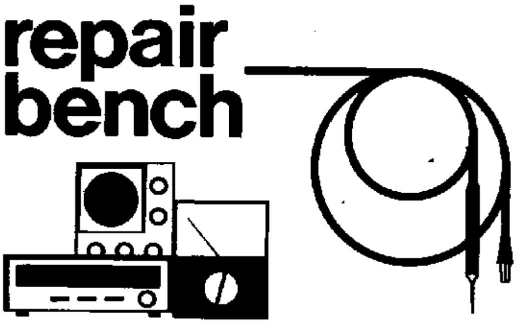
repair bench



Bob Stein, W6NBI

how to use the slotted line for transmission-line measurements

In a previous article,[1] several applications of the swr indicator (such as the Hewlett-Packard Model 415B) were described, *excluding* its use in conjunction with a slotted line. Since it was for that specific purpose that the swr indicator was developed, this article will actually be a continuation of the previous one as well as one which will discuss the use of coaxial slotted lines to measure swr, impedance, and transmission-line loss. The frequency range over which coaxial slotted lines are used is typically 400 to 5000 MHz, although it is possible, under certain conditions, to go as low as 100 MHz.

Since the purpose of this series of articles is to popularize the use of test equipment which is often available on the surplus market, let's begin by enumerating some of the coaxial slotted lines which you may run across. Hewlett-Packard Models 805A and 805C and General Microwave Type N200 are slab-type lines, which will be discussed shortly. Conventional coaxial lines, such as the GenRad (formerly General Radio) types 874-LBA and 874-LBB, are also available. Military types IM-24/U, IM-25/U, IM-92/U, and others are usually nothing more than the aforementioned commercial models which have been assigned military nomenclature. One exception to this is the TS-56A/AP, which appears to have been designed originally as military equipment.

By Robert Stein, W6NBI, 1849 Middleton Avenue, Los Altos, California 94022

principles of the slotted line

The principles governing the operation of the slotted line are those which apply to all rf transmission lines, and which will not be repeated here except as they apply directly to using the line. If we consider a section of transmission line which is fed from an rf source and is terminated in its characteristic impedance, Z_o, we know that there will be no reflection from the terminating load and therefore there will be no standing waves on the line. On the other hand, if the line is terminated by an impedance which is different from Z_o, a standing-wave pattern will result, as shown in **fig. 1**.

If the transmission-line section is coaxial, the voltage standing wave will exist as a potential difference or field between the inner and outer conductors. If we probe this field along the length of the line with a detector, and are careful not to disturb the field excessively with the probe, the detector will provide an output voltage which varies as the field intensity or voltage amplitude.

Since adjacent voltage minima or maxima along the line are always a half wavelength apart, the wavelength of the rf source can be determined by measuring the actual distance between adjacent minima or maxima. Furthermore, the detector is able to provide relative amplitudes of the voltage maxima, e_{max}, and minima, e_{min}, enabling us to determine the voltage standing-wave ratio from the following equations:

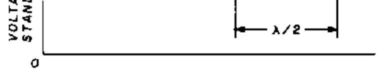


fig. 1. Standing wave on a transmission line terminated by a load impedance which is not equal to its characteristic impedance.

$$swr = \frac{e_{max}}{e_{min}}$$

$$swr\ (dB) = 20 \log \frac{e_{max}}{e_{min}}$$

Knowing the wavelength and the swr, it is also possible to determine the impedance of the load by means of transmission-line relationships. This will be explained later.

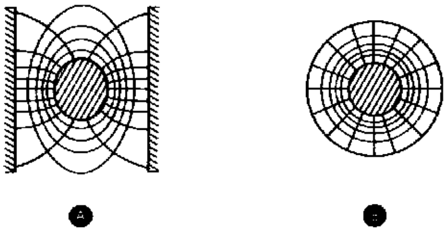


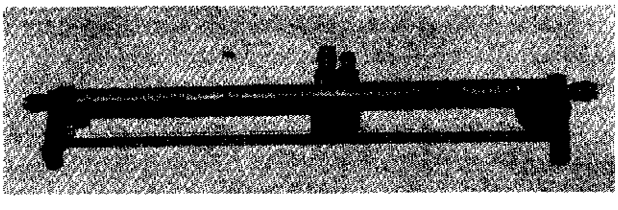
fig. 2. Cross-sections of the slab-type (A) and coaxial (B) slotted lines. The radial lines represent the electric field, the concentric lines the magnetic field. Courtesy Hewlett-Packard Company.

The conventional coaxial slotted line, such as the GenRad Type 874-LBB shown in the photograph, consists of a length of precision 50-ohm coaxial line with a narrow slot cut longitudinally along the outer conductor. A probe, mounted on a carriage which is movable along the length of the slot, extends into the line to sample the rf field. Connected to the probe is a microwave diode; a tuning probe or stub tuner (not shown in the photograph), also connected to the probe and diode assembly, tunes the structure for maximum sensitivity. A scale, graduated in centimeters and millimeters, is attached to the frame so that a pointer on the carriage can be used to measure distances along the line.

A somewhat different line configuration is the slab line used by Hewlett-Packard for their model 805 series and by General Microwave for the Type N200. As shown in the photograph of the Hewlett-Packard Model 805C, the probe carriage is mounted on a box-like structure which is actually two parallel conducting semi-planes separated by about 0.8 inch (20mm) and between which is the center conductor. **Fig. 2** shows cross-sections of the slab line and the conventional coaxial line. The equipotential field lines show that each of the semi-planes of the slab line is equivalent to one-half the outer conductor of the coaxial section. Precision machining results in a 50-ohm characteristic impedance and, according to Hewlett-Packard, the space between the semi-planes is equivalent to a slot width of less than 0.002 radian in a coaxial line.

The probe carriage contains a microwave diode detector, the probe, and a probe tuner. A scale, calibrated in centimeters and millimeters, is mounted on the frame and is used in conjunction with a vernier scale on the carriage to permit wavelength resolution to within 0.1 millimeter (about 0.004 inch).

In both types of slotted lines, the detector is usually a type 1N21 or 1N23 microwave diode, operating in its square-law region. Bolometer elements, such as a Narda Type N821, a PRD Type 610-A, or a selected 10-milliampere instrument fuse, may also be used. Bolometers require less attention relative to square-law operation, but are less sensitive than a diode detector.



The GenRad (formerly General Radio) Type 874-LLB Slotted Line. An adjustable stub or probe tuner is usually inserted into the left-hand connector on the movable carriage. Photo courtesy GenRad.

For impedance measurements, a precision short must be connected to one end of the slotted line. Because the GenRad line uses hermaphrodite GR874 connectors, the GR Type 874-WN3 Short-Circuit Termination will fit either end. The Hewlett-Packard and General Microwave slotted lines are equipped with type-N connectors, male at one end of the line and female at the other. These lines are supplied with precision male and female shorting terminations.

The low-frequency limit of the slotted line is a direct function of its usable length, that is, the distance over which the probe carriage can travel. The Hewlett-Packard Model 805A and 805C frequency range is specified as 500 to 4000 MHz, although these lines are usable down to about 400 MHz, since the probe travel is approximately 36.5 centimeters (one-half wavelength at 410 MHz). The GenRad Type 874-LBB is rated from 300 to 8500 MHz, based on its probe travel of 50 centimeters. The earlier Type 874-LBA has a specified upper frequency limit of 5000 MHz.

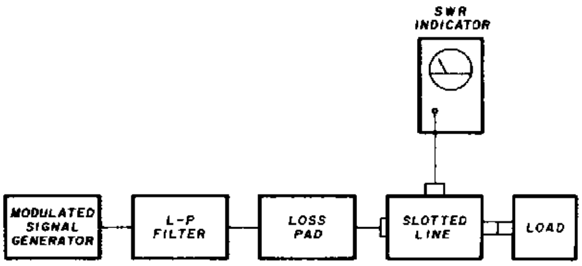


fig. 3. Equipment set-up for measuring swr, using an swr indicator for direct measurement readings.

These slotted lines can be used at frequencies below their specified minima, but such measurements may require the use of additional air-dielectric transmission-line sections or line stretchers. Such applications are beyond the scope of this article, but are covered in reference 2.

connecting the slotted line

The equipment set-up for using the slotted line is shown in **fig. 3**. The swr indicator was discussed in detail in reference 1. The signal generator must be amplitude modulated with a sine or square wave at the same frequency to which the swr indicator is tuned – usually 1000 Hz. Although an output of 1 milliwatt into 50 ohms is recommended for measurement of high standing-wave ratios, an output of 0.2 milliwatt (100 millivolts across 50 ohms) will generally suffice. The generator must supply a constant output which has minimum harmonic distortion and low incidental fm. The modulating voltage must also be stable to minimize measurement errors.

A lowpass filter, connected to the output of the signal generator, is desirable although not absolutely necessary. Severe harmonic distortion in the signal-generator output can result in erroneous measurements, but these are probably of minor importance for amateur use. A loss pad of at least 6 dB should be used to minimize loading effects of the test set-up on the signal generator.

All of the connections to the input of the slotted line can be made with interconnecting coaxial cables, but the load must be connected directly to the slotted-line connector. In the case of lines having a male connector at one end and a female at the other, connect the load to the end which will permit a direct connection or, only if absolutely necessary, one made with the fewest number of adapters. Otherwise, the swr of the adapter(s) will introduce errors into your readings.

The measurement procedures which follow are, of necessity, abbreviated and generalized so as to be applicable to most slotted lines. That is not to say that they cannot be applied directly to whatever line you may be using, for in fact, they can. But there are much more detailed instructions in the manufacturers' manuals, and I strongly recommend that either the applicable manual be obtained or that one of those specified in the references at the end of this article be purchased.

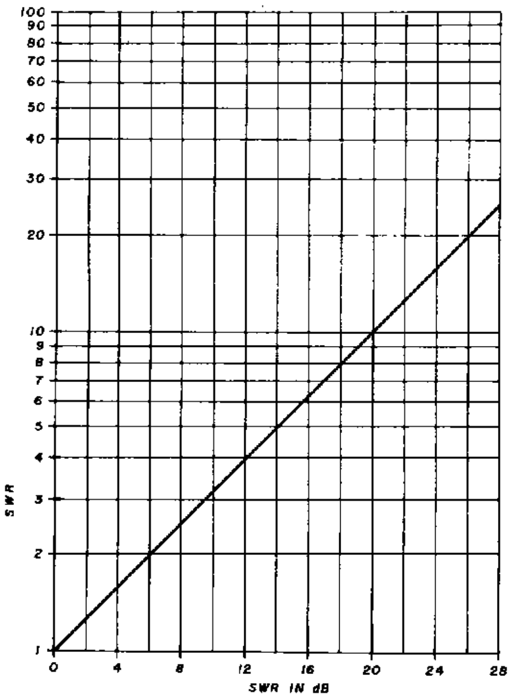


fig. 4. Swr vs swr in dB.

measuring swr less than 10:1

Direct method. The direct method of measuring swr is that which is most often used, although the alternate attenuator method will also be described. The procedure for direct measurement of swr is as follows:

1. Connect the equipment as shown in fig. 3, except that the load is left unconnected; allow sufficient warm-up time for the signal generator to become stable.

2. On the swr indicator, set the *gain* control fully counterclockwise and the *range* switch to 50.

3. Adjust the probe depth and tuning for a reading on the swr indicator, changing the *range* switch position clockwise, if necessary. If two peaks are obtained as the probe circuit is tuned, use that which results in the higher reading.

4. Connect the load to the slotted line and move the carriage along the line to find a voltage minimum.

5. Retune the probe circuit for a maximum meter reading. Then reduce the probe depth and retune the probe circuit (these adjustments interact) until a stable reading is obtained on the swr indicator with its *range* switch set to 50 or 60. It may also be necessary to adjust the signal-generator output. The main object, however, is to achieve a stable meter indication consistent with *minimum probe insertion*.

6. Move the carriage along the line to find a voltage maximum, and adjust the swr indicator *gain* control and *range* switch to obtain a meter reading of *1* on the swr scale.

7. Move the carriage to obtain a minimum meter reading, without changing any other adjustments or controls on the slotted line or on the swr indicator.

8. Read the standing-wave ratio directly from the swr scale on the meter. If the swr is greater than 3, switch to the next lower (counterclockwise) position of the *range* switch.

9. If the swr is less than 1.3, a more accurate indication can be achieved by setting swr indicator *meter scale* switch to *expand*, and repeating steps 6 and 7. In this case, the standing-wave ratio is read from the *expanded swr* scale on the meter.

Attenuator method. The attenuator method of measuring swr eliminates any error which may be introduced by deviation of the detector from true square-law response. It can also be used if an swr indicator is not available or if the signal source is unmodulated.

If the attenuator method is employed in conjunction with a *modulated* signal generator and an swr indicator, the test set-up of fig. 3 is applicable, except that a precision variable attenuator is used in place of the loss pad. The measurement procedure is as follows:

1. Perform steps 1 through 7, described under the direct measurement method, with the variable attenuator set to provide at least 6 dB of attenuation.

2. Adjust the *gain* control and the *range* switch on the swr indicator for a meter reading of 0 dB with the *range* switch set to 50 or 60.

3. Move the carriage along the line to find a voltage maximum; do not readjust the swr indicator controls.

4. Increase the variable attenuator setting until the swr indicator again reads 0 dB, or as close to it as can be obtained on-scale.

5. The swr, in dB, is equal to the variable attenuator

setting plus the meter reading (also in dB), minus the variable attenuator setting used in **step 1**.

6. Swr in dB can be converted to swr by reading the value from the scale on the meter which corresponds to the dB value of swr. This relationship is also plotted in **fig. 4**.

If an swr indicator is not available, or if the signal generator is *unmodulated*, connect the equipment as shown in **fig. 5**, leaving the load initially disconnected. Then proceed as follows:

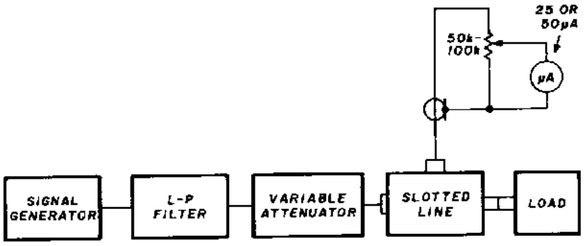


fig. 5. Equipment set-up for measuring swr, using a microammeter for an indicator. The signal generator does not have to be modulated in this arrangement.

1. Set the meter potentiometer to about mid-range and the variable attenuator to provide at least 6 dB of attenuation.

2. Adjust the probe depth and probe tuning for a reading on the meter, readjusting the meter pot if necessary.

3. Adjust the carriage position for maximum meter reading and retune the probe circuit for maximum. If two peaks are obtained as the probe circuit is tuned, use that peak which results in the higher current.

4. Connect the load to the slotted line.

5. Move the carriage along the line again to obtain maximum current.

6. Readjust the probe depth and tuning so that, with the meter pot set for maximum sensitivity, the meter current does not exceed 50 microamperes.

7. Move the carriage to obtain minimum current and note the meter reading.

8. Reset the carriage for maximum current, and increase the setting of the variable attenuator until the current is the same as that recorded in **step 7**.

9. The swr, in dB, is equal to the variable attenuator setting minus the setting used in **step 1**. Swr in dB can be converted to swr by the following expression, or from the curve of **fig. 4**.

$$swr = antilog\ \frac{swr\ in\ dB}{20}$$

measuring swr greater than 10:1

It is extremely unlikely that any amateur will be interested in *accurate* readings if the swr of the device under test is greater than 10:1. The techniques for making such measurements are explained in detail in references 2 and 3, and do not warrant coverage here.

The load impedance on a transmission line can be calculated from a knowledge of the swr present on the line and the position of a voltage minimum with respect to the load. Although this seems complicated, the physical measurements using a slotted line are quite simple. Other than the equipment required to measure swr, a precision (low-inductance) shorting termination is needed.

The measurement procedures involve the precise location of adjacent voltage minima along the line. When the swr is low, the exact location of a minimum is difficult to establish because the minimum-voltage region is quite broad. Improved accuracy in locating the minimum may be achieved by averaging the carriage positions which provide equal voltages on each side of the voltage minimum, as follows.

1. Mentally establish a convenient reference which is approximately the mid-point between the maximum and minimum readings obtained on the swr indicator (or on the microammeter, if the attenuator method of swr measurement is used).

2. Move the carriage to one side of the minimum until the reference level is obtained on the indicating device. Note the carriage position in millimeters on the slotted-line scale.

3. Repeat **step 2**, moving the carriage to the other side of the minimum.

4. Average the positions obtained in **steps 2** and **3** by adding the two position readings and dividing by two. This is the position of minimum voltage.

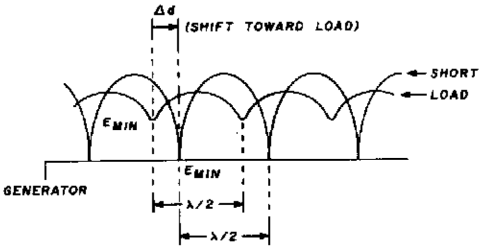


fig. 6. Standing-wave patterns on a slotted line with a capacitive load and with a shorting termination. Courtesy Hewlett-Packard Company.

The following procedures are used to measure the impedance of any load connected to the slotted line.

1. Measure and record the swr of the load, using any of the methods described previously.

2. Note the exact carriage positions in millimeters (from the scale) for two adjacent voltage minima. Record the difference between the two positions, which is equal to λ/2, as shown in **fig. 6**. Also record the position of one of the minima.

3. Replace the load with a precision short.

4. Move the carriage to find a new minimum which is closest to the one recorded in **step 2**.

5. Record the shift, Δd, between the positions recorded in **steps** 2 and 4 and note whether the shift is toward the generator or the load.

6. Calculate the electrical length, θ, in degrees, of Δd from the following expression

$$\theta = \frac{180(\Delta d)}{\lambda/2}$$

If the minimum shifted toward the load in **step 5**, θ is considered positive; if the minimum shifted toward the generator, θ is considered negative.

7. Determine the impedance from the following equation (where Z_o equals 50 ohms, the characteristic impedance of the system,

$$Z = Z_o \left[\frac{1 - j(swr)(\tan\theta)}{(swr) - j(\tan\theta)}\right]$$

or by means of a Smith chart, as explained below.

determining impedance from a Smith chart

Solving the equation in **step 7** above involves several rectangular-to-polar and inverse conversions, and is tedious, even with a scientific calculator which incorporates those conversion functions. Fortunately, the ubiquitous Smith chart provides a quick and simple solution to the problem. After proceeding through steps 1 through 6 under impedance measurements, continue as follows:

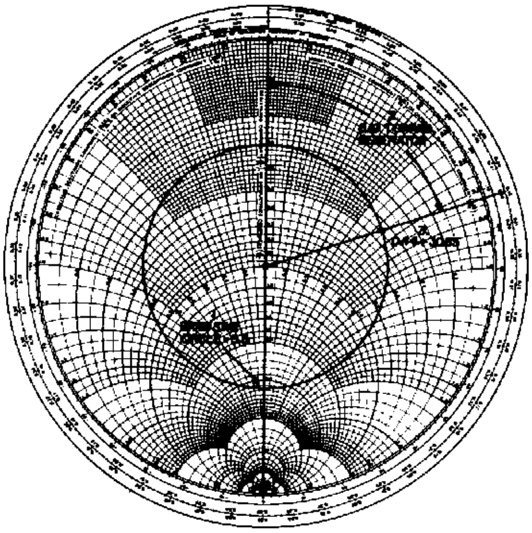


fig. 7. Example of determining impedance by use of a Smith chart. Courtesy Hewlett-Packard Company.

1. Convert Δd to wavelength ($\Delta\lambda$) by means of the expression

$$\Delta\lambda = \frac{\Delta d}{\lambda}$$

where λ is twice the value of $\lambda/2$ recorded in **step 2** of the impedance measurement procedures.

2. Draw a circle, on the Smith chart, whose center is at the origin (1.0) and whose radius is equal to the measured swr.

3. Along the periphery of the Smith chart, mark a point equal to $\Delta\lambda$, the shift in wavelength, either toward the generator or toward the load, as applicable.

4. Draw a radius line from the origin to the point established in step 3.

5. Read the normalized impedance at the intersection of the radius line and the swr circle.

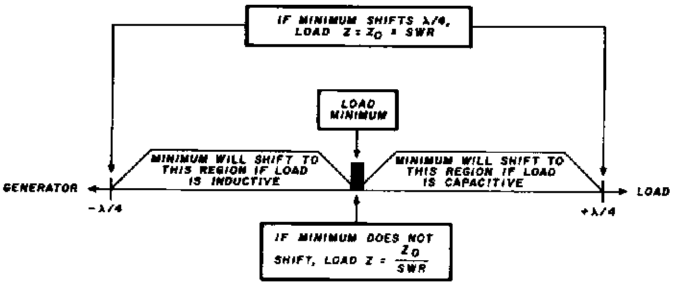


fig. 8. Summary of rules for impedance measurements. Courtesy Hewlett-Packard Company.

6. Multiply the normalized impedance by Z_o (50 ohms) to convert to the actual impedance.

As an example, assume the following values were obtained by measurement:

swr = 3.3
$\lambda/2$ = 150 mm, with one minimum at 220 mm
Δd = 30 mm, toward generator

a. Calculate $\Delta\lambda$

$$\Delta\lambda = \frac{\Delta d}{\lambda} = \frac{30}{2(150)} = 0.10\lambda$$

b. Draw an swr circle with a radius equal to 3.3, as shown in fig. 7.

c. Draw a radius line for a shift of 0.10λ toward the generator.

d. Fig. 7 shows the radius line and circle intersecting at $0.44 + j0.63$, which is the normalized series impedance of the load.

e. Multiply the normalized impedance by 50, giving the actual impedance as $22 + j31.5$ ohms.

rules of thumb for impedance measurements

Some rules of thumb that are helpful when making slotted-line measurements are:*

a. The shift in the minimum when the load is shorted is never more than ± one-quarter wavelength.

b. If shorting the load causes the minimum to move toward the load, the load impedance has a capacitive component.

c. If shorting the load causes the minimum to shift toward the generator, the load impedance has an inductive component.

---

*Reprinted from reference 3 by permission of Hewlett-Packard Company.

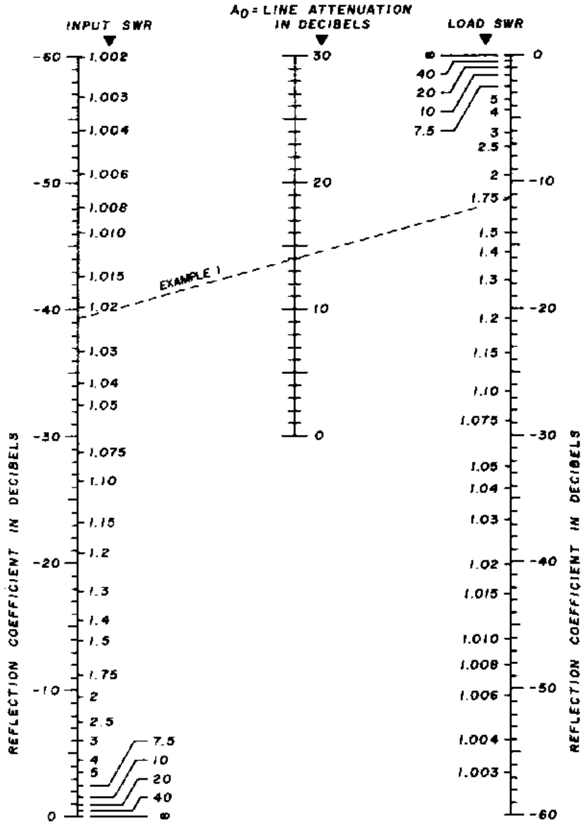


fig. 9. Line attenuation for low input standing-wave ratios. Reprinted from reference 4 by permission of Howard W. Sams & Co., Inc.

d. If shorting the load does not cause the minimum to move, the load impedance is completely resistive and has a value of Z_0/swr.

e. If shorting the load causes the minimum to shift exactly one-quarter wavelength, the load impedance is completely resistive and has a value of $Z_0 \ x \ swr$.

f. When the load is shorted, the minimum will always be a multiple of a half wavelength from the load.

These rules are summarized in **fig. 8**.

measuring transmission-line loss

Although the loss in a transmission line can be measured by means of an swr indicator and rf detector, as explained in reference 1, that technique requires that both ends of the line be accessible. This can be inconvenient, especially if the transmission line is connected to an antenna, and you want to find out whether the coax you put up five years ago is still good. Of course you could measure the power between the transmitter and the line, and then measure it between the line and the antenna, but this too has disadvantages (proper impedance terminations, carrying equipment to the roof or up the tower, a second person to energize the transmitter, and so on).

Let's consider how the loss can be measured with a slotted line. We know that the swr, measured at any point along a lossless transmission line, will be uniform and will depend *only* on the load impedance presented to the line. We also know that if the transmission line is lossy, the swr at the input end will appear to be better than that which is actually present at the load end. In fact, if the line is lossy enough, it will look like a pure resistance (equal to its characteristic impedance) at the input end, regardless of the terminating impedance.

Knowing these facts, it stands to reason that if the load impedance or swr is known, and the input swr can be measured, we should be able to calculate the transmission-line loss. The only problem would appear to be that of terminating the line in a known load — an antenna does not qualify — until we realize that a short is a known load with an infinite swr. Theoretically, an open circuit also presents an infinite swr, except that any connections or leads at the open end will bring the swr down.

Thus, the first step is to disconnect any existing load from the transmission line and connect a short in its place. Ideally, this should be a precision shorting termination if there is a connector at the load end of the line. If not, use a short, wide strap between the inner and outer conductors in order to minimize the inductance.

Then measure the swr at the input end of the transmission line. Obivously it should be measured at the frequency of interest because loss increases with frequency. Knowing the input swr and the load swr (∞), the line attenuation can be determined from either **fig. 9** or **fig. 10**. Those nomographs may be used for any known load; for the special case where the load swr is

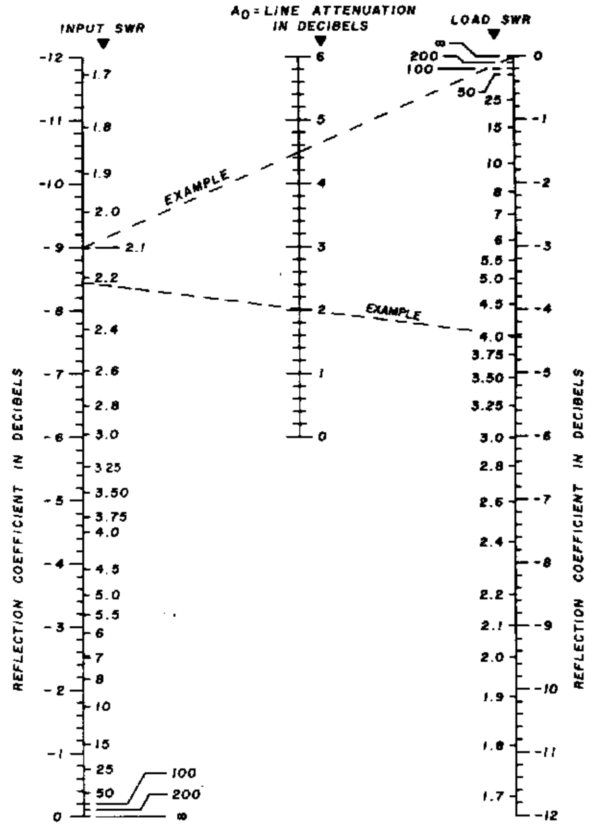
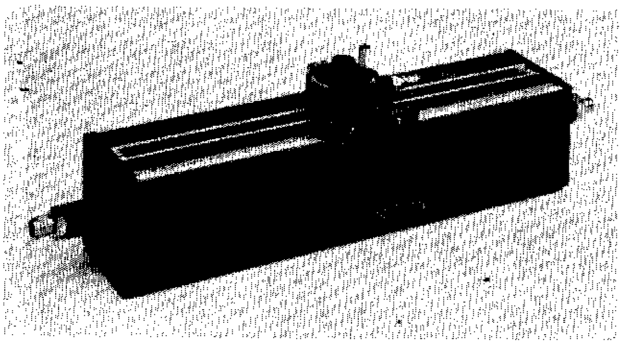


fig. 10. Line attenuation for high input standing-wave ratios. Reprinted from reference 4 by permission of Howard W. Sams & Co., Inc.



The Hewlett-Packard Model 805C Slotted Line utilizes slab-line construction. Photo courtesy Hewlett-Packard Company.

infinite, the following expression will also yield the attenuation, A_o, in dB:

$$A_o = 10 \log \frac{swr_{in} + 1}{swr_{in} - 1}$$

As an example, let's assume that you are feeding your two-meter antenna with 60 feet (18.3 meters) of RG-8A/U coaxial cable. The cable attenuation specifications, which have been plotted in **fig. 11**, indicate that the nominal attenuation of 100 feet (30.5 meters) should be approximately 2.3 dB at 144 MHz. However, we cannot normally use a slotted line at 144 MHz, so we must measure the loss at a higher frequency and assume that the measured loss can be translated to 144 MHz.

If we make the swr measurement at 400 MHz, the attenuation of 100 feet (30.5 meters) of RG-8A/U should be nominally 4.1 dB. Since we are concerned with the loss in only 60 feet (18.3 meters), the loss of that length should be about 2.46 dB at 400 MHz and 1.38 dB at 144 MHz.

Continuing with our example, assume that the swr measured at the input end of the coax is 2.1:1 when the load end is shorted. Going to the nomographs, it can be seen that the input swr is read more easily on **fig. 10**. Placing a straight-edge between the input swr of 2.1:1 and the load swr of ∞, we find that it intersects the line attenuation scale at about 4.5 dB.

Since the measured attenuation is more than 2 dB greater than what should be expected at 400 MHz, we can make a worst-case assumption that the coax has seen better days and should be replaced. If you are interested in knowing the actual loss at 144 MHz, it can be extrapolated from the curves of **fig. 11** graphically, as follows.*

1. Convert the measured loss to attenuation per 100 feet (30.5 meters). Since we measured a loss of 4.5 dB for 60 feet (18.3 meters) this becomes *4.5(100/60)*, or 7.5 dB per 100 feet (30.5 meters).

2. Using a scale or a pair of dividers, determine the distance between the appropriate curve and the attenuation per 100 feet (30.5 meters) calculated in **step 1**; this is shown as dimension L in **fig. 11**.

3. Lay off dimension L' equal to L, above the curve at 144 MHz; read the actual attenuation. In our case, it is approximately 4.35 per 100 feet (30.5 meters).

4. Determine the loss for the length of transmission line used. For 60 feet (18.3 meters), the loss is approximately 2.6 dB. Since the nominal loss for that length of line is only 1.38 dB, it can be seen that the line has aged sufficiently to cause an additional loss of more than 1.2 dB. Under the most favorable conditions, with a perfect match between the antenna and the coax, only 55 percent of the transmitter output power will reach the antenna, as compared to 72 percent for new line.

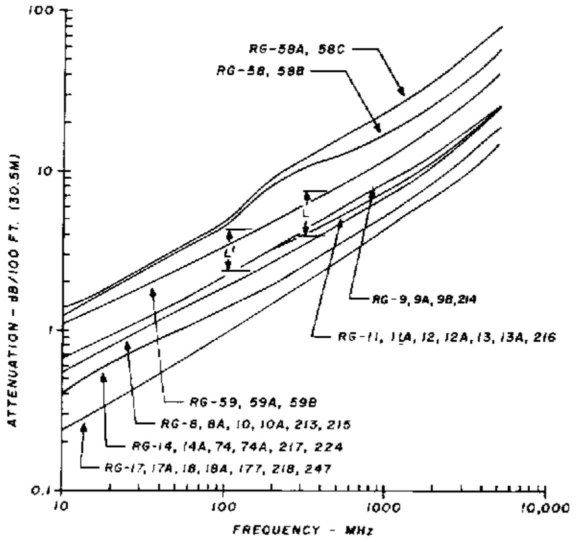


fig. 11. Attenuation vs frequency for commonly used coaxial cables. Dimension L and L′ are used in the example in the text of translating line loss to a lower frequency.

Note that measurement of transmission-line loss is one case where a high swr is desirable, indicating low attenuation. If this seems confusing, just remember that for a lossless line, an infinite load swr will show up as an infinite swr anywhere on the line. One further comment – if the input swr actually reads infinity, it is likely that you have a transmission line which is open near the input connector, rather than a lossless line.

---

*The extrapolation is based on the following approximations holding true over a *limited* frequency range: (1) the attenuation-vs-frequency characteristic is linear when plotted on log-log coordinates and (2) the attenuation-vs-frequency curve for cable having degraded characteristics varies in the same manner as that for new cable.

references

1. Robert S. Stein, W6NBI, "Using the SWR Indicator," *ham radio*, January, 1977, page 66.

2. *Instruction Manual, Type 874-LBB Slotted Line*, GenRad, West Concord, Massachusetts.

3. *Operating and Service Manual, 805C/D Slotted Line*, Hewlett-Packard Company, Palo Alto, California.

4. *Reference Data for Radio Engineers*, 6th Edition, Howard W. Sams & Co., Inc., Indianapolis, Indiana, Chapter 24, figures 5 and 6.

ham radio