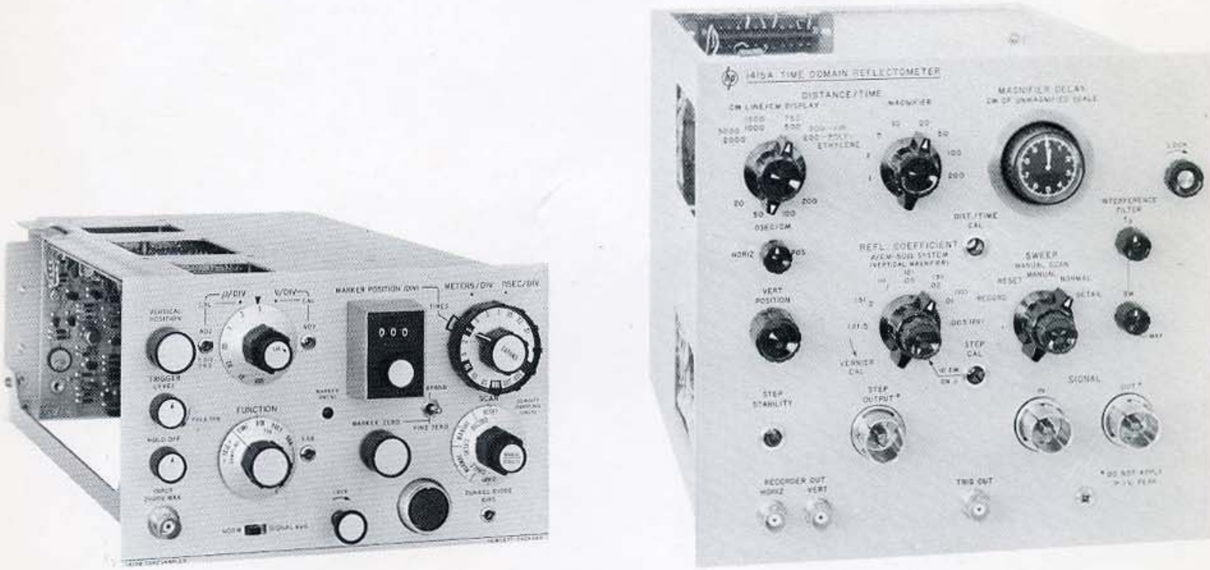
APPLICATION NOTE 67

Cable Testing with Time Domain Reflectometry



HEWLETT hp PACKARD

APPLICATION NOTE 67

CABLE TESTING WITH TIME DOMAIN REFLECTOMETRY

(TDR Slide Rule Located Inside Rear Cover)

1900 GARDEN OF THE GODS ROAD, COLORADO SPRINGS, COLORADO, U. S. A.

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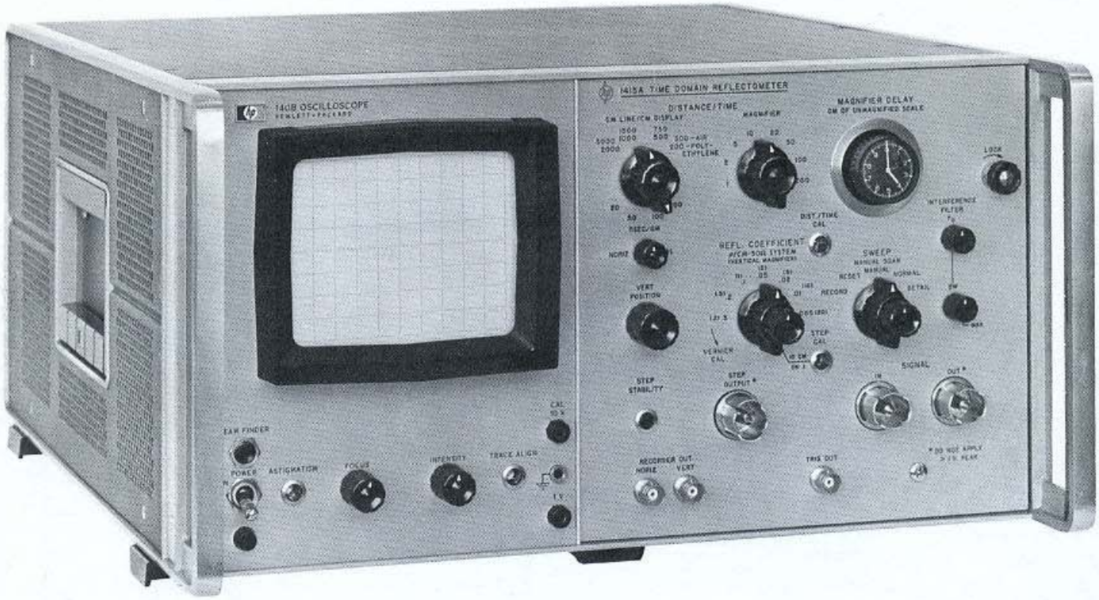


Model 1415A Time Domain Reflectometer installed in Model 140A Oscilloscope

SECTION I
INTRODUCTION

PULSE REFLECTION TESTING

Time Domain Reflectometry (TDR) is the state-of-the-art application of the proven pulse reflection measurement technique. Used by repair crews for many years to locate faults in high-voltage transmission lines, the pulse reflection method provides reasonably accurate distance measurement. A pulse or pulse burst is sent continuously down the transmission line. If the pulse encounters a short or open circuit the reflection travels back to the sending point, where it is compared in phase, time, and amplitude with the original pulse. This comparison shows the distance to the fault as well as an indication of its nature.

With the advent of sub-nanosecond pulse generators and oscilloscopes with equivalent bandwidths, the application of the pulse reflection technique to high frequency transmission systems has become practical. Distance resolution has shrunk from hundreds of yards to fractions of an inch, and the new generation of sampling oscilloscopes permits accurate measurement of reflections only a thousandth of a volt in amplitude.

The Time Domain Reflectometer is thus a type of closed-loop, one-dimensional radar system, in which the transmitted signal is a very fast step function, and the reflected signals are monitored on the oscilloscope screen. The faster the step, the greater the distance resolution, since distance is related to time in this technique. The amplitude of the reflected step is directly related to impedance, so any slight deviation from the 50-ohm output of the Model 1415A Time Domain Reflectometer can easily be recognized and measured. Thus cables, connectors, baluns, strip lines, tapered sections, and a host of other broadband devices can be analyzed with TDR.

INTERPRETING TIME DOMAIN REFLECTIONS

Faults occur in even the best high frequency transmission systems and can cause substantial losses of power or severely distort the transmitted signal. Dielectrics may deteriorate and change; water may leak into cables or connectors; contacts may corrode; conductors may open or short; the cable may be cut or damaged, or a clamp may be fastened too tightly. Such occurrences the Time Domain Reflectometer treats as "discontinuities," unexplained abrupt changes in the otherwise constant characteristic impedance of a transmission system. Since time is readily convertible into distance, the exact location of the discontinuity can be found.

Aside from discontinuities, the transmission line itself has a number of relevant properties. It has a characteristic impedance, which may or may not change with frequency, and may vary over its length. It has a certain dielectric, or velocity of propagation. It has a certain attenuation per unit length, which does vary with frequency. The Time Domain Reflectometer will provide quantitative as well as qualitative information on any transmission cable - impedance, loss, risetime, electrical length, and discontinuities - in a single measurement.

As in any measurement technique, there are limitations imposed both by the state of present-day technology and by the technique itself. Since the Time Domain Reflectometer relates time to distance, the finite risetime of the incident or reflected pulse limits the possible resolution of distance. It also limits the system bandwidth - the frequency range over which the measurements are valid. Reflections generated in waveguide systems, unlike coaxial systems, travel at various propagation velocities depending upon the mode of propagation. Analysis of waveguide reflections is therefore very complex, and further compounded by the inherent low-frequency cutoff making it a "narrow-band" measurement.

Standing wave ratio (SWR) measurements provide an immediate overall indication of a transmission line's performance, while time domain reflectometry (TDR) measurements isolate the line's characteristics in time (location). Multiple reflections, due to a number of discontinuities or numerous impedance changes, complicate the TDR measurement but are none the less easily evaluated.

THE SAMPLING TECHNIQUE

Since the speeds needed for TDR exceed the response of the fastest real time oscilloscope, the sampling technique is employed. Rather than providing a continuous monitoring of the reflected signals, the Model 1415A Time Domain Reflectometer takes a series of 4000 separate samples of the reflections every 20 milliseconds. Each sample is displayed as a single dot on the face of the oscilloscope, but the 4000 dots in a 10-cm display area appear as a contiguous line, or "trace." The samples are taken so each successive sample in a series is delayed with respect to the incident pulse by a predetermined time. In addition, the entire set of 4000 samples may be delayed so that reflections from a small area located a great distance down the line may be magnified for better resolution.

The combination of a very-fast-rise pulse generator and the sampling technique provides an overall system response of about 2.3 GHz or better in the Model 1415A. This corresponds to a rise time of about 150 picoseconds, which means that reflections generated only a centimeter or two apart may be resolved and isolated. In addition, the sampling method permits extraordinary dynamic range and sensitivity. A 0.1% reflection may be observed without the incident pulse overloading the system.

THE TDR SLIDE RULE

The Time Domain Reflectometer may be used to measure large ranges of impedance, both real and reactive; distances from fractions of centimeters to thousands of feet; frequency response; attenuation; and a myriad of other transmission parameters. The slide rule and tables included in this Application Note are intended to simplify such TDR measurements to the point that the transmission line formulas need only be used where extreme accuracy is required.

The distance/time scale of the slide rule simply converts electrical length (measured in units of time) to the Metric and English units of distance, modified by the propagation velocity of the line being used.

The SWR/reflection coefficient scale provides a quick conversion to standing wave ratio for resistive discontinuities. Resistive discontinuities such as a mismatched load appear as steps rather than short bumps or dips. Discontinuities of a finite length should be treated as complex impedances and the SWR calculated with a Smith Chart. The use of the Smith Chart is covered in Section III.

The impedance scale calibrates the 1-cm markings of the CRT graticule to ohms, and may be based on any impedance within the range of the slide rule. Impedance conversion overlays for 50-ohm based systems are provided with each Model 1415A.

A correction scale for second reflections is given on page 2-6. When dealing with Z_o's other than 50 ohms, the mismatch at the sampler input will modify the reflected pulse by re-reflecting it back into the system. The table corrects for these known re-reflections.

For 75Ω systems the 50Ω based 1415A can be converted to 75Ω by using 75Ω adapters. (10457A and 10458A) 75Ω impedance overlays are provided. The correction scale for second reflections is not needed when using these adapters.

SECTION II

CABLE CHARACTERISTICS

CHARACTERISTIC IMPEDANCE

The Time Domain Reflectometer may be conveniently used to measure the classic propagation characteristics of a transmission line, α, β, and Z_o. However, these "constants" actually will vary along the line, and a given section may have quite different characteristics from another. TDR isolates such variations in time (distance), providing an "impedance profile" along the length of the line. A given cable may therefore be 100% tested by a single measurement.

An ideal cable (Figure 1) should appear as a resistive load, with no reflections occurring except at the beginning and end of the cable. In practice, reflections will occur along the line which indicates changes in characteristic impedance (Figure 2). They may appear as steps or pedestals, which generally indicate that a section of different impedance cable has been spliced into the line (Figure 3), or they might appear as small bumps which indicate a fault or discontinuity (Figure 4). The profile might show a slowly rising or falling characteristic which indicates a series or shunt loss in the cable.

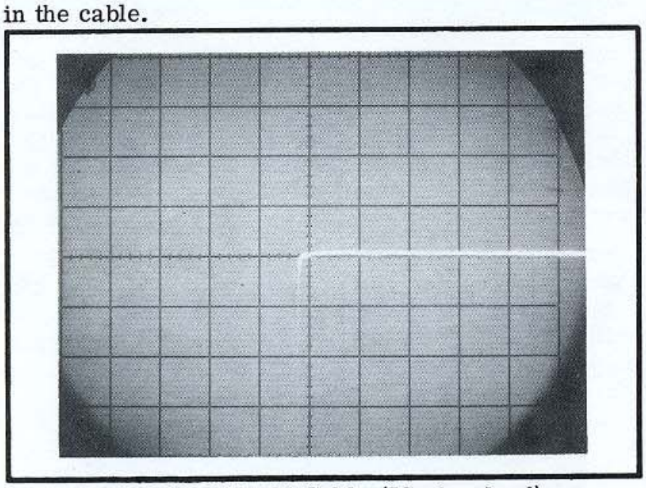


Figure 1. "Ideal" Cable (50-ohm load)

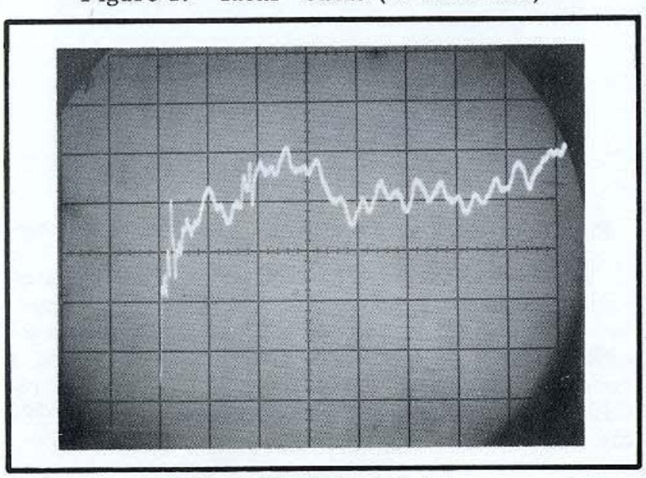


Figure 2. Actual Cable

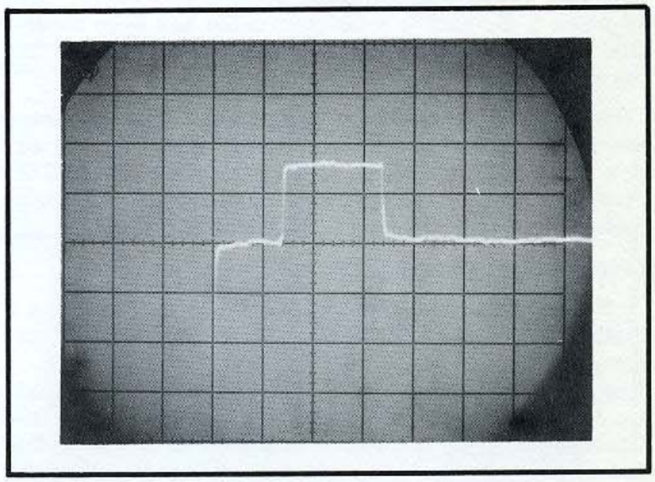


Figure 3. Section of 95-ohm cable spliced in length of 50-ohm line

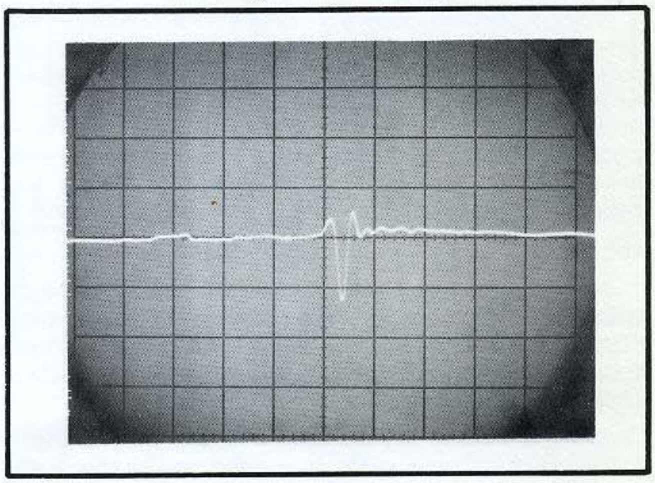


Figure 4. Discontinuity caused by BNC "T" connector in line

If the loss over the length of the line is less than about 0.25 db, and the total variation of impedance along the line is less than about ±10 ohms, the impedance profile is valid. The trace displayed on the screen is then an accurate presentation of the impedance at all points along the line, within the accuracy limits of the system.

The CRT is calibrated in reflection coefficient, which is related to impedance by the formula:

$$\rho = \frac{Z-50}{Z+50} \quad \text{or } Z = 50 \left(\frac{1+\rho}{1-\rho}\right)$$

A 50-ohm characteristic impedance has been chosen for the 1415A system because of general usage and availability of parts and calibration standards. The graticule overlays and slide rule are therefore based on 50 ohms, so correction factors must be applied if the transmission system's Z_o is much different from 50 ohms (see Multiple Reflections, Page 2-4).

A typical application of the impedance profile is checking the impedance specification of a cable. In Figures 5, 6, and 7, a 50-ohm cable has been specified to be 50 ohms ±1% (±0.5 ohms), so a trace in the shaded area represents a "no go" condition.

Although a swept-frequency reflectometer measurement could provide a similar final figure, it cannot determine the location of a discontinuity. The TDR display may well show the problem to be a poorly mated connector and not a cable problem at all.

LENGTH AND DISTANCE

The Model 1415A Time Domain Reflectometer has a distance/time scale calibrated directly in cm of air line, cm of polyethylene line, and in nanoseconds. The nanosecond scale reads in round trip time, that is, the time for the incident pulse to reach a discontinuity plus the time for the reflection to return to the sampler. The distance scales, on the other hand, read directly in distance to a discontinuity and not round trip distance.

The TDR slide rule provides a ready conversion between time and distance, even for lines other than polyethylene or air. To determine the relative propagation velocity, take a known length of cable, short or open circuit the end of the cable to provide a reflection, and note the round trip time in nanoseconds. Set the round trip time beneath the slide rule arrow, and read the propagation velocity v_p or the dielectric constant ϵ under the measured distance.

The electrical length of a cable is expressed in time, so it is important to remember that the true electrical length of a cable is half that displayed on the oscilloscope, since the scale is calibrated in round trip time.

When accuracy beyond the ±5% capability of the Model 1415A's time scale is needed, such as for multiple antenna phasing, relative measurement techniques should be used. Two cables may be paralleled and the distance between the end-cable reflections noted. One line may then be shortened or lengthened until the two reflections are superimposed, and the lines will be properly phased. It is good practice to terminate such lines with a small discontinuity, such as a Tee or an improperly mated connector. It is easier to line up two small discontinuities than two open or short circuits.

ATTENUATION

As the rise time and amplitude of the incident pulse becomes degraded along the length of a transmission line, so does the ability of the TDR to resolve small discontinuities or changes of impedance. In order to make reasonable measurements, the cable loss must first be determined.

The low-frequency loss in the distortionless 50-ohm line (Figure 8) can be measured readily by shorting the end of the cable and noting the amplitude of the reflection. If the reflection coefficient is 0.1, for example, the total loss (down and back) is 20 db, and

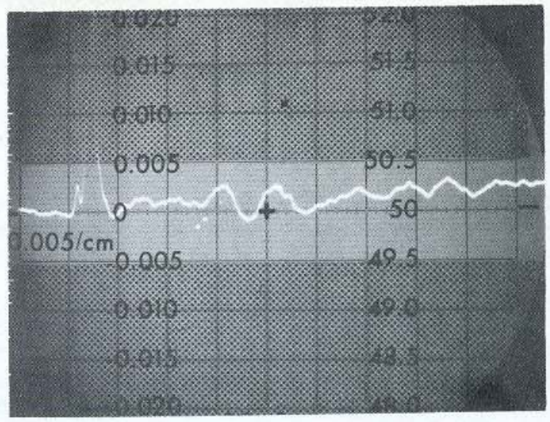


Figure 5. "Go"

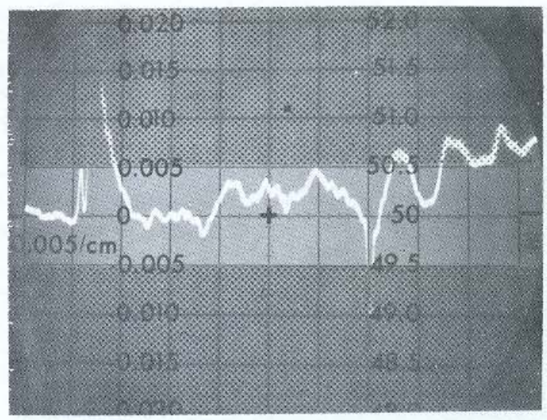


Figure 6. No Go. Kink in cables causes 1% reflection

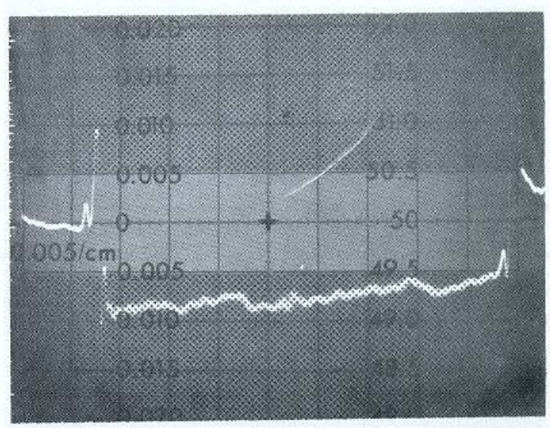


Figure 7. No Go. Nominal Z_o less than 49.5 ohms

The first centimeter of each trace is an air line calibrated at 50.1 ohms. The use of a known impedance immediately preceding the test cable avoids the effect of drift or pulse base line shift by providing a constant reference. The two positive spikes are reflections from connectors at the beginning and end of the test cable.

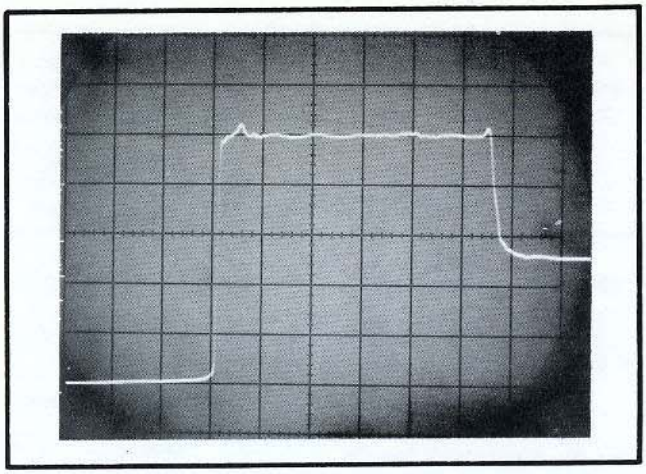


Figure 8. Short at end of cable measures dc loss

thus the one-way loss is 10 db. Normally the low-frequency loss is quite low for distortionless lines, and a low reading such as 0. 1 probably indicates a 10 db pad somewhere in the system.

The most common case is that involving a series loss which exceeds the shunt loss, causing a very long line to approximate an open circuit at dc. The TDR characteristic is a slowly rising one (Figure 9) and approximates a series capacitance termination. * If the line is near 50 ohms, the dc attenuation may again be measured by reading short-circuit reflected pulse height, and bandwidth by the reflected rise time.

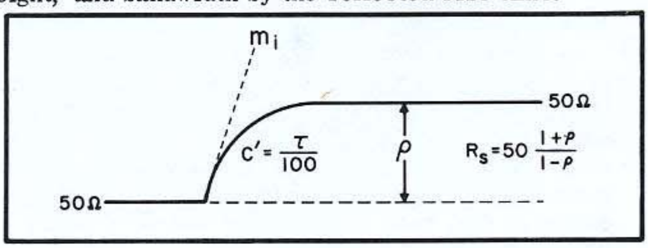


Figure 9. Displayed waveform of lossy line

The actual value of the series cable resistance is a function of the conductor skin depth and therefore varies with frequency. It would be erroneous, then, to assume the equivalent lumped circuit (Figure 10) is valid at all frequencies. But for very broadband usage or pulse work the equivalent circuit is a good approximation of the cable's performance - as long as its length is not changed.

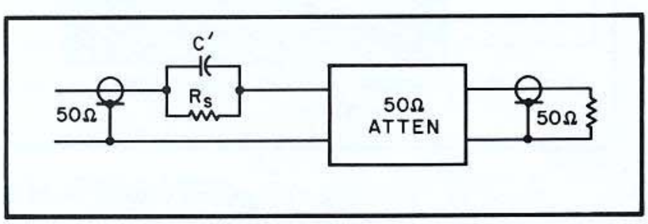


Figure 10. Approximation of equivalent circuit

Note that the trace shown in Figure 9 gives no indication of the actual attenuation in the line. It is valid only if the shunt conductance of the cable is known to be zero. Attenuation must still be measured by placing a known mismatch (such as a short) at the end of the line and measuring its amplitude and rise time.

Measurement of impedances at the end of the line may also be done easily by first placing a short at the end. The TDR unit may then be set (using the Reflection Coefficient vernier) so that the reflection from the short reads a ρ of -1. Then the end of the line effectively becomes the calibrated 50-ohm sampling point, and impedances may be measured in the normal manner.

The relative value of series resistance for cables of the same Z_0 may be compared by measuring the initial slope of the rising waveform. This method provides a quick check for excessive series loss if the other end of the cable cannot be reached.

A similar display will be obtained if the shunt losses of a cable exceed the series loss, except the trace will have a falling rather than rising characteristic.

High-frequency losses (Figure11) are shown by a degradation of the incident pulse. The reflected pulse rise time will be

$$T_{rr} = \sqrt{2\,T_{rc}^2 + T_{ri}^2}$$

where T_{ri} is the measured incident pulse rise time, T_{rc} is the rise time of the cable, and T_{rr} is the measured rise time of the reflected pulse. This is usually a good approximation for short cables assuming a gaussion response.

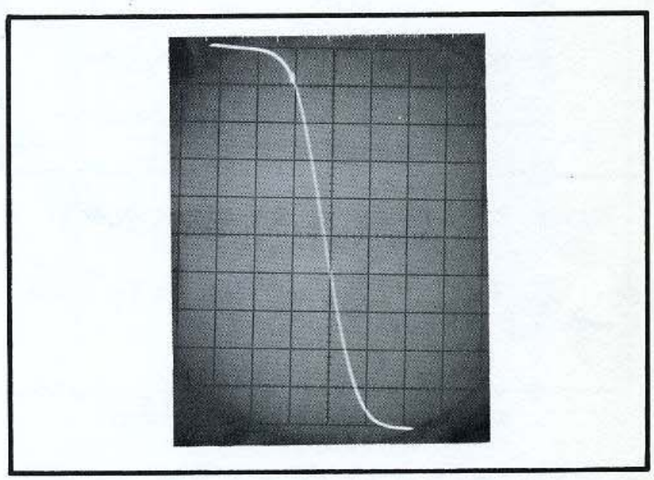


Figure 11. Fall time of reflected pulse indicates HF loss

SMALL DISCONTINUITIES

A single cable fault will often show up as a small positive or negative bump on the otherwise flat trace. A positive (upward) bump means either that the characteristic impedance of the line is high over a short section or that there is a series inductance at a point in the line. Similarly, a negative dip shows a lowering

*See ⓗⓟ Application Note 62, p. 3-5.

of impedance or a shunt capacitance. Within the bandwidth of the TDR system, the impedance change or lumped component method of determining SWR will result in nearly the same figure.

The inductance or capacitance causing a bump may be approximated by measuring the peak amplitude (a) of the bump and its width (w) at the 50% points (see Figure 13). Then the formula,

$$L \approx 2Z_0 aw \quad \text{or} \quad C \approx \frac{2aw}{Z_0},$$

holds when Z_0 is close to 50 ohms. If Z_0 is much different from 50 ohms, * the amplitude (a) should be modified by the factor

$$\frac{1}{1+\left(\frac{Z_0-50}{Z_0+50}\right)^2}$$

Thus a 65-ohm Z_0 will cause about a 2% error.
Example:

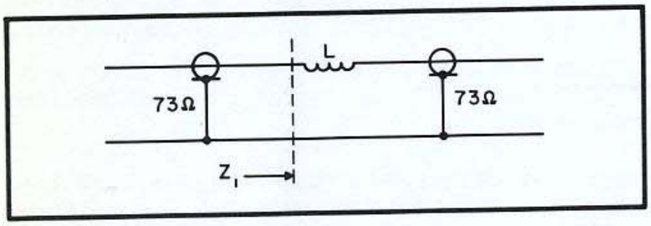


Figure 12. Equivalent Circuit

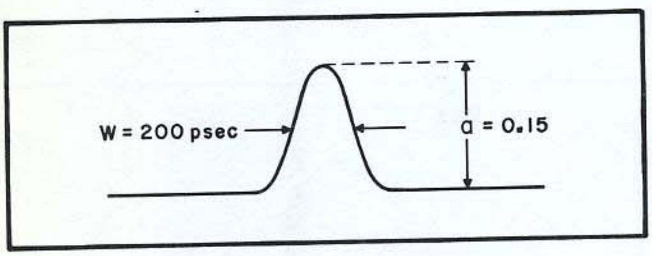


Figure 13. Discontinuity caused by inductor in Figure 12

First, the value of a must be corrected due to the 73-ohm Z_0, so

$$a' = \frac{a}{1+\left(\frac{73-50}{73+50}\right)^2} = \frac{0.150}{1-.035} = 0.156$$

Then $L \approx 2Z_0 a'W = 4.55 \times 10^{-9}$ h.

At a frequency of 1GHz, the impedance at the inductor Z_1 is 73 + j29 ohms, and would create an SWR of approximately 1.5 in a 73-ohm system.

If the discontinuity is flat-topped (see Figure 14), it is best to treat it as a section of higher impedance cable with a Z_0 calculated using a as ρ, and a length equal to W/2. It may in fact be two or three reactive discontinuities spaced so closely that the system cannot resolve them, but below about 2 GHz the SWR will turn out to be the same.

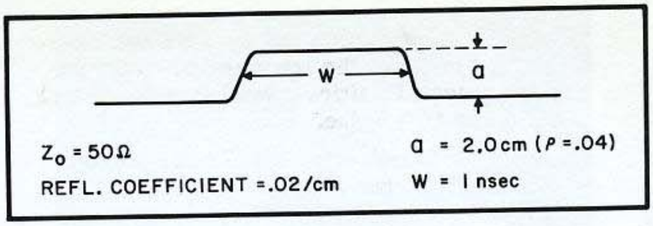


Figure 14. TDR display of short length of coax cable

Example: Figure 14 is equivalent to a short length of cable with a

$$Z_1 = 50\,\frac{1+\rho}{1-\rho} = 50\,\frac{1.04}{.96} = 54.2 \text{ ohms}$$

and an electrical length of $\frac{1 \text{ nsec}}{2} = 500$ psec. At 200 MHz this is equivalent to 0.1 λ and a quick Smith Chart calculation will show an SWR of 1.09.

It was previously stated that erroneous SWR results may be obtained if the effect of a small discontinuity is extrapolated for frequencies beyond the bandwidth of the TDR system. However, if the nature of the discontinuity is known to be a single lumped element (series inductor or shunt capacitor), the approximate inductance or capacitance measured by the TDR technique may be applied to higher frequencies if the physical length of the element is less than about 1/8 λ

MULTIPLE REFLECTIONS

Up to this point we have been dealing with 50-ohm systems, since that is the source impedance of the Model 1415A Time Domain Reflectometer. When any other impedance system is used, the mismatch at the sampler ouput affects both the outgoing pulse and the incoming reflections. More generally, what we are saying is that each discontinuity will affect the discontinuities which follow it.

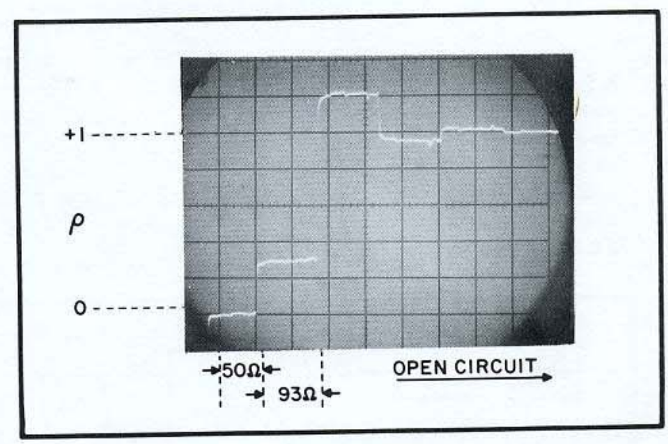


Figure 15. Multiple reflections caused by two discontinuities

Figure 15 illustrates this phenomena clearly. The jump from a 50- to a 93-ohm cable is evident, and follows the TDR rules. But the step from the 93-ohm cable to the open circuit does not. Instead of jumping

*No correction is needed if the transition from 50 ohms to the Z_0 is by a balun.

to +1, the reflection coefficient for an open circuit, the trace actually exceeds that value. Finally, at the extreme right hand edge of the trace the re-reflections between the two discontinuities diminish and the level settles down to the true value.

Even if three or more major discontinuities exist, the display of the first two discontinuities is not affected by the following ones. Both reflections may be measured and represented by an impedance. The third discontinuity, however, may produce a reflection which is mixed in with the re-reflection caused by the first two discontinuities. Because of this ambiguity, we can say that quantitative measurements should be restricted to the first two discontinuities.

SECOND REFLECTION ERROR

The second discontinuity is affected by the first. In Figure 16, notice that a 93-ohm cable inserted in the line will cause the 300-ohm load to appear greater than 300 ohms. When using the TDR slide rule, then, it is necessary to correct the reading for any second reflection.

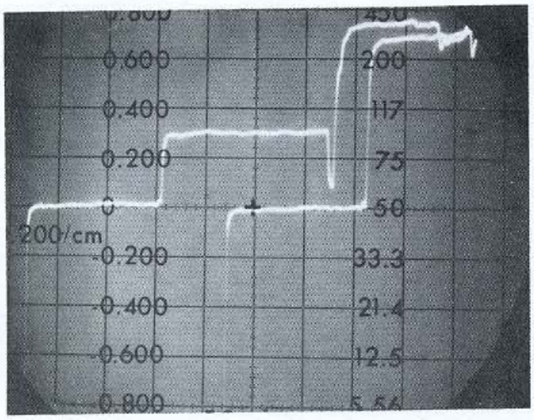


Figure 16. (Double exposure)
Upper Trace: 300-ohm load at end of 93-ohm cable
Lower Trace: same load at end of 50-ohm cable

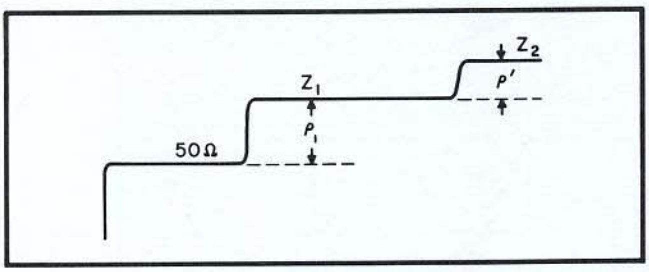


Figure 17. Determination of Z_2 when Z_1 = 50 ohms

The reason for this discrepancy is that the sum of ρ_1 and ρ' does not equal $\frac{Z_2 - 50}{Z_2 + 50}$. The figure ρ' must be adjusted by the factor:

$$\text{Correction} = \frac{-1}{1 + \frac{200 Z_1}{\rho'(Z_1+50)(Z_1-50)}}$$

The corrected value of ρ' should then be used on the slide rule, as in the example below. Graphs of the correction factor for various Z_1's are shown in Figure 20. The correction factor is applied to ρ', the measured difference between Z_1 and the unknown impedance, or to the measured number of centimeters when using the TDR slide rule.

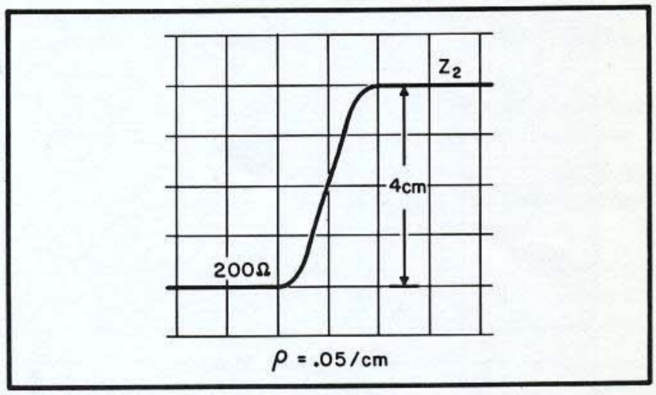


Figure 18. Determining unknown impedance at end of 200-ohm cable

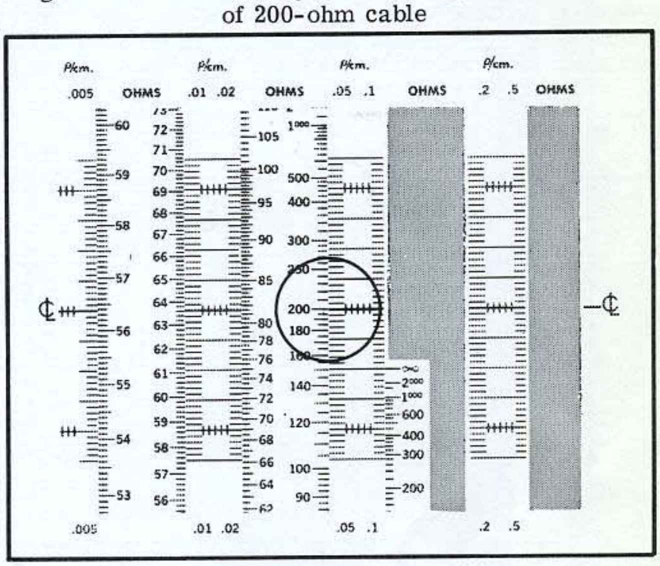


Figure 19. TDR Slide Rule Setting

Example: A 200-ohm standard is set to center screen (Figures 18 and 19). The unknown impedance Z_2 creates a +4 cm reflection. From the formula or the graph, a ρ' of .2 and a Z_1 of 200 ohms requires a correction factor of -16%; so a figure of 3.36 cm is used instead of 4. On the TDR slide rule, set 200 ohms at the center of the .05/cm scale, and read up 3.36 cm for an impedance of about 380 ohms. Without correcting, a 450-ohm impedance would be indicated.

If the reflection were -4 cm, the correction factor of -16% would yield a -4.64 cm corrected value, or 107 ohms.

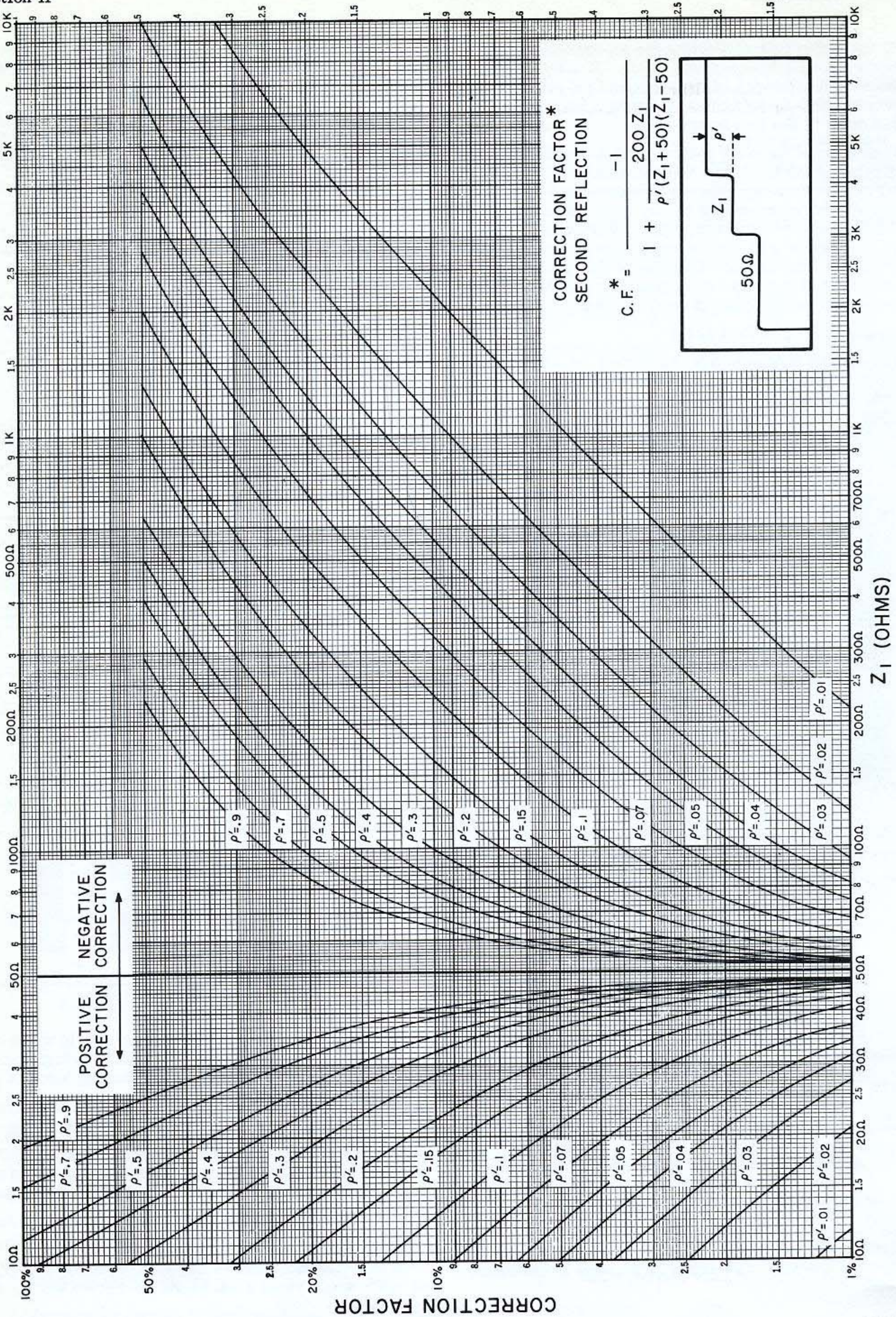


Figure 20. Second Reflection Correction Factor

RECALIBRATIONS FOR OTHER Z_O'S

One may, of course, calibrate the oscilloscope for direct reading of reflection coefficients based on a system other than 50 ohms. The simplest way to calibrate is to short (or open circuit) a short length of the cable, and adjust the Reflection Coefficient Vernier until a reading of 1.0 is obtained from the display of the reflection from the open or short. The measurement must be taken immediately after the open or short, because the first re-reflection will cause an error. It is also important to remember that any measurement after the first major discontinuity is likely to be invalid. The effects of small discontinuities can be largely overcome by using a tapered section which provides a gradual transfer from 50 ohms to the new Z_o.

BALUN

For measurements in the 200- to 300-ohm region, a balun is the best bet. A good balun will permit a 200-ohm line to be tested without the danger of re-reflections from the 50-ohm source. A broadband balun (such as the ⓗⓟ Model K10-185B) should be used so that the incident step is not appreciably affected by sag or loss of rise time.

MATCHING L-PAD

To completely eliminate the effect of multiple reflections in a non-50-ohm system, use a simple matching L-pad* (Figures 21 and 22). Although the incident step and the reflections are attenuated considerably, they may be corrected by using the Vernier to compensate for the loss. There is enough range to adjust for impedances from about 40 to 65 ohms; beyond this a combination of sensitivity switch setting and vernier control will provide the new calibration point (but the front panel calibration of ρ/cm will be incorrect).

The sacrifice made to achieve the reflectionless connection is sensitivity. It is a good rule of thumb, then, to use the L-pad technique when major discontinuities are to be encountered and the tapered section when small discontinuities are present (such as in cable testing). The impedance scale of the TDR slide rule should not be used when an L-pad is employed and should be used with appropriate correction factors when a tapered section provides the impedance transfer.

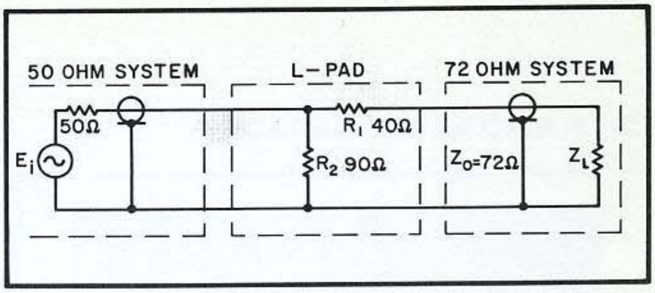


Figure 21. L-pad for matching Model 1415A 50-ohm source impedance to a 72-ohm system

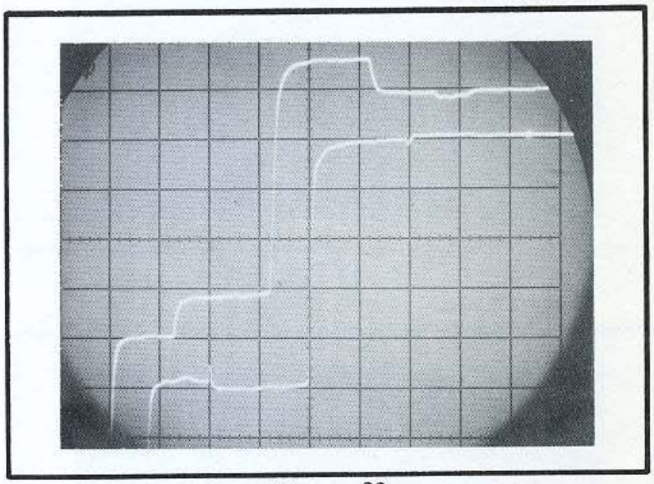


Figure 22
Top Trace: multiple reflections without L-pad
Lower Trace: multiple reflections reduced

*For Z_o > 50 ohms: resistance in series with Z_o, $R_1 = \sqrt{Z_o(Z_o - 50)}$; shunt resistance, $R_2 = \frac{50\ Z_o}{R_1}$.

For Z_o < 50 ohms: resistance in series with source, $R_1 = \sqrt{50(50 - Z_o)}$; shunt resistance, $R_2 = \frac{50\ Z_o}{R_1}$.

SECTION III
TESTING TECHNIQUES

MAXIMUM ACCURACY AND RESOLUTION

As with any measurement method, there are good and bad techniques for Time Domain Reflectometry. A glance at the Second Reflection Correction Factor chart (Figure 20) will show that measurements will be more accurate if reflections in the early part of the system are kept low. It is generally a good idea to use a two to three foot length of air line or very good cable between the Time Domain Reflectometer and the test circuit. This is done so that reflections between the sampler and the pulse generator will have died down to an unnoticeable level before attempting to measure reflections from the test circuit.

IMPEDANCE

Most oscilloscope measurements are limited by visual accuracy, so differential measurement techniques are employed; TDR is no exception. A 93-ohm impedance can be measured to within ±0.1 ohm if compared to a known 90-ohm load, but only to ±2 ohms if compared to a 50-ohm standard.

When measuring impedances near 50 ohms, a calibrated air line placed immediately before the test cable provides the best reference since a rigid line has a more constant Z_o over its length than does a flexible cable.

By far the most accurate method is the "Standard Mismatch" technique used by the National Bureau of Standards in Boulder, Colorado.* A long length of calibrated air line is used between the Model 1415A and the unknown, and a length of calibrated line with a Z_o slightly different from 50 ohms is inserted in the line. The reflection from this mismatch serves to calibrate the system, and only a relative measurement need be made.

To achieve a resolution compatible with this high accuracy, a Moseley X-Y Recorder is used to record the final results. The gain of the X-Y Recorder may be increased to the point where system noise is the limiting factor. This noise will be far less than that seen on the CRT, since the limited bandwidth of the X-Y Recorder will average out most of the noise.

DISTANCE

For greatest accuracy in distance measurements, it's important to preserve the fast rise time of the incident pulse, for distance resolution is only as good as the rise time. Because of this, it is wise to use a high-quality low-loss cable from the TDR unit to the start of the test cable.

Differential measurements may also be used when the relative length of two or more lines is more important than the absolute lengths (such as antenna lead phasing). In this technique two lines are paralleled, and the reflections from the ends of the lines appear on one trace. If the end-reflections are superimposed, the lines are phased. If they appear as separate reflections, the distance between the reflections represents the phasing error. TDR is especially useful for phasing since it measures electrical length rather than physical length; cables often have varying propagation velocity. Again, rise time degradation is the only parameter limiting resolution.

LONG LINE TESTING

When rise time is badly degraded due to long, lossy cables, both the amplitude and shape of the reflections are changed. For the best results before measurements are made, one should determine the dc and high-frequency loss in the line (see Attenuation, Page 2-2). If the dc loss is zero or very small, certain truths apply:

1. The formulas for determining impedance levels, including second reflection error, are still valid. Very short lengths of different impedance cable may appear as an inductance or capacitance, however.
2. The formulas for L and C (See Small Discontinuities, Page 2-3) are still valid. The amplitude will be less, but the width greater. The area remains the same.

Distance measurement is not so easy. A reflection from the end of only 100 feet of RG-214 cable will have a rise time of about 5 nsec. For the same length of RG-58A it should be about 20 nsec. A 20-nsec rise time will be roughly equivalent to a ±5 foot accuracy.

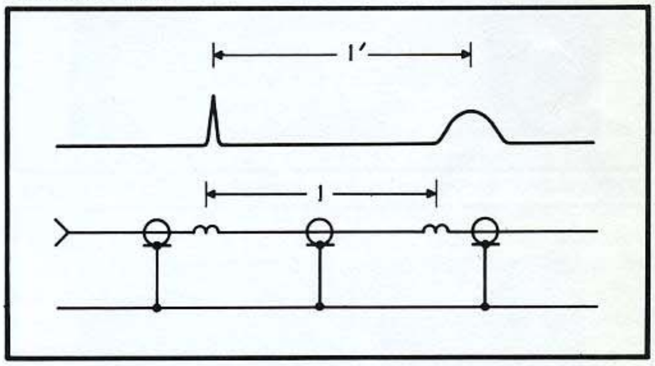


Figure 23. Distance error between two identical discontinuities caused by attenuation along the line

As can be seen from Figure 23, the integrating effect caused by a rise time degradation can be a source of error. If the distance between two like discontinuities is measured by taking the distance between the peaks of the reflections, a sizable error

*Cruz, J.E., Time Domain Reflectometry as a Broadband Coaxial Impedance Calibration System. NBS, Boulder, Colorado, December 1964.

could occur. This error can be cut by a factor of about 5:1 by measuring the distance between the 10% points on the leading edge of the reflections.

The conversion from Reflection Coefficient to Standing Wave Ratio may be made safely but only within a limited bandwidth. This bandwidth is determined by the longest rise time from the system's reflections.

UNWANTED SIGNALS

When a cable is terminated with an antenna or anything else that can receive RF signals, an unstable trace or excessive noise may appear on the CRT. Newer Model 1415A's are equipped with an adjustable interference filter, which restricts the bandwidth of the final vertical amplifier, to smooth out random unsynced signals. It does not restrict the bandwidth of the system. The 150 psec response is still maintained. A second control (f_o) of the interference filter adjusts the repetition rate of the pulse generator and sampler to minimize narrow band interference. This prevents the sampler from locking on to a signal close in frequency to its normal rate or a harmonic of its normal rate.

Signal coupled in by adjacent power lines may be effectively eliminated by using the K60-1415A.

Greater smoothing can be obtained with an X-Y recorder (Figures 24 and 25). Asynchronous signals even as great as the pulse amplitude (0. 25 v) itself will have little effect on the recorded trace.

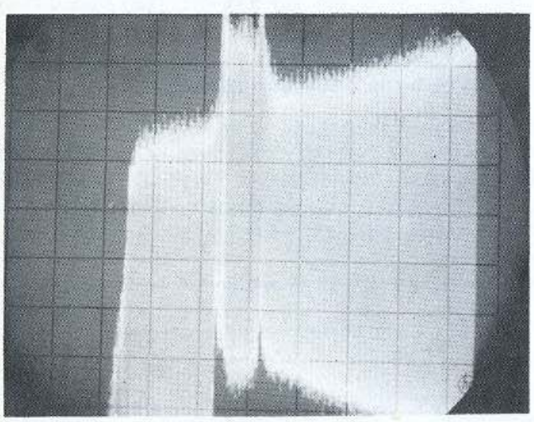


Figure 24. Noisy signal recorded with CRT camera

Figure 25. Same signal recorded with Moseley X-Y recorder

TDR/SWR

A swept frequency reflectometer measurement, using a sweep oscillator, or a single-frequency slotted-line SWR measurement remain the only accurate methods for determining the characteristics of a transmission system at any given frequency or band of frequencies. Although the user can arrive at a single frequency characteristic by the use of TDR measurements, a Smith Chart and the formula for multiple reflections, the measurement capability of TDR will only suffice for "low Q" systems. To attempt accurate analysis of highly resonant systems with TDR is like trying to read a pocket slide rule to six significant figures. But to find out what is causing an unwanted resonant condition, the TDR will provide a quick and ready answer.

When a single, resistive discontinuity is encountered such as a mismatched load, conversion may be directly made to SWR by the formula

$$SWR = \frac{1+\rho}{1-\rho}$$

A scale is provided for this on the slide rule.

When reactive discontinuities or multiple discontinuities are encountered, however, the Smith Chart is the best technique. Reactive discontinuities are first determined in units of capacitance or inductance, then converted to complex impedances. Distances, similarly, are converted to wavelengths for Smith Chart use. The following hypothetical example should illustrate the application:

A 50-ohm line runs to a 300-ohm antenna with a 50:300 ohm balun used to match the antenna to the line (Figure 26). The TDR display (Figure 27) shows, however, that from A to B a section of cable has been inserted which is not 50 ohms, and at C, D there is an inductive discontinuity, probably caused by the balun. Finally, at E, the antenna does not match the 300-ohm line. Frequency is 180 MHz.

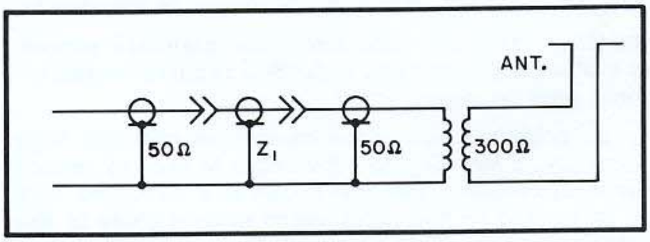


Figure 26. Equivalent circuit of antenna system

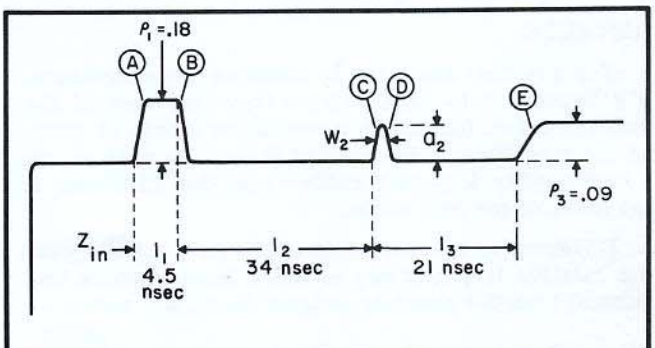


Figure 27. TDR display of antenna system

The first step is to determine the antenna impedance. The base line is known to be 300 ohms, so the measured ρ of 0.09 indicates an impedance of

$$Z_E = 300 \frac{1.09}{0.91} = 360\,\Omega$$

Actually, the impedance transfer from 50 to 300 ohms is irrelevant in this case, so the antenna impedance can be related to 50 ohms instead.

Then $$Z_E = 50 \frac{1.09}{0.91} = 60\,\Omega = 1.2(50)$$

Plotting a point at 1.2 +jo (point E) on the Smith Chart (Figure 28), a clockwise arc is generated equal to l_3, which is 21.5 nsec or 3.87 wavelengths. The resulting normalized impedance at point D is then 0.97 +j0.18.

The normalized inductance of the balun is:

$$L_{(50)} \approx 2a_2W_2 = 2 \times 0.07 \times 0.3 \times 10^{-9}$$
$$= .042 \times 10^{-9}$$
$$= +j0.048 \text{ at } 180\text{ MHz}$$

The total impedance at point C is then 0.97 +j0.18 + j0.048 = 0.97 +j0.23 and this point is plotted on the Smith Chart. From here, the arc corresponding to l_2 (34 nsec or 6.12 wavelengths) is drawn, and the resulting impedance at point B is 1.27 +j0.02 normalized to 50 ohms.

The cable has a measured ρ of +0.18, or an impedance of $$Z_1 = 50 \frac{1+0.18}{1-0.18} = 71.9\,\Omega$$
so the Smith Chart must now be normalized to this new impedance. The last point is now

$$\frac{50}{71.9}(1.27 + j\,0.02) = 0.88 + j\,0.014$$

and this point is plotted. Then the arc representing the length of the cable l_1 (4.5 nsec, 0.81λ) is made and the impedance at the beginning of the cable is 1.08 -j0.1, normalized to 71.9 ohms. Returning the normal figure to 50 ohms makes this impedance $\frac{71.9}{50}$(1.08 -j0.1) = 1.55 -j0.14 and this impedance will create an SWR of 1.57.

With a VSWR of 1.57 at the source, mismatch loss can be calculated to be approximately 5% if the generator has a 50-ohm source impedance. This type of analysis may seem to be laborious compared to a simple slotted-line measurement, but the fact that a complete Smith Chart has been generated means a wealth of useful information is available:

1) If the section of 72-ohm cable were replaced by a 50-ohm one, the VSWR would be reduced to 1.27.

2) If, in addition, the balun is improved to eliminate its inductive discontinuity, the VSWR would be further reduced to 1.2.

3) If instead of improving the balun, it is moved 1/4 wavelength in either direction, its inductance will help offset the antenna mismatch and the VSWR can be reduced to 1.13.

4) If additional turns are added to the balun to better match the antenna impedance to 50 ohms, only the inductance of the balun (VSWR = 1.055) will contribute to the overall standing wave ratio.

5) If a single-frequency SWR measurement is made, and found to be significantly different from the Smith Chart calculation, the signal generator or transmitter mismatch to the 50-ohm system is the likely culprit.

Successful application of the Time Domain Reflectometer requires a thorough knowledge of its advantages and limitations. Cable testing is but one of many applications, which include connector and antenna testing, strip line and switch design, impedance measurement, or the testing of practically any broadband passive circuit in the VHF-and-up range. For a more general approach to such measurements, see Application Note 62, "Time Domain Reflectometry."

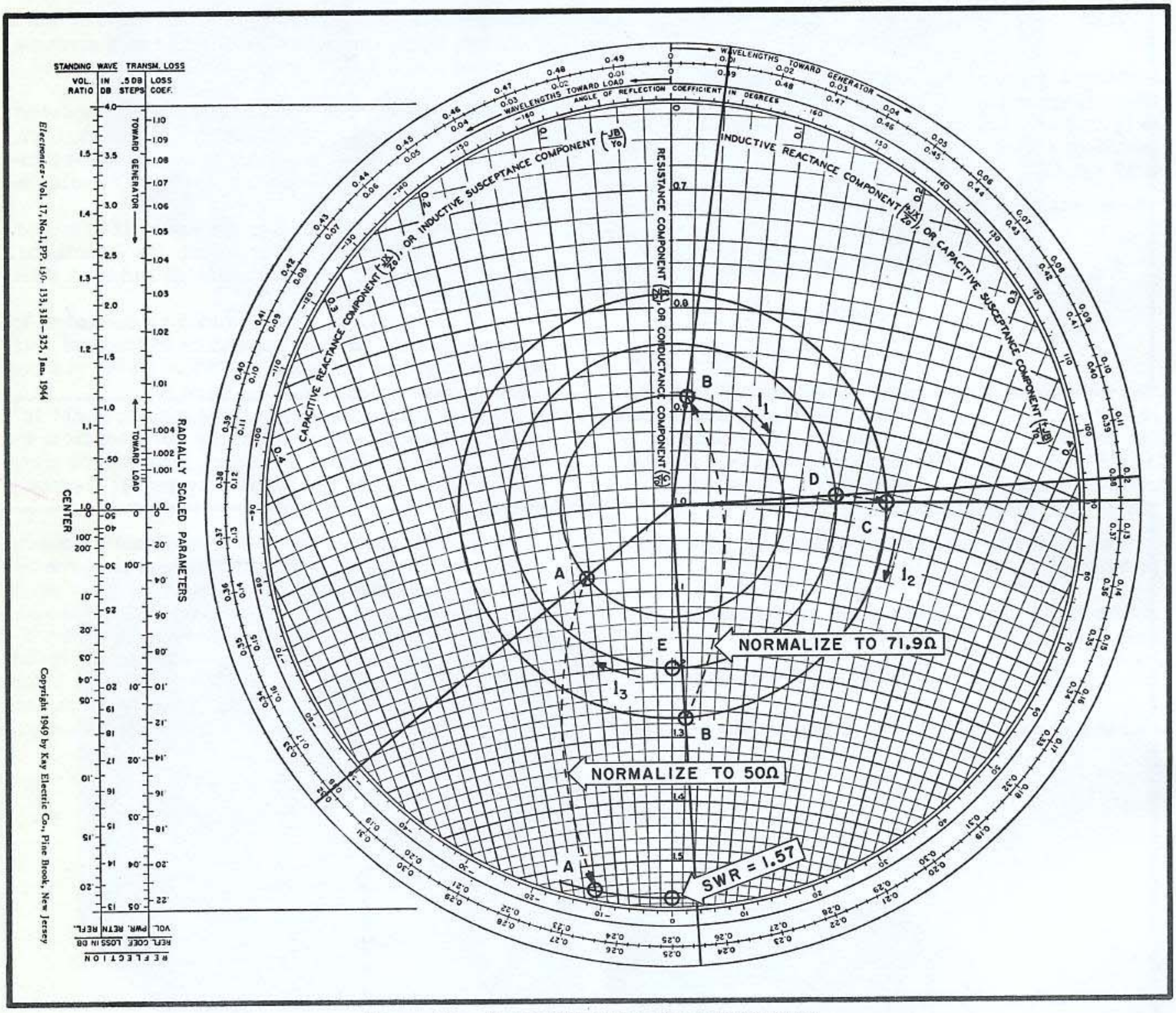
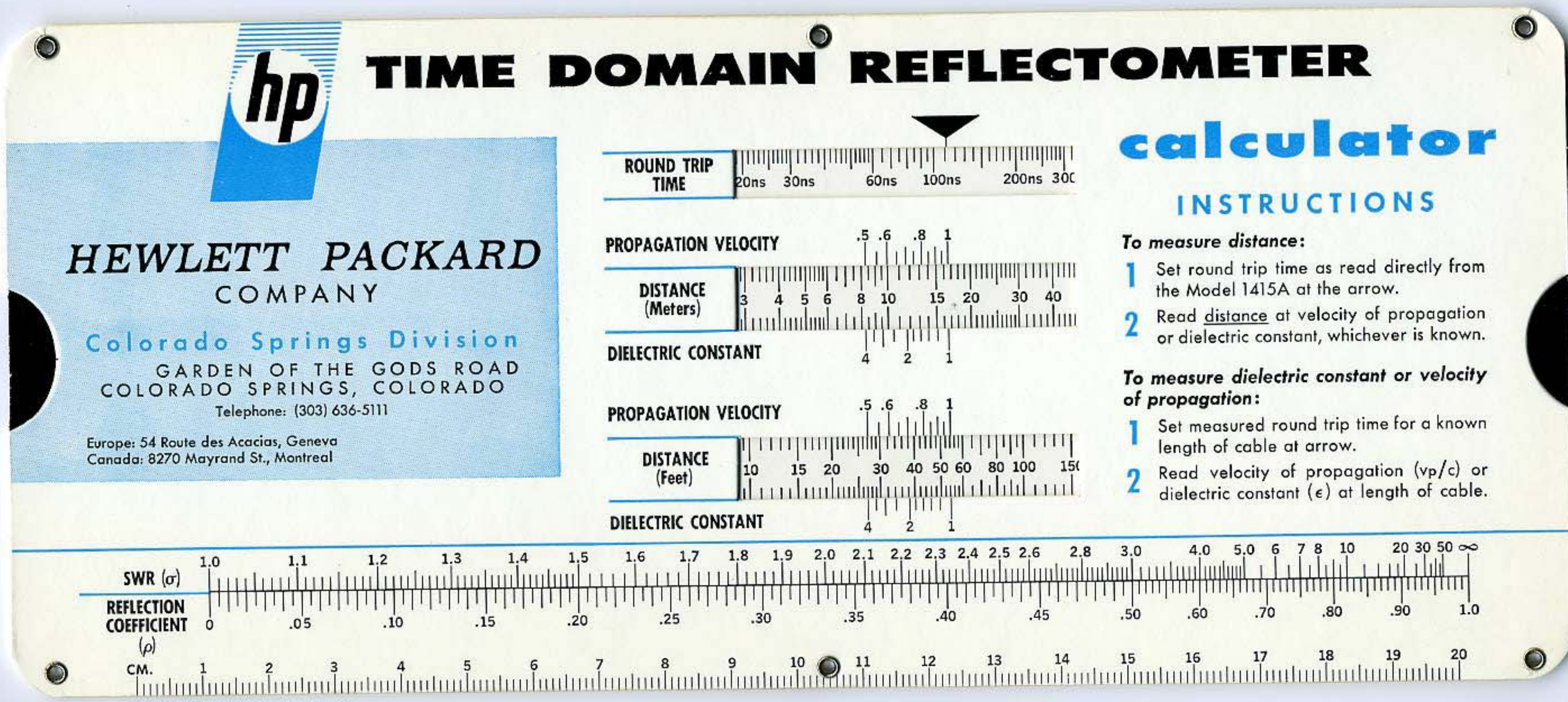


Figure 28. Smith Chart for Antenna System


hp
TIME DOMAIN REFLECTOMETER
calculator
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Europe: 54 Route des Acacias, Geneva
Canada: 8270 Mayrand St., Montreal
ROUND TRIP TIME
20ns 30ns 60ns 100ns 200ns 300
PROPAGATION VELOCITY
.5 .6 .8 1
DISTANCE (Meters)
3 4 5 6 8 10 15 20 30 40
DIELECTRIC CONSTANT
4 2 1
PROPAGATION VELOCITY
.5 .6 .8 1
DISTANCE (Feet)
10 15 20 30 40 50 60 80 100 150
DIELECTRIC CONSTANT
4 2 1
INSTRUCTIONS
To measure distance:
1 Set round trip time as read directly from the Model 1415A at the arrow.
2 Read distance at velocity of propagation or dielectric constant, whichever is known.
To measure dielectric constant or velocity of propagation:
1 Set measured round trip time for a known length of cable at arrow.
2 Read velocity of propagation (vp/c) or dielectric constant (ε) at length of cable.
SWR (σ)
1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.8 3.0 4.0 5.0 6 7 8 10 20 30 50 ∞
REFLECTION COEFFICIENT (ρ)
0 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50 .60 .70 .80 .90 1.0
CM.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

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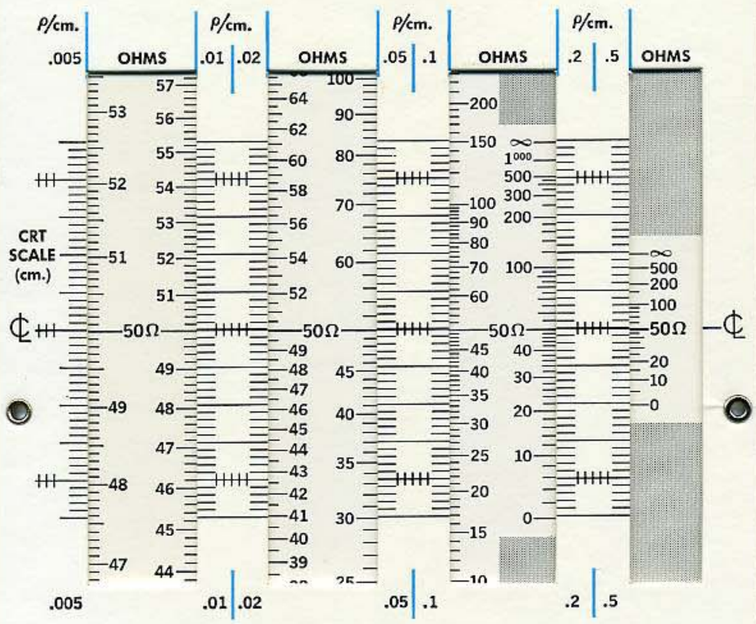
TIME DOMAIN REFLECTOMETER calculator

IMPEDANCE



INSTRUCTIONS

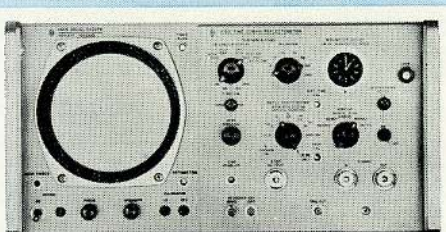
1 On oscilloscope, set the reflection from a known impedance even with the center horizontal graticule line. Note setting of REFLECTION COEFFICIENT (ρ/cm) control.

2 On the appropriate ρ/cm scale of the slide rule, set the known impedance at the center line (℄).

3 Replace known impedance with the unknown, and note the deflection from the center line.

4 Read impedance at appropriate CRT scale marking on slide rule.

If the unknown impedance is the second reflection, apply the appropriate correction factor. (See Application Note 67.)



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