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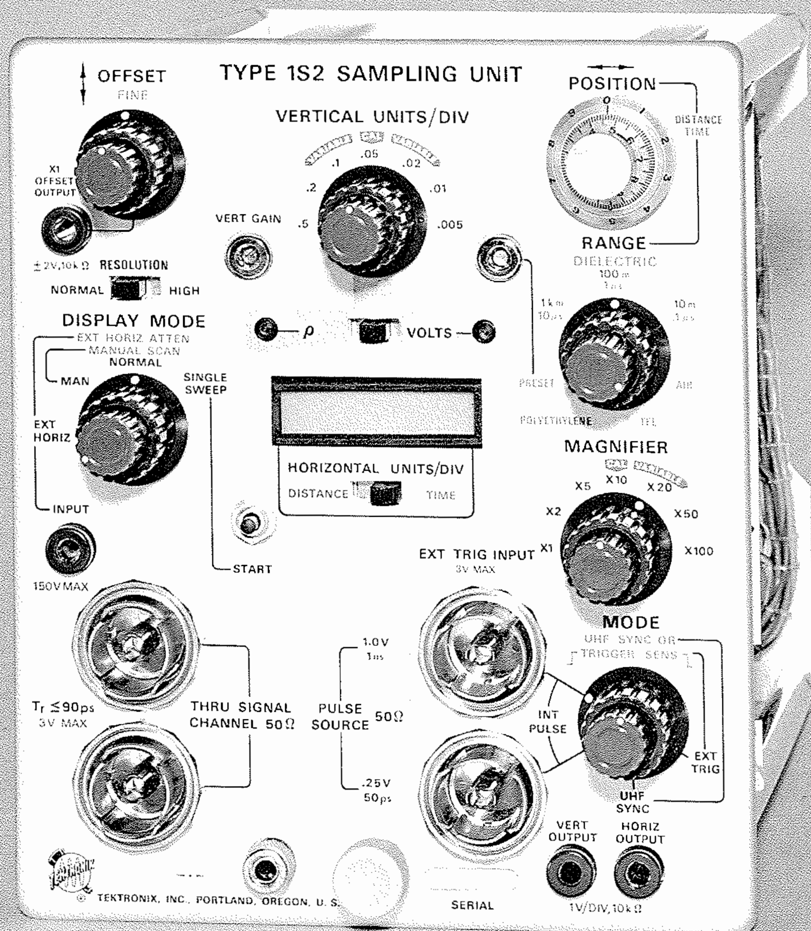


A Discussion of
Time Domain Reflectometry
Theory and Coaxial
Cable Testing.

TIME-DOMAIN REFLECTOMETRY THEORY AND THE TESTING OF COAXIAL TRANSMISSION LINES

INTRODUCTION:

Maintaining the fidelity of electronic signals that of necessity have to be transmitted from point to point is of primary concern to those that design, build and maintain electronic equipment. The simple, inexpensive coaxial transmission line is perhaps the most common method used to accomplish this task. The techniques for determining transmission line performance vary from simple visual inspection to elaborate instrumentation set-ups that require a great deal of skill and time. The availability of instruments such as the Tektronix Type 1S2 TDR Plug-In Unit have simplified the testing of transmission line performance.

This article begins with a comparison between two methods of testing transmission lines - Sinewave testing and Voltage step-function testing. The Sinewave testing method is known as Frequency-Domain Reflectometry (FDR) and the Voltage step-function method is known as Time-Domain Reflectometry (TDR). The FDR-TDR comparison is followed by a basic description of TDR testing principles; reflections from capacitors and inductors; reflections from resistive discontinuities; coaxial-cable response to a step signal; and finally, special applications.

The waveforms illustrated throughout this article were taken with a C-12 Camera using a Type 547 Oscilloscope and the Type 1S2 TDR Plug-In. The Type 1S2 Plug-In converts any Tektronix 530, 540, 550-Series Oscilloscope to a TDR measurement system.

FDR-TDR COMPARISON

Frequency domain reflectometers, the slotted line and bridges, drive and observe the input terminals of a transmission line as a function of frequency. They do not locate discontinuities on a distance basis. As a result, measurement techniques and the unique advantages of such devices differ from those of TDR.

A pure resistance measured by either time domain or frequency domain devices will appear as an infinitely long lossless transmission line. Thus, a perfectly terminated short length of lossless line will yield the same information to both kinds of testing, and neither test system can locate the termination. However, if the termination includes a small inductive or capacitive reactance, both systems will indicate its presence, but the TDR system will show where in the line the reactance is located.

The following comparisons of TDR and frequency domain (FDR) devices are supported by four specific examples and illustrations.

1. FDR measures Standing Wave Ratio (SWR) directly, but a TDR display can speed FDR testing by locating resonant frequencies of resonant networks prior to FDR testing.

2. TDR locates discrete discontinuities and permits analysis of their value. But FDR will indicate two different resonant discontinuities which may be located very close together when TDR may not.

3. FDR measures an antenna standing wave ratio directly while TDR will not. But TDR will locate faults more quickly and identify the type of fault more rapidly than will FDR, should a change in SWR indicate problems. The time domain display will validate a transmission line to an antenna, while frequency domain reflectometry cannot, unless the antenna is disconnected and the transmission line terminated.

4. TDR can locate small changes in transmission line surge impedance (such as a too-tight clamp holding a flexible line) while FDR will show whether or not the SWR is acceptable.

5. Both test systems will quantitatively evaluate single discrete reactances, with higher degree of accuracy possible with FD.

6. Both TDR and FDR have advantages, each being very valuable in its own way. Thus, the two systems complement each other and both aid where observations and measurements are required.

TDR vs FDR Measurements

A one pF discrete capacitor inserted in parallel with a transmission line will produce almost no TDR indication if the step pulse has a risetime of 1 nanosecond. The same capacitor will produce a significant reflection if the step pulse has a risetime of 150 picoseconds. A FDR test will produce a large SWR at the series resonant frequency determined by the capitance and its lead inductance. Such a discontinuity would require considerable time for proper FDR testing due to the numerous frequency test points, but with a fast rise TDR system the capacitance and resonant frequency can be quickly determined.

Fig 1 shows waveforms and SWR curves of first a single capacitor and then two capacitors inserted in parallel with a transmission line. Note that the FDR measurement on the right side of the figure plainly shows the two resonant circuits of the two closely spaced small capacitors, while the TDR display at the left shows two resonant frequencies, but not in a manner to permit separation of the two capacitors.

The single capacitor of this example was made of ¼ inch wide strip copper, ⅝ inch long, with one end soldered to the side of a component insertion unit (Tektronix Part No. 017-0030-00) and the other end near the center conductor. The insertion unit was modified to have a continuous center conductor using three inner transition pieces (Tektronix Part No. 358-0175-00). One of the inner transition pieces was shortened to fit between the two mounted end pieces, and then soldered in place. The second capacitor (resonant at 2.1 GHz) was a 0.5 to 1.5 pF piston trimmer with a total lead length of about 5/16 inch, and it was adjusted to about 1.2 pF. The piston capacitor was soldered in place in parallel with the strip copper capacitor about ⅛ inch away. It is obvious from both testing methods that neither capacitor was critically damped by the characteristic impedance of the transmission line. The physical and equivalent circuit of the single shunt capacitor is shown in Fig 2. The single capacitor test was made with a shield in place completely covering both openings.

Fig 3 shows the ability of TDR to locate an off-impedance point in a transmission line, and quickly resolve its value. The same through-connected insertion unit used in example number 1 was tested without any component inserted in it. The shield was in place for both TDR and FDR testing.

The TDR display of Fig 3 shows the increased surge impedance due to the increased diameter of the outer conductor at the two cutout access slots. Such a TDR display will permit rather rapid correction to be made to the center conductor diameter if one desires to make a truly constant impedance through the length of the insertion unit.

The SWR curve shows some changes from a constant impedance transmission line, but does not help to locate an aberration if it is inside a continuous piece of cable. Either FDR or TDR would help one to make the unit have a constant impedance if such a unit were being designed.

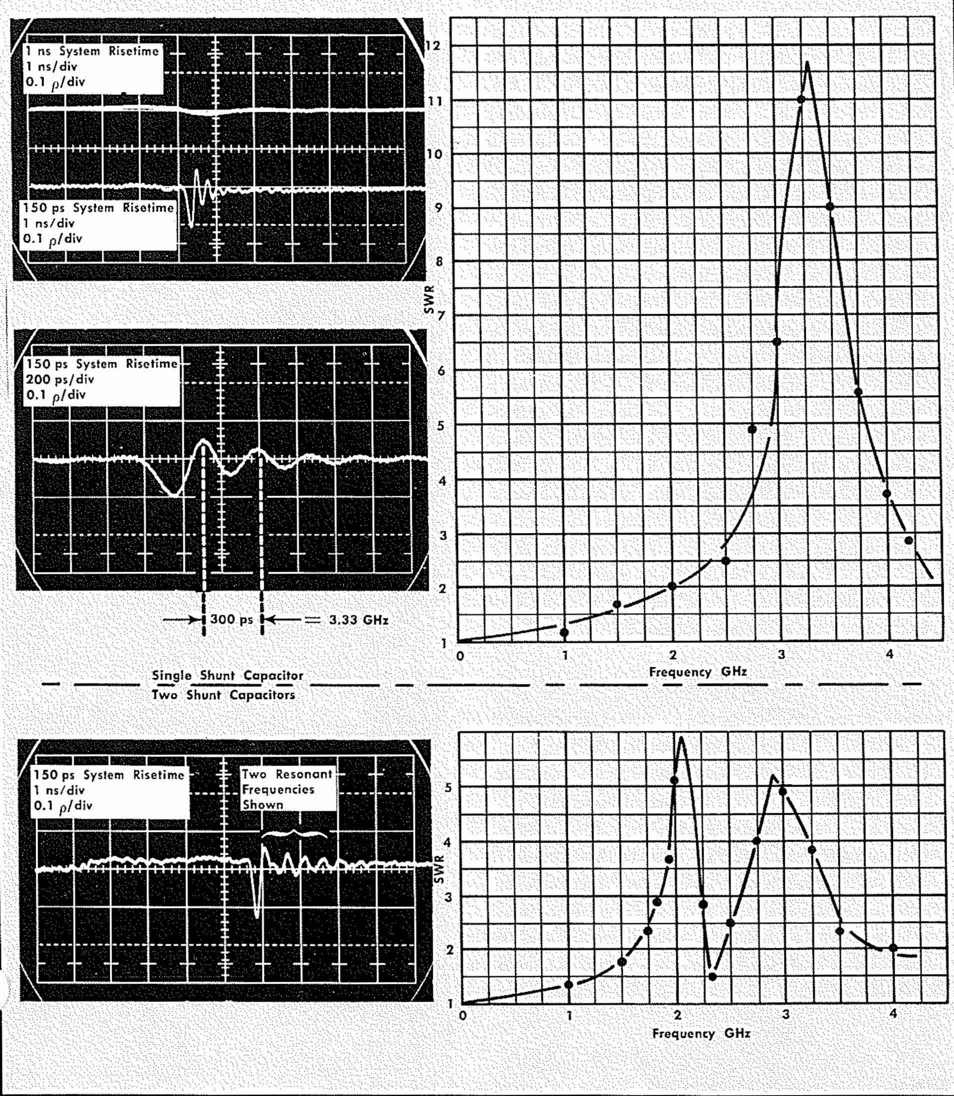


Fig 1. Two examples of discrete shunt capacitors.

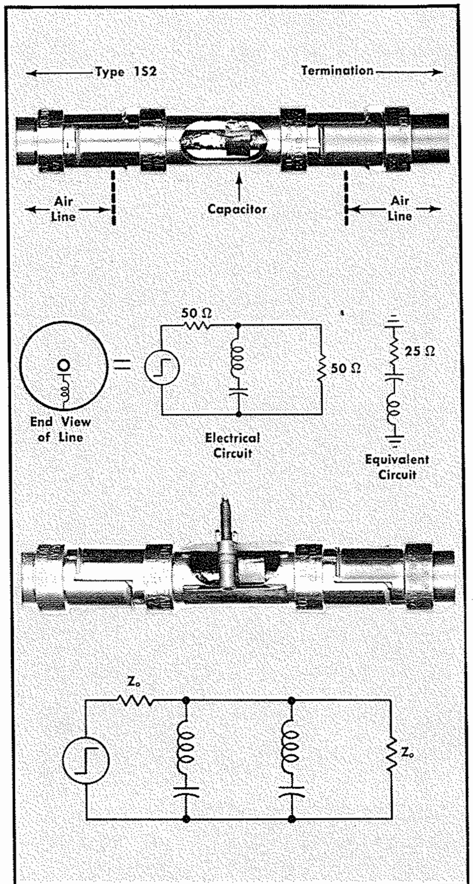


Fig 2. Capacitors measured in Fig 1.

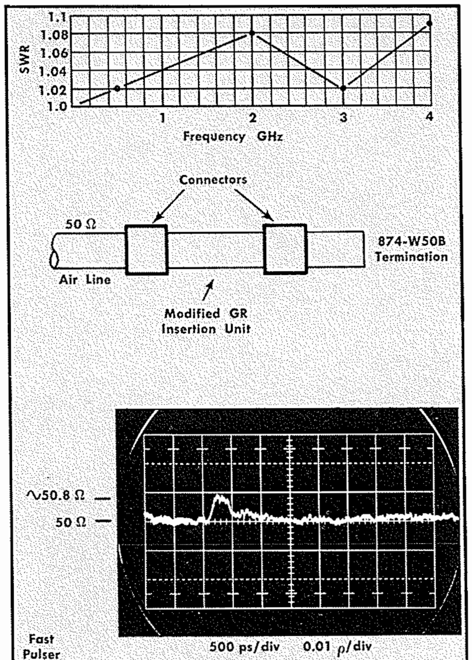


Fig 3. Modified (through-connected) Tektronix Insertion unit for testing small components in parallel with 50 Ω line.

Fig 4 shows two TDR and two SWR plots of a simple dipole antenna. The TDR waveforms at the left were photographed first, quickly locating the two radiating resonant frequencies and permitting a saving in time for the FDR testing. The SWR curves permit a direct evaluation of the antenna radiation resistance ($\frac{R_L}{Z_0} = \frac{V_{max}}{V_{min}}$ if R_L is purely resistive), while the TDR display tells only the transmission line quality and the radiating resonant frequencies of the non-shorting type antenna. An antenna design engineer could use the SWR data and FDR test equipment to test a compensating network to be located at the antenna to minimize standing waves in the transmission line. The TDR system cannot be used for such design assistance.

Fig 5 shows both TDR and FDR tests of a General Radio Type 874-K series blocking capacitor. The upper TDR display permits direct calculation of the series capacitance, in this case approximately 6.2 nanofarads (0.0062μF).

The SWR curve shows that the series capacitor does not upset the transmission line significantly except for low frequencies. The middle TDR waveform shows the change in surge impedance due to the physical shape of the series capacitor. Note that the disc capacitor reduces the transmission line surge impedance to approximately 49 ohms for only a very short period of time. The same display also permits the precise location of adjacent discontinuities that affect the high frequency performance. The combined TDR and FDR data tells more about the series capacitor unit than either testing method does alone.

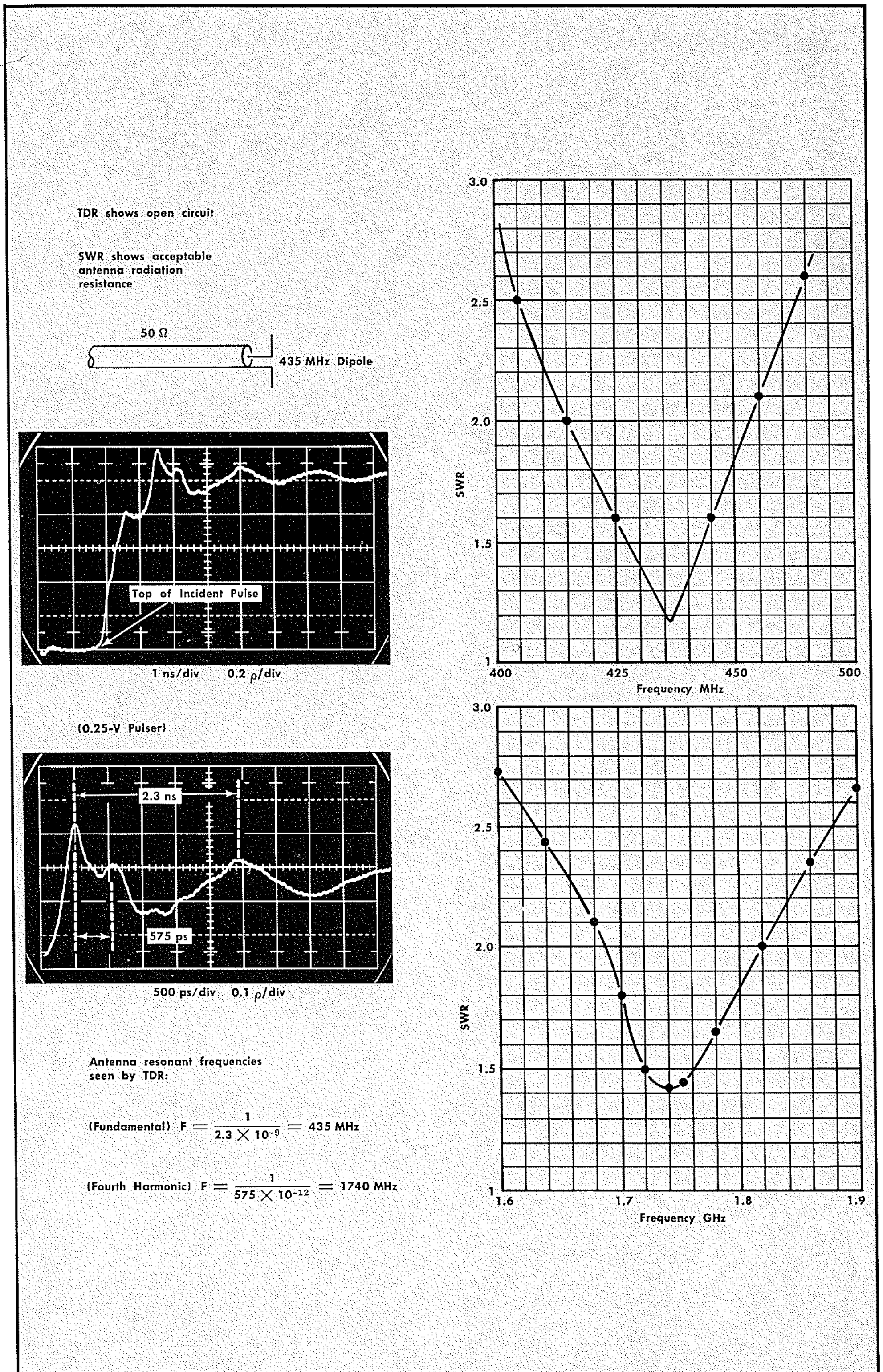


Fig 4. Two plots of 435 MHz dipole antenna.

BASIC APPROACH TO TDR

Time Domain Reflectiometry can be understood most easily if its operation is first compared with a DC circuit.

DC Analogy

Fig 6 shows three simple circuits that can be related to transmission lines and TDR. Fig 6A is the diagram of an ordinary resistance voltage divider, where the voltage across

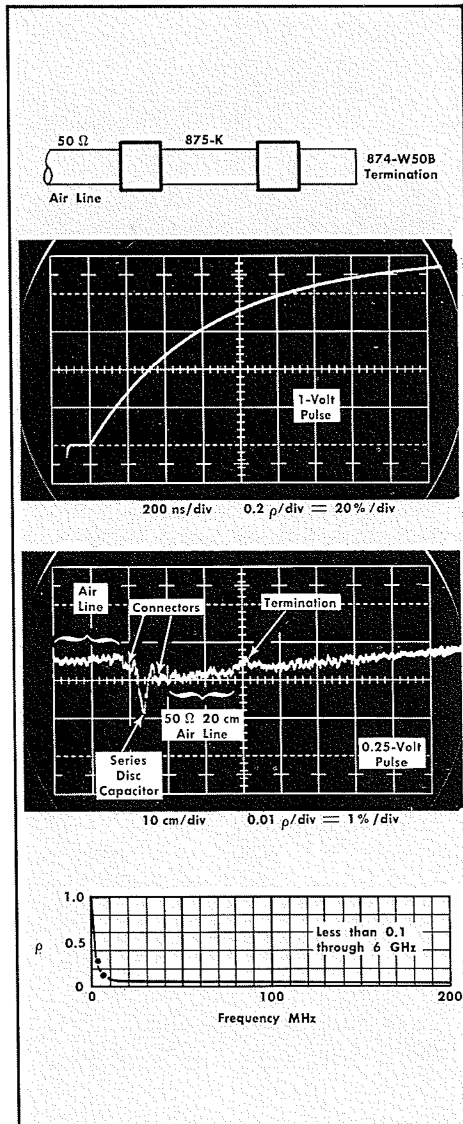


Fig 5. Series blocking capacitor: General Radio Type 874-K.

R_2 is $E_{R2} = \frac{R_2}{R_1 + R_2} \times E$ of the battery. (1)

Fig 6B substitutes R_{line} (or Z_o) for R_2, and substitutes R_g (generator resistance) for R_1. It is assumed the battery has zero internal resistance and that R_g is an inserted series generator resistance. If the battery is 1 volt and if $R_g = R_{line}$, then a voltmeter across R_{line} will indicate 0.5 volt when the switch is closed.

Fig 6C indicates a pair of zero resistance wires of same length physically connecting R_{line} to the battery and switch. A voltmeter across R_{line} will still indicate 0.5 volt when the switch is closed.

Adding the Time Dimension

Fig 7 substitutes a step generator for the battery and switch of Fig 6. The generator has zero source resistance so R_g is again added in series with the generator. The generator and R_g drive a finite length transmission line that has a characteristic impedance of Z_o. The transmission line has output terminals that permit connecting a load R_L. An oscilloscope voltmeter measures the voltage signal(s) at the input end of the transmission line.

Assume that no load resistance is connected to the transmission line output terminals ($R_L = \infty$) and that $R_g = Z_o$ (Z_o acts exactly as if it were the DC resistor R_{line} of Fig 6). As the zero impedance step generator applies its 1-volt step signal to R_g, the oscilloscope voltmeter indicates 0.5 volt. The oscilloscope voltmeter will continue to indicate a 0.5 volt signal until the wave has traveled down the line to the open end, doubled in amplitude due to no current into $R_L = \infty$, and reflected back to the generator end of the line. The oscilloscope finally indicates a signal of 1 volt after the measurable period of time required for the step signal to travel down and back the finite length of open ended transmission line.

Reflection Signal Amplitudes

Fig 8 shows TDR oscilloscope (voltmeter) displays related to the value of R_L vs the value of the transmission line Z_o. Apply resistance values of 50 Ω to R_g and Z_o, and 75 Ω to R_L of Fig 7. By formula (1), the oscilloscope display of the reflection amplitude will be 0.6 volt. The actual reflection, however, is only 0.1 volt added to the 0.5-volt incident step.

Reflection Coefficient

A somewhat more convenient method of handling signal reflections than has just been suggested, is to consider the reflection as having been added to or subtracted from the incident pulse. Thus the reflection amplitude is not measured from zero volts, but is referenced to the incident signal amplitude. This permits establishing a ratio between the incident and reflected signals which is called the reflection coefficient, rho (ρ). The value of ρ is simply the reflected pulse amplitude (the display total amplitude minus the incident pulse amplitude) divided by the incident pulse amplitude. Fig. 9 shows the two parts of the display appropriately labeled to identify the incident and reflected signals.

When $\rho = 0$, the transmission line is terminated in a resistance equal to its characteristic impedance Z_o. If the line is terminated in $R_L > Z_o$, then ρ is positive. If the line is terminated in $R_L < Z_o$, then ρ is negative. The dependence of ρ on the transmission line load is

$$\rho = \frac{R_L - Z_o}{R_L + Z_o} \qquad (2)$$

If ρ is known, R_L can be found by rearranging formula (2);

$$R_L = Z_o \left(\frac{1 - \rho}{1 + \rho}\right) \qquad (3)$$

Formula (3) applies to any display that results from a purely resistive load. The load shown in Fig 9 is assumed to be at the end of a lossless coaxial transmission line.

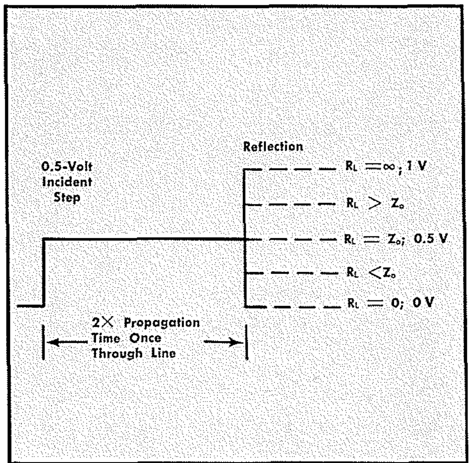


Fig 8. Oscilloscope voltmeter displays for circuit of Fig 7, dependent upon value of R_L vs. Z_o.

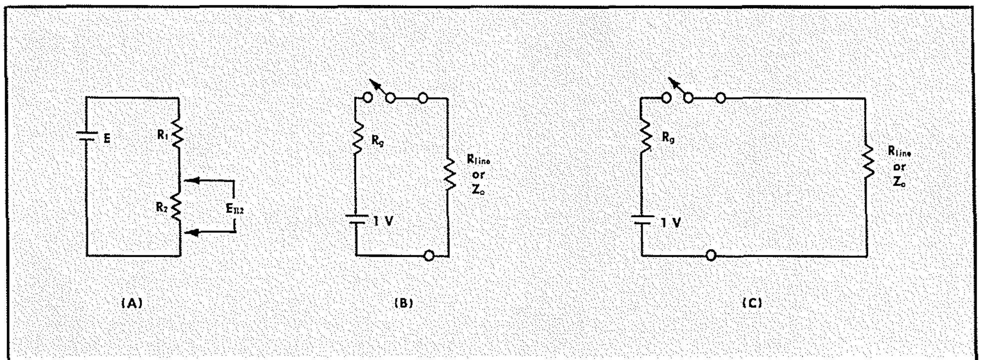


Fig. 6. Circuits showing DC analogy of TDR.

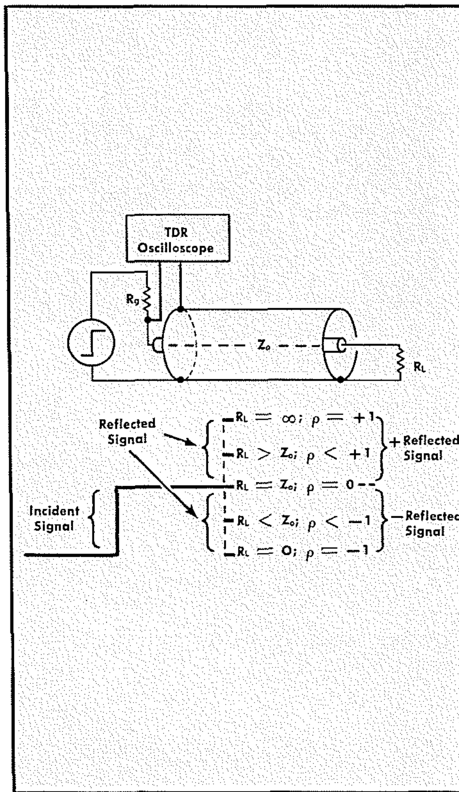


Fig 9. TDR oscilloscope displays for various values of R_L vs Z_o.

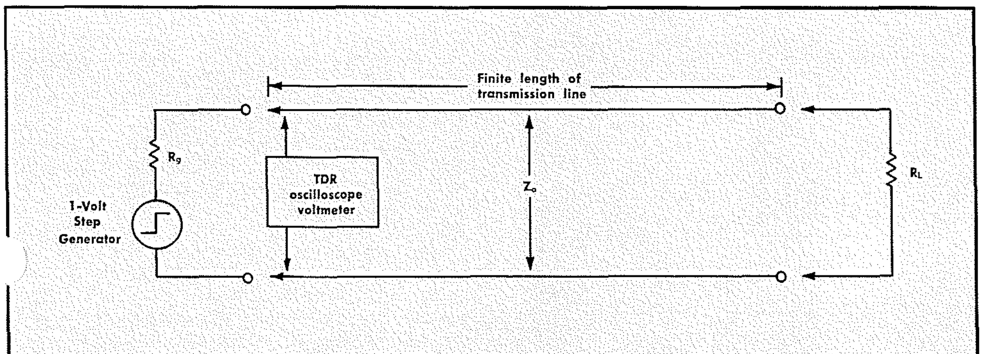


Fig 7. Adding the time dimension to the circuit of Fig 6.

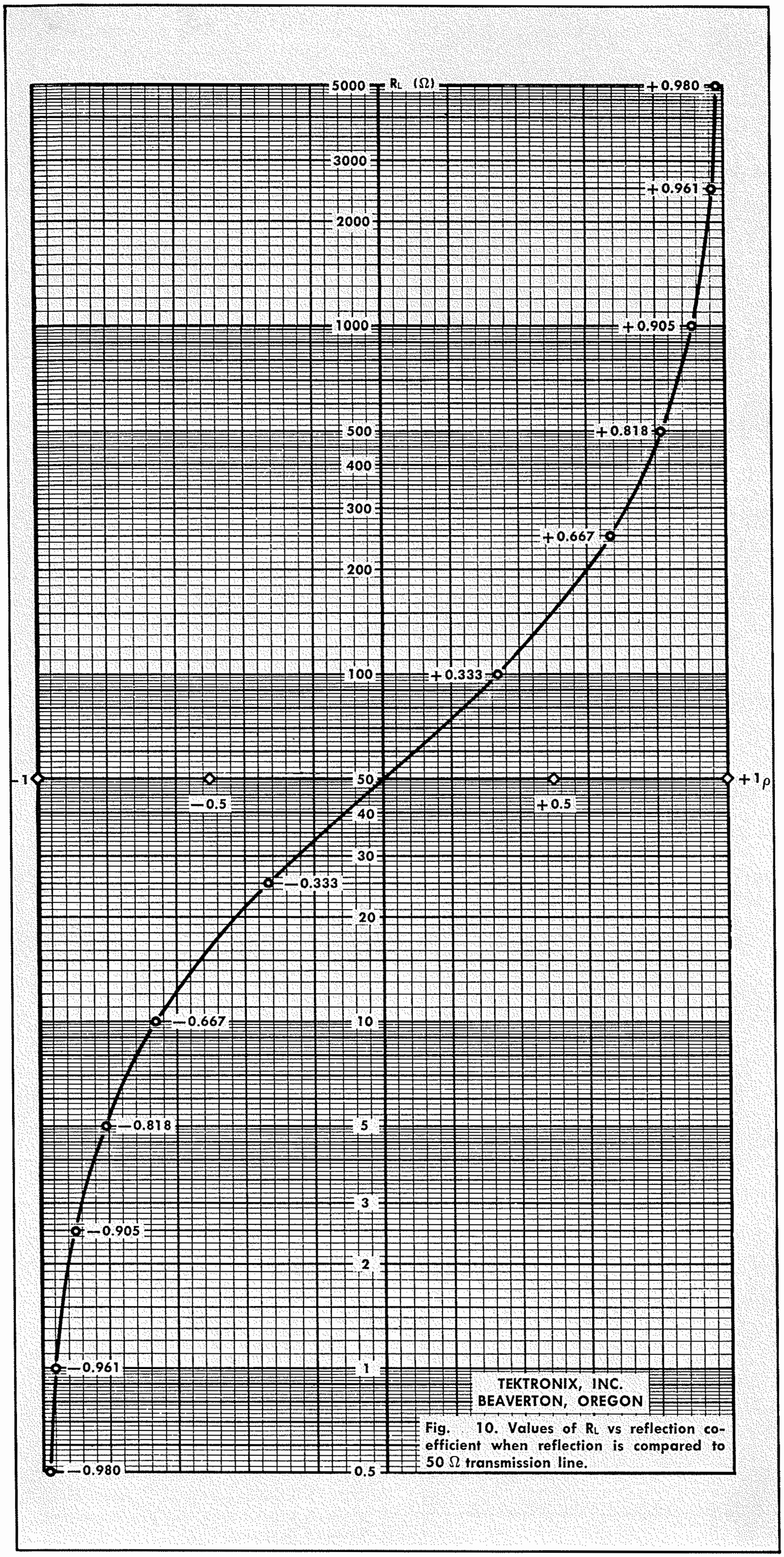


Fig. 10. Values of R_L vs reflection coefficient when reflection is compared to 50 Ω transmission line.

Substituting 50 Ω for Z_o in formula (3), calculations for small values of ρ show that each division of reflected signal is approximately equal to a certain number of ohms. Table 1 lists the ohms per division for vertical deflection factors of 0.005 ρ, 0.01 ρ and 0.02 ρ. Or, for R_L values near 50 Ω, you may use the approximation formula

$$R_L \approx 50 + 100\,\rho.$$

This approximation formula has an error of $\leq$ 2.2% for absolute values of $\rho \leq 0.1$ and an error of $\leq$ 8% for absolute values of $\rho \leq 0.2$.

R_L for reflections with ρ up to essentially +1 or —1 can be quickly determined using the graph of Fig 10. Fig 10 is based upon a transmission line surge impedance of 50 Ω just prior to the discontinuity that causes the reflection signal. The graph of Fig 10 may be photographically reproduced without special permission of Tektronix.

TABLE 1

R_L Approximations For Reflection Coefficients of 0.005, 0.01 and 0.02 Related to a 50 Ω Transmission Line

ρ/div	Ω/div	Error/div
0.005	½	~0.016 Ω
0.01	1	~0.066 Ω
0.02	2	~0.2 Ω

REFLECTIONS FROM CAPACITORS AND INDUCTORS

Contrary to frequency domain measurements, TDR response to a reactance is only momentary. Thus either an inductor or a capacitor located in a transmission line will give only a short duration response to the TDR incident pulse. Analysis of large reactances is relatively simple and makes use of time-constant information contained in the reflection display. Small reactances are not so simple to evaluate quantitatively, so will be treated separately.

Large Reactances

The difference between a "large" and a "small" reactance is not a fixed value of capacitance or inductance, but is instead related to the TDR display. If the displayed reflection includes a definite exponential curve that lasts long enough for one time constant to be determined, the reactance is considered "large".

Discrete (single) capacitors connected in series or parallel with a transmission line start to charge at the instant the incident pulse arrives. Inductors start to conduct current at the arrival of the incident pulse. Both forms of reactance cause an exponentially changing reflection to be sent back to the TDR unit. When a capacitor is fully charged, the TDR unit indicates an open circuit. When an inductor is fully "charged" (current through it has reached its stable state), the TDR unit indicates a short circuit. The TDR unit will indicate an inductor's series DC resistance if its value is significant in relation to Z_o. The general form of reflection and long term effect upon the TDR display by both inductors and capacitors is listed in Table 2 and Table 3.

Finding One Time Constant

In practice, TDR reactance displays usually contain aberrations of the desired pure exponential reflection. Such aberrations prevent finding the normal 63% one time-constant point of the curve accurately. (The aberrations are due to either the environment around the reactance, i.e. stray inductance in series with a capacitor, or stray capacitance in parallel with an inductor, or secondary system reflections.) However, accurate time-constant information can be obtained from less than a complete exponential curve. The principle used requires that a "clean" portion of the display must exist. The "clean" portion used must include the right-hand "end" of the displayed curve (a capacitor is then fully charged, or an inductor current has stopped changing). The "end" of the curve will appear on the display to be parallel to a horizontally scribed graticule line. Thus, aberrations that exist at the beginning of the curve can be ignored.

Fig 11 shows the first example of obtaining valid time-constant information from less than a full 100% exponential curve. The technique is to choose any "clean" portion of the display that includes the "end" of the exponential curve and find the half-amplitude point. The time duration from the beginning of any new 100% curve section to its 50% amplitude point is always equal to 69.3% of one time constant. Thus, the time duration for a 50% change divided by 0.693 is equal to one time constant.

Fig 11 shows the TDR displays of a capacitor placed in series with a transmission line center conductor (2 Z_o environment). This picture and the other waveform pictures shown in this article were taken with a Tektronix C-27 Camera mounted on a Tektronix Type 547 Oscilloscope with a Tektronix Type 1S2 Reflectometer and Wideband Sampling Plug-In Unit. Fig 11A waveforms comprise a double exposure with the left curve taken while the Type 1S2 RESOLUTION switch was at NORMAL and the right curve taken when the switch was at HIGH. Both curves give sufficient information to measure one time constant. Note that the top of the incident pulse is indefinite (in the displays) due to the sweep rate and short length of cable used between the Type 1S2 and the capacitor. Such a display does not have a definite beginning of the normal 100% exponential curve. This prevents 63% of the total curve from being read directly from the display. (It is also quite possible for lead inductance to cause a capacitor to ring. When a TDR display shows capacitor ringing, the ringing can sometimes be reduced by: 1. using the slower 1-Volt pulser, and/or 2. changing the transmission line environment to place a lower value Z_o in parallel with the capacitor.)

The double exposure of Fig 11B shows a full exponential curve beginning in the vicinity of 1 division from the graticule bottom. Then the same curve has been time-expanded for easier reading. The indefinite beginning of the 500 ns/DIV exponential curve prevents finding one time constant by measuring the time of 63% of the total curve amplitude. The new arbitrarily chosen 100% amplitude portion of the curve begins at the graticule center horizontal line and extends (off the right of the graticule) to the top graticule line. Three divisions were chosen for the new 100% exponential curve, with the 100% and 50% points marked. Then, dividing the time for the 50% amplitude change by 0.693 gives a total one time-constant time value of 650 ns. Since the equivalent circuit shows 2 Z_o in series with the capacitor, its value is found by formula (4) (Table 4) to be 6.5 nanofarads.

TABLE 3

Single Capacitor or Inductor TDR Displays when Connected Across End of Transmission Line

Reactance	Display	Line Impedance at Reactance
CAPACITOR		Z_o
INDUCTOR		Z_o

Large Capacitors

The difference between a "large" and a "small" capacitor is not a fixed value of capacitance, but is instead related to the TDR display. If the display includes a definite exponential curve that lasts long enough to permit one RC time constant to be determined, the capacitor value can be found by using a normal RC time-contsant formula). The actual formula varies according to the equivalent circuit in which the capacitor is located. Table 4 lists the possible configurations and their related formulae.

The first example of "large" capacitance measurement was given under the previous heading Finding One Time Constant. The large value of capacitor used is easy to measure and usually causes only one aberration to the exponential curve. That aberration is the indefinite curve beginning.

Moving A Reflection Aberration

When testing small capacitors that still produce a usable exponential curve, it may be difficult to get accurate time-constant data when there are reflections within the system.

Reactance	In Series with Line	In Parallel with Line	Line Impedance at Reactance
CAPACITOR			SERIES: 2 Z_o PARALLEL: $\frac{Z_o}{2}$
INDUCTOR			SERIES: 2 Z_o PARALLEL: $\frac{Z_o}{2}$

TABLE 2 Single Capacitor or Inductor TDR Displays Related to Terminated Transmission Lines.

Circuit		Equivalent Circuit	Formula	Display
Series with terminated line			$C = \frac{1}{2}\frac{TC}{Z_o}$ (4)	
Parallel with terminated line			$C = \frac{1\ TC}{Z_o/2}$ (5)	
Across line end			$C = \frac{1\ TC}{Z_o}$ (6)	

Where C = Farads; TC = Time Constant; Z_o = Line Surge Impedance.

TABLE 4 "Large" Capacitor Circuits and Formulae.

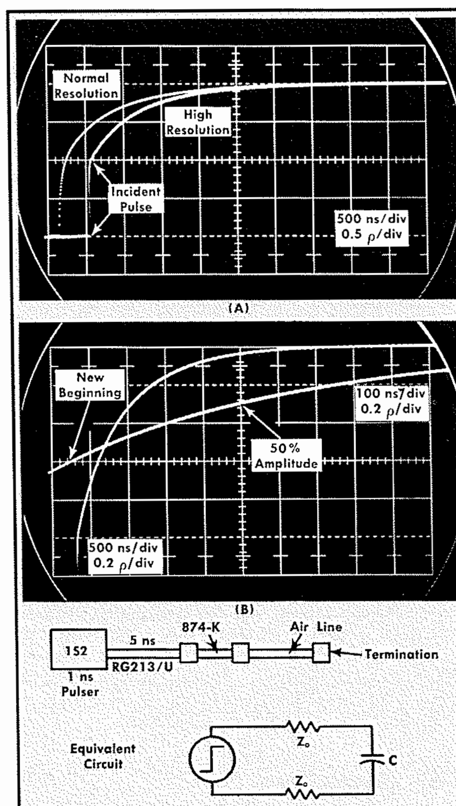


Fig 11. Exponential curves and circuit of 6.5 nF capacitor in series with terminated transmission line.

For example, a 100 pF discap was soldered into a General Ratio Radiating Line section (Fig 12). The 1-Volt pulser was used; re-reflections from the pulser distort the exponential curve at the arrow of Fig 12A. The re-reflection is moved to the right just outside the time window by placing a 20 nsec signal delay RG213/U cable between the pulser and the sampler. The acceptable waveform is shown in Fig 12B. Fig. 12C is a double exposure that shows first how the "end" of the exponential curve is set to a graticule line. Then the display is time expanded to 500 ps/DIV (leaving the vertical position as adjusted) and the new arbitrary 100% exponential curve is chosen and marked. The capacitor's value taken from the time expanded curve of Fig 12C and using formula (5) is 104 pF ($1.8 \times 10^{-9}/0.693 \div 25 = 1.04 \times 10^{-10} = 104$ pF). Note that the vertical ρ factor was changed for Fig 12C in order to make the time constant measurement from a clean section of the curve near its end.

Large Inductors

The difference between "large" and "small" inductors follows the same general display limits as large or small capacitors. A "small" inductor in series with a transmission line center conductor will give a display that does not permit normal time-constant analysis. The same inductor in parallel with a terminated transmission line may give a display that does allow normal time-constant analysis.

Ringing in the exponential TDR display is often observed when measuring inductors. It is usually caused by distributed capacitance across the coil that has not been adequately damped by transmission line surge impedance. Since an inductor with stray capacitance will ring unless adequately damped, an inductor in parallel with a transmission line ($Z_o/2$ environment) will be less likely to ring than the same inductor in series with a line ($2\ Z_o$ environment).

Fig 13 shows waveforms taken of the reflections from a seven turn ⅜ inch diameter coil. The coil was connected across the end of a 50 Ω transmission line (Z_o environment). Fig 13A was made using the Type 1S2 0.25-Volt fast pulser at High Resolution. The ringing makes it impossible to obtain an accurate time constant measurement from the display. Fig 13B was made using the Type 1S2 1-Volt pulser at Normal Resolution. Here the slower risetime incident pulse does not excite the ringing, and in addition the time averaging of fast changes by Normal-Resolution operation permits a time constant to be measured. Ringing could also have been reduced by a $Z_o/2$ environment by placing a termination across the inductor, or placing the inductor at a convenient mid point of a long line.

The triple exposure of Fig 13B includes three curves: #1, the total reflected signal at 10ns/div and 0.5 ρ/div; #2, increased vertical deflection and the exponential-curve end positioned to be one division below the graticule center horizontal line; and #3, the #2 curve time expanded to 1 ns/div for measurement of the L/R time constant. The new 100% to 50% amplitude time duration of curve #3 is shown as 3¾ ns. $3.75/0.693 = 5.41$ns for 1 time constant. Since the coil is at the end of a 50 Ω transmission line, the inductance is calculated by formula (9) of Table 5 to be 270.5 nH ($L = 50 \times (5.41 \times 10^{-9}) = 2.705 \times 10^{-7} = 270.5$ nH).

Small Reactances

"Small" reactances are here defined as series-connected inductors and shunt-connected capacitors that cause TDR reflections without apparent time-constant reaction to the incident pulse. Some small reactances are capable of being "charged" (capacitor voltage is stable; inductor current is stable) at a rate faster than the 0.25-Volt pulser incident pulse rate of rise. If the TDR display has no exponential section, normal RC and L/R calculations cannot be made. All small reactances generate TDR reflections with less than $+1\ \rho$ or $-1\ \rho$.

Small discrete capacitors with leads always include stray series inductance of a significant amount. Fig. 1 and associated discussion is an example of such a capacitor with inductive leads. Small shunt capacitors without leads may be produced by either an increase in a coaxial cable center conductor diameter or a reduction of its outer conductor diameter. Leadless capacitors are sometimes treated as a small reduction in Z_o rather than as a capacitor. Usually, such small capacitors are considered capacitance when the section of reduced Z_o line is so short physically that no level portion can be seen in the TDR display.

Small series inductors rarely have sufficient parallel (stray) capacitance to be significant in the TDR display. However, the coaxial environment around such a small inductor does affect the TDR display. Small series inductors without capacitive strays are sometimes caused by changes in diameter of a coaxial cable: decreased center conductor diameter, or increased outer conductor diameter. This form of inductor is usually treated as a small increase in Z_o rather than as an inductor. Usually, such inductors are considered to be inductance when the section of increased Z_o line is so short physically that no level portion can be seen in the TDR display.

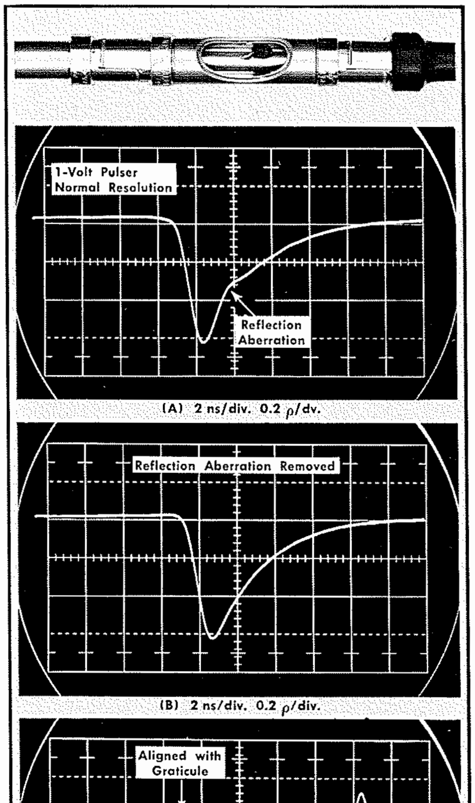


Fig 12. Example of moving display reflection aberrations to obtain a "clean" exponential curve.

Assumptions that Permit Analysis of Small Reactances

The usual TDR system does not have the required characteristics for accurately measuring small reactances. Yet small reactances can be measured provided the following assumptions are made regarding the TDR system.

1. That the actual TDR system may be adequately described by a model having a simple ramp as the pulse source and a lossless transmission line with an ideal sampler;

2. That the rounded "corners" of the actual pulse source may be ignored;

3. That the transmission line high frequency losses classed as "skin effect" or "dribble up" are not significant. ("Dribble up" is explained under Measuring Technique in connection with Fig 17).

4. That the sampler is non-loading, non-distorting and of infinitesimal risetime;

5. That parasitic (stray) reactances are insignificant.

The formula for small series inductance and small shunt capacitance in a tranmission line contain factors for (1) the system risetime at the spatial location of the reactance, (2) the observed reflection coefficient, and (3) the transmission line surge impedance.

The system risetime may be measured from the display by placing either an open circuit or a short circuit at the spatial location of the reactance.

The value for a small series inductor can be calculated using the formula

$$L = 2.5\ \alpha\ Z_o\ t_r \qquad (10)$$

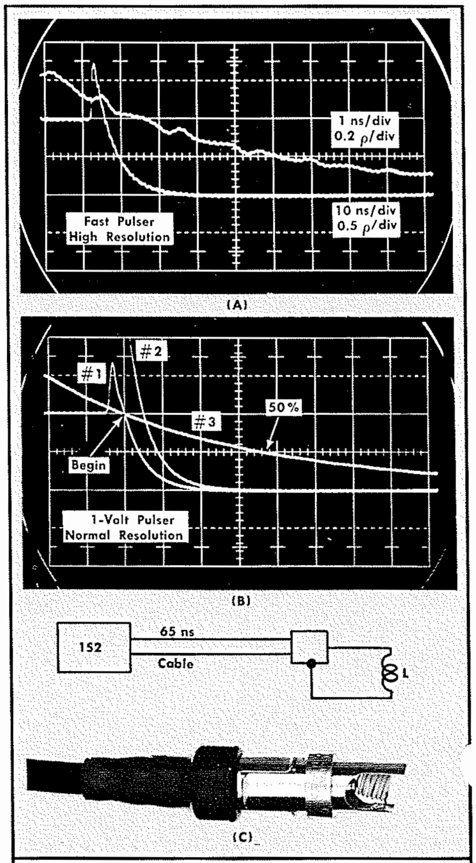


Fig 13. Seven turn coil across end of 50 Ω line.

where L is in henries, Z_o is in ohms, t_r is the system 10% to 90% risetime in seconds, and α is a dimensionless coefficient related to the observed reflection coefficient ρ by either the graph or Fig 14, or formula (11).

$$|\rho| = \alpha \left(1 - \varepsilon^{\frac{-1}{\alpha}}\right) \qquad (11)$$

A small shunt capacitor's value can be calculated using the formula

$$C = \frac{2.5\ \alpha\ t_r}{Z_o} \qquad (12)$$

where C is in farads, and the other units are as in formula (10).

Circuit	Equivalent Circuit	Formula	Display
Series with terminated line		(7) $L = 2\ Z_o \times 1\ TC$	
Parallel with terminated line		(8) $L = \frac{Z_o}{2} \times 1\ TC$	
Across line end		(9) $L = Z_o \times 1\ TC$	

TABLE 5 "Large" Inductor Circuits and Formulae

Small Series Inductor

Fig 15 is an example of TDR displays from a small inductor (1¾ turn) placed in parallel with a 50 Ω line at (A), and in series with the 50 Ω line at (B). Calculations were made on Fig 15A first because the display is a clean exponential that permits L/R time constant analysis. Waveforms #1 and #2 of Fig 15A show first the full exponential decay through five CRT divisions, then at #2 the waveform was positioned vertically so the exponential end is at —1 division. Waveform #3 used the same vertical calibration, but was time expanded to obtain the new 100% to 50% time duration.

The time duration of the 50% amplitude change section of the exponential curve is 450 ps. This time divided by 0.693 produces a one time-constant time duration of 650 × 10^{-12} seconds. Then from formula (8), the value of the inductor is 16.22 nH (1.622 × 10^{-8} H).

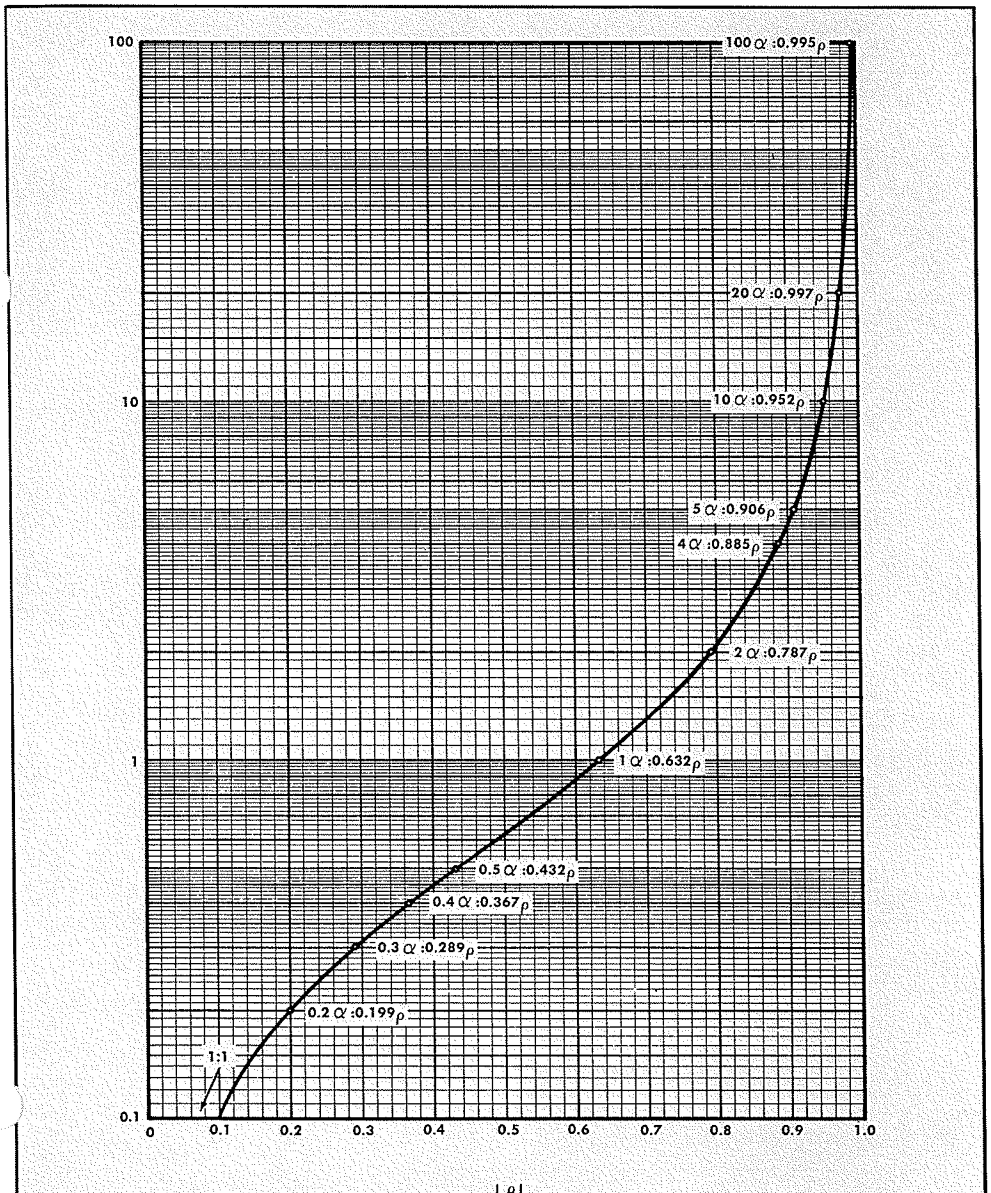


Fig 14. Graph for conversion of small reactance observed ρ to α for use in formulae (10) and (12).

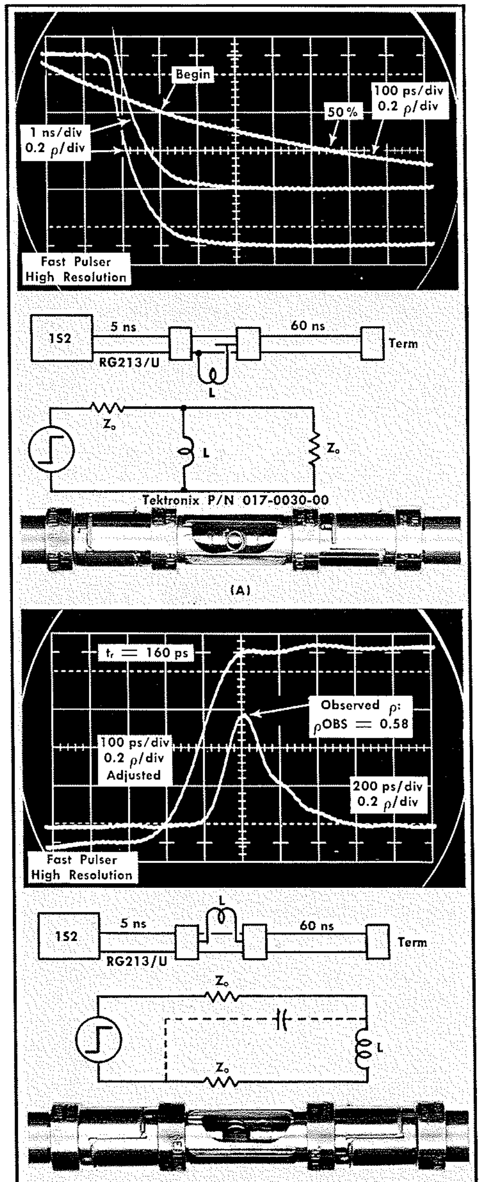


Fig 15. (A) 1¾ turn coil in parallel, (B) same coil in series, with 50 Ω coaxial line.

The waveform of Fig 15B has an observed deflection coefficient of +0.58. From the graph of Fig 14, 0.58 ρ is equal to 0.82 α. The risetime of the system was found to be 160 ps by disconnecting the insertion unit in which the inductor was located and measuring the reflection signal risetime. These figures placed into formula (11) give a value for the series inductor of 16.4 nH (1.64×10^{-8} H). This correlates very well with the previous parallel measurement.

Small Shunt Capacitor

Fig 16 is an example of a small shunt capacitor placed across a 50 Ω coaxial cable by compressing the cable outer diameter. Since the cable (RG8A/U) has normal impedance variations along its length, the peak reflection from the capacitor can only be approximated. Assuming a ρ of —1 division in Fig 16, then by formula (12), the capacitance is approximately 0.085 picofarads.

The Type 1S2 is useful for observing similar small discontinuities along transmission lines. In particular, high quality cable connectors can be evaluated for their ability to maintain a constant impedance where two cables are mated. Or, the quality of production installation of high quality connectors to flexible cable can be easily evaluated.

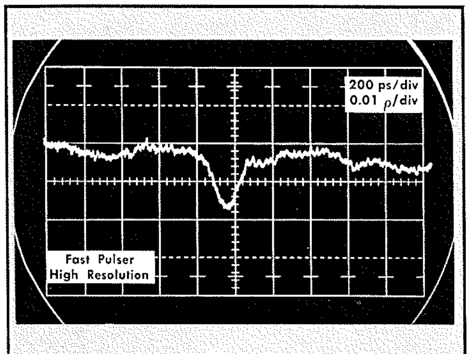


Fig 16. Shunt capacitor, ≈0.085 pF, caused by compressing RG8A/U coaxial cable with pliers.

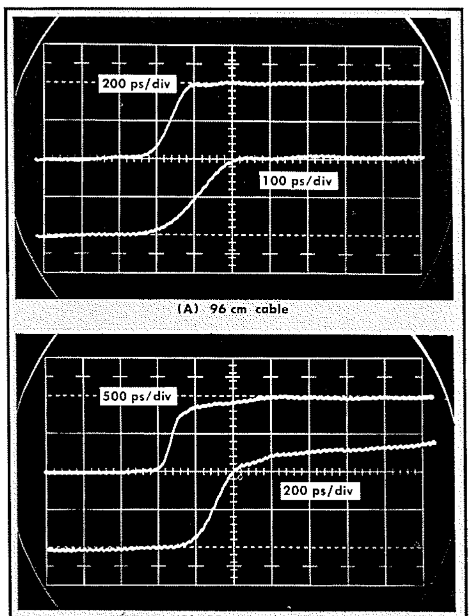


Fig 17. "Dribble up" characteristics of two lengths of RG8A/U.

Measuring Technique

The measurement of the small series inductor of Fig 15B is explained here to point out necessary techniques for measuring small reactances.

In evaluating small reactances with the TDR system, we have assumed the driving pulse to be a linear ramp; therefore, the ramp risetime must be determined for each change in the test system. The words "dribble up" refer to the characteristic of a coaxial cable to transport a step signal with distortion. The time required for the cable output signal to reach 100% of the step signal input amplitude is many times longer than the interval needed for the output signal to change from 0% to 50%. If we consider that the small reactance receives a pure ramp signal, then the rounded corners of the output pulse must be ignored.

Fig 17 shows the degradation of the Type 1S2 incident signal pulse by two different lengths of RG8A/U coaxial cable. Fig 17A is the reflection from an open cable 96 cm long, (192 cm signal path) and Fig 17B is the reflection from an open cable 550 cm long (1100 cm signal path). The upper waveform in each case was made with the Type 1S2 VERTICAL UNITS/DIV control set to 0.5 ρ/DIV, calibrated. The lower waveform in each case was made with the Type 1S2 vertical VARIABLE control advanced slightly clockwise to approximate a deflection factor of 0.5 ρ/DIV for just the ramp portion of the waveform. In each case the signal continues to rise after the inital step, but Fig 17B shows the "dribble up" characteristic very plainly. The lower waveform of Fig 17A and B does not permit an accurate measurement of the system risetime because the waveforms as shown are not large enough. However, the upper waveforms of Fig 18A and B are large enough to permit a reasonable measurement of the 10% to 90% risetime of the ramp that drives the small inductor. It is also obvious from Fig 18A and B that the series inductor peak reflection is truly caused by just the ramp portion of the driving signal and not by the "dribble up" portion.

Calculations made from Fig. 18A and B using formula (11) and the curve of Fig 14, indicate the series coil has an inductance of 16.40 nH at Fig 18A and inductance of 16.51 nH at Fig 18B. (Fig 18A: $L = (2.5)\,(0.82)\,(50)\,(1.60 \times 10^{-8}) = 1.64 \times 10^{-8}$ H.) (Fig 18B: $L = (2.5)\,(0.66)\,(50)\,(2.0 \times 10^{-8}) = 1.651 \times 10^{-8}$ H.) This indicates that an inductor in series with a coaxial transmission line can be accurately measured so long as the risetime of the ramp portion of the incident signal can be measured. Fig 18B indicates that a cable of RG8A/U a bit longer than 550 cm might make it difficult to measure the ramp risetime from the display. If a cable has sufficient length to prevent a reasonable display to measure the ramp 10% to 90% risetime, the small series inductor cannot be measured.

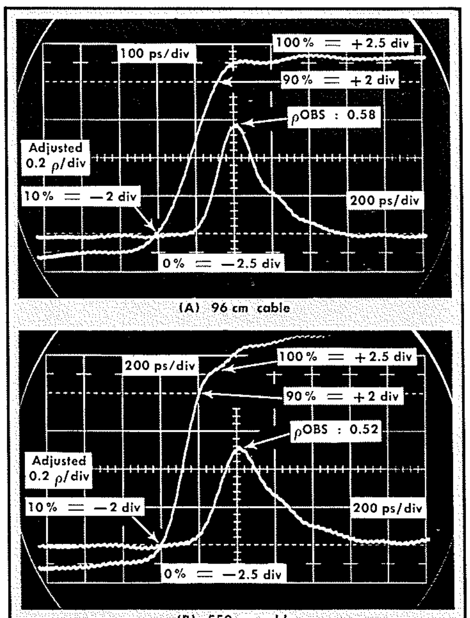


Fig 18. Small series inductor measured 96 cm and 550 cm away from Type 1S2 in RG8A/U coaxial cable.

Calculations of cable risetime will not permit small inductor measurements because the Type 1S2 vertical ρ/DIV calibration must be adjusted in each case. Once the vertical gain has been increased to measure the ramp risetime, the same new adjusted vertical ρ/DIV setting is used for measuring the observed ρ from the series inductor. If the cable is long enough to make it impossible to "see" the top of the ramp, the inductor cannot be measured. The same limitations apply when measuring small shunt capacitors.

Locating Small Reactances

The discussion of small reactances has thus far assumed that the TDR operator has access to all the cable between the TDR unit and the reactance being measured. This is, of course, not always the case. When a long length of cable indicates a fault, the reflected signal has not only been reduced in amplitude, it has also been smeared in time. The discontinuity is then located in time, closely related to the approximate 10% amplitude point or the beginning edge of the display rather than, as might be expected, at the peak of the reflection.

REFLECTIONS FROM RESISTIVE DISCONTINUITIES

Two types of reflections occur from two types or resistive discontinuity. They are a

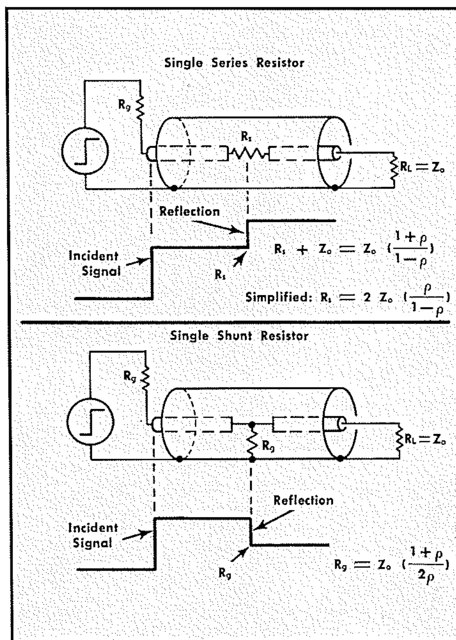


Fig 19. Single resistor discontinuities.

step reflection, or a continuously changing reflection. A resistance in series with a transmission line causes a positive reflection. A resistance in parallel with a transmission line causes a negative reflection. Discrete single resistors cause a step reflection, while distributed resistance causes a continuously changing reflection. The discrete resistor reflections are shown in ideal form in Fig 19, and the distributed resistance reflections are shown in ideal form in Fig 20.

Fig 20 has been exaggerated by showing the distributed resistance beginning at a particular point in the line. Normally, such series or shunt distributed resistance will be found in the total length of line tested by TDR.

All four forms of resistance are an indication of signal losses between the input and output ends of the transmission line. The single resistor discontinuities can occur due to discrete components or may indicate a loose connector with added series resistance. Such discontinuities can be physically located by special use of the POSITION RANGE control of the Type 1S2. Distributed losses are usually part of the particular line being tested and the TDR display can be of value for quantitative analysis of resistance per unit of line length.

No reflection should occur from a properly fabricated matched attenuator. Therefore, a TDR unit will not indicate losses when matched attenuators are used.

Distributed Resistance Examples

The examples of distributed resistance reflections that follow deal with the normal characteristics of transmission lines. Both small diameter lossy cables and moderate diameter quality cables are discussed.

Small, Lossy Cables

A small diameter 50 Ω transmission line (such as ⅛ inch diameter cable) will have sufficient DC resistance to mask "skin effect" losses. The DC resistance in its center conductor will cause a nearly exponential changing reflection. See Fig 21A. As the incident signal propagates down the line away from the TDR unit, the small series resistance causes small reflections to return to the TDR unit. If you mentally integrate the line into small sections of series resistance, you can then understand the continuous return of energy to the input end of the line. Each reflected energy "bit" is additionally attenuated on its way back to the TDR unit. This return attenuation is the factor that prevents the display from being a linear ramp, converting it into a nearly exponetial reflection. (Note the curve of the reflection between the incident signal plus step and the termination of Fig 21A.

Another way of expressing the effect of the nearly expoential reflection is to say that the transmission line input surge impedance changes with time. Fig. 21A shows the line surge impedance to be essentially 50 Ω at the beginning of the exponential reflection and to be approximately 64 Ω after 130ns ($+0.12\rho$ = 64 Ω).

The long nearly exponential decay after the termination of Fig 21A is related to high frequency losses and the previously described "dribble up". The negative reflection occurs at the termination because the 50 Ω termination was driven by approximately 64 Ω. If the long exponential decay after the termination were expanded vertically, it would follow the rules for distortion to pulses by coaxial cables described with Fig 25.

If the small diameter cable is shorted at its end instead of terminated, the TDR display will appear similar to Fig 21B. A lossless line would have a full -1ρ after the short, but the small lossy cable not only has attenuation of the signal to the short, but attenuation of the reflected signal back to the TDR unit. Again, the long nearly exponential curve after the short is caused by the cable distorting the reflected step signal.

Fig 21B also allows measuring the total cable DC resistance between the TDR unit and the short circuit of Fig 21B. The vertical distance between the incident pulse peak level and the right end flat portion of the reflected signal is due strictly to the cable DC resistance. In this case, —3.8 divisions = -0.76ρ which is equal to 6.5 Ω (from curve of Fig 10). (A bench multimeter type ohmmeter indicated 6.8 ohms for the same cable.)

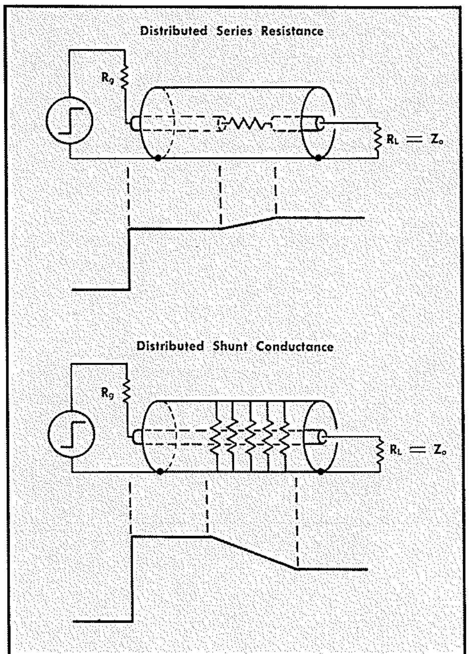


Fig 20. Distributed resistance reflections.

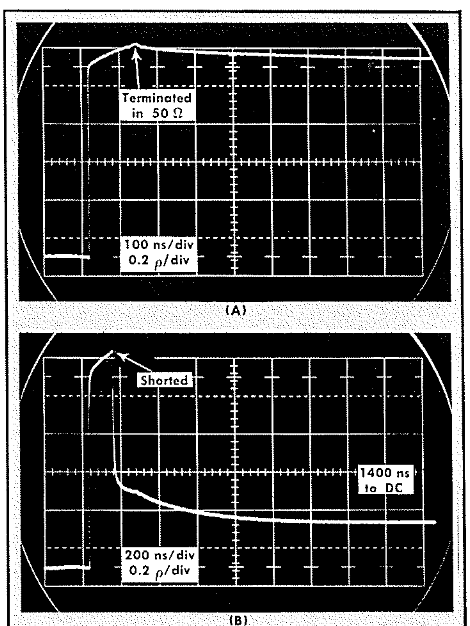


Fig 21. Waveforms of ⅛ inch diameter lossy 50 Ω cable.

Quality Cables

A quality cable, such as RG8A/U (52 Ω), RG213/U (50 Ω) or RG11/U (75 Ω) will exhibit similar characteristics to the small lossy cable just described, but the cable must be much longer to obtain a similar display of series resistance. Fig 22A and B show the same rising type of waveform caused by center conductor series resistance in RG213/U. Fig 22C shows the residual DC resistance of the line when shorted. Fig 22D is a time and voltage expansion of the (A) and (B) waveforms to show a possible use for the Type 1S2 in troubleshooting cable fabricating equipment.

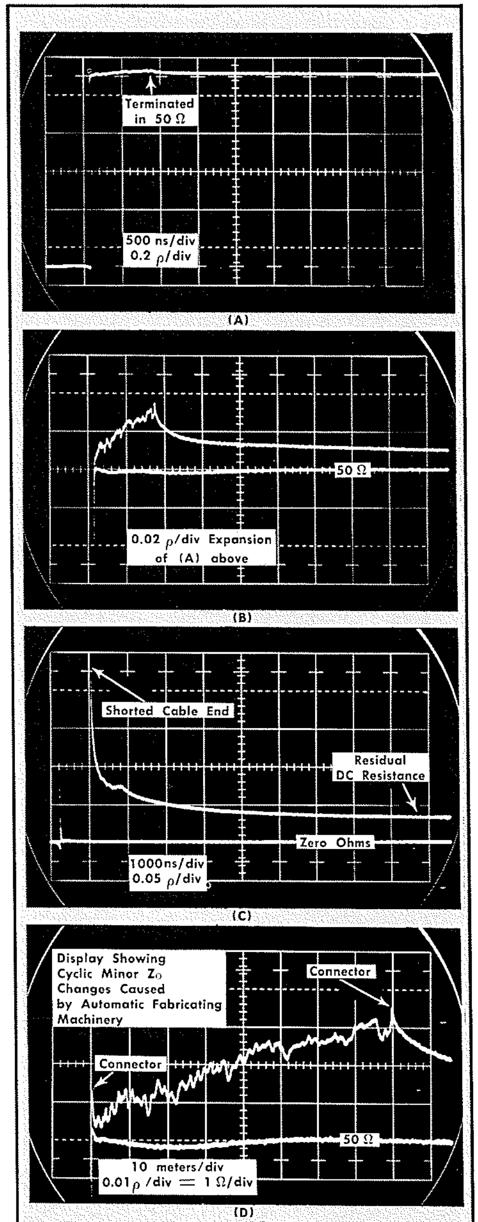


Fig 22. Quality RG213/U cable resistance and ΔZ_o characteristics. (Cable tested 260 feet long).

Fig 23 shows the same series resistance characteristics for RG11/U cable. However, instead of terminating the cable end, the series resistance was measured first with the end open, and then with the end shorted. Note the difference in slope of the waveform (apparent change in resistance) after the signal has traveled to the indicated line end. The change in slope is due to distortion of the originally flat incident pulse by traveling through the cable once. As the non-flat signal reaches the cable end, its reflection back through the cable is altered a second time. The net result is an obvious distortion to the true resistive slope of the reflected "bits" of the distributed series resistance during the 2nd half of the reflection. This example is given to show the desirability of properly terminating any line section in which you wish to measure its total distributed series resistance. (Conditions leading to this changing slope phenomenon are described by H. H. Skilling on page 397 of his text "Electronic Transmission Lines", McGraw-Hill, 1951.) Each of the three waveform pictures of Fig 23 is a double exposure with the lower waveform showing the normal Type 1S2 response to a termination resistance at (A) and (B) and a short circuit at (C).

COAXIAL CABLE RESPONSE TO A STEP SIGNAL

Coaxial cable have a step-function response that distorts the original signal. The distortion is caused by cable losses of several types which are frequency dependent. The longer the cable length, the greater the distortion. Response to a step signal can be evaluated by placing the cable in a TDR system, or by placing it between a fast rise pulser and a fast risetime sampler. (When a cable is tested by a TDR device, the signal traverses the line twice; when a cable is placed between a pulser and a sampler, the signal traverses the line once.)

Studies in the past that considered skin effect losses only[1] have indicated that some types of coaxial cables have a step-function response with decibel attenuation that varies as the square root of the frequency. Based upon this assumption (of skin effect losses only), the step response time from 0% to 50% will increase by a factor of 4 through a cable whose length is twice that of a previous test. Such is not the case in practice as seen by use of the Type 1S2. Other forms of losses due to the dielectric material between inner and outer conductors, radiation from lines whose outer conductor is braided, and reflection losses from surface variations of the conductors, are discussed in detail in an article by N. S. Nahman[2]. Nahman considers several techniques which are useful in analyzing the transient behavior of coaxial cables that have these forms of high frequency losses.

Long Cables

Distortion to pulse signals in coaxial cables is most easily evaluated (visually displayed on a CRT) when the cable is long. A long cable is here defined as one that exhibits significant losses in the system in which it is used. The tests shown in Fig 24 were made on a 100 foot section of RG11/U and a 260 foot section of RG213/U. In each case the signal traversed the line twice in a normal TDR manner. The cable far end was left an open circuit so that a return signal of $+1\rho$ could be observed. This gives the same effect as having sent the Type 1S2 signal through a line twice as long.

The term T_o, shown in Fig 24, is the length of time between the 0% amplitude and 50% amplitude points along the step rise of the cable output signal. 0% to 50% is chosen because it contains the fastest part of the transition and because it is easy to read. The usual practice of measuring risetime from 10% to 90% is perfectly valid if the display has an adequate rate of rise at the 90% point. The cables tested for Fig 24 have a 10% to 90% risetime that lasts about 18 times longer than T_o. Fig 24 shows plainly that the step response of a coaxial cable does not have the familiar Gaussian shape. For this reason the risetime of systems containing long coaxial cables cannot be calculated using the square root of the sum of the squares of the individual unit risetimes.

The length of time required for the output signal to rise to 100% of the input signal is many times longer than T_o. This distortion is called "dribble up" as first discussed earlier under Measuring Technique when measuring a small series inductor in a transmission line. Fig 25A is a double exposure using the 260 foot length of RG213/U connected between the Type 1S2 1-Volt pulser and the terminated Thru Signal Sampler. Both traces were made at 100 ns/div. The upper trace at 0.2 ρ/DIV and the lower trace at 0.05 ρ/DIV. The lower trace leads us to believe that the output pulse reaches 100% amplitude sometime between 4000 and 5000 ns after the initial step rise. More exact measurements can be made by comparing the cable output with the Type 1S2 no-cable response as shown in Fig 25B. Here both traces were made at 1000 ns/DIV and 0.02 ρ/DIV with an intentional small vertical repositioning. When the two traces become a constant distance apart, you can be relatively certain the cable output signal has reached 100% amplitude. Fig 25B indicates a possibility that the output signal had not completely reached 100% amplitude even after 8000 ns (8 μs).

Short Cables

Even though information just given on Long Cables is true for any length cable, a physically short cable can be treated as if it

[1]R. L. Wigington and N. S. Nahman, "Transient analysis of coaxial cables considering skin effect," Proc. IRE, vol. 45, pp. 166-174; February 1957. Q. Kerns, F. Kirsten and C. Winningstad, "Pulse Response of Coaxial Cables," Counting Notes, File No. CC2-1, Rad. Lab., University of California, Berkely, Calif.; March, 1956. Revised by F. Kirsten; Jan. 15, 1959.

[2]N. S. Nahman, "A Discussion on the Transient Analysis of Coaxial Cables Considering High-Frequency Losses," IRE Transactions On Circuit Theory, vol. CT-9, No. 2, pp. 144-152; June, 1962.

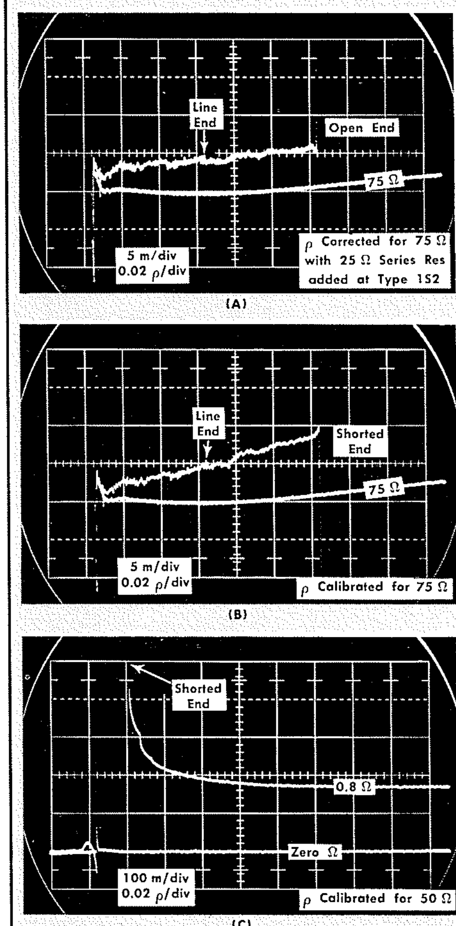


Fig 23. Quality RG11/U cable resistance and ΔZ_o characteristics. (Cable tested was 100 feet long).

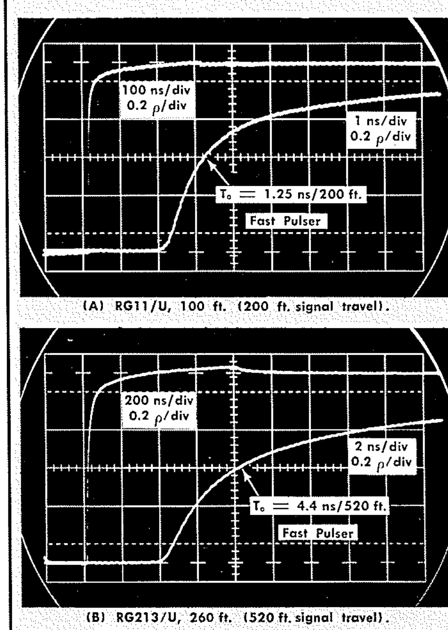


Fig 24. RG11/U and RG213/U distortion to a step signal. Waveforms are reflections from cable open end.

were Gaussian. A short cable will have a T_0 sufficiently faster than the Type 1S2 fast pulser 10% to 90% risetime, that the long slow rise ("dribble up") of Fig 25 will not be evident. Under these short cable conditions, it is reasonable to assume the bandpass upper limit of a cable and its system can be approximated from the 10% to 90% risetime display. A display of 10% to 90% risetime in 100 picoseconds then approximates a sine wave upper frequency 70% amplitude of: $0.35/(1 \times 10^{-10}) = 3500$ MHz.

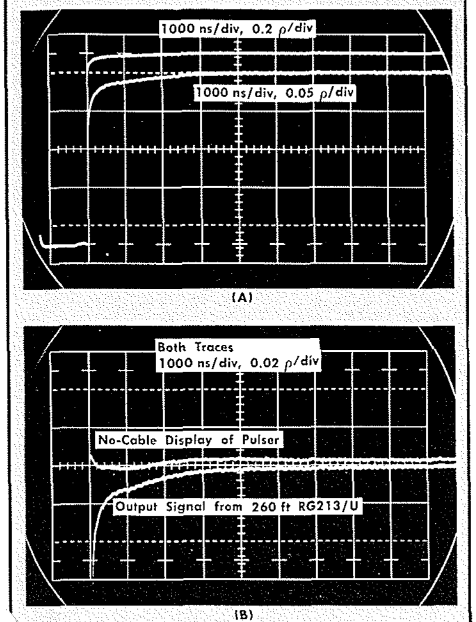


Fig 25. "Dribble up" output signals from 260 ft. RG213/U.

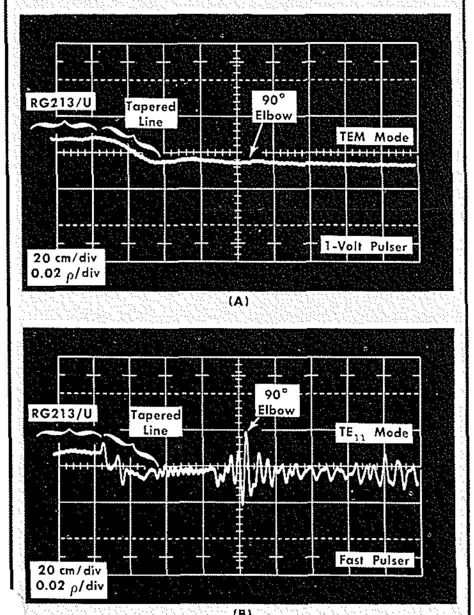


Fig 26. Propagation mode change in large diameter transmission line when driven by the Type 1S2 fast pulser.

Large Diameter Transmission Lines

Use of the Type 1S2 0.25-Volt fast-risetime pulser should be limited to use on lines whose outer conductor inner diameter is less than about one-quarter wavelength at 3500 MHz. Normal signal propagation mode in transmission lines is TEM, but will change to a waveguide mode, TE_{11}, if too high a frequency is used. Fig 26 shows both modes of propagation in a transmission line 3⅛ inch in diameter. Fig 26A picture was taken using the Type 1S2 1-Volt pulser. Fig 26B picture was taken using the Type 1S2 0.25-Volt fast pulser. The line elements were the same in each case; 1) a short section of RG213/U cable between the Type 1S2 and a tapered line section; 2) the tapered line section; and 3) a section of 3⅛ inch diameter rigid air line with a 90° elbow in the display time window. The numerous aberrations of Fig 26B are due to a change in propagation mode when the signal arrived at the 90° elbow. The resulting multiple reflections are of no value to the operator testing the line.

SPECIAL APPLICATIONS

General

Much of the previous portion of this article deals with using the Type 1S2 as a Time Domain Reflectometer. Many more uses can be made of the unit in a TDR mode, limited only by the measurement needs of the user. Listed below are suggestions of other TDR applications not yet described.

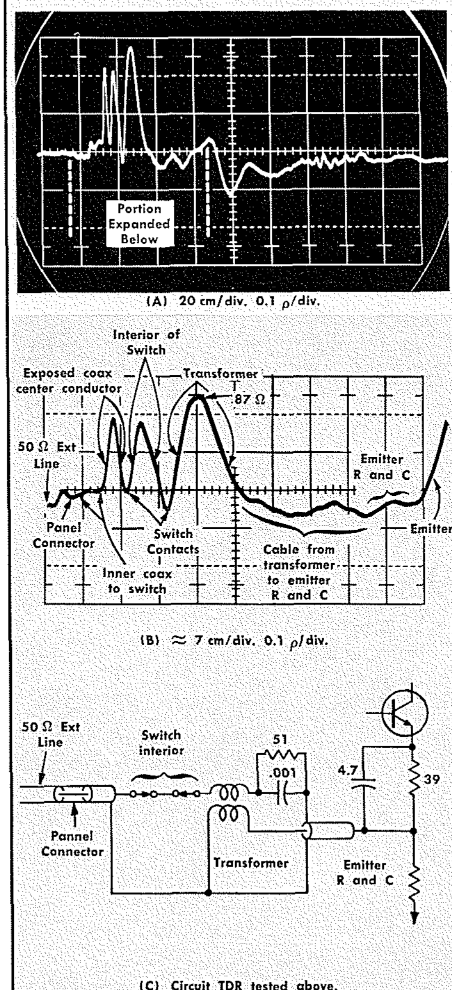


Fig 27. TDR view of broadband amplifier input circuit.

Signal Generator Output Impedance

The Type 1S2 can be connected to the output terminal of a signal generator to measure its output impedance. If the generator output signal can be turned off while keeping the output circuit active, a clean TDR can be obtained.

Broadband Amplifier Input Impedance

Fig 27 shows two pictures of a broadband amplifier input circuit. Fig 27A includes the active emitter circuit of the input common-base transistor amplifier. Fig 27B includes the parts between the input connector and the transistor emitter. The power was off when Fig 27B photo was taken to show the transistor emitter spatial location accurately.

Circuit Board Lead Impedance

Fig 28A shows changes in surge impedance of leads along an etched circuit board. (The board reverse side was fully plated.) The major dip is due to a right angle corner while the minor dip is due to a rounded corner.

Changes in surge impedance due to a change in lead width is also plainly seen by TDR. Fig. 28B shows an inductive section of line when the physical width of the line was reduced one half for a length of about 1.25 inches.

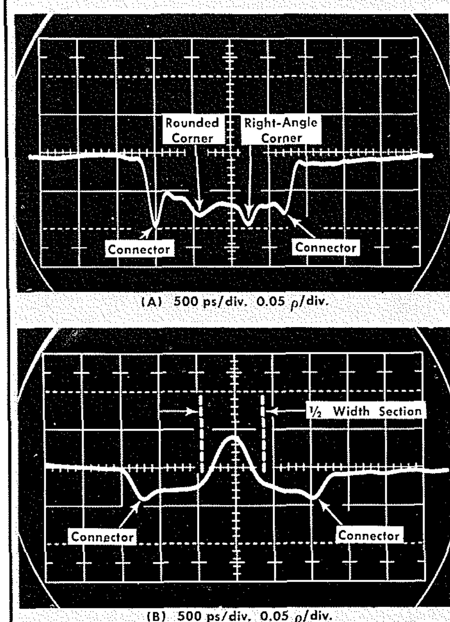


Fig 28. Etched circuit board Z_0 checked by TDR.

Frequency Compensation of Lossy Cables

A lossy coaxial cable connected between one of the Type 1S2 pulsers and the sampler (terminated) permits a view of the cable output signal. Fig 29 shows the same lossy cable described earlier with Fig 21. A double exposure shows at the top how the cable distorts the 1-Volt pulser while the lower waveform is flatter due to a simple RC compensation network placed between the pulser and the cable. The TDR unit will permit testing such compensation networks.

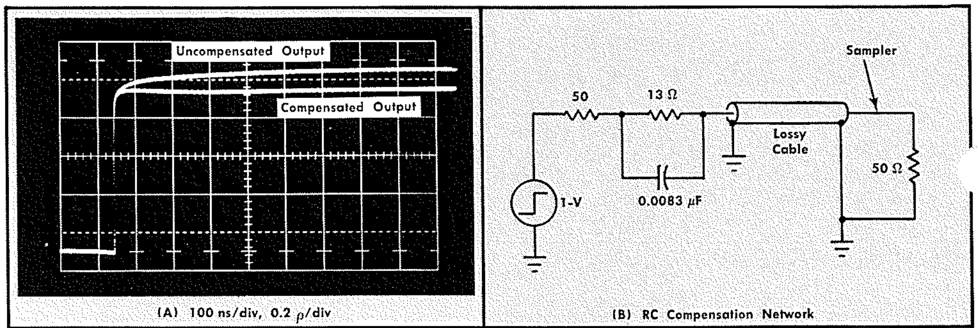


Fig 29. Simple frequency compensation for lossy coaxial cable.

Evaluation of Ferrite Beads and Cores

Ferrite beads and cores can be evaluated using the Type 1S2. Simple inductors wound on toroid ferrite cores are represented by an equivalent circuit which is essentially an inductance in parallel with a resistance. The resistance results from core losses and may be typically as low as 10 to 30 ohms/$(\text{turn})^2$. Both the resistance and inductance characteristics of ferrites can be seen in a TDR display.

Fig 30 shows two displays and the special adapter jig used to test a ferrite bead. The adapter jig is made from one half of a Tektronix Insertion Unit (Part No. 358-0175-00). The end of the center piece was flattened and a formed piece of #10 copper wire soldered in place with a ferrite bead included. Thus, there is only a small diameter change of the 50 center conductor (pip in both displays) and one turn through the ferrite center. (Use smaller wire for smaller beads.)

Fig. 30A shows the basic display. L/R time-constant analysis is similar to that of Fig. 15 and formula (8) of Table 5, except the core R is in parallel with the driving line Z_o.

Fig 30B shows the ferrite bead resistance as —0.16 ρ, or 36 Ω. (The 36 Ω is read directly from the curve of Fig 10.) The resistance value of a core is read by finding the curve knee (as marked in Fig 30B) where the inductance affect becomes obvious. The positive pip is ignored.

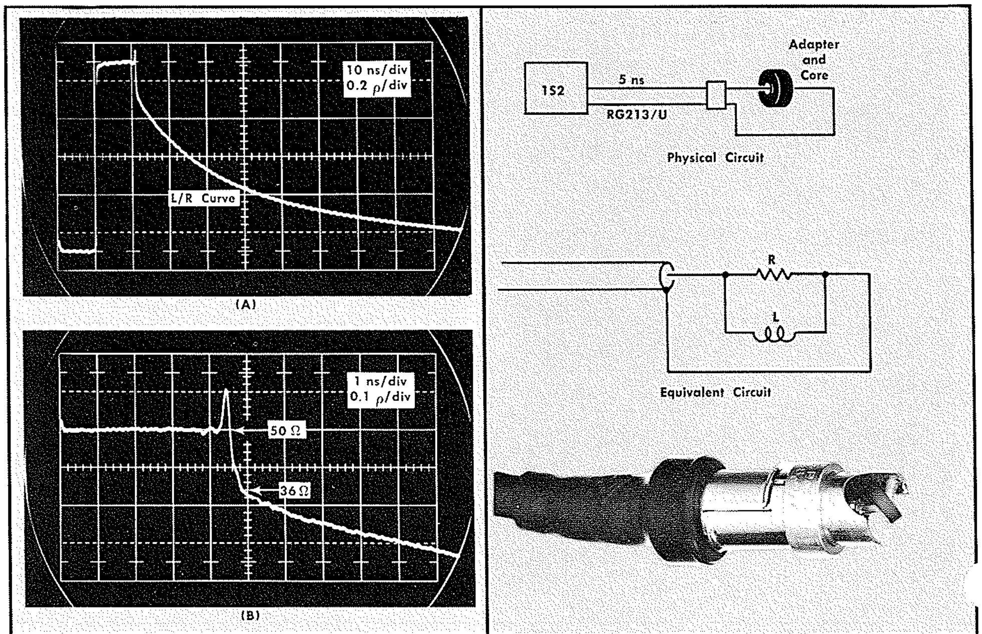
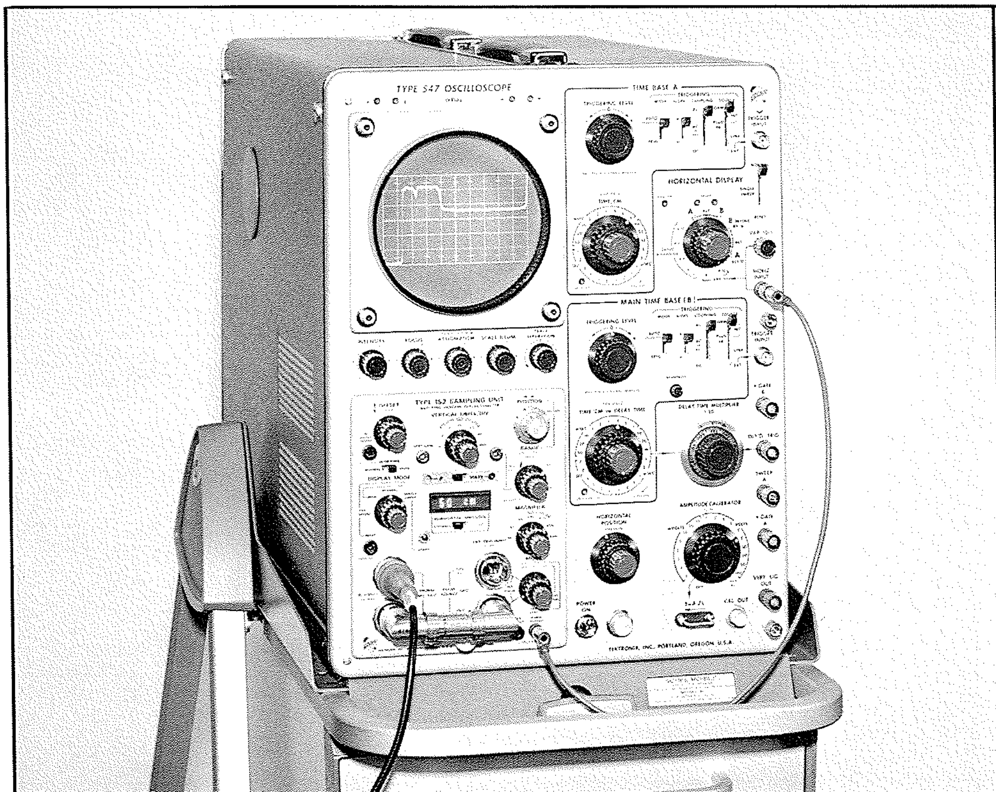


Fig 30. Evalution of a ferrite core.



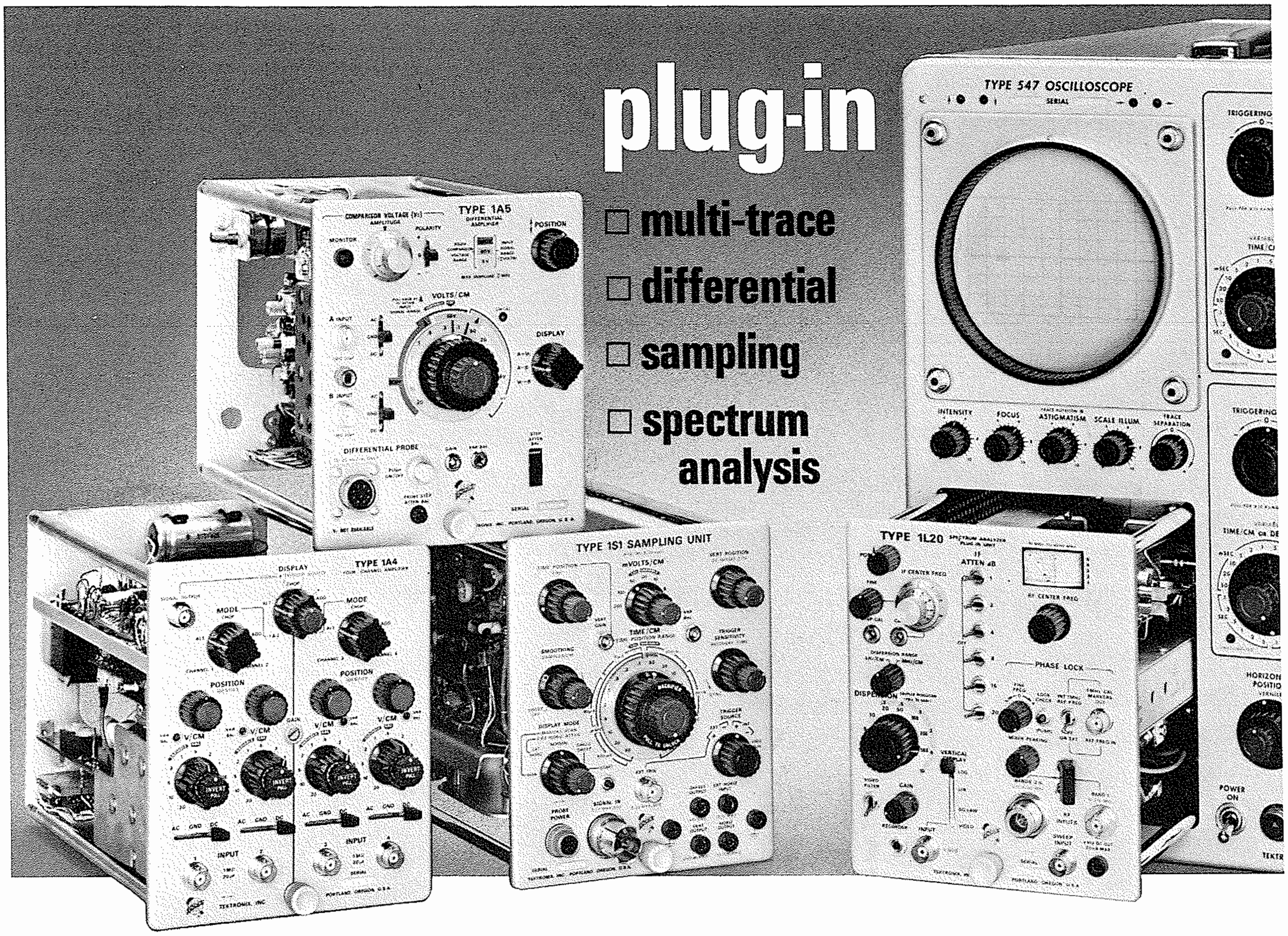
Tektronix Type 547 Oscilloscope with a Type 1S2 Sampling Plug-In Unit.

The measurements described in this article can be easily made with the Type 1S2 Plug-In Unit.

The Type 1S2 Sampling Plug-In converts any Tektronix 530, 540, 550-series oscilloscope to a time-domain reflectometry measurement system. It also has the ability to make many general sampling measurements.

As a TDR, the Type 1S2 has a system risetime of 140 ps and is calibrated in ρ (rho) from 0.005 ρ/div to 0.5 ρ/div. The horizontal is calibrated from 1 cm/div to 100 m/div for dielectrics of air, TFE and polyethylene. A 10-turn dial reads directly the one-way distance to the test-line discontinuity. Two pulse outputs provide either 50 ps T_r at 250 mV into 50 Ω or 1 ns T_r at 1 V into 50 Ω.

The 90-ps risetime, 5 mV/div deflection factor, 100ps/div sweep and built-in triggering capability make the Type 1S2 useful in many other sampling measurements.



Tektronix 530, 540 and 550-series plug-in oscilloscopes offer a wide range of performance, designed to meet your changing measurement needs. Select the performance and measurement functions you need from multi-trace, differential, sampling and spectrum analyzer plug-ins.

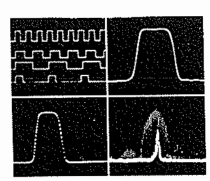
For multi-trace applications, the new Type 1A4 Four-Channel amplifier offers constant DC-to-50 MHz bandwidth and 7-ns risetime capabilities over its 10 mV/cm to 20 V/cm deflection factor range. Operating modes include alternate or chopped four channel, dual channel differential, and 2, 3, or 4 channels added or subtracted. Two dual-trace plug-ins are also available, the Type 1A1 with 28 MHz at 5 mV/cm (50 MHz at 50 mV/cm) and the Type 1A2 with 50 MHz at 50 mV/cm.

For differential applications, the new Type 1A5 Differential amplifier features 1 mV/cm deflection factor, 1,000:1 common-mode rejection ratio at 10 MHz, ± 5 V comparison voltage and 50 MHz bandwidth with 7-ns risetime at 5 mV/cm. The low-cost Type 1A6 Differential plug-in with 1 mV/cm deflection factor, 10,000:1 CMRR and 2-MHz bandwidth and the high-gain Type 1A7 Differential plug-in with 10 μV/cm deflection factor, 50,000:1 CMRR and 500 kHz bandwidth are also available.

For sampling applications, choose from two high performance plug-ins, the Type 1S1 general purpose sampling plug-in and the Type 1S2 TDR sampling plug-in. The Type 1S1 features internal triggering, 0.35-ns risetime, DC-to-1 GHz bandwidth and calibrated sweep speeds from 100 ps/cm to 50 μs/cm. The Type 1S2 is a time-domain reflectometer with a system risetime of 140 ps, 0.005 *ρ*/div deflection factor and sweep rates from 100 ps/div to 1 μs/div. With its 90-ps risetime, 5 mV/div deflection factor and built-in triggering, the Type 1S2 can be used in many other sampling applications.

Four spectrum analyzer plug-ins covering the spectrum from 50 Hz to 10.5 GHz convert your oscilloscope to a high-performance spectrum analyzer. The plug-ins cover the following frequency bands: Type 1L5 from 50 Hz to 1 MHz with 10 μV/cm deflection factor; Type 1L10 from 1 MHz to 36 MHz with —110 dBm sensitivity; Type 1L20 from 10MHz to 4.2 GHz with—110 to—90 dBm sensitivity; and Type 1L30 from 925 MHz to 10.5 GHz with —105 to —75 dBm sensitivity.

Multi-trace *differential*



sampling *spectrum analysis*

in all Tektronix 530-540-550-series plug-in oscilloscopes

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Tektronix, Inc.
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FRANK GREENWOOD
DEPARTMENT OF TRANSPORT
T & E SYSTEMS LAB.
BOX 4028, STATION E
OTTAWA, ONTARIO, CANADA

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