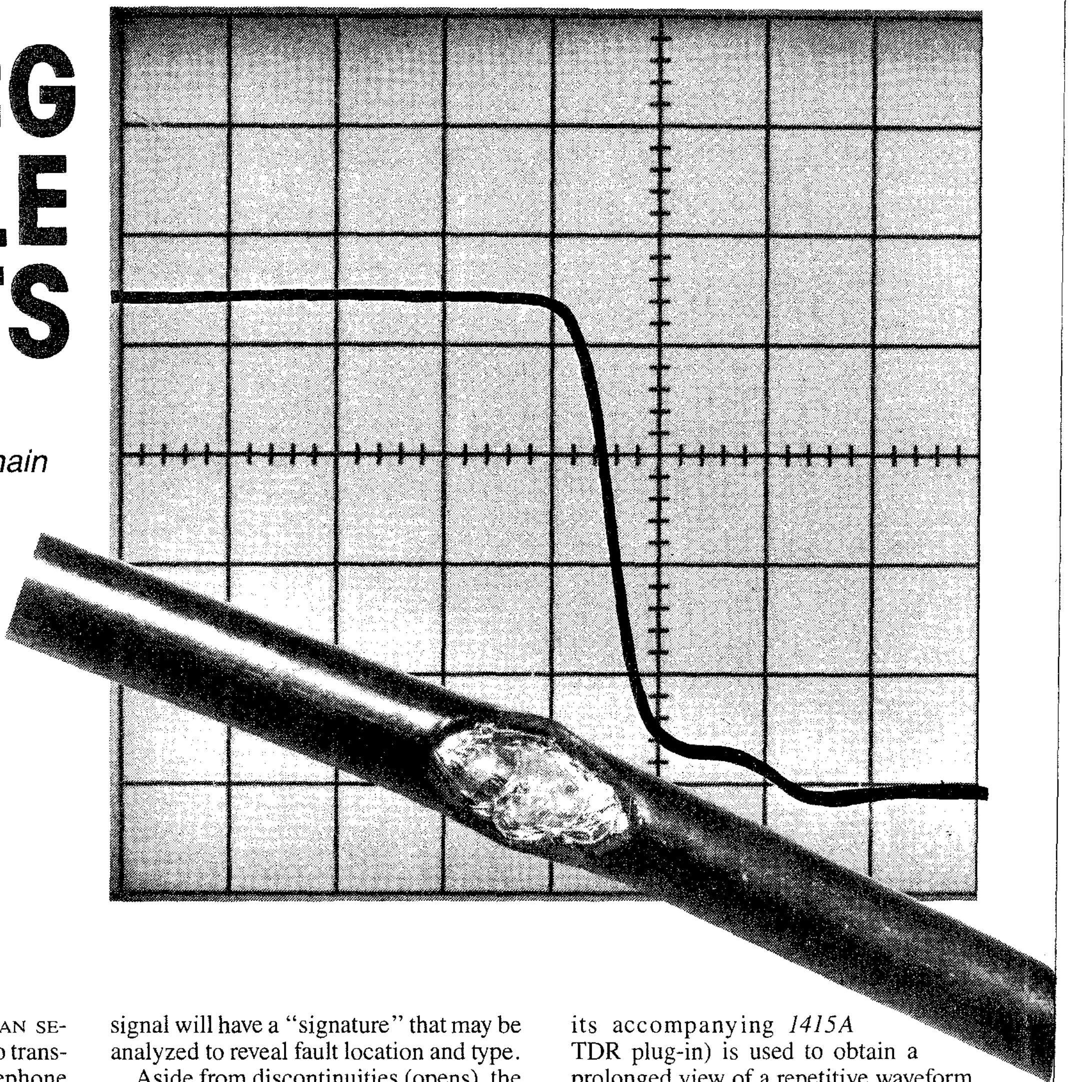
FINDING CABLE FAULTS



Never heard of time-domain reflectometry? Find out what it's all about right here.

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FAULTS IN TRANSMISSION LINES CAN SEVERELY disrupt the operation of radio transmitters, local-area networks, telephone systems, and many other high-power, high-speed devices. Without proper test equipment, locating faults can be extremely difficult—if not impossible. Simple DC-resistance tests seldom are able to reveal the location of a fault, not to mention its type.

Special test instruments do exist, however, that aid diagnosis of many types of cable faults—not just clean breaks. The *T*ime *D*omain *R*eflectometer (TDR) relies on AC impedance measurements to diagnose both the type and the location of many types of cable faults.

TDR overview

The basic idea behind time-domain reflectometry is this: Send a high-speed pulse (or pulse train) with well-defined characteristics down a transmission line. Eventually it will be reflected back to the source, where the original and the reflected signals may be compared in phase, frequency, and amplitude. Depending on the quality of the cable, its impedance, and any faults (which may include clean breaks, frayed shields, etc.), the reflected signal will have a "signature" that may be analyzed to reveal fault location and type.

Aside from discontinuities (opens), the transmission line itself has a number of relevant properties, including a characteristic impedance, which may or may not change with frequency, and which may vary with length. It also has its own velocity of propagation, and a characteristic attenuation per unit length, which varies with frequency. The TDR can provide quantitative and qualitative information on those characteristics in a single measurement.

The theory behind TDR's has been known for years, but it wasn't until about 20 years ago, when sub-nanosecond pulse generators and oscilloscopes with equivalent bandwidths became available, that time-domain reflectometry became practical.

With the new equipment, distance resolution shrank from hundreds of yards to fractions of an inch. Further, the new generation of sampling oscilloscopes permitted accurate measurements of reflected signals in the millivolt range.

By the way, the sampling scope is not to be confused with the storage scope. A sampling scope (like HP's early *140A* and its accompanying *1415A* TDR plug-in) is used to obtain a prolonged view of a repetitive waveform. The sampling scope actually measures the instantaneous voltage of a waveform at various points, so the waveform must be periodic, or else the whole trace will not appear on the screen. Each sample is displayed as a single dot on the scope's CRT; after a number of successive samples are taken, the waveform is "filled out" and appears as a complete trace on the screen.

A storage scope, by contrast, captures the entire portion of the desired signal at once, not just a small portion of it, and then displays it when desired.

Principles of operation

In some industries the TDR is called a "wire radar," because radar and time-domain reflectometry operate on similar principles. A block diagram of a typical TDR is shown in Fig. 1-*a*. As shown in Fig. 1-*b*, an ultra-fast (sub-nanosecond) voltage step is sent down the cable under test. The cable's propagation velocity is known, so the time for the reflected signal to bounce back can be measured, and the distance to the fault calculated. The faster the step, the greater the distance resolu-

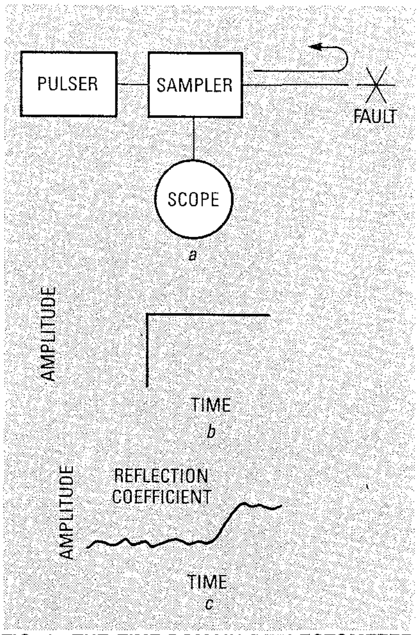

FIG. 1—THE TIME-DOMAIN REFLECTOMETER works by sending a very fast pulse down a transmission line, and then comparing the original with its reflection.

tion. The HP *140A* mentioned earlier had a response of 2.3 GHz, which corresponds to 150 picoseconds.

The reflected signal is shown in Fig. 1-*c*. The shape of the reflection is related to the impedance of the cable and other factors, as we'll see shortly. Any deviation from the initial signal can be recorded and analyzed. The effects, therefore, of cables, connectors, baluns, strip lines, tapered sections, and other broadband devices can be analyzed with a TDR.

Generally, the reflected signal is superimposed on the original signal, which results in a step-up or a step-down transition on the display. The step-up condition results when an inductive fault (or a fault with resistance higher than the cable's nominal impedance) causes an in-phase reflection with the initial pulse. The signals add, and the effect is the step-up transition manifested on the CRT display.

Conversely, the step-down transition results when a capacitive fault (or a fault with resistance lower than the cable's nominal impedance) causes an out-of-phase reflection with the initial pulse. Those signals subtract, and the result is the displayed step-down transition.

Real TDR's

With the basic theory in mind, let's take a look now at several real-world TDR's, namely, Tektronix' *1502* and *1503*, which are moderate- and long-range devices, respectively. The *1502* has shorter range but better resolution (2000 feet and 0.6 inches, respectively) than the *1503* (50,000 feet and 3 feet, respectively). The stated resolutions for both models are theoretical ideals, not real-world figures. The reason ideal figures are cited is that the resolution/accuracy issue is fraught with qualifiers to the extent that it is nearly impossible to make a blanket statement concerning both accuracy and resolution. We'll see why momentarily.

Reflected voltages

If we let E+ represent the initial pulse and E− the reflected signal, then the reflection coefficient ρ is given as follows:

$$\rho = E-/E+$$

The *1502* displays the fault-reflection coefficient ρ on the CRT; that value is referenced to the transmitted voltage by the vertical amplifier, which is directly calibrated in milli-ρ per division, for a 50-ohm system. If ρ is very small, then the cable's impedance would approach the reference impedance per this formula:

$$Z = Z_{REF} \cdot (1+\rho)/(1-\rho)$$

The reference impedance (Z_{REF}) is 50 ohms; it is set by a precision 50-ohm cable supplied by Tektronix. ρ may assume any value between −1 and +1. −1 corresponds to a short circuit, which appears as shown in Fig. 2; +1 corresponds to an open circuit, as shown in Fig. 3. A positive ρ corresponds to a rise on the CRT screen, and a negative ρ to a dip.

The *1502* TDR actually displays the reflection coefficient ρ versus the distance to the detected fault. You can think of that as impedance versus distance. The time delay between the initial signal and its reflection from the fault identifies the distance to the fault.

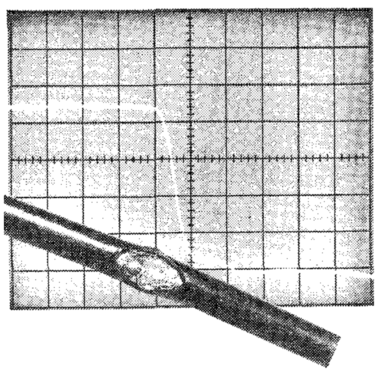

FIG. 2—A TEKTRONIX *1502* displays a short circuit.

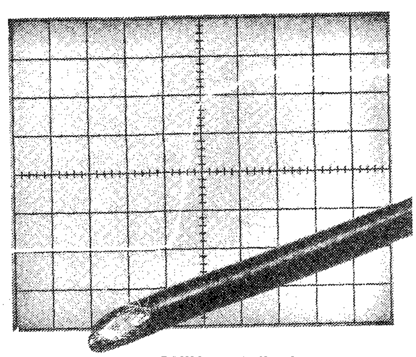

FIG. 3—A TEKTRONIX *1502* displays an open circuit.

Interpretation

Faults occur in even the best high-frequency transmission systems, and they can cause substantial losses of power, or severely distort the transmitted signal. Faults come in many forms: The dielectric 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. The TDR treats all such occurrences as discontinuities, abrupt transitions in the otherwise-constant characteristic impedance of a transmission system.

The ideal cable should appear as a resistive load, with no reflections occurring except at the beginning and the end of the cable.

In practice, reflections *do* occur, and they indicate changes in impedance. Reflections may appear as steps or pedestals, which generally indicate that a cable of different impedance has been spliced into the line. Reflections might also appear as small bumps, which indicate a fault or discontinuity. Further, the profile might show a slowly rising or falling characteristic, which indicates a series or shunt loss in the cable.

If the overall loss in a transmission line is less than about 0.25 dB, and if the total impedance variation along the line is less than about ±10 ohms, the impedance profile is valid. Therefore, the trace displayed on the screen is an accurate representation of the impedance at all points along the line, within the accuracy limits of the system.

As stated earlier, the CRT of the *1502* is calibrated in ρ per division; ρ is related to impedance by this formula:

$$\rho = (Z-50)/(Z+50)$$
$$= 50 \cdot (1+\rho)/(1-\rho)$$

Signatures

The nature of a fault may be discerned because the height and the shape of a reflection may be observed as a signature. With experience the operator becomes accustomed to interpreting signatures.

Figure 4 shows a number of TDR-detected cable faults with their resultant fault signatures.

As shown in in Fig. 4-*a*, a sharp pulse applied to a line with an inductive fault gives a pulse with a slowly falling output. The remaining parts of that figure show how pulses of different shapes appear after being fed through a line with the indicated type of fault.

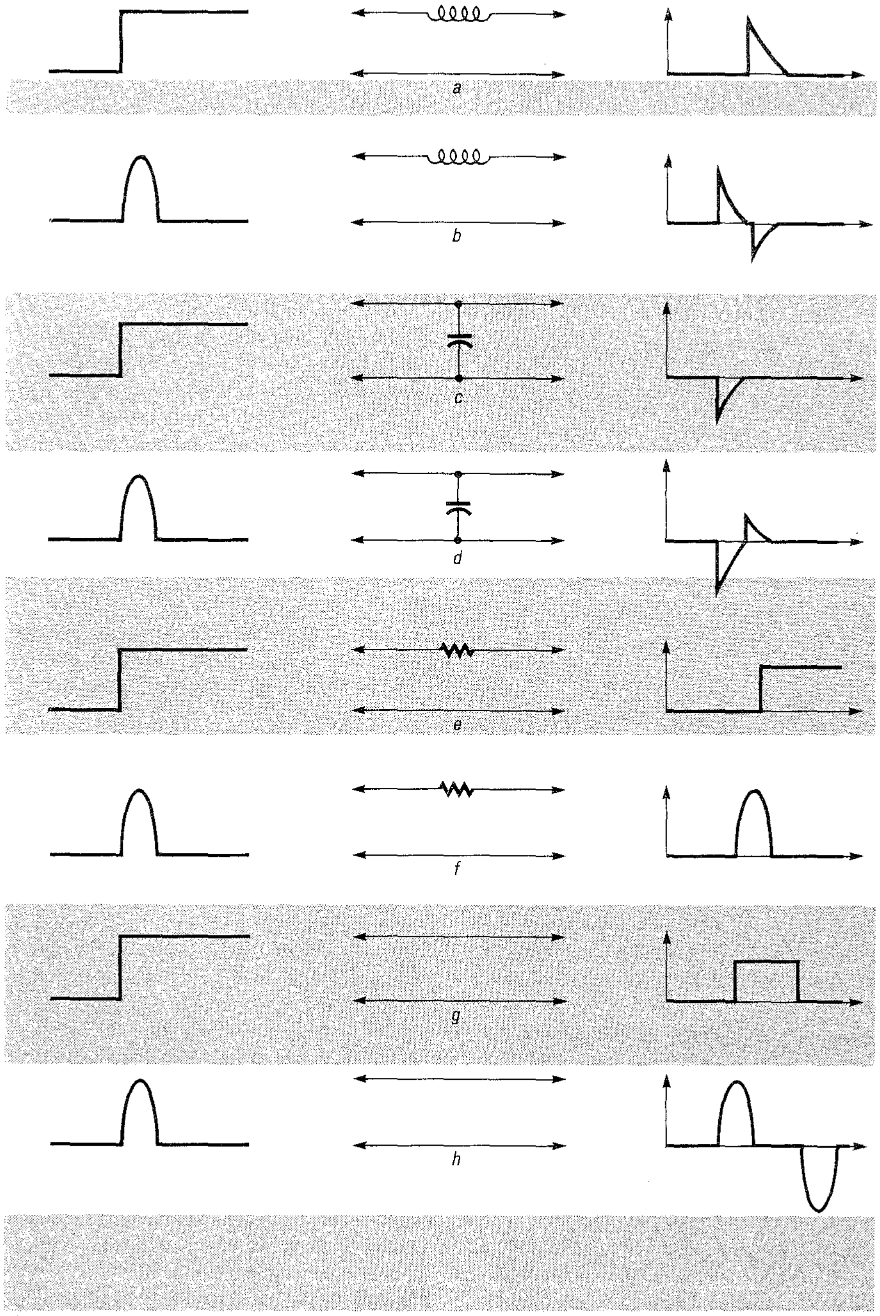

FIG. 4—SHARP PULSES are fed to inductive (*a*), capacitive (*c*), resistive (*e*), and straight-through (*g*), conductors. Half-sinewaves are fed to corresponding circuits in *b, d, f* and *h*.

As in any measurement technique, there are limitations imposed both by the state of present-day technology and by the technique itself. The TDR relates time to distance, so the risetime of the incident or the reflected pulse limits maximum distance resolution. It also limits system bandwidth—the frequency range over which measurements are valid. For example, reflections generated in waveguide systems, unlike coaxial systems, travel at various propagation velocities, depending upon the mode of propagation. Therefore, analysis of waveguide reflections is complex; it is further compounded by the inherent low-frequency cutoff of those systems. Hence the analysis is inherently narrow-band.

TDR and SWR

Whereas TDR measurements isolate a transmission line's characteristics in time (location), *S*tanding *W*ave *R*atio (SWR) measurements provide an immediate overall indication of a transmission line's performance. A TDR can be used to calculate worst-case VSWR (*V*oltage *S*tanding *W*ave *R*atio) by using the following formula:

$$\text{VSWR} = (1 + |\rho|)/(1 - |\rho|)$$

However, the TDR cannot predict the frequency at which that VSWR will occur. The equation is useful in verifying specifications on connectors or splices; however, since reflections combine in a complex manner, it is necessary to use frequency-domain techniques to determine a system's overall VSWR.

A long-range TDR

Tektronix' model *1503* is a TDR that is designed for long-range measurements of twisted-pair and other low-bandwidth cables. A block diagram illustrating basic operation is shown in Fig. 5-*a*. Because of the low bandwidth, it is necessary to use high-energy signals of controlled bandwidth. The *1503* uses 10-volt ½-sinewave-shaped pulses, as shown in Fig. 6-*b;* depending on the type of fault, the reflected signal will be a reduced-amplitude, time-delayed version of the original signal, as shown in Fig. 6-*c*.

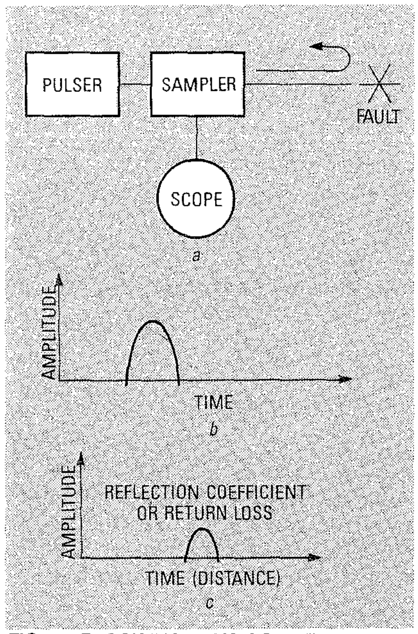

FIG. 5—BLOCK-DIAGRAM OF THE *1503 (a)* is similar to the *1502*, shown in Fig. 1. However, the *1503* uses half-sinewave signals (*b*) whose shape and amplitude (*c*) can be interpreted to diagnose cable faults.

The *1503* also has a precision log amplifier to amplify weak signals. Unlike the *1502*, which reads in ρ, the *1503* reads in return loss. Return loss may be related to ρ as follows:

$$\text{Return loss} = 20 \log \rho$$

or

$$|\rho| = 10^{-X}$$

where

$$X = \text{Return loss} / 20$$

As shown in Fig. 6, the *1503* has controls to calibrate the CRT display. Usually, the original pulse is adjusted to occupy two CRT divisions, and so is the reflected pulse. Then return loss may be read directly from the front-panel control.

Length problems

A long cable can yield erroneous readings. The reason is that, due to cable loss, a major fault at a great distance will yield reflections that appear similar to a minor

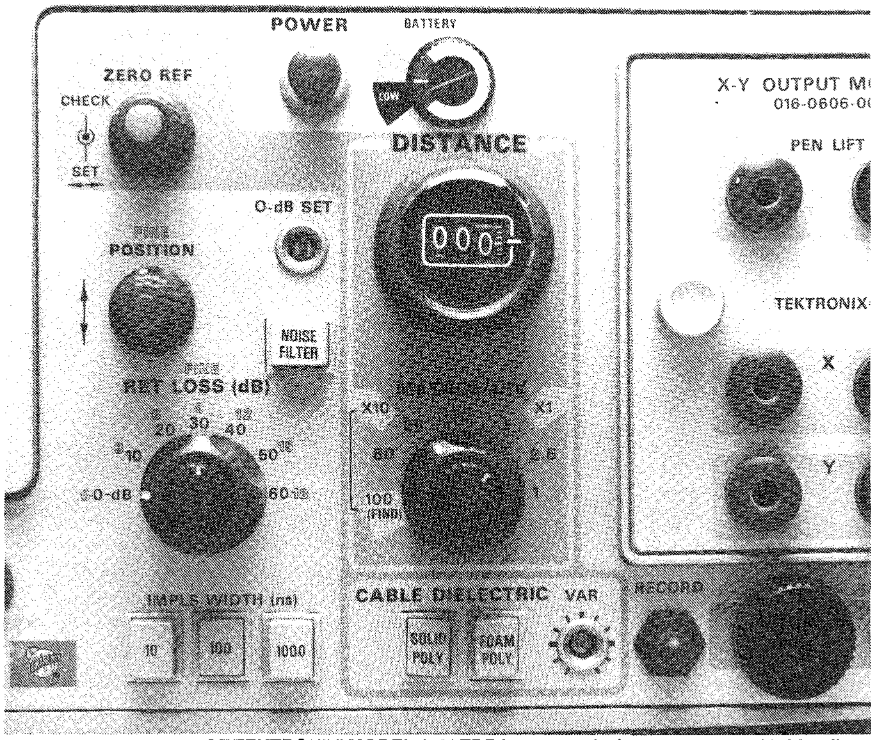

FIG. 6—FRONT PANEL OF TEKTRONIX' MODEL *1503* TDR has controls that calibrate the CRT for direct distance display.

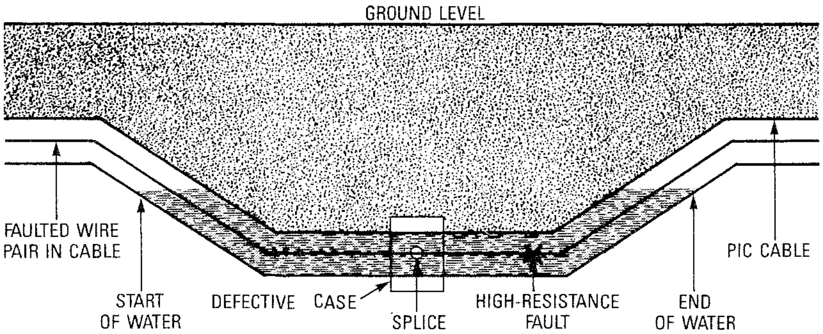

FIG. 7—A MOISTURE-LADEN TELEPHONE CABLE can fool a TDR about the location of the fault. A bridge-type tester may be necessary for maximum accuracy.

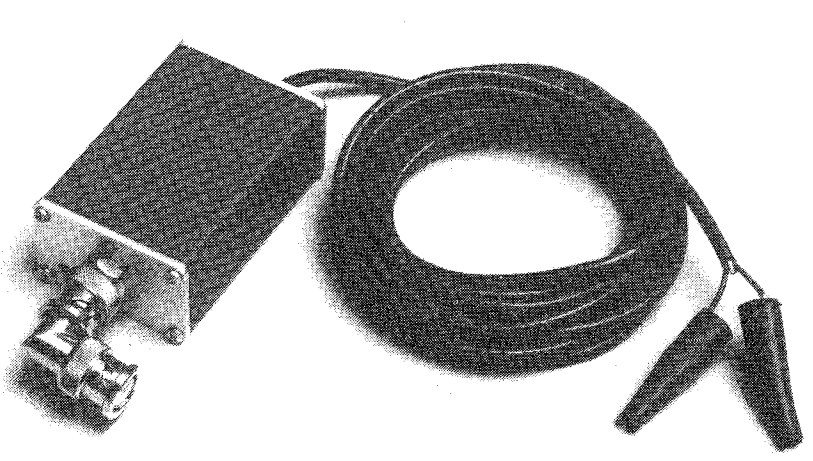

FIG. 8—AN ISOLATION NETWORK is available for the *1503;* the network improves noise immunity.

fault at a short distance. The cure is to include mathematical corrections that include the effect of pulse attenuation.

On a longer cable, the risetime t_R of the reflected pulse is almost totally a function of the cable itself; t_R in seconds is expressed by the following equation:

$$t_R = (13.133 \times 10^{-6}) \frac{\alpha_0^2}{f_0} L^2$$

In that equation, α_0 is cable attenuation in dB/1000 feet at f_0 (in Hz), and L is the cable's length in feet. When using that formula, you should double the value for length, because the pulse must travel down the cable and back. In practice, RG213 cable has a reflected risetime of 12 ns through 50 feet of cable; a 50-foot length of RG174 has a 120-nanosecond risetime.

The vertical accuracy (the accuracy with which ρ is displayed) of both the *1502* and the *1503* is specified at ±3%. Accuracy can be improved (as outlined in MIL-C-17, a specification devised for military use) by making measurements with the *1502* using a precision air-line reference to determine characteristic cable impedance.

Length determination

When attempting to relate electrical length to physical length, it is important to take into account four sources of possible error:

- Cable snaking, twisting, and looping.
- Variation in propagation velocity in a given type of cable.
- Sections composed of different cables with different propagation velocities.
- Measurement accuracy of physical cable length.

Snaking refers to the loss caused by cable take-up. For example, it may take 1000 feet of cable to cover a distance of 990 feet.

Propagation velocity depends on the cable's insulation and on the geometry of its cross-section. Most cable manufacturers control propagation to within 0.5 percent; however, different manufacturers' makes of the same cable can vary by as much as two percent. For example, Belden specifies the propagation velocity of its Teflon dielectric coaxial cable (type PTFE) as 69.5 percent of that in air; however, the same cable from ITT has a velocity of 71 percent.

Those figures are quoted for coaxial cable, the most stringently controlled type of cable. Twisted-pair and other types of cables yield greater differences.

When cable types are mixed, determining length can be difficult. For example, older sections of pulp-dielectric telephone cables are being spliced to new *P*olyethylene *I*nsulated *C*ables (PIC). The resultant change in propagation velocity when a signal moves from one to the other drastically alters a cable's signature.

The last problem of cable-length measurement is often brought about by the operator's inability to judge distance accurately. For example, to clear obstacles, a cable might snake around brush, go down into a ditch, around a torn-up sidewalk, etc.

There are several practices that can help minimize error. First, take multiple readings. Second, use known points on the

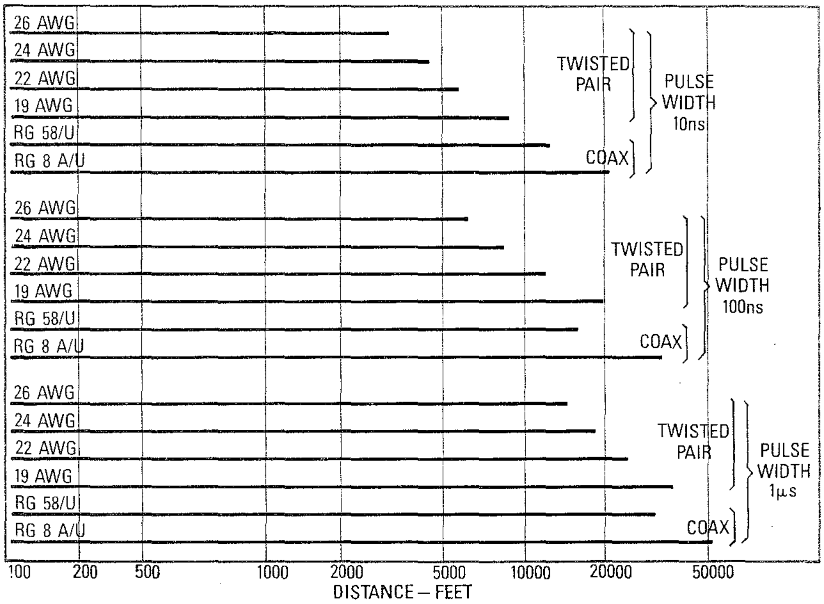

FIG. 9—**COAX FAULTS CAN BE MEASURED** at greater distances than twisted-pair faults.

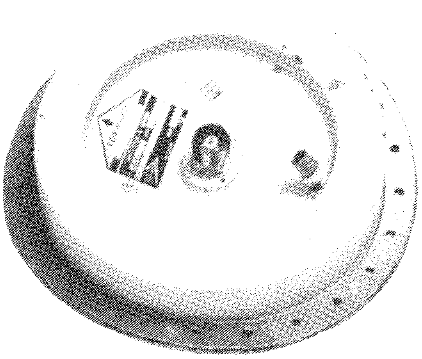

FIG. 10—**PERFORMANCE OF AN L-BAND** antenna can be measured with a TDR.

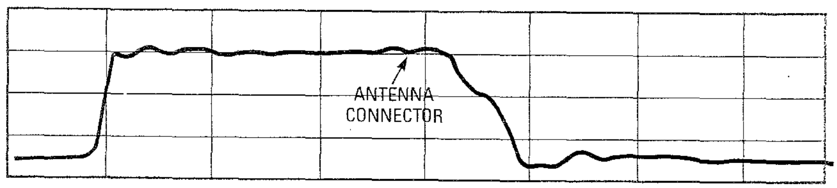

FIG. 11—**THE TDR SIGNATURE** of the L-band antenna pictured in Fig. 10 is shown here.

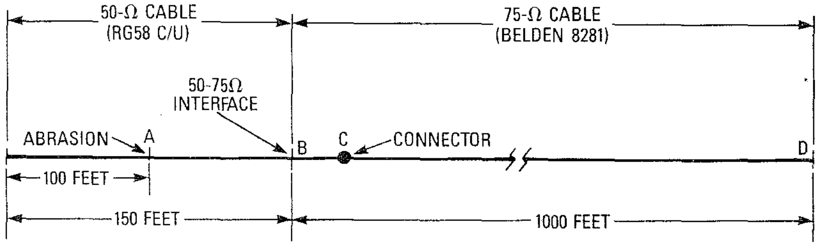

FIG. 12—**TEST-JIG CABLE ASSEMBLY** has two types of cables and several interconnections.

cable to calibrate the TDR. Last, take readings from both ends of the cable. The latter is a particularly good idea if the cable is composed of two spliced-together cables with different dielectrics.

Practical testing

First, it must be said that the TDR is not the only means by which cables may be tested; other methods may be used in some cases to obtain better results than with a TDR. For example, note the PIC cable in Fig. 7. Water has leaked into a below-ground telephone cable and will eventually cause insulation breakdown. That will place a resistance of several hundred thousand ohms across the cable. Further, through electrolysis, the cable's continuity will gradually be destroyed.

A TDR cannot detect the point where the insulation weakness begins, whereas a bridge-type fault locator can. On the other hand, the TDR can detect water in the cable, but a bridge cannot. In summary then, the TDR can detect the problem and the bridge can detect the symptom.

Realizing another limitation of the TDR will help preserve both the instrument and the well-being of the operator. The TDR cannot withstand any significant voltage on the cable under test. For example, with the *1502*, a voltage-carrying cable should be disconnected from any powered equipment, and the ends of the cable should be terminated or shorted to bleed off static charge that may have built up.

The *1503* is more rugged; it can withstand up to 400 volts (DC + peak AC) at frequencies as high as 440 Hz. You can obtain a good signal even with more than 100 volts of 60-Hz AC. The *1503* also comes with an isolation network, shown in Fig. 8; that network is recommended for use with twisted-pair lines.

Both the *1502* and *1503* possess variable noise filters that enhance their S/N ratios. To test a noisy cable you may want to use the isolation network to provide a crisp, clean trace.

In practice, the first thing to do is to match the TDR's impedance to the impedance of the cable under test as closely as possible. The object of impedance matching is to put as much energy into the cable under test as is possible. However, if you're only interested in the distance to a cable fault or its signature, it may be unnecessary to calibrate the TDR.

The *1503* comes with a 50-ohm impedance standard, and the *1502* comes with impedance adapters of 75, 93, and 125 ohms; those same impedances may be set through front-panel pushbuttons. Most twisted-pair cables are tested with the 93-ohm setting or adapter; however, when the isolation network is used with the *1503*, the 125-ohm setting should be chosen.

If an impedance adapter is unavailable, both the *1502* and the *1503* feature front-panel gain adjustments that allow precise recalibration for cables of any impedance. The effects of impedance mismatch are an invalid indication of ρ or return-loss calibration, reduced range, and re-reflections that appear as multiples of the distance to the actual fault.

It is very important to establish a good connection to the cable under test. Remember that the TDR contains high-frequency data that is not transmitted efficiently by pieces of lamp cord, battery clips, etc. In fact, low-quality cable substantially reduces the TDR's range and accuracy. Refer to Fig. 9 and note how large-diameter low-loss coax enables communications over a greater distance than small-diameter coax and twisted pair.

Antenna testing

In any kind of time-domain reflectometry, a chart recorder is useful for recording and preserving test data for later comparison with questionable equipment. For example, a chart recorder and a *1502* are

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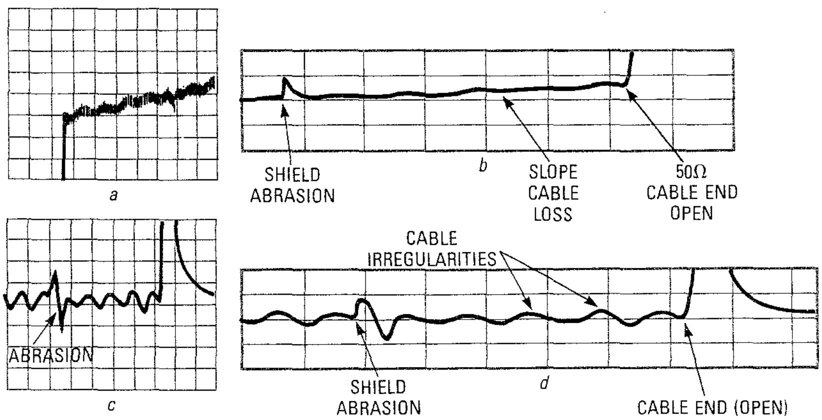

FIG. 13—CRT AND CHART-RECORDER outputs of the test assembly shown in Fig. 12 are illustrated here. Only the 150-foot section was measured; *1502* outputs are shown at *a* and *b*, and *1503* outputs at *c* and *d*.

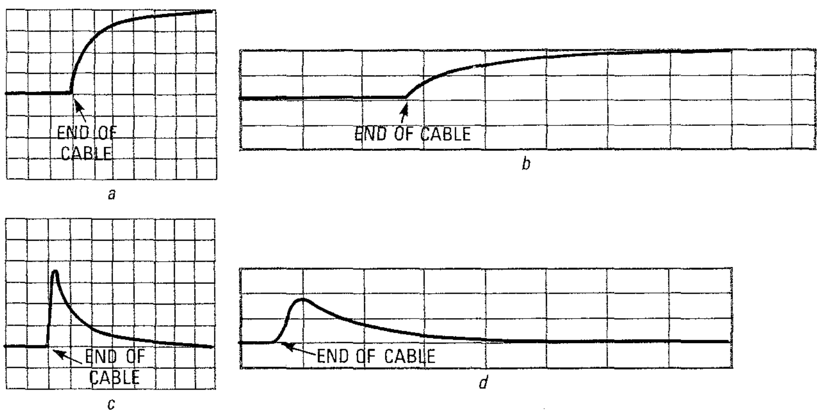

FIG. 14—AFTER CONNECTING THE 1000-FOOT TEST SECTION, outputs were again recorded. As before, *1502* outputs are shown at *a* and *b*, and *1503* outputs at *c* and *d*.

useful for measuring the signature of an antenna and its components. That type of comparison provides a quick yet accurate go/no-go indication.

Figure 10 shows an L-band aircraft antenna, and Fig. 11 shows its signature. The signature will vary depending on the length of the cable used, so the same length of cable should be used when testing a group of antennas. Remember that pulse risetime decreases on a long cable as a function of the length squared. Generally, it is best to use as short a cable as possible when using a TDR to test an antenna. If the antenna is to be tested with a cable in excess of 100 feet, or if the antenna resides in a strong RF environment, then a high-noise-immunity TDR (like the *1503*) would be a good choice. Use of an isolation network will improve noise immunity further.

TDR coax signatures

Figure 12 shows a cable assembly composed of a 150-foot section of 50-ohm RG58C/U cable connected to a 1000-foot section of 75-ohm Belden 8281. An abrasion is present at point A, a 50/75-ohm interface at point B, and a connector at point C. The assembly ends at point D; it is not terminated.

First we disconnected the 150-foot section of RG58C/U and measured it with a *1502* and a *1503*.

Figure 13-*a* shows a reproduction of the *1502's* CRT, and Fig. 13-*b* shows the chart-recorder output. Note that the CRT trace shows little more than the general upward slope recorded by the chart recorder, which itself clearly displays both the abrasion at point A and the open circuit at point B. Figures 13-*c* and 13-*d* show the same setup as recorded by the *1503*. Note that the chart recorder in effect gives a much-expanded view of the X axis, for better resolution.

Next, we reconnected point B (in Fig. 12) and readjusted both TDR's to view the signature at point D. Note how the curves shown in each section of Fig. 14 resemble each other closely in their depiction of the discontinuity at point D.

Conclusion

Time-domain reflectometry is a valuable technique, one that can significantly decrease the amount of time spent troubleshooting various types of faults in coax, twisted-pair, and other cables. We hope that this article has given you an understanding of the basic principles involved. **R-E**

SEMICONDUCTORS

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done in both the forward and the reverse directions, unless a protection diode is incorporated into the device. MOSFET's that have no protection diode should read the same in both directions. Because the insulating properties of the metal-oxide coating are far superior to those of a reverse-biased junction, the value of I_{GSS} in a MOSFET is considerably less than that of an FET.

Another current parameter often specified for FET's and MOSFET's is I_{DSS}, the drain-to-source leakage current with the gate shorted to the source. That test is often used to determine the amount of current flow in the constant-current mode.

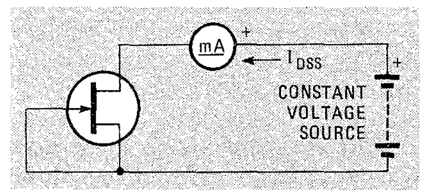

FIG. 8—MEASURE I_{DSS} by applying the manufacturer's stated value of V_{DSS} and reading the milli-ammeter.

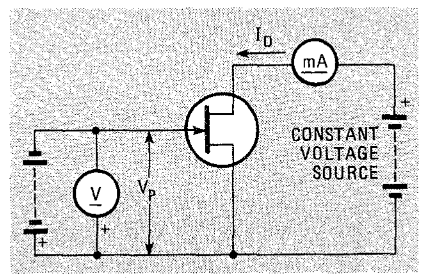

FIG. 9—MEASURE V_P by gradually increasing the gate voltage while monitoring I_D. When current stops increasing, V_P has been reached.

The circuit for measuring I_{DSS} is shown in Fig. 8. The drain voltage is maintained at the V_{DSS} value listed on the data sheet; then current is measured.

A circuit that combines both voltage and current measurements is shown in Fig. 9; that circuit is used to measure V_P. With no voltage on the gate, a normal depletion-mode transistor conducts current from source to drain. In order to halt that flow, a voltage must be applied to the gate. As stated earlier, the point at which source-to-drain current ceases to flow is called the pinchoff voltage. Sometimes you see that value listed as the cut-off voltage, which is a lingering term from our vacuum-tube past.

To measure V_P, gate voltage is gradually increased while drain current is monitored. When a change in gate voltage no longer produces a change in drain current, pinchoff voltage has been achieved. Ideally, current will drop to zero, but

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