HEWLETT hp PACKARD

SWEPT SWR TESTS IN X-BAND COAX

application note 66

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INTRODUCTION

BACKGROUND

Swept frequency testing has proven to be an important economic and technical tool in the microwave field. Such tests allow complete broadband plots or displays of reflection coefficient (ρ) over several gigacycles in a fraction of the time required for only a few point-by-point SWR tests with slotted lines. The conventional reflectometer was made practical by high directivity waveguide directional couplers such as the hp 752 series. Using these couplers, waveguide reflectometer systems have steadily been improved by new leveled sweep oscillators such as the hp 690 series and flat crystal detectors with good square-law response.

Swept frequency tests are equally important in coaxial systems since most coax microwave devices operate over frequency bands equal to, or greater than, their waveguide counterparts. Progress in coaxial reflectometers has been limited above 4 Gc by the low directivity of coax directional couplers designed for the higher frequency ranges. Typically, this directivity is only 15 db in the X-band region, and few coax couplers cover the entire 8.2 to 12.4 Gc band.

REFLECTOMETER ERRORS

Let's briefly consider how the directivity of a coupler affects the uncertainty in a reflectometer measurement. Figure 1a shows the essential components of a coax reflectometer setup using a leveled sweep oscillator. A small portion of the sweep oscillator output is coupled from port 1 to port 2 for leveling feedback information. The main portion of the output signal passes from port 1 to 4 where the test device is connected. If the reverse coupler has infinite directivity, the output from port 3 consists only of the signal reflected by the test device. The reflected voltage may be represented by a vector E_r as shown in Figure 1b.

The value of E_r relative to the voltage level at port 3 for a 100% reflection is given by the return loss expression: $-db = 20\log_{10}\rho$, relating the true reflection coefficient of the test load.

If the coupler does not have infinite directivity, part of the forward signal passing from 1 to 4 couples to port 3 and combines with E_r in random phase. This directivity signal may be represented by vector E_d. The measured value at port 3 is the vector sum of E_r and E_d. Since the phase relationship of the individual components is unknown, there is an uncertainty in the measurement of E_r and, therefore, in the measurement of ρ.

The uncertainty due to reverse coupler directivity may be calculated from the return loss equation as follows:

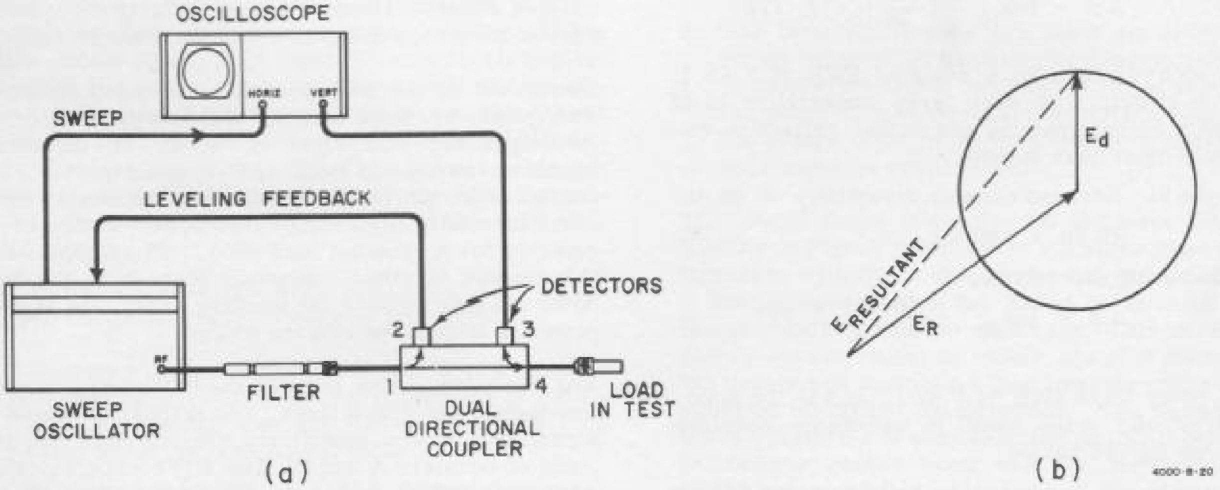

Figure 1. (a) Leveled Coaxial Reflectometer
(b) Vector Diagram of Voltage Components Comprising Signal at Port 3 of Coaxial Reflectometer

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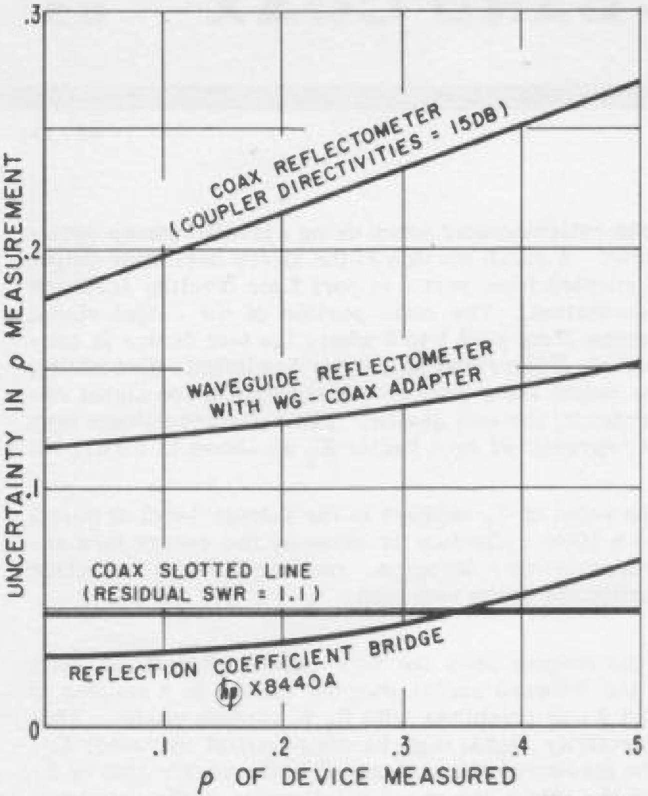

Figure 2. Uncertainty of various reflection coefficient (ρ) measuring techniques vs actual ρ of device in test. Curves are typical for coaxial systems at X-band frequencies.

Example 1: Reverse coupler directivity = 15 db

$$15 \text{ db} = -20 \log_{10}\rho$$

Transposing and solving,

$$\Delta\rho = \log_{10}^{-1}\left(\frac{-15}{20}\right) = \pm .178$$

This is equivalent to a residual SWR of 1.43:1. Clearly a system with such large uncertainty is of little value in determining the actual reflection coefficient of most coax devices.

Example 2: Reverse coupler directivity = 40 db

$$40 \text{ db} = -20 \log_{10}\rho .$$

Transposing and solving,

$$\Delta\rho = \log_{10}^{-1}\left(\frac{-40}{20}\right) = \pm .01$$

This is equal to an SWR of 1.02:1, and is the maximum directivity error found in waveguide couplers such as the hp 752 series.

If one were to use a waveguide reflectometer for its high directivity with a waveguide-to-coax adapter for connecting the device in test, the reflection of the adapter would add in random phase with the true reflection of the coax device. In this case, the uncertainty would depend primarily on the adapter ρ which is typically .11 or an SWR of 1.25:1. Because of reflection between the coax device and waveguide-to-coax adapter, a secondary term, $.11\rho^2$ is added to the uncertainty. Thus, the overall expression for uncertainty becomes $.12 + .01\rho + .11\rho^2$ where ρ = reflection coefficient of the device in test. This is still too large for most coax applications.

A DIFFERENT APPROACH

A unique approach to accurate swept-frequency testing in coax has been taken in the design of the hp X8440A REFLECTION COEFFICIENT BRIDGE. The bridge uses waveguide couplers for their high directivity and effectively cancels the waveguide-to-coax adapter reflection by a balancing scheme. Using a leveled 694A/B sweep oscillator and appropriate readout equipment, the X8440A measures ρ in coax over the complete 8.2 to 12.4 Gc band with an uncertainty of $\pm(.03 + .16\rho^2)$ or less; better accuracy than even a slotted line in the majority of applications. Figure 2 plots the uncertainty in ρ measured versus ρ of the device in test, for the various techniques discussed. Remember, the slotted line is not a swept-frequency device; however, its uncertainty is included for an overall comparison.

ACCURATE SWEEP TESTING IN COAX - 8.2 TO 12.4 GC

Figure 3 shows the bridge configuration with a leveled sweep oscillator and necessary detection and readout equipment connected. The bridge itself consists basically of four 10-db waveguide directional couplers, four 90° waveguide twists and two waveguide-to-coax adapters. The basic idea of the bridge is to balance out the residual reflection of the measuring arm adapter with an equal amplitude, but opposite phase reflection from the balancing-arm adapter. Any reflection from a test device connected to the measurement arm then causes a differential signal to appear at the detector. The amplitude of the differential signal is directly proportional to the reflection coefficient of the test device connected. The oscilloscope (or X-Y recorder) thus indicates reflection coefficient versus frequency independent of the adapter SWR.

Power out of the sweep oscillator is fed through a waveguide-to-coax adapter and low pass filter to a leveling array comprised of two 10-db directional couplers, waveguide load, and crystal detector. This configuration provides a good source impedance match and essentially maintains level power at the bridge detector for a constant load SWR. The calibration of the readout is, thus, constant throughout the band. After passing through the leveling array, the sweeper power is introduced into the bridge.

The two signal paths through the bridge are shown by the dashed and dotted lines. The dotted line shows the signal path to the measuring arm through the main guide of couplers A and D. Two 90° counterclockwise waveguide twists rotate the E field by a total of 180° as the signal passes from coupler A to D. Any signal reflected by the X281A waveguide-to-coax adapter at the measuring arm is coupled back through couplers D and C to the X424A Detector.

The dashed line shows the other signal path from coupler A to the balancing arm through coupler B. The

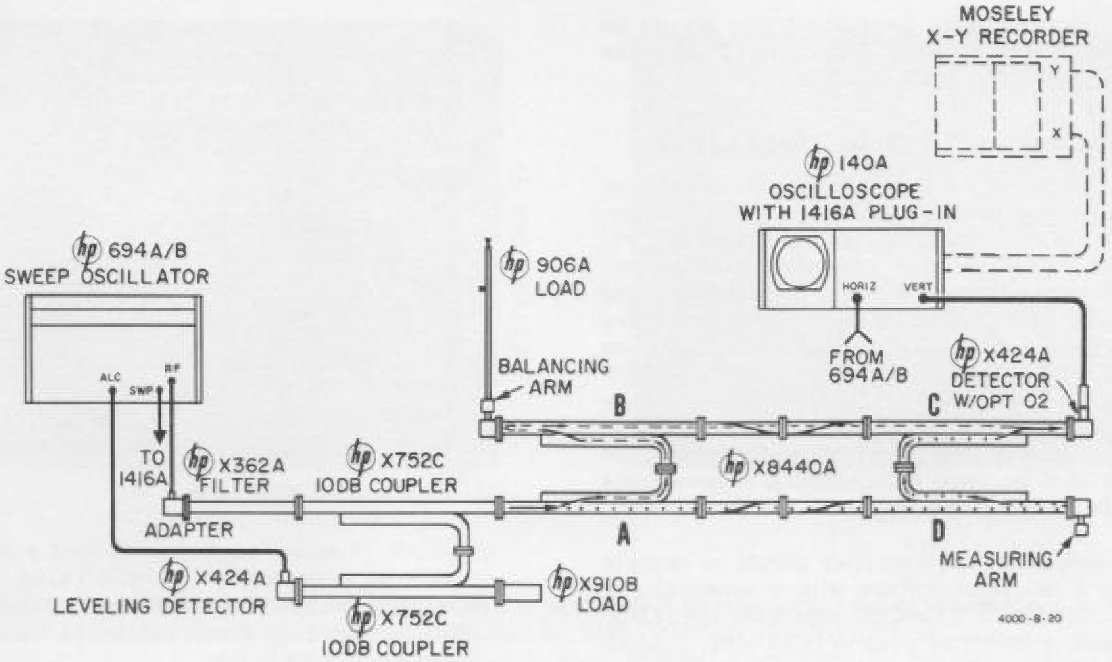

Figure 3. Reflection Coefficient Bridge with source and readout equipment connected for use. Dashed and dotted lines show the two signal paths from leveled sweep oscillator to bridge detector (connected to oscilloscope). Oscilloscope presents continuous display of reflection coefficient versus frequency for coax device connected to bridge measuring arm.

X281A adapter at the balancing arm is carefully impedance matched with the measuring arm adapter and terminated by a low reflection load[1] (906A).

The reflection from the balancing arm adapter is thus proportionately equal in magnitude to the reflection of the measuring arm adapter. The signal then passes through the main guide of couplers B and C through another pair of waveguide twists. These twists rotate the E field first 90° counterclockwise, then 90° clockwise for a net phase shift of zero degrees. The signal then combines in coupler C with the signal from the measuring arm and the X424A detects their vector sum. If the two signals are equal in magnitude and 180° out of phase, the detector output will be zero, effectively cancelling the ambiguity of the adapter ρ .

The following conditions are implemented by the X8440A to cancel residual adapter reflections:

1. The coupling factors of A and C are closely matched as are the coupling factors of B and D. Total attenuation through the couplers is thus nearly equal for both signal paths.
2. The impedances of the X281A adapters are selected and matched so the signals reflected from each arm are proportionately equal.
3. The twist arrangement results in the two signals being 180° out of phase.
4. Twists are used in the zero phase shift leg (dashed line) instead of straight waveguide to keep the cutoff characteristics equal in both paths. Straight waveguide exhibits a slightly different phase shift with frequency than twisted guide and would result in an error-producing shift, relative to the dotted line signal path.
5. The two path lengths are made equal by placing shims between the auxiliary arm waveguide flanges of couplers A and B or C and D. This assures that the phase of both signals transforms equally from the bridge input to the detector and phase difference remains close to 180°.

The small boxes appearing on the coax side of the X281As in Figure 3 represent stainless steel adapters furnished with the bridge to convert the standard type N female connector of the X281A to either a male or female type N precision connector. This arrangement allows measurement of either sex of N connector on the bridge and provides a long wearing connector with superior electrical performance. The impedances of these adapters are also selected and matched so their reflections cancel along with the reflections of the X281As.

The accuracy of the X8440A depends not only upon the matching of directional couplers and adapters, but also in large measure upon the technique and care of assembly. All bridge components are bolted together at the waveguide flanges and sealed against arbitrary disassembly which would impair bridge accuracy.

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[1] Coaxial load is not furnished with the X8440A.

The bridge is a precision instrument that should be handled with care to prevent bending or denting the waveguide components.

SYSTEM CALIBRATION AND OPERATION

System calibration is accomplished much the same as for a leveled reflectometer. Readout can be on an oscilloscope for a continuous display of reflection coefficient or plotted with an X-Y recorder. The continuous oscilloscope display is ideal for making rapid measurements with good accuracy on large quantities of coax devices or for making adjustments to a coax device while observing the effects on broadband performance. The X-Y recorder is used where either greater resolution or a low cost permanent record is needed, and speed is less important. An oscilloscope camera can also be used for obtaining a permanent record of the oscilloscope display.

The oscilloscope vertical amplifier should be capable of accepting a DC input voltage with a sensitivity of 100 μv/cm. The hp 140A Oscilloscope with type 1416A Swept Frequency Indicator plug-in is an ideal readout device for this application since it provides the necessary sensitivity, stable DC input amplifiers and resolution along with direct calibration in db of return loss. Convenient outputs are included in the 1416A for driving an X-Y recorder also.

The bridge must be calibrated for use with the same precision coax adapters as will be used in the actual measurements, e.g., when checking devices with male type N connectors, both arms of the bridge must have the male-to-female precision N adapters installed prior to calibration. Any time these adapters are removed or interchanged with the pair of male-to-male adapters, system calibration should be rechecked. Always connect the gold-colored end of the adapters to the bridge arm.

Set up the equipment as shown in Figure 3. When using the male adapters, use the .071 inch female center conductor and short thread outer conductor in the 906A, making sure it is well seated in the balancing-arm connector. When using the female adapters, use the .065 inch male center conductor and unslotted outer conductor supplied with the 906A termination. Adjust the Sweep Oscillator for a leveled RF output sweeping from 8.2 to 12.4 Gc.

DB RETURN LOSS READOUT ON HP 140A/1416A OSCILLOSCOPE

1. Make initial adjustments on 1416A for LOG display as described in instrument Operating and Service Manual.
2. With bridge measuring arm open circuited, increase sweeper ALC control for maximum leveled RF output without lighting 1416A SQUARE-LAW LIMIT indicator. Adjust VERTICAL POSITION for a reference trace at the top graticule line.
3. Connect the coax short (supplied with X8440A) to the bridge measuring arm and note trace deviation from the reference graticule line. Adjust 1416A VERTICAL POSITION as required so the mean of the open and short circuit display falls over the reference line.[2] The display is now calibrated in DB RETURN LOSS/CM.

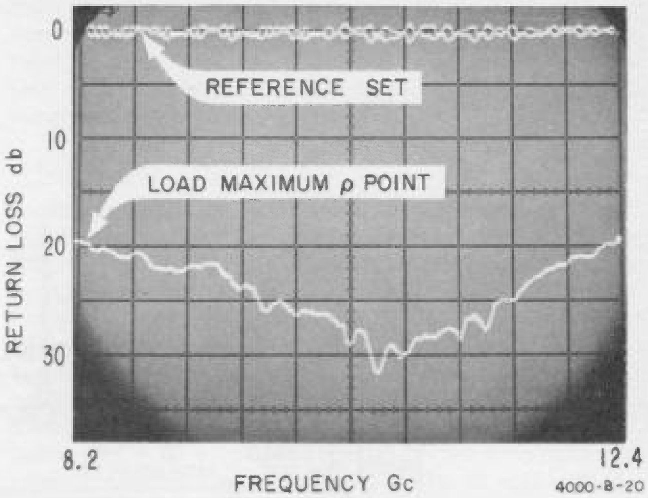

Figure 4. Continuous display of load ρ versus frequency presented on hp 140A/1416A Oscilloscope and Swept Frequency Indicator. Multiple exposure shows reference traces (upper) and load in test.

Example 1. Measuring ρ of Coaxial Termination (Refer to Figure 4)

a. Connect test load to bridge measuring arm.

b. Read db return loss (decrease from reference line) at point of interest. In this example, maximum ρ is the desired point and return loss is noted to be 20 db.

c. Use hp Reflectometer Calculator[3] for direct conversion of db to ρ or calculate using the equation

$$\rho = \log_{10}^{-1}\left(\frac{-\text{db return loss}}{20}\right) \text{ as follows:}$$

$$\rho = \log_{10}^{-1}\left(\frac{-20\text{ db}}{20}\right) \text{ or } .10 .$$

The 1416A vertical sensitivity may be increased in calibrated steps from 10 db/cm up to 0.5 db/cm for

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[2] Small reflections within the bridge plus differences in the two detectors and coupling coefficients of the leveling couplers and bridge couplers can cause the mean to deviate from a straight line. In most cases, the deviation is less than ±0.3 db. If the deviation is large, its effects can be calibrated out on the oscilloscope face by tracing the mean with a grease pencil.

[3] The hp Reflectometer Calculator is a slide rule type aid that allows direct conversion between db return loss, reflection coefficient, and SWR without calculations. The calculator also provides other useful microwave data and is available on request from your hp field engineer or hp sales office.

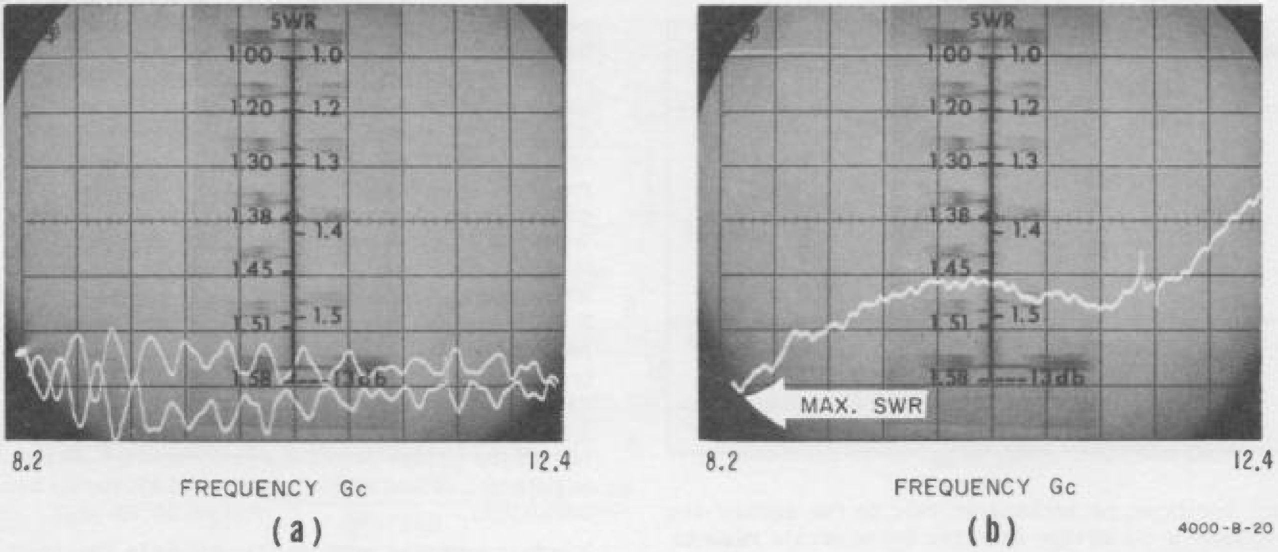

Figure 5. Oscilloscope display of hp X8440A Bridge output for (a) short then open circuit at measuring arm, vertical sensitivity 2 mv/cm; (b) coaxial attenuator in test, vertical sensitivity 0.1 mv/cm.

higher resolution as desired. Return loss may also be read with high resolution from a calibrated 3-turn control on the 1416A.

Calibrated markers in the hp 694A/B sweep oscillator may be used for accurate frequency location of discontinuities displayed on the CRT. This is done by depressing the MARK 1 (or MARK 2) button on the 694A/B and adjusting the corresponding marker frequency until the notch produced on the display is coincident with the point of interest. The frequency of interest is then read directly from the calibrated marker dial on the 694A/B.

VOLTAGE READOUT WITH OSCILLOSCOPE

This procedure applies when using a conventional oscilloscope with a linear vertical input system such as the hp 140A/1400A. Special oscilloscope graticule scales are available[4] for direct readout in SWR, eliminating calculation.

1. With the 694A/B LINE in STANDBY, set up oscilloscope vertical amplifier for positive DC input, making required DC balance adjustments. Vertically position trace 3 cm up from the center graticule line of CRT.
2. Switch the 694A/B LINE to RF and adjust ALC for a leveled output. With the bridge measuring arm open circuited, set oscilloscope CALIBRATED vertical SENSITIVITY for a reference trace approximately 3 cm below the center graticule line of the CRT. Read the DC voltage level indicated. If greater than 50 millivolts, the X424A detector is operating out of square law and RF power out of the sweep oscillator must be reduced with the ALC control.
3. Connect the coax short (supplied with X8440A) to the measuring arm and note any trace deviation from the vertical reference established in step 2. Using the sweeper ALC control, reposition trace slightly so the mean of the open and short circuit display falls over the reference graticule as illustrated by the two traces in Figure 5a.[5] The display is now calibrated for direct readout of SWR using the special graticule scales.

Example 2. Measuring ρ of a Coaxial Attenuator

a. Connect test attenuator (properly terminated) to bridge measuring arm and note trace position at point of interest (maximum SWR in this example).

b. Increase oscilloscope VERTICAL SENSITIVITY in calibrated steps for higher resolution, noting the ratio of the sensitivity increase. In this example, the reference short and open settings were made on the 2 mv/cm setting and the desired resolution obtained on the 0.1 mv/cm setting. The ratio of 0.1/2 yields .05.

c. Select the appropriate SWR graticule scale from Table 1 and place over the CRT. Table 1 indicates use of the scale marked 13 db for the .05 ratio used in this example.

d. Read SWR directly from the scale as shown in Figure 5b. Check oscilloscope DC BALANCE frequently and adjust as required.

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[4] Oscilloscope graticule scales for direct readout of SWR are included with hp Application Note 61, available from hp sales offices on request.

[5] See footnote 2.

Table 1

Ratio of Sensitivity Increase E_1/E_2^*	Use Scale Marked
1.0	0 db
.1	10 db
.05	13 db
.02	17 db
.01	20 db

* E_1 = Oscilloscope sensitivity in mv/cm giving best resolution

E_2 = Sensitivity in mv/cm used for bridge open and short circuit reference setting

Both oscilloscope techniques rely on the square-law response of the bridge detector for accurate readout. The hp X424A with its matched square-law load (option 02) is recommended for close adherence to square law over the full 30-db range of the bridge. The load does reduce detector sensitivity by about 6 db which limits resolution at readings much below 1.1 SWR. This limitation in resolution is generally significant only during initial bridge assembly and calibration and the speed and convenience of oscilloscope display can be enjoyed for most applications. For higher sensitivity the X-Y recorder - RF pre-insertion technique may be used.

X-Y RECORDER READOUT USING RF PRE-INSERTION

An accurate method of using an X-Y recorder with the X8440A Bridge is illustrated in Figure 6. The hp X382A variable attenuator is used to pre-insert specific values of return loss to the detector and a calibration grid is plotted for open and short circuit conditions at the bridge measuring arm. The X382A is then returned to zero db, the test device connected to the measuring arm, and a swept-frequency plot made of the device's reflection coefficient. This technique requires the 694A/B Sweep Oscillator output to be amplitude modulated at 1 Kc since a 415D Standing-Wave Indicator is used to drive the recorder.

The effects of readout variations discussed in footnote 2 are automatically calibrated out when using the X-Y recorder - RF pre-insertion technique. Deviation from detector square law is also eliminated since the detector always operates near the same RF level. For this reason, the option 02 square law load can be left off the bridge detector resulting in a 6-db increase in detector output and improvement of overall readout sensitivity.

Readout accuracy with this technique is governed primarily by the mismatch and accuracy of the calibrating variable attenuator. A reasonable estimate of the combined attenuator errors would be ±0.4 db.

BRIDGE ASSEMBLY AND INITIAL CALIBRATION

The calibration procedure that follows describes how the hp X8440A is initially assembled and adjusted during production. This need not be repeated in the field unless the bridge itself has been damaged or disassembled at the sealed waveguide flanges. The procedure also serves as a guide for those interested in assembling a similar bridge in other waveguide bands.

In addition to the leveled sweep oscillator, oscilloscope, and X-Y recorder, etc., described earlier

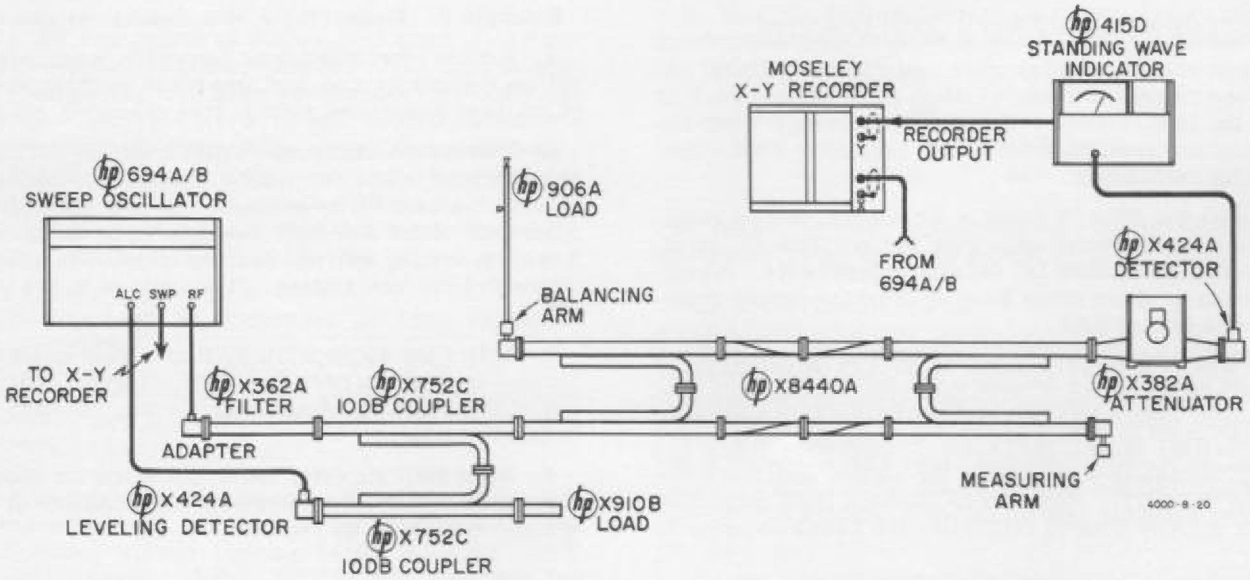

Figure 6. RF Pre-Insertion Technique for X-Y Recording. Precision variable attenuator ahead of bridge detector is used for plotting a calibration grid at specific return losses before test device is swept. Technique is slower than oscilloscope but offers best accuracy for critical applications.

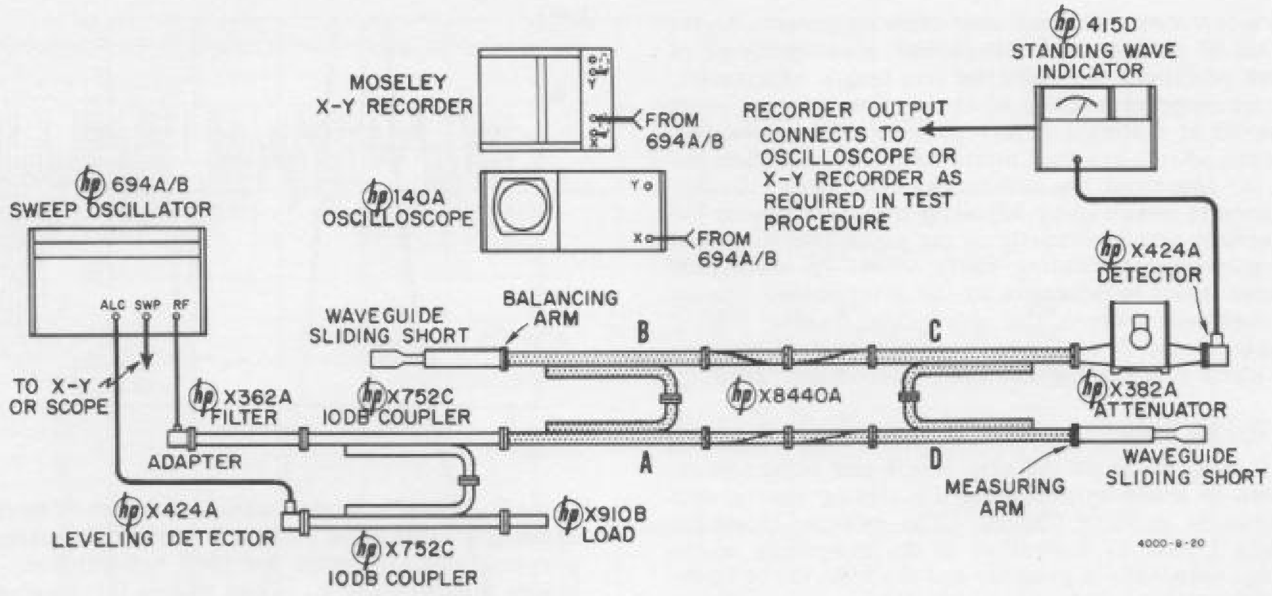

Figure 7. hp X8440A Bridge shown partially assembled (shaded components) and connected for initial calibration and adjustment

for normal bridge operation, Table 2 lists additional instruments required to perform this calibration.

Table 2

Quantity	Instrument
1	hp 906A Coaxial Sliding Termination (total of 2 required)
1	Type N female coaxial sliding short with SWR approximately 100:1 or greater across the band
1	Type N male coaxial sliding short with SWR approximately 100:1 or greater across the band
2	Choke type, waveguide sliding shorts with micrometer drive
1	hp 914B Waveguide Sliding Load

Initial calibration depends upon first having two pairs of high directivity, 10-db waveguide directional couplers which have been pretested and matched for coupling factor to within .1 db across the operating frequency band. (Note: All four couplers need not be matched to each other, only the individual couplers of a given pair.) Also, one pair each of special male-to-male and male-to-female type N adapters plus one pair of matched waveguide-to-coax adapters are required.[6] The bridge is partially assembled as indicated by the shaded portion of Figure 7 using the matched couplers and four waveguide twists. The hp 690-series sweeper, 382A attenuator and readout equipment is then connected as shown.

a. Twist Phase Equalization

This adjustment is made to assure equal phase shift in the two pairs of twist sections throughout the operating band. The waveguide sliding shorts are connected to couplers B and D and alternately adjusted for best overall bridge balance (minimum detector output) while continuously sweeping the band and observing the oscilloscope display. The sweeper is then set for single frequency operation at the frequency where the bridge balance was noted to be poorest. With the 382A Attenuator set for 10 db and a convenient reference level set on the 415D, the measuring-arm short is readjusted for maximum bridge output. The 382A Attenuator is then increased to restore the 415D reference level. The change in attenuator setting must be 26 db or more. If the change is less than 26 db, the attenuator and short are returned to their original settings for best balance while sweeping. Overall balance is then improved by gently squeezing the sides (H walls) of the twist sections in one leg. This decreases the cutoff wavelength of the twist and changes its phase shift versus frequency characteristics. The correct location for squeezing is determined experimentally using finger pressure only while observing the swept-frequency oscilloscope display. When the point is located where overall balance can be improved with the least amount of squeezing, a padded pair of waterpump pliers is used to carefully bend the waveguide permanently. Sharp dimples in the waveguide must be avoided for minimum reflections within the bridge. The 26-db check is then repeated.

b. Bridge Arm Length

Bridge arm length adjustment is made to equalize the two signal path lengths in the bridge so the 180° phase difference is maintained across the band. The waveguide sliding shorts used in the previous check

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[6] Matched sets of hp 752C directional couplers, 281A waveguide-to-coax adapters, and type N coax adapters are available on special order from hp for assembling bridges in various other bands.

are micrometer driven, thus allowing precise duplication of settings and differential measurements of short position. To make the arm length adjustment, the micrometer reading of the measuring arm short is noted at optimum bridge balance while sweeping. The two shorts are then interchanged without disturbing the setting of the reference-arm short. Bridge balance is restored by adjusting the short now on the reference arm (previously on the measuring arm) and its micrometer reading again noted. A waveguide spacer equal in thickness to the micrometer change is inserted between the waveguide flanges joining coupler A and B, or C and D, whichever path includes the short with the highest final micrometer reading.

c. Bridge Balance Check

A final check on the arm length and twist adjustments is made by replacing the sliding shorts with waveguide shorting flanges. The sweeper is set for single frequency operation at the frequency where bridge unbalance is greatest and the 382A set at 10 db. A reference level is set on the 415D. The short at the measuring arm is then replaced by an hp 914B load and the reference level restored on the 415D by increasing the 382A attenuation. If the previous adjustments were made properly, the attenuator increase will be 20 db or greater.

d. Completed Bridge Balance Check

The bridge configuration is now completed by installing a matched pair of 281A waveguide-to-coax adapters at the measuring and reference arms and the matched pair of male-to-female coax adapters. An hp 906A coaxial termination is attached to the reference arm using the .065 inch diameter male center conductor and unslotted outer conductor in the 906A. An hp 11512A Fixed Coax Short is then connected to the measuring arm. The 415D recorder output is then connected to the Y input of a Moseley X-Y Recorder.

Reference grid lines of bridge output versus frequency are now plotted on the recorder at 382A attenuator settings of 30.5, 34.0, and 40 db. These settings correspond to the equivalent return losses for reflection coefficients of .03, .02, and .01 respectively at the measuring arm. The reference plots are repeated for an open circuit at the measuring arm. (The mean of the open and short circuit plots represents the true calibration lines.) After plotting the reference lines, another 906A Coax Load (with the .065 inch center conductor) is connected to the measuring arm and the 382A Attenuator set to 10 db. Next, the 415D sensitivity is increased by 10 db with the RANGE switch. The 906A in the measuring arm is phased continuously as the sweeper slowly covers the band and the bridge output is plotted over the reference grid lines previously drawn.

Figure 8 shows a typical plot resulting from the bridge balance check. The cyclic amplitude variations represent the sums and differences of the 906A Load reflections and the bridge's unbalance signal as the two vary in phase relationship. These variations must be separated and evaluated to determine if the bridge is within balance specification. A signal separation chart is shown in Figure 9 to simplify the evaluation.

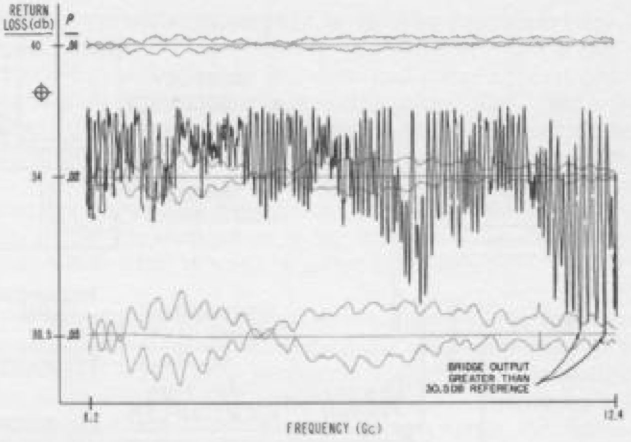


Figure 8. X8440A Bridge balance is checked by first drawing a calibration grid on X-Y recorder using pre-insertion attenuator and 100% reflection at bridge measuring arm. Coax sliding termination is then phased continuously as swept frequency plot is made, indicating how well adapter reflections are cancelled.

To evaluate the plot:

1. Note the locations where bridge output is greater than the -30.5 db reference line (see Figure 8). At these locations, note the minimum and maximum db levels caused by phasing the 906A load and determine their DIFFERENCE IN DB.
2. Enter the ordinate of Figure 9 at the DIFFERENCE IN DB determined in step 1. Intersect the two curved coordinates in the chart and read the corresponding CORRECTIONS IN DB from the abscissa.
3. Add the two CORRECTIONS separately to the MINIMUM DB reading of step 1. The corrected values should each be greater than 30.5 db (i.e., 31, 32 db, etc.).

Interchange the two 906A terminations and repeat the swept check while phasing the 906A at the measuring arm. It is not necessary to repeat the entire procedure of drawing calibration grid lines if the previous X-Y plot is left on the recorder. This check will reveal any excess reflections from either of the two 906A terminations used.

e. Sliding Short Test

Replace the 906A at the bridge measuring arm with the coaxial sliding short. Leave the other 906A connected to the balancing arm. Slowly sweep through the frequency band while phasing the short, and recording the bridge output on the X-Y recorder. Note the frequencies where the maximum excursions of the X-Y recorder pen occur. After the plot is made, use the MANUAL SWEEP control of the hp 690-series sweeper to adjust the sweep oscillator frequency to

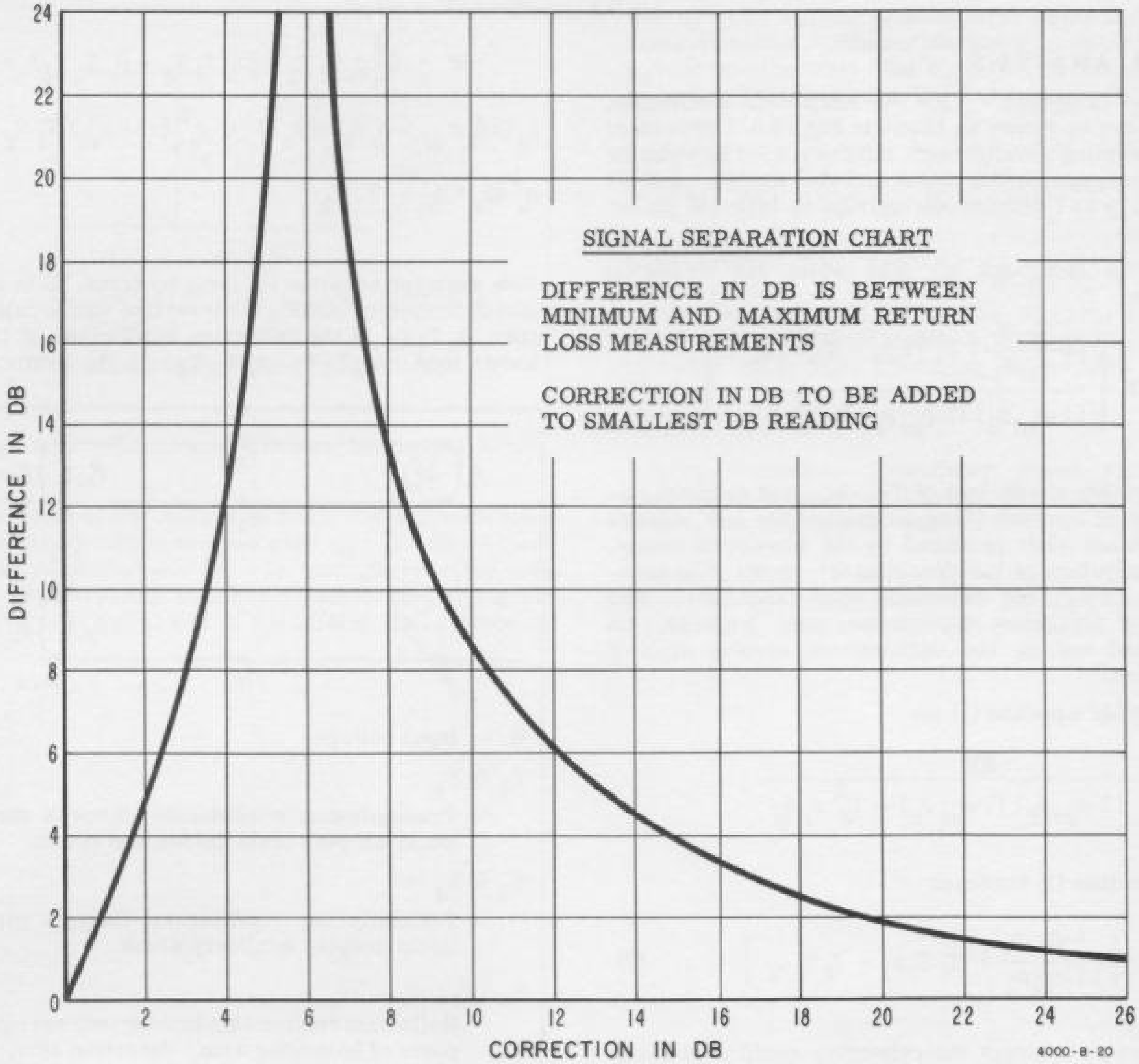


Figure 9. Chart for separating two signals when their sum and difference are known

the points where maximum pen excursions were noted. At each point, adjust the sliding short to the position where maximum output is noted on the hp 415D INDICATOR. Set 415D gain for a reference reading of 1.00 on the SWR scale. Slide the short to the point of null on the 415D and read the SWR. The SWR should not exceed 1.38.

Repeat stepd d and e using the matched pair of male-to-male type N coax adapters at the bridge measuring and balancing arms. Use the .071-inch female center conductors and short thread outer conductors in the 906A terminations, hp 11511A female fixed short, and female coax sliding short for this check. This completes the bridge assembly and initial calibration.

APPENDIX

ERROR ANALYSIS

A signal flowgraph[1, 2] for the Reflection Coefficient Bridge can be drawn as shown in Figure A-1 provided: 1) the leveling arrangement effects a good impedance match between bridge input and the source, and 2) directional coupler directivity is high (40 db or greater).

From the flowgraph we may write the following equation:

$$M = EK \left[\frac{\left(\frac{1-\rho_{xr}\rho_r}{1-\rho_{xl}\rho_1}\right) T_1 T_2 \rho_1 - T_3 T_4 \rho_r}{(1-\rho_{xd}\rho_d)(1-\rho_{xr}\rho_r) - T_3^2 \rho_r \rho_d} \right]. \qquad (1)$$

The negative coefficient of T_3, T_4, and ρ_r in the numerator of equation (1) is a result of the 180° differential phase shift produced by the waveguide twists. An examination of the denominator shows it is independent of ρ_1, but dependent upon frequency. The effect of frequency dependence can, however, be calibrated out on the oscilloscope display or X-Y recording.*

To simplify equation (1) let

$$C = \frac{EK}{(1-\rho_{xd}\rho_d)(1-\rho_{xr}\rho_r) - T_3^2 \rho_r \rho_d},$$

thus equation (1) becomes

$$M = C \left[\left(\frac{1-\rho_{xr}\rho_r}{1-\rho_{xl}\rho_1}\right) T_1 T_2 \rho_1 - T_3 T_4 \rho_r \right]. \qquad (2)$$

The term ρ_r includes the reflection coefficient of the balancing arm adapter and the coaxial load connected (hp 906A). The term ρ_1 is a combination of the measuring arm adapter and the unknown load reflection coefficients. By means of a signal flowgraph of the bridge's measuring arm, we can further analyze the term ρ_1. This flowgraph is shown in Figure A-2.

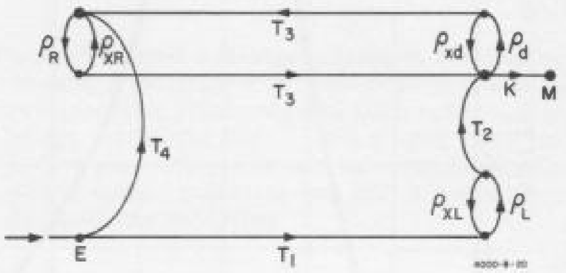
Then from the flowgraph

$$\rho_1 = \rho_a + \frac{\rho_u (1-\rho_a^2)}{(1-\rho_a \rho_u)}. \qquad (3)$$

Now the coefficient of $T_1 T_2$ in equation (2) is expanded, ignoring all terms containing ρ_x and ρ_r to the third power or any combination of ρ^3 except ρ_1. Equation (3) is expanded in a similar manner. Substituting the expansions into equation (2) and combining terms yields

$$M = C\Big[\rho_u T_1 T_2 + (\rho_a T_1 T_2 - \rho_r T_3 T_4) + \rho_u (2\rho_a \rho_{xl} - \rho_r \rho_{xl} - \rho_a^2) + \rho_u^2 (\rho_a + \rho_{xl}) T_1 T_2 + \rho_u^3 (\rho_a + \rho_{xl})^2 T_1 T_2\Big]. \qquad (4)$$

Now examine equation (4) term by term. C is a function of frequency and signal level that can be calibrated out. $\rho_u T_1 T_2$ is the reflection coefficient of the unknown load. $(\rho_a T_1 T_2 - \rho_r T_3 T_4)$ is the error term*



E = Input voltage

T_1 & T_3 = Transmission coefficients through directional coupler main guides and twists

T_2 & T_4 = Transmission coefficients through directional coupler auxiliary arms

ρ_{xr}, ρ_{xd}, ρ_{xl} = Reflection coefficients looking into waveguide ports of balancing arm, detection arm, and measuring arm respectively

ρ_1 = Combined reflection coefficient of unknown load and measuring-arm adapter

ρ_r = Combined reflection coefficient of 906A coax load and balancing-arm adapter

ρ_d = Reflection coefficient of detector

K = Attenuation between the RF output of the bridge and the readout device. Includes both RF and video attenuation; detector deviation from square law, conversion loss in the diode detector and any errors in the readout device

M = Indicated bridge output

Figure A-1. Flowgraph of X8440A Bridge

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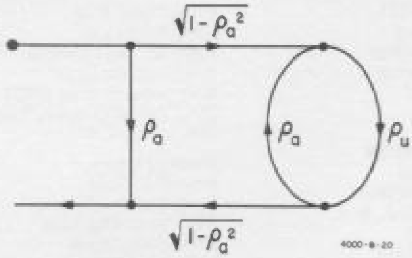
* See footnote 2 on page 4.

* The magnitude of this term is a measure of the bridge phase balance, coupling and transmission coefficient matching of the directional couplers, impedance matching of the adapter pair, and the coaxial load. In the X8440A this error is .03 or less.



ρ_a = waveguide-to-coax adapter reflection coefficient

ρ_u = unknown load reflection coefficient

Figure A-2. Flowgraph of Bridge Measuring Arm

independent of the reflection from the unknown load, and is the quantity measured when $\rho_u = 0$. Since there are no reflectionless ($\rho_u = 0$) loads in practice, one must use a sliding load and separate the two signals $(\rho_a T_1 T_2 - \rho_r T_3 T_4)$ and ρ_u the sliding load reflection.

The $\rho_u^2 (\rho_a + \rho_{xl}) T_1 T_2$ term contributes the primary error at higher values of the unknown load reflection ρ_u. It may be seen that ρ_{xl} must be small in order to reduce bridge errors.

$\rho_u (2\rho_a\rho_{xl} - \rho_r\rho_{xl} - \rho_a^2)$ and the last term $\rho_u^3 (\rho_a + \rho_{xl})^2 T_1 T_2$ are small compared to the ρ_u^2 term. When a test for error in ρ_u is made with $\rho_u = 1$, a good approximation of the error for any ρ_u is the product of ρ_u^2 and the error found in measuring all phases of $\rho_u = 1$. Thus, we obtain the $.16\rho^2$ term in the X8440A specification. The .03 error and $.16\rho^2$ error are added algebraically in the X8440A specification of ρ uncertainty producing $.03 + .16\rho^2$.

References

[1] Kuhn, Nicholas, "Simplified Signal Flow Graph Analysis", Microwave Journal, Nov. 1963, Horizon House, Inc., Dedham, Mass.

[2] Hunton, J. K., "Analysis of Microwave Measurement Techniques by Means of Signal Flowgraphs", Trans. IRE, Vol. MTT-8, March 1960.

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