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

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

or

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

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.

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.

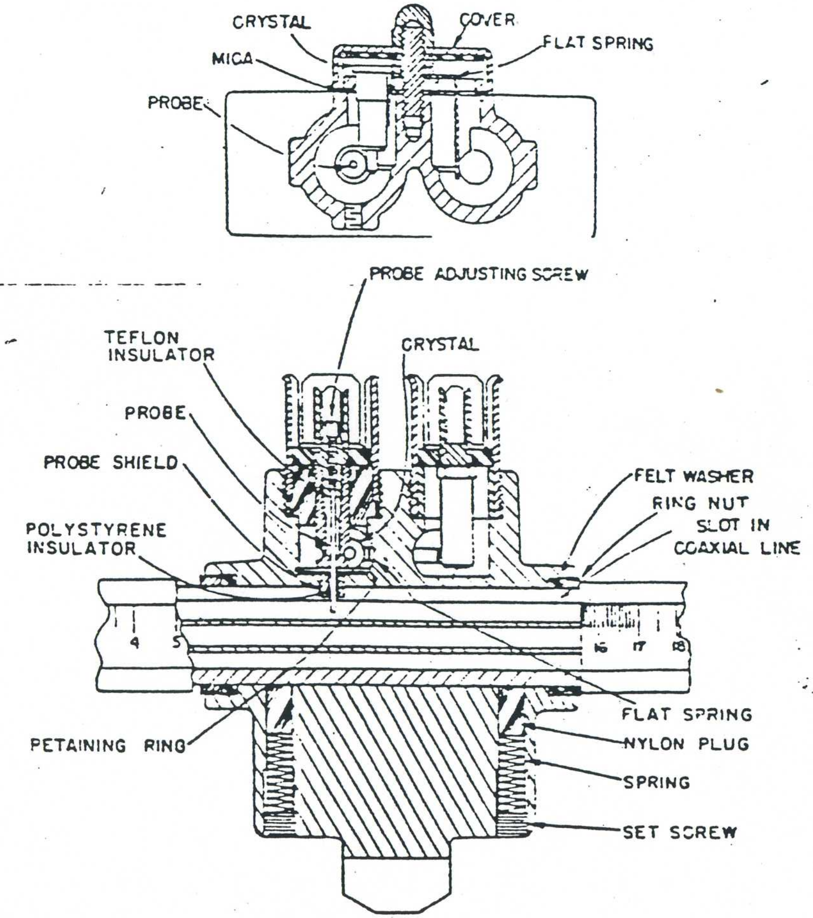

Figure 9a. Cross-sectional views of the carriage on the Type 874-LBA Slotted Line, showing the crystal mount and the adjustable probe.

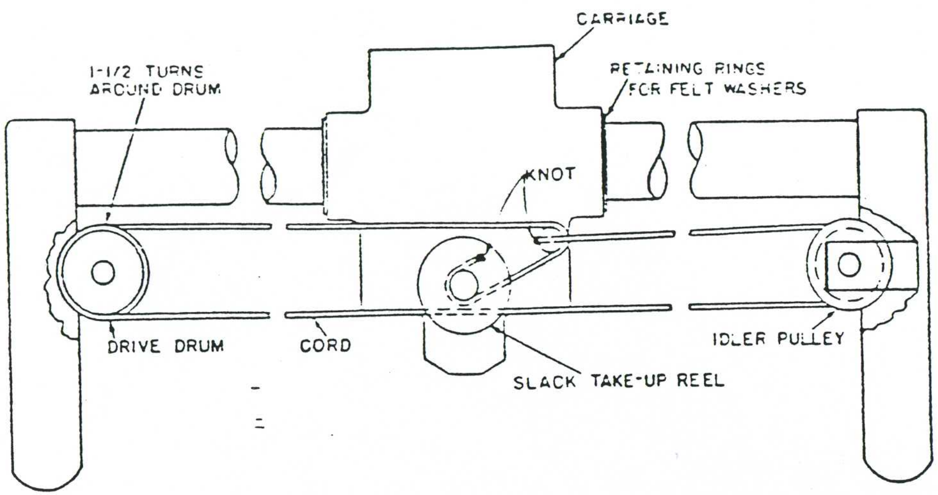

Figure 9b. Backview of drive mechanism showing arrangement of nylon cord.

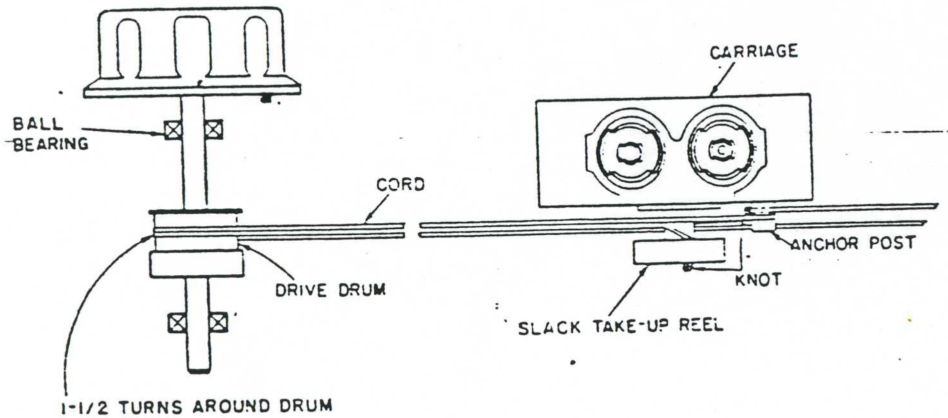

Figure 9c. View from top of carriage of arrangement of nylon cord.

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.

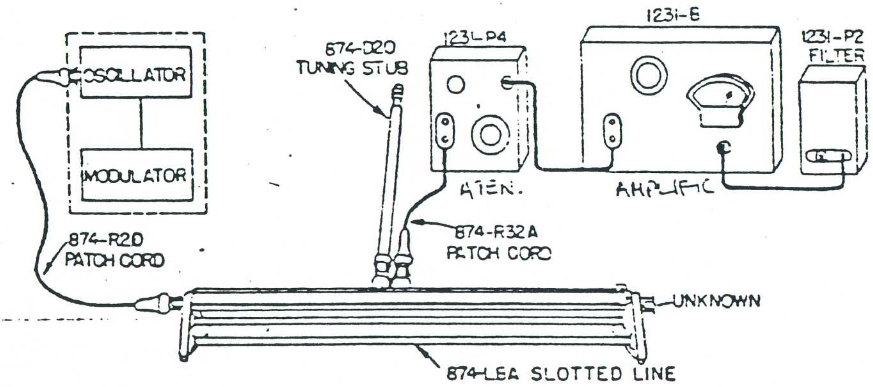

Figure 10. A typical setup for measurements with the Type 874-LBA Slotted Line, using a modulated source. The built-in crystal detector and an external tuned audio amplifier are used to detect the voltage induced in the probe. The probe is tuned by means of the tuning stub shown.

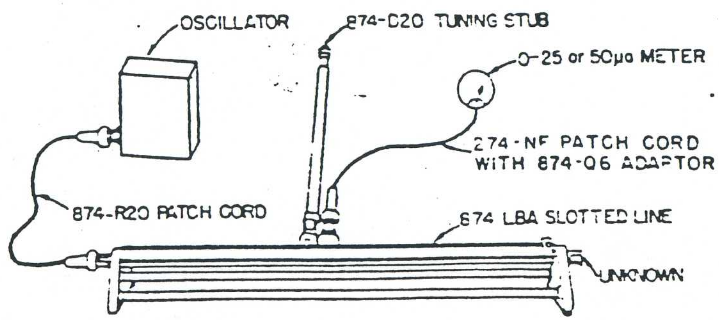

Figure 11. A typical setup for measurements with the Type 874-LBA Slotted Line using an unmodulated source and a microammeter as the indicator.

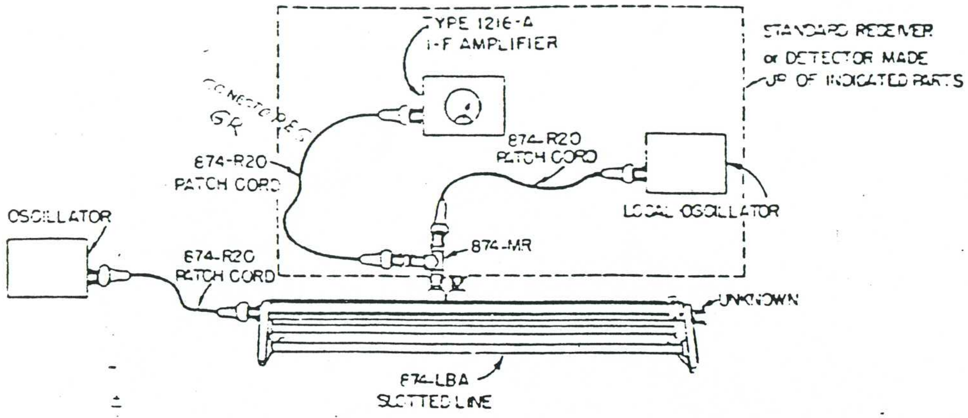

Figure 12. A typical setup for measurements with the Type 874-LBA Slotted Line using an unmodulated source and a superheterodyne detector or receiver.

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 1219-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 Ampli-
fier and associated filter and attenuator are used, the square-law region[5] 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 maxi-
mum 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 at-
tenuation required to produce the same meter reading for a voltage minimum
as for a voltage maximum. <u>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.</u>

3.32 <u>Crystal Rectifier and Microammeter</u>: An even simpler detector sys-
tem consists of the built-in crystal rectifier used with an external microam-
meter, as shown in Figure 11. In this case, the rectified d-c output of the crys-
tal 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 en-
countered in measuring even moderately high VSWR's unless the oscillator
output is large, as the probe coupling required may be excessive (see Para-
graph 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 mini-
mum 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 <u>The Type 874-MR Mixer Rectifier as a Detector</u>: The combination of
the Type 874-MR Mixer Rectifier, a local oscillator or signal generator such

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[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 re-
ceiver 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 cir-
cuits with high VSWR's, as the sensitivity and harmonic rejection are very good
(see Paragraph 4.63). The communications receiver used should have a band-
width 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 ob-
tained 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 fre-
quency 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 ac-
curately 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 pro-
vides 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

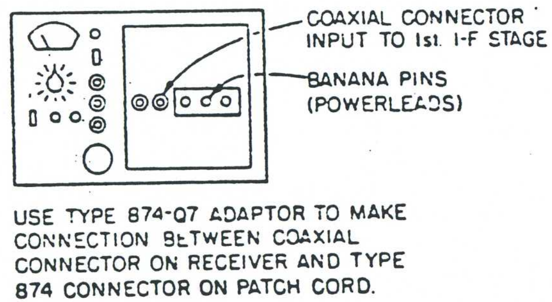

Figure 13. Method of connecting the 30-Mc output of a Type 874-MR Mixer Rectifier to the i-f amplifier in an AN/APR-1 or AN/APR-4 Receiver. The receiver tuning unit is removed for this application.

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[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

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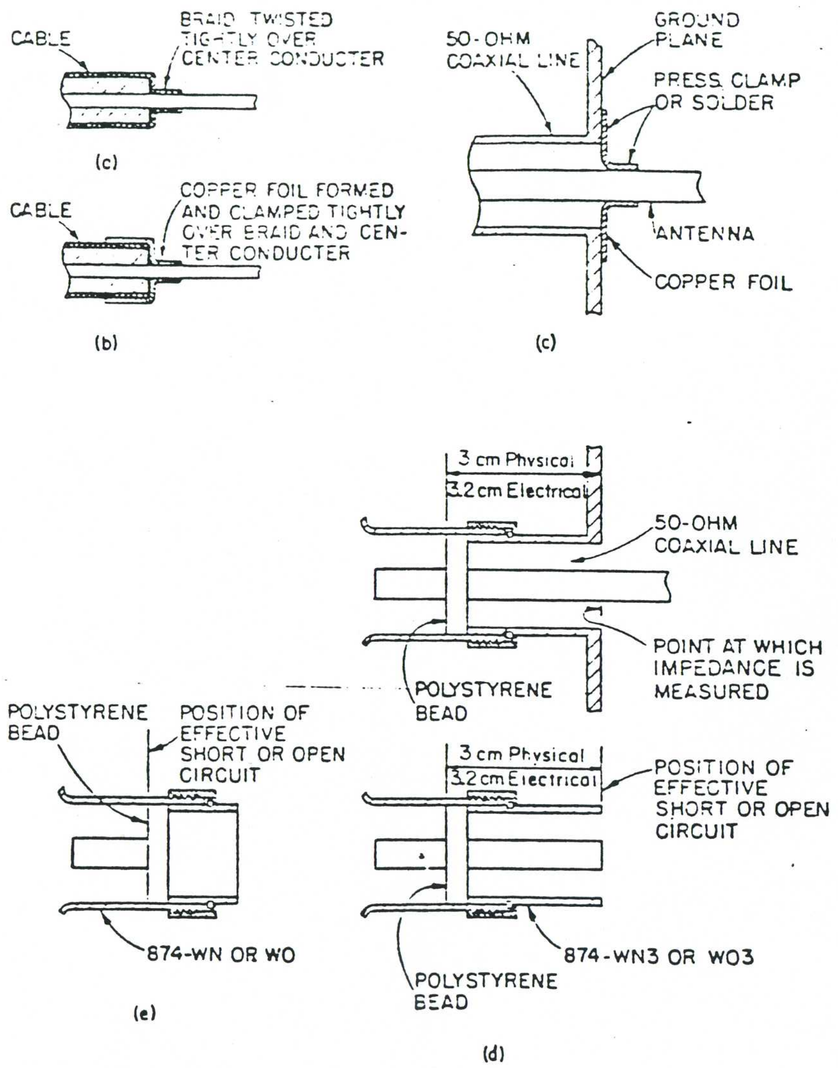
[8] The front face of the bead is located at the bottom of the slots between the contacts on the outer connector. Hence, its position can be easily determined from the outside of the connector.



(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.

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 <u>Mixer Rectifier Tuning</u>: 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. <u>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.</u>

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.

...ion in probe coupling along the line is affected by the depth of ...t large penetrations the variation tends to increase. The ...-% holds for penetrations of 30%.

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

$$\lambda = 2d \tag{20}$$

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

$$\lambda = \frac{2d}{n} \tag{21}$$

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

is then moved to a voltage m...num, ... ditions is greater than about one-fourth of full scale with any setting of the Type 1231-P4 Attenuator, the ... 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

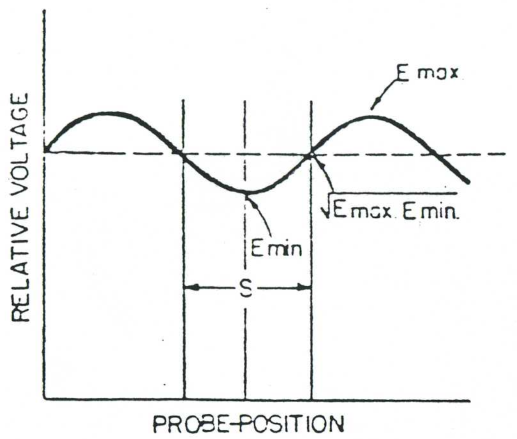


Figure 15. Method of improving the accuracy of the determination of the position of a voltage minimum on the line when the VSWR is low.

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 vo[illegible]ge 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

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

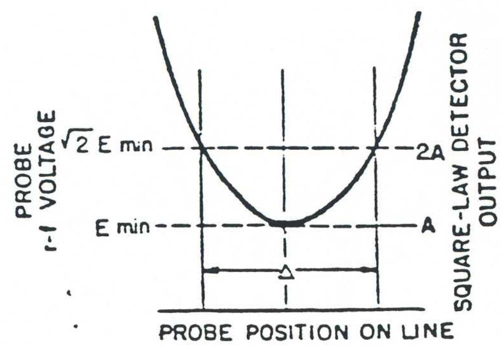
If the detector is operating in the square-law region, $\sqrt{2}$ times the r-f voltage corresponds to twice the minimum rectified output or a 6-db change in output.

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 ± 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,

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

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

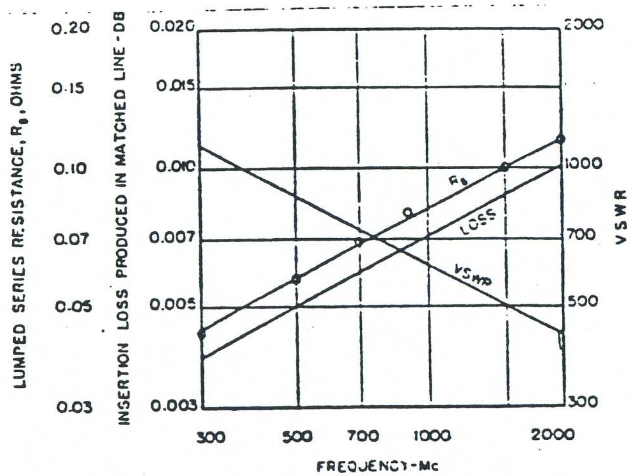


Figure 17a. Plot of the effective lumped series resistance at the connector measured on a typical Type 874-LBA Slotted Line. The insertion-loss produced in a matched line by the measured value of lumped resistance is also indicated, as well as the VSWR which would be produced by the measured lumped resistance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

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 x 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.