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Time-Domain Reflectrometry

This material originally appeared in the *ARRL Antenna Book*, 23rd and prior editions.

A time-domain reflectometer (TDR) is a simple but powerful tool used to evaluate transmission lines. When used with an oscilloscope, a TDR displays impedance "bumps" (open and short circuits, kinks and so on) in transmission lines. Commercially produced TDRs cost from hundreds to thousands of dollars each, but you can add the TDR described here to your shack for much less. This material is based on a *QST* article by Tom King, KD5HM, (see Bibliography), and supplemented with information from the references.

A handy "free" TDR is sometimes available from oscilloscopes with a trigger output pulse synchronized with the start of the sweep. The output pulse generally has a very fast rise time and although not adjustable, does serve the same purpose as an external TDR pulse generator.

HOW A TDR WORKS

A simple TDR consists of a square-wave generator and an oscilloscope. See **Figure 27.33**. The generator sends a train of dc pulses down a transmission line, and the oscilloscope lets you observe the incident and reflected waves from the pulses (when the scope is synchronized to the pulses).

A little analysis of the scope display tells the nature and location of any impedance changes along the line. The nature of an impedance disturbance is identified by comparing its pattern to those in **Figure 27.34**. The patterns are based on the fact that the reflected wave from a disturbance is determined by the incident-wave magnitude and the reflection coefficient of the disturbance. (The patterns shown neglect losses; actual patterns may vary somewhat from those shown.)

The location of a disturbance is calculated with a simple proportional method: The round-trip time (to the disturbance) can be read from the oscilloscope screen (graticule). Thus, you need only read the time, multiply it by the velocity of the radio wave (the speed of light adjusted by the velocity factor of the transmission line) and divide by two. The distance to a disturbance is given by:

$$\ell = \frac{983.6 \times VF \times t}{2} \quad \text{(Eq 16)}$$

where

ℓ = line length in feet

VF = velocity factor of the transmission line (from 0 to 1.0)

t = time delay in microseconds (μs).

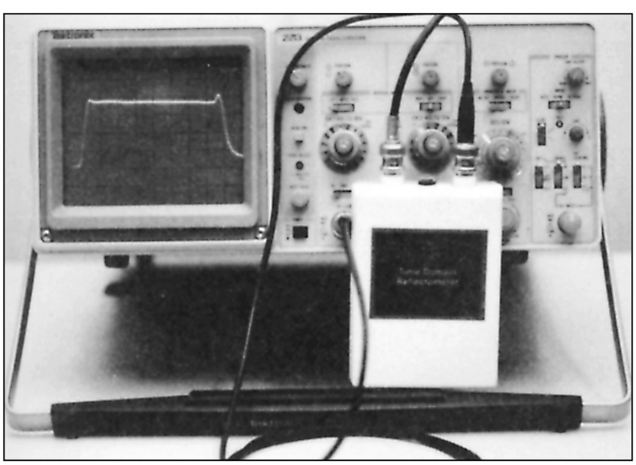

Figure 27.33 — The time-domain reflectometer shown here is attached to a small portable oscilloscope.

THE CIRCUIT

The time-domain reflectometer circuit in **Figure 27.35** consists of a CMOS 555 timer configured as an astable multivibrator, followed by an MPS3646 transistor acting as a 15-ns-risetime buffer. The timer provides a 71-kHz square wave. This is applied to the 50-Ω transmission line under test (connected at J2). The oscilloscope is connected to the circuit at J1.

CONSTRUCTION

An etching pattern for the TDR is shown in **Figure 27.36**. **Figure 27.37** is the part-placement diagram. The TDR is designed for a 4 × 3 × 1-inch enclosure (including the batteries). S1, J1 and J2 are right-angle-mounted components. Two aspects of construction are critical. First use *only* an MPS3646 for Q1. This type was chosen for its good performance in this circuit. If you substitute another transistor, the circuit may not perform properly.

Second, for the TDR to provide accurate measurements, the cable connected to J1 (between the TDR and the oscilloscope) must not introduce impedance mismatches in the circuit. *Do not make this cable from ordinary coaxial cable.* Oscilloscope-probe cable is the best thing to use for this connection.

(It took KD5HM about a week and several phone calls to determine that scope-probe cable isn't "plain old coax." Probe cable has special characteristics that prevent undesired ringing and other problems.)

Mount a binding post at J1 and connect a scope probe to the binding post when testing cables with the TDR. R5 and C2 form a compensation network — much like the networks in oscilloscope probes — to adjust for effects of the probe wire.

An alternative that avoids issues associated with loading of the TDR's OSCILLOSCOPE output is to attach the TDR's CABLE UNDER TEST output and the cable under test to a BNC tee connector mounted on the scope input. (In this configuration the OSCILLOSCOPE output is not used.)

The TDR is designed to operate from dc between 3 and 9 V. Two C cells (in series — 3 V) supply operating voltage in this version. The circuit draws only 10 to 25 mA, so the cells should last a long time (about 200 hours of operation). U1 can function with supply voltages as low as 2.25 to 2.5.

If you want to use the TDR in transmission-line systems with characteristic impedances other than 50 Ω, change the value of R_L to match the system impedance as closely as possible.

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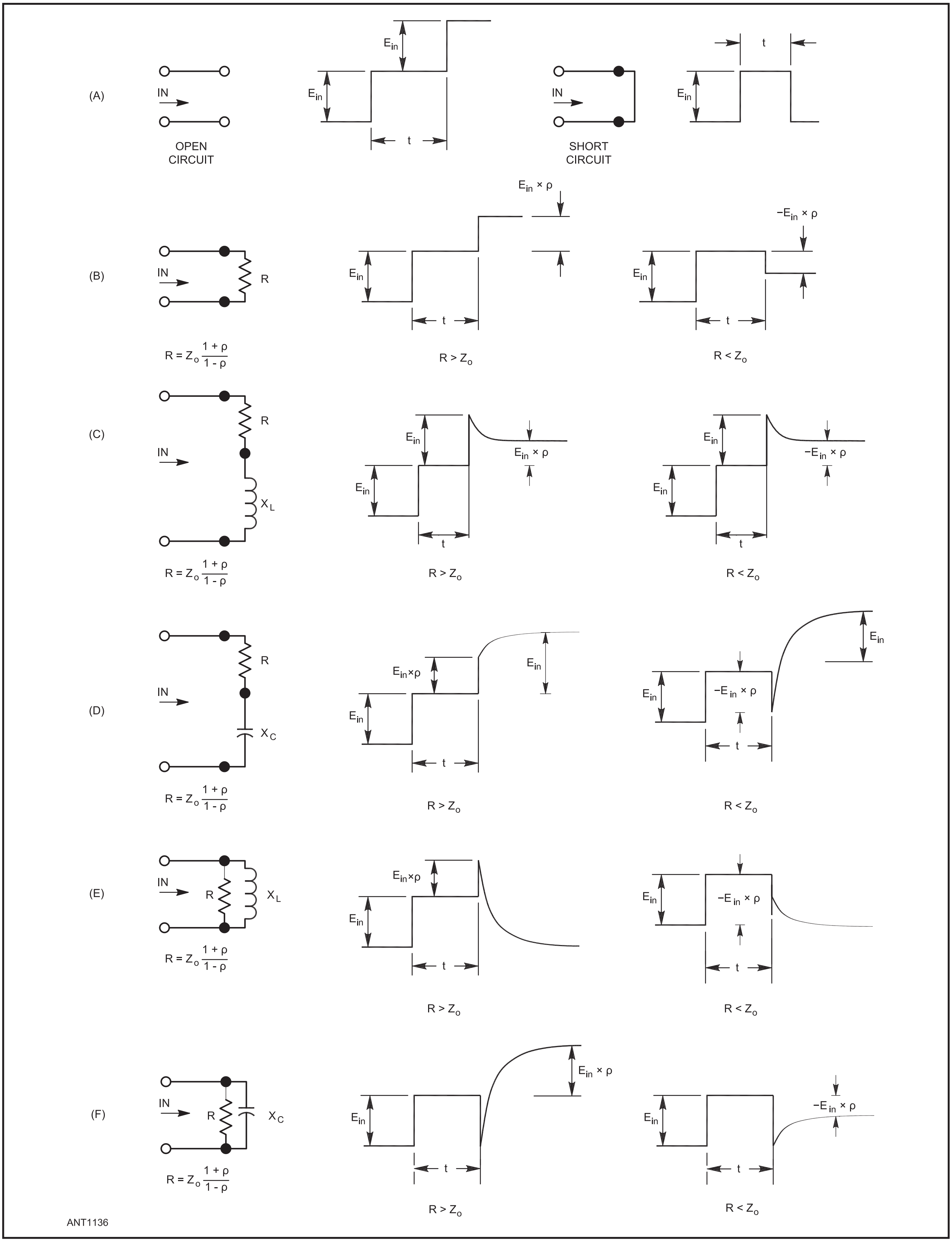

Figure 27.34 — Characteristic TDR patterns for various loads. The location of the load can be calculated from the transit time, t, which is read from the oscilloscope (see text). R values can be calculated as shown (for purely resistive loads only — $\rho < 0$ when $R < Z_0$; $\rho > 0$ when $R > Z_0$). Values for reactive loads cannot be calculated simply.

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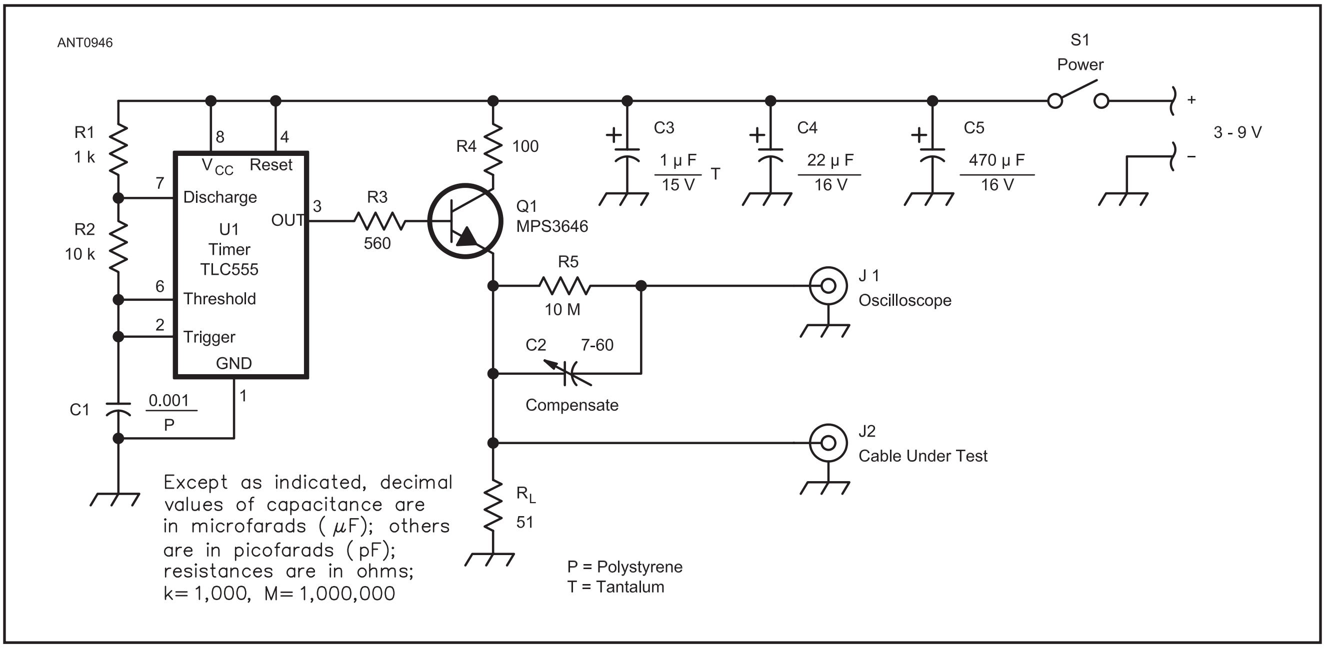

Figure 27.35 — Schematic diagram of the time-domain reflectometer. All resistors are ¼-W, 5% tolerance. U1 is a CMOS 555 timer. Circuit current drain is 10 to 25 mA. When building the TDR, observe the construction cautions discussed in the text.

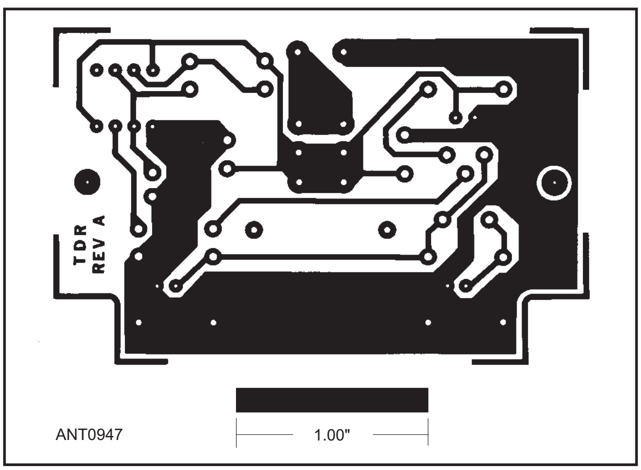

Figure 27.36 — Full-size PC-board etching pattern for the TDR. Black areas represent unetched copper foil. (A PC-board is available from FAR Circuits at www.farcircuits.net.)

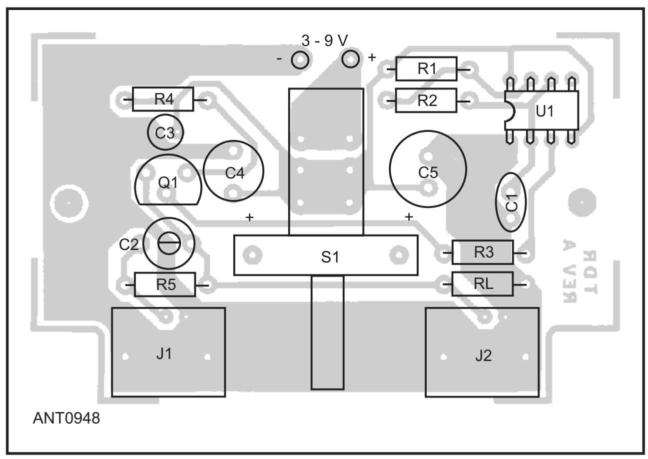

Figure 27.37 — Part-placement diagram for the TDR. Parts are mounted on the nonfoil side of the board; the shaded area represents an X-ray view of the copper pattern. Be sure to observe the polarity markings of C3, C4 and C5.

CALIBRATING AND USING THE TDR

Just about any scope with a bandwidth of at least 10 MHz should work fine with the TDR, but for tests in short-length cables, a scope with at least 50 MHz bandwidth provides for much more accurate measurements. To calibrate the TDR, terminate CABLE UNDER TEST connector, J2, with a 51-Ω resistor. Connect the scope vertical input to J1. Turn on the TDR, and adjust the scope timebase so that the rise time from the TDR fills as much of the scope display as possible (without uncalibrating the timebase). The waveform should resemble **Figure 27.38**. Adjust C2 to obtain maximum amplitude and sharpest corners on the observed waveform. That's all there is to the calibration process!

To use the TDR, connect the cable under test to J2, and connect the scope vertical input to J1. If the waveform you observe is different from the one you observed during calibration, there are impedance variations in the load you're testing. See **Figure 27.39**, showing an unterminated test cable connected to the TDR. The beginning of the cable is shown at point A. (AB represents the TDR output-pulse rise time.)

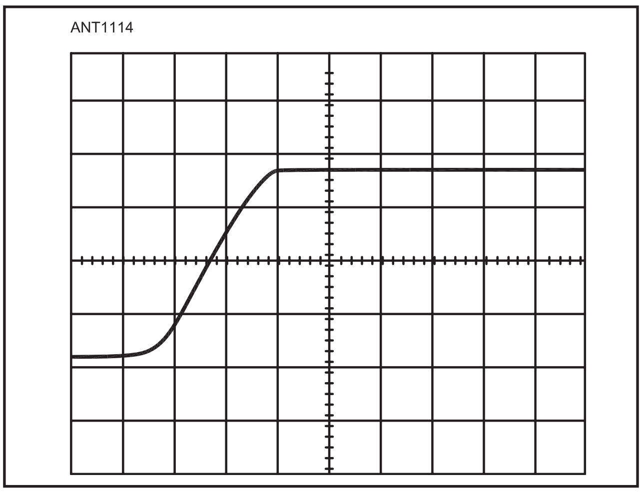

Figure 27.38 — TDR calibration trace as shown on an oscilloscope. Adjust C2 (See Figures 27.35 and 27.37) for maximum deflection and sharpest waveform corners during calibration. See text.

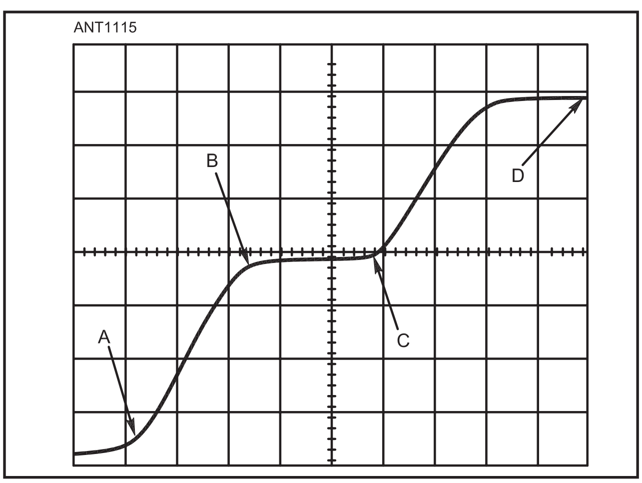

Figure 27.39 — Open-circuited test cable. The scope is set for 0.01 ms per division. See text for interpretation of the waveform.

Segment AC shows the portion of the transmission line that has a 50-Ω impedance. Between points C and D, there is a mismatch in the line. Because the scope trace is higher than the 50-Ω trace, the impedance of this part of the line is higher than 50 Ω — in this case, an open circuit.

To determine the length of this cable, read the length of time over which the 50-Ω trace is displayed. The scope is set for 0.01 μs per division, so the time delay for the 50-Ω section is (0.01 μs × 4.6 divisions) = 0.046 μs. The manufacturer's specified velocity factor (VF) of the cable is 0.8. Eq 16 tells us that the 50-Ω section of the cable is

$$\ell = \frac{983.6 \times 0.8 \times 0.046\ \mu s}{2} = 18.1 \text{ feet}$$

The TDR provides reasonable agreement with the actual cable length — in this case, the cable is really 16.5 feet long. (Variations in TDR-derived calculations and actual cable lengths can occur as a result of cable VFs that can vary considerably from published values. Many cables vary as much as 10% from the specified values.)

A second example is shown in **Figure 27.40**, where a length of ¾-inch hardline is being tested. The line feeds a 432-MHz vertical antenna at the top of a tower. Figure 27.40 shows that the 50-Ω line section has a delay of (6.6 divisions × 0.05 μs) = 0.33 μs. Because the trace is straight and level at the 50-Ω level, the line is in good shape. The trailing edge at the right-hand end shows where the antenna is connected to the feed line.

To determine the actual length of the line, use the same procedure as before: Using the published VF for the hardline (0.88) in Eq 16, the line length is

$$\ell = \frac{983.6 \times 0.88 \times 0.33\ \mu s}{2} = 142.8 \text{ feet}$$

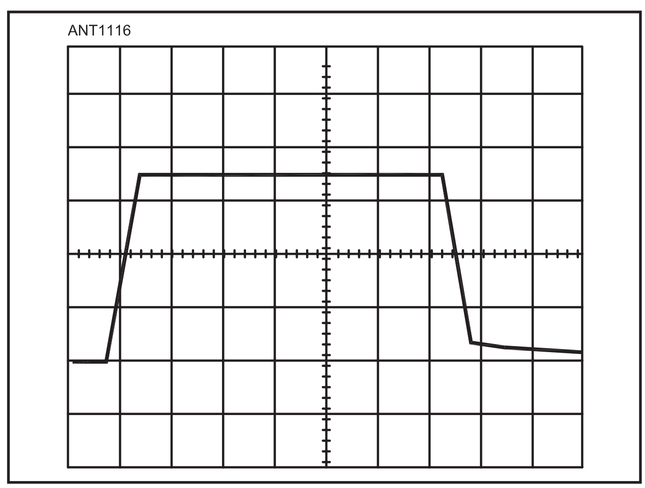

Figure 27.40 — TDR display of the impedance characteristics of the 142-foot hardline run to the 432-MHz antenna at KD5HM. The scope is set for 0.05 ms per division. See text for discussion.

Again, the TDR-derived measurement is in close agreement with the actual cable length (142 feet).

FINAL NOTES

The time-domain reflectometer described here is not frequency specific; its measurements are not made at the frequency at which a system is designed to be used. Because of this, the TDR cannot be used to verify the impedance of an antenna, nor can it be used to measure cable loss at a specific frequency. Just the same, in two years of use, it has never failed to help locate a transmission-line problem. The vast majority of transmission-line problems result from improper cable installation or connector weathering.

TDR LIMITATIONS

Certain limitations are characteristic of TDRs because the signal used to test the line differs from the system operating frequency and because an oscilloscope is a broadband device. In the instrument described here, measurements are made with a 71-kHz square wave. That wave contains components at 71 kHz and odd harmonics thereof, with the majority of the energy coming from the lower frequencies. The leading edge of the trace indicates that the response drops quickly above 6 MHz. (The leading edge in Figure 27.40 is 0.042 µs, corresponding to a period of 0.168 µs and a frequency of 5.95 MHz.) The result is dc pulses of approximately 7 µs duration. The scope display combines the circuit responses to all of those frequencies. Hence, it may be difficult to interpret any disturbance which is narrowband in nature (affecting only a small range of frequencies, and thus a small portion of the total power), or for which the travel time plus pattern duration exceeds 7 µs. The 432-MHz vertical antenna in Figure 27.40 illustrates a display error resulting from narrow-band response.

The antenna shows as a major impedance disturbance because it is mismatched at the low frequencies that dominate the TDR display, yet it is matched at 432 MHz. For an event that exceeds the observation window, consider a l-µF capacitor across a 50-Ω line. You would see only part of the pattern shown in Figure 27.34C because the time constant ($1 \times 10^{-6} \times 50 = 50$ ms) is much larger than the 7-µs window.

In addition, TDRs are unsuitable for measurements where there are major impedance changes inside the line section to be tested. Such major changes mask reflections from additional changes farther down the line.

Because of these limitations, TDRs are best suited for spotting faults in dc-continuous systems that maintain a constant impedance from the generator to the load. Happily, most amateur stations would be ideal subjects for TDR analysis, which can conveniently check antenna cables and connectors for short and open-circuit conditions and locate the position of such faults with fair accuracy.

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