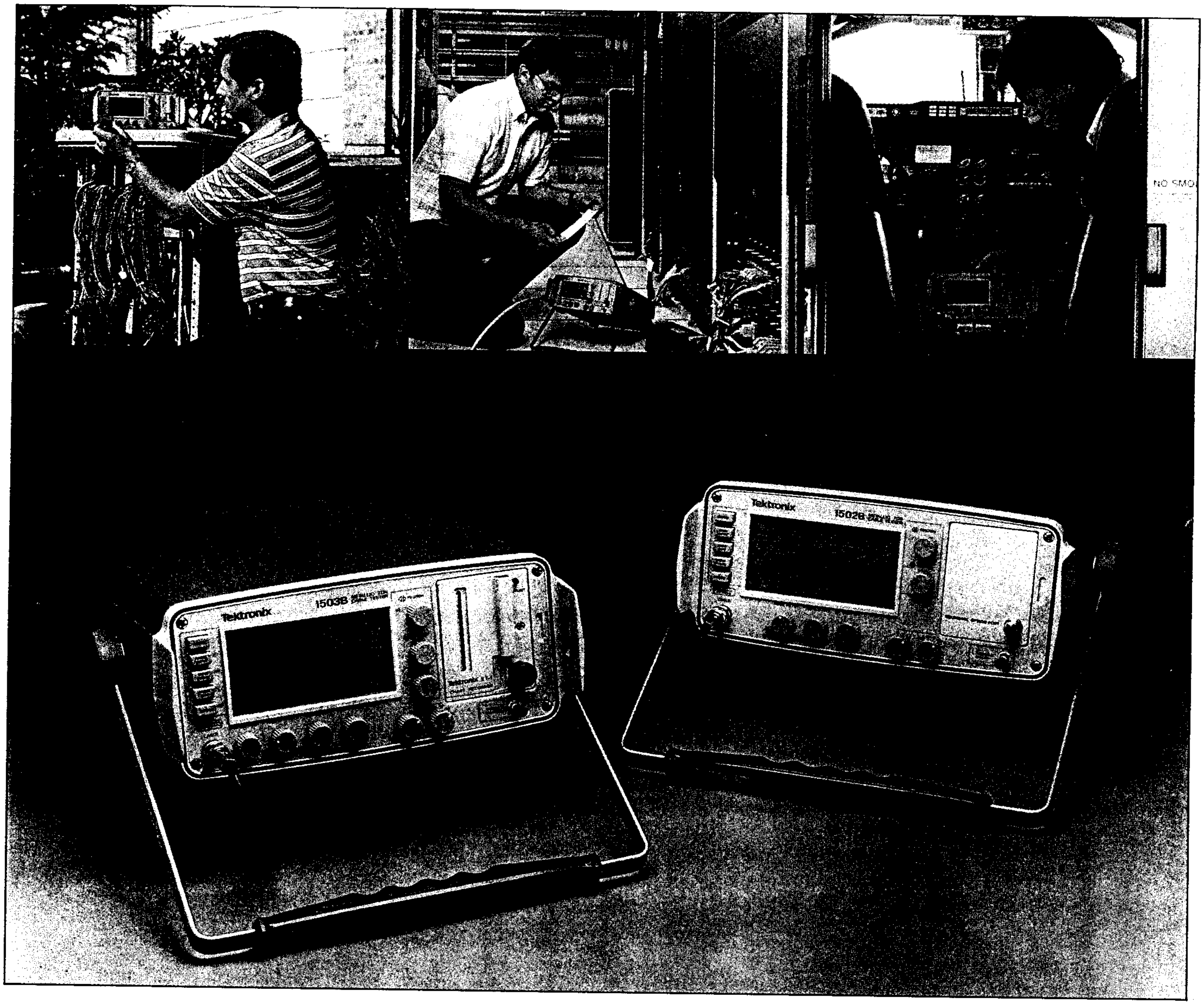
TEK 1500B SERIES
METALLIC CABLE TDR'S

APPLICATION
NOTE

TEKTRONIX METALLIC TDR'S FOR CABLE TESTING



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TDR'S FOR CABLE TESTING

Introduction

TDR stands for 'Time Domain Reflectometry,' a most straightforward and easy to use method for locating and identifying problems or faults in any type of *dual conductor cable*. The TDR can indicate both the nature of the problem and the location–quickly, precisely and with no operator calculations.

The TEKTRONIX 1502B and 1503B (1500B Series TDR's) have been designed as maintenance tools for maximum usefulness under rugged field conditions. The 1500B Series TDR's are compact, waterproof, battery powered, ruggedized and inexpensive. The 1502B and 1503B are also very easy to use with an on-line menu system containing operation and reference information.

The TEKTRONIX 1502B (figure 1) is a moderate range TDR that will test cable up to 2000 feet (500 meters) with a resolution to 1 inch. The 1502B is optimized for checking all types of cabling encountered in aircraft, ships, ground vehicles and data/voice communications installations.

The TEKTRONIX 1503B (figure 2) is long range TDR that will test cabling up to 50,000 feet (10,000 meters) with resolution to 12 inches. The 1503B is optimized for checking either long or short runs of cable encountered in telephone, computer/LAN, military, CATV and other communications installations.

The 1500B Series TDR's each weigh less than 18 pounds. An optional dot matrix chart recorder that will function in either unit is available. Both instruments operate on AC, 12 VDC or an optional battery pack and are designed to meet the environmental specifications for flight line rated test equipment per MIL-T-28800, Class II, Type 2, Style A.

How the 1502B Works

TDR works on the same basic principles as radar, and in fact has been called "wire radar" by some industries. Conventional or "step-type" TDR is used in the 1502B, as shown in figure 3. In this method, ultra-fast rise time (200-ps) voltage steps are sent down the cable under test. Each cable fault will cause energy to be reflected back toward the cable input, where a sampler detects voltage. The returned voltage, sometimes called the reflected voltage, is superimposed on the advancing initial step, and will appear as a step-up to step-down transition on the display, depending on whether it is reflected in-phase or out-of-phase with respect to the initial step. Inductive faults or faults of higher resistance than the cable impedance will

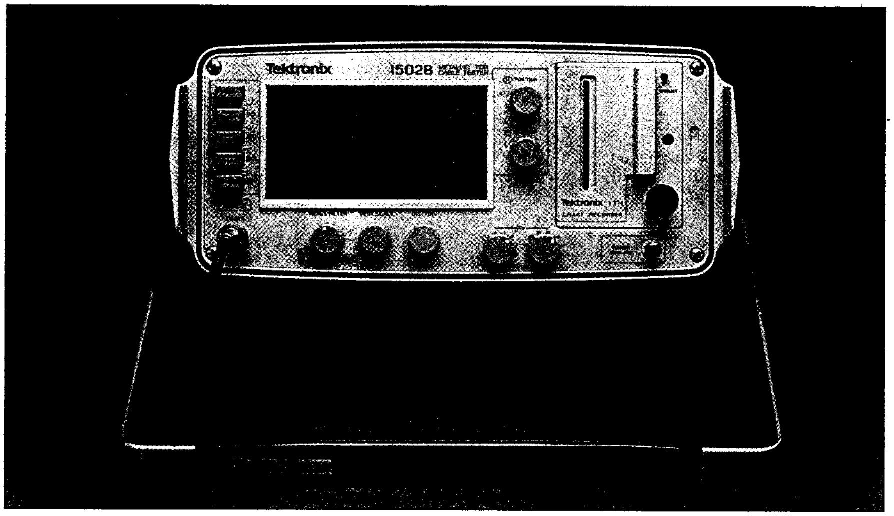


Figure 1.

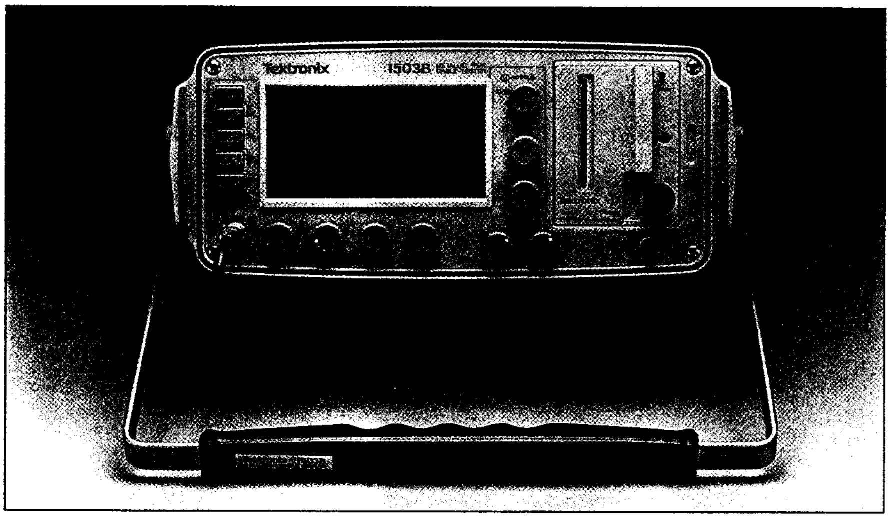


Figure 2.

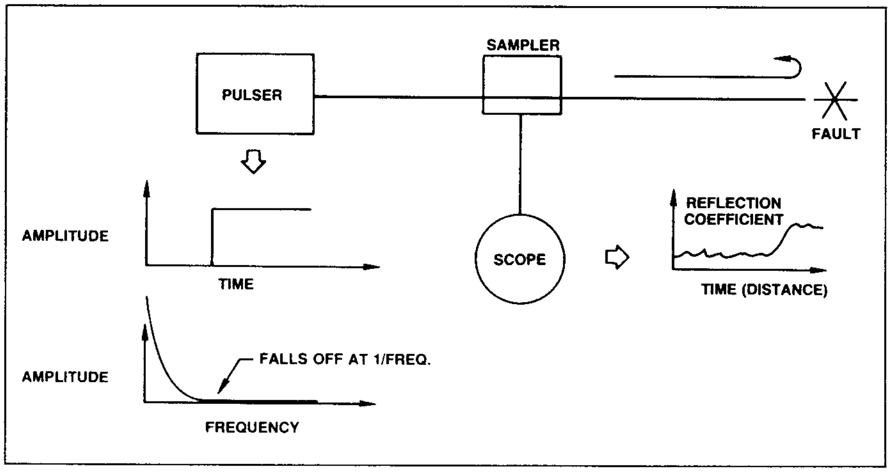


Figure 3. Conventional "Step-Type" TDR.

cause reflections in-phase with the initial step, resulting in a step-up transition. Capacitive faults or faults of lower resistance than the cable impedance will cause out-of-phase reflections, resulting in a step-down transition.

If the voltage wave sent down the cable is termed E+ and any reflected voltage wave E–, it is possible to define a reflection coefficient (ρ) as:

$$\rho = \frac{E-}{E+} \qquad (1)$$

The fault reflection coefficient, ρ, is displayed on the LCD referenced to the transmitted voltage "base line." The 1502B vertical amplifier is directly calibrated in millirho per division for a 50-ohm system. Note that, in "lossless" cable, it is possible to relate ρ to cable impedance by the simple formula:

$$Z = Z_{REF}\left[\frac{1+\rho}{1-\rho}\right] \qquad (2)$$

Where Z_{REF} is usually set by the precision 50-ohm cable supplied with the 1502B, giving:

$$Z_{REF} = 50p \qquad (3)$$

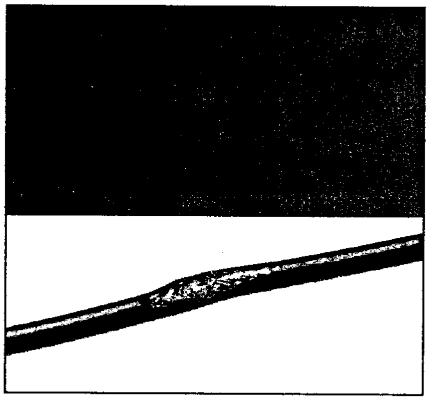


Figure 4. A 1502B Display of a Shorted Cable.

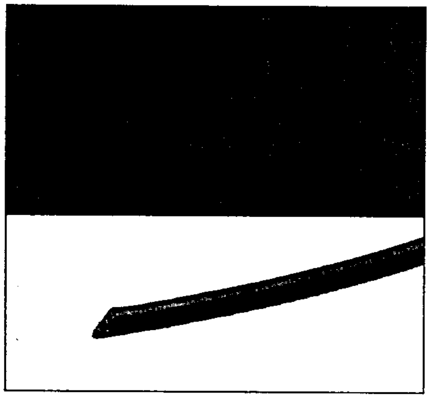


Figure 5. A 1502B Display of a Cut (Open-Circuited) Cable.

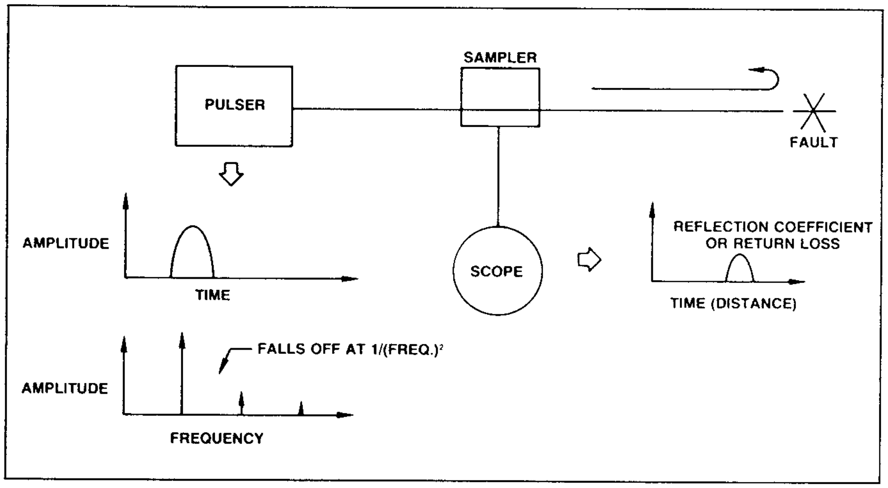


Figure 6. Pulse-Type TDR.

A "rise" on the display indicates a positive ρ, or an increase in cable impedance, a "dip" on the LCD display indicates the opposite. In general, ρ may assume any value between –1 and +1, where –1 corresponds (see equation 3) to a short circuit (figure 4) and +1 corresponds to an open circuit (figure 5).

The 1502B LCD displays reflection coefficient, ρ, versus distance down the cable under test; this is equivalent to taking a picture of cable impedance level versus distance. The time delay between a transmitted pulse and the reflection from a cable fault uniquely measures the fault distance down the cable. The height of the reflection defines the impedance change at the fault, and it will be shown in this note that the shape or "signature" of the reflection uniquely defines the type of cable fault. This means that TDR directly displays the location of and indicates the severity of every cable fault–in addition to presenting the fault "signature," which allows the probable cause of each fault to be diagnosed.

It is interesting to note that TDR can also predict the worst-case vswr (voltage standing wave ratio) that will result from a single cable fault,

$$\text{VSWR} = \frac{1+|\rho|}{1-|\rho|} \qquad (4)$$

although it cannot predict the frequency at which the worst-case vswr will occur. Equation 4 is useful for verifying specifications on connectors or splices. Since reflections in large cable assemblies combine in a complex manner, it is generally necessary to use frequency domain techniques to verify overall system vswr specifications.

How the 1503B TDR Works

For long-range TDR over cables of low bandwidth (twisted pair, etc.), it is necessary to use high energy signals of controlled bandwidth. The 1503B uses –5 volt, ½-sine shaped pulses as shown in figure 6, features a precision log amplifier to boost faint signals, and reads in "return loss" rather than ρ.

$$\text{Return loss} = 20 \log \rho \qquad (5)$$

or

$$|\rho| = 10^{-\left(\frac{\text{Return Loss}}{20}\right)} \qquad (5a)$$

For precise measurements, the pulse of the 1503B TDR can be adjusted. Turn the noise average knob to vertical set reference, then turn the vertical scale knob so the pulse is 3 divisions on the LCD graticule and press store (Figure 7). Now return the noise aver-

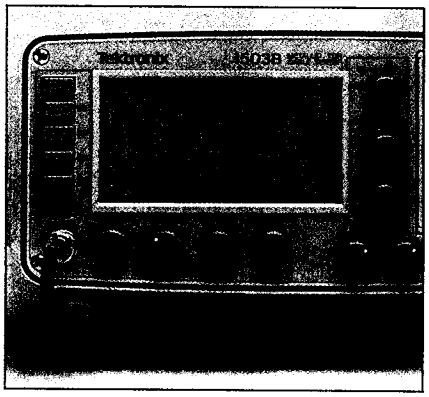


Figure 7. 1503B Front Panel Controls.

age knob to the appropriate average setting, set the vertical scale on the reflected pulse to be measured to 3 divisions and read the return loss (dB) from the LCD. ρ may be calculated (equation 5a) if desired. Once again, "dips" below the base line correspond to negative reflection coefficients and "rises" above the base line correspond to positive reflection coefficients.

When measuring a long section of cable, a problem arises that makes the exact calculation of fault impedance (equation 2) tedious. The loss in the cable causes TDR pulses to be traveling to the fault and back, and the reflection coefficient (or return loss) "seen" by an instrument at the cable input must be corrected for cable loss to yield the actual reflection coefficient at the fault. Because of cable loss, major faults at long distances will yield reflections no larger than minor faults close to the test end of the cable. Appendix A details some practical techniques for making accurate fault impedance measurements on long cables by first correcting equation 5 for pulse attenuation.

For purposes of cable maintenance, it is usually sufficient to merely locate and identify cable faults. This is to say, the location or "signature" of a fault on a long cable is generally of considerably more interest than the precise impedance change at the fault. For these applications, no calculations are required.

TDR Resolution and Accuracy

It is important to distinguish between "resolution" and "accuracy" in a TDR. Resolution and accuracy are two entirely different things. Resolution measures how closely together two separate cable faults may be located before the TDR perceives only one fault, and is determined primarily by the rise time of the pulses received by the TDR. Since the rise time of any pulse is degraded by the transmission through a long cable, resolution to a large extent depends upon both the TDR instrument and the cable under test. The 1502B resolves faults to within 1 inch on short, high-quality cables; the 1503B resolves faults to within 12 inches under the same conditions.

On longer cables, the rise time of the reflected pulse is determined almost entirely by the cable. Deher gives the following equation for the 10/90-percent output rise time of coaxial cable responding to an ideal (zero-rise-time) excitation pulse:

$$t_r = (13.133 \times 10^{-6}) \frac{\alpha_0^2}{f_0} L^2 \text{Seconds} \qquad (6)$$

where α_0 is cable attenuation in dB/100 feet at frequency f_0 in Hz, and L is the cable length in feet. Since TDR pulses must pass down the cable and back, twice the physical length of the cable should be used in this formula to calculate reflected rise time. It is interesting to note that the reflected rise time through 50 feet of RG 213 is 12 ns, through RG 58 is 78 ns, and through RG 174 is 120 ns even for a perfect (zero-rise-time) TDR. It is also interesting to note that rise time varies as the square of cable length; 1000 feet of cable exhibits a rise time 100 times greater than that of 100 feet of cable!

> CONCLUSION: On lengths of cable over 100 feet or so, the useful fault resolution of the 1503B is every bit as good as that of the 1502B, despite the fact that the 1502B uses much faster (higher bandwidth) pulses for excitation.

Vertical accuracy relates to how precisely a TDR displays ρ or return loss. The basic specifications on the 1502B and 1503B are ±3 percent.

Horizontal accuracy relates to how precisely the distance to a fault can be measured. It is determined by TDR time base stability and linearity, as well as by how closely the propagation velocity of the cable is known. The time base accuracy of the 1502B and 1503B is ±2 percent of the distance measured.

It is important to remember that any TDR provides the electrical length from the instrument to the cable fault. To relate electrical length to actual physical length, it is necessary to take into account the following factors:

1. Cable "snaking," twist, and loops.
2. Propagation velocity variation in a given type of cable.
3. Sections composed of different cables with different propagation velocities.
4. Accuracy of physical cable length measurement.

"Snaking" loss is caused by cable take-up, by ups, downs, and zig-zags of the cable inside the trench or conduit. This usually causes a 1000-foot cable to cover only about 990 feet of trench length (about a 1-percent distance loss). Much higher percentage errors are common in the short cable runs used in ships and aircraft. Telephone cables can contain more than 2400 twisted wire pairs, and those on the outside of the cable are longer than those on the inside. Because of twist, reel length and twisted pair lengths always differ slightly, and long cables are sometimes looped to relieve stress and allow spare length for splicing.

The term "propagation velocity" measures the speed at which a signal travels down a cable, and depends upon both the dielectric material used for cable insulation and the geometry of the cable cross-section. The accuracy to which propagation velocity is known and controlled will also determine the relationship between electrical and physical length. Although most cable manufacturers control propagation velocity to within 0.5 percent, cables advertised as the same from different manufacturers will often vary by more than 2 percent in propagation velocity, thus causing distance errors of over 2 percent. For example, Belden specifies the signal propagation velocity of its "Teflon" (PTFE) dielectric coaxial cable as 69.5 percent of air, whereas ITT specifies a velocity of 71 percent of air for its PTFE cables. This is a discrepancy of about 2.2 percent; greater variations can occur as the cable ages.

The propagation velocity variation figures quoted above are for coax–the most carefully controlled type of cable. Other types of cable (twisted pair, etc.) will yield greater discrepancies. Worse yet, cable sections of different types are sometimes spliced together, such as the older sections of pulp dielectric that are being replaced by new Polyethylene Insulated Cables (PIC) in the telephone industry. Pumping reclamation compound through a section of cable also changes its signal propagation velocity. Each section of "different" cable may have its own signal propagation velocity, and this must be taken into account.

> NOTE: It is generally conceded, even for twisted pair cable, that propagation velocity is less susceptible to variations than other cable constraints. Worst case variations in new high-quality twisted pair cable are ±4 percent for capacitance (C) and ±3 percent for inductance (L). Cable resistance (R) doesn't vary much from sample to sample (±1 percent or so), but can vary by more than 25 percent because of temperature changes. Temperature change effects cannot be corrected in a practical sense unless the entire length of the cable is in a constant temperature environment.

Fortunately, cable propagation velocity varies by a factor proportional to $\sqrt{LC}$, and the physical effects that tend to increase L will usually decrease C (and vice versa), so that the cable propagation velocity remains constant within a percent or so if the cable dielectric or geometry does not change. Since TDR distance measurements depend only on cable propagation velocity, the measurements are generally quite accurate.

In contrast, bridge techniques determine the distance to a "clean" short or open by measuring either cable R or C. Although extremely high measurement accuracies (±0.05 percent) of R and C are achievable, R varies widely because of temperature (and splices, etc.), and C varies widely because of cable geometrical tolerance. The resultant distance measurement accuracy of bridge techniques is mediocre, and bridges can detect only a few types of cable faults.

The last factor to be accounted for is the physical length measuring accuracy of the person making the measurement. After he has determined from his TDR instrument that the fault is, say 1540 feet away, how closely can he step off this distance through brush, ditches, torn-up sidewalks, etc.? With lots of luck, he might get to within 10 or 20 feet on a 1000-foot stretch. This is another 1- to 2-percent distance error. Most plate maps and wiring diagrams are even less accurate. The authors have seen the short runs of cable on a ship or aircraft differ by 5-10 percent from the specified values.

Because of many physical causes of distance error, it can be seen that the electrical length accuracy of either the 1502B or 1503B (±2 percent) usually exceeds the accuracy to which cable propagation velocity or physical length is known.

Improving Distance Accuracy

Some maintenance personnel, particularly those with very long cable runs, will quickly point out that even a ±2-percent error on a 20,000 foot cable results in a measurement uncertainty of ±400 feet. "Surely," they say, "it's not reasonable to expect me to dig an 800 foot ditch to excavate a cable fault!"

The solution to this problem is **not** found by spending more money to buy or build a TDR with a very high accuracy crystal controlled time base. In practice, such a unit is quite expensive, and worse, it generally yields no better accuracy when making field measurements because of cable "snaking," propagation velocity variation, and other factors just discussed.

There are several simple ways to improve distance measurement accuracy.

1. **Take multiple readings.** Remember how golf is played. It is usually not possible to put the ball into the hole in one drive. Since all TDR distance errors are percentage errors, a good technique is to move closer to the fault and take a second reading. If a reading from 20,000 feet has a ±400 foot error, a reading from 400 feet will have only a ±8 foot error, and a reading from 100 feet will have a ±2 foot error.

2. **Use all available information.** By using known points on the cable to calibrate TDR timing, extreme accuracy is possible if the cable dielectric is the same for the entire length of the cable (it usually is). For example, if you know that there is a cable splice or connector at exactly 2500 feet, you can easily adjust your 1503B TDR (via front panel adjustment) so that its short-term accuracy is within a few tenths of a percent on that particular cable. The same technique is useful at shorter ranges with the 1502B.

3. **Shoot from both ends of the cable.** This can be particularly useful if the cable is made up of sections having different dielectric constants. Generally, it's sufficient to "split the difference" in measurements from each end, but more exact formulas are easily derived (appendix B).

A 1500B Series TDR, used with reasonable care and the above techniques, will allow you to dig a hole or remove an access hatch and be assured that the fault will be there.

Special Features of the 1500B Series TDR units

The exceptional ease of use, performance, portability, and ruggedness of the 1502B and 1503B are, of course, the features most often mentioned by users. In addition, however, the following features are also unique and greatly enhance operator convenience:

1. 4⅛ inch × 2⅛ inch LCD flat panel display with readout of all major switch settings.
2. Direct readout of distance in feet or meters (menu selectable).
3. Knob selection of common cable vp (velocity of propagation) settings (.30 through .99).
4. Knob selectable noise filter (1, 2, 4, 8, 16, 32, 64, 128 averages).
5. Optional dot matrix chart recorder.
6. Knob selection of cable impedances of 50, 75, 93 and 125 ohm and pulse widths of 2, 10, 100 and 1000 ns (1503B only).
7. Non-volatile RAM for storage of one waveform.
8. Menu system for added ease of use.
9. Optional battery pack.

Fault Signatures

In the early days of high-speed TDR, researchers devoted considerable attention to detailed analysis of typical TDR reflections. It is possible to not only identify, for instance, a capacitor imbedded in a cable with TDR, but to also calculate the exact value of the capacitor from the TDR "signature." Flow graph methods allow analysis of the effects of multiple reflections, even in complex systems. This type of detailed analysis is of considerable value in the design laboratory, but is usually not of interest for cable maintenance purposes.

The shape, or "signature," of a TDR reflection uniquely defines the fault that is causing the reflection, for either step- or pulse-type TDR. In fact, by considering a pulse to be formed by the superposition of two steps (figure 8), the detailed analysis of step-type TDR systems may also be applied to pulse TDR.

Figure 9 shows TDR signatures for most of the "textbook" faults analyzed in the literature; these faults are the types most commonly encountered in the field. For example, a crimped coaxial cable exhibits a capaci-

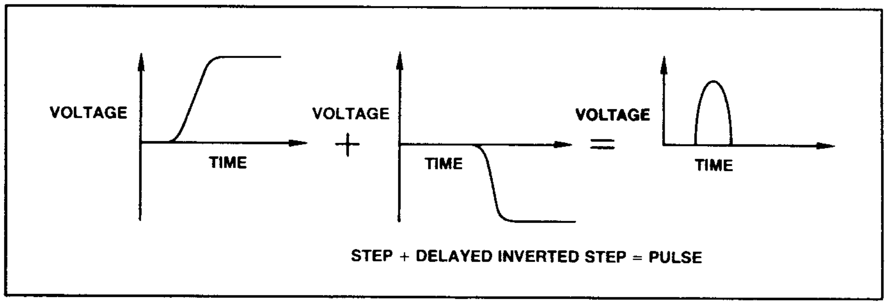


Figure 8. A Pulse as the Superposition of Two Steps.

tance in the vicinity of the crimp (figure 10), an abraded coaxial cable exhibits an inductance (figure 11) in the vicinity of the abraded portion; a bad splice or corroded connector appears as a series resistance; a section of cable containing water exhibits a lowered characteristic impedance, etc.

Observable Faults

The authors are often asked, "What faults can a TDR see?" We tend to answer, "All faults." This is the correct answer for communications cables, but there are limits to any technique, TDR included.

Basically, TDR depends on a disturbance in cable impedance to "see" a fault. TDR can easily see faults that change cable impedance by as little as 0.5 percent ($\rho = 0.005$; return loss = −46 dB) and can be pushed into revealing faults that disturb impedance less than 0.1 percent ($\rho = 0.001$; return loss = −60 dB). This means that, on a 100-ohm cable, a series resistance of 0.2 ohm and/or a shunt resistance of perhaps 49k ohms can be "seen" by a skilled operator pushing TDR to the limit of a "lossless" noise-free cable. Faults that disturb cable impedance less than this cannot be seen.

Can any conditions exist that may be termed "faults" and yet disturb the cable so little? The answer is a conditional "yes."

Take the case of a high-voltage power cable carrying several tens of kilovolts. A very minor insulation "pinhole" would not disturb cable impedance, but could cause an arc when high voltage is applied. TDR can't see this type of fault.

Another example stems from water in a PIC telephone cable.

This condition eventually causes insulation breakdown, which initially results in faults of several hundred thousand ohms across a cable pair (figure 12). Gradually, these faults get worse or electrolysis action totally destroys cable continuity, and all wire pairs in the cable eventually fail completely. In this case, TDR cannot detect the point of initial insulation weakness (some bridge-type fault locators can), but it can easily detect the water in the cable (a bridge cannot), where the water is (a bridge cannot), and where the water probably entered. TDR can locate the **problem** (i.e., water in the cable, which will eventually cause all wire pairs to fail), but not the **symptom** (i.e., a very high-resistance fault somewhere in the wet section); a resistance bridge can locate the **symptom**, but not the **problem**.

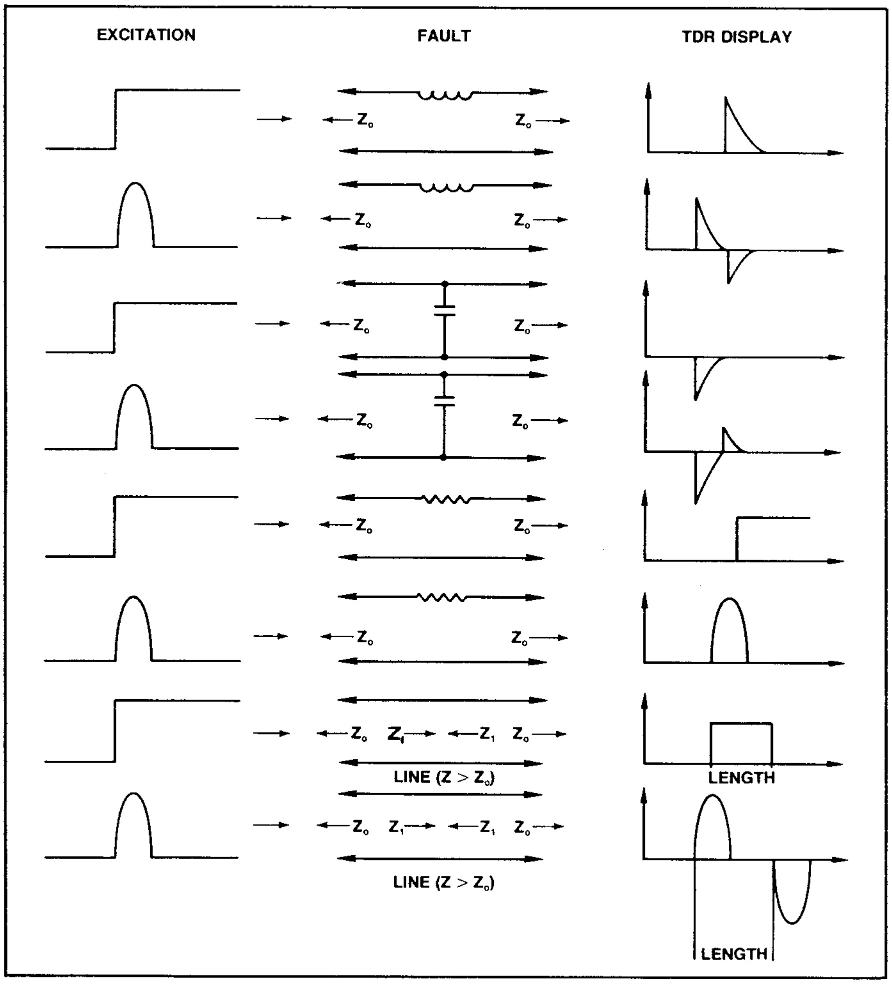


Figure 9. Sample TDR Fault Signatures.

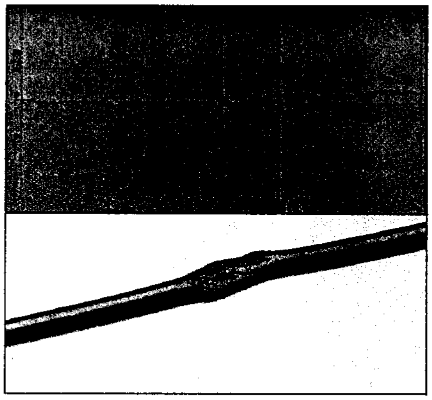


Figure 10. 1502B Display of Crimped Cable.

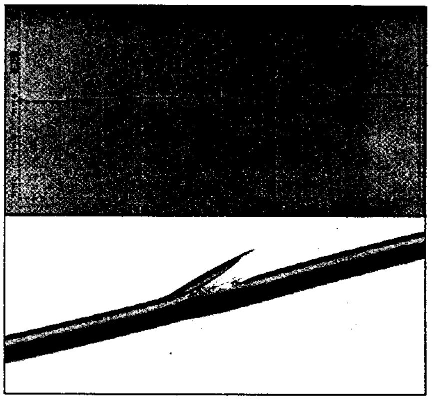


Figure 11. 1502B Display of Frayed Cable.

The repair supervisor hence faces a philosophical problem: Does one break into the cable to "clear" a single wire pair knowing that it's just a matter of time before it fails again or the other wire pairs in the cable fail; or does one switch the service on the faulted pair to a spare pair to get the telephone with the problem back in service quickly and then remove the water and repair the cable when convenient? Stated another way, does one repair cables or patch wire pairs? The authors are firmly convinced that, now that a practical method exists for locating water in cables, telephone service could be improved by repairing basic cable problems rather than doing repeated "first aid" by fixing wire pairs. Regardless of which choice is made, TDR offers the telephone outside plant supervisor a new option.

Practical Cable Testing

It is important to note that some cables (particularly twisted pair) carry voltages sufficient to damage test equipment or present an operator hazard. The ultra-fast 1502B cannot withstand any significant voltage on the cable under test, and we recommend powering down and bleeding static charge from a cable (i.e., short or otherwise apply a termination) before hooking it to a 1502B. The 1503B is protected up to 400 volts (dc + peak ac) at up to 440 hertz, but the 1503B isolation network (order P/N 013-0169-00) is recommended for operator safety on twisted pair lines. See figure 13.

Many cables, particularly faulty cables, contain high levels of 60-hertz power or other contaminating signals that will swamp out TDR signals. The selectable noise filters built into both the 1502B and 1503B considerably enhance the signal-to-noise ratio of either instrument. The 1503B has a signal amplitude 50 times greater than the 1502B, and hence possesses more noise immunity. For extremely noisy cables, a 1503B with an isolation network is best; it yields a crisp clean trace even with more than 100 volts of 60-hertz signal on the cable under test. Cables feeding large antennas in strong signal environments pose similar problems, and, once again, a 1503B is often the answer.

The first thing to do is to impedance match the TDR as closely as possible to the cable to be tested. The 1502B is matched to 50-ohm cables, and standard adapters can be used to match to other impedances (75, 93, and 125 ohms). The 1503B features knob selection of all these impedances, and requires no adapters.

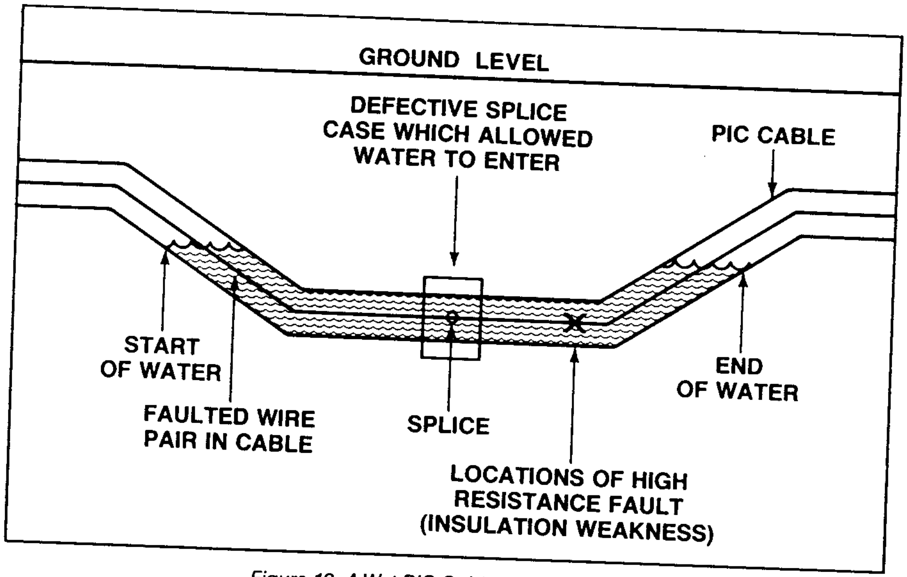


Figure 12. A Wet PIC Cable Starting to Fail.

Note:

1. *A TDR will locate and identify the start of water, splice, slice case, and end of water, but not the high-resistance point of insulation wetness.*
2. *The proper type of bridge will locate the point of insulation wetness, but none of the other points.*

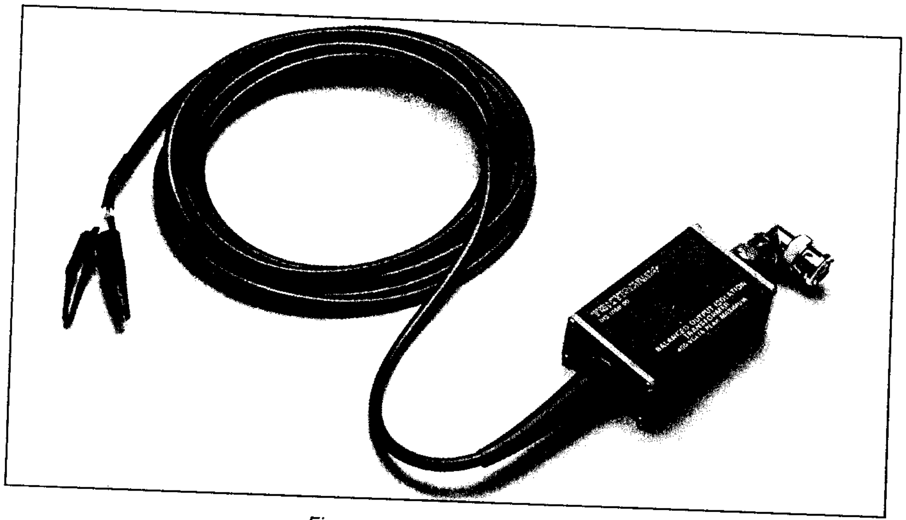


Figure 13. 1503B Isolation Network.

In all cases, it is very important to establish a good connection to the cable under test. Remember that TDR signals contain high-frequency information (appendix C) that is not efficiently transmitted by pieces of lamp cord, battery clips, etc. Low-quality cable will substantially reduce TDR range. The 1503B effective range of 50,000 feet on low-loss (large diameter) coax is reduced to about 35,000 feet on communications grade 19 AWG twisted pair and to about 10,000 feet on 26 AWG twisted pair. Wiring harnesses and low-grade power cables can cause even greater range reduction.

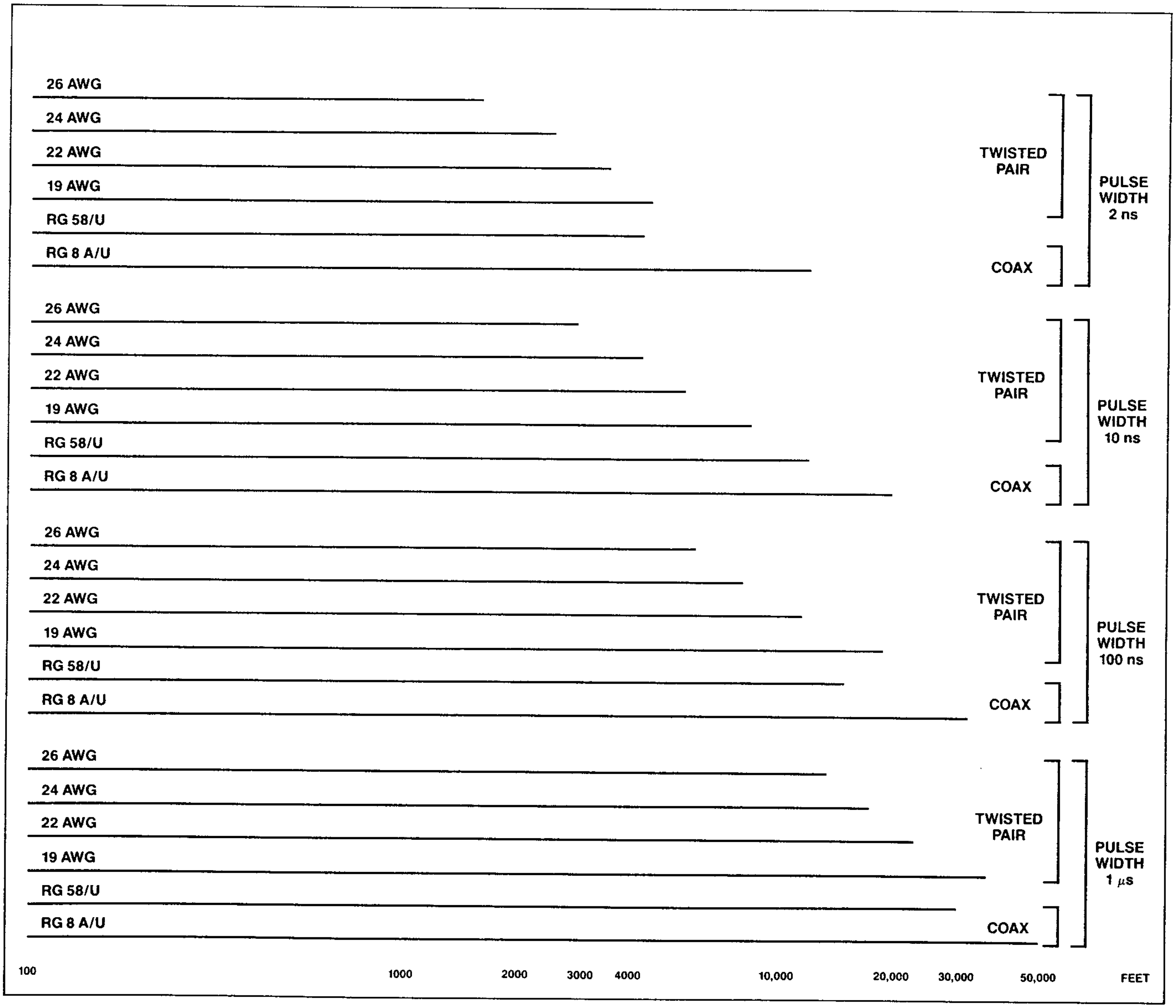
Component/Antenna Testing

In addition to testing cables and connectors, a high-resolution TDR such as the 1502B is also useful for comparing the characteristics of components and antennas. In these applications, the TDR "signature" may not be a simple one and it may be quite difficult to evaluate it analytically. That is to say, unless one is very clever, it is difficult to look at a "bump" on a TDR signature and state, "Oh, yes. The third dipole of that antenna is 2.7 inches too long." NOTE: An expert **can** make such statements.

Generally, what is done in a maintenance context is to make a permanent record of the signature of a known good antenna or component, using the optional chart recorder. Once this is done, it is easy to compare components under test against the reference signature for fast "GO"/"NO GO" tests.

Note that the TDR signature of a component will vary, depending on the length of cable running from the TDR to the component under test (remember–pulse rise time degrades on long cables as a function of the length squared), so TDR component/antenna comparison testing should always be done using exactly the same length of cable. Best results are obtained when the cable connecting the TDR to the component or antenna is as short as possible.

Generally, the 1502B is best for antenna testing if the cable run to the antenna is short and the antenna is not in a strong rf environment. If the cable runs to the antenna are more than approximately 100 feet or the antenna is in a strong environment (i.e., broadcast antennas), the 1503B will have equivalent resolution and much better noise immunity. For extreme cases, use of an isolation network (P/N 013-0169-00) with the 1503B will further improve noise immunity.



Note:

1. Ranges shown are typical and will vary depending on cable vendor, cable condition, presence of splices and connectors, noise on cables, etc.

2. Ranges shown were measured or computed based on 60-dB dynamic range. The 1503B is actually capable of more than 76 db.

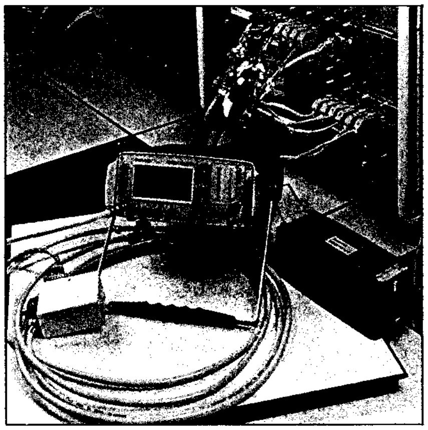
Figure 14. Useful 1503B Range on Coax and Grade Twisted Pair.

Note that the term "component" may be quite broad in definition. One of the important uses of the 1502B in the aircraft industry is locating defective cable and sensors in aircraft fuel quantity monitors. This had been a most troublesome problem before the 1502B because faulty sensors were almost always intermittent and faults would almost invariably disappear before bulky and complex test equipment could be set up. In some cases, a 1502B has been used to monitor such systems during flight when sensor icing was suspected.

Actual 1502B and 1503B TDR Signatures

The 1502B and 1503B TDR's are capable of detecting and locating most major cable faults as well as certain components on the cable. Shorts, opens, frays, crimps, water, loading coils and transceivers are just some of the faults and components that can be found with the 1502B and 1503B.

The following chart recordings show a various selection of cable signatures from coax and twisted pair cable.



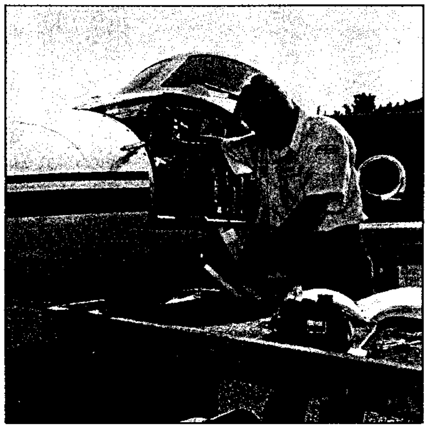


Figure 15. The 1503B chart recording of twisted pair shows an open. The distance to the open is 2,240 feet. 1000 ns pulse width was used for this measurement.

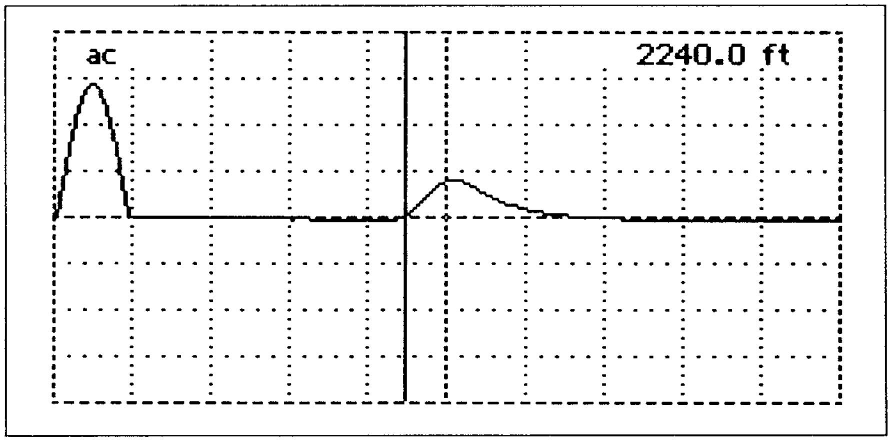


Figure 16. This 1503B chart recording shows a short on coax cable at 23.6 feet. Notice the large reflection due to the short distance the pulse had to travel.

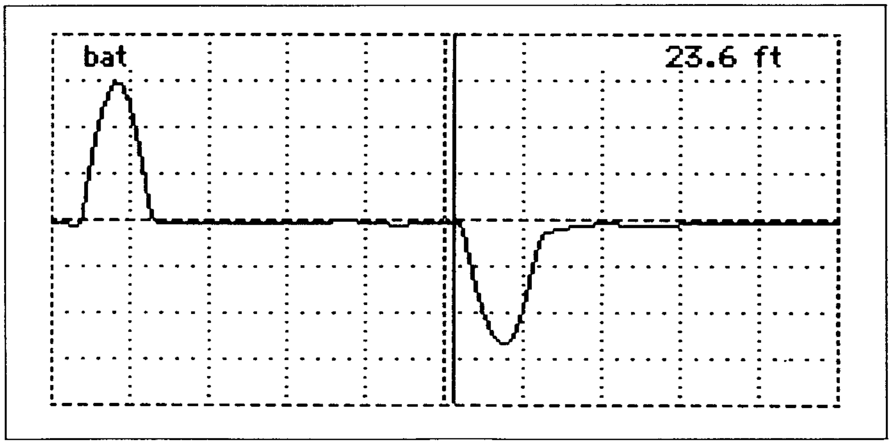


Figure 17. This 1502B chart recording shows a frayed cable at 17.8 feet and an open at the end of the cable.

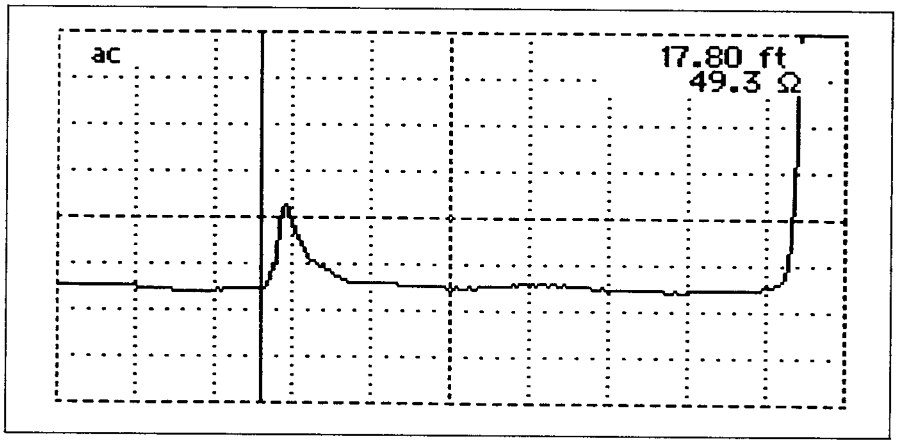


Figure 18. This 1502B chart recording shows a section of coax with a tee connector, barrel connector and tee connector.

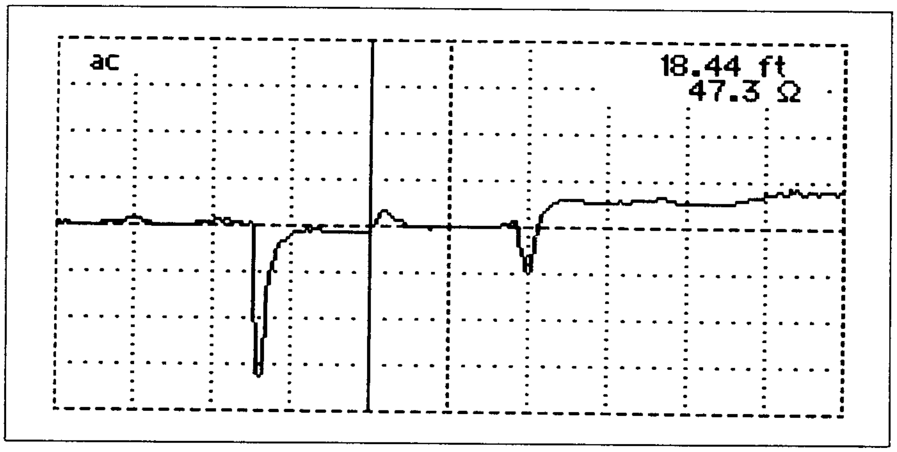


Figure 19. This recording from the 1502B shows 50 Ω coax connected to 75 Ω coax cable.

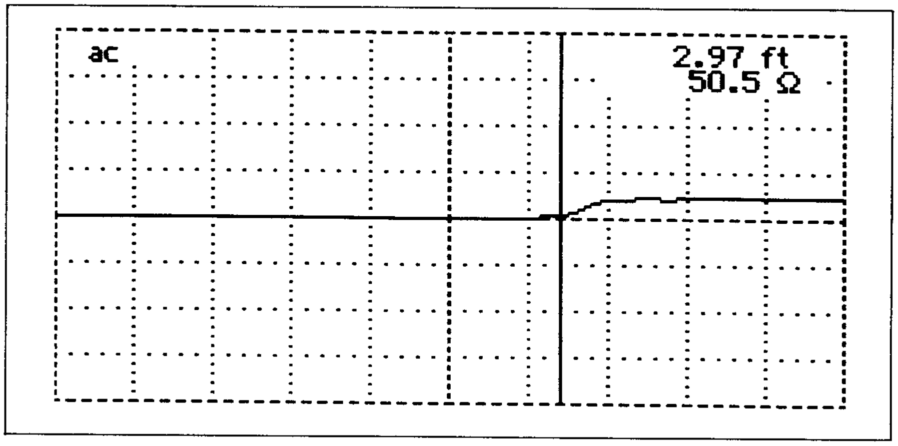


Figure 20. By turning up the vertical scale on the 1503B, this section of twisted pair shows that the cable is in water. The initial downward slope indicates the beginning of water and the upward rise shows the end of the water.

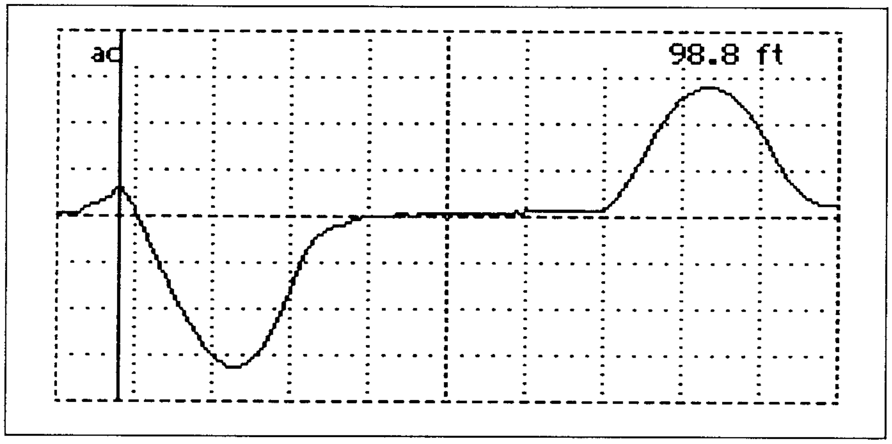


Figure 21. This 1503B chart recording shows a split and resplit on twisted pair. The split is the initial rise with the resplit at the point where the cursor intersects the signature.

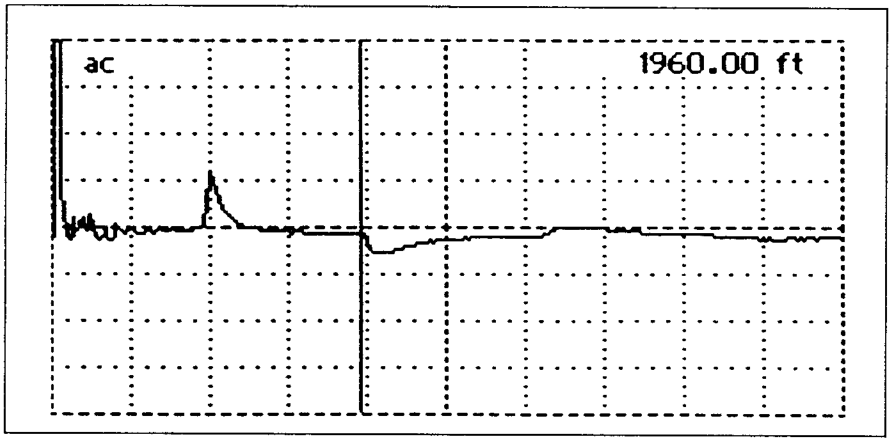


Figure 22. This 1502B chart recording shows a splice in a 50 Ω cable. Note the cursor position and the 66.5 Ω reading showing a change in impedance from 50 to 66.5 Ω at the splice.

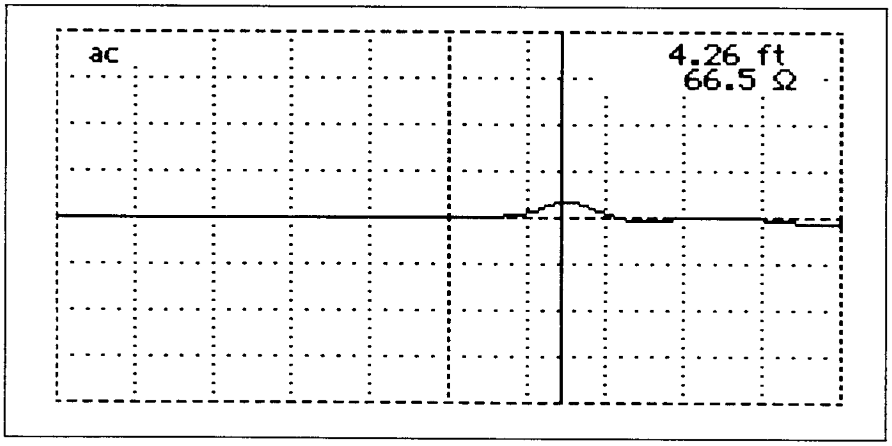


Figure 23. This 1502B chart recording shows a delta measurement between the first and the second tap (2.48 meters). Note: the 1502B and 1503B have a menu selectable item for displaying distance in feet or meters.

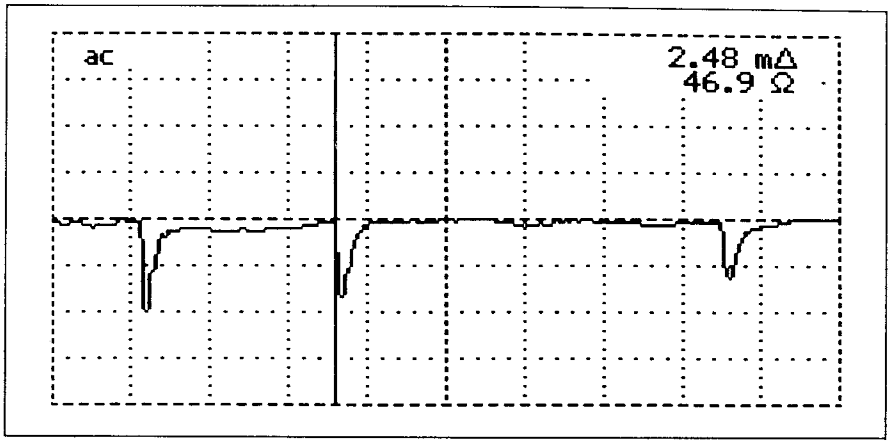
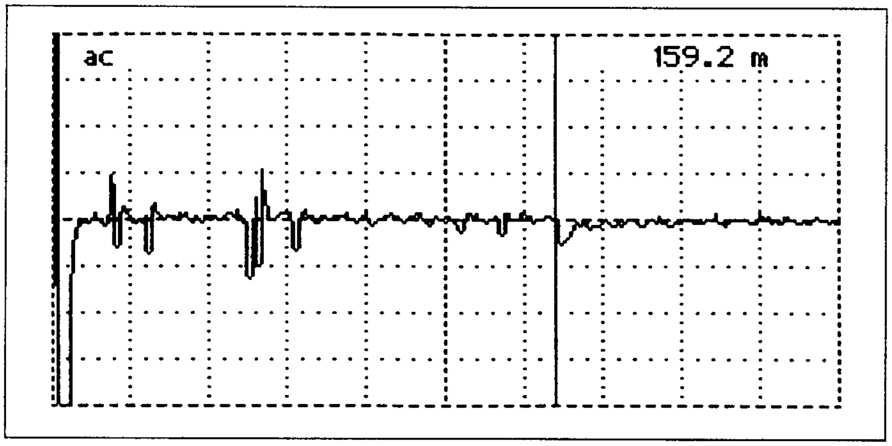


Figure 24. 1503B chart recording of a live ethernet network. The cursor is at the end terminator at 159.2 meters. There are 7 transceivers on the network. Some of the spikes are from data.



The 1500B series TDR's have non-volatile RAM that allows you to store a waveform. The stored waveform can be compared to current input waveform. Another feature called view difference allows the difference between the current input and the stored waveform to be viewed. Following are a few examples.

Figure 25. The 1503B chart recording shows a stored waveform above the current input waveform. The stored waveform shows an open and the current input waveform shows a short.

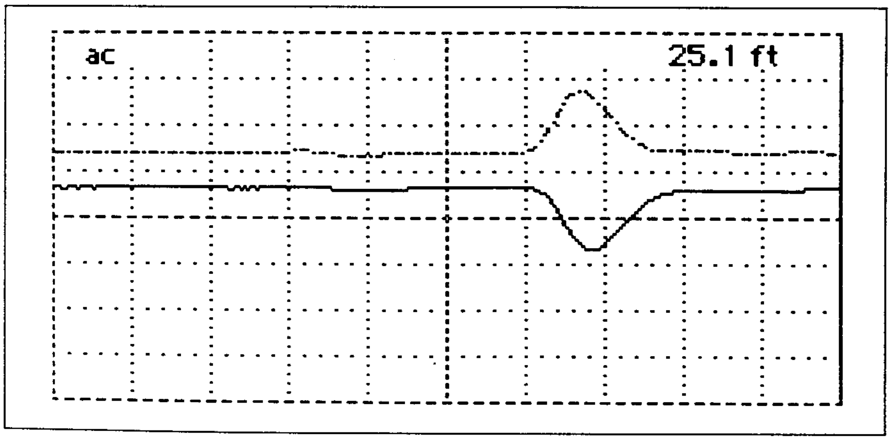
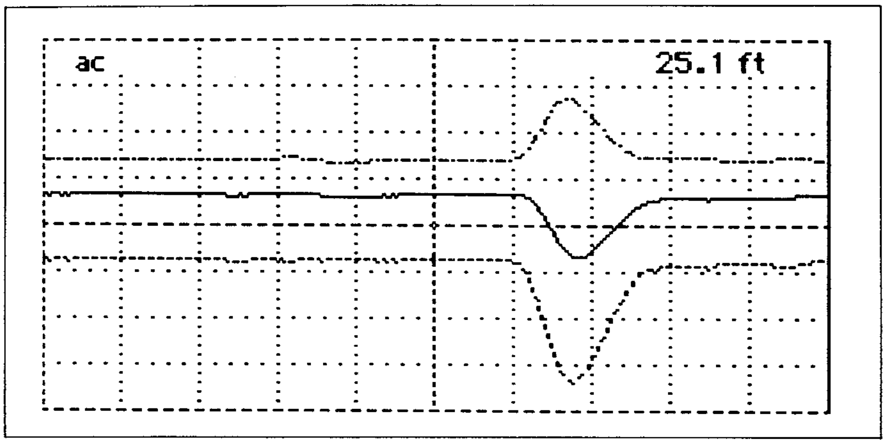


Figure 26. This 1502B chart recording shows the stored waveform, current input waveform and the view difference waveform. The "difference" waveform is made by subtracting each point in the stored waveform from each point in the current input waveform.



TDR Versus FDR

Every measurement technique has its advocates and its detractors, and TDR is no exception. The most popular techniques for testing cables are time domain reflectometry (TDR) and frequency domain reflectometry (FDR).

For a variety of reasons, we believe that TDR is by far the most viable technique for the field maintenance of cable systems. Either TDR or FDR will detect cable faults. However, it is an error to conclude that there is any "magical" ability associated with either technique. If you are forced to choose, the choice should be made on the basis of cost, performance, ease of use, and suitability for your requirement. In the authors' opinion, TDR is best for cable fault location/identification, FDR is best for system specification verification.

There is a system called 3-DR, which is an FDR modification that allows some TDR-type measurements to be made. Likewise, TDR can be modified by adding computer processing, yielding a system known as TDM (Time Domain Metrology), that allows FDR-type measurements to be made. The primary drawbacks of both 3-DR and TDM are excessive cost, bulk, and complexity.

TDR Versus Bridge Techniques

Bridges are traditionally used for locating faults on twisted pair telephone lines, and are generally rugged, easy to use, inexpensive, and come in many varieties and brands. Generally, bridges offer less accuracy than a TDR (see the section entitled "TDR Resolution and Accuracy"), but have greater fault detection range.

The primary problem with bridge techniques is that each type of bridge can locate only certain types of faults. One type of bridge locates shorts, another locates "clean" opens, and still a third type locates resistive ("light") shorts or leaky ("dirty") opens. Basically, one must know the type of fault before selecting a bridge, and many different types of bridges are required to perform the job that one TDR can do. The typical complement of bridges and auxiliary equipment found on a telephone service truck represents an investment of $5,000-$10,000.

NOTE: Some faults that are easily detectable by a TDR (i.e., splits/resplits, etc.) cannot be detected by any combination of bridges.

Perhaps the worst feature of a bridge is that the user is tempted to try to convert his cable condition to one that his bridge can detect. A device called a "breakdown test set" is sometimes used to generate bridge detectable faults. This unit applies high voltages at significant currents to burn faults into a hard short or a clean open condition. Unfortunately, on modern Polyethylene Insulated Cables (PIC), the faults simply do not burn. On this type of cable, use of a breakdown set can cause extensive cable damage. On any type of cable, breakdown sets can damage switch office equipment, start fires, and present operator hazards.

Appendix A. Correcting TDR Measurements For Cable Loss

The fact that long cables (over 100 feet) greatly degrade pulse rise time, hence TDR resolution, has already been discussed (see the section entitled "TDR Resolution and Accuracy"). It is evident that the shape of pulses returned from resistive discontinuities (including shorts and opens) on long cables is determined by the cable, not by the TDR. On long cables, these reflections initially rise quickly but take a very long time to reach the final value. This phenomenon is termed "dribble up." For example, if such a reflection reaches its 50 percent point at time T_0 it takes about 30 T_0 to reach its 90-percent point. **For this reason, it is extremely important to reference all long-range TDR distance measurements to the point at which the reflected pulse just starts to rise. The operator should adjust the gain as high as is necessary to do so.**

Both pulse spreading ("dispersion") and energy loss cause the pulses reflected from distant faults to be reduced in amplitude. There is generally no problem in determining that a fault exists and reading its "signature," but major faults at long distances will appear to be of the same amplitude as minor faults close to the test end of the cable.

Pulse amplitude reduction does not create major problems in locating and identifying cable faults, but it does make it difficult to measure absolute reflection coefficient at a point some distance down a cable. This problem can arise in performing quality assurance on cable splices, connectors, etc.

If one knew how much a given length of a given type of cable attenuated the TDR pulse, it would be a simple matter to correct for cable loss. Unfortunately, such parameters are not specified by cable vendors and efforts to predict pulse amplitude reduction by computer techniques have, to date, not correlated very well with actual measurements. Fortunately, one generally has access to a cable at the point of a splice or a connector if quality verification is made at the same time the connector of splice is installed.

The following is one technique that is useful for connector or splice verification with a 1503B:

1. Break the cable at the point of the splice or connector. Make a measurement from the terminal end with the cable open at the splice (or connector). Note the return loss indication. Call it dB (o).
2. Make the splice or connect the connector. Make another measurement from the terminal end using the same pulse width and note the return loss. Call it dB (m).
3. Compute the actual return loss.
   dB (a) = dB (m) − dB (o)

From equation 5a, the actual ρ at the splice (or connector) can be determined.

$$\rho = 10^{-\left(\frac{\text{dB (a)}}{20}\right)} \tag{A-1}$$

Impedance at this point is given by equation 2.

$$Z = Z_0\left(\frac{1+\rho}{1-\rho}\right) \tag{A-2}$$

and the vswr caused by this single fault is:

$$\text{VSWR} = \frac{1+|\rho|}{1-|\rho|} \tag{A-3}$$

It is necessary to know the cable characteristic impedance. For coaxial cable, this is always well specified. For twisted pair cables at high frequencies, Z_0 is a function of cable gauge, cable type, and whether or not the cable is loaded. GT&E specifies that unloaded 22 AWG and 24 AWG high-capacity cable has a Z_0 of 85 ohms at 15 MHz, whereas 26 AWG is 91 ohms at 10 MHz. Other sources list different characteristic impedances for cable that is quite similar, so it's best to check. Each telephone company has a standard practices book that specifies the characteristic impedance of its outside plant.

Example

A splice is being made in a long section of 24 AWG twisted pair 1500 feet from the terminal end of the cable. With the cable open at the point of the splice, the cable is tested with a 1503B, using the 100-ns pulse. The measured return loss is 16.8 dB [dB (o) = 16.8]. The cable is spliced and again tested using the same pulse length. The measured return loss is 52.3 dB [dB (m) = 52.3]. We know that the Z_0 of the cable is specified as 85 ohms. For this example, the specification for a good splice is that it not disturb cable impedance by more than 5 ohms.

First, we calculate dB (a).

$$\text{db (a)} = 52.3 - 16.8 = 35.5 \tag{A-4}$$

Next we calculate reflection coefficient from A-1.

$$|\rho| = 10^{-\frac{35.5}{20}} = 0.01679 \tag{A-5}$$

Finally, we compute impedance at the splice from A-2, knowing that it is positive since the "bump" on the TDR display was upwards (see the paragraph entitled "How the TDR Works").

$$Z = Z_0\frac{1+\rho}{1-\rho} = 85\left[\frac{1+0.01679}{1-0.01679}\right] \tag{A-6}$$

$= 87.9$ ohms

We note that the cable impedance has been disturbed by only 2.9 ohms, so the splice is good.

Appendix B. Simultaneous Measurements

If the actual overall cable length is known, it is possible to make simultaneous fault measurements from either end of a cable. Simultaneous measurements always allow increased fault location accuracy, but are tedious and unnecessary in many cases.

Consider figure B-1, and assume that TDR measurements are inaccurate because of "snaking," cable propagation velocity variation, improper Vp setting, or similar effects. Let X represent the true location of the cable fault being sought. Assume that the cable under test has the same dielectric constant throughout, and that the same TDR is used to make measurements from each end of the cable. Without loss of generality, assume that the fault is closest to end #2 (i.e., $d_1 > d_2$).

Let:

d_1 = indicated fault distance from end #1 (known)

d_2 = indicated fault distance from end #2 (known)

d'_1 = actual fault distance from end #1 (unknown)

d'_2 = actual fault distance from end #2 (unknown)

L = actual cable length (known)

From the previous assumptions, the percentage error is the same from each end of the cable. Thus:

$$\frac{d'_1}{d_1} = \frac{d'_2}{d_2} \tag{B-1}$$

Also:

$$d'_1 = L - d'_2 \tag{B-2}$$

Therefore:

$$\frac{L - d'_1}{d_1} = \frac{d'_2}{d_2} \tag{B-3}$$

$$L - d'_2 = d'_2\left(\frac{d_1}{d_2}\right) \tag{B-3a}$$

$$L = d'_2\left(\frac{d_1}{d_2} + 1\right) \tag{B-3b}$$

Or:

$$d'_2 = \frac{L}{\left[\frac{d_1}{d_2} + 1\right]} \tag{B-4}$$

Example

A cable known to be 9800 feet long has developed a fault. A 1503B TDR is connected and the proper Vp knobs are set. Measurement from one end of the cable indicates a fault at 8200 feet, but measurement from the other end indicates the same fault at 2100 feet. Since the two measurements do not add up to 9800 feet, we suspect that distance error exists.

Referring to equation B-4:

L = 9800

d_1 = 8200

d_2 = 2100

and actual distance, d'_2, is given by:

$$d'_2 = \frac{9800}{\left(\frac{8200}{2100} + 1\right)} = 1998.06 \text{ feet}$$

The fault will be found approximately 1998 feet from the far end of the cable.

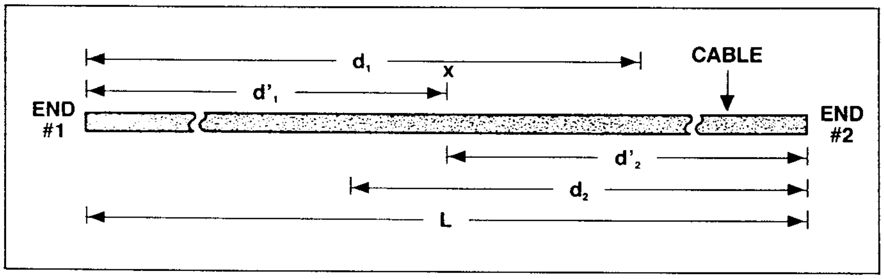


Figure B-1. Simultaneous Measurements

Discussion Question

What else can be done to further improve accuracy or check results for the example just presented?

The errors in the example were rather large; all readings were high by about 5.1 percent. This suggests that, if the TDR can "see" the far end of the cable, it might have been best to have first used Vp knobs and to have adjusted the TDR to display the correct 9800-foot length. Likewise, since errors are sometimes made in calculation, it's best to "double check." For this example, it would be wise to adust the Vp knobs of the TDR to display the fault at 1998 feet from the far end, and then go back to the first end and see if the fault shows at 7802 feet.

If the readings still do not correlate, there are several possibilities:

A. An error was made in calculation.

B. The cable propagation velocity is not constant (i.e., the cable had been spliced together with different sections, had been partially treated with reclamation compound, etc.)

NOTE: This is usually obvious since splices or abrupt changes in dielectric constant will show up as "faults."

Making precise measurements over a cable with mixed sections of significantly different propagation velocities is "messy," but, fortunately, this case arises infrequently. A reasonable technique for the mixed dielectric case is to continue to apply equation B-4, adjust the Vp knobs, and keep testing from alternate ends and adjusting until the answer is converged upon.

C. The overall length of the cable is not correct. Try again to verify it with the TDR. If the correct cable length cannot be determined, it is best to make measurements from only one end.

D. The fault extends over a considerable physical distance. For example, simultaneous measurements wouldn't aid accuracy if several hundred feet of cable contained water, although one still should measure from both ends to accurately determine where the fault started and ended. Fluid contamination of cables is really a special instance of the mixed propagation velocity case.

For the cases in which a fault extends over a significant distance, of course, one must replace or reclaim a long section of cable and accuracy becomes less important.

E. You are looking at two different faults, at two different cables (it happens!), or your TDR should be serviced.

Appendix C.
TDR Frequency Specifications

People accustomed to thinking in the frequency domain sometimes ask, "What frequency range does a TDR cover?" There are several answers to this question, ranging from the mathematical to the philosophical to the practical.

Philosophically, it is dangerous to think of TDR in frequency domain terms, since TDR is **not** a frequency domain technique. For verification of frequency specifications, FDR excels; for location or identification of cable faults, TDR excels. It is as inappropriate to place frequency specifications on TDR equipment as it is to place rise time specifications on FDR equipment.

Practically speaking, frequency response is not particularly relevant for cable maintenance (though it may be for cable system verification). Cable faults invariably result from physical cable damage (i.e., crimps, abrasions, fluid contamination, connector corrosion, etc.) and are broadband in nature. Generally, one is far more interested in what caused a cable fault and where the fault is than in the frequency response of the fault.

Mathematically, of course, it is possible to use Fourier transform techniques to convert the pulse specifications of a TDR to equivalent frequency specifications and an estimate of the pulse frequency spectrum. We say "an estimate" since the frequency spectrum of a TDR is not a specified parameter.

The nominal time domain waveform for a 1502B step-type is shown in figure C-1, where:

$t \approx 10\mu s$
$T \approx 60\mu s$
$A \approx 225mV$

From standard Fourier series tables, we see that the amplitude of the n^{th} harmonic is given by:

$$Cn = 2A_{qv} \frac{\sin (n\pi t/T}{\pi t/T} \qquad \text{(C-1)}$$

where:

$$A_{qv} = A \frac{t}{T} \qquad \text{(C-2)}$$

The Fourier series representation of figure C-1 is:

$$f(x) = A_{qv} + \Sigma_{n+1}^{\infty} Cn \cos \frac{2n\pi}{T} x \qquad \text{(C-3)}$$

which shows that the fundamental frequency is:

$$f = 1/T = 16.6 \text{ kHz} \qquad \text{(C-4)}$$

although the frequency spectrum extends to infinity. At microwave frequencies, the amplitude of each spectral line is quite low, but there is a very large number of spectral lines in any reasonable bandwidth. A good "rule of thumb" for the effective upper energy limit of a step TDR pulse is:

$$F_{max} = \frac{0.35}{t_r} \qquad \text{(C-5)}$$

where t_r is pulse rise time. For the 200-ps steps of the 1502B:

$$F_{max} = \frac{0.35}{0.110} 10^9 = 1.75 \text{ GHz} \qquad \text{(C-6)}$$

It is possible to carry through a similar analysis for pulse-type TDR. The 1503B uses a constant repetition rate, and the fundamental frequency is approximately 2.8 kHz (2.5 kHz at Vp< = .35). Spectral energy of a pulse-type TDR falls off as a function of frequency squared, so it is contained in a relatively narrow bandwidth.

The pulses of the 1503B are specified to be 100, or 1000 ns at the 50-percent amplitude points. Using similar "rules of thumb" as before, we can say that the 2-ns pulse contains significant energy to about 330 MHz, the 10-ns pulse to about 66 MHz, the 100-ns pulse to about 6.6 MHz, and the 1000-ns pulse to about 660 kHz.

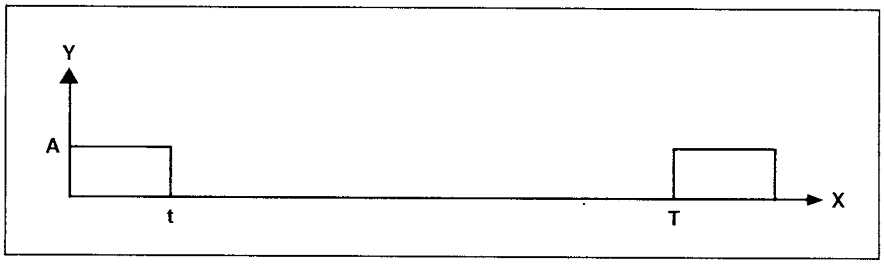


Figure C-1. Nominal Time Domain Waveform