Evaluation of Antenna Tuners and Baluns–An Update

How to have high confidence in your measurements.

By Frank Witt, AI1H

In a two-part article in April and May 1995 *QST,*[1] I described a simple method for evaluating antenna tuners. Application to the evaluation of baluns was described the following year.[2] The method involves a resistance-load box and a low-power analyzer, and it works equally well for evaluating the performance of equipment with balanced as well as unbalanced loads. A simple extension was described that allows the equipment evaluation with complex-impedance loads as well.

Amateurs around the world have since used the method, which has been dubbed the "indirect method," the "AI1H method" and the "Witt method." It provides—at moderate cost—a simple means for evaluating antenna tuners and baluns. The method was used to evaluate four antenna tuners for a Product Review in March 1997 *QST*.[3]

Most hams had been ignorant about the performance of their antenna tuners. They only knew the circuits were lossy when they got very hot or when a component failed (if running high power). QRPers had no way of knowing whether or not their antenna tuners handicapped them. Some manufacturers' claims for their antenna tuners were (and still are) unreliable, and that is being kind. Much light was shed on this matter by the programs written by Dean Straw, N6BV, *TLA* and its successor *TLW*,[4] which compute antenna-tuner performance. The indirect method complements this analysis tool by providing a very accessible measurement tool.

From the source in Note 1 (May 1995, page 37): "This new application of low-power SWR testers is a demanding one, since the accuracy must be excellent for valid results. Perhaps we will see even more accurate SWR testers in the future, and maybe antenna tuner manufacturers will be inspired to improve their designs." That day has arrived. Improved SWR analyzers and antenna tuners[5] are now available.

The purpose of this article is to show how measurement instruments that are now available provide improved accuracy for the simple characterization of antenna tuners and baluns. It summarizes a better understanding of any inherent limitations of the evaluation method. Finally, it provides a comparison with other measurement methods.

[1]Notes appear on page 14.

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SWR, Reflection-Coefficient Magnitude and Return Loss

Before getting into the subject of improving the measurement accuracy, it is appropriate to discuss the quantities to be measured. The relationship between reflection coefficient, ρ, the impedance of the device to be tested, Z_L, and the reference resistance of the analyzer, R_{REF}, is as follows:

$$\rho = \frac{Z_L - R_{REF}}{Z_L + R_{REF}} \qquad \text{(Eq 1)}$$

The value of R_{REF} for the analyzers we consider here is around 50 Ω. For our purposes in this application, *SWR*, reflection-coefficient magnitude ($|\rho|$) and return loss (*RL*, in decibels) are equivalent in the sense that we can measure any of them and find the antenna-tuner loss. The relationships between them are:

$$SWR = \frac{1+|\rho|}{1-|\rho|} \qquad \text{(Eq 2)}$$

$$|\rho| = \frac{SWR-1}{SWR+1} \qquad \text{(Eq 3)}$$

$$RL = -20\log|\rho| \qquad \text{(Eq 4)}$$

For a discussion of the nature of *SWR*, $|\rho|$ and *return loss* and how *SWR* is sloppily used, see my discussion of "SWR Bandwidth."[6]

I've included these relations because some instruments measure $|\rho|$ more accurately than *SWR*, whereas others might measure return loss more accurately. So, to achieve the highest accuracy, the correct parameter must be used.

The Indirect Method

The indirect method involves connecting a resistance load box with switchable resistors to the output terminals of the antenna tuner. The load box has been named the "geometric resistance box," because the values of resistance follow a geometric progression. For each load, the resistances of the adjacent loads are twice and half the load resistance.

The input of the antenna tuner is connected to a meter that measures *SWR*, reflection coefficient magnitude, $|\rho|$, or return loss, *RL*, in decibels. The measurement is carried out as follows:

1. Set the geometric resistance box to the desired load resistance, R_L.
2. Adjust the antenna tuner so that SWR = 1:1, $|\rho| = 0$ or *RL* is maximized.
3. Switch to the next lower load resistance, $R_L/2$, and record the *SWR*, S_1, or $|\rho_1|$ or RL_1.
4. Switch to the next higher load resistance, $2R_L$, and record the *SWR*, S_2, or $|\rho_2|$ or RL_2.
5. Calculate the antenna-tuner loss, *L*, in decibels and percentage of power lost, P_{LOST}, from:

$$L = 5\log\frac{(S_1+1)(S_2+1)}{9(S_1-1)(S_2-1)} = -5\log\left(9|\rho_1||\rho_2|\right) = \frac{RL_1+RL_2}{4} - 4.77\text{ dB} \qquad \text{(Eq 5)}$$

$$\begin{aligned} P_{LOST} &= 100\left(1-10^{\frac{-L}{10}}\right) \\ &= 100\left(1-3\sqrt{\frac{(S_1-1)(S_2-1)}{(S_1+1)(S_2+1)}}\right) \\ &= 100\left(1-3\sqrt{|\rho_1||\rho_2|}\right) \\ &= 100\left(1-3\cdot 10^{-\frac{RL_1+RL_2}{40}}\right) \end{aligned} \qquad \text{(Eq 6)}$$

These measurements are carried out the same way for unbalanced and balanced loads.

Antenna-Tuner Loss in Decibels versus Percentage of Power Lost

The loss of an antenna tuner is presented above in two ways: as power loss, *L*, in decibels, and percentage of power lost, P_{LOST}. P_{LOST} has an advantage in the antenna-tuner loss application. We all know approximately how much power our transmitter delivers when it is feeding a 50-Ω

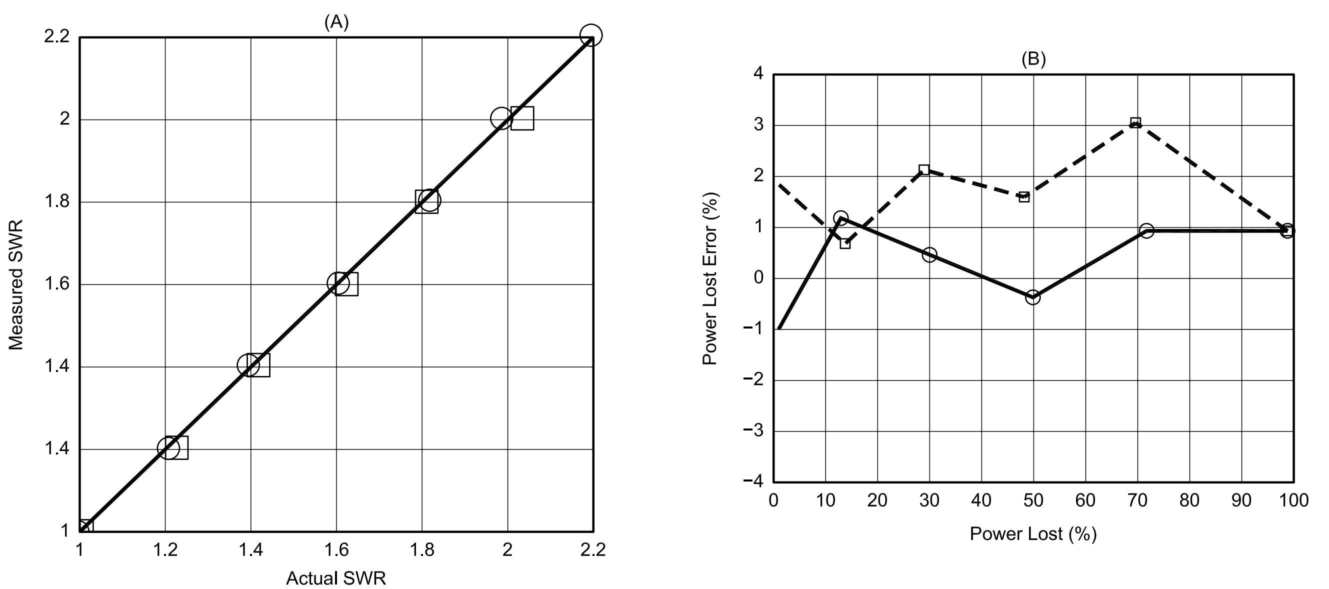

Fig 1—In A: Measured *SWR* for resistive loads using a calibrated MFJ-259B. The circles are for R_L > 50 Ω and the squares are for R_L < 50 Ω. In B: Error in percentage of power lost. The solid trace is for R_L > 50 Ω and the dashed trace is for R_L < 50 Ω. These measurements apply over the entire HF band.

load. What we want to know is how much of that power is being absorbed or radiated by the antenna tuner and not reaching the antenna system. Percentage of power lost tells us this directly. For example, a kilowatt transmitter feeding an antenna tuner with a 20% of power lost figure means that 200 W are lost in the antenna tuner. Most of that power is usually heating components in the tuner.

On the other hand, if the loss is expressed in decibels, we must make a mental translation to percentage of power lost in order to know what is happening. Some familiar decibel-loss quantities are 0, 1, 3 and 10 dB, which equate to 0%, 21%, 50% and 90% of the power lost in the antenna tuner, respectively. Other quantities of decibel loss are far less familiar to most of us. So, the preferred loss-characterization method is percentage of power lost. It is interesting to notice from Eq 6 that percentage of power lost is linearly related to the geometric mean of the reflection-coefficient magnitude readings.

Accuracy of the Analyzers

MFJ-259B

When I first discovered the indirect method, I used low-power SWR testers. These were the Autek Research Model RA1 and the MFJ Model MFJ-259. These units displayed *SWR*, so the *SWR* reading was used for loss calculations using Eqs 5 and 6. These instruments do not display $|\rho|$, although it is the basic quantity measured. *SWR* is calculated internally from the value of $|\rho|$. This calculation is a source of error. Fortunately, some newer instruments

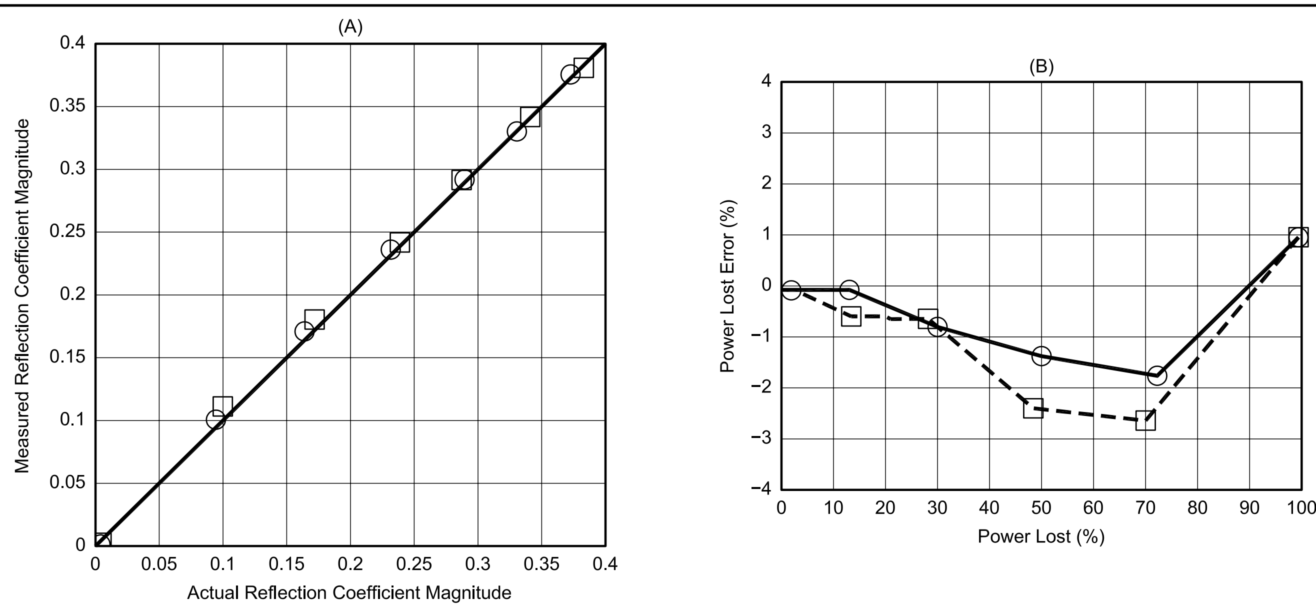

Fig 2 — In A: Measured reflection-coefficient magnitude for resistive loads using a calibrated MFJ-259B. The circles are for R_L > 50 Ω and the squares are for R_L < 50 Ω. In B: Error in percentage of power lost. The solid trace is for R_L > 50 Ω and the dashed trace is for R_L < 50 Ω. These measurements apply over the entire HF band.

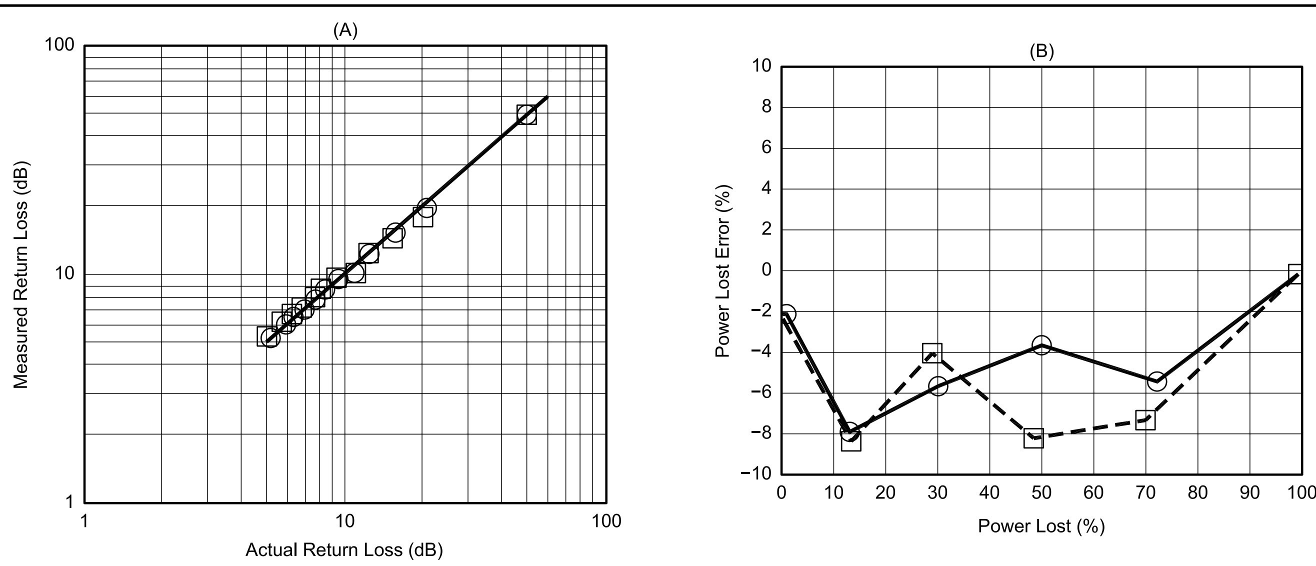

Fig 3 — In A: Measured *return loss* for resistive loads using a calibrated MFJ-259B. The circles are for R_L > 50 Ω and the squares are for R_L < 50 Ω. In B: Error in percentage of power lost. The solid trace is for R_L > 50 Ω and the dashed trace is for R_L < 50 Ω. These measurements apply over the entire HF band.

display $|\rho|$ and *return loss* directly. Further, *SWR*, $|\rho|$ and *return loss* are displayed on a LCD, which is easier to read reliably than an analog meter. An instrument for measuring the loss of antenna tuners is the MFJ-259B, the successor to the MFJ-259. Some features of other candidates for this application are discussed later in the article, but here we will primarily answer the question of whether or not the MFJ-259B will perform adequately in this application.

Although the MFJ-259B impedance analyzer measures many properties of the unknown connected to its terminals, we will focus here on the antenna-tuner evaluation application. It fared well compared with similar units in a recent review.[7] As indicated above, antenna-tuner loss can be determined from *SWR*, $|\rho|$ or *return loss*. The accuracy of the MFJ-259B can be improved through a calibration procedure, which is described below. *SWR*, $|\rho|$ and *return loss* were measured. The date on the unit tested is 1998 and the software version is 2.02. The measurement frequency was 1.8 MHz and the load resistors were 1/4-W, 1% metal-film resistors with very short leads. These resistors are the "standard" for the evaluation of the analyzer. Tests confirmed that the 1.8-MHz data applies over the entire HF band. The dc values for the load resistors were measured with a digital multimeter. I have made measurements using complex-impedance loads that show similar accuracy. This is important, because the impedances seen by the MFJ-259B in this application are complex.

The results are shown in Figs 1, 2 and 3 for *SWR*, $|\rho|$ and *return loss*, respectively.[8] Notice that separate data points and traces are obtained for load resistances above and below R_{REF}. Although the "measured versus actual" plots are interesting, the useful information is contained in the graphs. They show the error in percentage of power lost versus the actual percentage of power lost. These graphs use Eq 6 to find the percentage of power lost, but make the assumption that $|\rho_1|$ and $|\rho_2|$ are the same. The "true" percentage of power lost is assumed to be that calculated from the measured dc resistance values. The error is found by subtracting this true percentage of power lost from that calculated using measurements from the MFJ-259B. For both *SWR* and $|\rho|$, the errors are less than about 3% for percentage of power losses from 0 to 100%. The error for *return loss* is around 8%, however. These differences arise from deficiencies in the algorithm that converts the basic $|\rho|$ measurement into *return loss* and the poor resolution of return-loss measurements in part of the desired region, which is discussed later.

For all calculations, it was assumed that the reference resistance, R_{REF}, for this particular MFJ-259B is 50.1 Ω. This is the value of R_{REF} that gives the lowest mean-square error (0.77%) for percentage of power losses from 0 to 100%. R_{REF} is nominally 50 Ω, but this method of finding the actual value provides a better evaluation of the MFJ-259B.

Measurement Resolution

A measuring instrument is limited by its resolution. Even if the accuracy is perfect, the ability to display the result is controlled by its resolution. The display on the LCD for each parameter measured limits its resolution.

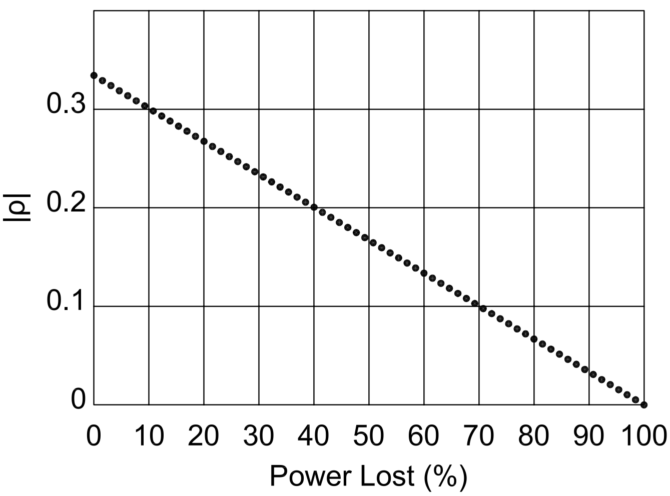

Fig 4—Values of reflection-coefficient magnitude that can be displayed by the MFJ-259B. This results in a resolution capability for percentage of power lost of 0.75%. Notice the linear relationship between percentage of power lost and |ρ|.

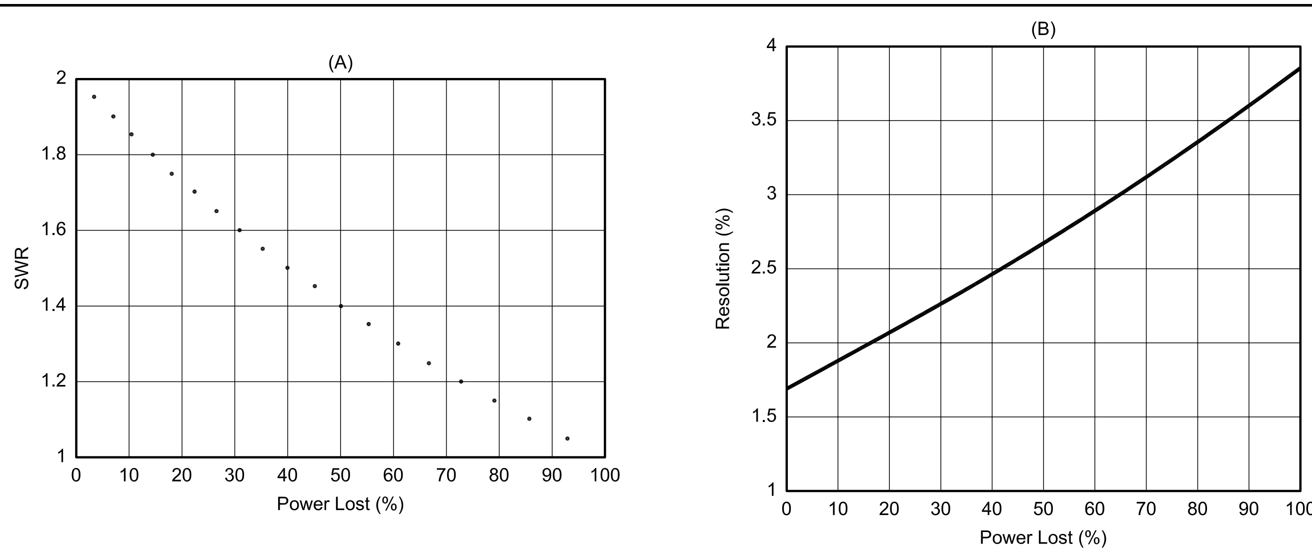

Fig 5—Resolution of the MFJ-259B for *SWR*. In A: The values of *SWR* that may be displayed. In B: The resolution over the 0 to 100% percentage of power lost range.

For the MFJ-259B, *SWR*, $|\rho|$, and *return loss* results are two-digit displays, so only a limited number of data values may be displayed over the range of percentage of power lost from 0 to 100%.

For the purpose of this analysis, assume $|\rho_1| = |\rho_2| = |\rho|$ (and $S_1 = S_2 = SWR$ and $RL_1 = RL_2 = RL$). Reflection coefficient magnitude, $|\rho|$, values range from 0 to 0.33. For example, two adjacent values of $|\rho|$ are 0.11 and 0.12, which correspond to percentage of power losses of 67% and 64%, respectively, from Eq 6. If the displayed $|\rho|$ value bounces between these two values, $|\rho|$ is interpreted as the average of these values, or *0.115* and the percentage of power lost as *65.5%*. All interpolated values are italicized. Thus the resolution in this region of the range of $|\rho|$ is 0.75% [(67 – *65.5*)/2 or (*65.5* – 64)/2)]. In fact, since there is a linear relationship between percentage of power lost and $|\rho|$, the resolution is a constant 0.75% over the entire 0 to 100% percentage of power lost range. Fig 4 shows all the $|\rho|$ data points that can be displayed by the MFJ-259B over the range of interest.

What about *SWR* and *return loss*? Figs 5 and 6 show the resolution capability for those parameters. The *SWR* resolution (Fig 5B) of the MFJ-259B varies from 1.7 to 3.8%. The *return loss* resolution (Fig 6B) has a jagged shape because displayed *return loss* values in decibels are: 9.6, *9.65*, 9.7, . . . *9.95*, 10, *10.5*, 11, *11.5* . . . 30, *30.5*, 31, *31.5*, 32, *33*, 34 . . . *37*, 38, *40*, 42, *45*, 48

The sharp deterioration in resolution occurs at RL = 10 dB because only two digits are used to display the *return loss* values. The resolution is as high as 2.6% around RL = 10 dB and the percentage of power lost is 10%.

For the MFJ-259B, its resolution (0.75%) makes $|\rho|$ the clear winner for measuring antenna-tuner loss, especially in light of the very good accuracy (3%) shown in Fig 2. However, there are two regions in the measurement range of $|\rho|$ = 0 to 0.33 where improved resolution is very desirable. These are the regions at the ends of this range. The antenna tuner is considered tuned when $|\rho|$ = 0. The focus of the calibration procedure (described in the next section) is around $|\rho|$ = 0.33. A close look at Fig 6B reveals that *return loss* resolution is best for percentage of power lost regions near 0% and near 100%. We will make use of this fact in calibrating the MFJ-259B and in tuning the antenna tuner during the evaluation process.

We can take advantage of the higher internal resolution in the region around $|\rho|$ = 0 by just maximizing *return loss* when we are striving to achieve the best tuner settings. In order to take advantage of the better resolution around $|\rho|$ = 1/3, we can use Table 1, which shows the relationship between the displayed, interpolated and actual values of *return loss* and reflection coefficient magnitude. This way, we can pick up almost another decimal digit of resolution of $|\rho|$ when the unit is calibrated. The actual values of $|\rho|$ were obtained by evenly distributing values between the displayed values.

Notice that the displayed *return loss* reading that comes closest to $|\rho|$ = 1/3 is 9.4 dB, not the actual value of 9.54 dB. Also shown in Table 1 is the value of *return loss* corresponding to the actual value of $|\rho|$, which points up the inaccuracy of the return-loss algorithm

Table 1—Relationship between Return Loss (*RL*) and Reflection-Coefficient Magnitude, |ρ|

Interpolated values are in italics

Displayed Values		***Actual Values***	
RL (dB)	*|ρ|*	*|ρ|*	*RL (dB)*
9.05	*0.345*	0.345	9.24
9.1	0.34	0.3433	9.29
9.15	0.34	0.3417	9.33
9.2	0.34	0.340	9.37
9.25	0.34	0.3383	9.41
9.3	0.34	0.3367	9.46
9.35	*0.335*	0.335	9.50
9.4	**0.33**	**0.3325**	**9.56**
9.45	0.33	0.330	9.63
9.5	0.33	0.3275	9.70
9.55	*0.325*	0.325	9.76
9.6	0.32	0.3233	9.81
9.65	0.32	0.3217	9.85
9.7	0.32	0.320	9.90
9.75	0.32	0.3183	9.94

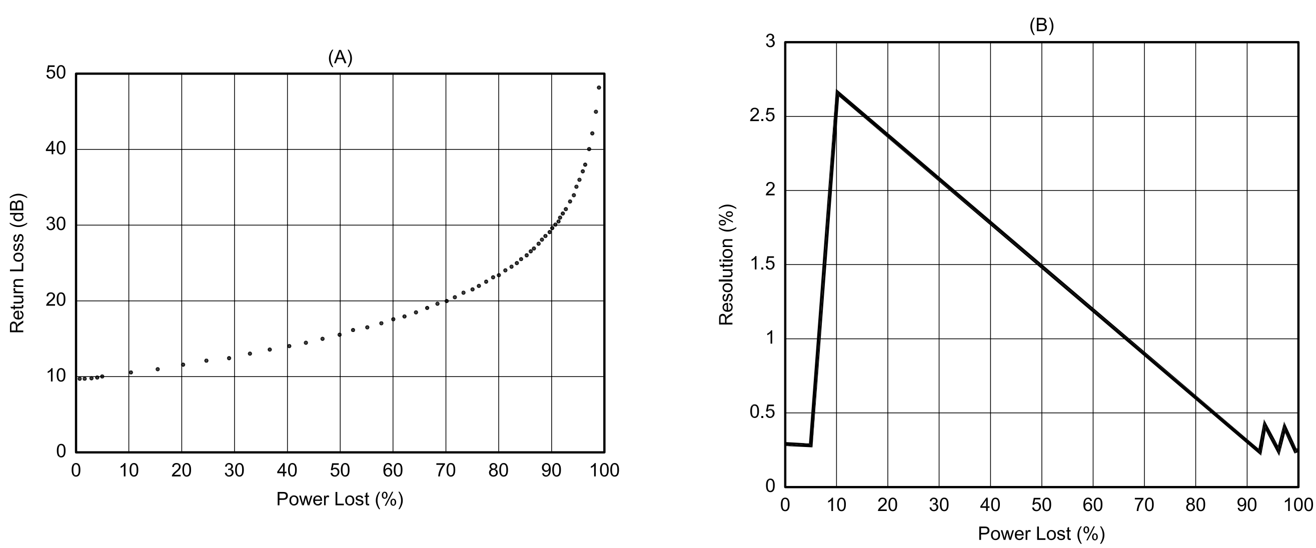

Fig 6—Resolution of the MFJ-259B for *return loss.* In A: The values of *return loss* that may be displayed. In B: The resolution over the 0 to 100% percentage of power lost range.

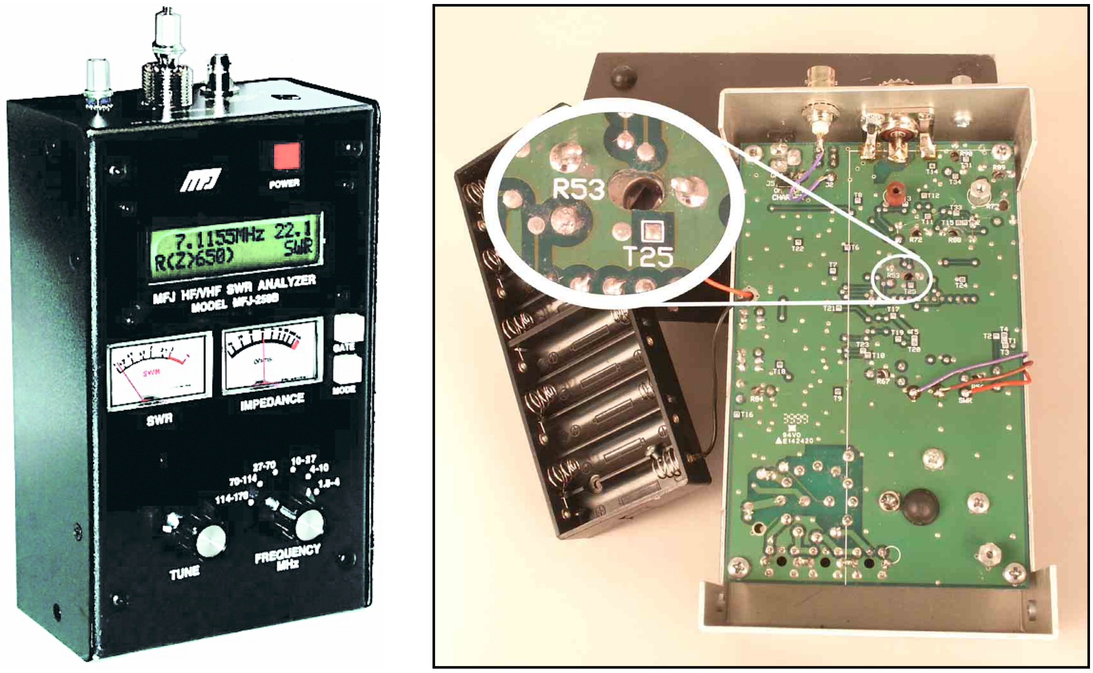

Fig 7—Photograph of MFJ-259B. Notice the location of R53, which is used to calibrate the unit.

in the MFJ-259B software.

Care must be taken in the use of Table 1 for other vintages of MFJ-259B software, if they exist, since the values may be different. This is easy to check by confirming several readings of *return loss* and $|\rho|$ in the region around $|\rho| = 0.33$.

MFJ-259 Calibration Procedure

I do not recommend you try this calibration process unless you have a good reason to do so and unless you are confident that you can do it. If the unit is in warranty, you may void the warranty. There are risks. You could inadvertently turn the wrong adjustment screw and really mess up the instrument. Wires or circuit-board pads could be brought into contact and damage to the unit could result.

I have found that MFJ-259B impedance analyzers as delivered (a sample of two) have adequate accuracy for getting a good idea of how well a particular antenna tuner performs. However, if you want to squeeze the most out of your analyzer, calibration is possible and can be helpful for evaluating an antenna tuner. The effectiveness of the calibration process is seen in Fig 2B, where the percentage-of-power-lost error is less than 1% for power losses up to 30%. As will be seen, the calibration is made in this region.

The basic idea is to connect known load resistances to the unit and then adjust the proper potentiometer (and there are several, so take care) so that the appropriate reading is correct. For our purposes, we want the LCD reading of *SWR*, $|\rho|$ and *return loss* to be correct. Since $|\rho|$ is the fundamental measurement from which SWR and return loss are calculated, calibration involves getting the $|\rho|$ reading (which is displayed only on the LCD and not on an analog meter) to be as close to the correct value as possible. Adjustments to calibrate other quantities such as LCD impedance, analog-meter SWR and analog-meter impedance are also exposed when the $|\rho|$ calibration control is made available for adjustment. These other adjustments need not be touched to calibrate the instrument for antenna tuner and balun evaluation.

You will need two resistive loads, 25 Ω and 100 Ω, for the calibration. These should be 1%-tolerance resistors with minimal parasitic inductance and capacitance, hence very short leads. Ideally, they should be mounted *inside* a PL-259 connector, but this is not essential. Quarter-watt, metal-film resistors are ideal because they fit inside the center conductor tube of the connector. If you have an AI1H geometric resistance box, the 25-Ω and 100-Ω settings provide adequate test loads, since the test frequency is low, 1.8 MHz. These values of resistance, 25 Ω and 100 Ω, should give a $|\rho| \approx 1/3 = 0.\overline{333}$. From Table 1, the closest we can come to this condition is for the *return loss* reading to equal 9.4 dB. Notice the row shown in bold type.

I recommend that you power the MFJ-259B from ac if you want the calibration to hold. This eliminates possible changes in calibration as the batteries age. Perform the following pretest before removing the back cover of the unit.

1. Turn on the MFJ-259B, enter the "Advanced" mode by simultaneously pushing the **GATE** and **MODE** buttons, and set the unit to display "Return Loss & Reflection Coefficient" by depressing only the **MODE** button once. This provides a simultaneous display of frequency, *SWR*, $|\rho|$ and *return loss*.
2. Set the measurement frequency to 1.8 MHz.
3. Connect the 25-Ω load. Wait one hour. This assures thermal stabilization of the unit.
4. Switch between the 25-Ω and 100-Ω loads and observe the values of $|\rho|$. If they equal 0.33, *0.335* or 0.34 for both loads, adjustment is not necessary. If not, follow the procedure below to achieve this condition.

The calibration procedure is as follows:

1. Remove the back cover by removing eight screws on the sides of the unit. Remove the batteries. Loosen the battery holder by removing two screws. Fig 7 shows an MFJ-259B with the back cover and battery holder removed.
2. Place the battery holder to the side without disconnecting it. Be careful to not let any of the exposed contacts touch the case or any metal parts of the MFJ-259B. You may want to wrap it in a paper towel to help avoid problems.
3. Referring to Fig 7, adjust R53 so that for both the

25- and 100-Ω loads the return loss = 9.4 dB. This may require several iterations. I recommend using a plastic alignment screwdriver, however, this is optional. If you cannot achieve RL = 9.4 dB with both loads, adjust R53 so that both readings are as close to 9.4 dB as possible.[9]

Other Analyzers

The major effort in improving the accuracy of measurements for antenna-tuner and balun evaluation was focused on the MFJ-259B. This emphasis was based on the potential shown by that unit in a comparison of MFJ, AEA and Autek Research analyzers. To be fair, no effort was made to tweak the AEA and Autek Research units to optimize their performance for this application. Some general observations follow.

The measuring instrument used for the measurements back in 1995, when the indirect measurement technique was discovered, was the Autek Research Model RF1 RF Analyst. This instrument displays SWR with two-digit resolution. The unit evaluated (no serial number or firmware version) was "as purchased" and not calibrated for this application. It was powered by a fresh 9 V battery. The accuracy in measuring percentage of power lost was better than 2% for $R_L > 50\ \Omega$; however, for $R_L < 50\ \Omega$ this error was as high as 15%. The two-digit LCD SWR display prevents precise tuning of the antenna tuner, which leads to a tuning error that will be discussed later.

The Model VF1 RX Analyst is a more recent offering by Autek Research. The unit evaluated (no serial number or firmware version) was tested "as purchased." No calibration was performed. A fresh 9 V battery was installed. For this application, this instrument displays only SWR on a three-digit LCD display. The accuracy in measuring percentage of power lost was better than 5%.

The AEA Model CIA-HF Complex Impedance Analyzer is another candidate for making loss measurements on antenna tuners and baluns. One unit (serial #0136, Firmware Revision 1.4) was evaluated. The unit was evaluated "as delivered" and was not calibrated. It was powered by an external power supply. The analyzer displays *SWR* and *return loss*, but not reflection coefficient magnitude. All results are displayed on an LCD. For most values of *SWR* and *return loss*, three significant figures are shown. For loads > 50 Ω, the error in percentage power loss was 4% or better for both *SWR* and *return loss*; however, for loads < 50 Ω, the error was as much as 10%, again for both *SWR* and *return loss*. It is possible that calibration would improve this performance. The resolution was good (three digits), but the instability of the readings made it impossible to capitalize on this feature.

It is clear from the above tests that the MFJ-259B performed better than the Autek Research and AEA products for this application. I calibrated only the MFJ-259B for these tests. It should not be inferred that the MFJ-259B is to be preferred over the other units for general analyzer applications. More recent units might perform better. These devices will improve with time because radio amateurs are becoming more discriminating and aware of their capabilities. Further, the imaginative ham spirit leads us to applications that are more demanding of these analyzers. Fortunately, such improved capabilities continue to be made available at a reasonable cost.

Other instruments of laboratory grade could be used for this application. The "Cadillac" would be an HP (now Agilent Technologies) Network Analyzer. Also the HP 415-series Standing Wave Indicator with an amplitude-modulated signal generator, a return-loss bridge and a square-law detector would do a good job. The HP 415-series is a selective voltmeter (tuned to 1 kHz) calibrated in SWR units, which assumes that the detector has a square-law behavior. I suspect that each of these will beat the MFJ-259B in precision and resolution, although this has not been confirmed.

Other Sources of Error

Limits of Accuracy of the Indirect Method

Every method for measuring losses in antenna tuners is subject to multiple sources of error. An analysis of error sources for the indirect method is described below. Similar analyses should be performed for competing methods.

Eqs 5 and 6 for calculating the loss in decibels and percentage of power lost are approximations. As explained in Note 1 (*QST*, Apr 1995, p 33): "Through computer simulation of many antenna tuners using a wide range of loads, I have found that this method of estimating loss is accurate to within a few tenths of a decibel, assuming that the SWR tester is perfect." In spite of this, there was lingering healthy skepticism about the accuracy of the indirect method, largely because its validity is not obvious.

I have since been sent independent mathematical analyses from Chris Kirk, NV1E, and Kevin Schmidt, W9CF.[10] They both calculated the error inherent in the use of the indirect method by using the scattering matrix formulation. They determined bounds on the error, that is, the worst-case error. For a given situation, the worst-case error may not occur; but the error caused by the use of the indirect method will never be worse than that value. We will call this source of error the "method error."

The antenna tuner will in general be matched at one port: the input port. At the input port, the tuner is adjusted so that $Z_{in} = R_{REF}$, which is nominally 50 Ω. The output impedance, Z_{out} (when the tuner input is terminated in 50 Ω), will be the complex conjugate of Z_L, the load impedance, only if the tuner is loss-less, but we are not measuring loss-less tuners. The source of the error in the indirect method is this mismatch at the output port. How large is this error?

Assuming that the antenna tuner is perfectly tuned, the loads are precise and the *SWR*, $|\rho|$ or *return loss* measurements are perfect, the worst-case method error bounds in decibels and in percentage of power lost are calculated in Eq 7 and 8 below.

Fig 8 shows the worst-case error expressed in decibels as well as percentage plotted against the actual percentage of power lost. Notice that the error in decibels is

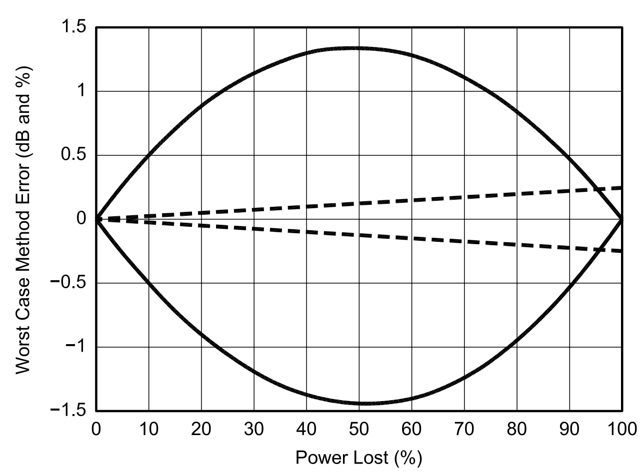

Fig 8—Worst-case method errors for the indirect method. The dashed curves show the bounds for error expressed in decibels. The more useful solid curves define the error bounds in percentage of power lost units.

between –0.26 dB and +0.23 dB when the antenna tuner is absorbing most of the transmitter power. In percentage of power lost, the highest error is between –1.45% and +1.33%, and this occurs when the tuner is absorbing about half of the transmitted power. This means that if perfect instrumentation and measurement skill were applied using the indirect method on a tuner with 50% actual power loss, the loss measurement would be between 48.5% and 51.3%. The worst-case percentage-of-power-lost error goes to zero as the tuner loss goes to either 0 or 100%. *The conclusion is that for all practical purposes, the method error caused by using the indirect method is negligible.*

Why is the method error so low? The error is low because of the use of the geometric averaging of $|\rho_1|$ (halving R_L) and $|\rho_2|$ (doubling R_L). See Eq 6. The process leads to a cancellation of the large first-order error terms, and only a much smaller second-order error term remains. If the loss were calculated without using geometric averaging (by either halving or doubling R_L), the calculated value could be too high by as much as 10.8% or too low by as much as 16%. Halving or doubling R_L can yield either positive or negative errors, and the error bounds are identical for the two cases

One can think of the antenna tuner as an impedance-transforming device. When the loss is low, the impedance ratio at the output will be seen virtually unchanged at the input of the tuner. Hence the error is near zero for low-loss tuners. When the tuner loss is very high, the 50-Ω input impedance of the tuned tuner is mostly made up of lossy elements *within* the tuner. Hence, changes in the load impedance do not much influence the input impedance, and the error is necessarily very low.

Incidentally, Kirk's and Schmidt's analyses showed that with one additional measurement, the error may be found, and hence subtracted. Of course, with such a low worst-case method error, such a correction is unnecessary. Other sources of error will be discussed below.

Initial Setting of Antenna Tuner

When testing an antenna tuner using the indirect method, Step 2 says "Adjust the antenna tuner so that *SWR* = 1:1, $|\rho|$ = 0 or *RL* is maximized." It is not necessary that R_{REF} = 50 Ω exactly, since the tuner behavior will be essentially the same if it is tuned so its input impedance is within a few ohms of that figure. It is important, however, that the input impedance of the tuner be adjusted as close to the analyzer's reference resistance, R_{REF}, (usually near 50 Ω) as possible to get the most accurate results.

We will call the error introduced by imperfect tuning the *mistuning* error. From Kevin Schmidt's S-parameter analysis, the mistuning error bounds in percentage of power lost are estimated in Eq 9 below.

The error in percentage of power lost introduced by imperfect tuning is shown in Fig 9. Notice that the effect of mistuning worsens as tuner loss increases.

With the MFJ-259B, what displayed value should be used, *SWR*, $|\rho|$ or *return loss*? All three parameters were examined in the vicinity of the desired tuned condition. *Return loss* is the most sensitive indicator of the "tuned" condition. The *return loss* reading has to drop from 48 dB to 38 dB before $|\rho|$ changes (from 0 to 0.01) and all the way to 25 dB before the SWR changes (from 1.0 to 1.1). This is a direct result of the two-decimal-digit display limitation for *SWR*, $|\rho|$ and *return loss*. The *return loss* display has more resolution for this measurement and may be used. It turns out, however, that $|\rho|$ has enough resolution to be used as well. For the MFJ-259B, SWR should not be used for this appli-

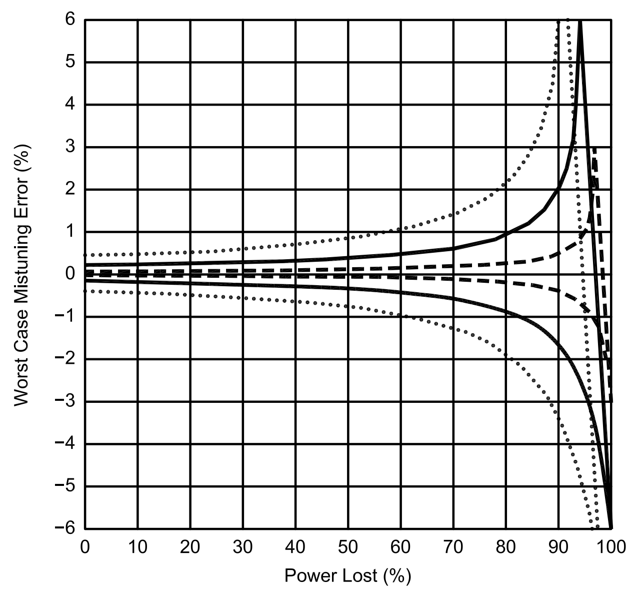

Fig 9—Worst-case error in percentage of power lost introduced by imperfect tuning. The dashed, solid and dotted lines show the error bounds for $|\rho_{in}|$ = 0.01, 0.02 and 0.03, respectively.

$$5\log\left(\frac{8+10^{\frac{-L_{ACTUAL}}{10}}}{9}\right) \le MethErrdB \le 5\log\left(\frac{10-10^{\frac{-L_{ACTUAL}}{10}}}{9}\right) \quad \text{(Eq 7)}$$

$$(100-P_{LOST})\left[1-\left(1-\frac{P_{LOST}}{900}\right)^{-\frac{1}{2}}\right] \le MethErr\% \le (100-P_{LOST})\left[1-\left(1+\frac{P_{LOST}}{900}\right)^{-\frac{1}{2}}\right] \quad \text{(Eq 8)}$$

where

L_{ACTUAL} = the actual antenna tuner loss in decibels,

P_{LOST} = percentage of power lost, and

MethErrdB and *MethErr%* = the method error in decibels and percentage, respectively.

cation because of the poor SWR resolution.

The best technique is to adjust the antenna tuner to achieve an SWR_{in} near 1:1 on the analog meter. Then look at the LCD indication of RL_{in} and $|\rho_{in}|$ and continue tuning for maximum *return loss*. *If* $|\rho_{in}| \le 0.02$, *then the error due to mistuning for low-loss tuners is less than 0.2%. The error grows to about 1.2% as the percentage of power lost increases to 85%.* For higher percentage-of-power-lost values, the error gets larger but never higher than 6%. For all practical purposes, this degree of accuracy is sufficient.

In some cases, the $|\rho_{in}| \le 0.02$ condition cannot be achieved. One reason is that the antenna tuner is difficult

$$(100-P_{LOST})\left[1-\left|1+\frac{90000|\rho_{in}|^2}{(100-P_{LOST})^2}\right|^{\frac{1}{2}}\right] \le MTErr\% \le (100-P_{LOST})\left[1-\left|1-\frac{90000|\rho_{in}|^2}{(100-P_{LOST})^2}\right|^{\frac{1}{2}}\right] \qquad \text{(Eq 9)}$$

where

$MTErr\%$ = the mistuning error in percentage,

ρ_{in} = the input reflection coefficient due to imperfect tuning, and

P_{LOST} = percentage of power lost.

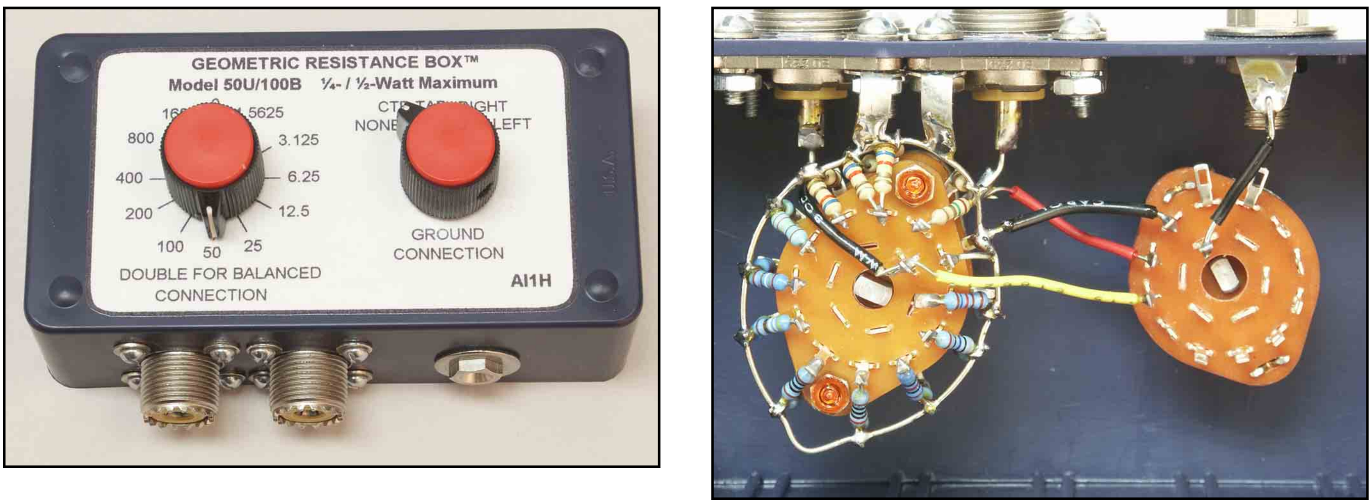

Fig 10—The AI1H geometric resistance box. It is designed to provide both unbalanced and balanced resistive loads.

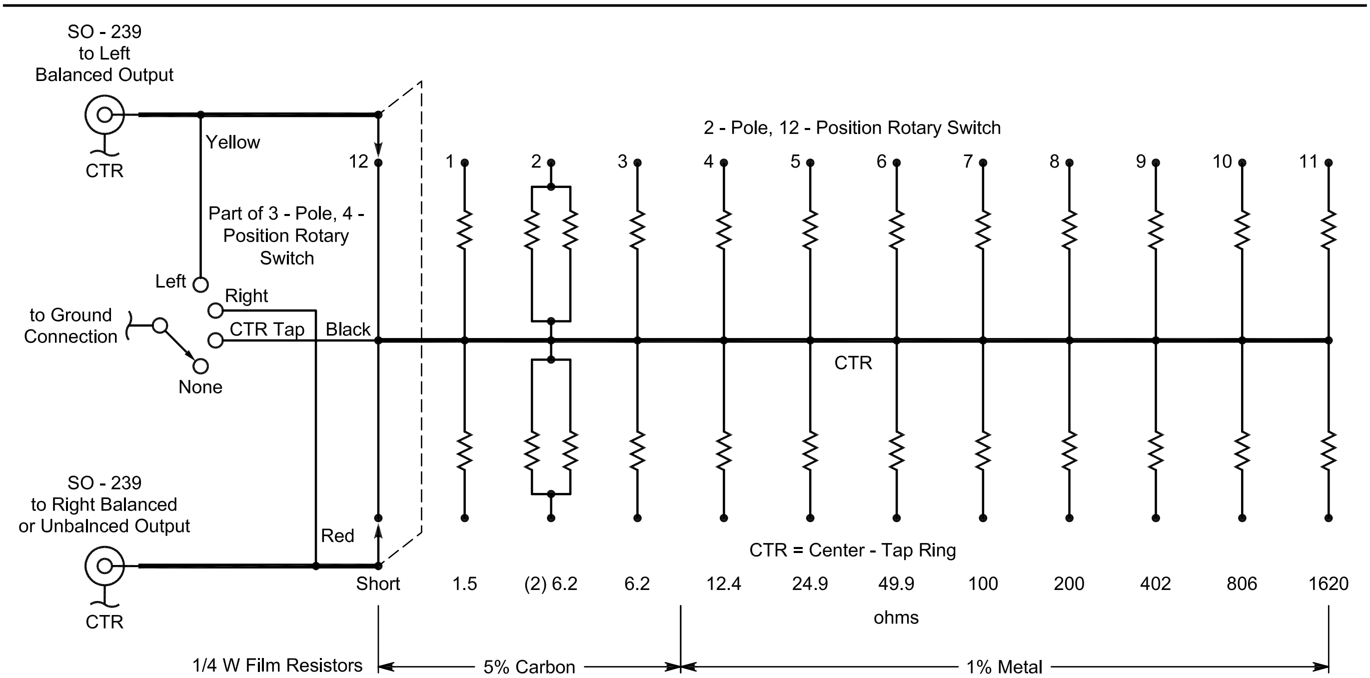

Fig 11—Schematic diagram of the AI1H geometric resistance box.

or impossible to tune for the particular load being used. Another is that the antenna tuner is made up of switched and variable components, and precise tuning ($Z_{in} = R_{REF}$) is not possible. This problem can be overcome by first tuning the unit as close as possible to the $|\rho_{in}| \le 0.02$ condition. Then insert a low-loss tuner with continuous-tuning capabilities between the tuner under test and the analyzer. The low-loss tuner is then tuned to achieve the $|\rho_{in}| \le 0.02$ condition. The loss calculation is then the sum of the loss of the two tuners. Most antenna tuners will perform well as the second tuner since they are simply transforming impedances near R_{REF} to R_{REF}.

Another potential problem is that the harmonic content of the analyzer signal source is excessive. When the analyzer is connected to a frequency-independent load impedance equal to R_{REF}, the *SWR*, $|\rho|$ and *return loss* are the same at the fundamental and at harmonics of the source, so the $|\rho_{in}| \le 0.02$ condition is easily achieved. However, when the analyzer is connected to the input of a tuned antenna tuner, the load impedance equals R_{REF} only at the fundamental frequency. At harmonics of the fundamental frequency, the mismatch is huge, so harmonic signal energy will disturb the reading.

The MFJ-259B contains a sufficiently clean generator so that the $|\rho_{in}| \le 0.02$ condition is achieved. *The conclusion is that when the signal generator has little harmonic content, mistuning error is a minor error contributor.*

Accuracy of Load Resistance

An advantage of the indirect method for evaluating antenna tuners and baluns is the simple way in which the resistive loads are obtained. A geometric resistance box provides the load resistors and a rotary switch. The physical layout is such that *the parasitic inductance and capacitance of the short connecting leads do not change when the load resistance is changed.* The parasitic inductance and capacitance become a part of the tuner being tested, and have a negligible effect on the test result.

The geometric resistance box was described in the article of Note 1. There were two boxes, one for unbalanced measurements and one for balanced measurements. I have combined these two into a single box, which is pictured in Fig 10. The schematic diagram is shown in Fig 11. Notice that most of the resistors are ¼ W, 1% metal-film units. For the lesser values, only 5% carbon-film resistors are available, so the desired tolerance is achieved by selection. In addition to the switched resistors, a switch is included for balance quality evaluation.[11]

The absolute value of the load resistance, R_L, does not contribute to the error. The change in tuner loss for a ±5% variation in R_L is negligible. What is important, however, is the error due to imperfect ratios of adjacent loads, since Eqs 5 and 6 are based on an assumed ratio of two. Eq 6 can be generalized to include ratios other than two:

$$P_{LOST} = 100\left(1 - \frac{r+1}{r-1}\sqrt{|\rho_1\|\rho_2|}\right) = 100\left(1 - \frac{\sqrt{|\rho_1\|\rho_2|}}{|\rho_L|}\right) \qquad \text{(Eq 10)}$$

where

r = the geometric ratio, or the ratio of the resistances of adjacent load resistors, and

$|\rho_L|$ = the load-box reflection-coefficient magnitude.

What is the error introduced when $r \ne 2$ because of the tolerance of the load resistors? An analysis reveals that the worst-case error due to load resistance tolerance in percentage of power lost is given by:

$$\frac{4t}{300}\left(P_{LOST} - 100\right) \le TolErr\% \le \frac{4t}{300}\left(100 - P_{LOST}\right) \qquad \text{(Eq 11)}$$

where

t = the tolerance of the load resistors in percentage, and

TolErr% = error due to load resistance tolerance in percentage.

A subtle factor-of-two error reduction occurs by using the $2R_L$ and $R_L/2$ settings in the measurement process. In effect, the tolerance of R_L, the center setting causes an error in the $2\times R_L$ setting, which is offset by an error of the opposite sign when switching to $R_L/2$. *Thus for ±1% resistors, the worst-case error is only 1.33%, and this occurs for the loss-less tuner. The error from this source goes linearly to zero as the percentage of power lost increases to 100%.* See Fig 12.

If the application required it, this error could be reduced by resistor selection. The resistors cost only a few cents each. Another alternative that can essentially remove the resistor tolerance error completely is to calibrate the geometric resistance box at dc with the aid of a precision digital multimeter. The various load resistors are measured and the value of $|\rho_L|$ for each R_L is calculated from:

$$|\rho_L| = \sqrt{\frac{R_{ABOVE} - R_L}{R_{ABOVE} + R_L} \cdot \frac{R_L - R_{BELOW}}{R_L + R_{BELOW}}} \qquad \text{(Eq 12)}$$

where

R_{ABOVE} = the resistance value above R_L, which is very close to $2\times R_L$, and

R_{BELOW} = the resistance value below R_L, which is very close to $R_L/2$.

The value of $|\rho_L|$ is substituted into Eq 10 to find P_{LOST}. The same calibration procedure should be applied for unbalanced and balanced loads.

Human Error

As with any measurement process, the skill of the person performing the measurement is important. Fortunately, the indirect method is simple to apply. Lots of data can be obtained in a relatively short period of time, so the data should be processed in an orderly way. I like to use special forms that are designed for the application. The calculations are simple and can be made with a scientific calculator like the one included with Microsoft *Windows*.

Most antenna tuners have redundant tuning adjustments. For example, the popular CLC T topology has three

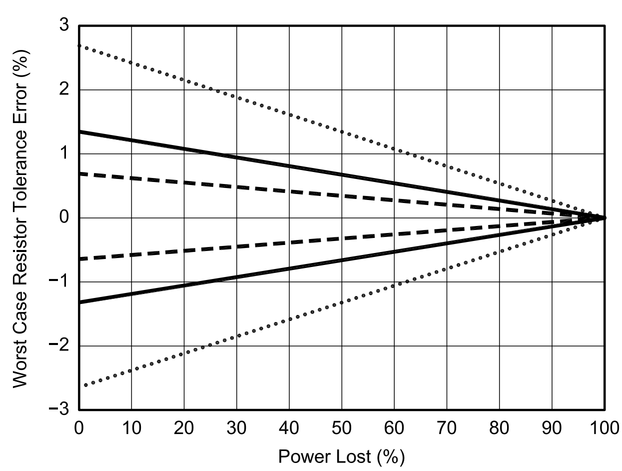

Fig 12—Worst-case error in percentage of power lost introduced by the tolerance of the load resistors. The dashed, solid and dotted lines show the error bounds for resistors with tolerance values of 0.5%, 1% and 2%, respectively.

adjustments, but one can be set and the other two adjusted for the $Z_{in} = R_{REF}$ condition. This means that there are an infinite number of settings that will achieve this condition. If we make a loss measurement with a particular load at a particular frequency, then make some measurements with other loads and frequencies, and then try to repeat the original measurement, chances are good that the result will be different. One reason is that the tuner adjustments have some play, and an earlier setting is difficult to duplicate. Unless great care is taken, there is a high likelihood that the error from this effect will be greater than the other errors discussed thus far, especially when the SWR bandwidth is small or the loss is high.

Human error is common to all methods for evaluating antenna tuners and baluns.

Total Worst-Case Error

Fig 13 shows the bounds on error for percentage power lost between 0 and 90% exclusive of measurement instrument error and human error. It includes method error, mistuning error and load resistance tolerance effects. It assumes that $|\rho_{in}| \leq 0.02$ and the tolerance of the resistors is 1%. *The maximum worst-case error from these causes is only about 2.5%. This is entirely acceptable for evaluating tuners and baluns.*

Incidentally, these are worst-case errors. The worst-case errors from several causes were added up to get the total worst-case error. The actual error will usually be much less than the worst-case error.

Balanced Output Evaluation

In the original article describing the evaluation of antenna tuners (Note 1), a method was presented for evaluating the balance quality of antenna tuners. An improved interpretation of the balance measurement was presented in the balun evaluation paper[12] and will be summarized here. This method is applicable to the evaluation of antenna tuners with a balanced output port.

Ideally, a balanced antenna tuner with a balanced load whose center tap is grounded should force equal currents (equal in magnitude and phase, but opposite in direction) to flow in each leg of the load. Let's define these currents as I_1 and I_2. If we have the ideal situation, $I_1 = I_2$. In general, the current flowing from the center tap to ground is $I_1 - I_2$ which ideally should be zero. Hence an excellent measure of the balance quality is "imbalance" or IMB, which is defined as:

$$IMB = \frac{\text{Current flowing from center tap}}{\text{Average current in the balanced load}} \qquad \text{(Eq 13)}$$

$$IMB = 2 \times \left| \frac{I_1 - I_2}{I_1 + I_2} \right| \qquad \text{(Eq14)}$$

Thus, if *IMB* is zero, the balun in the antenna tuner is doing its job.

IMB has physical significance in an antenna system. For example, if the balanced tuner's load is a balanced antenna fed with a balanced feed line, the common mode radiation from the feed line can be derived from *IMB*.

A good estimate of the imbalance for tuners with current baluns can be found by connecting a balanced geometric resistance box to the balanced output terminals of the tuner. The switchable center tap lead is connected to the tuner ground terminal. The imbalance test is performed as follows:

1. Adjust the antenna tuner for $SWR = 1$ or $|\rho| = 0$ or maximized return loss when the center tap is floating.

2. Ground the center tap and observe the value of SWR, $|\rho|$, or return loss which we will call S_B, $|\rho_B|$ or RL_B, respectively.

3. For antenna tuners with 1:1 baluns, calculate an estimate of the imbalance, *IMB*, from:

$$IMB = 2(S_B - 1) = 4\frac{|\rho_B|}{1-|\rho_B|} = \frac{4}{10^{RL_B/20} - 1} \qquad \text{(Eq15)}$$

4. For antenna tuners with 4:1 baluns, calculate an estimate of *IMB* from:

$$IMB = 4(S_B - 1) = 8\frac{|\rho_B|}{1-|\rho_B|} = \frac{8}{10^{RL_B/20} - 1} \qquad \text{(Eq16)}$$

The measurement of imbalance requires no setup beyond that required for measuring the tuner loss. It simply requires noting the value of *SWR*, $|\rho|$ or *return loss* when the center tap of the load is grounded. Although Eqs 15 and 16 are most accurate for current baluns, they may be used for voltage baluns as well.

Comparison of the Direct and Indirect Methods

The direct method for determining antenna tuner loss is, in concept, very straightforward, but can be done in a variety of ways. The best accuracy can be achieved with a laboratory-grade network analyzer. This test equipment has a built in signal source, a calibrated "standard" attenuator, which operates at a fixed frequency, and a detector. The device under test, in our case the antenna tuner, is inserted between the two ports of the analyzer. The analyzer measures return loss and insertion loss, so both tuning and loss measurement can be performed. Most network analyzers are designed to operate in a 50-Ω unbalanced impedance environment.

For an unbalanced tuner terminated in a 50-Ω load, the measurement is a piece of cake. The problem arises when the load is not 50 Ω or the load is not balanced. Of course, we want to evaluate our antenna tuners for non-50-Ω loads. A simple way to overcome this problem is to construct a set of minimum-loss resistive pads that match the desired load resistances to 50 Ω. These must be calibrated, of course, and this can be done with the network analyzer. The pad is connected to the output of the tuner so that the desired

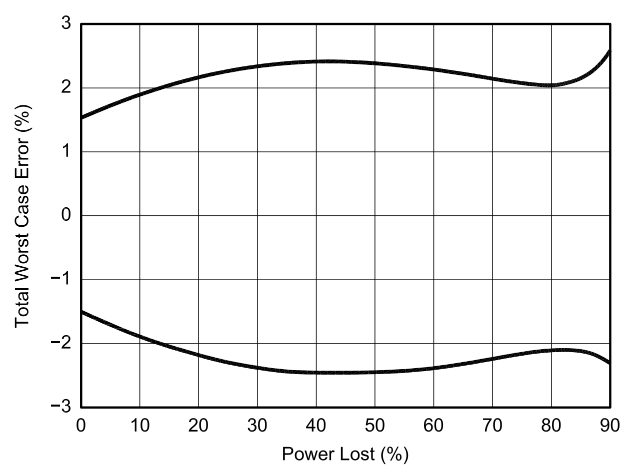

Fig 13—Total error bounds for all causes except for measurement instrument inaccuracy and human error. This includes method, mistuning and load-resistance tolerance effects. It assumes that $|\rho_{in}| \leq 0.02$ and the tolerance of the load resistors is 1%.

R_L is achieved, and the combination tuner/pad is tuned and measured. The tuner loss is the measured loss minus the loss of the resistive pad.

The loss of antenna tuners with balanced outputs can be measured directly in a similar way, but the resistive pad design would be more complicated. The pad would be a balanced pad matching the load resistance to 100 Ω. Half of the 100-Ω resistance is a 50-Ω resistor and the other half is the 50-Ω input impedance of the analyzer, so the center tap of the load is grounded. Some indication of balance quality can be obtained by swapping the connection leads at the output of the antenna tuner. If the loss is unchanged, the balance quality is very good.

Theoretically, a simple implementation of the direct method would be to use a power source and two reflected-power meters, one at the input of the tuner and the other at the output of the tuner. At the input to the tuner, the reference resistance of the meter would need to be 50 Ω so that the tuner can be tuned (displayed reflected power equals zero). At the output of the tuner, a reflected-power meter with any reference resistance could be used between the tuner and the load impedance. The input power is the forward power displayed on the input power meter. The output power for the loss calculation is found by subtracting the displayed reflected power value from the displayed forward power value on the output power meter.

For balanced loads, the center tap of the load is grounded. Two output power readings are taken: one for each half load. A measure of the balance quality is how closely the two readings match. Unfortunately, the accuracy of the reflected-power meters available on the Amateur Radio market makes this method unattractive at this time.

A variety of other implementations of the direct method are possible. The direct method with a network analyzer and calibrated pads will yield very accurate loss measurements if done properly and could be considered the "gold standard" when making comparisons with other approaches, both direct and indirect. Extreme care must be exercised to be sure the antenna tuner settings are not disturbed when the different measurement schemes are applied. I have seen the settings change if the table on which the tuner is resting is bumped.

When other methods are compared with the indirect method, the same kind of detailed analysis of the error sources as summarized here for the indirect method should be performed. One variation of the direct method was employed in the evaluation of five antenna tuners. (See Note 5.) It involved the use of a laboratory-grade wattmeter, a switchable power attenuator and a number of non- inductive 50-Ω power resistors mounted in suitable fixtures so that they could be connected in series or in parallel. The source was a 100-W transmitter. The 50-Ω resistors had a tolerance rating of 5%. This approach provides a suitable load for the antenna tuner. However, a part of the composite load was made up of the input impedance of the power attenuator, so a loss contributor resulted from this division of power. The wattmeter and attenuator accuracy and the stability of the output power of the source are all potential error sources. All of these loss error contributors must be included in the worst-case error analysis.

All of the above direct methods involve swapping equipment and/or load resistors. Hence, the measurements are tedious and take more time than those required with the indirect method.

Summary

In terms of cost, speed and convenience, the indirect method is hard to beat. A very wide range of loads is provided. Evaluation with complex impedance loads is possible. Evaluations of antenna tuners with balanced outputs are as easy as those made on tuners with unbalanced outputs. In addition, balance quality is easy to find with the indirect method.

Improvements in the MFJ antenna analyzer have made the indirect method for evaluating antenna tuners and baluns very competitive with other methods for doing the same job. A careful characterization of the MFJ-259B has shown that the LCD readout of reflection coefficient magnitude (rather than SWR or return loss) provides adequate accuracy for this application.

I am grateful to Chris Kirk, NV1E, and Kevin Schmidt, W9CF, who each independently performed the mathematical analyses using the scattering matrix to determine the accuracy potential of the indirect method. I am indebted to Chris Kirk who offered valuable corrections and suggestions. Kevin Schmidt offered favorable comments as well.

Notes

[1] F. Witt, AI1H, "How to Evaluate Your Antenna Tuner," *QST*, Apr 1995, pp 30-34 (*Part 1*) and May 1995, pp 33-37 (*Part 2*).

[2] F. Witt, AI1H, "Baluns in the Real (and Complex) World," *The ARRL Antenna Compendium*, Vol 5, (Newington: ARRL 1996), pp 171-181.

[3] "*QST* Compares: Four High-Power Antenna Tuners," *QST*, Mar 1997, pp 73-77.

[4] *TLW* is bundled with the 19th edition of *The ARRL Antenna Book*.

[5] "*QST* Reviews Five High-Power Antenna Tuners," *QST*, Feb 2003, pp 69-75. The Ameritron Model ATR-30 is an example of an antenna tuner design that benefits from more enlightened design concepts.

[6] F. Witt, AI1H, "SWR Bandwidth," *The ARRL Antenna Compendium*, Vol 7, (Newington: ARRL 2002), pp 65-69.

[7] Dan Maguire, AC6LA, "**T**-Time for the Analyzers." *The ARRL Antenna Compendium*, Vol 7, (Newington: ARRL 2002), pp 40-49.

[8] The mathematical analysis, data processing and graphs for this article were done with the aid of *Mathcad*. See: W. Sabin, WØIYH, "*Mathcad* 6.0: A Tool for the Amateur Experimenter," *QST*, Apr 1996, pp 44-47.

[9] A refinement of this process takes advantage of the excellent resolution of the return-loss display in this region. The 25-Ω and 100-Ω resistors are measured with a precision digital multimeter. The target reflection-coefficient magnitudes are calculated by assuming R_{REF} of the MFJ-259B is 50 Ω. Then Table 1 is used to convert these into target *return-loss* values. This mapping between $|\rho|$ and *return loss* may be different for other software versions, so Table 1 should be checked if the version is not 2.02.

[10] Private communication.

[11] Model 50U/100B Geometric Resistance Boxes (as pictured in Fig 10) are available from the author. The units are completely assembled and tested and come with the necessary test leads, adapters and forms for recording the data.

[12] F. Witt, AI1H, "Baluns in the Real (and Complex) World," *The ARRL Antenna Compendium*, Vol 5, (Newington: ARRL 1996), p 179.

Frank was first licensed in 1948 and has held the calls W3NMU, K2TOP, W1DTV and EI3VUT. He holds BS and MS degrees in Electrical Engineering from Johns Hopkins University and is a Life Member of the IEEE. He is retired from AT&T Bell Telephone Laboratories where he worked for 37 years. He is one of five hams in his family: Barbara, N1DIS; Mike, N1BMI; Chris, N1BDT; and Jerry, N1BEB.

Frank's novel Amateur Radio contributions include the top-loaded delta loop, the coaxial-resonator match, the transmission-line resonator match and the geometric resistance box. He is a recipient of the ARRL Technical Excellence Award and serves as ARRL Technical Advisor. His other interests include golf and tennis. □□