connectors are used in establishing the residual VSWR specifications.

Characteristic Impedance: 50 Ω ± 0.5%.

Probe Travel: 50 cm. Scale in cm; 1 mm per division.

Scale Accuracy: ± (0.1 mm + 0.05%).

Frequency Range: 300 MHz to 8.5 GHz (usable to 9 GHz). Operation below 300 MHz (where probe travel equals one-half wavelength) is possible by use of lengths of GR874 air line.

Constancy of Probe Pickup: ±1.25%.

Residual SWR: $<1.01 + 0.0016\ f^2_{GHz}$ to 7.5 GHz; 1.10 from 7.5 to 8.5 GHz.

Accessories Supplied: Storage box, rf probe, 2 microwave diodes, and Smith Charts.

Accessories Required: 900-DP Probe Tuner (recommended) or 874-D20L Adustable Stub for tuning diode when audio-frequency detector such as the GR 1234 is used; suitable generator and detector; one each 874-R22LA and 874-R22A Patch Cords (supplied with Detectors and GR Oscillators).

Accessories Available: The 874-LBB with accessories required for impedance and SWR measurements is available as the 874-EKA Basic Slotted-Line Kit. For measurement of SWR >10 the 874-LV Micrometer Vernier is recommended. Also available are Smith Charts and adaptors to other popular connectors.

Dimensions (width x height x depth): 26 x 4½ x 3½ in. (660 x 115 x 89 mm).

Weight: Net, 8½ lb (3.9 kg); shipping, 23 lb (10.5 kg).

MICROMETER VERNIER — 874-LV

For precise measurements of high SWR by the width-of-minimum method, and for precise phase measurements. Consists of a micrometer head calibrated in centimeters (calibrated to 0.001 cm), mounted on an arm that can be attached to the rear base rod of the slotted line. One turn of the micrometer barrel advances the head by 0.5 mm. Maximum range is 2.5 cm. Can be read to ±0.002 mm.

PROBE TUNER — 900-DP

An accessory for the 874-LBB, this Probe Tuner can be used in place of an rf probe and adjustable stub. It has convenient, calibrated probe-depth adjustment and vernier tuning for resonance at any frequency from 300 MHz to 9 GHz. Installation tools are included.

Frequency Range: 0.3 to 9 GHz. **Tuning:** Shunt.

Probe Depth Scale: Calibrated in inches (0.001/div).

Stub Tuner: Calibrated in cm.

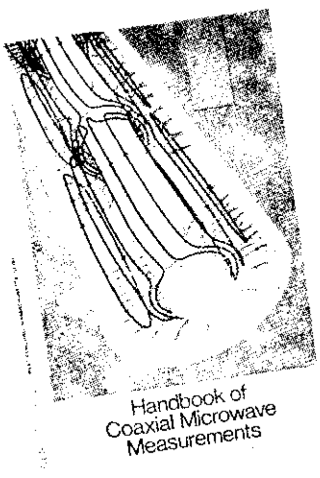
Dimensions: Length 11 in. (280 mm), dia ⅞ in. (23 mm), closed.

Net Weight: 8½ oz (245 g).

Several copies of Smith Charts are supplied with the Slotted Line. Additional copies can be obtained from General Radio at the following prices:

Catalog Number	*Description*	
5301-7568	**Type Y Smith Chart**	(20-mmho admittance coordinates)
5301-7569	**Type Z Smith Chart**	(50-ohm impedance coordinates)
5301-7560	**Type N Smith Chart**	(normalized coordinates)
5301-7561	**Type NE Smith Chart**	(normalized expanded coordinates)
5301-7562	**Type HE Smith Chart**	(normalized highly expanded coordinates)

Price per unit of 50 (minimum quantity sold) — **$2.50**



The General Radio "Handbook of Coaxial Microwave Measurements," a 172-page compendium of introductory theory and practice, is available from General Radio Company, West Concord, Mass., U.S.A. Price is $2.00.

TABLE OF CONTENTS

GR874® COAXIAL COMPONENTS

GR874 CABLE CONNECTORS

APPLICABLE CABLE TYPES	CONNECTOR TYPE	CABLE	CABLE LOCKING	PANEL FLANGED	PANEL LOCKING	PANEL LOCKING RECESSED	PANEL LOCKING (KEYED)
50-OHM	874-A2	-CA	-CLA	-PBA	-PLA	-PRLA	-PBRLA
50-OHM	RG-8A/U RG-9B/U RG-10A/U RG-87A/U RG-116/U RG-156/U RG-165/U RG-166/U RG-213/U RG-214/U RG-215/U RG-225/U RG-227/U	-C8A	-CL8A	-PB8A	-PL8A	-PRL8A	-PBRL8A
NON-50-OHM	RG-11A/U RG-12A/U RG-13A/U RG-63B/U RG-79B/U RG-89/U RG-144/U RG-146/U RG-149/U RG-216/U						
50-OHM	874-A3 RG-29/U RG-55/U (Series) RG-58/U (Series) RG-141A/U RG-142A/U RG-159/U RG-223/U	-C58A	-CL58A	-PB58A	-PL58A	-PRL58A	-PBRL58A
NON-50-OHM	RG-59/U RG-62/U (Series) RG-71B/U RG-140/U RG-210/U	-C62A	-CL62A	-PB62A	-PL62A	-PRL62A	-PBRL62A
50-OHM	RG-174/U RG-188/U RG-316/U	-C174A	-CL174A	-PB174A	-PL174A	-PRL174A	-PBRL174A
NON 50-OHM	RG-161/U RG-187/U RG-179/U						

Example: For a locking cable connector for RG-8A/U, order Type 874-CL8A.

GR874 ADAPTORS

TO TYPE		TYPE 874-
APC-7	7-mm	QAP7L*
BNC	plug	QBJA QBJL*
	jack	QBPA
C	plug	QCJA QCJL*
	jack	QCP
GR900		Q900L*
HN	plug	QHJA
	jack	QHPA
LC	plug	QLJA QLPA
Microdot	plug	QMDJ QMDJL*
	jack	QMDP
N	plug	QNJA QNJL*
	jack	QNP QNPL*
SMA**	plug	QMMJ QMMJL*
	jack	QMMP QMMPL*
SC (Sandia)	plug	QSCJ QSCJL*
	jack	QSCP
TNC	plug	QTNJ QTNJL*
	jack	QTNP
UHF	plug	QUJ QUJL*
	jack	QUP
UHF 50-Ω Air Line	7/8-in. 1-5/8-in. 3-1/8-in.	QU1A QU2 QU3A

*Locking Type 874 Connector

Example: To connect Type 874 to a type N jack, order Type 874-QNP.

** Also mates with NPM, STM, and others.

OTHER COAXIAL ELEMENTS

TYPE 874-	DESCRIPTION	TYPE 874-	DESCRIPTION
A2	50-Ω cable (low loss)	MB	coupling mount
A3	50-Ω cable	MR, MRL, MRAL	mixer-rectifier
D20L, D50L	20-, 50-cm adjustable stubs	R20A, R20LA	patch cord, double shield
EL, EL-L	90° ell	R22A, R22LA	patch cord, double shield
F185L	185-MHz low-pass filter	R33, R34	patch cord, single shield
F500L	500-MHz low-pass filter	T, TL	tee
F1000L	1000-MHz low-pass filter	TPD, TPDL	power divider
F2000L	2000-MHz low-pass filter	U	U-line section
F4000L	4000-MHz low-pass filter	UBL	balun
FBL	bias insertion unit	VCL	variable capacitor
G3, G3L, G6, G6L G10, G10L, G14, G14L G20, G20L	3-, 6-, 10-, 14-, and 20-dB attenuators	VI VQ, VQL VR, VRL	voltmeter indicator voltmeter detector voltmeter rectifier
GAL	adjustable attenuator	W100	100-Ω termination
JR	rotary joint	W200	200-Ω termination
K, KL	coupling capacitor	W50B, W50BL	50-Ω termination
L10, L10L L20, L20L L30, L30L	10-, 20-, and 30-cm rigid air lines	WN, WN3, WNL WO, WO3, WOL X	short-circuit terminations open-circuit terminations insertion unit
LAL	35-58 cm adjustable line	XL	series inductor
LK10L, LK20L	constant-Z adjustable lines	Y	cliplock
LR	radiating line	Z	stand
LTL	trombone constant-Z line	-9508	air line inner conductor
ML	component mount	-9509	air line outer conductor

CONNECTOR ASSEMBLY TOOLS

TYPE 874-	FUNCTION
TOK	Tool Kit
TO58	Crimping Tool
TO8	Crimping Tool

MISCELLANEOUS COAXIAL CONNECTORS

CONNECTOR TYPE	TYPE NO.	USED WITH
Basic	874-B	50-ohm air line
Basic Locking	874-BBL	50-ohm air line
Panel Locking Feedthrough	874-PFL	Type 874 patch cords

L suffix indicates locking Type 874 Connector.

SECTION 1 INTRODUCTION

1.1 PURPOSE

The Type 874-LBB Slotted Line is a coaxial instrument basic to the measurement of the impedance, voltage standing wave ratio (VSWR), and reflection coefficient of distributed and lumped elements from 300 MHz to 8.5 GHz,

The Slotted Line is fitted with Type 874-BBL Connectors. It is extremely versatile for it can be used, through adaptors, with most other standard coaxial line elements, including the very precise GR900 line.

1.2 DESCRIPTION

The Type 874-LBB Slotted Line is designed to measure accurately the voltage standing-wave pattern produced by any load connected to it. Its characteristic impedance is 50 ohms. The outer conductor is slotted for a length of approximately 50 centimeters, and a small shielded probe extends into the region between the two conductors. The probe is mounted on a carriage, which slides along the outside of the outer conductor. The penetration of the probe into the line and, hence, the capacitive coupling between the probe and the line, can be adjusted over a wide range by means of a screw adjustment.

Since the probe is capacitively coupled to the line, the voltage induced in the probe circuit is proportional to the voltage existing between the inner and outer conductors of the line at the probe position.

The carriage is driven by means of a nylon cord which passes around a drum mounted on the casting at one end of the line and around an idler pulley which is mounted on the casting at the other end of the line. The driving knob is attached to the same shaft as the drum. The drive depends upon friction. This drive method facilitates recorder-driving of the slotted-line.

1.3 ACCESSORIES SUPPLIED

With the Type 874-LBB Slotted Line are supplied two detector diodes, an rf probe (with Type 874-BL Connector), a storage case, and a few Smith charts.

1.4 ACCESSORIES REQUIRED

Required to operate the Type 874-LBB Slotted Line are a suitable generator and detector (refer to Section 2), and an adjustable probe (Type 874-D20L), or a Type 900-DP Probe Tuner, for tuning the diode rectifier when the audio frequency detector or the microammeter is used. The Type 900-DP Probe Tuner is recommended for the greatest convenience and accuracy.

SECTION 2 INSTALLATION

2.1 GENERAL

The Type 874-LBB requires a laboratory quality rf signal source, a standing-wave meter and means of tuning the detector (adjustable stub or probe tuner) to be ready for operation.

The line is compatible with all commercial instruments available as rf source and indicator. Table 2-1 lists the recommended General Radio generators; suggested hookups are shown in Figures 2-1, 2-2, and 2-3.

Table 2-2 lists some of the adaptors available and Figures 2-7 a, b, and c show the residual VSWR performances of the line and adaptors.

2.2 GENERATOR

The generator requirements are dependent on the type of detector used and on the standing-wave ratio of the load to be measured. Table 2-1 is a chart showing several possible generators with their respective frequency ranges. The Type 1264 Modulating Power Supply is an ideal source of 1-kHz square-wave modulation as well as a regulated power supply, for the unit oscillators in slotted-line uses.

TABLE 2-1 GENERATORS

Type	*Name*	*Frequency Range*
1215	Unit Oscillator	50- 250 MHz
1362	UHF Oscillator	220-920 MHz
1363	VHF Oscillator	56- 500 MHz
1361	UHF Oscillator	450- 1050 MHz
1218	Unit Oscillator	900-2000 MHz
1360	Microwave Oscillator	1.7- 4.0 GHz

2.3 DETECTOR

2.3.1 GENERAL

Either the built-in diode detector (using one of the two diodes supplied), or an external receiver can be used as a detector.

The choice of microwave diode depends upon operating frequency, since such diodes have a self-resonant frequency which may reduce sensitivity slightly and broaden the tuning-stub resonance. Two diodes (types 1N21C and 1N23B) with different resonant frequencies are supplied. If the above condition is encountered, it can be eliminated by interchange of diodes. Note that a diode is used only with a modulated signal source.

CAUTION

The diode should be removed before unscrewing the RF Probe or the Probe Tuner.

If desired, Type 610-A Bolometer elements, manufactured by Polytechnic Research and Development Company or similar bolometers can be inserted in place of the diode. With bolometers, less attention is required relative to operation in the square-law region.

2.3.2 DIODE RECTIFIER AND STANDING WAVE METER

The most commonly used and the most generally satisfactory detector is the built-in diode rectifier with the Type 1234 VSWR meter (Figure 2-1). The oscillator driving the line should be modulated, preferably square wave.

At very low levels, the diode operates in the "square-law" portion of its characteristic curve, that is, the rectified output is proportional to the square of the rf input. At high levels, the diode approaches a linear characteristic. For reference: for a rectified output of up to 2 mV, the supplied diodes operate in their square-law region. This will be the case for most measurements.

The diode rectifier is tuned by means of the adjustable stub (Type 874-D20L) or the Type 900-DP Probe Tuner. (Refer to paragraph 3.4.)

2.3.3 HETERODYNE DETECTOR (Table 2-3)

The Type 1241 Detector (Figure 2-2) is also a satisfactory detector for the slotted line, particularly for the measurement of high VSWR's, because of its good sensitivity and harmonic rejection. It is recommended when the minimum position must be determined accurately, such as in the measurement of electrical length. It is also preferable when measuring by the width-of-minimum method.

The shielding of this detector is excellent, a property which is useful in the measurement of radiating systems. Harmonics of the local oscillator frequency can be used to beat with the signal from the

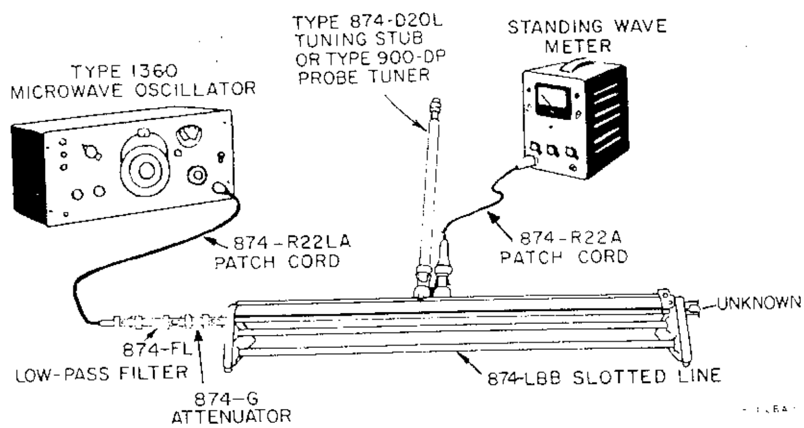


Figure 2-1. Use of a modulated source for measurements with the Type 874-LBB Slotted Line. The built-in diode detector and a standing-wave meter are used to detect the voltage induced in the probe. The probe is tuned by means of the adjustable stub shown, or a Type 900-DP Probe Tuner.

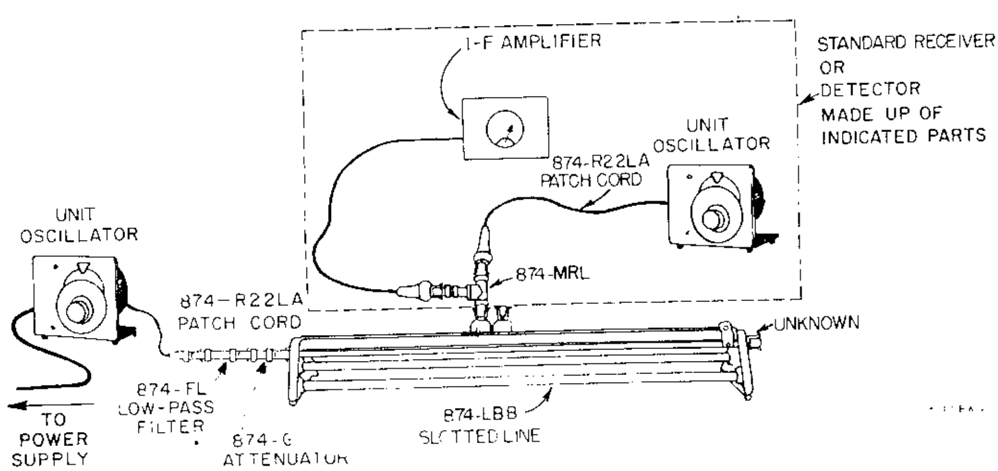


Figure 2-2. Use of an unmodulated source and a superheterodyne detector or receiver for measurements with the Type 874-LBB Slotted Line.

slotted line. Hence, the upper frequency limit may be several times the upper frequency limit of the oscillator.

NOTE

The diode must be removed from the carriage mount in this application.

2.3.4 DIODE RECTIFIER AND MICROAMMETER

A simple detector system consists of the built-in diode rectifier used with an external microammeter, as shown in Figure 2-3. In this case, the rectified dc output of the diode is measured on a sensitive microammeter connected between the inner and outer terminals of the right-hand connector on the probe carriage. In most cases, the rectified dc output is closely proportional to the square of the rf input at currents up to roughly 50 microamperes.

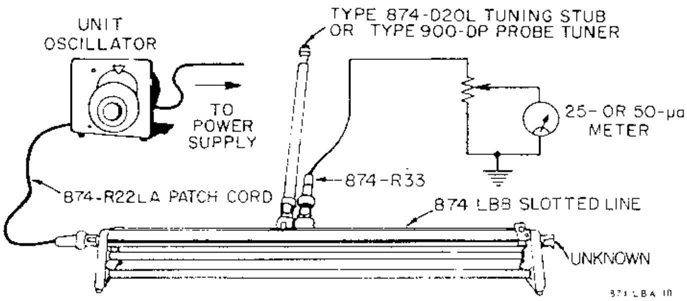


Figure 2-3. Use of an unmodulated source for measurements with the Type 874-LBB Slotted Line. The indicator is a microammeter.

2.4 COAXIAL CONNECTORS, ADAPTORS AND ACCESSORIES

2.4.1 CONNECTORS

The new low VSWR Type 874-BBL locking connectors are used for connection at both ends of the Type 874-LBB Slotted Line. The improvement due to the Type 874-BBL is evident in the graph of Figure 2-4 which shows the residual VSWR of both the Type 874-BBL and the old Type 874-B (one pair of connectors).

Connections to generator and detector are made with Type 874-R22LA Patch Cords.

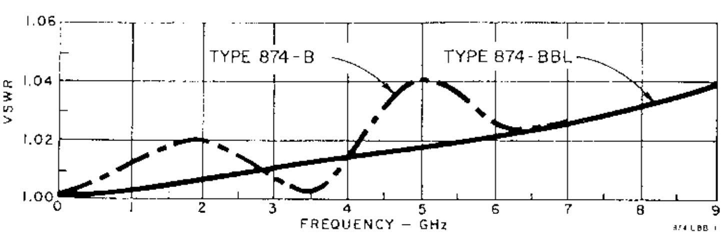


Figure 2-4. Residual VSWR for a pair of Type 874-BBL Locking Connectors.

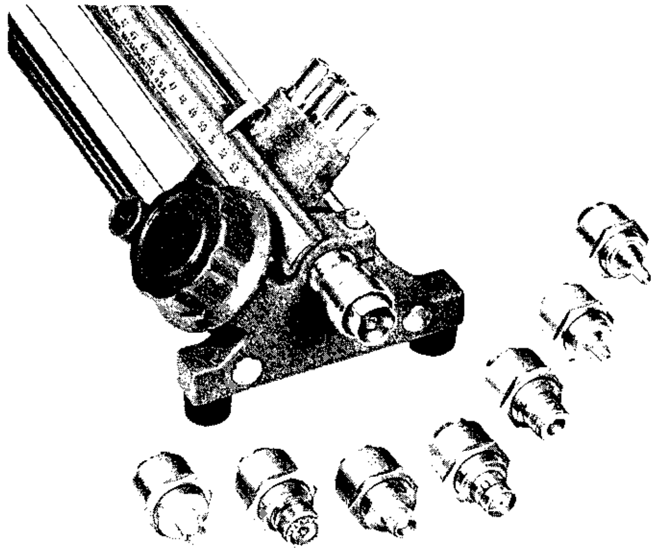


Figure 2-5. The Type 874-LBB and some of the GR adaptors.

2.4.2 ADAPTORS

If the unknown, the generator or the detector, is fitted with connectors other than the Type 874, adaptors can be used to make the necessary transition to the Type 874 connectors. The conversion to all the other leading coaxial connectors series is fast and inexpensive. The performance is excellent in those line sizes. Table 2-2 lists some of the GR adaptors; Figure 2-5 shows them with the slotted line.

Connection to the more precise GR900 line is also offered, through the Type 874-Q900L (Figure 2-6).

Figure 2-6.
The Type 874-Q900L converts the GR874 line to the GR900 line.

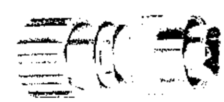
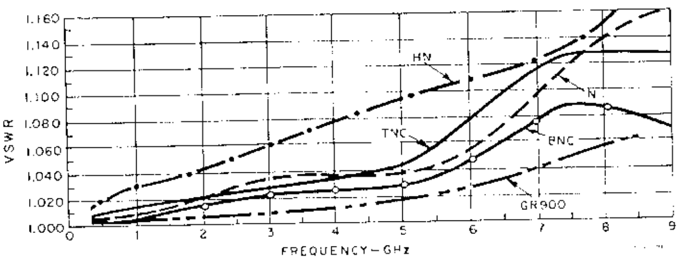


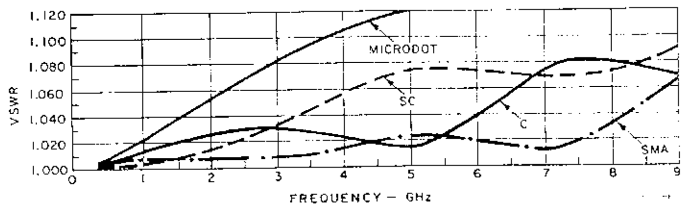
TABLE 2-2 GR874 ADAPTORS

Type	*Contains GR874 and . . .*	*Connects GR874 and . . .*
*874-QBJL	BNC jack	BNC plug
*874-QHJL	HN jack	HN plug
*874-QNJL	N jack	N plug
*874-QTNJL	TNC jack	TNC plug
*874-QMDJL	Microdot jack	Microdot plug
*874-QSCJL	SC jack	SC plug
*874-QCJL	C jack	C plug
*874-QMMJL	SMA jack	SMA plug
**874-QLJA	LC jack	LC plug
**874-QJTJ	LT jack	LT plug
* 874-QAP7L	APC-7	APC-7 (7 mm)

* Locking Adaptor. A nonlocking version of jack and plug is available.
** Nonlocking



(a)



(b)

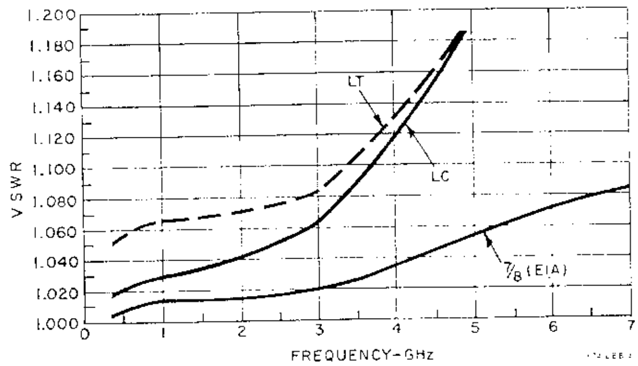
2.4.3 RESIDUAL VSWR OF THE TYPE 874-LBB LINE WITH DIFFERENT ADAPTORS

Quite naturally, the Type 874-LBB Slotted Line will have a different residual VSWR performance when terminated in an adaptor.

The graphs in Figures 2-7 a, b and c show residual VSWR for the Type 874-LBB when fitted with different adaptors (locking connectors). These curves are not to be taken as specifications but rather as typical.

2.4.4 COAXIAL ACCESSORIES

In addition to the adaptors, there are available Type 874 tees, ells, air lines, rotary joints, and other accessories for convenience of connection. Refer to the list at the rear of this manual or, for full description, to the latest General Radio Catalog.



(c)

Figure 2-7. Residual VSWR on the Type 874-LBB line fitted with the different adaptors indicated on the graphs.

TABLE 2-3 HETERODYNE DETECTORS

Catalog Number		Frequency Range — MHz				Local Oscillator Supplied	Filter Supplied
Bench	Rack	Fundamental	2nd Harmonic*	3rd Harmonic*	4th Harmonic*		
1241-9700	1241-9701	40÷-530	82-1030	138-1530	194-2030	**1363**	**874-F500L**
1241-9702	1241-9703	190-950	410-1870	630-2790	850-3710	**1362**	**874-F1000L**
1241-9704	1241-9705	870-2030	1770-4030	2670-6030	3570-8030	**1218**	**874-F2000L**

* For harmonic operation, the appropriate low-pass filter must be used.

÷ 40 MHz is the practical low-frequency limit.

SECTION 3 OPERATING PROCEDURE

3.1 GENERAL

Once the rf generator, the detecting system and the different accessories have been chosen (Section 2) the probe penetration has to be adjusted (paragraph 3.3) and the detector has to be tuned (paragraph 3.4) then the slotted line is ready to operate (paragraph 3.5 and subsequent paragraphs).

Often the line will have to be short- or open-circuited and these operations are discussed first (refer to paragraph 3.2).

3.2 METHODS OF SHORT- AND OPEN-CIRCUITING A LINE.

The method of producing a short-circuit for line-length measurement or adjustment is important. When an antenna or other element terminating a line is measured, the short circuit can be made, as shown in Figure 3-1.

An accurately positioned open-circuit is more difficult to obtain than an accurately positioned short-circuit because of fringing capacitance. Compensation for this effect is provided in the open-circuit termination described below.

The recommended method of producing a short- or open-circuit is to use a Type 874-WN, -WNL or -WN3 Short-Circuit Termination or Type 874-WO, -WOL or -WO3 Open-Circuit Termination Unit. The -WN3 and -WO3 Units produce a short- or open-circuit at a physical distance of 3 cm (3.2 cm electrical distance) from the front face, on the measuring instrument side of the insulating bead, as shown in Figure 3-1 a. The front face of the bead is located at the bottom of the slots between the contacts on the outer conductor.

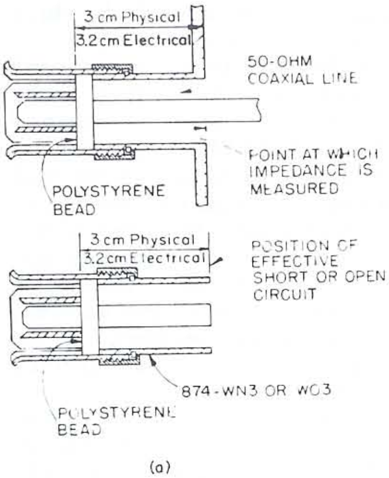
The Types 874-WN, -WNL or -WO, -WOL Termination Unit produce a short or open circuit directly at the front face of the insulating bead (Figure 3-1 b and 3-1 c). In the case of the locking terminations the reference plane set up by these locking terminations on the slotted-line is nominally 0.025-inch, toward the load because of the inherent disengagement of the locking connectors. These units can be used even if the impedance is desired at a point on the line other than at the face of the bead, if the electrical distance between the two points is added to or subtracted from the line length measured with the short- or open-circuit termination unit connected. The electrical line length for air dielectric line is equal to the physical length. Each bead in the Type 874 connector has an electrical length of 0.55 cm.

To determine the impedance at the input to a coaxial circuit connected to the slotted line, a Type 874-WN or -WNL Short-Circuit can be used to produce a short circuit directly at the front face of the insulating bead in the Type 874 Connector on the circuit under test. (The front face of the bead is located at the bottom of the slots in the outer conductor.)

3.3 PROBE PENETRATION ADJUSTMENT

3.3.1 GENERAL

The probe penetration should be adjusted for adequate sensitivity as well as insignificant effect on the measured VSWR. The presence of the probe affects the VSWR because it is a small admittance in shunt with the line. It has the greatest effect at a voltage maximum, where the line impedance is high.



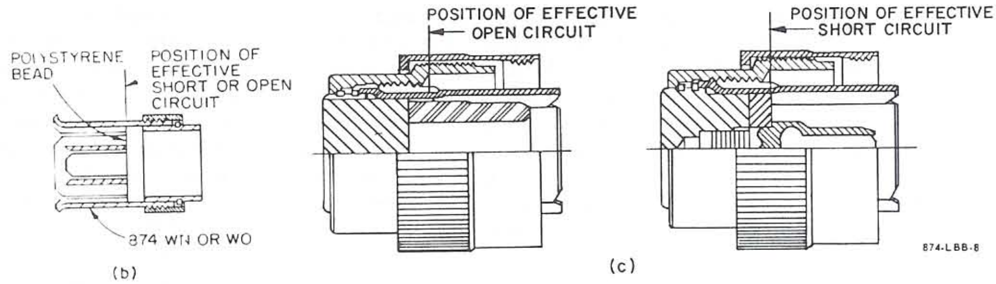


Figure 3-1. Use of Type 874-WN3 Short-Circuit Termination Unit or Type 874-WO3 Open-Circuit Termination Unit to make a short circuit or open-circuit when measuring point is located 3 cm from face of bead, as in (a). Upper unit is similar to a Type 874-ML Component Mount. Position of the short- or open-circuit when a Type 874-WN Short-Circuit Termination Unit or Type 874-WO Open-Circuit Termination Unit is used (b). Locking-type terminations used in (c).

3.3.2 TYPE 900-DP PROBE TUNER

Adjust probe penetration by means of the small control knob at the top of the tuning stub, as shown in Figure 3-2. Set it at 0.100 for routine measurements. The adjustment scale is calibrated in thousandths of an inch and reads the distance between the tip of the probe and the center conductor of the slotted line. A stop, which prevents the probe from touching the center conductor, holds the minimum distance to about 0.010 inch; maximum is about 0.150 inch after initial adjustment.

The effect of the probe coupling on the residual reflection coefficient of the slotted line is shown in Figure 3-3, or it can be determined by measurement of the VSWR at two different degrees of coupling. If the measured VSWR is the same in both, the probe coupling used has no significant effect on the measurement. If the measured VSWR's are different, additional measurements should be made, with decreasing amounts of probe penetration, until no difference occurs.

CAUTION

Always remove the diode prior to installation or removal of tuner.

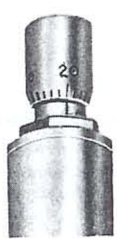


Figure 3-2. Probe depth control.

3.3.3 RF PROBE

If connected, remove the tuning stub from the left hand connector in order to change the penetration and turn the small screw found inside the inner connector. Clockwise rotation increases penetration.

CAUTION

Do not screw this probe down tight against the center conductor of the slotted line, as it will damage the probe or the center conductor. Always remove the diode prior to installation or removal or probe.

NOTE

Late model probes have a built-in stop to prevent over-penetration.

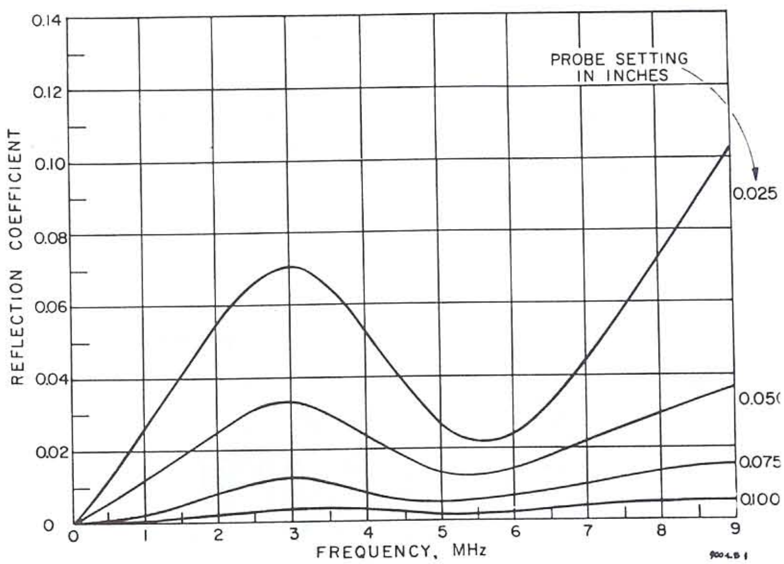


Figure 3-3. Typical probe reflections at four penetrations.

In most cases in which moderate VSWR's are measured, a distance of 0.1-inch from the inner conductor to the probe (Figure 3-4 a) will give the best results. This is achieved by backing off 5.5 turns of the screw after contact between probe and inner conductor has been made. Contact has to be very carefully approached and the following method is to be used:

Short the end of the line and connect an ohmmeter as shown in Figure 3-4 b. Contact is made when the ohmmeter shows conductivity (ohmmeter on R x 100 or x 1000).

NOTE

The diode has to be present in this procedure but the polarity of the ohmmeter has to be such that the forward resistance (low) of the diode is measured. The backward resistance is so high that it would make a reading of conductivity very difficult.

The amount of probe penetration can be visually checked by looking at the probe through the slot from one end of the line.

3.3.4 VARIATION IN PROBE COUPLING

The variation in probe coupling along the line is affected by the depth of penetration. At large penetration the variation tends to increase. The specified 1.25% holds for a penetration of 0.1-inch out (Figure 3-4 a).

When performing electrical length measurements (high VSWR), greater penetration may be employed. The probe is at a voltage minimum and therefore has a minimal effect on the position of the standing wave minimum.

3.4 DETECTOR TUNING

3.4.1 DIODE RECTIFIER TUNING

The diode rectifier built into the carriage is tuned either by means of the Type 900-DP Probe Tuner for highly sensitive tuning or by the adjustable stub (Type 874-D20L). These are effectively connected in parallel with the rectifier in order to increase the sensitivity and to provide selectivity. The probe tuner or the stub is adjusted until maximum output is indicated by the detector. Readjust the signal level as necessary to keep the audio output of the diode below 2 mV, which ensures operation in its square-law region.

Be sure the stub (or the probe tuner) is not tuned to a harmonic of the desired signal rather than to the fundamental. Confusion may result in some cases if the tuning is done with a high VSWR on the line, as the minima of the harmonics may not be coincident with the minima of the fundamental. To minimize the possibility of mistuning, the probe should be tuned with a low VSWR on the line, for instance, with the line terminated in a Type 874-W50B, -W50BL Termination Unit. As a check, the distance between two adjacent voltage minima on the line can be measured. If the stub (or the probe tuner) is tuned correctly, the spacing should be half a wavelength.

The diode can be tuned to frequencies from about 275 MHz to 8.5 GHz with the Type 874-D20L Adjustable Stub, from 300 MHz to 8.5 GHz with the Type 900-DP Probe Tuner.

For operation at frequencies below 275 MHz a Type 874-D50L Adjustable Stub can be used down to 150 MHz or various lengths of Type 874-L Air Line can be inserted in series with the adjustable stub.

3.4.2 HETERODYNE DETECTOR

When the DNT Detector is used, care must be taken to tune the local oscillator to beat with the desired signal and not with one of its harmonics. Harmonics of the oscillator signal can beat with harmonics of the signal picked up from the slotted line and produce an output at the intermediate frequency, if the local oscillator is tuned to a wrong frequency. Proper settings of the local oscillator are given by the following expression, assuming that the intermediate frequency is 30 MHz:

$$f_{LO} = \frac{f_S \pm 30}{n}$$

where f_{LO} is the frequency of the local oscillator, f_S is the signal frequency, and n is an integer, corresponding to the harmonic of the local-oscillator signal used. Always use the lowest possible harmonic.

If n = 1, there are two possible settings of the local oscillator, separated by 60 MHz and centered about the signal frequency. If n = 2, the two possible settings are separated by 30 MHz and are centered about f_S/n.

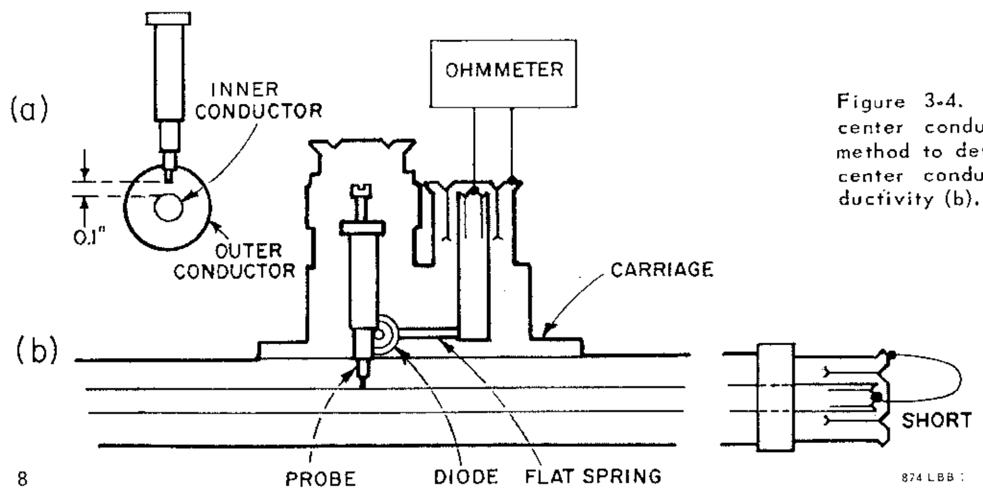


Figure 3-4. The distance between probe and center conductor for best results (a). Best method to determine that the probe touches the center conductor; the ohmmeter shows conductivity (b).

In the general case, the two possible settings are separated by 60/n and are centered about the frequency f_S/n.

The second harmonic of the desired signal frequency will produce a beat frequency of 30 MHz when the local-oscillator frequency is

$$f_{LO} = \frac{2f_S \pm 30}{n} = \frac{f_S \pm 15}{\frac{n}{2}}$$

or, in general,

$$f_{LO} = \frac{f_S \pm \frac{30}{h}}{\frac{n}{h}}$$

where h is the harmonic of the signal frequency. It can be seen from the above equation that some of the harmonic responses may be located reasonably close to the frequency at which the fundamental is detected. The higher the harmonic of the local oscillator, the closer will be the spurious responses.

In general, spurious responses do not cause much difficulty, as the frequency to which the detector is tuned can be easily checked by measuring the distance between two voltage minima on the line, which should be half a wavelength at the operating frequency. The use of an appropriate Type 874-F Low-Pass Filter is often convenient in these cases.

At some frequencies it is necessary to insert a Type 874-L10L, 10-cm Air Line, between the connector on the carriage and the mixer rectifier, in order to develop sufficient local-oscillator voltage across the diode.

3.5 MEASUREMENT OF WAVELENGTH

The free-space wavelength of the exciting wave can be measured using the slotted line by observing the separation between adjacent voltage minima when the line is short- or open-circuited. The spacing between adjacent minima, d is one-half wavelength or

$$\lambda = 2d$$

For greater accuracy at the higher frequencies, the distance over a span of several minima can be measured. If the number of minima spanned, not counting the starting point, is n, then

$$\lambda = \frac{2d}{n}$$

3.6 MEASUREMENT OF LOW VSWR (BELOW 10:1)

3.6.1 TWO METHODS

When the standing-wave ratio to be measured is less than about 10:1, the VSWR can be read directly on the scale of a standing-wave indicator (follow the manufacturer's instructions); or, with the Type 1232 Tuned Amplifier and Null Detector or the Type 1241 Detector, it can be determined from the difference between the two decibel-scale readings corresponding to the voltage maximum and voltage minimum on the slotted line.

The dB difference can be converted to VSWR on the auxiliary scales at the bottom of the Smith Chart or can be computed from the expression

$$\text{VSWR} = \log^{-1} \frac{\text{dB}}{20}$$

When using the Type 1232 Amplifier with a square-law detector, the difference in dB must be divided by two to obtain the value to use in the above formula.

The probe coupling can vary a maximum of 1.25% along the line, and the VSWR measured is in error by the difference in coupling coefficients at the maximum and minimum voltage points. This error can be avoided by calibration of the variation of coupling with probe position, as outlined in paragraph 5.5, or it can be reduced greatly by measuring several minima and several maxima, then averaging the results.

3.6.2 DETERMINATION OF IMPEDANCE FROM VSWR

To determine the impedance of the unknown, the VSWR and the electrical distance between a voltage minimum on the line and the unknown must be determined. The unknown impedance is calculated as outlined in paragraphs 4.3 and 4.4.

To find the effective distance to the unknown, short-circuit the line with a very-low-inductance short at the position of the unknown (refer to paragraph 3.2) and measure the position of a voltage minimum on the line. This minimum is an integral number of half-wavelengths from the unknown. Since the impedance along a lossless line is the same every half-wavelength, the position of the voltage minimum found with the line short-circuited is the effective position of the unknown.

3.6.3 BROAD MINIMUM

When the VSWR is very low, the minima will be very broad, and it may be difficult to locate the minimum positions accurately. In this case, better results usually can be obtained by measuring the positions of points on either side of a voltage minimum at which the voltage is roughly the mean of the minimum and maximum voltages, as shown in Figure 3-5. The minimum is located midway between these two points.

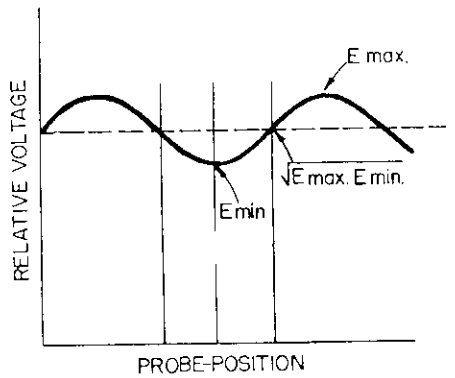


Figure 3-5. Method of improving the accuracy of the determination of the position of a voltage minimum on the line when the VSWR is low.

(Either the geometric or the arithmetical mean can be used. It is necessary only to have an identifiable value.)

3.6.4 ADDITIONAL PRECAUTIONS

If the line connecting the unknown to the slotted line has a significant amount of loss, a correction can be made for the effect of the loss on the unknown impedance, as outlined in paragraph 3.7.2.

Harmonics of the oscillator frequency may also cause an error in VSWR measurement, as discussed in paragraph 3.7.6. The effect will tend to be most serious when the VSWR at the harmonic frequencies is high. A low-pass filter installed at the input is recommended to reduce this error.

3.7 MEASUREMENT OF HIGH VSWR

3.7.1 LIMITATIONS

When the VSWR on the line is 10 to 1 or more, direct accurate measurements of a voltage maximum and a voltage minimum are difficult because:

1. The effect of a fixed probe-coupling coefficient on the measurement increases as the VSWR increases, because the line impedance at the voltage maximum increases and the shunt impedance produced by the probe has greater effect.
2. As the VSWR increases, the voltage at the voltage minimum usually decreases and, hence, a greater probe-coupling coefficient is required to obtain adequate sensitivity. The increased probe coupling may cause errors as outlined in 1 above.
3. The accuracy of the measurement of the relative voltage decreases as the VSWR increases. The voltage range becomes too great to permit operation entirely in the square-law region. (Not applicable when heterodyne detector is employed.)

3.7.2 USE OF A HETERODYNE DETECTOR

All three of the above restrictions can be reduced in effect, or eliminated, by employing a heterodyne detector.

1. The probe may be retracted because of the greater sensitivity of the detectors. (Approximately 30 dB more sensitive than the square-law, video, detector.) Greatest sensitivity can be achieved by teeing in an adjustable stub (Type 874-D20L) at the mixer input. Retraction of the probe reduces the shunting effect.
2. The heterodyne detector has considerably greater sensitivity than the video detector; (a video detector is defined as a diode detector plus a 1 KHz amplifier, employed with a modulated source).
3. The heterodyne detector has a large dynamic range; it is accurately used over about an 80-dB range.
4. The source need not be modulated. This improves accuracy because incidental FM produced by modulation is reduced, and the possibility of klystron source moding is eliminated.

3.7.3 WIDTH OF MINIMUM METHOD

Accurate measurements of VSWR's greater than 10 can be made using the width-of-minimum method. This is analogous to the determination of circuit Q by measurement of the frequency increment between the two half-power points. In the slotted-line case, the spacing, Δ, between points on the line at which the rf voltage is $\sqrt{2}$ times the voltage at the minimum, is measured, as shown in Figure 3-6. The VSWR is related to the spacing, Δ, and the wavelength, λ, by the expression

$$\mathrm{VSWR} \cong \frac{\lambda}{\pi \Delta}$$

If the detector is operating in the square-law region, $\sqrt{2}$ times the rf voltage corresponds to twice the minimum rectified output, or a 6-dB change in output.

All standing wave meters are calibrated to take the square-law operation into account, therefore, a 3-dB change will be indicated.

For very sharp minima, the width of the minimum can be measured to a much greater accuracy by use of the Type 874-LV Micrometer Vernier than by means of the centimeter scale on the slotted line. The vernier can be read to ±0.002 cm. When the vernier is used, the probe is moved slightly to the right of the minimum and the vernier is adjusted to have its plunger strike the carriage on the unpainted surface below the output connector. To adjust the position of the vernier, loosen the thumbscrew which clamps the vernier to the reinforcing rod, slide it along to the proper position, and relock it.

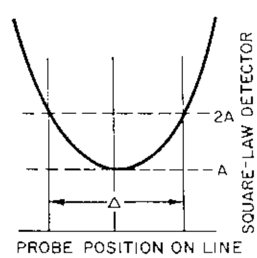
Then, drive the probe through the minimum and the twice-power points by turning the micrometer screw. Determine the output-meter reading corresponding to the minimum; set the standing-wave indicator for 6 dB more attenuation.

Back off the micrometer and return the probe to the right side of the minimum. Then, again drive the probe through the minimum and twice-power points and note the two micrometer readings corresponding to the original output meter reading. The difference between these readings is equal to Δ.

If the minimum is too close to the right-hand end of the line to permit the use of the vernier in the usual manner, the vernier can be moved to the left-hand side of the carriage and the other end of the plunger can be used to drive the carriage.

The electrical distance between the unknown and the minimum found on the line can be determined as outlined in paragraph 3.6.2.

Figure 3-6. Method of measuring the width of the voltage minimum for VSWR determinations when the VSWR is high.



At very high standing-wave ratios, the losses in the slotted line and in any connecting line or cable used can have an appreciable effect on the measurements. To keep this error as low as possible, the voltage minimum nearest the load should be measured. A correction for the loss in the line can be made as outlined in paragraph 3.7.4.

3.7.4 CORRECTION FOR LOSS IN LINE BETWEEN MEASURING POINT AND UNKNOWN

When a load is connected to the slotted line through a length of air line or cable, the loss in the air line or cable may appreciably affect the measurements. Loss in the cable tends to make the measured VSWR less than the true VSWR produced by the load. For extremes of VSWR or impedance even the slotted-line loss can affect the measurements.

The amount of loss in a length of cable can be estimated from the published cable data or can be measured. The slotted-line loss should be measured for greatest accuracy. The loss and the loss correction for VSWR can be determined by first short-circuiting then open-circuiting the cable or slotted-line. The Type 874-WN or -WNL, and the Type 874-WO or -WOL are recommended for this purpose. If the line is perfectly uniform, then only a short-circuit or only an open-circuit measurement is required, as is also the case when the highest accuracy is not required. The relation between the attenuation, $A = \alpha l$, and the measured reflection coefficients, Γ_M, is,

$$A = 10 \log_{10} |\Gamma_M| \text{ dB}$$

$$\text{where } |\Gamma_M| = \sqrt{|\Gamma_{SC}| \times |\Gamma_{OC}|}$$

Γ_{SC} = reflection coefficient with short-circuit connected

Γ_{OC} = reflection coefficient with open-circuit connected

Note that $|\Gamma| = \dfrac{VSWR - 1}{VSWR + 1}$

A quantity employed below, for loss correction derived from Γ_M, is

$$\frac{1}{(VSWR)_L} = \frac{|\Gamma_M| - 1}{|\Gamma_M| + 1}$$

The attenuation can also be determined from the short-circuit and open-circuited VSWR by use of the TRANSMISSION LOSS and STANDING WAVE RATIO scales located below the Smith Chart, shown in Figure 3-8. The point corresponding to this VSWR is located on the $\dfrac{E_{MAX}}{E_{MIN}}$ or DB scales under STANDING WAVE RATIO. At the same distance from the center, find a corresponding point on the TRANSMISSION LOSS scale. Attenuation of the line is equal to the number of decibels between the left-hand end of the scale labeled 1 DB STEPS and this latter point.

In most cases the loss in the slotted line itself can be neglected, but the loss in the line or cable used to connect the slotted line and the load is usually of importance. The unknown impedance can then be calculated in the same manner as for the lossless case, if the measured voltage standing-wave ratio, $(VSWR)_M$, is first corrected for the effect of the loss in the line. The actual or true voltage standing-wave ratio, (VSWR), is then exactly

$$(VSWR) = \frac{(VSWR)_M - \dfrac{1}{(VSWR)_L}}{1 - \dfrac{(VSWR)_M}{(VSWR)_L}}$$

3.7.5 CORRECTION FOR LOSS IN THE CONNECTOR

In the measurement of a very high VSWR, the loss at the Type 874 Connector on the slotted line can have an important effect. The magnitude of this loss for a typical line is plotted in Figure 3-7. The loss can be considered as being caused by a lumped series resistance at the lower frequencies shown.

Correction for loss as described in paragraph 3.7.4 assumes loss uniformity on the transmission line and slotted-line. As indicated here, lumped losses, occur for example in the connector, and this loss can produce an error in loss-correction. This error can be eliminated essentially by employing a substitution method. A short-circuit or open-circuit is constructed, employing a low-loss section of line, to produce a

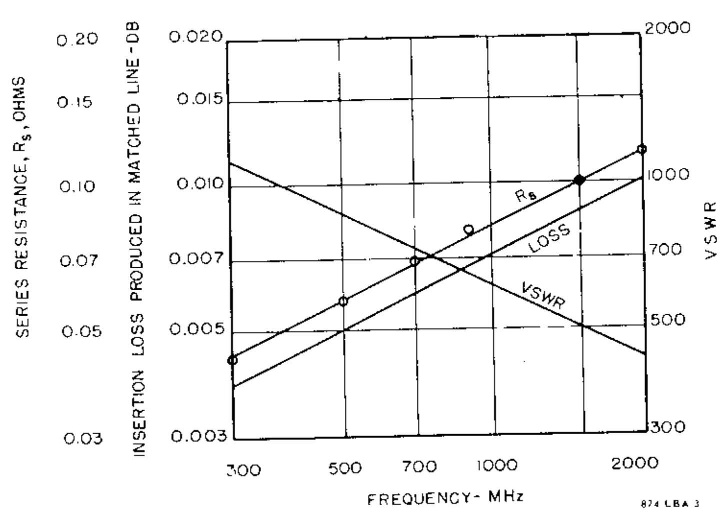


Figure 3-7. Plot of the effect of loss in the connector, measured on a typical Type 874-LBB Slotted Line. The insertion-loss produced in a matched line and the corresponding value of series resistance is also indicated, as well as the VSWR which would be produced by the connector in an open- or short-circuited 50-ohm line that has no other losses.

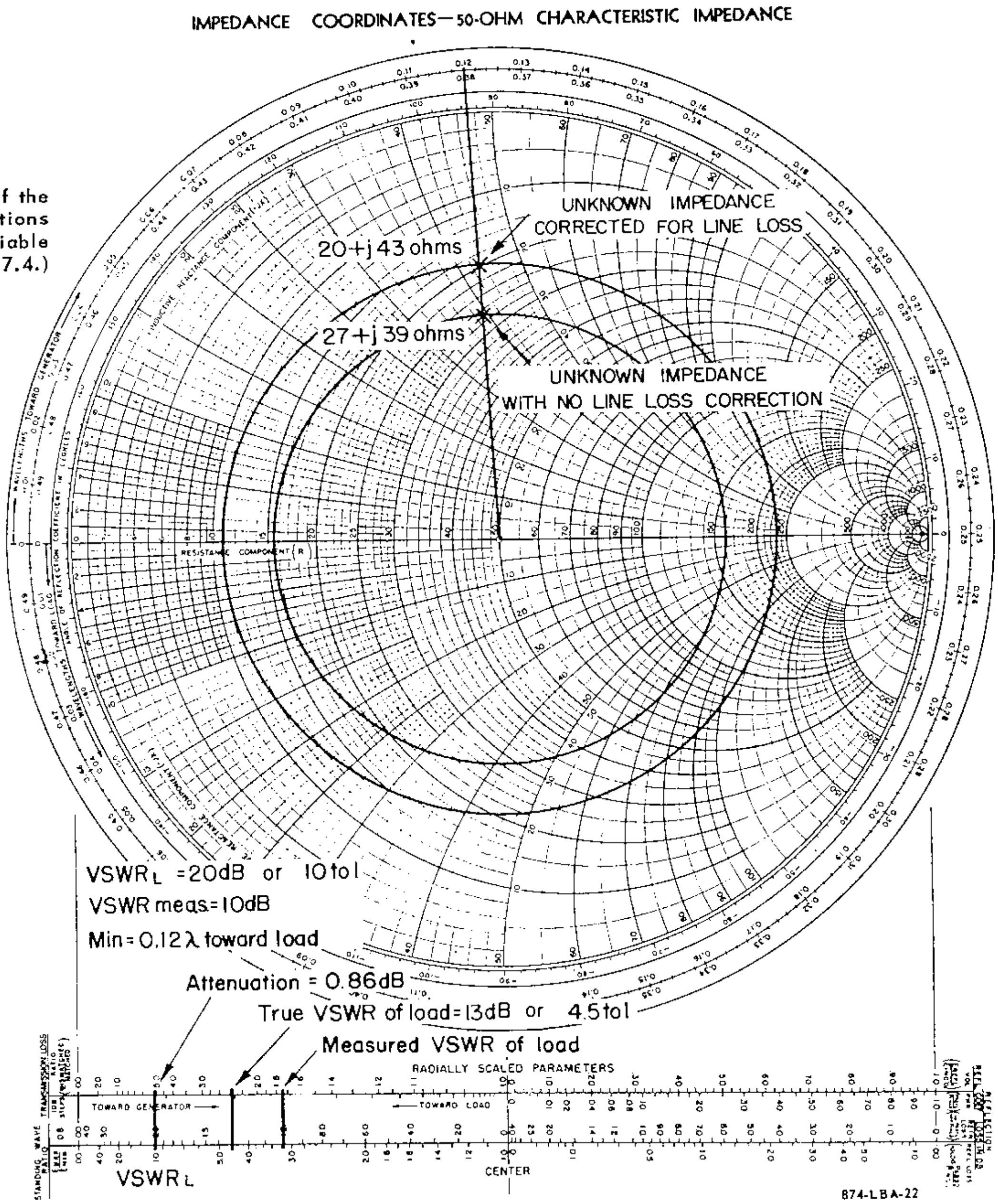


Figure 3-8. Example of the use of the Smith Chart for line length corrections when the line has an appreciable amount of loss. (See paragraph 3.7.4.)

voltage minimum at exactly the same position in the slotted-line as produced with the unknown connected. The lumped loss therefore has essentially the same effect in both cases. The actual or true VSWR in this case is:

$$\frac{1}{VSWR} \cong \frac{1}{(VSWR)_M} - \frac{1}{(VSWR)_C}$$

$$VSWR = \frac{(VSWR)_M}{1 \quad \frac{(VSWR)_M}{(VSWR)_C}}$$

Where $(VSWR)_C$ is the VSWR with the special short- or open-circuit.

3.7.6 OSCILLATOR FREQUENCY SHIFTS

In some cases, when the slotted-line is short- or open-circuited and the position of a voltage minimum is measured to determine the effective position of the unknown, errors can be caused by shifts in the oscillator frequency with the change in the load impedance between the short-circuited and loaded conditions. The effect can become more serious as the ength of line between the load and the slotted line is increases. Oscillators which are tightly coupled to the line can have relatively large frequency shifts. The effect can be greatly reduced by the insertion of a pad, such as a Type 874-G10, 10-dB Pad, between the oscillator and the slotted line. If the resultant decrease in input cannot be tolerated, the oscillator tuning can be adjusted to compensate for the frequency shift. The oscillator frequency can be measured and readjusted. Signal generators, in general, are loosely coupled, and the frequency shift is usually small.

3.7.7 HARMONICS

Another possible source of error in the measurement of high standing-wave ratios is the presence of harmonics in the wave traveling along the line. Harmonics can be generated by the driving oscillator or by a non-linear unknown such as a diode rectifier. The minima for the harmonics will not necessarily appear at the same points along the line or have the same relative amplitudes as the fundamental minima. Hence, a small harmonic content in the signal may produce a harmonic signal many times that of the fundamental at a minimum point. Therefore, if the detector will respond at all to harmonics, difficulty may be encountered. Superheterodyne receivers and the mixer rectifier detector, in general, have excellent harmonic rejection; but the tuned diode or video detector may not have a large amount of rejection for various harmonics because the tuning stub has higher-order resonances. When the diode detector is used for measurements of high VSWR's, and preferably even when a receiver is used, a good low-pass filter, such as the Type 874-F500L, -F1000L, -F2000L or -F4000L Low-Pass Filters, is required between the oscillator and the line to reduce the harmonics to an insignificant value. The Type 1241 Detector is recommended when the VSWR is very high.

3.7.8 FREQUENCY MODULATION

The presence of appreciable frequency modulation on the applied signal may produce errors when the standing-wave ratio is very high. Frequency modulation is usually produced when a high-frequency oscillator is amplitude-modulated. The amount of frequency modulation for a given degree of amplitude modulation usually increases as the oscillator frequency approaches its upper limit. The Type 1362 UHF Oscillator is satisfactory for modulated signal measurements on very high VSWR's at 50% modulation, up to about 750 MHz. At the higher frequencies, reasonably large errors are produced in measurements of standing-wave ratios of the order of 500 or 1000. At standing-wave ratios below 50, the error is usually negligible if the over-all line length is short. Square-wave modulation should be used to minimize frequency modulation. The Type 1264 Modulating Power Supply is recommended for use with the oscillators listed in Table 2-1.

This problem is minimized by employing a heterodyne detector as indicated in 3.7.2

3.8 MEASUREMENT OF 50-OHM COAXIAL LINE CIRCUITS

3.8.1 USE OF CONNECTING CABLE

In coaxial-line measurements, the VSWR on the line, the impedance seen looking into an unknown line, or the impedance at the far end of a line maybe needed. In measurements on antennas, either the VSWR on a line terminated in the antenna or the actual antenna impedance may be desired. However, in most cases it is not possible to connect the antenna directly to the slotted line and an intermediate length of cable or air line must be used. The line or cable should have a 50-ohm characteristic impedance. Lengths of Type 874-A2 or RG214/U Cable can be used for this purpose. The connecting line has no effect on the VSWR if it is a lossless, uniform line, hence the VSWR produced by the load is the same as that measured on the slotted line. *In practice, however, the connecting cable and connectors will not be absolutely uniform but will have small discontinuities which will have some effect on the VSWR. The uniformity of lengths of Type 874-L Air Line is much better than that of coaxial cable and should be used if possible, to obtain the most accurate results.* There is usually significant loss in the connecting cable. A correction can be made for it, as outlined in paragraph 3.7.4

3.8.2 MEASUREMENT OF VSWR ON A 50-OHM LINE

To determine the VSWR on a 50-ohm line terminated in the unknown, the following procedure can be used:

a. Set up the equipment and tune the detector, as outlined in paragraphs 2.3, 3.3, and 3.4.

b. Connect the unknown directly to the slotted line, if possible, or use lengths of 50-ohm air line or cable provided with constant-impedance connectors, such as Type 874. If the unknown is fitted with other than Type 874 Connectors, use one of the adaptors listed in Table 2-2.

c. Check the output from the detector at a voltage minimum and maximum and determine that the probe coupling is satisfactory, as outlined in paragraph 3.3. Only the voltage minima need be measured, if the width-of-minimum method can be used.

d. If the VSWR is less than 10, measure the relative output from the detector at several minima and maxima. Actually, only one minimum and one maximum need be measured, but because of the small variations in probe coupling along the line, greater accuracy can be obtained if several minima and maxima are averaged or if the probe coupling is calibrated, as outlined in paragraph 5.5. If the VSWR is greater than 10, use the heterodyne detector or the width-of-minimum method, outlined in paragraph 3.7.2 to determine the VSWR.

3.8.3 UNKNOWN IMPEDANCE CONNECTED AT THE END OF A 50-OHM LINE

To obtain the actual load impedance, use the following method:

a. Follow procedures a through d of paragraph 3.8.2.

b. Measure the position of the voltage minimum nearest the load end of the line.

c. Short-circuit the end of the line at the point of connection to the unknown. Use a very low inductance metal sheet or strap, or a Type 874-

WN3, -WNL Short Circuit, as described in paragraph 3.2. Then find the position of a voltage minimum on the line with the line shorted and record the scale reading corresponding to the probe position (refer to paragraph 3.7).

d. Determine the difference in position, ℓ, between the minimum measured with the line shorted, and the minimum measured with the unknown connected. Divide the result by the wavelength to obtain ℓ/λ. If several measurements are to be made at different frequencies on the same circuit, the over-all electrical line length between any point on the slotted line and the short circuit can be determined. Then the line needs to be short-circuited only once.

e. On the 50-ohm Smith Chart, determine the radius of the circle on which the impedance must lie from the scale labeled STANDING WAVE RATIO, located at the bottom of the chart. Draw a circle having this radius on the chart, with its center at the center of the chart. (Refer to paragraph 4.5.3) The transmission-line equations presented in paragraph 4.1 can be used in place of the Smith Chart. (The 50-ohm impedance version is considered here.)

f. Note whether the minimum found with the line shorted lies on the generator side or on the load side of the minimum found with the load connected. If the short-circuit minimum lies on the load side, travel from zero around the circle along the WAVELENGTHS TOWARD LOAD scale the number of wavelengths found in step d. If the minimum lies on the generator side, travel in the opposite direction along the WAVELENGTHS TOWARD GENERATOR scale. Draw a line from this point to the center of the chart.

g. Find the impedance in ohms of the unknown from the coordinates of the intersection of the line drawn in step f and the circle drawn in step e. If the admittance is desired, travel around the chart another 0.25 wavelength and draw another line to the center of the chart. The coordinates of the intersection of this line with the circle multiplied by 0.4 are the components of the admittance of the unknown in millimhos.

3.8.4 MEASUREMENT OF THE INPUT IMPEDANCE TO COAXIAL-LINE CIRCUITS

To measure the input impedance to a coaxial-line circuit, connect the circuit directly to the slotted line by means of a coaxial connector. Then use the procedure outlined in paragraph 3.8.3. In this measurement, the point in the connector at which the impedance is to be obtained must be specified, because the impedance may vary appreciably from one point to another in the connector. In many cases, it is advantageous to measure the impedance at the front face of the polystyrene bead in the unknown connector. (Refer to paragraph 3.2.) In order to determine the impedance at this point, the electrical distance from the insulator in the connector and the position of a voltage minimum on the slotted line must be found.

To determine the electrical distance, measure the physical distance between the two points in question and add 0.48 cm to the length obtained to account for the lower velocity of propagation in the insulators at the end of the slotted line.

Another more accurate method of determining the effective electrical distance is to short-circuit the end of the slotted line with a Type 874-WN, -WNL Short Circuit and then determine the position of a voltage minimum on the slotted line, as outlined in paragraph 4.4. The short circuit is made at the face of the bead in this unit.

Measure the VSWR and calculate the unknown impedance, as outlined in paragraph 3.8.3.

3.9 MEASUREMENTS ON COMPONENTS AND LUMPED CIRCUITS

3.9.1 PROCEDURES

The Type 874-LBB Slotted Line can be used to measure the impedance of components of all types. At high frequencies, this type of measurement is complicated by many factors, the most important of which generally are:

1. The position of the element with respect to ground, leads, and other circuit elements can have a large effect on the impedance of an element.
2. The reactances of leads used to connect the component to the measuring device, any leads which may be part of the component under test, and the stray capacitance of the measuring terminals and supplementary leads, may also appreciably affect the measurements.

To minimize the effects of the first difficulty, the component should be measured while mounted in the position in the circuit in which it is to be used, or under as similar conditions as possible. One method of measuring a component in position in a circuit is to connect it to the slotted line by means of a length of flexible cable or rigid coaxial line, as shown in Figure 3-9. The rigid line is preferred, as its characteristic impedance is more uniform. The impedance is measured, as outlined in paragraph 4.5.3. The line is short-circuited at its load end by one of the methods shown in Figure 3-1.

The supplementary leads used to connect the component to the end of the coaxial line should be as short as possible to minimize the effects of the lead and terminal reactances.

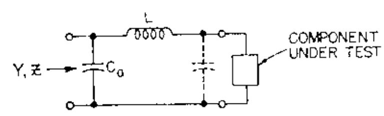
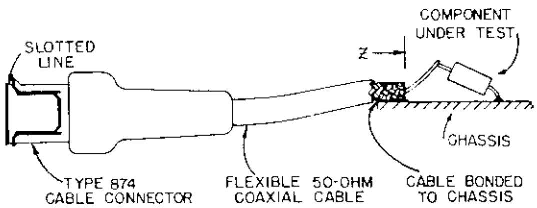


Figure 3-9. Approximate equivalent circuit of connecting lead reactances encountered when components are measured.



The leads referred to do not include those normally used to connect the unknown to the circuit. If the supplementary leads are short, the stray reactances can be considered as lumped into two elements: a shunt capacitance across the end of the line, and an inductance in series with the line, as shown in Figure 3-9. The lead and terminal reactances affect the measured impedance Z_M, as can be seen from the equivalent circuit in the figure. In order to determine the actual impedance of the unknown, the measured impedance should be corrected for the effects of the lead and terminal reactances, using the following equations:

$$R_X = \frac{R_M}{D}$$

$$X_X = \frac{X_M\left(1 - \frac{X_M}{X_A}\right) - \frac{R_M^2}{X_A}}{D} - X_L$$

where

$$D = \left(1 - \frac{X_M}{X_A}\right)^2 + \left(\frac{R_M}{X_A}\right)^2$$

$$X_A = -\frac{1}{\omega C_A} \text{ ohms}$$

$$X_L = \omega L \text{ ohms}$$

where L is the magnitude of the lead inductance in henrys and C_A is the magnitude of the shunt capacitance in farads.

The magnitudes of the lead and terminal reactances can be determined from measurements of the reactance seen with the leads short-circuited by a low-inductance copper sheet at the point of connection to the unknown, and the reactance seen with the leads open-circuited at the point of connection to the unknown. The inductive reactance is measured when the leads are short-circuited and the capacitive reactance is measured when the leads are open-circuited. For this approximation to hold, the lead-capacitive reactance should be greater than five times the lead-inductive reactance.

A somewhat better approximation can be made if the lead capacitance is assumed to be distributed between the two ends of the leads, as shown by the dotted capacitor of Figure 3-9. The ratio of the two capacitances can be estimated from the physical configuration of the circuit.

An even better approximation can be made when the leads are reasonably long, if the inductance and capacitance are assumed to be uniformly distributed and the leads are treated as a section of transmission line. The characteristic impedance, Z_o, of this line and the tangent of the electrical length, tan θ, are related to the short- and open-circuit impedances, Z_{OC} and Z_{SC}, by the expressions:

$$Z_o = \sqrt{Z_{OC} Z_{SC}}$$

$$\tan\theta = \sqrt{\frac{Z_{SC}}{Z_{OC}}} = \frac{X_{SC}}{Z_o}$$

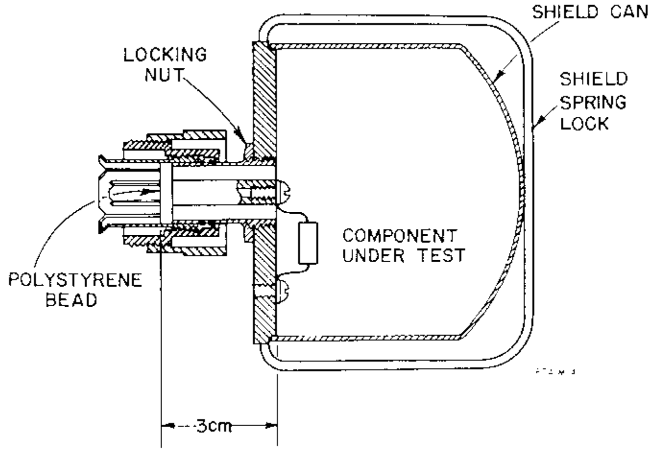


Figure 3-10. Sketch of the Type 874-ML Component Mount.

The equation in paragraph 4.1, or the Smith Chart, can be used to correct the measured impedance for the effect of the equivalent section of transmission line. If a Smith Chart designed for lines having a 50-ohm impedance is used, the measured values should be divided by $\frac{Z_o}{50}$ before entering the chart and the resultant corrected impedance multiplied by $\frac{Z_o}{50}$. In most cases the capacitance is not uniformly distributed but the approximation usually gives reasonably accurate results. A normalized Smith Chart is better suited to this application.

In most cases more accurate measurements can be made by use of the Type 874-ML Component Mount, shown in Figure 3-10, on which the component or lumped circuit can be mounted. The end of the center conductor of a section of air line is used as the ungrounded terminal, and the outer conductor is extended in the form of a disk for a ground plane. The line can be short-circuited at the terminal by means of a very low inductance disk (supplied) or the mount can be disconnected and replaced by a Type 874-WN3 Short-Circuit Termination Unit. The distance from the front face of the polystyrene bead in the connector mount is located 3 cm away from the ground-plane surface; hence, the termination unit referred to places a short-circuit effectively at the ground-plane surface when it is substituted for the component mount.

A correction must be made for the reactance of supplementary leads, as previously outlined.

To remove the coaxial-line section from the ground plate or to mount it on another one, loosen the locking nut. It can then be installed in any other plate if a 3/4-27 tapped hole is provided.

3.9.2 EXAMPLE OF MEASUREMENT OF A 200-OHM RESISTOR AT 600 MHz.

In this case, the resistor is mounted on a Type 874-ML Component Mount, shown in Figure 3-10, which is connected to the slotted line. A block diagram of the setup is shown in Figure 2-1. The stub is tuned with slotted line terminated with Type 874-W50B or -W50BL, as indicated in paragraph 3.4. The unknown is connected and the input power is adjusted to operate the diode within the square-law range. Averages of several VSWR readings are taken to minimize the effect of the variation in probe coupling along the line, and an average reading of 3.16 is obtained. Position of the voltage minimum nearest load was 40.25 cm.

The component mount is then disconnected, the Type 874-WN3 Short Circuit is connected to the slotted line, and the position of a voltage minimum is located. The position of the minimum nearest the load is found to be at 51.20 cm. Therefore,

$$\text{VSWR} = 3.16$$

$$\frac{\ell}{\lambda} = \frac{51.20 - 40.25}{50} = 0.219 \text{ wavelength}$$

The measured resistance and reactance, calculated by the use of the Smith Chart, are:

R_M = 118 ohms; X_M = -66 ohms.

In this case, the impedance directly across the ends of the resistor is needed. However, the resistor is connected to the mount by means of its own leads, which affect the measurements. Since it is not desirable to clip the leads at the ends of the resistor to measure the lead reactances, the resistor is removed and identical leads are substituted. The position of the minimum on the line is determined with the leads open-circuited and is found to be 39.90 cm. The ends of the leads are short-circuited by spot-soldering a copper sheet about three inches in diameter to the ends of the leads and the minimum position is found again. In this case it is at 32.95 cm.

The short-circuit reactance, X_{SC}, calculated from the Smith Chart, is +57 ohms. The open-circuit reactance, X_{OC}, is -330 ohms. The actual impedance appearing across the resistor terminals is then calculated by

$$R_M = 118 \text{ ohms}$$

$$X_M = -66.0 \text{ ohms}$$

$$X_L = X_{SC} = +57 \text{ ohms}$$

$$X_A = X_{OC} = -330 \text{ ohms}$$

$$D = \left(1 - \frac{-66}{-330}\right)^2 + \left(\frac{118}{330}\right)^2 = 0.768$$

$$R_X = \frac{118}{0.768} = 154 \text{ ohms}$$

$$X_X = \frac{-66\left(1 - \frac{-66}{-330}\right) - \frac{118^2}{-330}}{0.768} = \frac{-57}{0.768} = -72.2 \text{ ohms}$$

The measured resistance is less than the dc value of 200 ohms, due to the shunt capacitance of the resistor itself.

3.10 OPERATION AT FREQUENCIES BELOW 300 MHz

Since the probe travel is only 50 cm, it will not always be possible to measure both a voltage minimum and maximum on the line at frequencies below 300 MHz, as the range of travel of the probe is one-half wavelength at 300 MHz. At frequencies below 150 MHz, where the line is less than a quarter of a wavelength, it will never be possible to measure both a voltage maximum and minimum on the line directly. If both a voltage minimum and maximum do not appear on the line at frequencies above 150 MHz, additional lengths of Type 874-L30, -L10, -L30L, and -L10L Air Lines can be inserted between the line and the load until both a minimum and a maximum do appear. Of course, if the VSWR is greater than 10, only the minimum need appear on the slotted section of line, because the measurement can be made by the width-of-minimum method.

At frequencies below 150 MHz, lengths of air line can be inserted between the line and the load until either a minimum or maximum can be measured. Sections of air line are then *transferred* to the other side of the slotted line, that is, between the line and the generator, until the maximum or minimum appears and can be measured. The sections are transferred, rather than removed, to keep the load on the oscillator and, hence, the relative voltage amplitude on the line, constant.

A somewhat better solution is to use two slotted lines and add sections of air line between them or between one of them and the load until a minimum appears on one line and a maximum on the other. The probes are set at the respective maximum and minimum and the outputs from the detector and the position of the probe at the minimum are recorded. A Type 874-W50B and -W50BL Termination Unit is then connected to the end of the line and the outputs of the two detectors again recorded. Since the voltage is constant all along the line with the termination connected, the probe couplings in this case are proportional to the outputs if the detector is linear. If the detector is square-law, the probe couplings are proportional to the square roots of the outputs. The outputs observed with the load connected can then be corrected for any difference in coupling. This calibration corrects for differences in probe penetration, differences in probe couplings, and differences in sensitivity of the detectors.

Alternately the slotted-lines may be connected together directly and the probes adjusted to produce the same output with the line terminated with the Type 874-W50B or -W50BL. The standing-wave pattern is observed first with one line and continued with the next by switching the detector connection.

The Type 874-D20L Stub will tune the diode rectifier down to 275 MHz. The Type 874-D50L Stub will tune down to 125 MHz. Additional lengths of air line can be inserted in series or in shunt, using a Type 874 Tee for operation at lower frequencies. With the long stub in place, smoother operation of the carriage is obtained if the whole slotted line is tilted slightly forward to make the stub almost vertical.

3.11 USE OF THE ADJUSTABLE SCALE AND THE VERNIER DRIVE

The scale of the Type 874-LBB Slotted Line is adjustable and can be locked in position, permitting the choice of a convenient reference point.

This feature together with the Type 874-LV Vernier Drive enables simple and accurate length measurements.

For example, when measuring the distance between two minima (Figure 3-11), find the first minimum and set the scale to have a convenient full division in front of the pointer (A), then set the pointer to the full division closest to the second minimum (B) and use the vernier drive to reach the minimum. The distance desired is then AB plus (or minus) the distance traveled by the vernier drive.

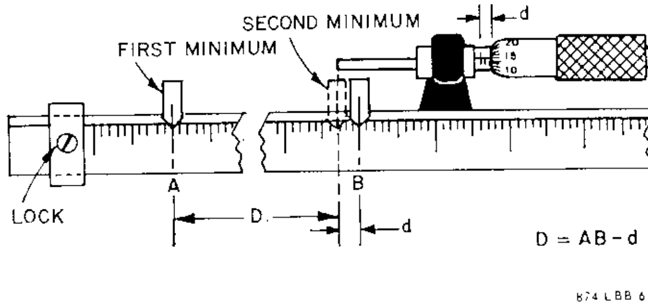


Figure 3-11. An accurate way to find the distance between two minima.

SECTION 4 PRINCIPLES OF OPERATION

4.1 TRANSMISSION LINE CHARACTERISTICS

4.1.1 CHARACTERISTIC IMPEDANCE

A coaxial transmission line has uniformly distributed inductance and capacitance, as shown in Figure 4-1. The series resistance due to conductor losses and the shunt resistance due to dielectric losses are also uniformly distributed. The square root of the ratio of the inductance-per-unit-length, L, to the capacitance-per-unit-length, C, is defined as the characteristic impedance, Z_o, of the line.

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{L}{C} \times \frac{1 - j\frac{R}{\omega L}}{1 - j\frac{G}{\omega C}}}$$

where:

L = the inductance-per-unit-length in henrys,
C = the capacitance-per-unit-length in farads,
R = the series-resistance-per-unit-length in ohms, and
G = the shunt-conductance-per-unit-length in mhos.

When line losses are low (or when $\frac{R}{L} = \frac{G}{C}$) and the rf skin effect depth is much smaller than the diameter tolerances, the following approximation is valid:

$$Z_o \approx \sqrt{\frac{L}{C}}$$

As frequency decreases, the path of the average current flow tends to move away from the surfaces of the conductors. It moves toward the center of the inner conductor and away from the inner surface of the outer conductor. Thus, the effective diameters are shifted (in opposite directions), thereby causing a slight increase in the ratio which determines the characteristic impedance. The extent of this shift varies with the material used for the conductors and is least with a

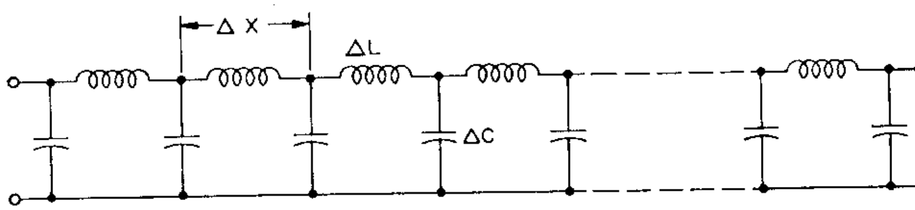


Figure 4-1. Distribution of inductance and capacitance along a transmission line.

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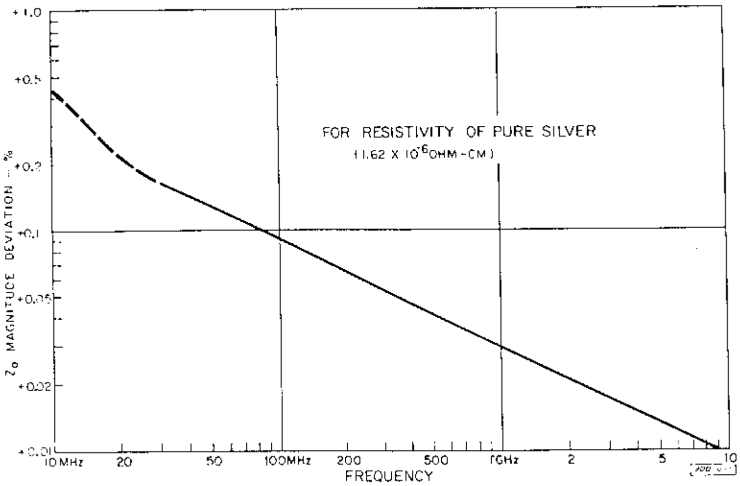


Figure 4-2. Skin-effect error as a function of frequency.

conductor such as silver. In silver this effect is enough to cause a change of 0.1% at 100 MHz; see Figure 4-2.

The characteristic impedance of a coaxial line derives directly from the diameters of the conductors, the ratio that these diameters bear to one another, their respective concentricity, and the dielectric constant of the medium separating them. Thus, for concentric coaxial lines in general, the expression is:

$$Z = \frac{A}{\sqrt{\epsilon}} \log_e \frac{a}{b}$$

where:

a = inner diameter of outer conductor

b = outer diameter of inner conductor

ϵ = dielectric constant

$A = \frac{2c}{10^9} = 59.9585$

c = velocity of light, cm/sec

The dielectric constant of air under standard laboratory conditions is 1.0007.

The accuracy of the characteristic impedance, therefore, is controlled by the precision with which the inner and outer conductors can be machined. Furthermore, the constancy of impedance depends in turn upon the ability of the fabrication process to maintain uniform size and to preserve straightness throughout, since deviations result in impedance variations.

The uniformity of the impedance along the line is also dependent upon the concentricity of the conductors. An important factor bearing upon this consideration is sag occurring in the center conductor. The characteristic impedance of a coaxial transmission line with an eccentric inner conductor is given by the following:

$$Z_o = \frac{A}{\sqrt{\epsilon}} \cosh^{-1}\left[\frac{b}{2a}\left(1 - 4\frac{e^2}{b^2}\right) + \frac{a}{2b}\right],$$

where:

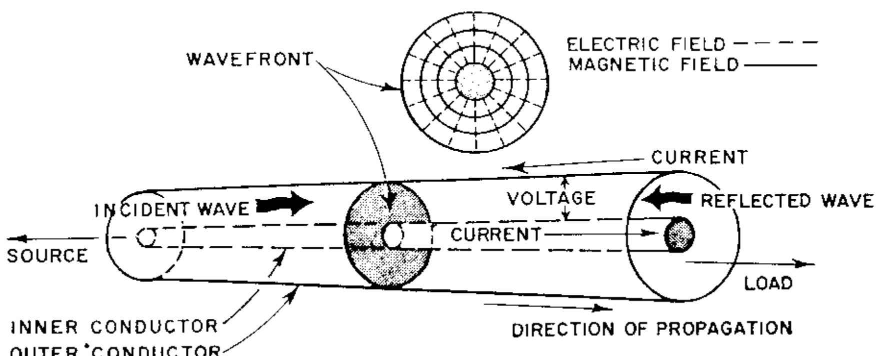
e = amount of eccentricity of the center conductor.

4.1.2 WAVE PROPAGATION

As with all transmission-line types, the purpose of coaxial line is to carry energy from a source to a load. The efficiency with which it performs this function at uhf and above is dependent upon (among other things) the mode in which it propagates electromagnetic-wave energy. Such modes of propagation can best be described in terms of their electrical and magnetic field patterns within the line.

A coaxial transmission line may provide the means for more than a single mode of propagation. Commonly, the dominant mode is that in which both electrical and magnetic field components of the wave lie entirely in planes transverse to the direction of propagation (see Figure 4-3). The wave is therefore called a transverse electromagnetic (TEM) wave. There is no longitudinal component of the field in this mode, as in rectangular waveguide. Thus, this mode is broadband and has no cutoff frequency.

Figure 4-3. TEM-mode field pattern in coaxial transmission line.



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4.1.3 VELOCITY OF PROPAGATION

In subsequent paragraphs, transmission-line behavior will be discussed in terms of electromagnetic waves propagating along the line. The waves travel with a velocity, v, which depends on L and C in the following manner:

$$v = \frac{1}{\sqrt{LC}}$$

In an evacuated line, the dielectric constant is unity and the velocity of propagation is equal to the velocity of light, c, (2.997925×10^{10} cm/sec). If the effective dielectric constant, ϵ, is greater than unity, the velocity of propagation will be the velocity of light divided by the square root of the effective dielectric constant:

$$v = \frac{c}{\sqrt{\epsilon}}$$

The relationship between frequency, f, and wavelength, λ, in the transmission line, if the dielectric is air, is

$$\lambda = \frac{2.99687 \times 10^{10}}{f} \text{ cm/sec}$$

if λ is in centimeters and f is in hertz.

4.1.4 TRAVELING AND STANDING WAVES

The performance of a transmission line having a uniform characteristic impedance can be explained in terms of the behavior of the electromagnetic wave that travels along the line from the generator to the load, where all or a portion of it may be reflected, with or without a change in phase, as shown in Figure 4-4. The reflected wave travels in the opposite direction along the line, back toward the generator. The phases of these waves are retarded linearly 360° for each wavelength traveled.

The wave traveling from the generator is called the incident wave, and the wave traveling toward the generator is called the reflected wave. The combination of these two traveling waves produces a stationary interference pattern which is called a standing wave. The maximum amplitude of the standing wave occurs when the incident and reflected waves are in phase or when they are an integral multiple of 360° out of phase. The minimum amplitude occurs when the two waves are 180°, or an odd integral multiple thereof, out of phase. The amplitude of the standing wave at other points along the line is the vector sum of incident and reflected waves. Successive minima and maxima are spaced, respectively, a half wavelength along the line.

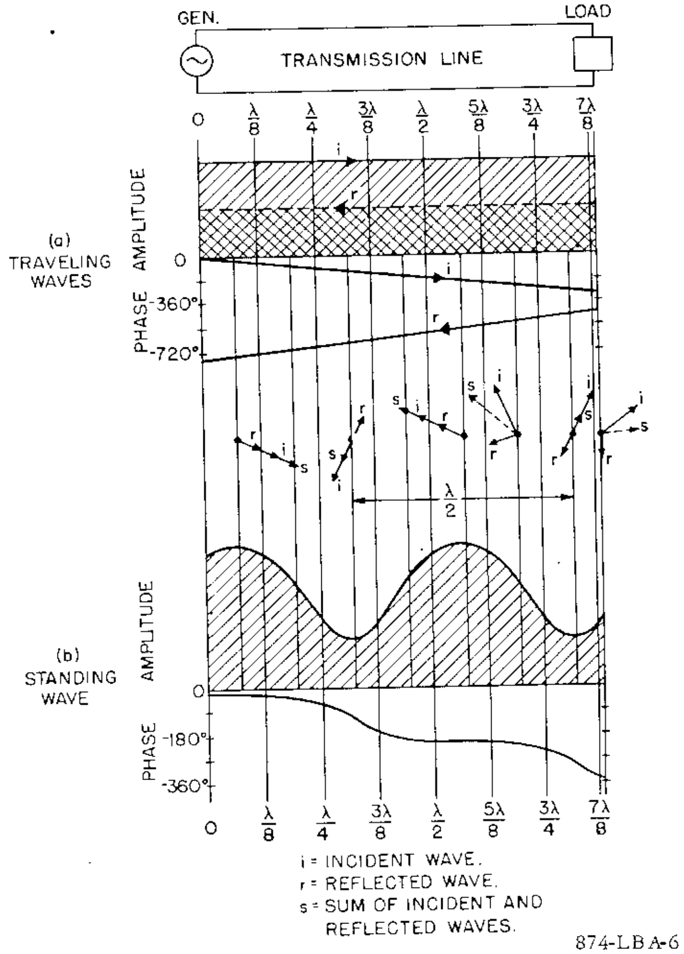


Figure 4-4. Variations in the amplitude and phase of incident and reflected waves along a transmission line with a 3:1 mismatch condition. Vector combination of incident and reflected waves at various points along the line and resultant standing wave are shown.

The magnitude and phase of the reflected wave at the load, relative to the incident wave, are functions of the load impedance. For instance, if the load impedance is the same as the characteristic impedance of the transmission line, the incident wave is totally absorbed in the load and there is no reflected wave. On the other hand, if the load is lossless, the incident wave is always completely reflected, with no change in amplitude but with a change in phase.

A traveling electromagnetic wave actually consists of two component waves: a voltage wave and a current wave. The ratio of the magnitude and phase of the incident voltage wave, E_i, to the magnitude and phase of the incident current wave, I_i, is always equal to the characterisitc impedance, Z_o. The reflected waves travel in the opposite direction from the incident waves, and consequently the ratio of the reflected voltage wave, E_r, to the reflected current wave, I_r, is $-Z_o$. Since the characteristic impedance in most cases is practically a pure resistance, the incident voltage and current waves are in phase with each other, and the reflected voltage and current waves are 180° out of phase.

$$\frac{E_i}{I_i} = Z_o$$

$$\frac{E_r}{I_r} = -Z_o$$

These equations are valid at all points along the line.

The magnitude and phase of the reflected voltage wave, E_r, relative to the incident wave, E_i, at the load is called the reflection coefficient, Γ, which can be calculated from the expression

$$\Gamma = \frac{Z_x - Z_o}{Z_x + Z_o} = \frac{Y_o - Y_x}{Y_o + Y_x}$$

$E_r = E_i \Gamma$ at the load

$I_r = -I_i \Gamma$ at the load

where Z_x and Y_x are the complex load impedance and admittance, and Z_o and Y_o are the characteristic impedance and admittance of the line ($Y_o = \frac{1}{Z_o}$).

4.2 VOLTAGE AND CURRENT DISTRIBUTION

If the line is terminated in an impedance equal to the characteristic impedance of the line, there will be no reflected wave, and $\Gamma = 0$. The voltage and current distributions along the line for this case are shown in Figure 4-5.

If the line is open-circuited at the load, the voltage wave will be completely reflected and will undergo no phase shift on reflection, ($Z_x = \infty$), while the current wave will also be completely reflected but will undergo a 180° phase shift on reflection, as shown in Figure 4-6. If the line is short-circuited, the current and voltage roles are interchanged, and the impedance pattern is shifted $\lambda/4$ along the line. The phase shifts of the voltage and current waves on reflection always differ by 180°, as the reflected wave travels in the opposite direction from the incident wave. A current maximum, therefore, always occurs at a voltage minimum, and vice versa.

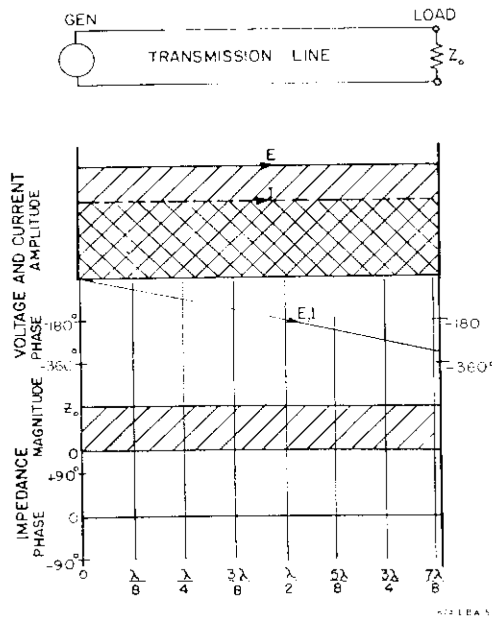


Figure 4-5. Voltage and current waves along a transmission line terminated in its characteristic impedance. Note the absence of reflected waves and that the impedance is constant and equal to the characteristic impedance at all points along the line.

The voltage at a maximum of the standing-wave pattern, E_{max}, is $|E_i| + |E_r|$ or $|E_i|(1 + |\Gamma|)$ and at a minimum, E_{min}, is $|E_i| - |E_r|$ or $|E_i| \times (1 - |\Gamma|)$. The ratio of the maximum to minimum voltages, which is called the voltage standing-wave ratio, VSWR, is

$$\text{VSWR} = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

The standing-wave ratio is frequently expressed in decibels or percent

$$\text{VSWR in dB} = 20 \log_{10} \frac{E_{max}}{E_{min}}$$

$$\text{VSWR in \%} = 100\left(\frac{E_{max}}{E_{min}} - 1\right)$$

4.3 LINE IMPEDANCES

At any point along a uniform lossless line, the impedance seen looking towards the load, Z_p, is the ratio of the complex voltage to the complex current at that point. It varies along the line in a cyclical manner, repeating each half wavelength of the line, as shown in Figure 4-6.

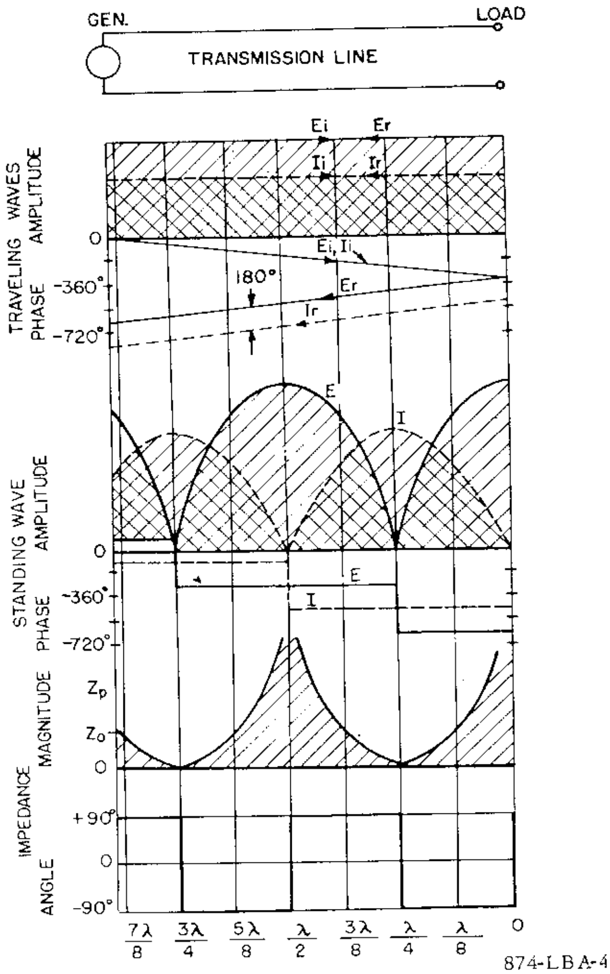


Figure 4-6. Voltage and current waves along a transmission line terminated in an open-circuit. Note that the minima of the voltage waves occur at the maxima of the current waves, and vice versa, and that the separation of adjacent minima for each wave is a half wavelength. The variation in the magnitude and phase angle of the impedance is also shown.

At a voltage maximum on the line, the incident and reflected voltage waves are in phase, and the incident and reflected current waves are 180° out of phase with each other. Since the incident voltage and incident current waves are always in phase (assuming Z_o is a pure resistance), the effective voltage and current at the voltage maximum are in phase and Z_p at that point is pure resistance. At a voltage maximum, Z_p is equal to the characteristic impedance multiplied by the standing-wave ratio.

$$Z_p = Z_o \times \text{VSWR}$$

At a voltage minimum, the two voltage waves are opposing and the two current waves are aiding. Again the effective impedance is a pure resistance and is equal to the characteristic impedance of the line divided by the standing-wave ratio.

$$Z_p = \frac{Z_o}{\text{VSWR}}$$

The impedance, Z_p, at any point along the line is related to the load impedance by the expression

$$Z_p = Z_o \left(\frac{Z_x + jZ_o \tan\theta}{Z_o + jZ_x \tan\theta} \right)$$

where

Z_o = characteristic impedance,

Z_x = complex load impedance,

$\theta = \frac{2\pi \ell_e}{\lambda}, = \beta \ell_e$

ℓ_e = electrical length of line between point p and load, $\ell\sqrt{\epsilon}$

ℓ = physical length.

Thus, if ℓ_e is in cm,

$\theta = 12 \times f_{GHz} \times \ell_e$, degrees.

In Figure 4-7, point p is shown at a voltage minimum. However, the expressions above are valid for any location of point p on the line.

Conversely, the load impedance, Z_x, can be determined if the impedance, Z_p, at any point along a lossless line is known. The expressions relating the impedances are:

$$Z_x = Z_o \left(\frac{Z_p - jZ_o \tan\theta}{Z_o - jZ_p \tan\theta} \right)$$

The load impedance can be calculated from a knowledge of the VSWR present on the line and the position of a voltage minimum with respect to the load, since the impedance at a voltage minimum is related to the VSWR. The expression for the load impedance in

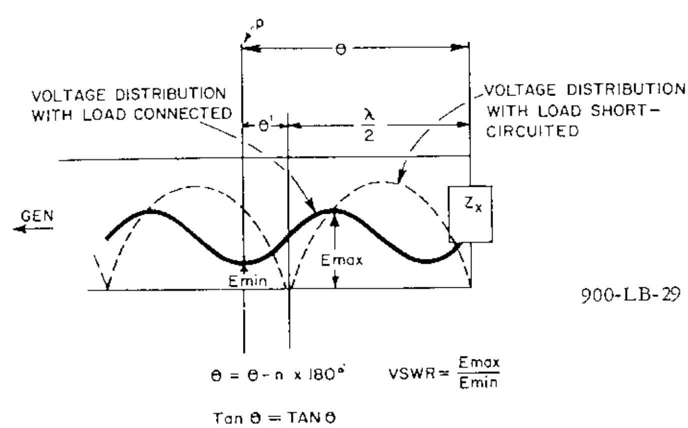


Figure 4-7. Voltage variation along a transmission line with a load connected, and with the line short-circuited at the load end.

terms of the VSWR, S, and the electrical distance, θ, between the voltage minimum and the load, is:

$$Z_x = Z_o \left(\frac{1 - jS\tan\theta}{S - j\tan\theta} \right)$$

$$= Z_o \left(\frac{2S - j[S^2 - 1] \sin 2\theta}{[S^2 + 1] + [S^2 - 1] \cos 2\theta} \right)$$

Since in a lossless line the impedance is the same at half-wavelength intervals along the line, θ' can be the electrical distance between a voltage minimum and any multiple of a half-wavelength from the load (see Figure 4-7). Of course, if the half-wavelength point used is on the generator side of the voltage minimum located with the load connected, θ' will be negative. The points corresponding to half-wavelength distances from the load can be determined, with the line short-circuited at the load, from the positions of the voltage minima on the line. The minima will occur at multiples of a half-wavelength from the load.

If the VSWR is greater than 10 tan θ, the following approximation gives good results:

$$R_x \cong \frac{Z_o}{S\cos^2\theta}$$

$$X_x \cong -Z_o \tan\theta$$

Corresponding general equations in admittance terms are:

$$Y_p = Y_o \left(\frac{Y_x + jY_o \tan\theta}{Y_o + jY_x \tan\theta} \right)$$

$$Y_x = Y_o \left(\frac{Y_p - jY_o \tan\theta}{Y_o - jY_p \tan\theta} \right)$$

4.4 DETERMINATION OF THE LOAD IMPEDANCE FROM THE STANDING-WAVE PATTERN

The load impedance can be calculated from a knowledge of the VSWR present on the line and the position of a voltage minimum with respect to the load, since the impedance at a voltage minimum is related to the VSWR. An expression for the load impedance in terms of the VSWR and the electrical distance, θ, between the voltage minimum and the load is readily obtained.

$$Z_X = Z_o \cdot \frac{1 - j\,(\mathrm{VSWR}) \tan\theta}{\mathrm{VSWR} - j\tan\theta}$$

$$= Z_o \cdot \frac{2(\mathrm{VSWR}) - j\left[(\mathrm{VSWR})^2 - 1\right] \sin 2\theta}{\left[(\mathrm{VSWR})^2 + 1\right] + \left[(\mathrm{VSWR})^2 - 1\right] \cos 2\theta}.$$

Since in a lossless line the impedance is the same at half-wavelength intervals along the line, θ can be the electrical distance between a voltage minimum and any multiple of a half-wavelength from the load (see Figure 4-7). Of course, if the half-wavelength point used is on the generator side of the voltage minimum located with the load connected, θ will be negative. The points corresponding to half-wavelength distances from the load can be determined by short-circuiting the line at the load and noting the positions of the voltage minima on the line. The minima will occur at multiples of a half-wavelength from the load.

If the VSWR is greater than 10 tan θ, the following approximation of the previous equation gives good results:

$$R_X \cong \frac{Z_o}{\mathrm{VSWR}\cos^2\theta}$$

$$X_X \cong -Z_o \tan\theta$$

4.5 SMITH CHART

4.5.1 GENERAL

The calculation of the impedance transformation produced by a length of transmission line using the equations previously presented can be time consuming. Mr. P. H. Smith[1] has devised a chart, shown in Figure 4-8, which simplifies these calculations. In this chart the circles whose centers lie of the resistance component axis correspond to constant values of resistance. The arcs of circles whose centers lie on an axis perpendicular to the resistance axis correspond to constant values of reactance. The chart covers all values of impedance from zero to infinity. The position of a point corresponding to any given complex impedance can be found from the intersection of the resistance and reactance coordinates corresponding to the resistive and reactive components of the unknown impedance.

As the distance from the load is increased or decreased, the impedance seen looking along the line toward a fixed unknown will travel around a circle with its center at the center of the chart. The angular movement around the circle is proportional to the electrical displacement along the line. One complete traverse of the circle will be made for each half-wavelength of travel. The radius of the circle is a function of the VSWR.

[1] Smith, P. H., *Electronics*, Vol 17, No. 1, pp 130-133, 318-325, January 1944.

4.5.2 CALCULATION OF IMPEDANCE AT ONE POINT FROM THE IMPEDANCE AT ANOTHER POINT ON A LINE

If the impedance at one point of a line, say at a point p, is known and the impedance at another point a known electrical distance away (for instance, at the load) is desired, the problem can be solved using the Smith Chart in the following manner: First, locate the point on the chart corresponding to the known impedance, as shown in Figure 4-8. (For example, assume that Z_P = 20 + j25 ohms.) Then, draw a line from the center of the chart through Z_P to the outside edge of the chart. If the point at which the impedance is desired is on the load side of the point at which the impedance is known, travel along the WAVELENGTHS TOWARD LOAD scale, from the intersection of the line previously drawn, a distance equal to the electrical distance in wavelengths between the point at which the impedance is known and the point at which it is desired. If the point at which the impedance is desired is on the generator side of the point at which the impedance is known, use the WAVELENGTHS TOWARD GENERATOR scale. (In this example, assume that the electrical distance is 0.11 wavelength toward the load.) Next, draw a circle through Z_P with its center at the center of the chart, or layout on the last radial line drawn a distance equal to the distance between Z_P and the center of the chart. The coordinates of the point found are the resistive and reactive components of the desired

IMPEDANCE COORDINATES—50-OHM CHARACTERISTIC IMPEDANCE

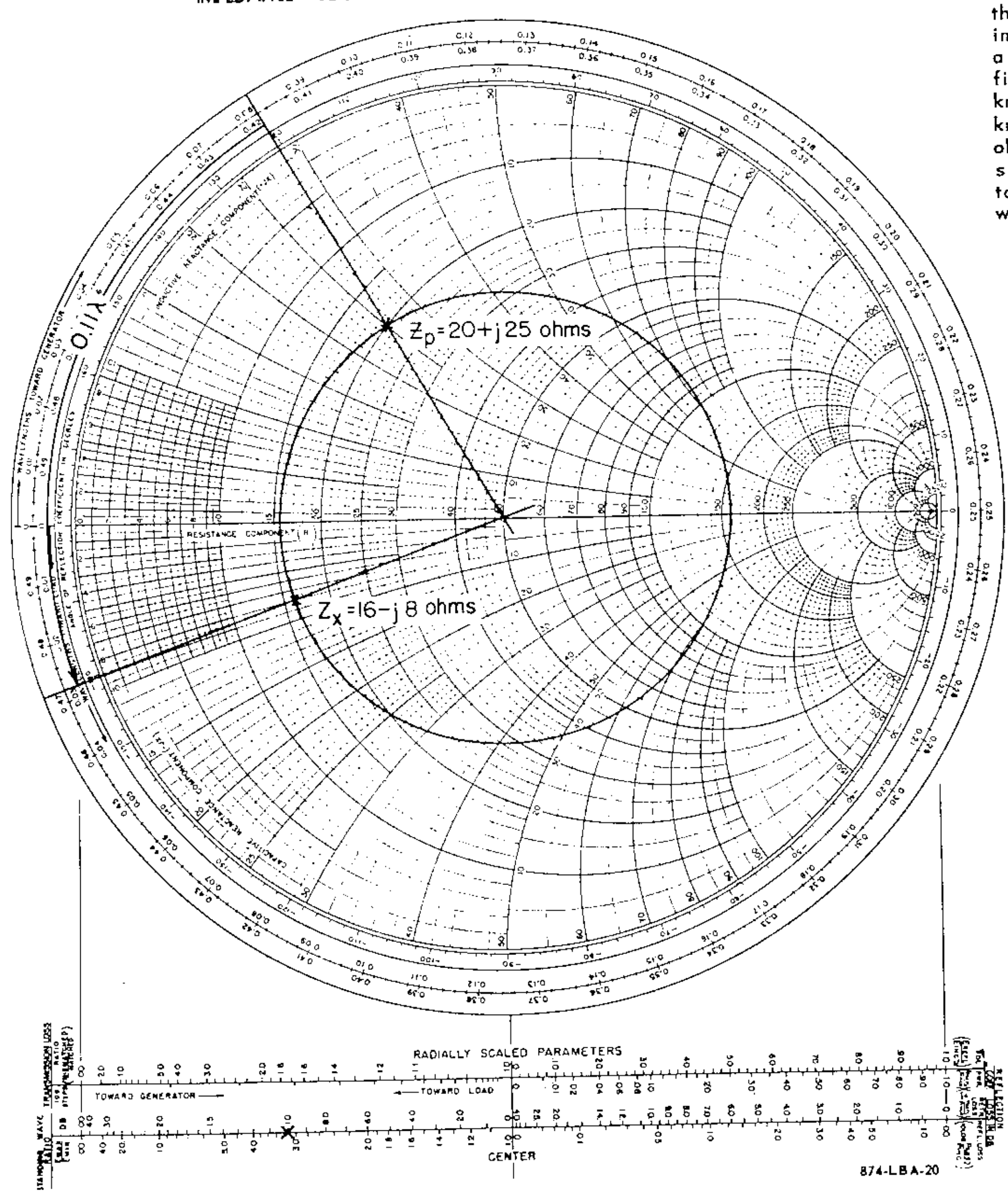


Figure 4-8. Illustration of the use of the Smith Chart for determining the impedance at a certain point along a line when the impedance a specified electrical distance away is known. In the example plotted, the known impedance, Z_p, is 20 + j25 ohms and the impedance, Z_x, is desired at a point 0.11 wavelength toward the load from the point at which the impedance is known.

impedance. (In the example chosen, the impedance is 16 - j8 ohms.)

The VSWR on the line is a function of the radial distance from the point corresponding to the impedance, to the center of the chart. To find the VSWR, lay out the distance on the STANDING WAVE RATIO scale located at the bottom of the chart, and read the VSWR as a ratio, $\frac{E_{MAX}}{E_{MIN}}$, or in dB on the appropriate scale. (In the example of Figure 4-8, the VSWR is 3.2 or 10.1 dB.)

4.5.3 CALCULATION OF IMPEDANCE AT THE LOAD FROM THE VSWR AND POSITION OF A VOLTAGE MINIMUM

In impedance measurements in which the voltage standing-wave pattern is measured, the impedance at a voltage minimum is a pure resistance having a magnitude of $\frac{Z_o}{VSWR}$. Plot this point on the resistance component axis and draw a circle having its center at the center of the chart drawn through the point. The impedance at any point along the transmission line must lie on this circle. To determine the load impedance, travel around the circle from the original point an angular distance on the WAVELENGTHS TOWARD LOAD scale equal to the electrical distance, expressed as a fraction of a wavelength, between the voltage minimum and the load (or a point a half-wavelength away from the load, as explained in paragraph 4.4). If the half-wave point chosen lies on the generator side of the minimum found with the load connected, travel around the chart in the opposite direction, using the WAVELENGTHS TOWARD GENERATOR scale. The radius of the circle can be determined directly from the VSWR, expressed as a ratio, or, if desired, in decibels by use of the scales labeled STANDING WAVE RATIO, located at the bottom of the chart.

4.6 SLOTTED LINES

4.6.1 GENERAL

The most accessible property of a transmission line, in measurement terms, is VSWR. A common method of measuring VSWR amplitude and phase is by observation of the standing-wave pattern in the line. This is accomplished by means of a narrow, longitudinal slot cut in the outer conductor of a standardized section of coaxial line, so that interior rf fields can be sampled with a movable probe inserted through the slot. The probe is part of an assembly mounted on a carriage capable of moving over the entire length of the slot on an accurately calibrated track. Within the probe assembly is an adjustable, thin rod that penetrates the line to extract the rf sample. Ideally, the probe is part of a tuned structure, so that it will provide a maximum pickup, which is detected by a microwave diode, an integral part of the assembly. The output of the diode is an audio voltage directly proportional to the rf power sampled, provided that the diode is operated in the square-law region of its response characteristic.

The output of the probe assembly must then be fed to a calibrated amplifier-indicator to measure VSWR magnitude. In addition, phase information (with respect to a fixed reference plane) can be determined from the position of the probe, when it is in a minimum of the standing-wave pattern. The reflection coefficient can be calculated from VSWR measurements, as can impedance. Impedance or admittance data can also be plotted by use of the Smith chart.

Desirable characteristics of a good slotted line include the following:

1. The coaxial line must be uniform, with straight and concentric conductors, so that it does not itself introduce reflections.
2. It should possess a true coaxial cross section, free of step discontinuities.
3. It should be terminated at the measurement end with a precision coaxial connector possessing dimensional and electrical uniformity nearly identical to that of the line.
4. The line of motion of the tip of the probe and the axis of the line must all be accurately parallel.
5. The instrument must have mechanical rigidity.
6. Wear of moving parts in the carriage must be low.

4.6.2 SLOTTED-LINE ERRORS

There are certain inherent errors in a slotted line which must be considered. The instrument errors may be neglected in many applications, but they must be taken into account when accuracies of a few percent or less are desired.

Certain rather obvious operational precautions are required, even for less-stringent accuracies. For example, the signal source must be stable in both amplitude and frequency and present a low harmonic level, all connectors must be tight and properly mated, and the response law of the detector must be accurately known.

Some of the more common sources of inherent instrument error are:

1. Residual VSWR.
2. Probe effects.
3. Losses.

The design of the Type 874-LBB Slotted Line, to a very great degree, either compensates directly for these errors or provides operator adjustments to overcome them. Still further reductions can be achieved by the precision calibration procedures given in Section 5.

Residual VSWR. The residual VSWR of a slotted line is that measured when the line is terminated in a perfect impedance match. It can have several causes.

1. Characteristic Impedance Under the Slot.

The slot in the outer conductor increases the characteristic impedance in the area under the slot. The fractional change in impedance canbe calculated from the dimensions of the coaxial line, as follows:

$$\Delta Z_o = \frac{Z_o w^2}{4\pi^2 (x^2 - y^2)}$$

where

x = the radius of the inner conductor,
y = the radius of the outer conductor,
w = the width of the slot.

The minute change in impedance introduces a discontinuity which must be compensated for by a small increase in the diameter of the inner conductor under the slotted region. The slot should be accurately centered and free from burrs and dimensional defects.

2. Step Discontinuities.

Changes in diameter, such as occur in transitions from coaxial to a slab-type cross-section, cause severe reflections which cannot be compensated for completely enough for precision measurements over a frequency band. The Type 874-LBB avoids this difficulty by maintaining a true coaxial cross-section in both the slotted and unslotted sections of the line. The sole exception to this is a small step, to compensate for the slot effect, which causes only negligible VSWR. No dielectric support bead other than the one in the Type 874-BBL connector is necessary.

3. Connector Reflections.

A primary source of residual VSWR is reduced by use of the Type 874-BBL Connector.

Probe Effects.

1. Constancy of Probe Pickup.

Small irregularities in either the inner or the outer conductor of a slotted line lead to variations in probe penetration along the line. This variable is

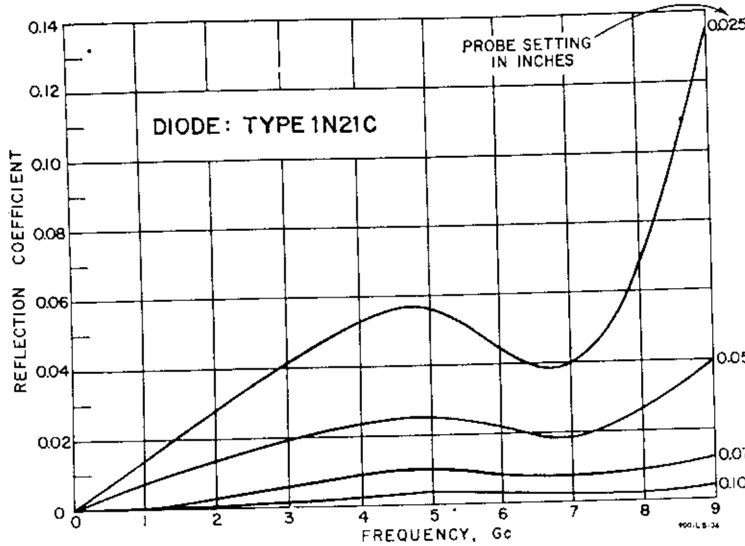


Figure 4-9. Probe reflections at four penetrations, with type 1N21C.

usually called "flatness" and is expressed in terms of equivalent VSWR. These variations cause corresponding changes in probe output even with a perfect termination and are easily confused with true VSWR, when the measured VSWR approaches the size of the flatness curve. For this reason the flatness specification determines the minimum VSWR measurable by conventional standing-wave indicators.

2. Probe Reflection.

Some of the incident wave in the slotted line is reflected by the probe and travels back toward the generator. If the generator is well matched, all is well, but a mismatched generator will re-reflect some of the energy and the probe will detect and respond to its own reflection, as well as to that of the termination. The magnitude of the erroneous VSWR thus detected is:

$$VSWR_e = \frac{1 + \Gamma_P \Gamma_G}{1 - \Gamma_P \Gamma_G}$$

where

Γ_P = the reflection coefficient of the probe
Γ_G = reflection coefficient of the generator.

The probe reflection depends upon frequency, probe penetration, probe tuning, and diode-detector characteristics. See Figure 4-9.

4.7 TYPE 874-LBB SLOTTED LINE

4.7.1 GENERAL

The Type 874-LBB Slotted Line comprises a slotted section mounted on a calibrated carriage structure which also mounts an adjustable probe and tuner. It has a nominal frequency range of 300 MHz to 8.5 GHz, but measurements can be made at low as 150 MHz (refer to paragraph 3.10).

Connections to the load and the generator are made through Type 874-BBL Connectors and the residual VSWR of the line and connectors is less than $1.01 + 0.0016\ f_{GHz}^2$ up to 7.5 GHz, 1.10 from 7.5 to to 8.5 GHz.

The line is based on a single slotted section 26 inches long. A 50-cm slot cut longitudinally in the top of the outer conductor permits insertion of the pickup probe. Thus, the *single* slotted section, accurately positioned at the time of factory installation, provides up to five octaves of coverage from UHF through X-band. The probe can travel a half-wavelength at the lowest normal test frequency (i.e., 50 centimeters at 300 MHz) with a residual slope that is very small (±1.25%).

The slotted section is an air-dielectric coaxial line, with inner and outer conductors made to close dimensional tolerances to ensure a characteristic impedance of 50.0 Ω.

4.7.2 PROBE CARRIAGE DRIVE

One electrostatic-pickup-probe assembly (rf probe) with external depth adjustment is furnished. The assembly mounts in the rigid cast carriage which transports the probe throughout the entire length of the slot. The mechanism for driving the carriage offers nearly constant probe coupling along the line, with negligible backlash.

In order to minimize the effects of any slight distortion in the line and the changes in effective probe coupling resulting from forces applied to the carriage, the driving knob is mounted in a fixed position of the right-hand-end casting and the carriage is driven by means of a nylon cord. The cord forms a complete loop, which is attached to the carriage at one point, and passes over an idler pulley on one end of the line and around a drum attached to the knob shaft on the other. The connection between the cord and the driving drum is obtained by means of friction, and one and a half turns of the cord around the drum have been found sufficient for positive drive without slippage. Since there are no teeth or grooves involved in the drive mechanism, a very smooth adjustment is obtained. Ball bearings are used on the drum and pulley shafts to reduce the driving force required and to minimize wear. A small ratchet-type take-up reel is mounted on the back of the carriage to permit adjustment of the tension in the nylon cord.

The fixed position of the driving knob, the use of ball bearings, and the durability of the nylon cord make the line easily adapted to motor drive, i.e., to the Type 1640-A Slotted Line Recorder System. A bevel gear is required to engage the motor drive.

4.7.3 PROBE CARRIAGE CONSTRUCTION (See Figure 4-10).

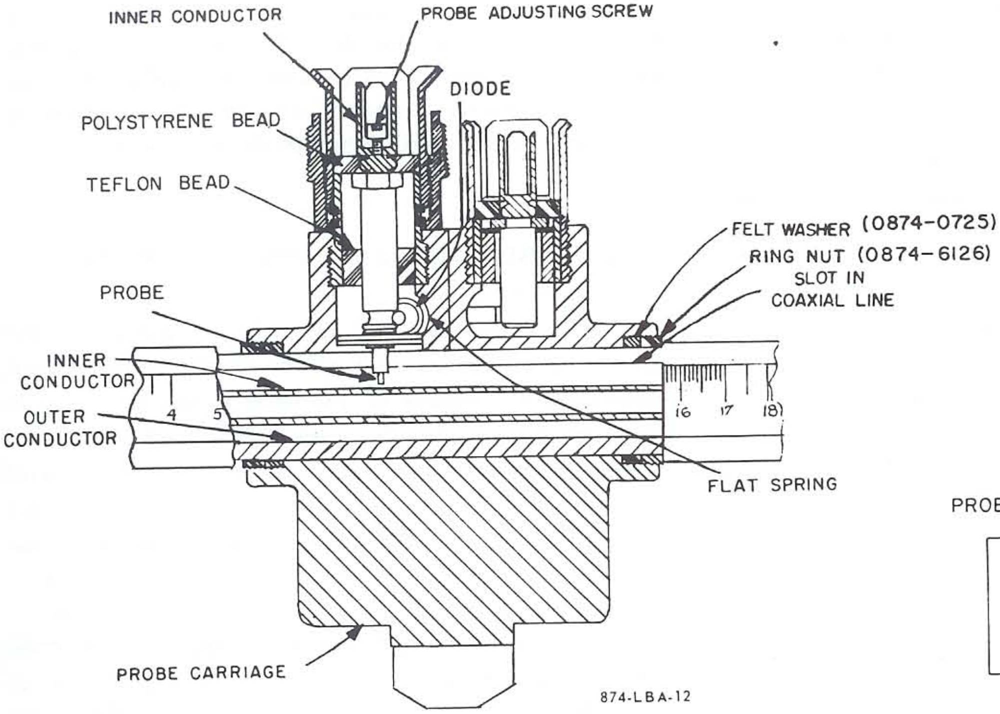
The probe carriage is made of cast brass and its honed sleeve bearing slides on the finely ground, chrome-plated surface of the outer conductor. Play in the carriage, which can cause rocking and consequent changes in probe coupling when the direction of travel is reversed, is negligible, since the tolerance of the bearing surface is 0.0001 inch. Probe travel is further stabilized by a second sleeve-type bearing machined in the carriage body. This consists of a semicircular bearing surface in the lower end of the casting which rides along the polished stainless-steel guide rod at the front of the instrument. This bearing surface prevents rotation of the carriage about its axis.

Rubber washers at each end of the slotted section, just inside the guide-rod supports, serve as bumpers to protect the mechanism in the event of carriage overdrive.

A felt washer, held in place by a metal ring nut, is mounted at each end of the carriage to prevent dirt and other foreign material, which may collect on the surface of the outer conductor, from entering the bearing. Oil holes in the top of the carriage permit these washers to be filled with oil for long-lasting lubrication of the bearing surfaces.

A 3/4-inch-diameter hole in the top of the carriage, beside the output connector, is tapped to receive either of two threaded probe assemblies. The small hole, in the center of the base of this opening, is the access for the pickup probe. A probe-shield assembly, consisting of a brass disk with a two-stepped hub on its underside, shields the probe from undesirable variation in its capacity to ground as it travels the slot. The hub is lined with clear polystyrene to insulate the probe from the rest of the carriage. The shield assembly is held in place by a retaining ring which seats in a groove at the base of the opening.

Beneath the probe mount, at the rear of the carriage, is a shallow, cylindrical cavity which houses the diode detector and a built-in by-pass capacitor. One of two symmetrically spaced holes in the inner wall of the cavity is the diode holder and the other provides access for a spring contact, which connects the



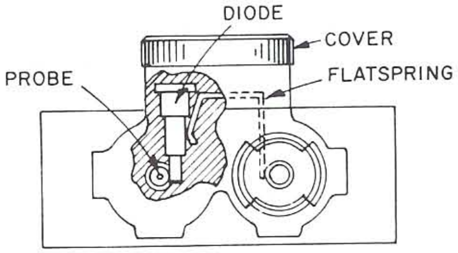


Figure 4-10. Cross-sectional views of the carriage on the Type 874-LBB Slotted Line, showing the diode mount and the adjustable probe.

diode output to the center conductor of the output connector.

The diode holder will also accept bolometers of a similar outline. The diode mounts small-end-first and bottoms in the holder; the small ends fits snugly in a concave ridge in the chuck holding the probe tip. The spring contact makes the connection at the large end of the diode and also clamps the diode securely in position.

The two interchangeable microwave diodes supplied, types 1N21C and 1N23B, furnish adequately overlapping coverage for the frequency range of the instrument. For low-noise applications, types 1N21F and 1N23F are suggested.

The flange at the wide end of the diode rests against a brass plate, which is insulated from the carriage body by a Mylar disk of the same shape as the plate, but with smaller-diameter holes. The plate and the opposing surface of the carriage body constitute a diode by-pass capacitor, with the Mylar disk as the dielectric. Plate, disk, and contact are fastened by a threaded stud that also secures the knurl-rimmed aluminum cover. The stud is insulated from plate and contact.

SECTION 5 SERVICE AND MAINTENANCE

5.1 WARRANTY

We warrant that each new instrument manufactured and sold by us is free from defects in material and workmanship, and that, properly used, it will perform in full accordance with applicable specifications for a period of two years after original shipment. Any instrument or component that is found within the two year period not to meet these standards after examination by our factory, District Office, or authorized repair agency personnel, will be repaired, or, at our option, replaced without charge, except for tubes or batteries that have given normal service.

5.2 SERVICE

The two-year warranty stated above attests the quality of materials and workmanship in our products. When difficulties do occur, our service engineers will assist in any way possible. If the difficulty cannot be eliminated by use of the following service instructions, please write or phone our Service Department (see rear page), giving full information of the trouble and of steps taken to remedy it. Be sure to mention the serial and type numbers of the instrument.

Before returning an instrument to General Radio for service, please write to our Service Department or nearest District Office, requesting a "Returned Material" number. Use of this number will ensure proper handling and identification. For instruments not covered by the warranty, a purchase order should be forwarded to avoid unnecessary delay.

5.3 DIODE CHECK (Figure 4-10).

To remove the detector diode, unscrew the cover on the back of the carriage and pull the diode from its socket.

The diode can be checked with a VOM (Simpson 260, or equivalent). Measure the resistance with both polarities of applied dc voltage. The resistance should be below 700 ohms in one direction and above 50,000 ohms in the other.

Occasionally, a diode that passes the above test may be noisy, as demonstrated by erratic output indication. Such a diode must be replaced.

5.4 CLEANING AND LUBRICATION

The Slotted Line should be kept in its storage box or covered when not in use to keep dirt from accumulating on the carriage track. The track should be cleaned and lubricated occasionally for best performance.

The felt washers shown in Figure 4-10 are libricated through the oil holes provided. Use a light oil and keep the oil ports filled so that there is a light oil film on the outer tube. It may occasionally be necessary to tighten the retaining rings to keep the felt washers in contact with the tube. Do not tighten them too much, or they will make it difficult to slide the carriage, causing backlash.

When the track needs cleaning, spread a coat of kerosene or light oil, such as clock oil, over the whole outside of the outer conductor. Use a pipe cleaner or a cloth. Then slide the carriage back and forth several times to dislodge any dirt caught in the felt rings. Finally, wipe the track dry with a cloth. Repeat this procedure until the cloth does not pick up any dirt.

If the line is very dirty, remove and clean the felt washers. To remove them, unscrew the retaining washers at both ends of the carriage (see Figure 4-10 and pull out the felt. Clean the felt in a solvent. When replacing the felt washers, flatten them out and push them into place. Reload the felt washers with a light oil through the oil holes at the ends of the carriage.

An oil port at the bottom of the carriage permits lubrication at the point of contact with the tie bar. This is especially important if the slotted line is motor driven.

The slot in the outer conductor can be cleaned with a pipe cleaner.

CAUTION

Do not attempt to disassemble the line, this operation requires special tooling, and should be done be our service department.

5.5 CALIBRATION OF THE VARIATION IN PROBE COUPLING

The variation in probe coupling along the line can be calibrated and the measurements very easily corrected for the variations. A 1000-Hz signal of at least 10 volts from the audio oscillator is applied to the slotted line whose load end is open-circuited. The tuning stub and crystal are removed and the input to the amplifier (Type 1232 is suitable) is connected directly to the connector normally used for the tuning stub. The variation in indication on the amplifier meter is then recorded as a function of the probe position. The curve thus obtained can be applied to rf measurements. In this calibration, the diode is not used and the output is directly proportional to the coupling, and not to the square of the output as when the diode is employed.

The variations in probe coupling will change somewhat as the probe penetration is varied. Hence, for most accurate results, the calibration curve should be made with the same probe penetration as was used in the rf measurements, and preferably 0.100 inches out.

5.6 ADJUSTMENT OF NYLON CORD TENSION

The nylon cord will stretch slightly with time, causing some backlash. A take-up reel on the back of the carriage can be used to adjust the cord tension. The inner flange of the reel has a number of holes around its outer edge; a pin, on the carriage body, enters one of the holes to provide a ratchet-type lock. To turn the reel, first pull it out about 1/16 inch to withdraw the pin from the hole in the flange. Then rotate the reel to produce the desired cord tension, and lock it by pushing it in so that the pin enters one of the holes.

5.7 REPLACEMENT OF NYLON CORD

The nylon cord is very tough, and should last a long time unless it rubs against a sharp cutting edge. An additional cord can be obtained from General Radio Company. The cord is 0.045 inch in diameter and 74-1/2 inches long; part number is 0874-3690.

Install the cord as shown in Figures 5-1 and 5-2. Knot the cord near one end, and thread the other end through the hole in the anchor post. Then pass the cord around the idler pulley and wrap it 1-1/2 times around the drive drum. Make sure that the end of the first turn is on the knob side of the beginning of the first turn (see Figure 5-2) so that the turns travel in the correct direction on the drum. Then pass the cord around the anchor post and thread it through the hole in the outer flange of the take-up reel. Knot the cord near the end to keep it from slipping back through the hole. Then adjust the tension by pulling out the take-up reel, to disengage the pin. Rotate it clockwise until the action of the drive knob feels satisfactory. It may be necessary to slide the cord axially along the driving drum to center it properly and to prevent it from riding over the flange at one end.

5.8 CALIBRATION

5.8.1 GENERAL

The residual VSWR of the Type 874-LBB Slotted-Line may be calibrated accurately with GR900 components.[1] A Type 900-Q874, GR900-to-GR874 Adaptor is employed to convert to the GR900 system. The adaptor

1 A. E. Sanderson, Nineteenth Annual Conference of the I.S.A., October 12, 1964. Available as a General Radio Reprint B 21.

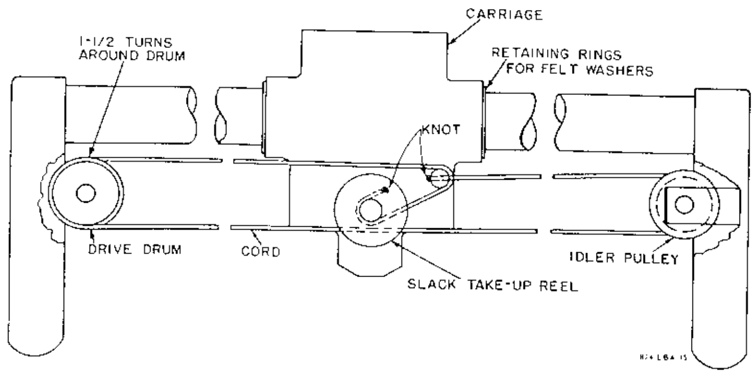


Figure 5-1. Rear view of the drive mechanism, showing the arrangement of the nylon cord.

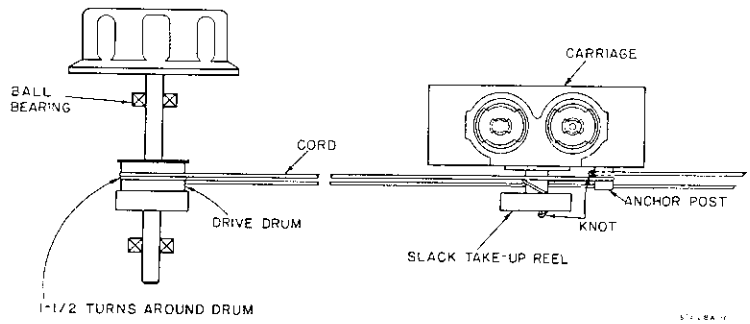


Figure 5-2. Installation of the nylon cord, viewed from the top of carriage.

VSWR is insignificant in this measurement because, by definition, the residual VSWR is specified for a mated pair of Type 874-BBL Connectors at the slotted-line terminals. The VSWR of the GR900 connector in the adaptor is considered negligible.

5.8.2 PROCEDURE

a. Connect the slotted-line in accordance with the standard procedure for measuring VSWR. Preferably the source should be matched, or a low-VSWR attenuator should be installed directly at the input connector of the slotted-line.

b. Install a Type 900-Q874 at the slotted-line measurement terminal to be calibrated.

c. Choose a Type 900-LZ Reference Air Line that is an odd multiple of a quarter wavelength at the calibration frequency or alternately choose the frequency to correspond to the quarter wavelength.

d. Install a Type 900-TUA or -TUB Tuner terminated in a Type 900-W50 Termination. Tune for the smallest possible VSWR.

e. Install the appropriate Type 900-LZ Air Line between the tuner and the Type 900-Q874 GR900 terminals and measure the VSWR. The slotted-line residual VSWR is,

$$(VSWR)_{SL} = 1 + \frac{[(VSWR) - 1]}{2}$$

f. If in step d unity VSWR is not achieved, the small VSWR that remains produces an error, but correction is possible. In fact if a tuner is not used, correction for the value obtained in step d is possible in the same manner. Measurement obtained in step d is supplemented by measuring the phase. Likewise, measurement obtained in step e is supplemented by measuring the phase. The two results are plotted on a Smith Chart. The Slotted-Line residual is the midpoint of the line joining the two measured values.

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