User's Guide

Publication number 54753-97015
Third edition, May 2000

For Safety information, Warranties, and Regulatory information, see pages behind the index

Agilent 54753A and 54754A TDR Plug-in Modules

Agilent 54753A and 54754A Plug-in Modules

The Agilent 54753A and 54754A TDR plug-in modules provide you with TDR and TDT measurement features. In addition to the TDR and TDT measurement features, the TDR plug-ins provide two accurate oscilloscope measurement channels with user selectable bandwidths of 12.4 or 18 GHz. The lower bandwidth mode provides excellent oscilloscope noise performance for accurate measurement of small signals. The high bandwidth mode provides high-fidelity display and measurement of very high-speed waveforms.

The Agilent 54753A TDR plug-in module provides:

- Automatic and manual single-ended TDR and TDT measurement capability
- Automatic and manual waveform, histogram, FFT, waveform math, eye pattern measurements, statistical measurements, and limit testing capabilities.
- User selectable 12.4 or 18 GHz bandwidth (Channel 1).
- User selectable 12.4 or 20 GHz bandwidth (Channel 2).
- 2.5 GHz bandwidth trigger channel.
- 3.5 mm (m) connectors.

The Agilent 54754A TDR plug-in module provides:

- Automatic and manual single-ended and differential TDR and TDT measurement capability.
- Automatic and manual waveform, histogram, FFT, waveform math, eye pattern measurements, statistical measurements, and limit testing capabilities.
- User selectable 12.4 or 18 GHz bandwidth.
- 2.5 GHz bandwidth trigger channel.
- 3.5 mm (m) connectors.

Accessories Supplied

The following accessories are supplied with the TDR plug-in modules:

One 50 ohm SMA (m) terminator, Agilent part number 1250-2153

Two SMA shorts (m), Agilent part number 0960-0055

TDR Demo Board, Agilent part number 54754-66503

One User's Guide

One Programmer's Guide

One Service Guide

Accessories Available

The following accessories are available for use with the TDR plug-in modules.

Options

Option 0B1 Additional set of user documentation

Option 001 Agilent 83480A mainframe operating system upgrade

Option 002 Agilent 54750A mainframe operating system upgrade

Option 003 Delete demo board

Agilent 54755A TDR option for Agilent 83480A mainframe operating system upgrade

Optional Accessories

Agilent 10086A ECL terminator

Agilent 54006A 6 GHz divider probe

Agilent 54007A accessory kit

Agilent 54008A 22 ns delay line

Agilent 54118A 500 MHz to 18 GHz trigger

Agilent 54701A 2.5 GHz Active Probe with Option 001

Connection Devices

SMA (f-f) adapter, Agilent part number 1250-1158

APC 3.5 (f-f) adapter, Agilent part number 1250-1749

In This Book

This book is the operating manual for the Agilent 54753A and 54754A TDR plug-in modules, and contains 13 chapters.

General Information Chapter 1 contains overview information, menu and front panel key information, and trigger information. Chapter 2 contains important information on the care of the TDR plug-in connectors.

TDR Front Panel and Menu Keys Chapter 3, 4, 5 and 6 describe the front panel keys and all the menu keys.

Task Oriented Examples Chapter 7 contains example single-ended TDR measurements using a demo board included with each TDR plug-in module. Chapter 8 contains example differential TDR measurements.

TDR Theory Chapters 9, 10, and 11 contain in-depth theory of TDR transmission lines and how to use TDR in designing systems.

Specifications and Characteristics Chapter 12 contains the specifications and characteristic for the TDR plug-in modules.

Problems and Error Messages Chapter 13 contains troubleshooting information and error messages.

Contents

Specifications and Characteristics 12-1

In Case of Difficulty 13-1

1

The Instrument at a Glance

Operating the Instrument

What you'll find in this chapter

This chapter describes:

- the key conventions used in this manual
- the front panel, rear panel and keys that do *not* display menus on the screen

Understanding the information in this chapter will help you successfully operate the instrument.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

Menu and Key Conventions

The keys labeled Trigger, Disk, and Run are all examples of front-panel keys. Pressing some front-panel keys accesses menus of functions that are displayed along the right side of the display screen. These menus are called softkey menus.

Softkey menus list functions other than those accessed directly by the front-panel keys. To activate a function on the softkey menu, press the unlabeled key immediately next to the annotation on the screen. The unlabeled keys next to the annotation on the display are called softkeys.

Additional functions are listed in blue type above and below some of the front-panel keys. These functions are called shifted functions. To activate a shifted function, press the blue front-panel Shift key and the front-panel key next to the desired function.

Throughout this manual front-panel keys are indicated by bold lettering of the key label, for example, **Time base**. Softkeys are indicated by italic lettering of the key label, for example, *Scale*. The softkeys displayed depend on the front-panel key pressed and which menu is selected. Shifted functions are indicated by the front-panel **Shift** key followed by the shaded shifted function, for example the Local function (above the **Stop/Single** front-panel key) will be shown as **Shift**, **Local**.

A softkey with On and Off in its label can be used to turn the softkey's function on or off. To turn the function on, press the softkey so On is highlighted. To turn the function off, press the softkey so Off is highlighted. An On or Off softkey function will be indicated throughout this manual as: *Test* `On`.

A softkey such as *Sweep Triggered Freerun* offers you a choice of functions. In this case you could choose Triggered by pressing the softkey until Triggered is highlighted, or choose Freerun by pressing the softkey until Freerun is highlighted. Softkey choices will be indicated throughout this manual as: *Sweep Triggered Freerun* `Triggered`.

When some softkeys, such as *Calibrate Probe*, are pressed the first time, a calibration will be made. Some softkeys, such as *Offset* require the entry of a numeric value. To enter or change the value, use the general purpose knob located below the front-panel Measure section.

The Agilent 54753A, 54754A TDR Plug-In Modules

The TDR plug-in modules are two of several plug-in modules available for the Agilent 83480A and Agilent 54750A mainframes.

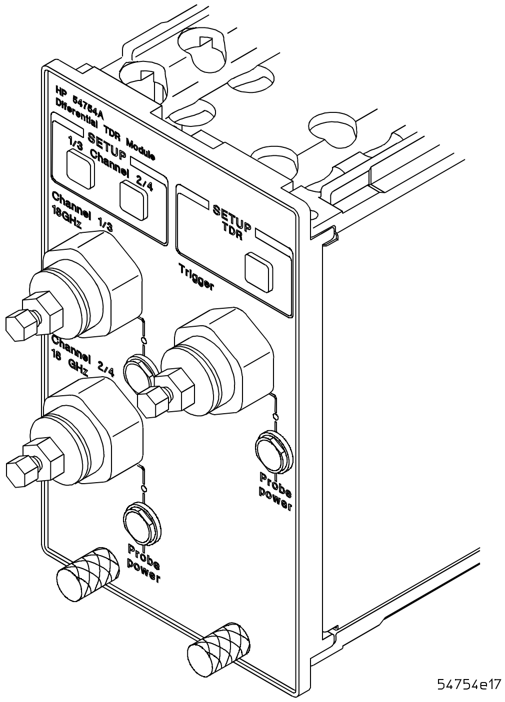
Plug-in Module Purpose

The purpose of the plug-in module is to provide measurement channels, including sampling, for the mainframe. The plug-in module scales the input signal, sets the bandwidth of the system, and allows the offset to be adjusted so the signal can be viewed. The output of the plug-in module is an analog signal that is applied to the ADCs on the acquisition boards inside the mainframe. The plug-in module also provides a trigger signal input to the time base/trigger board inside the mainframe.

Front Panel of the Plug-in Module

The plug-in module takes up two, of the four, mainframe slots. The front panel of the plug-in module has two channel inputs and an external trigger input. The front panel also has two probe power connectors for Agilent 54700-series probes, an auxiliary power connector for general purpose use, and a key for each channel that displays the softkey menu. The softkey menu allows you to access the channel setup features of the plug-in module for the selected input.

Figure 1-1



Front panel of the plug-in module.

Getting the Best Performance

To ensure you obtain the specified accuracy, you must perform a plug-in module vertical calibration. The calibration must also be performed when you move a plug-in module from one slot to another or to a different mainframe. Refer to "Performing a Plug-in Module Vertical Calibration" on page 3-12 for information on performing a plug-in module vertical calibration.

Installing a Plug-in Module

You do not need to turn off the mainframe to install or remove a plug-in module. The plug-in module can be installed in slots 1 and 2 or 3 and 4 on the Agilent 83480A, 54750A mainframe. The plug-in module will *not* function if it is installed in slots 2 and 3.

To make sure the instrument meets all of the published specifications, there must be a good ground connection from the plug-in module to the mainframe. The RF connectors on the rear of the plug-in module are spring loaded, so finger-tighten the knurled screw on the front panel of the plug-in module to make sure the plug-in is securely seated in the mainframe.

CAUTION Do not use extender cables to operate the plug-in module outside of the mainframe. The plug-in module and/or mainframe can be damaged by improper grounding when using extender cables.

Trigger

The external trigger level range for this plug-in module is ±1 V. The trigger source selection follows the slots the plug-in module is installed in. For example, if the plug-in module is installed in slots 1 and 2, then the trigger source is listed as trigger 2. If it is installed in slots 3 and 4, then the trigger source is listed as trigger 4.

CAUTION ⚠ The maximum safe input voltage is ±2 V + peak ac (+16 dBm). Therefore, to avoid damaging the trigger input circuitry, do not apply any voltage outside this range.

CAUTION The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

2

Care and Handling of Precision Connectors

The Care and Handling of Precision Connectors

What you'll find in this chapter

This chapter describes:

- 3.5 mm connector care
- connector wear
- device specifications
- accuracy considerations
- visual inspection
- mechanical inspection
- connecting devices

Understanding the information in this chapter will help you successfully operate the instrument.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

3.5 mm Connector Care

This chapter shows you how to take care of 3.5 mm connectors so that you can maintain high levels of accuracy, repeatability, and system performance. Taking appropriate care of your connectors will also extend their service life. Most of the information can also be applied to 2.4 mm connectors. For additional information on 2.4 mm connectors, refer to operating note "2.4 mm Adapters and Calibration Accessories" Agilent part number 11900-90903.

Connector Wear

Connector wear will eventually degrade performance. The calibration devices, which are typically used only a few times each day, should have a very long life. However, because the connectors often undergo many connections a day, they wear rapidly. Therefore, it is essential that all connectors on the Agilent 54753A or 54754A TDR plug-in modules be inspected regularly, both visually (with a magnifying glass) and mechanically (with a connector gage), and replaced as necessary. Procedures for visual and mechanical inspection are given in the next section of this manual. It is easier and cheaper to replace a worn adapter than a worn channel connector.

Operator Skill

Operator skill in making good connections is essential. The mechanical tolerances of the precision 3.5 mm connectors used in the Agilent 54007A kit are two or three times better than the tolerances in regular 3.5 mm connectors. Slight errors in operator technique that would go unnoticed with regular connectors often appear with precision connectors in the calibration kit. Incorrect operator technique can often result in lack of repeatability. Carefully study and practice the connection procedures that are explained later in this manual until your calibration measurements are consistently repeatable.

Device Specifications

Electrical specifications depend upon several mechanical conditions. A 3.5 mm connector is a precision connector dedicated to very specific tolerances. SMA connectors are not precision mechanical devices. They are not designed for repeated connections and disconnections and are very susceptible to mechanical wear. They are often found, upon assembly, to be out of specification. This makes them potentially destructive to any precision 3.5 mm connectors to which they might be mated.

Use extreme caution when mating SMA connectors with 3.5 mm precision connectors. Prevent accidental damage due to worn or out-of-specification SMA connectors. Such connectors can destroy a precision 3.5 mm connector, even on the first connection.

Agilent Technologies recommends that you keep three points clearly in mind when you mate SMA and precision 3.5 mm connectors: SMA inspection, alignment, and mechanical mismatch.

SMA Inspection

Before mating an SMA connector (even a new one) with a precision 3.5 mm connector, carefully inspect the SMA connector, both visually and mechanically with a precision connector gauge designed to measure SMA connectors. A male SMA connector pin that is too long can smash or break the delicate fingers on the precision 3.5 mm female connector. Gauging SMA connectors is the most important step you can take to prevent damaging your equipment.

Alignment

Be careful when aligning the connectors. Push the two connectors together with the male contact pin precisely concentric with the female. Do not overtighten or rotate either center conductor. Turn only the outer nut of the male connector and use a torque wrench (5 lb.in., 60 N-cm) for the final connection. Note that this torque is less than that when mating precision 3.5 mm connectors with each other. A torque wrench suitable for SMA connectors preset to 5 lb.in. is available (Agilent part number 8710-1582, CD 0).

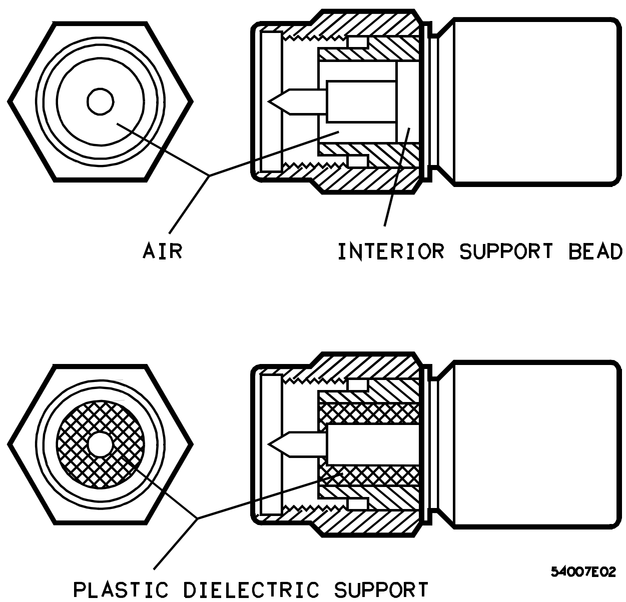
The TDR plug-in modules come with adaptors already installed to prevent damage to the channel connectors. Then, if accidental damage does occur, the adapter is all that needs to be replaced. It is easier and cheaper to replace a damaged adapter than a channel connector. SMA connectors can then be mated with precision 3.5 mm connectors without difficulty or fear of expensive and time-consuming repairs.

Mechanical Mismatch

Significant structural and dimensional differences exist between these two types of connectors. Precision 3.5 mm connectors, also known as APC-3.5 connectors, are air-dielectric devices. Only air exists between the center and outer conductors. The male or female center conductor is supported by a plastic "bead" within the connector. In SMA connectors, a plastic dielectric supports the entire length of the center conductor. In addition, the diameter of both the center and outer conductors of an SMA connectors differ from that of a precision 3.5 mm connector.

If these precautions and recommendations are followed, SMA connectors can be mated with 3.5 mm precision connectors without fear of expensive and time consuming repairs.

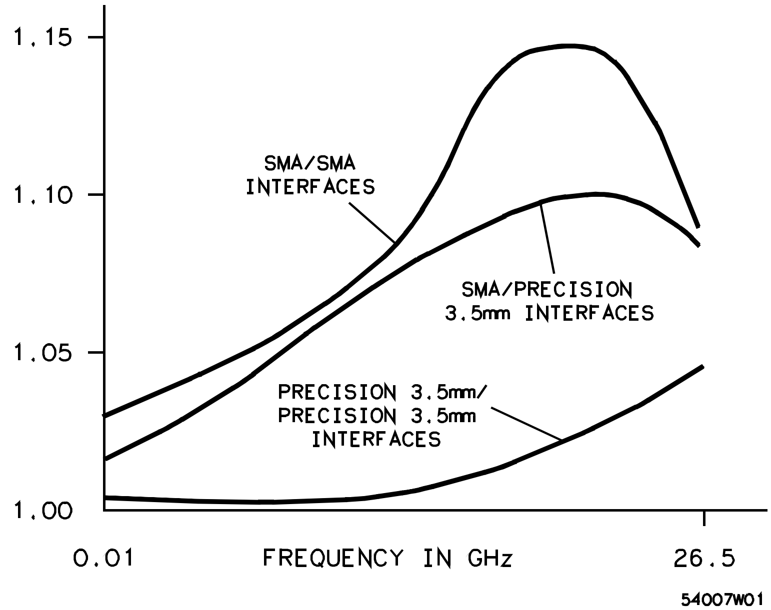
Figure 2-1



SMA and a Precision 3.5 mm Connectors

When an SMA connector is mated with a precision 3.5 mm connector, the connection exhibits a continuity mismatch (SWR), typically about 1.10 at 20 GHz. This mismatch is less than when precision 3.5 mm connectors are mated. Keep this fact in mind when making measurements on SMA and precision 3.5 mm coupled junctions.

Figure 2-2



Typical SWR of SMA and Precision 3.5 mm Connectors

Accuracy Considerations

Accuracy requires that 3.5 mm precision connectors be used. However, SMA connectors can be used if special care is taken when mating the two, and all connectors are undamaged and clean. Before each use, the mechanical dimensions of all connectors must be checked with a connector gauge to make sure that the center conductors are positioned correctly. All connections must be made for consistent and repeatable mechanical (and therefore electrical) contact between the connector mating surfaces.

Carefully study and practice all procedures in this chapter until you can successfully perform them repeatedly. Accuracy and repeatability are critical for good high frequency measurements. Note that the device connection procedures differ in several important ways from traditional procedures used in the industry. Agilent Technologies procedures have been developed through careful experimentation.

Handling Precision 3.5 mm Connectors

- Precision 3.5 mm connectors must be handled carefully if accurate calibrations and measurements are to be obtained.
- Store the devices in the foam-lined storage case when not in use.
- Avoid bumping or scratching any part of the mating surfaces.
- Be careful to align the center connectors.
- Check the alignment carefully before tightening the connector nuts.
- Use a torque wrench for all final connections in order to avoid overtightening.
- Support the devices being used in order to avoid vertical or lateral force on any connectors. This precaution is critical when using the airline, 6 cm "L", or cables.

When Disconnecting Devices:

- Do not rock or bend any connections.
- Pull the connector straight out without unscrewing or twisting.
- Before storage, screw the connector nut all the way out to help protect the surfaces, and use the plastic caps provided. These plastic caps can be taken off easily by unscrewing, rather than pulling.

CAUTION

Do not use a damaged or defective connector. It will damage any good connector to which it is attached. Throw the connector away or have it repaired.

A connector is bad if it fails either the visual or mechanical examinations or when an experienced operator cannot make repeatable connections. The time and expense involved in replacing channel connectors warrants considerable caution when any connector might be less than perfect.

If any doubts exist about a connector, call your Agilent Technologies representative. Agilent Technologies field offices offer limited professional advice and have access to the factory for information.

Visual Inspection

Always begin a calibration with a careful visual inspection of the connectors, including the test set connectors to make sure they are and undamaged.

CAUTION

Make sure that you and your equipment are grounded before touching any center conductor so you won't cause static electricity and create a potential for electrostatic discharge. When using or cleaning connectors, be aware that you are touching exposed center connectors that are connected directly to the internal circuits of the oscilloscope. Touching the center conductor, especially with a wiping or brushing motion, can cause an electrostatic discharge (ESD) and severely damage these sensitive circuits.

Use an illuminated, 4-power magnifying glass for visual inspection.

1. Before you begin, make sure you and any equipment you are using are grounded to prevent electrostatic discharge.
2. Examine the connectors first for obvious problems, such as deformed threads, contamination, or corrosion.
3. Next concentrate on the mating surfaces of each connector. Look for scratches, rounded shoulders, misalignment, or any other signs of wear or damage.
4. Make sure that the surfaces are clean, free of dust and solvent residues. Dirt or damage visible with a 4-power magnifying glass can cause degraded electrical performance and possible connector damage. All connectors should be repaired or discarded immediately.

Mechanical Inspection

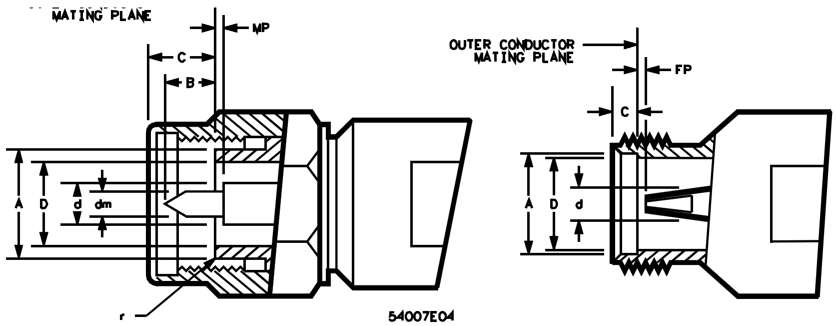
Mechanical inspection of the connectors is the next step. This inspection consists of using the appropriate male or female precision 3.5 mm connector gauge to check the mechanical dimensions of all connectors, including those on the test set. The purpose of doing this is to make sure that perfect mating will occur between the connector surfaces. Perfect mating assures a good electrical match and is very important mechanically to avoid damaging the connectors themselves, especially on the oscilloscope.

Center Conductor

The critical dimension to be measured is the recession of the center conductor. This dimension is shown as MP and FP in Figure 2-3 and Figure 2-4. No protrusion of the center conductor's shoulder is allowable on any connector. The maximum allowable recession of the center conductor shoulder is 0.003 in. (0.08 mm) on all connectors, except those on the channel connectors.

On the channel connectors, not only is no protrusion allowable, the shoulder of the center conductor must be recessed at least 0.0002 in. (0.005 mm). The maximum allowable recession of the center conductor shoulder on the channel connectors is 0.0021 in. (0.056 mm).

Figure 2-3

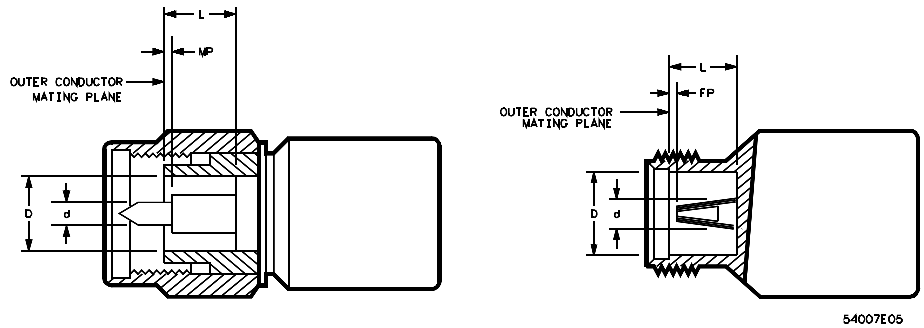


D = inside diameter of the outer conductor
d = diameter of male/female center connector
A = outside diameter of outer conductor at the mating plane
r = corner relief for male connector
B = protrusion of the male contact pin tip beyond the outer conductor mating plane
C = recession of the outer conductor mating plane behind outer face of connector
MP = recession of male contact pin shoulder behind outer conductor mating plane

Male Connectors				Female Connectors			
inches		millimeters		inches		millimeters	
D = 0.1378	± 0.0005	3.500	± 0.013	D = 0.1378	± 0.0005	3.500	± 0.013
d = 0.0598	± 0.0003	1.519	± 0.008	d = 0.0598	± 0.0003	1.519	± 0.008
A = 0.1803	+ 0.000 - 0.002	4.580	+ 0.00 - 0.05	A = 0.1807	+ 0.002 - 0.000	4.590	+ 0.05 - 0.00
r = 0.003		0.08		r = 0.003		0.08	
B = 0.085	+0.005 - 0.015	2.16	+ 0.13 - 0.38	N/A			
C = 0.120	± 0.015	3.05	± 0.38	C = 0.176	± 0.002	1.93	± 0.05
Mp = 0.00	+ 0.003 - 0.000	0.000	+ 0.08 - 0.00	Fp = 0.000	+ 0.003 - 0.00	0.000	+ 0.08 - 0.00
dm = 0.037	+ 0.000 - 0.001	0.94	+ 0.00 - 0.03	N/A			

Mechanical Dimensions of Connector Faces

Figure 2-4



Mechanical Dimensions of the Short Circuit

Outer Conductor

If any contact protrudes beyond the outer conductor mating plane, the contact is out of tolerance and must be replaced. If the center conductor is not recessed at least 0.0002 in. (0.005 mm), it is out of tolerance and must be replaced. In both cases the out-of-tolerance connector will permanently damage any connector attached to it. Destructive electrical interference will also result due to buckling of the female contact fingers. This is often noticeable as a power hole several dB deep occurring at about 22 GHz.

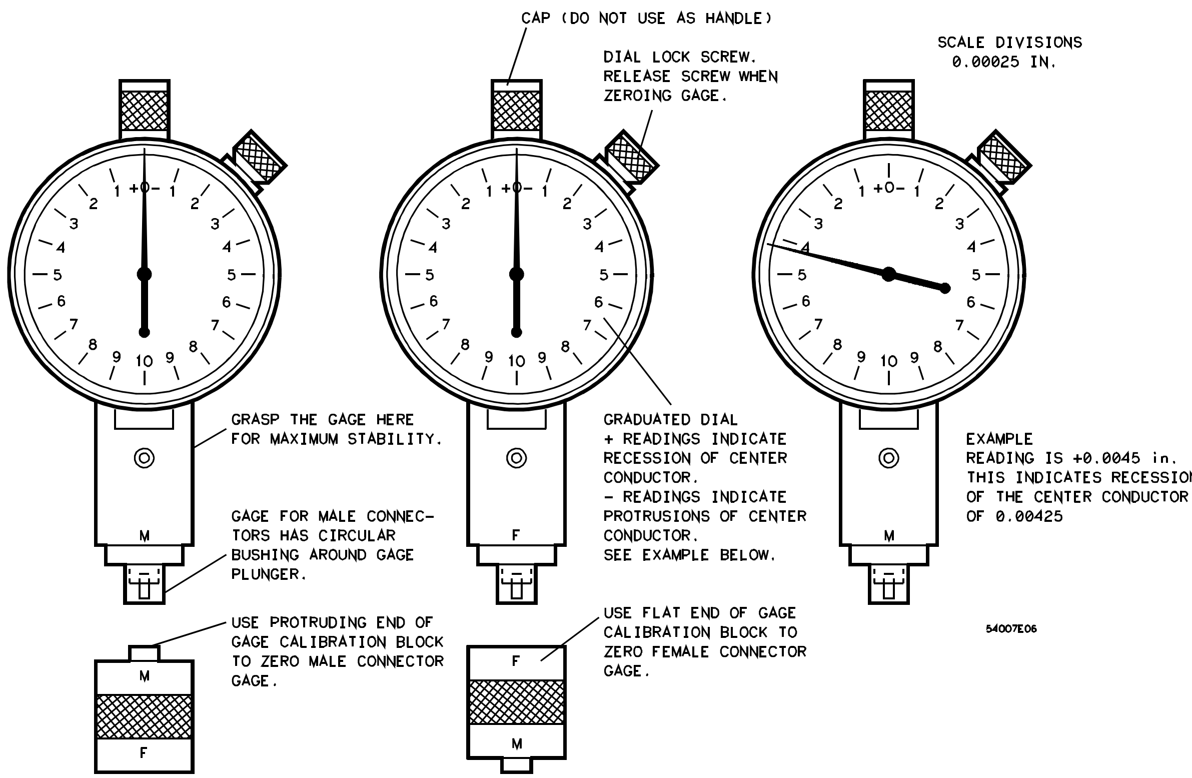
If any contact is recessed too far behind the outer conductor mating plane (0.0021 in. 0.056 mm, except in test sets), poor electrical contact will result, causing high electrical reflections. Careful gauging of all connectors will help prevent this condition.

Before using the connector gauge to measure the connectors, visually inspect the end of the gauge and the calibration block in the same way that you inspected the connectors. Dirty or damaged gauge facings can cause dirty or damaged connectors. Two connector gauges are available from Agilent Technologies, one for each connector type, male and female. Refer to Figure 2-5. A single gauge calibration block is used to zero both gauges; one end protrudes for zeroing the male connector gauge. The part number for both gauges, as well as the calibration block is 85052-80010.

Figure 2-5 to Figure 2-8 show how to use the connector gauges. Zero the gauge with the calibration block. Refer to Figure 2-5. It is recommended that you zero both gauges first, then measure each of the terminations and/or adapters that will be used. Then, as the last step, measure the channel connectors.

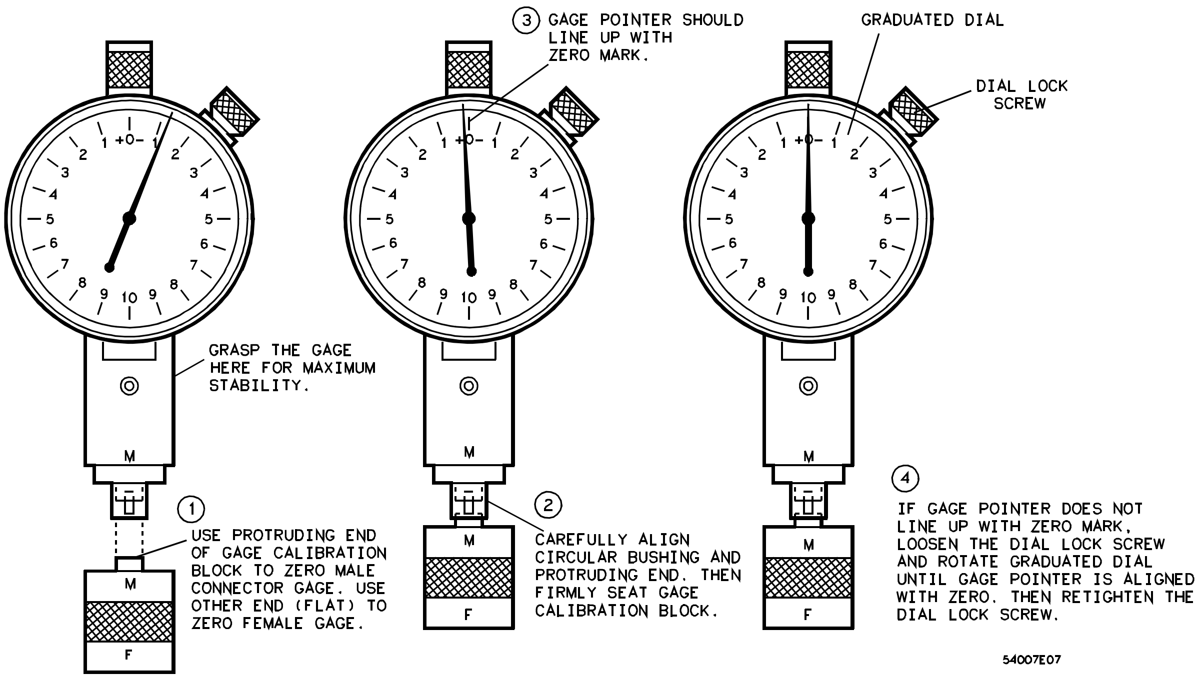
Figure 2-7 and Figure 2-8 show how to measure precision 3.5 mm connectors. Note that a plus (+) reading on the gauge indicates recession of the center conductor and a minus (-) reading indicates protrusion. Since no protrusion of either connector is allowable, readings for connectors within the allowable range will be on the plus (+) scale of the gauge. Also note that the allowable tolerance range for the test set connectors is different from the range for other connectors. Both ranges are shown in Figure 2-7 and Figure 2-8. Before measuring test set connectors, be sure that the power to the test set is off and that you and your equipment are grounded to prevent electrostatic discharge.

Figure 2-5



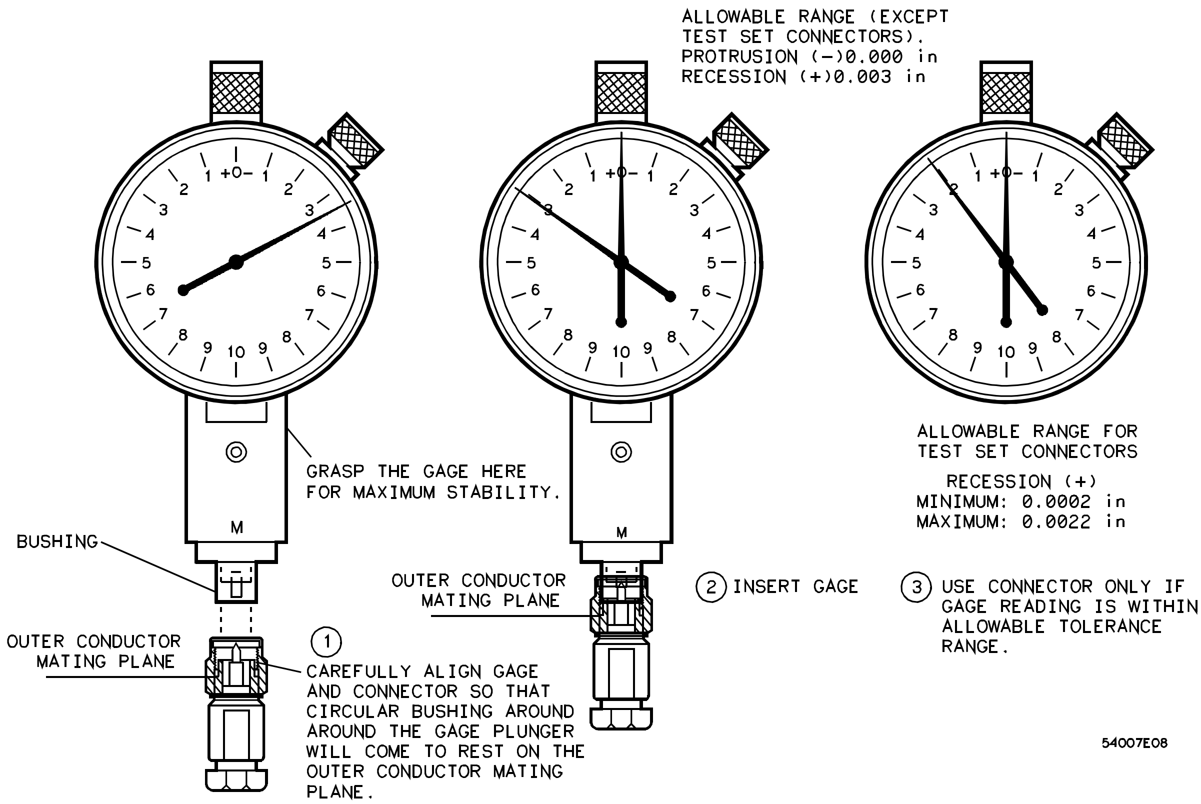
Precision 3.5 mm Connector Gauges

Figure 2-6



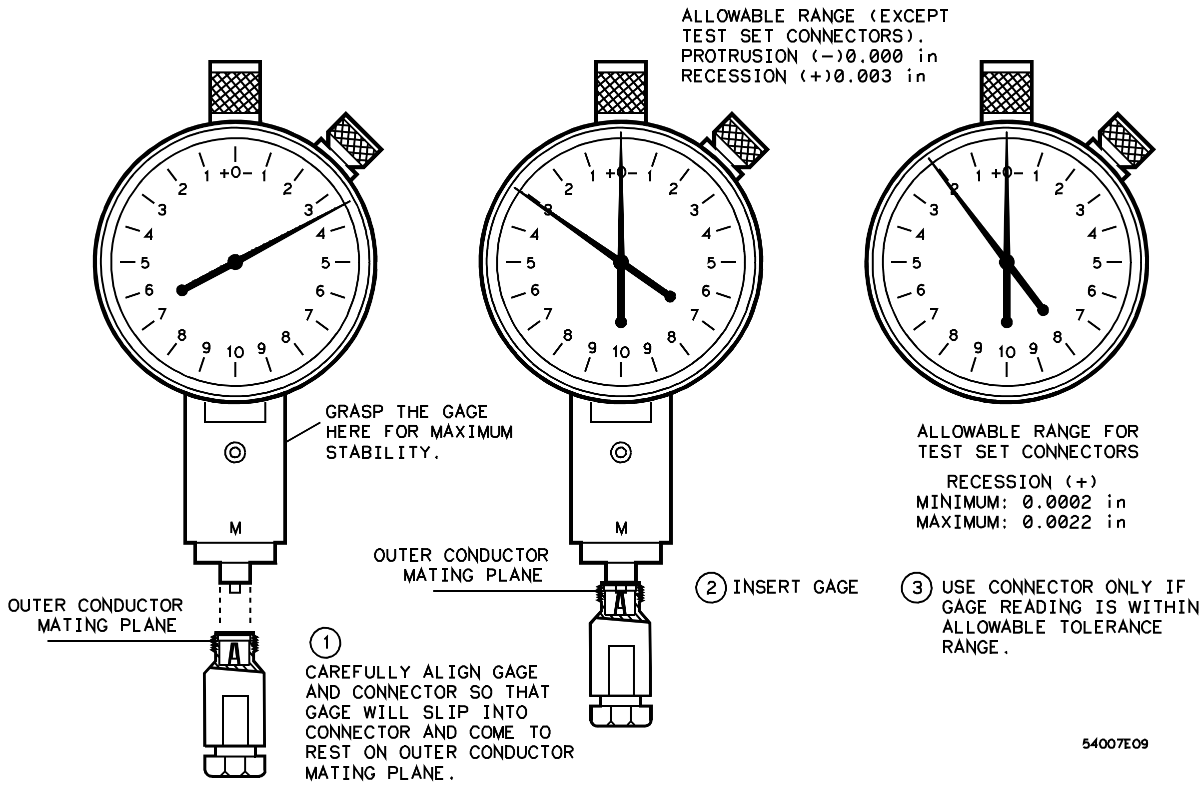
Zeroing Precision 3.5 mm Connector Gauge

Figure 2-7



Measuring Precision 3.5 mm Male Connectors

Figure 2-8



Measuring Precision 3.5 mm Female Connectors

Connecting the Devices

Figure 2-9 and Figure 2-10 illustrate Agilent Technologies' recommended procedures for making connections with the calibration devices. Notice that these recommended procedures differ from traditional procedures used in the microwave industry, especially the counter-rotation technique and procedure for connecting the airline.

The counter-rotation technique, recommended here, involves a slight rotation of the termination or adapter just before the final tightening of the connector nut. This eliminates the very small air wedge between the outer conductors that frequently occurs when the body is held stationary during tightening, as it is in the traditional procedure. The Agilent 54753A or Agilent 54754A plug-in modules will detect the reflections caused by such small wedges.

The counter-rotation technique does not harm the connectors. The gold plating on the outer conductor surface will become burnished in time. This is normal, and as long as the surface remains smooth, the connector is still good. After much use the gold plating may eventually wear through and expose the beryllium-copper substratum. This too is normal, and if it is smooth the connector is still good, although the beryllium-copper surface may oxidize if the connector is used infrequently.

If the burnished surface is rough, scratched, rippled, or has other irregularities, too much tightening force is being used. If the roughness is severe, the connector is ruined and should not be used.

CAUTION **Damage can result if SMA connectors are overtightened to precision 3.5 mm connectors. Use a torque wrench designed for SMA connectors, set to a 5 in lb (60 N/cm). A torque wrench suitable for SMA connectors is available, Agilent part number 8710-1582.**

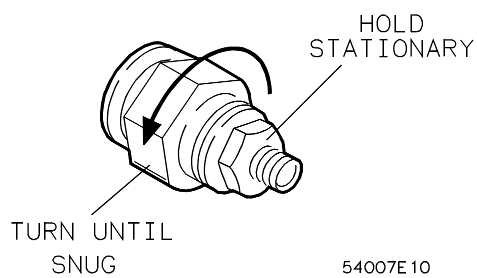
Counter-Rotation Technique

The recommended Agilent Technologies counter-rotation technique is for precision 3.5 mm connectors. Before making any connections to the channel connectors, ground yourself with a grounded wrist strap. Also, it is good practice to grasp the outer shell of the test port before you make any connections to the channel connectors in order to discharge any static electricity on your body. This is the most effective single safeguard to prevent ESD damage to your instruments.

1 If the device has a retractable connector nut, fully retract the nut before mating the connectors. Carefully align the male and female contact pins and slide the connectors straight together until the center and the two outer conductors meet. Be careful not to twist or bend the contact pins. You should feel a slight resistance as the connectors mate.

2 Make the preliminary connection by attaching the connector nut of the male connector to the female. The male connector is held stationary as the female connector is tightened and draws the male pin into the female connector. Refer to Figure 2-9. Any other method used may cause the male pin to damage the female connector. Support the body of the device and turn the connector nut until the mating surfaces make light contact. Do not overtighten. All you want is a connection of the outer conductors with gentle contact at all points of both mating surfaces.

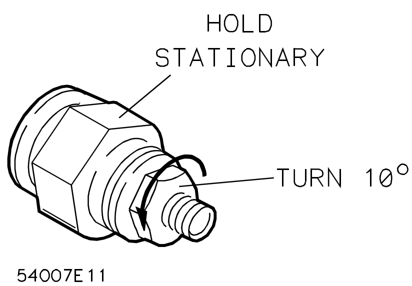
Figure 2-9



Connecting 3.5 mm Devices

3 When you are satisfied with this preliminary connection, use the following counter-rotation technique to eliminate air wedges between the mating planes. Refer to Figure 2-10. If the calibration device is male, hold the connector nut firmly. Very slowly rotate the body of the device about 10-20 ° counterclockwise. Note that this slight rotation or backwiping is sufficient. Greater rotation does not improve electrical performance and increases wear on the connector surfaces.

Figure 2-10



Counter-rotation Technique

If the calibration device is female (the connector nut is on the TDR plug-in module), very slowly rotate both the connector nut and the body of the device clockwise 10-20 ° (counterclockwise rotation will loosen the connection).

Light, smooth frictional resistance felt during the counter-rotation indicates you have made the preliminary connection correctly and that the counter-rotation technique has been successful. Roughness felt during counter-rotation indicates either that the connectors are damaged or that there is roughness in the connector nut/thread contact. Inspect both connectors again before proceeding, to make sure that the roughness is due to roughness in the connector nut interface rather than on the connector mating planes.

4 Tighten the connector nut finger tight, allowing the device to turn with the nut if it tends to do so. A small rotation of the body of the device at this point is acceptable and tends to occur naturally.

5 Use a torque wrench to make the final connection. Use of the torque wrench assures the final connection will be tight enough for optimum electrical performance, but not so tight as to distort or damage the connectors.

To disconnect, follow this procedure:

1. Loosen the connector nut on the male connector with the torque wrench. Leave the connection finger tight.
2. While supporting the calibration device, gently unfasten the connectors and pull the calibration device straight out of the channel connector. Do not twist either the center conductor or the outer conductor housing or exert lateral or vertical (bending) force on the connection.

> Some precision 3.5 mm female connector fingers are very tight and can pull the center pin of their mates out past specifications as they are disconnected. If such a male pin is inserted into a female connector, it can cause considerable damage by pushing the female center conductor back too far. Be aware of this possibility and check all connectors before mating them again.

3

Setup Channel Menu

Setup Channel Menu

What you'll find in this chapter

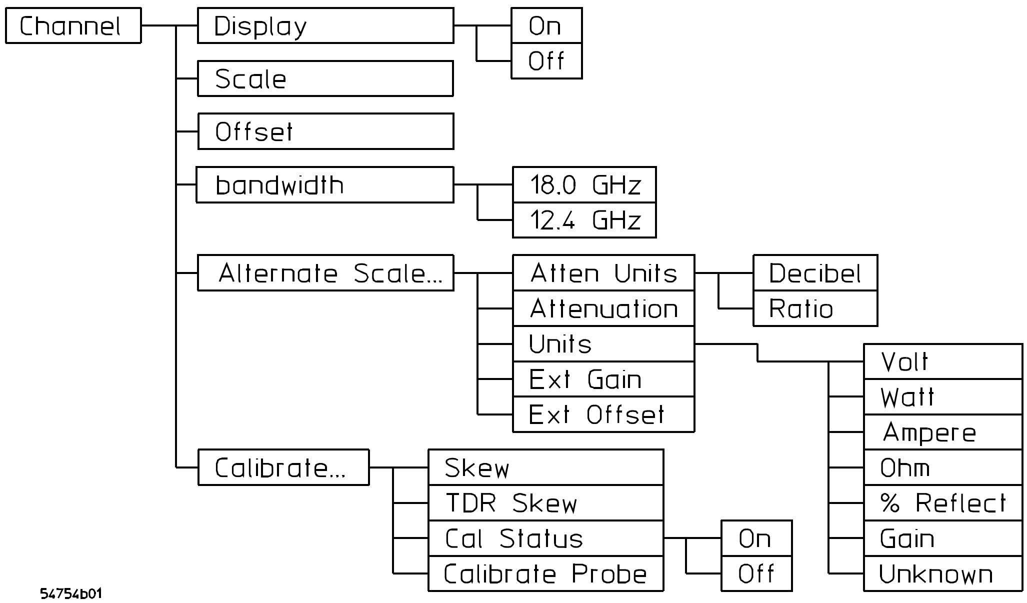
This chapter describes the Setup Channel menu. A key tree and description of the available functions are included.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

The top left keys of the plug-in module are the **Channel** keys. These keys give you access to the Setup Channel menu for each input. The Setup Channel menu is displayed on the right side of the screen when the **Channel** key is pressed. There are several types of softkeys available. A description of the different softkeys and their functions is provided in the *Agilent 83480A, 54750A User's Quick Start Guide* supplied with the mainframe.

Figure 3-1



Electrical Setup Channel menu.

Displaying the Setup Channel menu

To display the Setup Channel menu, press the **Channel** key.

Display

The *Display* softkey turns the channel display off and on. When the channel display is on, a waveform is displayed for that channel, unless the offset is adjusted so the waveform is clipped off of the display or the instrument is not triggering.

The channel number, vertical scaling, and offset are displayed at the bottom left of the waveform area. They remain on the display until the channel is turned off, or an automatic measurement is performed. The automatic measurement results share the same area of the display as the channel setups.

When the channel display is off, the waveform display for that channel is turned off, pulse parameter measurements are stopped and acquisition on that channel is stopped, unless it is needed as an operand for waveform math functions or TDR/TDT responses.

Even though the channel display is off, you can still use the plug-in as a function source in the Math menu or as a source for four normalize, differential, or common mode responses. However, the instrument will not trigger unless one or more of the other channel displays are turned on, or unless a math function or TDR/TDT response is using one of the channels.

Key Path **Channel** *Display*

Scale

The *Scale* softkey controls the vertical scaling of the waveform. If the fine mode is off, then the knob and arrow keys change the vertical scaling in a 1-2-5 sequence. When fine mode is on, the knob and arrow keys change the vertical scaling in 1 mV increments. You can also use the keypad to enter values in 1 mV increments, independent of the fine mode selection.

The units the scale is displayed in depend on the unit of measure selected with the *Units* softkey. The choices for units are volts, watts, amperes, ohms, % reflect, gain, or unknown.

When the ohm, % reflect, or gain units are selected, the control changes to *Magnify scale*. In this mode of operation, the TDR plug-in's hardware scale behaves as it would when the units mode is selected for all stimulus except for differential or common mode.

If the TDR/TDT stimulus is set to differential or common mode, the control also changes to *Magnify scale*. However, the hardware scale is set so that the displayed waveform is never clipped. The *Magnify scale* control is a software scaling control.

Key Path **Channel** *Scale*

Offset

The *Offset* softkey moves the waveform vertically. It is similar to the position control on analog oscilloscopes. The advantage of digital offset is that it is calibrated. The offset voltage is the voltage at the center of the graticule area, and the range of offset is 500 mV. You can use the knob, arrow keys, or keypad to change the offset setting. The fine mode also works with offset.

When an Agilent 54700-series active probe is used with the plug-in module and is connected to the probe power connector adjacent to the channel input, the offset control adjusts the external scale factor and offset of the hybrid inside the active probe. A probe connected to the auxiliary power connector adjacent to the trigger input will function, but the channel scale factor will not be adjusted automatically.

The units the offset is displayed in depend on the unit of measure selected with the *Units* softkey. The choices for units are volts, watts, amperes, ohms, % reflect, gain, or unknown.

When the ohm, % reflect or gain units are selected, the control changes to *Magnify offset*. In this mode of operation, the TDR plug-in's hardware offset behaves as it would when the units mode is selected for all stimulus except for differential or common mode.

If the TDR/TDT stimulus is set to differential or common mode, the control also changes to *Magnify offset*, however, the harrower scale is set so that the displayed waveform is never clipped. The *Magnify offset* control is a software offset control.

Key Path **Channel** *Offset*

Bandwidth. . .

You can use the *Bandwidth* function to select either 12.4 GHz or 18 GHz bandwidth. For the Agilent 54753A TDR plug-in module, channel 2 can be either 12.4 GHz or 20 GHz bandwidth.

Key Path **Channel** *Bandwidth. . .*

Alternate scale. . .

The *Alternate Scale* function allows you to change the units used to label the vertical scale of the display. It also allows you to select the attenuation units and the attenuation factor.

Key Path **Channel** *Alternate scale . . .*

Atten units

The *Atten Units* function lets you select how you want the probe attenuation factor represented. The choices are either decibel or ratio. The formula for calculating decibels is:

$$20\log\frac{V_{out}}{V_{in}} \text{ or } 10\log\frac{P_{out}}{P_{in}}$$

The *Atten Units* function is not available when the units are set to ohm, % reflect, or gain.

Attenuation

The *Attenuation* function lets you select an attenuation that matches the device connected to the instrument. When the attenuation is set correctly, the instrument maintains the current scale factors, if possible. All marker values and voltage or wattage measurements will reflect the actual signal at the input to the external device.

The attenuation range is from 0.0001:1 to 1,000,000:1. When you connect a compatible active probe to the probe power connector, adjacent to the corresponding channel input, the instrument automatically sets the attenuation. For all other devices, set the probe attenuation with the knob, arrow keys, or keypad.

Refer to "Calibrating Voltage Probes" on page 3-12 for information on calibrating to the tip of the probe.

The Attenuation function is not available when ohm, % reflect, or gain units are selected.

Key Path **Channel** *Alternate scale . . . Attenuation*

Units

The Units function lets you select the unit of measure appended to the channel scale, offset, trigger level, and vertical measurement values. For the plug-in module, the units are volts, watts, amperes, ohms, % reflect, gain, or unknown. Use volt for voltage probes, ampere for current probes, watt for optical-to-electrical (O/E) converters, and unknown when there is no unit of measure or when the unit of measure is not one of the available choices. The gain selection is only available when the channel has been chosen as a TDT destination.

The two additional choices, ohms and % reflect are selectable once a TDR/TDT normalization and reference plane have been established (see the 54753A Setup Menu or 54754A Setup Menu chapter under *Establish normalization & ref plane* for more information). Use Ohms when TDR/TDT vertical scale units of ohms/div are required for making measurements. Use % reflect when TDR/TDT percentage of reflection units are required.

Key Path **Channel** *Alternate scale . . . Units*

Ext gain and Ext offset

When you select ampere, watt, or unknown, two additional functions become available: External Gain and External Offset. These two additional functions allow you to compensate for the actual characteristics of the probe rather than its ideal characteristics. For example, you might have an amplified lightwave converter with ideal characteristics of 300 V/W with 0 V offset. But, its actual characteristics are 324 V/W with 1 mV of output offset. Therefore, set the External Gain to 324 V/W and the External Offset to 1 mV.

Key Path **Channel** *External scale . . . Units Volt Ext gain* or *Ext Offset*
Channel *External scale . . . Units Watt Ext gain* or *Ext Offset*
Channel *External scale . . . Units Unknown Ext gain* or *Ext Offset*

Calibrate . . .

The calibrate menu allows you to null out any skew between probes or cables and to check the present calibration status of the instrument.

Key Path **Channel** *Calibrate . . .*

Skew

The Skew function changes the horizontal position of a waveform on the display. The Skew function has a range of approximately 100 µs. You can use skew to compensate for differences in cable or probe lengths. It also allows you to place the triggered edge at the center of the display when you are using a power splitter connected between the channel and trigger inputs. Another use for skew is when you are comparing two waveforms that have a timing difference between them. If you are more interested in comparing the shapes of two waveforms rather than the actual timing difference between them, you can use Skew to overlay one waveform on top of the other waveform.

To adjust the skew on two channels

1. Turn both channels on and overlay the signals vertically.
2. Expand the time base, so the rising edges are about a 45 degree angle.
3. Adjust the skew on one of channels, so that the rising edges overlap at the 50 percent points.

Key Path **Channel** *Calibrate . . . Skew*

TDR Skew

The TDR Skew function changes the position of the TDR step. The TDR Skew function has a range of ≅ ±400 pS. The units of the function are shown in % of the maximum range, or ±100%. The Skew function and the TDR Skew function differ in that Skew moves the acquired waveform with respect to the trigger, while the TDR Skew function moves the TDR step with respect to the trigger. TDR Skew can be used to align the TDR steps of the two TDR channels for more accurate differential TDR measurements when cable or probe lengths are different.

To deskew the two TDR channels

1. Turn on both channels and overlay the signals vertically with no cables attached.
2. Expand the time base so the rising edges are about a 45 degree angle.
3. Adjust the TDR skew on one of the channels, so that the rising edges overlap at the 50 percent points.
4. Attach the cables. If the cables differ in length, then the waveforms will not overlay each other.
5. Using the ΔTime auto measurement or manual markers, measure the Δtime (the skew) between the TDR channels.
6. Adjust the channel Skew for the channel whose waveform is to the right of the other channels waveform until the skew is ½ of the measured Δtime.
7. Adjust the TDR Skew for the right most waveform until the remaining skew is ≅ 0.

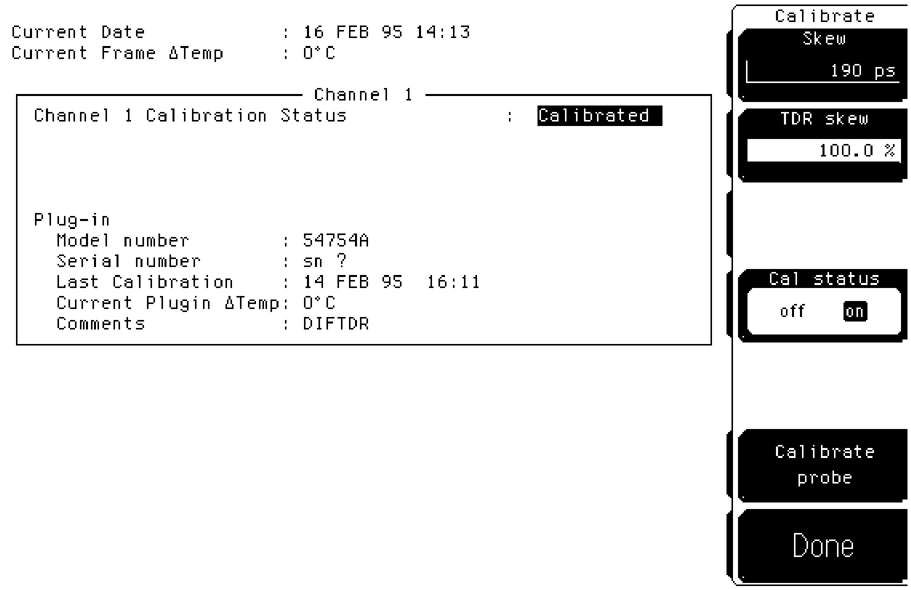
Key Path **Channel** *Calibrate . . . TDR Skew*

Cal status

The Cal Status function displays a screen similar to Figure 3-8.

Key Path **Channel** *Calibrate Cal Status*

Figure 3-8



A typical Cal Status display.

Current Date This is the current date and time. You can compare this to the last plug-in module calibration time. That way you will know how long it has been since the last plug-in module calibration was performed.

Current Frame ΔTemp This is the temperature change on the inside of the instrument since the last mainframe calibration was performed. A positive number indicates how many degrees warmer the mainframe is currently as compared to the temperature of the mainframe at the last mainframe calibration.

Channel 1 Calibration Status The instrument displays **`Calibrated`** when the plug-in module has been calibrated in the current mainframe slot otherwise the instrument displays **`Uncalibrated`**. Once a plug-in is calibrated, the temperature difference (ΔTemp) between when the plug-in was calibrate and the current temperature is displayed. The plug-in module will met dc accuracy specifications as long as the ΔTemp is within the range of -5 °C to +5 °C. Also displayed, is a list of the plug-in module's model number, serial number, date of last calibration, and time of last calibration.

Calibrate probe

Connect a voltage probe to the plug-in and then press:

Calibrate probe

Continue

The instrument calibrates to the tip of the probe by setting the probe attenuation to the actual attenuation ratio of the probe. The instrument also automatically compensates for any offset that the probe may introduce.

Key Path **Channel** *Calibrate Calibrate probe Continue*

Calibration Procedures

What you'll find in this section

This sections contains procedures for performing:

- a plug-in module vertical calibration
- calibration of voltage probes
- calibration of other devices

Performing a Plug-in Module Vertical Calibration

1 To perform a plug-in module vertical calibration, press:
Utility
Calibrate . . .
Calibrate plug-in. . .

2 Select the plug-in module to be calibrated by pressing:
1 and 2 or *3 and 4*

3 Start the calibration procedure by pressing:
Start cal

4 Follow the on screen instructions.

Calibrating Voltage Probes

Because the mainframe's CAL signal is a voltage source, you can let the instrument compensate for the actual characteristics of your probe by letting the instrument calibrate to the tip of the probe.

Performing the Calibration

To calibrate a voltage probe to the probe tip, set the instrument as follows:

Atten units `ratio`
Units `Voltage`
Calibrate Probe

The instrument automatically calibrates to the tip of the probe, sets the probe attenuation and compensates for any probe offset.

Calibrating Other Devices

Because the mainframe's CAL signal is a voltage source, it cannot be used to calibrate to the probe tip when the units are set to ampere, watt, or unknown. Instead, set the external gain and external offset to compensate for the actual characteristics of the probe or device. If you do not know the actual characteristics, you can refer to the typical specifications that came with the probe or device.

Performing the Calibration

To compensate for the actual characteristics of the probe or device, set the instrument as follows:

Atten units `ratio`

Attenuation `1:1`

Units `Ampere` (Watt or unknown)

Ext gain actual gain characteristics of the probe or device.

Ext offset offset introduced by the probe or device.

4

Agilent 54753A TDR/TDT Setup Menu

Agilent 54753A TDR/TDT Setup Menu

What you'll find in this chapter

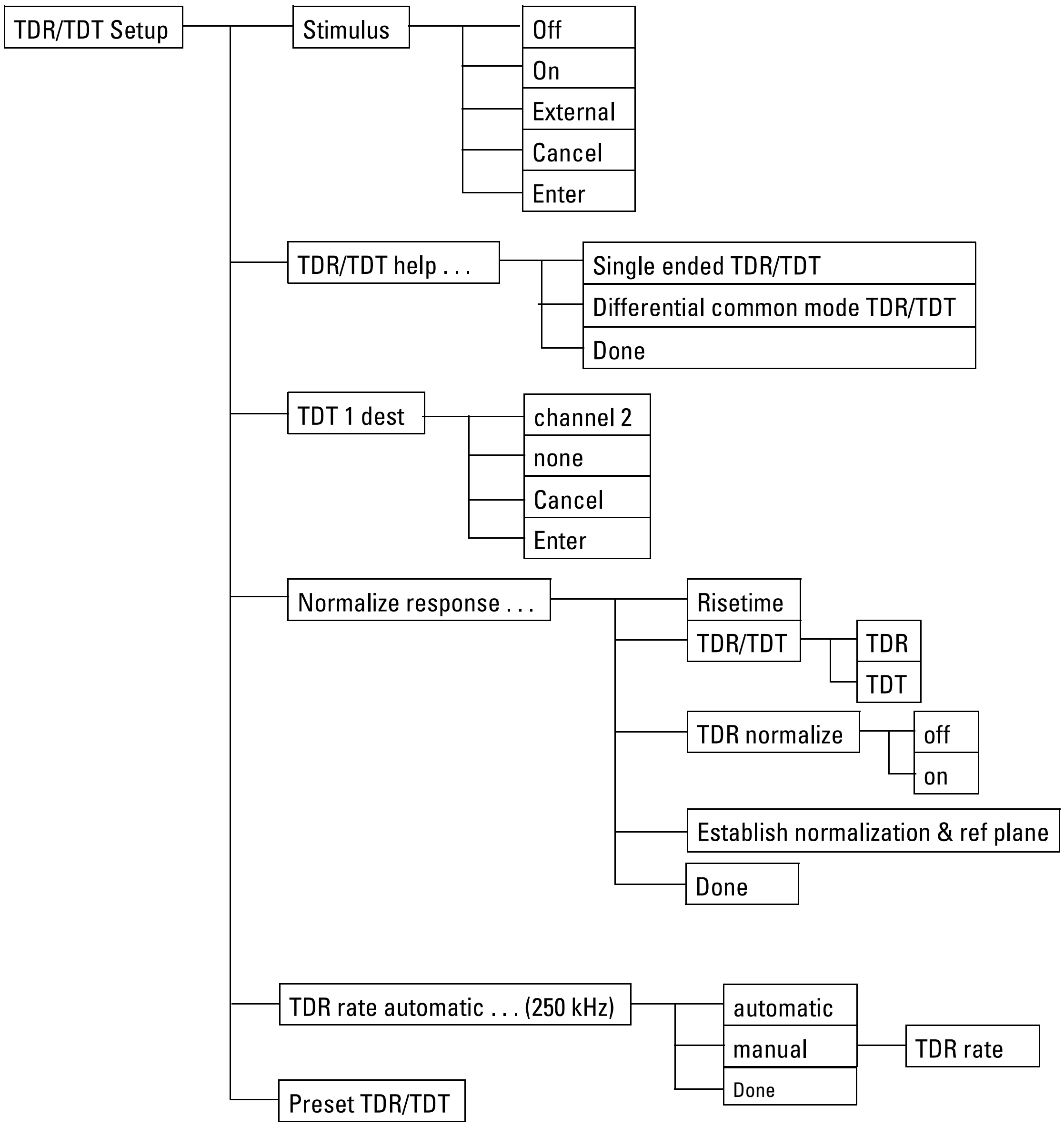
This chapter describes the TDR/TDT Setup menu. A key tree and description of the available functions is included.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

The top right key of the plug-in module is the **TDR/TDT Setup** key. This key gives you access to the **TDR/TDT Setup** menu. The **TDR/TDT Setup** menu is displayed on the right side of the screen when the **TDR/TDT Setup** key is pressed. There are several types of softkeys available.

Figure 4-1



TDR/TDT Setup Menus

Displaying the TDR/TDT Setup Menu

To display the TDR/TDT Setup menu, press the **TDR/TDT Setup** key on the TDR plug-in module.

Stimulus

Pressing the *Stimulus* softkey produces a pull-down menu used to turn on or turn off the TDR step. The Agilent 54753A is a single-ended TDR plug-in and has one TDR stimulus channel. The following table contains a list of the available stimulus menu choices and their descriptions.

Table 4-1

Stimulus Menu Choices

Stimulus	Description
off	Turns the TDR step off and disables the TDR measurement system.
on	Turns the TDR step on and enables the TDR measurement system.
external	This setup provides control for and requires an external step generator before measurements can be made.

Key Path **TDR/TDT Setup** *Stimulus*

TDT 1 dest

The *TDT 1 dest* softkey only appears when the *Stimulus* is set to on or external. Pressing the *TDT 1 dest* softkey produces a pull-down menu used to select the channel used as the destination channel for TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is a valid TDT destination channel. If external stimulus is selected, the TDT destination may not be set to the currently defined TDR destination channel.

If no other valid TDT destination channels are available, then "none" is the only choice. If a TDT destination other than none is selected, then the *Preset TDR/TDT* control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 1 dest*

TDR 1 dest

The *TDR 1 dest* softkey only appears when the stimulus is set to external. Pressing the *TDR 1 dest* softkey produces a pull-down menu used to select the channel used as the destination channel for TDR measurements. Any electrical channel is a valid TDR destination channel. The TDR destination may not be set to the currently defined TDT destination.

Key Path **TDR/TDT Setup** *TDR 1 dest*

Normalize response . . .

The *Normalize response* function allows you to change the risetime of the normalized step, to select TDR and TDT normalization, to turn on or off the display of the normalized TDR or TDT trace, to change the scaling of the normalized trace, and to establish the normalization filter values and reference plane.

Risetime

The Risetime function allows you to change the normalized step's risetime from a minimum of

10 ps

or

$$min = 8 \text{ points} \times \frac{\text{time per division (s/div)} \times 10 \text{ divisions}}{\text{record length}}$$

whichever is greater, to a maximum of

$$max = 5 \times \text{time per division (s/div)}$$

While the TDR step's risetime applied to the system under test is fixed, the measured response has a set of mathematical operations applied to it. These mathematical operations effectively change the displayed response to the system just as if a different TDR step risetime had actually been applied. This allows you to select a risetime for TDR/TDT measurements that is close to the actual risetime used in your system. This risetime value applies to both TDR and TDT normalized channels. For more information on normalization, see the chapter titled *Improving Time Domain Network Measurements*.

Key Path **TDR/TDT Setup** *Normalize response . . . Risetime*

TDR/TDT

The *TDR/TDT* function is used to select between TDR and TDT for normalization. Both TDR and TDT channels can be normalized. This control selects which normalized trace is referred to for the following controls. Before TDT normalization can be done, you must select a TDT destination (*TDT 1 dest*).

Key Path **TDR/TDT Setup** *Normalize response . . . TDR/TDT*

TDR or TDT normalize

The *TDR normalize* function is available if the TDR mode is selected by using the previous control; otherwise, the TDT normalize function is available. In either case, this function turns on or off the display of the normalized trace. The TDR and TDT normalization functions can be on at the same time.

Key Path **TDR/TDT Setup** *Normalize response . . . TDR normalize*

Normalize scaling . . .

The *Normalize scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR or TDT normalize is set to on.

Key Path **TDR/TDT Setup** *Normalize response . . . Normalize scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Y Scale* and *Y Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Y Scale* and *Y Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Horizontal*

Establish normalization & ref plane

The *Establish normalization & ref plane* function establishes the filter values used to normalize a channel and to set the reference plane for TDR and TDT measurements. This function must be performed separately for TDR and TDT modes. The normalization and reference plane must be re-established when power is lost or when the instrument is turned off. However, the values used for normalization and reference plane calculations can be stored to and re-loaded from disk. (See the *Disk Menu* chapter in the *Agilent 83480A, Agilent 54750 User's Guide* for more information.)

> The normalization filter values and reference plane become invalidated when the timebase scale, record length or channel bandwidth is changed. Also, the normalization process will not be able to remove small synchronous noise in the channels baseline if the timebase position is changed. For most measurements this error is very small.

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the *Reference* `ref plane` function is not available in the **Marker** menu.

The function steps you through the normalization and reference plane procedure for the selected measurement type. The procedure steps are displayed at the top of the screen. The items required for calibration are shown in Table 4-2.

Table 4-2

Establish normalization & ref plane Hardware Requirements

Measurement	**Requirements**
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

Key Path **TDR/TDT Setup** *Normalize response . . . Establish normalization & ref plane . . .*

TDR rate automatic . . . (250 kHz)

The *TDR rate automatic . . . (250 kHz)* function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** *Scale* is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The *Preset TDR/TDT* function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 4-3.

Table 4-3

Preset TDR/TDT Configuration

Menu	**Menu Item**	**Set To**
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup	Display	on
	Scale	100 mV/div
	Offset	200.0 mV (for Stimulus on) 0.0 mV (form Stimulus external)
	Bandwidth	12.4 GHz (for Stimulus on) 18.0 GHz (for Stimulus external)
	Attenuation units	ratio
	Attenuation	1.000 : 1

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

5

Agilent 54754A TDR/TDT Setup Menu

Agilent 54754A TDR/TDT Setup Menu

What you'll find in this chapter

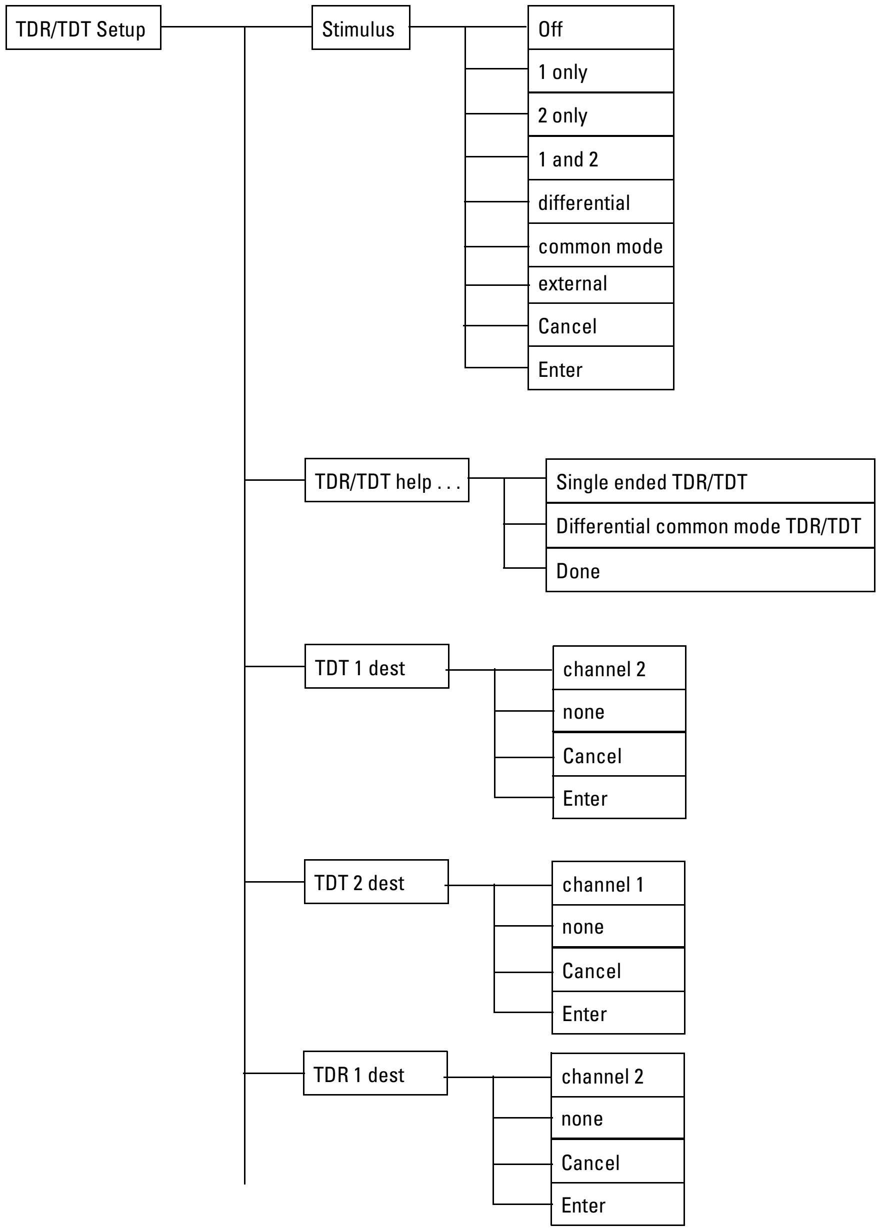
This chapter describes the Agilent 54754A TDR/TDT Setup menu. A key tree and description of the available functions is included.

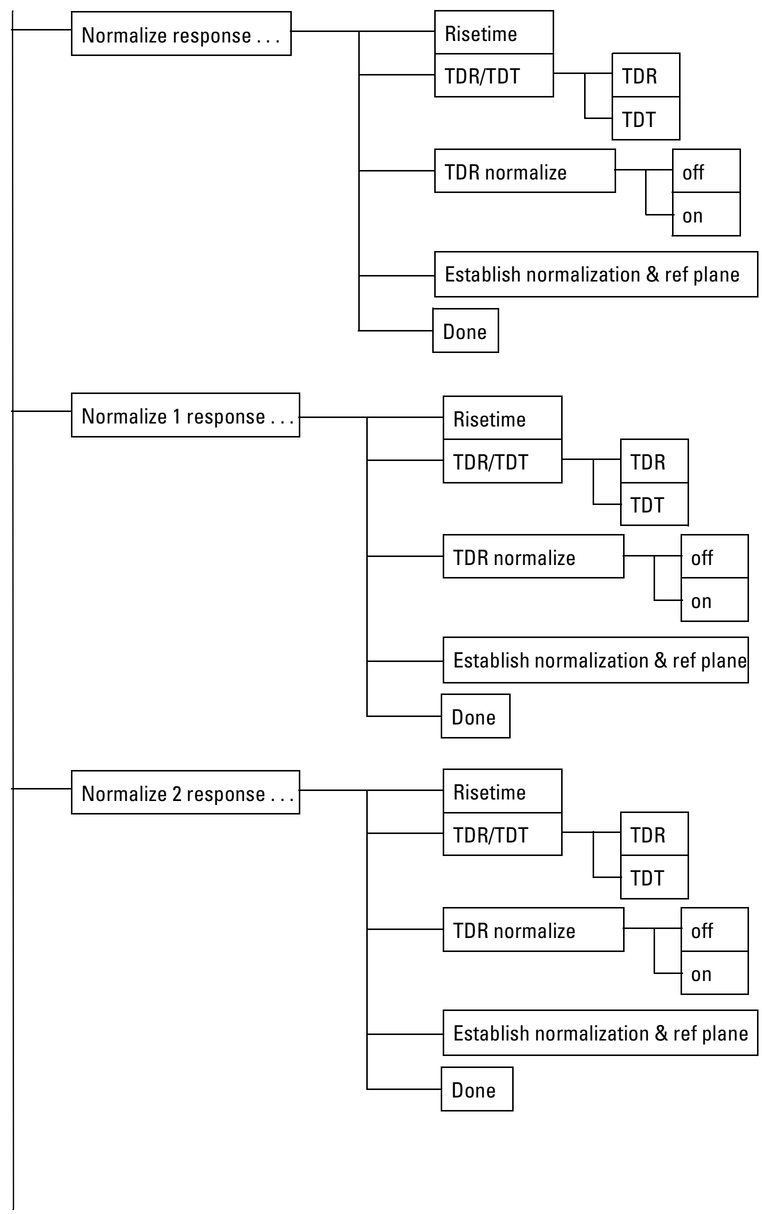
CAUTION

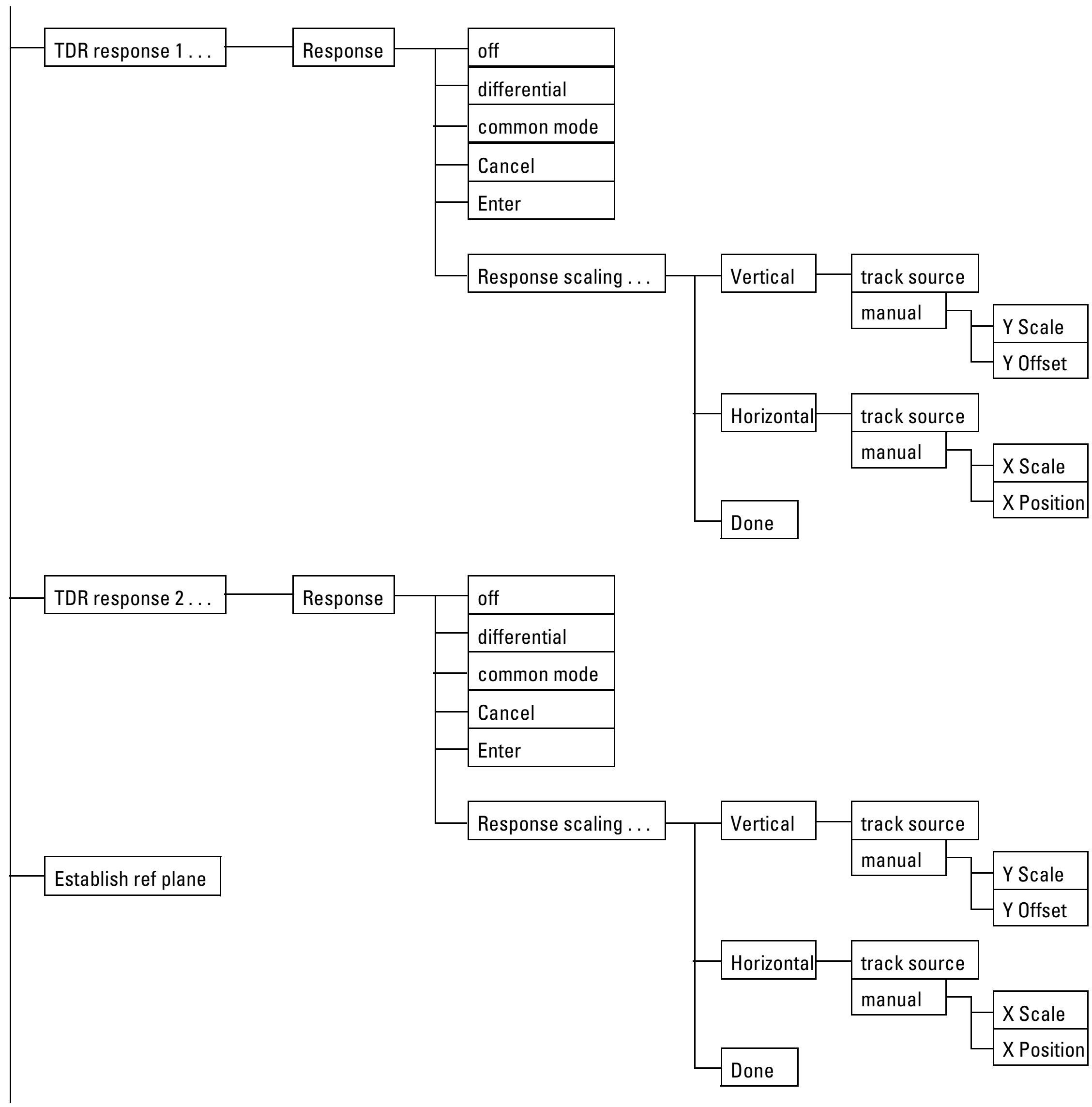
The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

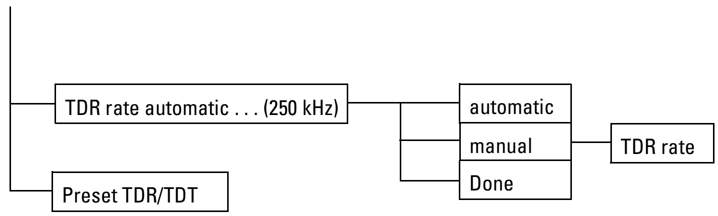
The top right key of the plug-in module is the **TDR/TDT Setup** key. This key gives you access to the TDR/TDT Setup menu. The TDR/TDT Setup menu is displayed on the right side of the screen when the **TDR/TDT Setup** key is pressed. There are several types of softkeys available.

Figure 5-1


TDR/TDT Setup
Stimulus
Off
1 only
2 only
1 and 2
differential
common mode
external
Cancel
Enter
TDR/TDT help . . .
Single ended TDR/TDT
Differential common mode TDR/TDT
Done
TDT 1 dest
channel 2
none
Cancel
Enter
TDT 2 dest
channel 1
none
Cancel
Enter
TDR 1 dest
channel 2
none
Cancel
Enter


Normalize response . . .
Risetime
TDR/TDT
TDR
TDT
TDR normalize
off
on
Establish normalization & ref plane
Done
Normalize 1 response . . .
Risetime
TDR/TDT
TDR
TDT
TDR normalize
off
on
Establish normalization & ref plane
Done
Normalize 2 response . . .
Risetime
TDR/TDT
TDR
TDT
TDR normalize
off
on
Establish normalization & ref plane
Done


TDR response 1 . . .
Response
off
differential
common mode
Cancel
Enter
Response scaling . . .
Vertical
track source
manual
Y Scale
Y Offset
Horizontal
track source
manual
X Scale
X Position
Done
TDR response 2 . . .
Response
off
differential
common mode
Cancel
Enter
Response scaling . . .
Vertical
track source
manual
Y Scale
Y Offset
Horizontal
track source
manual
X Scale
X Position
Done
Establish ref plane



TDR/TDT Setup Menu.

Displaying the TDR/TDT Setup Menu

To display the TDR/TDT Setup menu, press the **TDR/TDT Setup** key on the TDR plug-in module.

Stimulus

Pressing the *Stimulus* softkey produces a pull-down menu used to turn on or turn off the TDR step. The differential TDR plug-in has two TDR channels. The following table contains a list of the available stimulus menu choices and their descriptions.

Table 5-1

Stimulus Menu Choices

Stimulus	Description
off	Turns the TDR steps off for both TDR channels and the TDR measurement system off.
1 only	Turns the TDR step on for channel 1 only and enables the TDR measurement system.
2 only	Turns the TDR step on for channel 2 only and enables the TDR measurement system.
1 and 2	Turns the TDR steps on for both channels. This mode is used to make two independent single-ended TDR measurements.
differential	Turns the differential TDR steps on for both channels. The step for channel 1 is a positive going step while the step for channel 2 is effectively a negative going step. This mode is used to make differential TDR measurements
common mode	Turns the common mode TDR steps on for both channels. Both steps are positive going steps. Unlike the *1 and 2* mode, this mode is used to make common mode measurements.
external	This setup provides control for and requires an external step generator before measurements can be made.

Key Path **TDR/TDT Setup** *Stimulus*

1 Only Stimulus Menus

This section describes the menus that are available when the stimulus is set to `1 only`.

TDT 1 dest

Pressing the *TDT 1 dest* softkey produces a pull-down menu used to select the channel used as the destination channel for TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is potentially a valid TDT destination channel. The TDT destination may not be assigned to a channel already assigned as a TDT destination.

If no other valid TDT destination channels are available, then "none" is the only choice. If a TDT destination other than none is selected, then the *Preset TDR/TDT* control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 1 dest*

Normalize response . . .

The *Normalize response* function is available for all the *Stimulus* types except differential and common mode. The *Normalize response* function allows you to change the risetime of the normalized step, to select TDR and TDT normalization, to turn on or off the display of the normalized TDR or TDT trace, to change the scaling of the normalized trace, and to establish the normalization filter values and reference plane.

Risetime

The Risetime function allows you to change the normalized step's risetime from a minimum of

10 ps

or

$$min = 8 \text{ points} \times \frac{\text{time per division (s/div)} \times 10 \text{ divisions}}{\text{record length}}$$

which ever is greater, to a maximum of

$$max = 5 \times \text{time per division (s/div)}$$

While the TDR step's risetime applied to the system under test is fixed, the measured response has a set of mathematical operations applied to it. These mathematical operations effectively change the displayed response to the system just as if a different TDR step risetime had actually been applied. This allows you to select a risetime for TDR/TDT measurements that is close to the actual risetime used in your system. This risetime value applies to both TDR and TDT normalized channels. For more information on normalization, see Chapter 10, "Improving Time Domain Network Measurements".

Key Path **TDR/TDT Setup** *Normalize response . . . Risetime*

TDR/TDT

The *TDR/TDT* function is used to select between TDR and TDT for normalization. Both TDR and TDT channels can be normalized. This control selects which normalized trace is referred to for the following controls. Before TDT normalization can be done, you must select a TDT destination (*TDT 1 dest*).

Key Path **TDR/TDT Setup** *Normalize response . . . TDR/TDT*

TDR or TDT normalize

The TDR normalize function is available if the TDR mode is selected by using the previous menu otherwise the TDT normalize function is available. In either case, this function turns on or off the display of the normalized trace. The TDR and TDT normalization functions can be on at the same time.

Key Path **TDR/TDT Setup** *Normalize response . . . TDR normalize*

Normalize scaling . . .

The *Normalize scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR or TDT normalize is set to on.

Key Path **TDR/TDT Setup** *Normalize response . . . Normalize scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Y Scale* and *Y Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Y Scale* and *Y Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Horizontal*

Establish normalization & ref plane

The *Establish normalization & ref plane* function establishes the filter values used to normalize a channel and to set the reference plane for TDR and TDT measurements. This function must be performed separately for TDR and TDT modes. The normalization and reference plane must be re-established when power is lost or when the instrument is turned off. However, the values used for normalization and reference plane calculations can be stored to and re-loaded from disk. (See the *Disk Menu* chapter in the *Agilent 83480A, Agilent 54750 User's Guide* for more information.)

> The normalization filter values and reference plane are invalidated when the timebase scale, record length or channel bandwidth is changed. Also, the normalization process will not be able to remove small synchronous noise in the channels baseline if the timebase position is changed. For most measurements this error is very small.

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the *Reference* `ref plane` function is not available in the **Marker** menu.

The function steps you through the normalization and reference plane procedure for the selected measurement type. The procedure steps are displayed at the top of the screen. The items required for calibration are shown in Table 5-2 on page 5-11.

Table 5-2

Establish normalization & ref plane Hardware Requirements

Measurement	Requirements
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

Key Path **TDR/TDT Setup** *Normalize response . . . Establish normalization & ref plane . . .*

TDR rate automatic . . . (250 kHz)

The *TDR rate automatic . . . (250 kHz)* function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** *Scale* is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The Preset TDR/TDT function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 5-3.

Table 5-3

Preset TDR/TDT Configuration

Menu	**Menu Item**	**Set To**
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup	Display	on
	Scale	100 mV/div
	Offset	200.0 mV
	Bandwidth	12.4 GHz
	Attenuation units	ratio
	Attenuation	1.000 : 1

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

2 Only Stimulus Menus

This section describes the menus that are available when the stimulus is set to `2 only`.

TDT 2 dest

Pressing the *TDT 2 dest* softkey produces a pull-down menu used to select the channel used as the destination channel for TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is potentially a valid TDT destination channel. The TDT destination may not be assigned to a channel already assigned as a TDT destination.

If no other valid TDT destination channels are available then "none" is the only choice. If a TDT destination other than none is selected then the preset TDR/TDT control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 2 dest*

Normalize response . . .

The *Normalize response* function is available for all the *Stimulus* types except differential and common mode. The *Normalize response* function allows you to change the risetime of the normalized step, to select TDR and TDT normalization, to turn on or off the display of the normalized TDR or TDT trace, to change the scaling of the normalized trace, and to establish the normalization filter values and reference plane.

Risetime

The Risetime function allows you to change the normalized step's risetime from a minimum of

10 ps

or

$$min = 8 \text{ points} \times \frac{\text{time per division (s/div)} \times 10 \text{ divisions}}{\text{record length}}$$

which ever is greater, to a maximum of

$$max = 5 \times \text{time per division (s/div)}$$

While the TDR step's risetime applied to the system under test is fixed, the measured response has a set of mathematical operations applied to it. These mathematical operations effectively change the displayed response to the system just as if a different TDR step risetime had actually been applied. This allows you to select a risetime for TDR/TDT measurements that is close to the actual risetime used in your system. This risetime value applies to both TDR and TDT normalized channels. For more information on normalization, see Chapter 10, "Improving Time Domain Network Measurements".

Key Path **TDR/TDT Setup** *Normalize response . . . Risetime*

TDR/TDT

The *TDR/TDT* function is used to select between TDR and TDT for normalization. Both TDR and TDT channels can be normalized. This control selects which normalized trace is referred to for the following controls. Before TDT normalization can be done, you must select a TDT destination (*TDT 2 dest*).

Key Path **TDR/TDT Setup** *Normalize response . . . TDR/TDT*

TDR or TDT normalize

The TDR normalize function is available if the TDR mode is selected by using the previous menu otherwise the TDT normalize function is available. In either case, this function turns on or off the display of the normalized trace. The TDR and TDT normalization functions can be on at the same time.

Key Path **TDR/TDT Setup** *Normalize response . . . TDR normalize*

Normalize scaling . . .

The *Normalize scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR or TDT normalize is set to on.

Key Path **TDR/TDT Setup** *Normalize response . . . Normalize scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Horizontal*

Establish normalization & ref plane

The *Establish normalization & ref plane* function establishes the filter values used to normalize a channel and to set the reference plane for TDR and TDT measurements. This function must be performed separately for TDR and TDT modes. The normalization and reference plane must be re-established when power is lost or when the instrument is turned off. However, the values used for normalization and reference plane calculations can be stored to and re-loaded from disk. (See the *Disk Menu* chapter in the *Agilent 83480A, Agilent 54750 User's Guide* for more information.)

> The normalization filter values and reference plane are invalidate when the timebase scale, record length or channel bandwidth is changed. Also, the normalization process will not be able to remove small synchronous noise in the channels baseline if the timebase position is changed. For most measurements this error is very small.

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the *Reference* `ref plane` function is not available in the **Marker** menu.

The function steps you through the normalization and reference plane procedure for the selected measurement type. The procedure steps are displayed at the top of the screen. The items required for calibration are shown in Table 5-4.

Table 5-4

Establish normalization & ref plane Hardware Requirements

Measurement	Requirements
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

Key Path **TDR/TDT Setup** *Normalize response . . . Establish normalization & ref plane . . .*

TDR rate automatic . . . (250 kHz)

The ***TDR rate automatic . . . (250 kHz)*** function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** *Scale* is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The Preset TDR/TDT function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 5-5.

Table 5-5

Preset TDR/TDT Configuration

Menu	Menu Item	Set To
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 2 Setup	Display	on
	Scale	100 mV/div
	Offset	200.0 mV
	Bandwidth	12.4 GHz
	Attenuation units	ratio
	Attenuation	1.000 : 1

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

1 and 2 Stimulus Menus

This section describes the menus that are available when the stimulus is set to `1 and 2`.

TDT 1 dest

Pressing the ***TDT 1 dest*** softkey produces a pull-down menu used to select the channel used as the destination channel for channel 1 TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is potentially a valid TDT destination channel. The TDT destination may not be assigned to a channel already assigned as a TDT destination.

If no other valid TDT destination channels are available then "none" is the only choice. If a TDT destination other than none is selected then the preset TDR/TDT control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 1 dest*

TDT 2 dest

Pressing the ***TDT 2 dest*** softkey produces a pull-down menu used to select the channel used as the destination channel for channel 2 TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is potentially a valid TDT destination channel. The TDT destination may not be assigned to a channel already assigned as a TDT destination.

If no other valid TDT destination channels are available then "none" is the only choice. If a TDT destination other than none is selected then the preset TDR/TDT control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 2 dest*

Normalize 1 response . . .
Normalize 2 response . . .

When the Stimulus is 1 and 2, there are two menus, *Normalize 1 response* and *Normalize 2 response*, which are used to normalize the two independent TDR channels separately. The functions allow you to change the risetime of the normalized step, to select TDR and TDT normalization, to turn on or off the display of the normalized TDR or TDT trace, to change the scaling of the normalized trace, and to establish the normalization filter values and reference plane.

Risetime

The Risetime function allows you to change the normalized step's risetime from a minimum of

10 ps

or

$$min = 8 \text{ points} \times \frac{\text{time per division (s/div)} \times 10 \text{ divisions}}{\text{record length}}$$

which ever is greater, to a maximum of

$$max = 5 \times \text{time per division (s/div)}$$

While the TDR step's risetime applied to the system under test is fixed, the measured response has a set of mathematical operations applied to it. These mathematical operations effectively change the displayed response to the system just as if a different TDR step risetime had actually been applied. This allows you to select a risetime for TDR/TDT measurements that is close to the actual risetime used in your system. This risetime value applies to both TDR and TDT normalized channels. For more information on normalization, see Chapter 10, "Improving Time Domain Network Measurements".

Key Path **TDR/TDT Setup** *Normalize response . . . Risetime*

TDR/TDT

The *TDR/TDT* function is used to select between TDR and TDT for normalization. Both TDR and TDT channels can be normalized. This control selects which normalized trace is referred to for the following controls. Before TDT normalization can be done, you must select a TDT destination (*TDT 1 dest*).

Key Path **TDR/TDT Setup** *Normalize response . . . TDR/TDT*

TDR or TDT normalize

The TDR normalize function is available if the TDR mode is selected by using the previous menu otherwise the TDT normalize function is available. In either case, this function turns on or off the display of the normalized trace. The TDR and TDT normalization functions can be on at the same time.

Key Path **TDR/TDT Setup** *Normalize response . . . TDR normalize*

Normalize scaling . . .

The *Normalize scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR or TDT normalize is set to on.

Key Path **TDR/TDT Setup** *Normalize response . . . Normalize scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Horizontal*

Establish normalization & ref plane

The *Establish normalization & ref plane* function establishes the filter values used to normalize a channel and to set the reference plane for TDR and TDT measurements. This function must be performed separately for TDR and TDT modes. The normalization and reference plane must be re-established when power is lost or when the instrument is turned off. However, the values used for normalization and reference plane calculations can be stored to and re-loaded from disk. (See the *Disk Menu* chapter in the *Agilent 83480A, Agilent 54750 User's Guide* for more information.)

> The normalization filter values and reference plane are invalidate when the timebase scale, record length or channel bandwidth is changed. Also, the normalization process will not be able to remove small synchronous noise in the channels baseline if the timebase position is changed. For most measurements this error is very small..

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the *Reference* `ref plane` function is not available in the **Marker** menu.

The function steps you through the normalization and reference plane procedure for the selected measurement type. The procedure steps are displayed at the top of the screen. The items required for calibration are shown in Table 5-6.

Table 5-6

Establish normalization & ref plane Hardware Requirements

Measurement	Requirements
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

Key Path **TDR/TDT Setup** *Normalize response . . . Establish normalization & ref plane . . .*

TDR rate automatic . . . (250 kHz)

The *TDR rate automatic . . . (250 kHz)* function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** *Scale* is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The Preset TDR/TDT function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 5-7.

Table 5-7

Preset TDR/TDT Configuration

Menu	Menu Item	Set To
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup and	Display	on
Channel 2 Setup	Scale	100 mV/div
	Offset	200.0 mV
	Bandwidth	12.4 GHz
	Attenuation units	ratio
	Attenuation	1.000 : 1

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

Differential and Common Mode Stimulus Menus

This section describes the menus that are available when the stimulus is set to `differential` or `common mode`.

TDR/TDT

This TDR/TDT function allows you to select either TDR measurements or TDT measurements. The TDT measurement capability requires that an additional TDR or electrical plug-in module be installed in the mainframe.

Key Path **TDR/TDT Setup** *TDR/TDT*

TDR response 1

The *TDR response 1* function is used to enable or disable the display of the differential or common mode TDR response 1. The choices available are off, differential, or common mode.

Key Path **TDR/TDT Setup** *TDR response 1*

Response scaling . . .

The *Response scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR response 1 is set to differential or common mode.

Key Path **TDR/TDT Setup** *TDR response 1 Response scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *TDR response 1 . . .Response scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *TDR response 1 . . .Response scaling . . . Horizontal*

TDR response 2

The *TDR response 2* function is used to enable or disable the display of the differential or common mode TDT response 2. The choices available are off, differential, or common mode.

Key Path **TDR/TDT Setup** *TDR response 2*

Response scaling . . .

The *Response scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR response 2 is set to differential or common mode.

Key Path **TDR/TDT Setup** *TDR response 2 Response scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *TDR response 2 . . .Response scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *TDR response 2 . . .Response scaling . . . Horizontal*

TDT response 1

The *TDT response 1* function is used to enable or disable the display of the differential or common mode response 1. The choices available are off, differential, or common mode.

Key Path **TDR/TDT Setup** *TDT response 1*

Response scaling . . .

The *Response scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDT response 1 is set to differential or common mode.

Key Path **TDR/TDT Setup** *TDT response 1 Response scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *TDT response 1 . . .Response scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *TDT response 1 . . .Response scaling . . . Horizontal*

TDT response 2

The *TDT response 2* function is used to enable or disable the display of the differential or common mode response 2. The choices available are off, differential, or common mode.

Key Path **TDR/TDT Setup** *TDT response 2*

Response scaling . . .

The *Response scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDT response 2 is set to differential or common mode.

Key Path **TDR/TDT Setup** *TDT response 2 Response scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *TDT response 2 . . .Response scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *TDT response 2 . . .Response scaling . . . Horizontal*

Establish ref plane

The *Establish ref plane* function is used to set the reference plane for TDR and TDT measurements for differential or common mode stimulus. The function steps you through the calibration procedure for the selected measurement type. The steps are displayed at the top of the screen. The items required for calibration are shown in Table 5-8 on page 5-27.

Table 5-8

Establish ref plane Hardware Requirements

Measurement	**Requirements**
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

> The reference plane is invalidated when the timebase scale, record length or channel bandwidth is changed.

Before establishing a reference plane for common mode and differential TDR, the test setup must be deskewed. See Chapter 8, "Differential TDR Measurements" for information on how to deskew a test setup.

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the ***Reference*** `ref plane` function is not available in the **Marker** menu.

Key Path **TDR/TDT Setup** *Normalize response . . . Establish ref plane . . .*

TDR rate automatic . . . (250 kHz)

The ***TDR rate automatic . . . (250 kHz)*** function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** ***Scale*** is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The Preset TDR/TDT function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 5-9 and Table 5-10.

Table 5-9

Differential Stimulus Preset TDR/TDT Configuration

Menu	Menu Item	Set To
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup	Display	on
	Scale	100 mV/div
	Offset	200.0 mV
	Bandwidth	12.4 GHz
	Attenuation units	ratio
	Attenuation	1.000 : 1
Channel 2 Setup	Scale	100 mV/div
	Offset	-200 mV

Table 5-10

Common Mode Stimulus Preset TDR/TDT Configuration

Menu	Menu Item	Set To
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup	Display	on
	Scale	100 mV/div
	Offset	200.0 mV
	Bandwidth	12.4 GHz (for Stimulus on) 18.0 GHz (for Stimulus external)
	Attenuation units	ratio
	Attenuation	1.000 : 1
Channel 2 Setup	Scale	100 mV/div
	Offset	200.0 mV

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

External Stimulus Menus

This section describes the menus that are available when the stimulus is set to `external`.

TDT 1 dest

Pressing the ***TDT 1 dest*** softkey produces a pull-down menu used to select the channel used as the destination channel for TDT measurements. The choices available for this pull-down menu depend on the other TDR or electrical plug-in, if any, in the mainframe.

Any electrical channel is potentially a valid TDT destination channel. The TDT destination may not be assigned to a channel already assigned as a TDT destination. The TDT destination may not be set to the currently defined TDR destination channel.

If no other valid TDT destination channels are available then "none" is the only choice. If a TDT destination other than none is selected then the preset TDR/TDT control will turn on and preset the TDT destination channel.

Key Path **TDR/TDT Setup** *TDT 1 dest*

TDR 1 dest

Pressing the ***TDR 1 dest*** softkey produces a pull-down menu used to select the channel used as the destination channel for TDR measurements. Any electrical channel is a valid TDR destination channel. The TDR destination may not be set to the currently defined TDT destination.

Key Path **TDR/TDT Setup** *TDR 1 dest*

Normalize response . . .

The *Normalize response* function allows you to change the risetime of the normalized step, to select TDR and TDT normalization, to turn on or off the display of the normalized TDR or TDT trace, to change the scaling of the normalized trace, and to establish the normalization filter values and reference plane.

Risetime

The Risetime function allows you to change the normalized step's risetime from a minimum of

10 ps

or

$$min = 8 \text{ points} \times \frac{\text{time per division (s/div)} \times 10 \text{ divisions}}{\text{record length}}$$

which ever is greater, to a maximum of

$$max = 5 \times \text{time per division (s/div)}$$

While the TDR step's risetime applied to the system under test is fixed, the measured response has a set of mathematical operations applied to it that effectively displays the response to the system as if a different TDR step risetime had actually been applied. This allows you to select a risetime for TDR/TDT measurements that is close to the actual risetime used in your system. This risetime value applies to both TDR and TDT normalized channels. For more information on normalization, see Chapter 10, "Improving Time Domain Network Measurements".

Key Path **TDR/TDT Setup** *Normalize response . . . Risetime*

TDR/TDT

The *TDR/TDT* function is used to select between TDR and TDT for normalization. Both TDR and TDT channels can be normalized. This control selects which normalized trace is referred to for the following controls. Before TDT normalization can be done, you must select a TDT destination (*TDT 1 dest*).

Key Path **TDR/TDT Setup** *Normalize response . . . TDR/TDT*

TDR or TDT normalize

The TDR normalize function is available if the TDR mode is selected by using the previous menu otherwise the TDT normalize function is available. In either case, this function turns on or off the display of the normalized trace. The TDR and TDT normalization functions can be on at the same time.

Key Path **TDR/TDT Setup** *Normalize response . . . TDR normalize*

Normalize scaling . . .

The *Normalize scaling* function is used when vertical and horizontal scaling of the normalized response is required that is independent from that of the source channel. This function only appears when TDR or TDT normalize is set to on.

Key Path **TDR/TDT Setup** *Normalize response . . . Normalize scaling . . .*

Vertical There are two choices for vertical mode: *track source* and *manual*. The track source mode sets the control of the vertical scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Offset* menus appear allowing you to independently change the vertical scale and offset of the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Vertical*

Horizontal There are two choices for horizontal mode: *track source* and *manual*. The track source mode sets the control of the horizontal scaling for the normalized trace to that of the source channel. When manual mode is selected, the *Scale* and *Position* menus appear allowing you to independently change the horizontal scale and position for the normalized trace.

Key Path **TDR/TDT Setup** *Normalize response . . .Normalize scaling . . . Horizontal*

Establish normalization & ref plane

The *Establish normalization & ref plane* function establishes the filter values used to normalize a channel and to set the reference plane for TDR and TDT measurements. This function must be performed separately for TDR and TDT modes. The normalization and reference plane must be re-established when power is lost or when the instrument is turned off. However, the values used for normalization and reference plane calculations can be stored to and re-loaded from disk. (See the ***Disk Menu*** chapter in the *Agilent 83480A, Agilent 54750 User's Guide* for more information.)

> The normalization filter values and reference plane are invalidate when the timebase scale, record length or channel bandwidth is changed. Also, the normalization process will not be able to fully remove step non-flatness if the timebase position is changed since the filter values have been established.

The reference plane must be established before ohm, % reflect or gain units are selectable for the channel. Also, the ***Reference*** `ref plane` function is not available in the **Marker** menu.

The function steps you through the normalization and reference plane procedure for the selected measurement type. The procedure steps are displayed at the top of the screen. The items required for calibration are shown in Table 5-11.

Table 5-11

Establish normalization & ref plane Hardware Requirements

Measurement	**Requirements**
TDR	50 ohm 3.5 mm SMA terminator
	3.5 mm SMA short
TDT	1 or 2 each 3.5 mm SMA cables
	3.5 mm barrel connector

Key Path **TDR/TDT Setup** *Normalize response . . . Establish normalization & ref plane . . .*

TDR rate automatic . . . (250 kHz)

The *TDR rate automatic . . . (250 kHz)* function allows you to manually or automatically select the repetition rate of the TDR step. The range of values for manual mode selection are from 50 Hz to 250 kHz repetition rate using a 1-2-5 sequence. When this function is set to automatic, the TDR step repetition rate varies automatically as the **Time base** *Scale* is changed to keep multiple steps off screen. As the TDR rate decreases, TDR measurements can be made on longer transmission lines.

Key Path **TDR/TDT Setup** *TDR rate* `automatic`

Key Path **TDR/TDT Setup** *TDR rate* `manual`

Preset TDR/TDT

The Preset TDR/TDT function prepares the oscilloscope for making TDR/TDT measurements by automatically setting several menu fields. The TDR preset feature appears in the **TDR/TDT Setup** menu once a stimulus has been selected. The menus that are affect by this feature are shown in Table 5-12.

Table 5-12

Preset TDR/TDT Configuration

Menu	Menu Item	Set To
Acquisition	Averaging	on
	Best	Flatness
Time Base	Scale	500.0 ps/div
	Position	Set to a value which places the incident edge on screen.
Channel 1 Setup	Display	on
	Scale	100 mV/div
	Offset	0.0 mV
	Bandwidth	18.0 GHz
	Attenuation units	ratio
	Attenuation	1.000 : 1

Key Path **TDR/TDT Setup** *Preset TDR/TDT*

6

Measure and Other TDR Specific Menus

Measure and Other TDR Specific Menus

What you'll find in this chapter

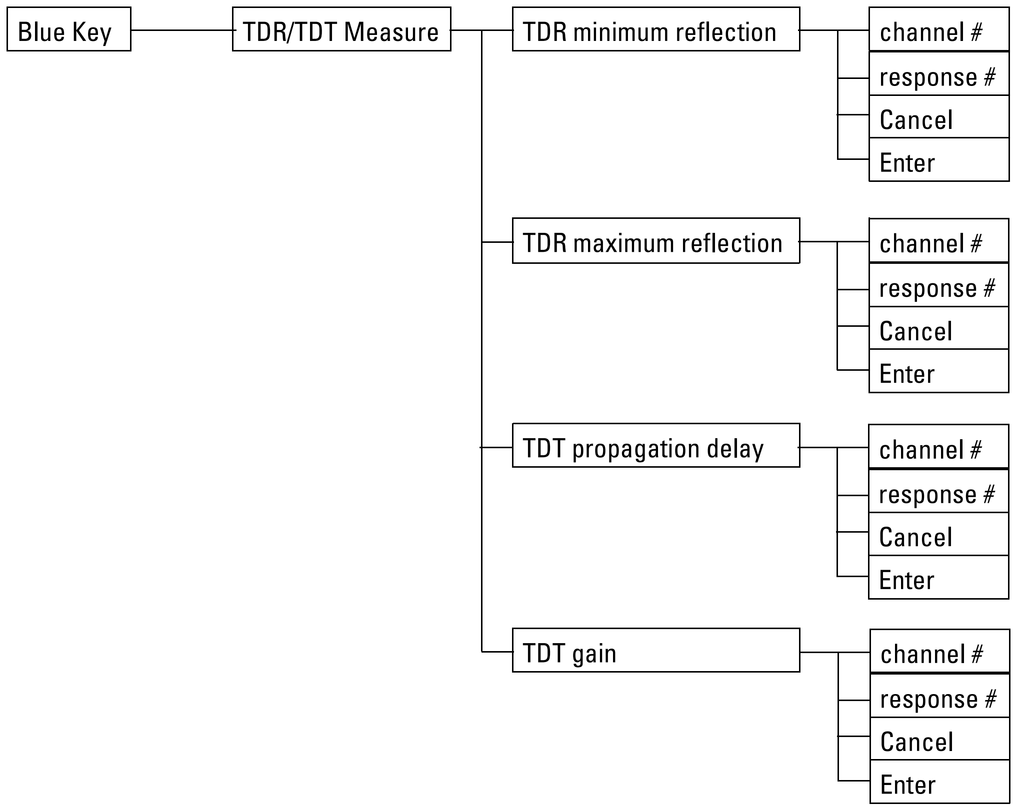
This chapter describes the Measure menu and the mainframe menu changes that occur when a TDR plug-in module is in the mainframe.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

There are several mainframe menus which change when a TDR plug-in module is inserted into the mainframe menus. This chapter will cover only the changes that occur to the mainframe menus and will not discuss the menu functions which are already documented in the *Agilent 83480A, 54750A User's Guide*.

Figure 6-1



TDR Setup menu.

TDR/TDT Measure Menu

To display the Measure menu, press the **blue key** immediately followed by the **TDR/TDT Measure** key on the TDR plug-in module. There are four automated measurements which may be selected: *TDR minimum reflection*, *TDR maximum reflection*, *TDT propagation delay*, and *TDT gain*.

TDR Minimum Reflection

Pressing the *TDR minimum reflection* softkey display the automatically calculated minimum percent reflection value at the bottom of the display under the waveform graticule.

> The TDR plug-in module must be calibrated and a reference plane established before this measurement can be selected.

The calculation of the value is dependant on the type of response and stimulus that are selected.

For differential response to differential stimulus and common mode response to common mode stimulus, the following formula is used:

$$\text{Minimum reflection} = 100\left[\frac{V_{min} - (V_{1ref50\Omega} + V_{2ref50\Omega})}{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}\right]$$

where:

V_{min} = the minimum voltage value along the waveform
$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load
$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short
$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load
$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For differential response to common mode stimulus and common mode response to differential stimulus, the following formula is used.

$$\text{Minimum reflection} = 100\left[\frac{\frac{V_{min} - (V_{1ref50\Omega} + V_{2ref50\Omega})}{2}}{\frac{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}{2}}\right]$$

where:

V_{min} = the minimum voltage value along the waveform

$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load

$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short

$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load

$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For all other stimulus, the following formula is used.

$$\text{Minimum reflection} = 100\left(\frac{V_{min} - V_{ref50\Omega}}{V_{ref50\Omega} - V_{ref0\Omega}}\right)$$

where:

V_{min} = the minimum voltage value along the waveform

$V_{ref50\Omega}$ = the reference plane voltage into a 50 ohm load

$V_{ref0\Omega}$ = the reference plane voltage into a short

Key Path **blue key TDR/TDT Measure** *TDR minimum reflection*

TDR Maximum Reflection

Pressing the *TDR maximum reflection* softkey display the automatically calculated maximum percent reflection value at the bottom of the display under the waveform graticule.

> The TDR plug-in module must be calibrated and a reference plane established before this measurement can be selected.

The calculated value is dependant on the type of response and stimulus that are selected.

For differential response to differential stimulus and common mode response to common mode stimulus, the following formula is used:

$$\text{Maximum reflection} = 100\left[\frac{V_{max} - (V_{1ref50\Omega} + V_{2ref50\Omega})}{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}\right]$$

where:

V_{max} = the maximum voltage value along the waveform
$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load
$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short
$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load
$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For differential response to common mode stimulus and common mode response to differential stimulus, the following formula is used.

$$\text{Maximum reflection} = 100\left[\frac{\dfrac{V_{max} - (V_{1ref50\Omega} + V_{2ref50\Omega})}{2}}{\dfrac{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}{2}}\right]$$

where:

V_{max} = the maximum voltage value along the waveform
$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load
$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short
$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load
$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For all other stimulus, the following formula is used.

$$\text{Maximum reflection} = 100\left(\frac{V_{max} - V_{ref50\Omega}}{V_{ref50\Omega} - V_{ref0\Omega}}\right)$$

where:

V_{max} = the maximum voltage value along the waveform
$V_{ref50\Omega}$ = the reference plane voltage into a 50 ohm load
$V_{ref0\Omega}$ = the reference plane voltage into a short

Key Path **blue key TDR/TDT Measure** *TDR maximum reflection*

TDT Propagation Delay

Pressing the *TDT propagation delay* softkey display the automatically calculated propagation delay value at the bottom of the display under the waveform graticule.

> The TDR plug-in module must be calibrated and a reference plane established before this measurement can be selected.

The value is calculated using the following formula.

$$\text{TDT propagation delay} = T_{edge} - T_{ref}$$

where:

T_{edge} = the time value of the reflected edge
T_{ref} = the time value of the reference plane

Key Path **blue key TDR/TDT Measure** *TDT propagation delay*

TDT Gain

Pressing the *TDT gain* softkey display the automatically calculated value at the bottom of the display under the waveform graticule.

> The TDR plug-in module must be calibrated and a reference plane established before this measurement can be selected.

The calculated value is dependant on the type of response and stimulus that are selected.

For differential response to differential stimulus and common mode response to common mode stimulus, the following formula is used:

$$\text{TDT gain} = 100\left[\frac{V_{max} - V_{min}}{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}\right]$$

where:

V_{max} = the maximum voltage value along the waveform
V_{min} = the minimum voltage value along the waveform
$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load
$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short
$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load
$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For differential response to common mode stimulus and common mode response to differential stimulus, the following formula is used.

$$\text{TDT gain} = 100\left[\frac{V_{max} - V_{min}}{\frac{(V_{1ref50\Omega} - V_{1ref0\Omega}) + (V_{2ref50\Omega} - V_{2ref0\Omega})}{2}}\right]$$

where:

V_{max} = the maximum voltage value along the waveform
V_{min} = the minimum voltage value along the waveform
$V_{1ref50\Omega}$ = the channel 1 reference plane voltage into a 50 ohm load
$V_{1ref0\Omega}$ = the channel 1 reference plane voltage into a short
$V_{2ref50\Omega}$ = the channel 2 reference plane voltage into a 50 ohm load
$V_{2ref0\Omega}$ = the channel 2 reference plane voltage into a short

For all other stimulus, the following formula is used.

$$\text{TDT gain} = 100\left(\frac{V_{max} - V_{min}}{V_{ref50\Omega} - V_{ref0\Omega}}\right)$$

where:

V_{max} = the maximum voltage value along the waveform
V_{min} = the minimum voltage value along the waveform
$V_{ref50\Omega}$ = the reference plane voltage into a 50 ohm load
$V_{ref0\Omega}$ = the reference plane voltage into a short

Key Path **blue key TDR/TDT Measure** *TDT gain*

Marker Menu

To display the Marker menu, press the **SETUP Marker** key. There is a marker mode, the *TDR/TDT* marker mode, that is affected by the presence of a TDR plug-in module in the mainframe. Selecting the *TDR/TDT* mode produces the *+ Source*, *+ Position*, *X Source*, and *X Position* just like other plug-in modules. However, when a TDR plug-in module is present and one of the TDR channels is selected as *+* or *X source*, the *Reference* menu has an additional choice called `ref plane`.

Reference

Pressing the *Reference* softkey allows selection of either `trigger` or `ref plane`. When `trigger` is selected, the marker positions are displayed with respect to the trigger point. Choosing `ref plane` displays the marker positions with respect to the reference plane. The `ref plane` selection requires establishing a reference plane before the markers will display information.

Key Path **Marker** *Reference*

Marker units . . .

Pressing the *Marker units* softkey produces two menus: a *Horiz units* menu and a *Vertical units* menu. The *Horiz units* menu is used to set the X marker units located at the bottom of the display. The unit choices are `second`, `meter`, and `feet`.

When either meter or feet is selected, two additional menus are displayed: *Propagation* and *Dielectric*. The Propagation softkey is used to select the propagation constant's unit of measure: dielectric constant, velocity in meters per second, or velocity in feet per second.

When one of the velocity propagation constants is selected, the *Dielectric* menu changes to *Velocity*. You should set the propagation constant to the value of the device under test's propagation constant. This constant is used for distance calculations.

The *Vertical units* menu is used to set the Y marker units located at the bottom of the display. The unit choices are `Volt`, `Ohm`, and `% reflect`.

Key Path **Marker** *Reference* `ref plane` *Marker units . . .*

Response Menu Items

When a TDR plug-in module is present in the mainframe, `response` menu choices will appear in many of the mainframe menus. The following is a list of the mainframe menus which will contain `response` menu choices.

- **Disk** *store waveform From waveform*
- **Display** *Graph*
- **Histogram** *Window*
- **Limit Test** *Fail Action*
- **Marker** *+ Source*
- **Marker** *X Source*
- **Mask** *Fail Action*
- **Mask** *Scale Automask*
- **Math** *Define function . . . Operand 1*
- **Math** *Define function . . . Operand 2*
- **Measure** *Source*
- **Waveform** *From waveform*

7

Single-ended TDR Measurements

Single-ended TDR Measurements

What you'll find in this chapter

This chapter describes how to make singe-ended TDR measurements and describes the reason for the processes required to make these measurements.

CAUTION The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

Single-ended TDR Features

The Agilent 54753A and Agilent 54754A TDR plug-in modules are both capable of performing singe-ended TDR measurements. These measurements include characterizing microstrip lines, PC board traces, and coaxial cables. Because TDR measurements are complex, the TDR plug-in modules have several features which make measurements easier.

The Preset TDR/TDT Feature

The Preset TDR/TDT feature prepares the oscilloscope for making Time Domain Reflectometry (TDR) and Time Domain Transmission (TDT) measurements by automatically setting several menu fields. The Preset TDR/TDT feature appears in the TDR/TDT Setup menu once a stimulus has been selected.

TDR Establish Normalization and Reference Plane Feature

This feature performs the following:

- Establishes the Reference Plane.
- Measures the negative going step reflected from a short.
- Builds a normalization filter.
- Measures the response to a 50 ohm terminator.

The Reference Plane is defined as the point in time that coincides with the 50% point of the negative going step that is reflected from a short connected to a 50 ohm line. Once the Reference Plane is established, cursor measurements can be made with respect to this point in time rather than to the trigger point. Typically, the short is connected at the end of a cable which will be connected to the device under test. This effectively establishes this end of the cable as the Reference Plane.

The next stage in the Establish Normalization and Reference Plane process involves measuring the negative going step reflected from the short at the end of the cable. This allows the oscilloscope to base the percent reflection and ohms measurements on the actual measured step height rather than the nominal step height of 200 mV.

Also, from this information, the oscilloscope builds a normalization filter which can be applied to any reflected signal. When applied to the short, the filter produces a step which has no preshoot or overshoot and has an impulse response which is approximately Gaussian. The risetime of this filtered step can be selected when making TDR measurements of systems using a range of risetimes. This filter removes any losses or discontinuities from the TDR plug-in to the shorted end of the cable. Also, it allows the TDR response to be measured as though it had been stimulated by a step with no preshoot or overshoot rather than the actual step.

The final stage in Establishing Normalization is measuring the response of the cable when a 50 ohm terminator is connected to the end of the cable in place of the short. This response will be subtracted from all TDR measurements as long as the Time base position has not been changed since the reference plane was established. The normalization filter is applied to the resultant waveform. This process removes the incident step from the normalized waveform and any small synchronous noise that may be present.

TDT Establish Normalization and Reference Plane Feature

This feature performs the following:

- Establishes the Reference Plane.
- Measures the step transmitted to the TDT destination channel.
- Builds a normalization filter.

The Reference Plane is defined as the point in time that coincides with the 50% point of the step that is transmitted when the cables used to connect to a device under test (DUT) are connected together. Once the Reference Plane is established, cursor measurements can be made in terms of propagation delay rather than referenced to the trigger point.

The next stage in establishing the TDT Normalization process involves measuring the step transmitted when the cables used to connect to the DUT are connected together. As long as the transmitted step is allowed to settle to its final value, this step height is equal to the incident step height. The sweep speed must be slow enough to allow any slow tails caused by cable losses to settle. This allows the oscilloscope to base its calculations of gain on the actual measured height of the step instead of the nominal step height of 200 mV.

Also, from this information the oscilloscope builds a normalization filter which can be applied to any transmitted signal. When applied to the step transmitted through the cables used for TDT measurements, this filter removes any losses or discontinuities caused by the cables. It also allows the TDT response of a DUT to be measured as if stimulated by a perfect step rather than by the actual step of the oscilloscope. The risetime of the perfect step is selectable allowing TDT measurements of systems to be made at several different risetime values.

Bandwidth Limit

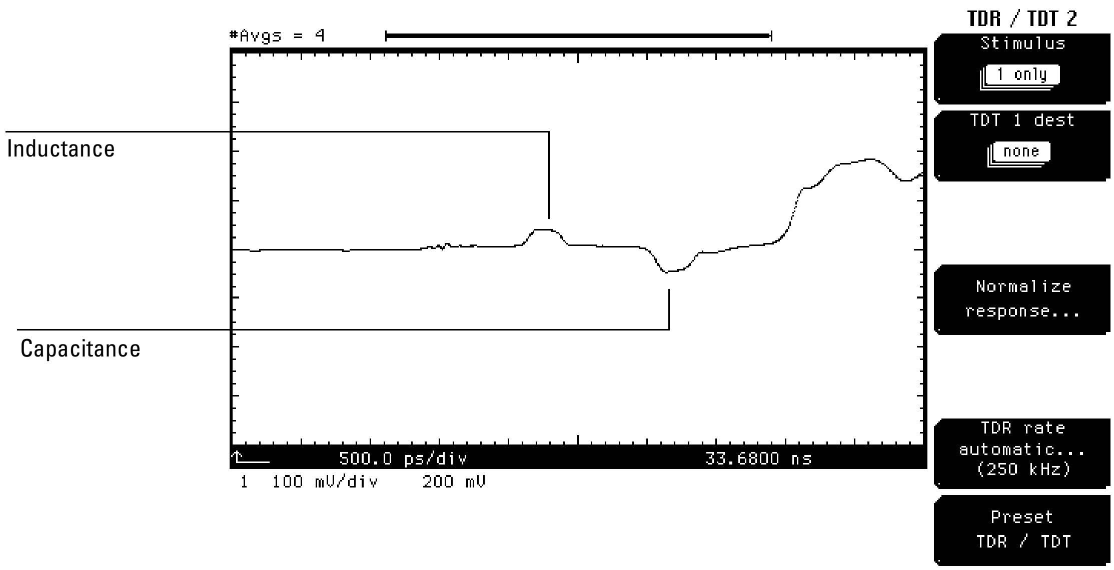
This feature, which is located under waveform math, allows any waveform on screen to be filtered by a digital low pass filter. This filter is a 4th order Bessel-Thompson filter. It has no pre-shoot and very little overshoot. The inherent risetime of the TDR plug-in modules is 35 pS. For many real world systems, this risetime is much too fast.

Often, it is necessary to test the response of a DUT using a step with a slower risetime. One way of doing this is to use a TDR normalization filter. This is the best way because it removes cable losses and discontinuities from the measured values. It does, however, require that a normalization calibration be performed at the reference plane. In cases where doing a normalization calibration is difficult or where the highest degree of accuracy is not needed, the Bandwidth Limit filter can be used to simulate the DUT with a slower risetime step, providing good measurement results. In fact, if good quality cables and connectors are used to connect to the DUT, this method can produce very similar results to normalization, especially for slower risetimes.

Excess L/C

The most common discontinuities seen on an TDR waveform are due to series inductances or shunt capacitances. Some causes of series inductances are wire bonds or traces that are too narrow. Some causes of shunt capacitance are wire bond pads or traces that are too wide. A series inductance is seen as a positive bump while a shunt capacitance is seen as a negative bump in the oscilloscope waveform (Figure 7-1).

Figure 7-1



Series Inductance and Shunt Capacitance

A feature called Excess L/C can be used to calculate the excess inductance (L) or excess capacitance (C) between the x and + markers. The Excess L/C feature is enabled by setting the **Marker** *Mode* menu to TDR/TDT and the *Reference* menu to ref plane. If a reference plane has been established by selecting the *Establish normalization & ref plane* in the **TDR/TDT Setup** *Normalize response...* menu, then a readout appears at the bottom of the screen called "Excess L/C." The excess L or C in this case is defined as the equivalent amount of series L or shunt C that would cause a discontinuity with equal area to the discontinuity between the x and + markers.

In cases where a discontinuity is due to a lumped L or C, the Excess L/C can be used to directly measure the L or C value. This is done by placing one marker just to the left of the discontinuity and the other marker just to the right of the disconinuity. The oscilloscope will calculate the excess L/C by integrating the % reflection between the markers.

When measuring discontinuities on lines whose impedance is not 50 ohms, the Excess L/C measurement is still valid as long as the 50 ohm measurement system is connected the non-50 ohm line without using matching resistors.

It is also possible measure the Excess L/C of shunt inductors and series capacitors using TDT measurements. A TDT measurement of a 50 ohm system with a shunt inductance produces a negative bump in the transmitted response while a series capacitance produces a positive bump in the transmitted response.

Alternate Channel Scales

Many times when making TDR measurements, you may want to view a TDR waveform in units of % reflection or ohms as the vertical scale. This can be done using the *Alternate Scale . . .* control in the **SETUP Channel** menu. You must establish normalization and reference plane values before you can select either of these two scales.

When making TDT measurements, channels may be viewed in units of gain, volts, watts, amperes, and unknown.

> The reference plane calibrations as well as normalization calibrations are volatile and are lost when power is cycled.

Establishing the Reference Plane and Normalizing

Establishing a reference plane allows you to effectively change the launch point of the TDR step from the TDR plug-in module's connector to the input of the device under test (DUT). Typically, a cable is connected between a DUT and the TDR plug-in module. Establishing a reference plane and normalizing removes any effects caused by the cable.

Normalization produces a TDR step which has no preshoot or overshoot and has an impulse response that is approximately Gaussian. Establishing normalization and reference plane increases the accuracy of TDR and TDT measurements.

Normalization requires the TDR step to be on screen and not clipped.

To perform the tasks in this section, you need the following:

- 1 good quality SMA cable one meter in length, such as the Agilent 8120-4948 cable.
- 1 SMA short found on the Agilent 54754A plug-in module.
- 1 SMA 50 ohm load found on the Agilent 54754A plug-in module.
- 1 Agilent 54754A or Agilent 54753A TDR Module.

Performing TDR Normalization

The purpose of this section is to show the process used to normalize a coaxial cable for TDR measurements. The following procedure shows how to perform TDR normalization.

1 Connect a 1 m SMA coaxial cable to channel 1 of the TDR plug-in module.

2 Press the **STORAGE Setup** menu key above the display.

3 Press the *Default setup* softkey.

4 Press **TDR/TDT Setup** on the TDR plug-in module.

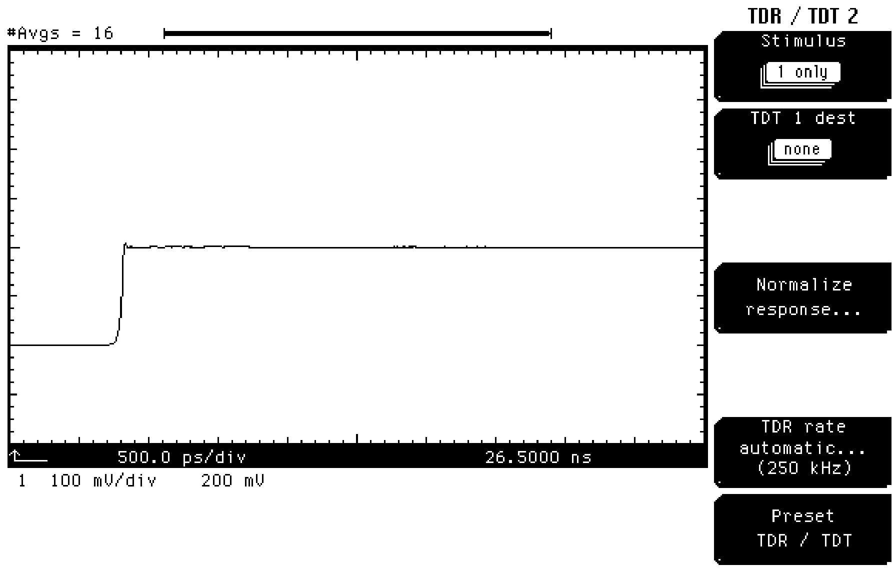
5 Press the *Stimulus* softkey and select `1 only` (`on` for the Agilent 54753A).

6 Press the *Enter* softkey.

7 Press the *Preset TDR/TDT* softkey.

These steps set the oscilloscope to a known condition and activates the TDR step on channel 1. You should see a display similar to the one shown in Figure 7-2.

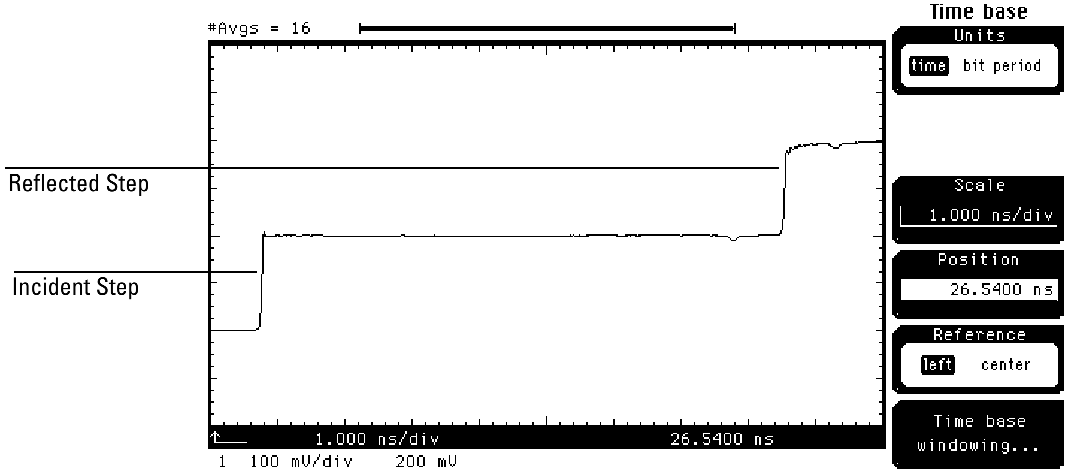
Figure 7-2


#Avgs = 16
TDR / TDT 2
Stimulus
1 only
TDT 1 dest
none
Normalize
response...
TDR rate
automatic...
(250 kHz)
Preset
TDR / TDT
500.0 ps/div
26.5000 ns
1 100 mV/div 200 mV

1. Press the **SETUP Time base** key located below the display.
2. Change the *Scale* until you see two positive going edges on screen (Figure 7-3).

   The left-most edge is the incident step and starts at 0 mV and goes to 200 mV. The right-most edge is the reflected step that has traveled from the TDR step generator to the end of the cable and back to the TDR sampler. This step starts at 200 mV and goes to 400 mV.

Figure 7-3

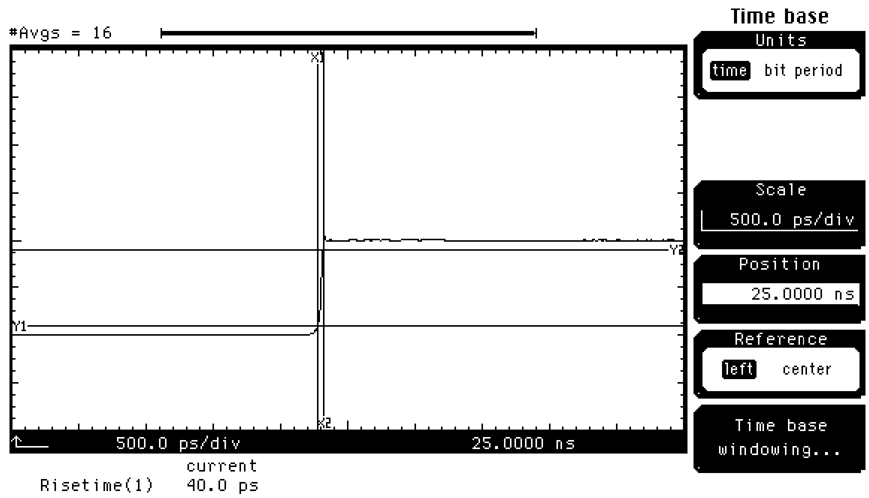


1. Change the *Scale* and *Position* to approximately center the incident step in the middle of the display and to move the reflected step off screen.
2. Press the **blue** key followed by the **7** key to turn the automated risetime measurement on and select `channel 1`.

3 Press the *Enter* softkey.

You should see a display similar to the one in Figure 7-4. Note that the value of Risetime is 40 ps.

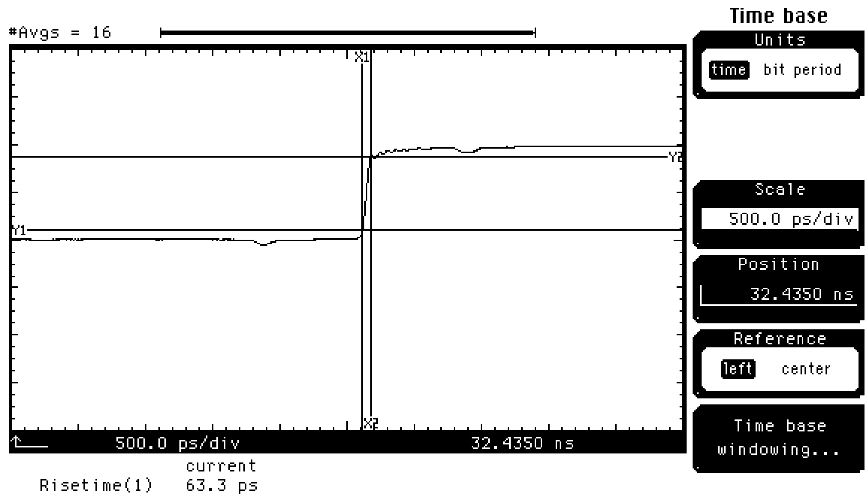
Figure 7-4



1 Change the *Position* until the reflected edge is displayed at the approximate center of the display.

You should see a display similar to the one shown in Figure 7-5, however, the risetime will depend on the quality of cable being used.

Figure 7-5

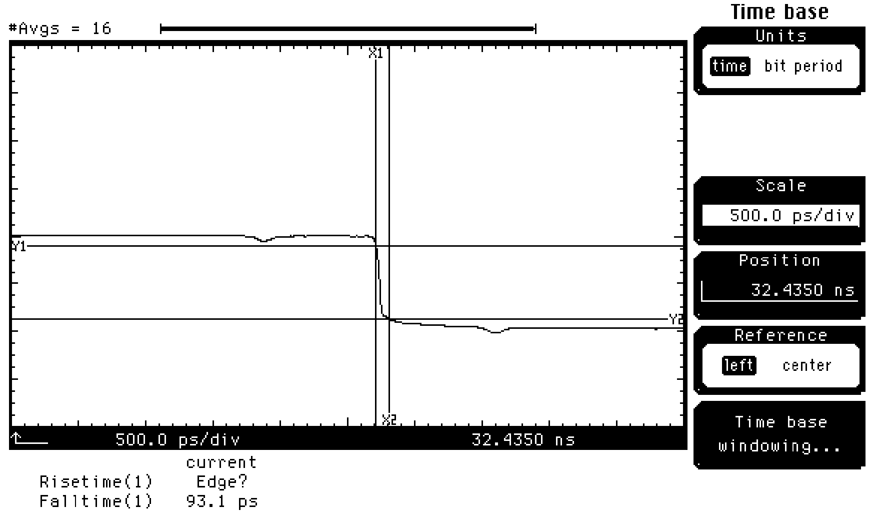


Note that the risetime of the reflected step is greater than the 40 ps of the incident step. This difference is due to the losses in the cable and connectors.

1 Press the **blue** key followed by the **8** key to turn on the automated Falltime measurement and select `channel 1`.
2 Press the *Enter* softkey.
3 Connect an SMA short to the end of the cable.
4 Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.

You should see a display similar to the one in Figure 7-6.

Figure 7-6

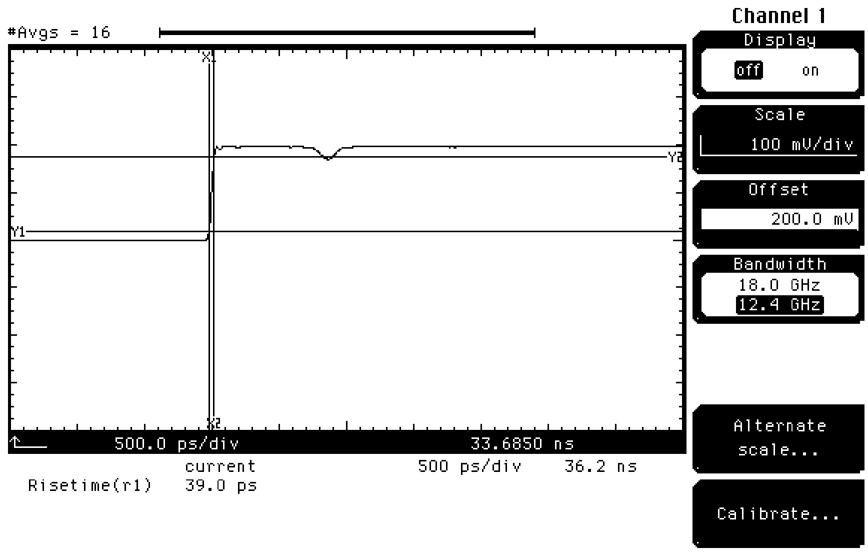


The falltime of the reflected step is also greater than the risetime of the incident step. The next set of steps will establish normalization and the reference plane.

1. Change the *Position* until the negative edge is at the third graticule from the left side of the display.
2. Press the **blue** key followed by the **Clr** key.
3. Press the **TDR/TDT Setup** key.
4. Press the *Normalize response . . .* softkey.
5. Press the *Establish normalization & ref plane* softkey.
6. Press the *Continue* softkey.
7. Replace the SMA short with a SMA 50 ohm load.
8. Press the *Continue* softkey.
9. Press the *TDR normalize* softkey to turn on the normalized trace.
10. Set the *Risetime* to 39 ps.
11. Remove the 50 ohm load from the end of the cable.
12. Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.
13. Press the **SETUP Channel 1/3** key.
14. Press the *Display* softkey to turn off the channel 1 display.
15. Press the **blue** key followed by the **7** key to turn on the automated risetime measurement and select `response 1`.

16 Press the *Enter* softkey.

Figure 7-7



The risetime of the normalized step is now approximately equal to the risetime of the incident step.

1 Press the **blue** key followed by the **8** key to turn on the automated measurement and select response 1.

2 Press the *Enter* softkey.

3 Connect an SMA short to the end of the cable.

4 Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.

The falltime is now approximately equal to the risetime of the incident step. Therefore, the normalization has removed cable loss effects by boosting the higher frequencies.

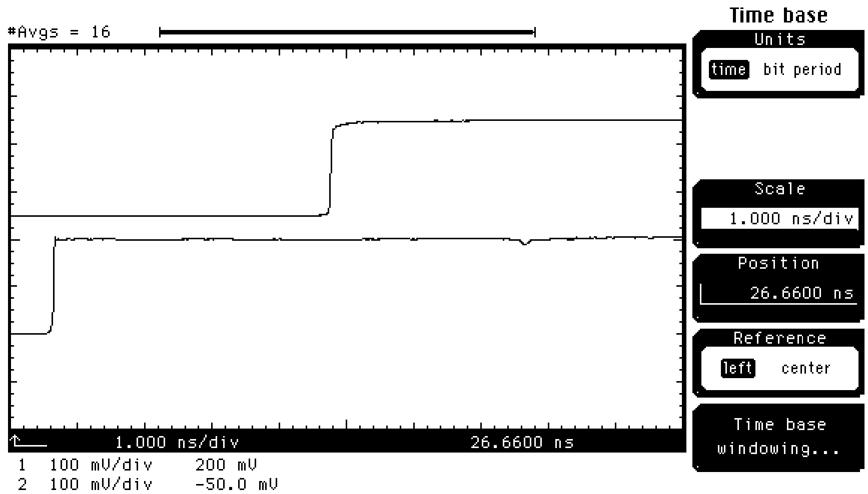
Performing TDT Normalization

The purpose of this section is to show the process used to normalize a coaxial cable for TDT measurements. The following procedure shows how to perform TDT normalization.

1. Connect a 1 m SMA coaxial cable from channel 1 to channel 2 of the TDR plug-in module.
2. Press the **STORAGE Setup** menu key located above the display.
3. Press the *Default setup* softkey.
4. Press **TDR/TDT Setup** on the TDR plug-in module.
5. Press the Stimulus softkey and select `1 only` (`on` for the Agilent 54753A) in.
6. Press the *Enter* softkey.
7. Press the *TDT 1 dest* softkey and select channel 2. This selects the destination channel for the TDT measurements.
8. Press the *Enter* softkey.
9. Press the *Preset TDR/TDT* softkey.
10. Press the **SETUP Channel 2/4** key.
11. Change the *Offset* to 50 mV/div.
12. Press the **SETUP Time base** key located below the display.

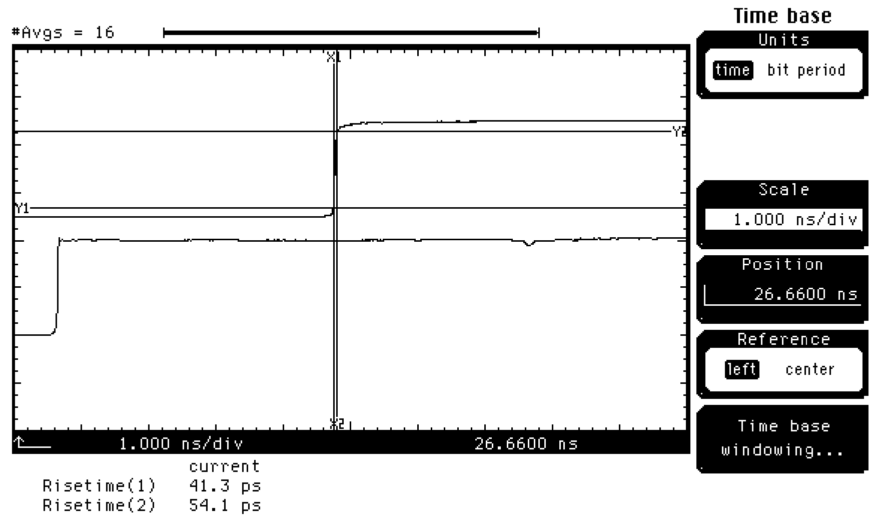
13 Change the *Scale* until you see two positive going edges on screen (Figure 7-8).

Figure 7-8



1. Press the **blue** key followed by the **7** key to turn on the automated risetime measurement.
2. Select channel 1 to turn on the automated risetime measurement for channel 1.
3. Press the *Enter* softkey.
4. Press the **blue** key followed by the **7** key.
5. Select `channel 2` to turn on the automated risetime measurement for channel 2.
6. Press the *Enter* softkey (Figure 7-9).

Figure 7-9

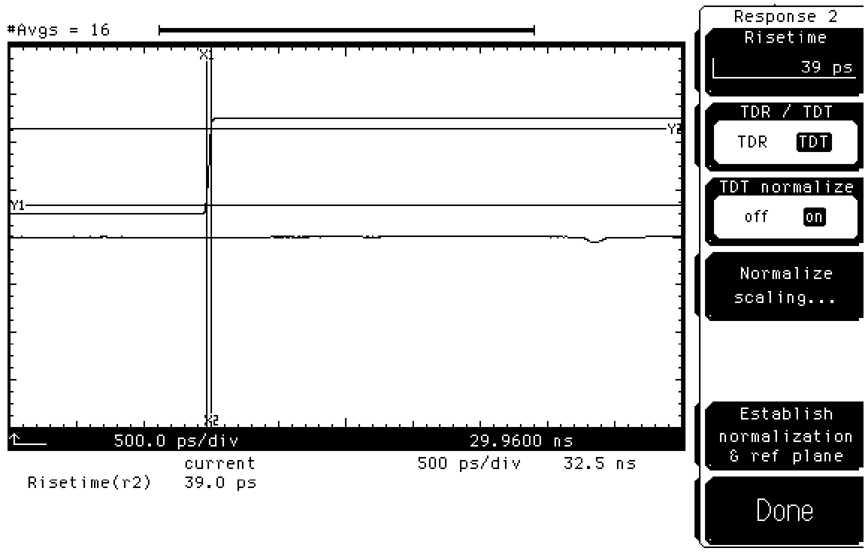


The risetime for channel 1 (incident step) is approximately 40 ps while the risetime for channel 2 (received step) is greater than 40 ps. This is due to cable and connector losses. We will now perform a TDT normalization.

1 Change the *Scale* to 500.0 ps/div.
2 Change the *Position* until the positive step on channel 2 is positioned at the 3rd graticule from the left side of the display.
3 Press the **TDR/TDT Setup** key.
4 Press the *Normalize response . . .* softkey.
5 Press the *TDR/TDT* softkey to select TDT.
6 Press the *Establish normalization & ref plane* softkey.
7 Press the *Continue* softkey.
8 Press the *TDT normalize* softkey to select on.
9 Press the **SETUP Channel 2/4** key.
10 Press the *Display* softkey to turn off channel 2 display.
11 Press the **blue** key followed by the **Clr** key.
12 Press the **blue** key followed by the **7** key and select response 2.
13 Press the *Enter* softkey.
14 Press the **TDR/TDT Setup** key.
15 Press the *Normalize response . . .* softkey.

16 Set the *Risetime* to 39 ps.

Figure 7-10



The risetime of the normalized TDT step is approximately the same as the risetime of the incident step. This shows that the effects due to cable and connector losses are removed.

Measuring Transmission Line Impedance

This section shows how to measure transmission line impedance. To perform the tasks in this section, you need the following:

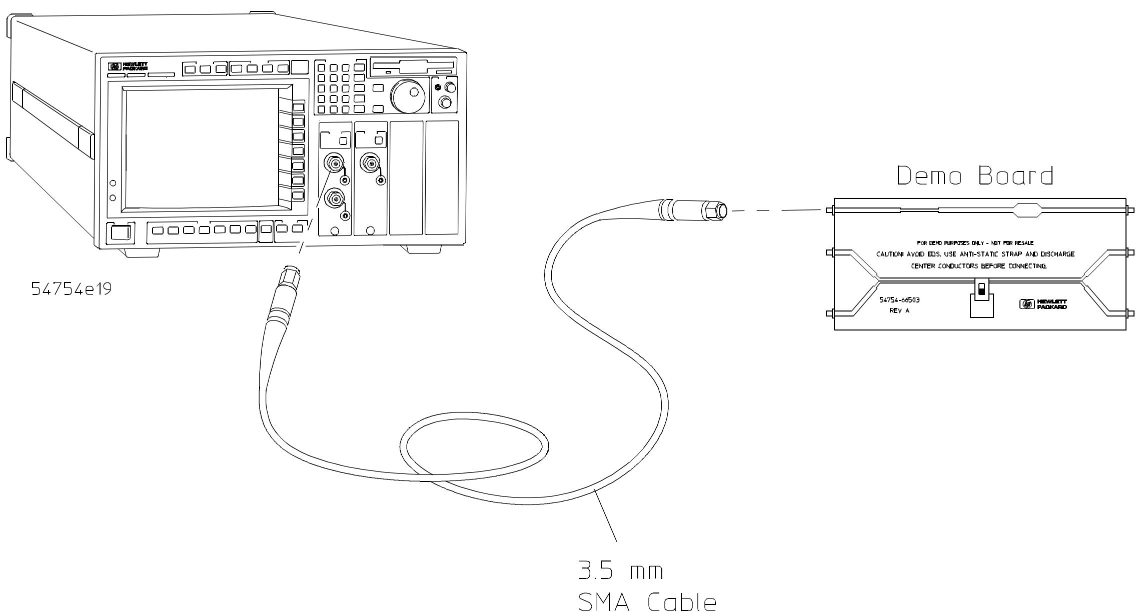
- 1 good quality SMA cables one meter in length, such as the Agilent 8120-4948 cable.
- 1 demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short supplied with the TDR plug-in.
- 1 SMA 50 ohm load supplied with the TDR plug-in.
- 1 Agilent 54754A or Agilent 54753A TDR Module.

The following procedure shows how to perform an impedance measurement.

1 Connect a 1 m SMA cable to channel 1 of the TDR plug-in module.

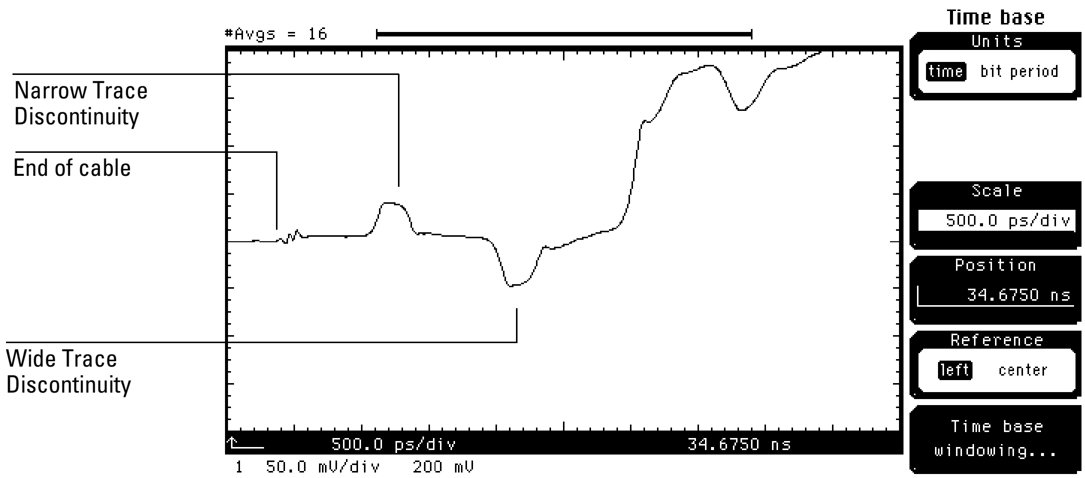
2 Connect the other end of the cable to the demo board's single transmission line connector that is closest to the narrow trace (Figure 7-11).

Figure 7-11



1. Press the **STORAGE Setup** menu key above the display.
2. Press the *Default setup* softkey.
3. Press **TDR/TDT Setup** on the TDR plug-in module.
4. Press the *Stimulus* softkey and select `1 only` (`on` for the Agilent 54753A).
5. Press the *Enter* softkey.
6. Press the *Preset TDR/TDT* softkey.
7. Press the **SETUP Channel 1/3** key.
8. Change the *Scale* to 50.0 mV/div.
9. Press the **Time base** key.
10. Change the *Position* until you see a display similar to Figure 7-12.

Figure 7-12



The narrow trace discontinuity is more inductive than the nominal 50 ohm transmission line while the wide trace discontinuity is more capacitive than the nominal 50 ohm line. The end of the cable is the TDR step launch point into the transmission line. If the cable was not good quality cable and had major discontinuities of its own, it would be difficult to find the discontinuities of the transmission line.

We will now measure the impedance of the narrow trace using the measured voltage along the discontinuity (*vd1*) of the transmission line and the following equation:

$$Z = 50\Omega \times \frac{1+p}{1-p}$$

where:

$$p = \frac{vd1 - 200\ \text{mV}}{200\ \text{mV}}$$

The 50 ohms is the impedance of the transmission line up to the narrow trace and the 200 mV is the nominal height of the TDR step.

We will use the markers to measure the voltage as follows.

1 Press the **SETUP Channel 1/3** key.

2 Change the *Scale* to 100.0 mV/div.

> Before making any marker measurements, the on screen waveform must not be clipped. Therefore, you must always adjust the channel scale until the waveform is not clipped.

3 Press the **SETUP Marker** key.

4 Press the *Mode* softkey and select **TDR/TDT** from the list.

5 Press the *Enter* softkey.

6 Press the *Reference* softkey to select `ref plane`.

7 Press the *Marker units . . .* softkey.

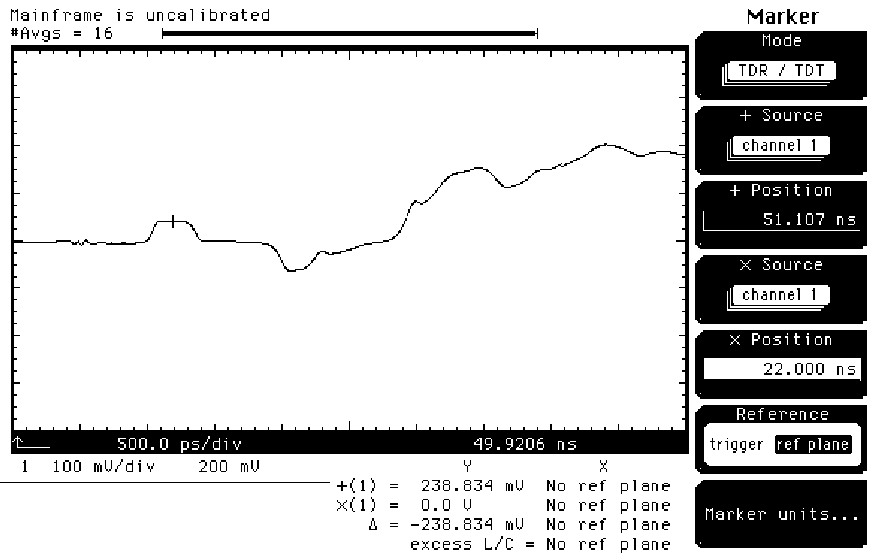
8 Press the *Vertical units* softkey to select `Volt`.

9 Press the *Done* softkey.

10 Change the *+ Position* until the + marker is over the narrow trace discontinuity.

11 At the bottom of the display, read the number of volts for the narrow trace discontinuity (Figure 7-13).

Figure 7-13



Narrow Trace Voltage

In this case, the voltage, *vd1*, is approximately equal to 238.834 mV. Substituting and solving for p we have:

$$p = \frac{238.834 - 200}{200} = 0.19417$$

therefore,

$$Z = 50\Omega \times \frac{1 + 0.19417}{1 - 0.19417} = 74.09565\Omega$$

Instead of calculating the impedance from the measured voltage, we can have the oscilloscope calculate the impedance. Before we can do this we must first establish normalization and the reference plane at the end of the cable connected to the demo board. This requires a very accurate low reflection 26.5 GHz 50 ohm load, such as the Agilent 909D.

1 Press the **TDR/TDT Setup** key.

2 Press *Normalize response . . .* softkey.

3 Disconnect the cable from the demo board.

4 Press the *Establish normalization & ref plane* softkey.

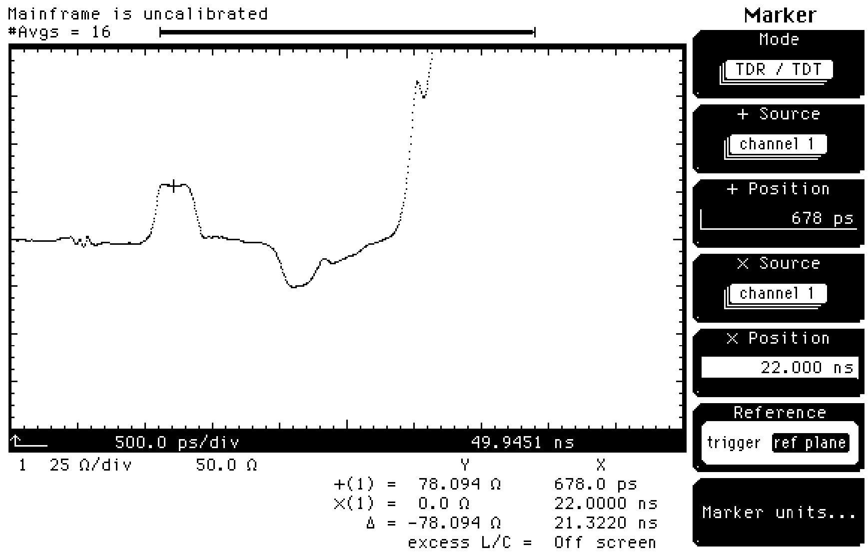
5. Connect an SMA short to the end of the cable.
6. Press the *Continue* softkey.
7. Remove the SMA short and connect an SMA 50 ohm load to the end of the cable.
8. Press the *Continue* softkey.
9. Remove the 50 ohm load and re-connect the cable to the demo board.
10. Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.

Next we will use the oscilloscopes impedance measurement feature to measure the impedance of the narrow trace discontinuity.

1. Press the **SETUP Channel 1/3** key.
2. Press the *Alternate scale . . .* softkey.
3. Press the *Units* softkey and select `Ohm`.
4. Press the *Enter* softkey.
5. Press the *Done* softkey.
6. Press the **SETUP Marker** key.
7. Press the *Reference* softkey to select `ref plane`.
8. Press the *Marker units . . .* softkey.
9. Press the *Vertical units* softkey to select `Ohm`.
10. Press the *Done* softkey.

11 Change the *+ Position* until the + marker is over the peak of the narrow trace discontinuity (Figure 7-14).

Figure 7-14



The automated impedance measurement shows a value of 78.094 ohms which agrees approximately with our manually calculated value. However, the automated measurement is more accurate since it measured the actual step height instead of assuming a 200 mV step.

Measuring Transmission Line Percent Reflection

This section shows how to measure transmission line percent reflection with a step risetime of 500 ps. To perform the tasks in this section, you need the following:

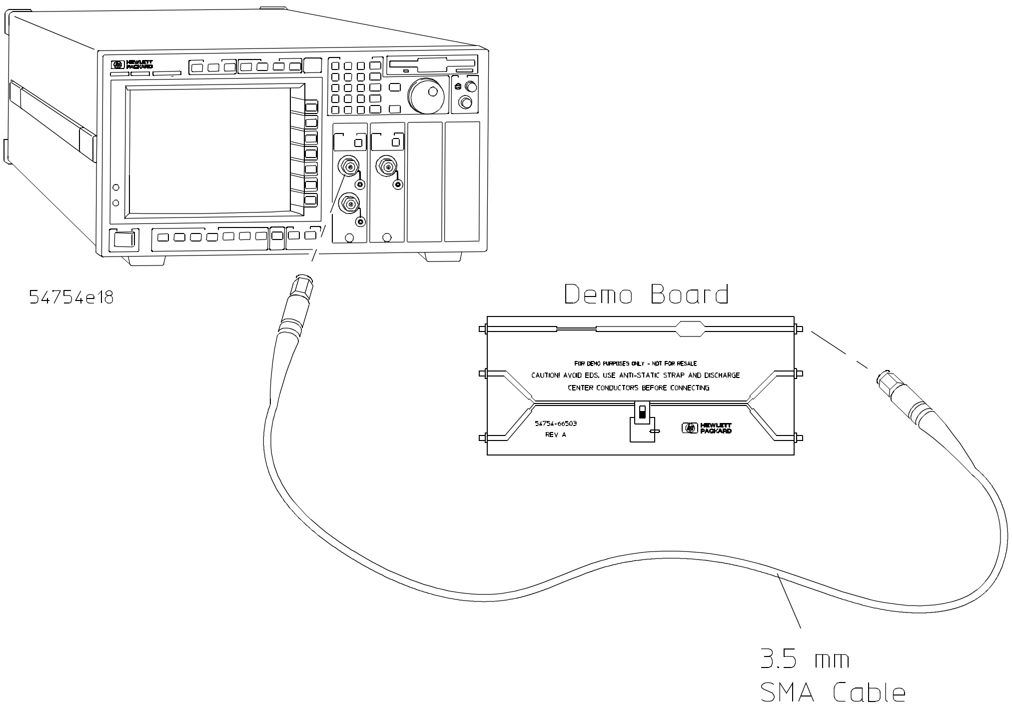
- 1 good quality SMA cable one meter in length, such as the Agilent 8120-4948 cable.
- 1 each demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short.
- 1 SMA 50 ohm load.
- 1 Agilent 54754A or Agilent 54753A TDR Module.

The following procedure shows how to perform a percent reflection measurement.

1 Connect a 1 m SMA cable to channel 1 of the TDR plug-in module.

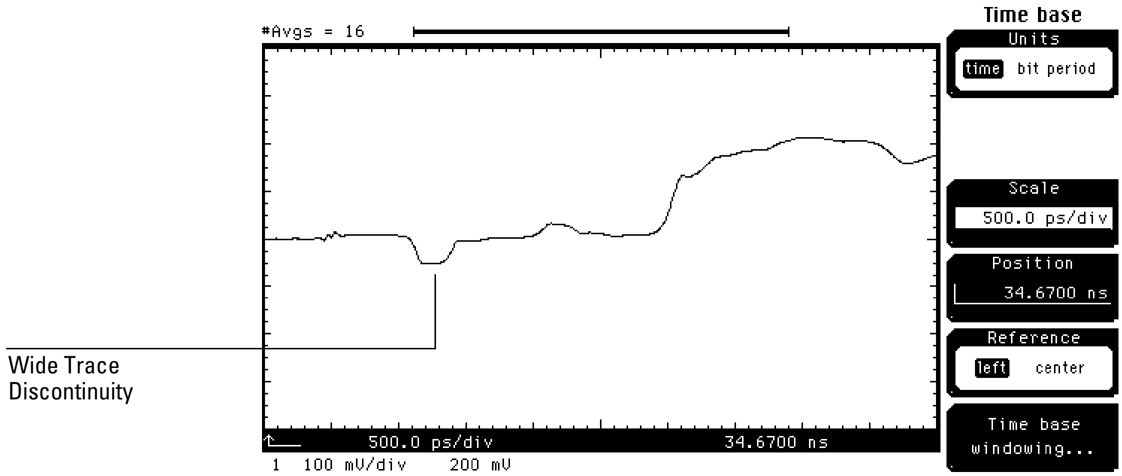
2 Connect the other end of the cable to the demo board's single transmission line connector that is closest to the wide trace (Figure 7-15).

Figure 7-15



1 Press the **STORAGE Setup** menu key above the display.
2 Press the *Default setup* softkey.
3 Press **TDR/TDT Setup** on the TDR plug-in module.
4 Press the *Stimulus* softkey and select `1 only` (`on` for the Agilent 54753A).
5 Press the *Enter* softkey.
6 Press the *Preset TDR/TDT* softkey.
7 Press the **Time base** key.
8 Change the *Position* until the display is similar to Figure 7-16.

Figure 7-16



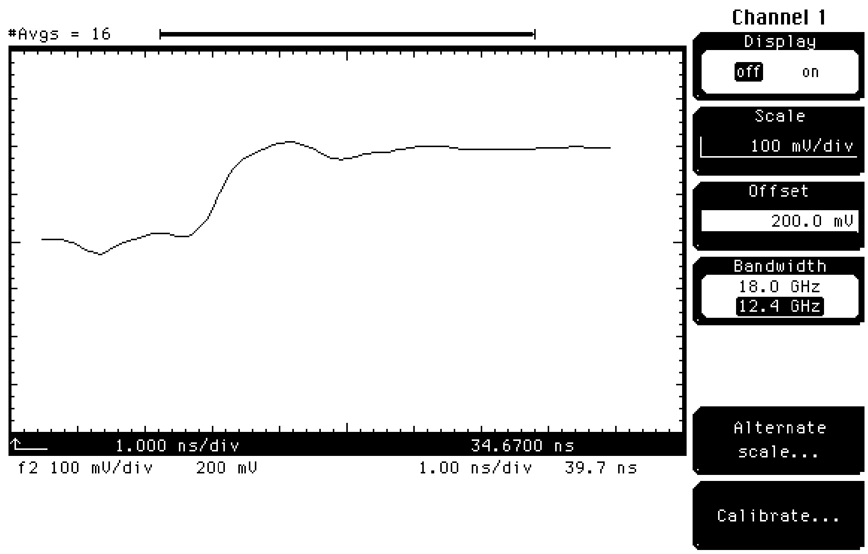
Since the generated TDR step has a risetime of 35 ps, it is impossible to directly measure the percent reflection to a 500 ps step. One way to measure the percent reflection of a 500 ps step is by using the waveform math bandwidth limit function. The bandwidth limit function effectively applies a low pass filter to the selected waveform.

The following shows how to use the waveform math bandwidth limit function to measure percent reflection.

1. Change the *Scale* to 1 ns/div.
2. Press the **SETUP Math** key.
3. Press the *Function* softkey to select `f2`.
4. Press the *Define function . . .* softkey.
5. Press the *Operand 1* softkey and select `channel 1`.
6. Press the *Enter* softkey.
7. Press the *Operator* softkey and select `bw limit`.
8. Press the *Enter* softkey.
9. Change the *Risetime* to 500 ps.
10. Press the *Done* softkey.
11. Press the *Display* softkey to display the f2 function.
12. Press the **SETUP Channel 1/3** key.

13 Press the *Display* softkey to turn off channel 1 display.

Figure 7-17



The green waveform is function 2 which is the 500 ps filtered waveform of channel 1. Because 500 ps is much greater than 35 ps, the overall system risetime is approximately 500 ps.

We will now calculate the peak percent reflection using the measured voltage and the following formula:

$$p_{max} = 100 \times \frac{v - 200\text{ mV}}{200\text{ mV}}$$

This method does not require establishing normalization or the reference plane which is useful for quick measurements or when establishing normalization and the reference plane is difficult to do.

1 Press the **SETUP Marker** key.

2 Press the *Mode* softkey and select `TDR/TDT`.

3 Press the *Enter* softkey.

4 Press the *+ Source* softkey and select `function 2`.

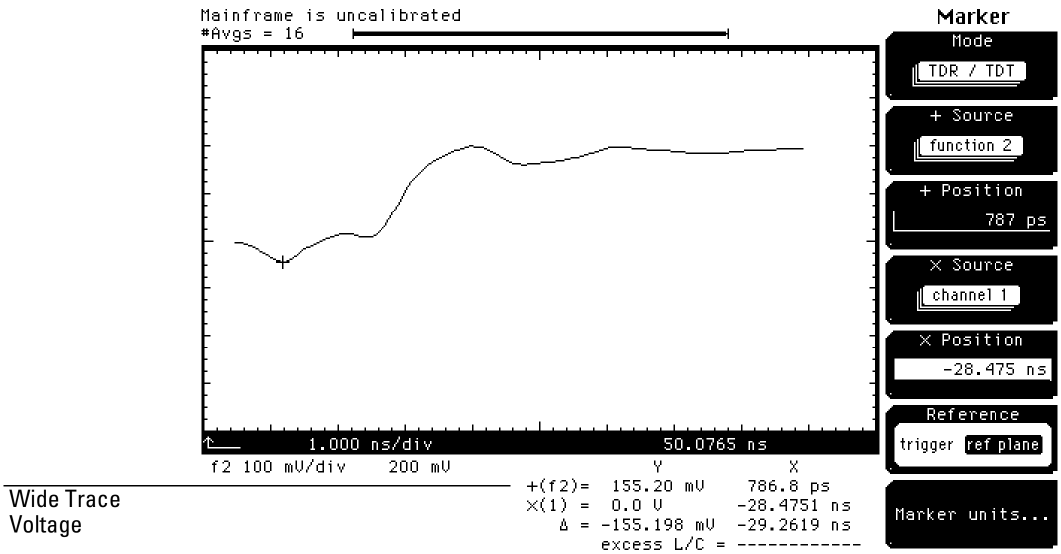
5 Press the *Enter* softkey.

6 Press the *Reference* softkey to select `ref plane`.

7 Press the *Marker units . . .* softkey.

8 Press the *Vertical units* softkey to select `Volt`.
9 Press the *Done* softkey.
10 Change the *+ Position* until the + marker is over the negative peak of the wide trace discontinuity.
11 Read the Y voltage value at the bottom of the display.

Figure 7-18



The measured voltage (v) is 155.20 mV. Substituting into the equation:

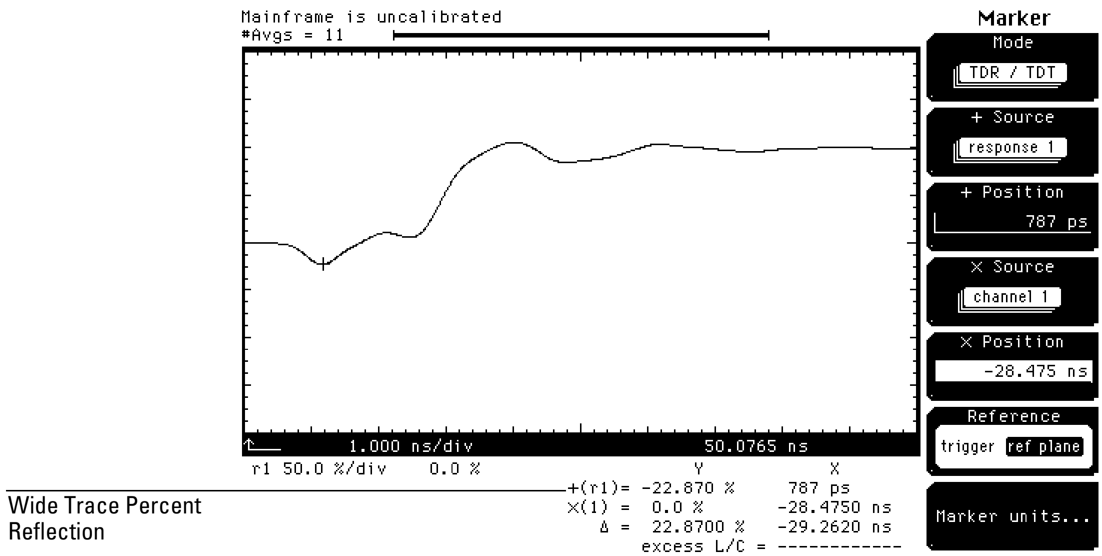
$$p_{max} = 100 \times \frac{155.20 - 200}{200} = -22.40\ \%$$

We will now have the oscilloscope make this measurement for us. This requires establishing normalization and the reference plane as follows.

1 Press the *+ Source* softkey and select `response 1`.
2 Press the *Enter* softkey.
3 Press the **SETUP Math** key.
4 Press the *Display* softkey to turn the function 2 display off.
5 Press the **TDR/TDT Setup** key.
6 Remove the cable end connected to the demo board.
7 Press the *Normalize response . . .* softkey.

8. Press the *Establish normalization & ref plane* softkey.
9. Connect an SMA short to the end of the cable.
10. Press the *Continue* softkey.
11. Remove the short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
12. Press the *Continue* softkey.
13. Reconnect the demo board.
14. Set the *Risetime* to 500 ps.
15. Press the *TDR normalize* softkey to turn the normalized trace on.
16. Press the **SETUP Channel 1/3** key.
17. Press the *Alternate scale . . .* softkey.
18. Press the *Units* softkey and select `% reflect`.
19. Press the *Enter* softkey.
20. Press the *Done* softkey.
21. Press the **SETUP Marker** key.
22. Press the *Reference* softkey to select `ref plane`.
23. Press the *Marker units . . .* softkey.
24. Press the *Vertical units* softkey to select `% reflect`.
25. Press the *Done* softkey.

Figure 7-19



The automated percent reflection at the + marker is seen at the bottom of the display. The measured value of -22.870 % agrees approximately with the previously calculated value of -22.40 %.

Measuring Excess L/C

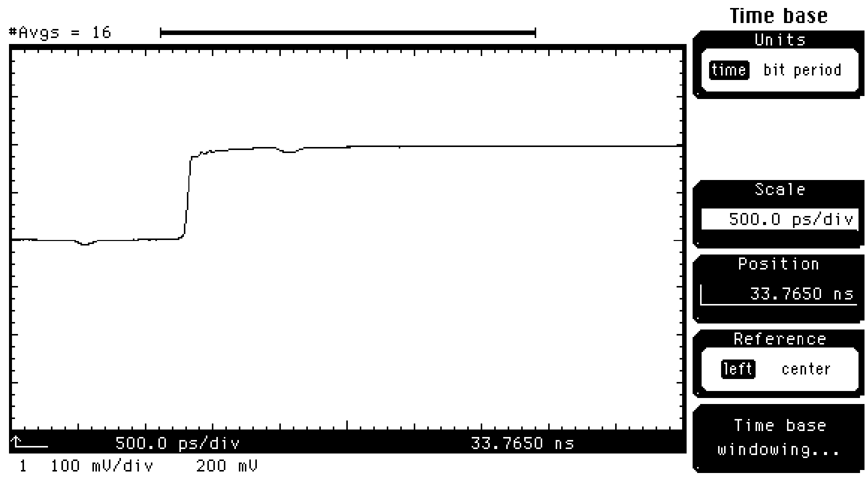
This section shows how to measure excess inductance and capacitance. To perform the tasks in this section, you need the following:

- 1 good quality SMA cable one meter in length, such as the Agilent 8120-4948 cable.
- 1 each demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short.
- 1 SMA 50 ohm load.
- 1 Agilent 54754A or Agilent 54753A TDR Module.

The following procedure shows how to perform an excess L/C measurement.

1. Connect a 1 m SMA cable to channel 1 of the TDR plug-in module.
2. Press the **STORAGE Setup** menu key above the display.
3. Press the *Default setup* softkey.
4. Press **TDR/TDT Setup** on the TDR plug-in module.
5. Select `1 only` (`on` for the Agilent 54753A) in the *Stimulus* menu.
6. Press the *Enter* softkey.
7. Press the *Preset TDR/TDT* softkey.
8. Press the **Time base** key.
9. Change the *Position* to bring the reflected step on screen. The display should be similar to Figure 7-20.

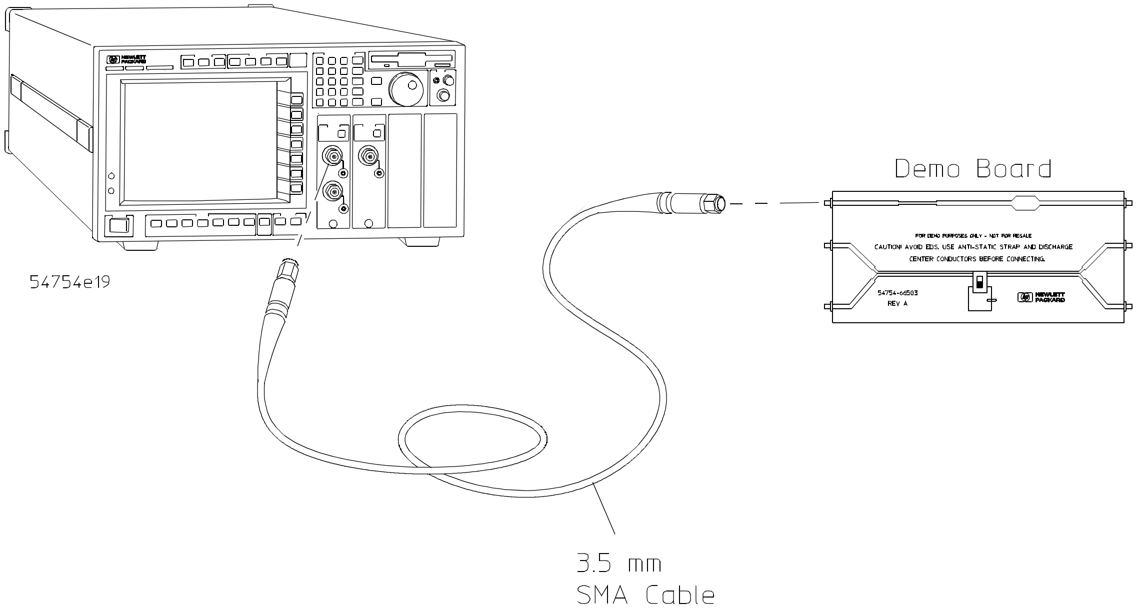
Figure 7-20



1 Press **TDR/TDT Setup** on the TDR plug-in module.
2 Press the *Normalize response . . .* softkey.
3 Press the *Establish normalization & ref plane* softkey.
4 Connect an SMA short to the end of the cable.
5 Press the *Continue* softkey.
6 Remove the short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
7 Press the *Continue* softkey.
8 Remove the 50 ohm load from the end of the cable.

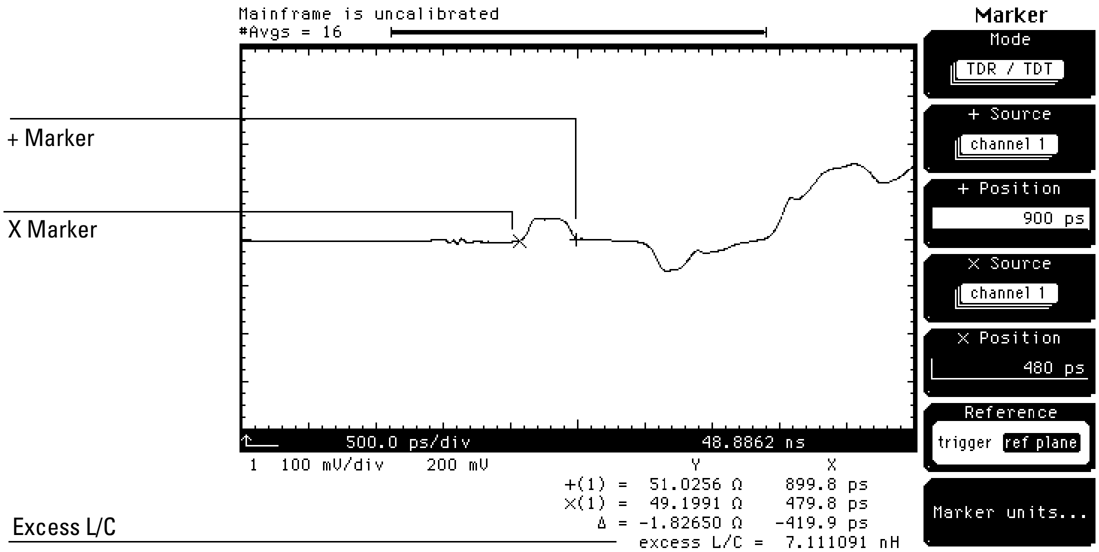
9 Connect the cable to single transmission line connector closest to the narrow trace (Figure 7-21).

Figure 7-21



1. Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.
2. Press the **SETUP Marker** key.
3. Press the *Mode* softkey and select `TDR/TDT`.
4. Press the *Enter* softkey.
5. Press the *Reference* softkey to select `ref plane`.
6. Change the *+ Position* until the + marker is on the right side of the positive bump.
7. Change the *X Position* until the X marker is on the left side of the positive bump.

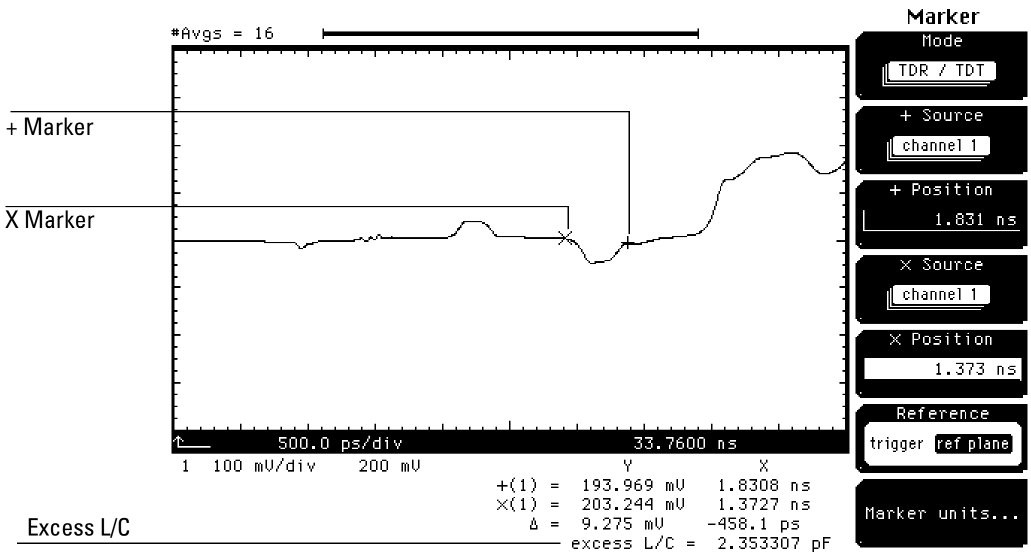
Figure 7-22



At the bottom of the display is shown the excess L/C which is 7.111091 nH for the narrow trace discontinuity. We will now measure the wide trace discontinuity's excess L/C.

1 Change the *+ Position* until + marker is on the right side of the negative bump.
2 Change the *X Position* until the X marker is on the left side of the negative bump.

Figure 7-23



The excess L/C of the negative bump is 2.353307 pF. The negative bump is not as well defined (or as square) as the positive bump. This is due to the filtering effect that the positive bump (inductive section) has on the negative bump (capacitive section). For example, the reflections off the capacitive section have to pass back through the inductive section before it can be viewed. To get a more accurate measure of the capacitive section, connect the cable to the single transmission line closer to the wide trace.

Measuring the Distance to a Discontinuity

This section shows how to measure the distance to a capacitive or inductive discontinuity. To perform the tasks in this section, you need the following:

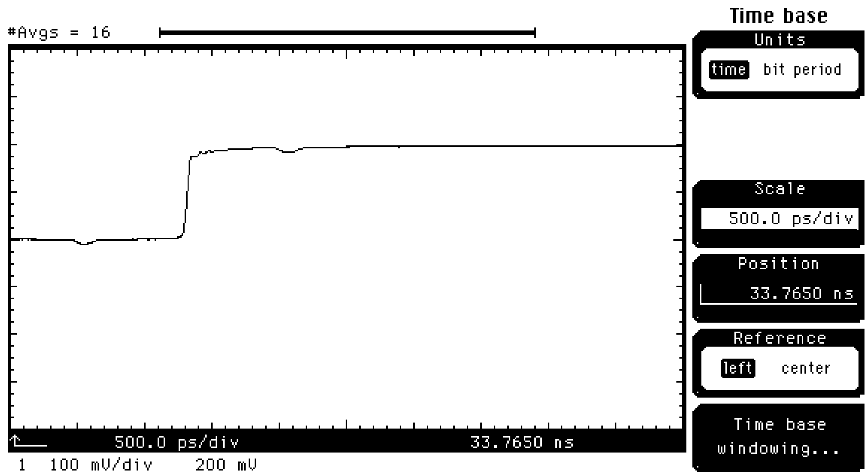
- 1 good quality SMA cable one meter in length, such as the Agilent 8120-4948 cable.
- 1 each demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short.
- 1 SMA 50 ohm load.
- 1 Agilent 54754A or Agilent 54753A TDR Module.

The following procedure shows how to perform a distance measurement.

1 Connect a 1 m SMA cable to channel 1 of the TDR plug-in module.
2 Press the **STORAGE Setup** menu key above the display.
3 Press the *Default setup* softkey.
4 Press **TDR/TDT Setup** on the TDR plug-in module.
5 Select `1 only` (`on` for the Agilent 54753A) in the *Stimulus* menu.
6 Press the *Enter* softkey.
7 Press the *Preset TDR/TDT* softkey.
8 Press the **Time base** key.

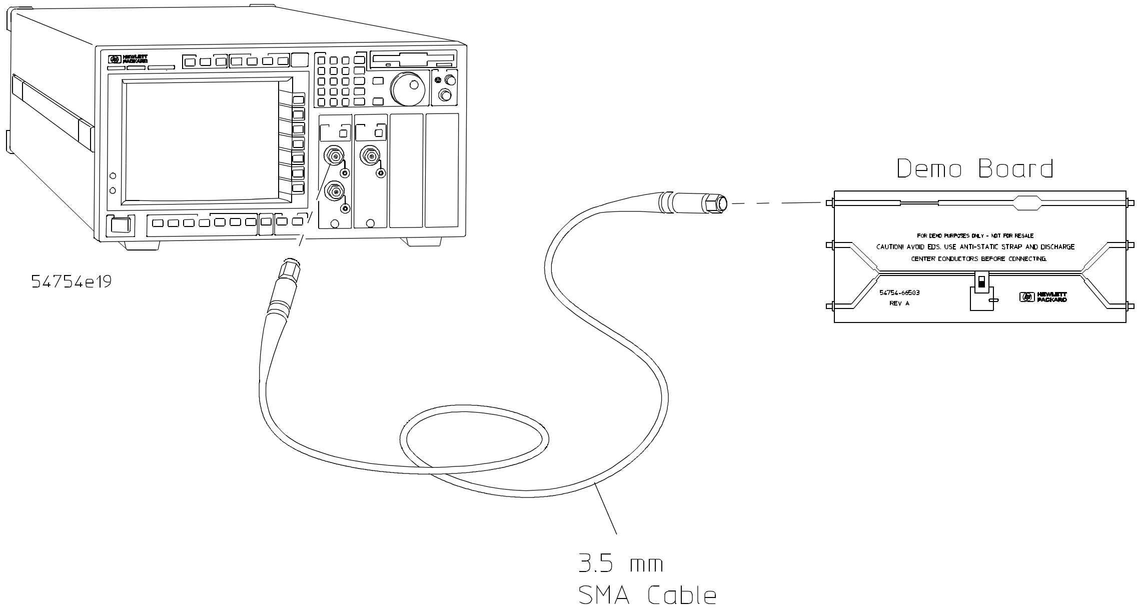
9 Change the *Position* until the display is similar to Figure 7-24.

Figure 7-24



1 Press **TDR/TDT Setup** on the TDR plug-in module.
2 Press the *Normalize response . . .* softkey.
3 Press the *Establish normalization & ref plane* softkey.
4 Connect an SMA short to the end of the cable.
5 Remove the short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
6 Press the *Continue* softkey.
7 Press the *Done* softkey.
8 Remove the 50 ohm load from the end of the cable.
9 Connect the channel 1 cable to the single transmission line connector closest to the narrow trace on the demo board (Figure 7-25).

Figure 7-25

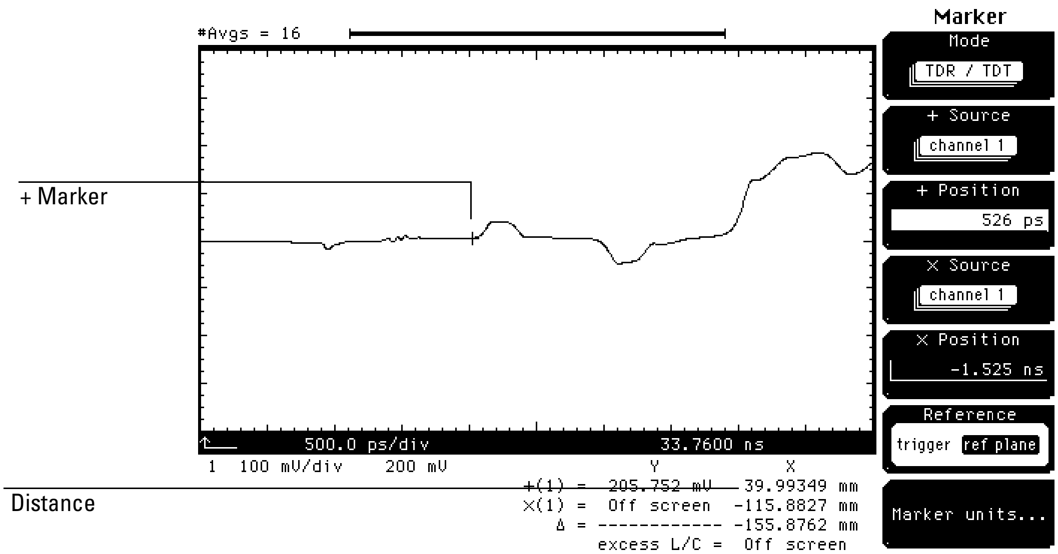


1 Press the **Clear display** key. Whenever an external connection is changed, **Clear display** should be pressed to reset averaging.
2 Press the **SETUP Marker** key.
3 Press the *Mode* softkey and select `TDR/TDT`.
4 Press the *Reference* softkey to select `ref plane`.
5 Press the *Marker units . . .* softkey.
6 Press the *Horiz units* softkey to select `meter`.

   Before the distance from the reference plane (the end of the cable) to the narrow trace can be computed, either the dielectric constant or the velocity of the transmission line must be known. For the demo board the dielectric constant is approximately 3.945.
7 Change the *Dielectric c* to 3.945.
8 Press the *Done* softkey.

9 Change the *+ Position* until the + marker is on the left side of the positive bump.

Figure 7-26



The distance from the reference plane to the narrow trace is shown at the bottom of the display (Figure 7-26).

8

Differential TDR Measurements

Differential TDR Measurements

What you'll find in this chapter

This chapter describes how to make differential TDR measurements and describes the reason for the processes required to make these measurements.

CAUTION

The input circuits can be damaged by electrostatic discharge (ESD). Therefore, avoid applying static discharges to the front-panel input connectors. Before connecting any coaxial cable to the connectors, momentarily short the center and outer conductors of the cable together. Avoid touching the front-panel input connectors without first touching the frame of the instrument. Be sure the instrument is properly earth-grounded to prevent buildup of static charge.

Differential TDR Features

The Agilent 54754A TDR plug-in module is capable of performing differential TDR measurements. These measurements include characterizing differential microstrip lines, differential PC board traces, and differential cables. Because differential TDR measurements are complex, the differential TDR plug-in module has several features which make measurements easier.

The Preset TDR/TDT Feature

The Preset TDR/TDT feature prepares the oscilloscope for making TDR and TDT measurements by automatically setting several menu fields. The Preset TDR/TDT feature appears in the TDR/TDT Setup menu once a stimulus has been selected.

Differential and Common Mode Stimulus Feature

The feature allows you to deliver to a TDR system either differential or common mode stimulus. Differential stimulus launches a positive going step on channel 1 and an effective negative going step on channel 2. Common mode stimulus launches a positive going step on both channels.

Responses to Differential and Common Mode Stimulus

Response controls are provided which show the differential or common mode response of a TDR system under test stimulated by differential or common mode stimulus. It is also possible to view the individual channels responses.

TDR Channel Deskewing Feature

Before accurate differential or common mode TDR measurements can be made, it is necessary to deskew the two TDR step generators. Under the channel menu for each TDR channel there is a *Calibrate . . .* softkey. When this softkey is selected, it allows you to enter a channel *Skew* and a *TDR skew* parameter.

Channel *Skew* is a feature that allows the acquired signal to be moved in time with respect to other acquired channels. Since sampling oscilloscopes do not have negative time, this control only allows waveforms to be moved to the left or more positive in time. This control is used in deskewing differential TDR and in normal signal acquisition applications.

TDR skew is a feature that allows positioning of the actual TDR step. It has an approximate range of ±400ps. The units of the control are in % of the maximum range of ±100%. This control moves the position of the TDR step whereas the channel *Skew* control moves the position of the acquired waveform. Both controls are needed to properly deskew the TDR step generators for differential TDR.

Differential TDR measurements require two cables to be connected from the TDR channels to the device under test. These cables should be good quality cables of equal length (within 1 ns delay of each other). The procedure for deskewing the differential TDR to the ends of the cables is as follows:

- Insure that the open reflection of each TDR channel overlay each other with no cables attached. If they are not, either do a plug-in calibration or adjust the *TDR Skew* so they overlay each other.
- Attach the cables. Notice that unless the cables are matched in electrical length, the open reflections now do not overlay each other. Using the ΔTime auto measurement or manual markers, measure the delta time (skew) between the TDR channels.
- Now go to the channel *Skew* control for the channel that is more to the right on the screen. Adjust this control until the skew between the TDR channels is reduced to half of what it was initially.
- Now use one of the *TDR Skew* controls from either TDR channel to reduce the remaining skew to approximately 0.

The TDR step generators are now deskewed to the ends of the cables. The open reflections off the end of the cables should overlay each other. Note that the incident steps of the two channels probably do not overlay each other. They won't unless the cables are the same electrical length. This is not a problem because only the reflected signals need to be deskewed. The system in now ready to make differential TDR measurements. If differential TDT measurements are to be made, an additional deskew of the destination channels needs to be done for TDT.

- Connect an additional two cables to the two TDT destination channels.
- Using some SMA or 3.5 mm F-F adaptors, connect the TDR channels to the TDT channels. The transmitted steps should now be seen on the TDT destination channels.
- Unless the electrical lengths of the two transmission paths happen to be identical, the transmitted steps will not overlay each other.
- Now go to the channel *Skew* control for the channel that is more to the right on the screen. Adjust this control until the skew between the TDT channels is reduced to approximately 0.

The TDT paths are now deskewed. The device under test can now be connected to the 4 cables, and the transmitted response observed.

If markers are to be used on the differential responses, then a *Establish ref plane* should be done after the system is deskewed. This will allow the channel scales to be set to `Ohm` or `% reflect`, and allow the *Reference* under the **Marker** *Mode* `TDR/TDT` menu to be set to `ref plane`. The marker will be based on the average of the two channels' reference planes.

Alternate Channel Scales

As in single ended TDR, the TDR channels can be set to have a vertical scale of % reflection or ohms. If both TDR channels of a differential TDR measurement are set to either % reflection or ohm, then the combined response, for example Response 1 or Response 2, will also be in those units.

Measuring Differential and Common Mode Impedance

This section will show how to deskew the TDR step generators, establish the reference planes, and measure the differential and common mode impedances. To perform the tasks in this section, you need the following:

- 2 good quality SMA cables one meter in length, such as the Agilent 8120-4948 cable.
- 1 each demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short.
- 1 SMA 50 ohm load.
- 1 Agilent 54754A TDR Module.

Deskewing Differential TDR Step Generators

This first thing that must be done before you can measure differential impedance is to deskew the TDR step generators. There are two ways to deskew the TDR step generators. One way is to calibrate the TDR plug-in module. The other way is to use the channel TDR skew control. This section describes how to use the TDR skew control to deskew the TDR step generators.

> Refer to the Agilent 54750A, Agilent 83480A User's Guide for information on calibrating plug-in modules.

The following steps describe the deskewing process.

1 Press the **STORAGE Setup** menu key above the display.

2 Press the *Default setup* softkey.

3 Press **TDR/TDT Setup** on the TDR plug-in module.

4 Press the *Stimulus* softkey and select `differential`.

5 Press the *Enter* softkey.

6 Press the *Preset TDR/TDT* softkey.

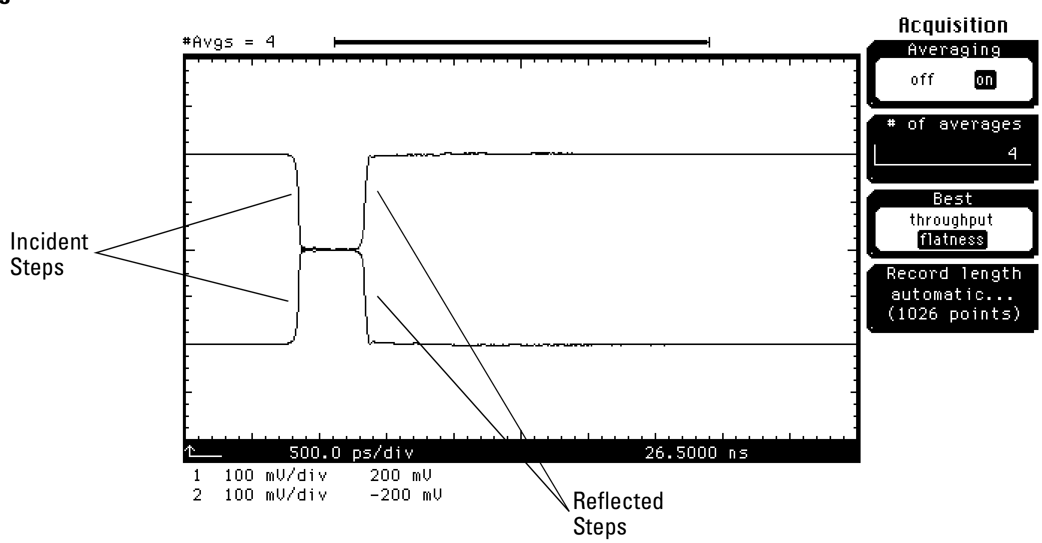
7 Press the **SETUP Acquisition** menu key below the display.

8 Change the *# of averages* from 16 to 4.

These steps set the oscilloscope to a known condition and activate the TDR steps on channel 1 and channel 2. You should see a display similar to Figure 8-1.

> Channel skew is set to 0.0 s for both channels. It is important to set these controls to 0.0 s before adjusting the TDR skew otherwise the TDR step generator skew will be incorrectly set.

Figure 8-1



1 Press the **SETUP Time base** key.

2 Change the *Scale* to 100 ps/div.

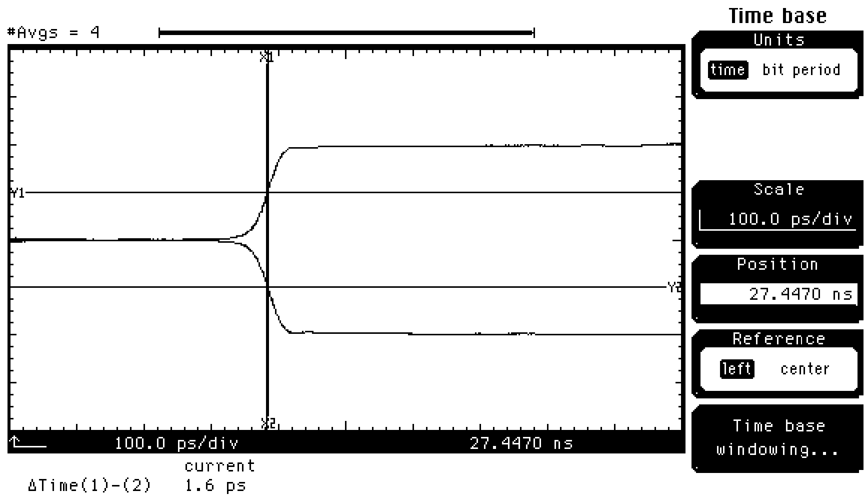
3 Change the *Position* until the incident edge is off screen to the left.

4 Press the **blue** key followed by the **milli** key to turn on the ΔTime measurement.

5 Press the *Stop src* softkey and select `channel 2`.

6 Press the *Enter* softkey (Figure 8-2).

Figure 8-2



1 Press the **SETUP Channel** key for the channel whose reflected step is the right-most step on the display.

2 Press the *Calibrate . . .* softkey.

3 Change the *TDR Skew* until the remaining ΔTime is approximately 0. You will need to move the control slowly as it takes a short amount of time for the waveform to settle.

Deskewing Differential Cables

The next thing that must be done before you can measure differential impedance is to deskew the TDR step generators to the end of the cables. The following steps describe the deskewing process.

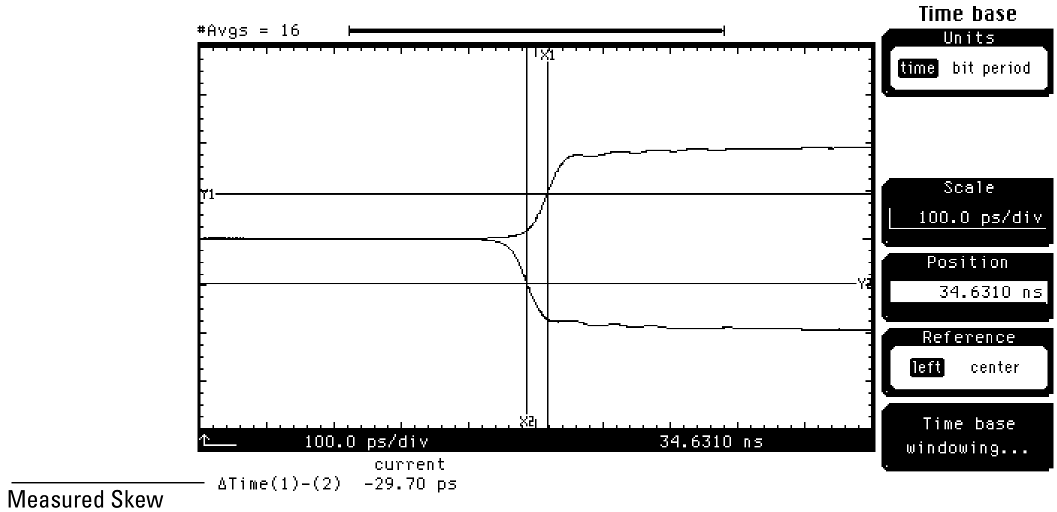
1 Connect an SMA cable to the TDR plug-in channel 1.

2 Connect an SMA cable to the TDR plug-in channel 2.

3 Press the **SETUP Time base** key.

4 Change the *Position* until the reflected edge is approximately centered in the display (Figure 8-3).

Figure 8-3



A Δtime (skew) value of 7 ps (one fifth the TDR step risetime of 35 ps) or less is small enough that the skew will not introduce errors into TDR measurements. However, for the purposes of demonstration, the following process shows how to deskew the cables.

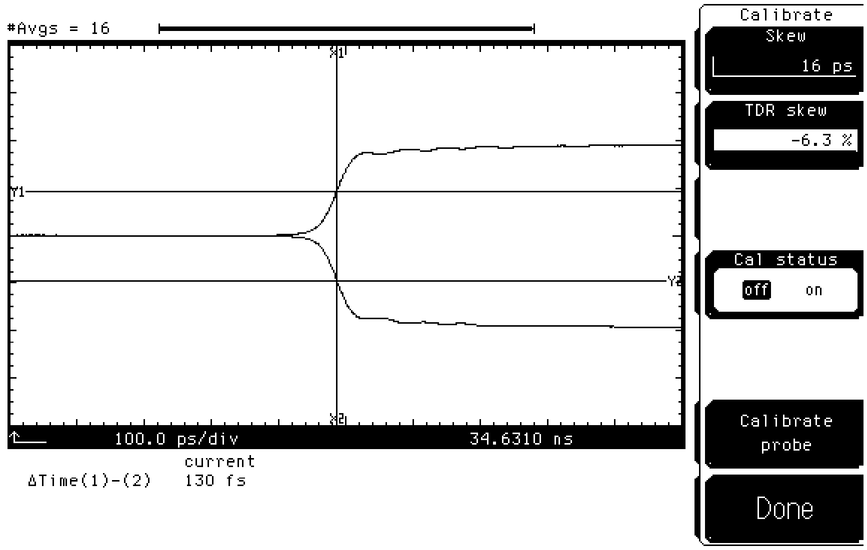
1 Press the **SETUP Channel** key for the channel whose reflected step is the right-most step on the display.

2 Press the *Calibrate....* softkey.

3 Change the *Skew* until the ΔTime is ½ its initial value.

4 Change the *TDR Skew* until the remaining ΔTime is approximately 0. You will need to move the control slowly as it takes a short amount of time for the waveform to settle (Figure 8-4).

Figure 8-4



Establishing the Reference Plane

Since we want to measure the impedance of a differential line, we must establish the reference plane so the scope can measure the height of the TDR step height.

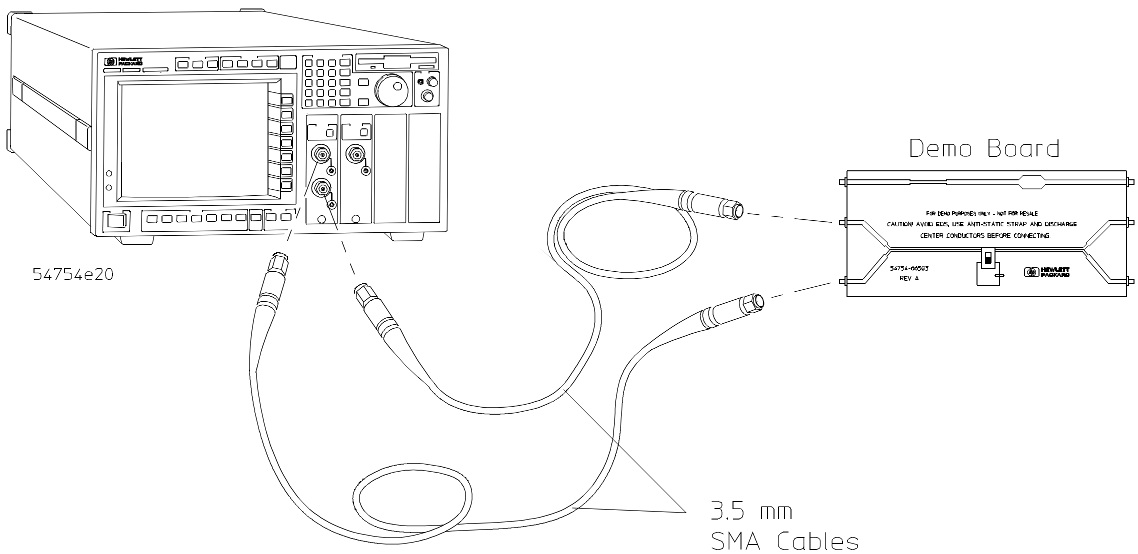
1. Press the **TDR/TDT Setup** key.
2. Press the *Establish ref plane* softkey.
3. Connect an SMA short to the end of the cable on channel 1.
4. Press the *Continue* softkey.
5. Remove the SMA short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
6. Press the *Continue* softkey.
7. Remove the SMA 50 load from the end of the cable.
8. Connect an SMA short to the end of the cable on channel 2.
9. Press the *Continue* softkey.
10. Remove the SMA short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
11. Press the *Continue* softkey.
12. Remove the SMA 50 load from the end of the cable.

Measuring Differential Impedance

We are now ready to measure the differential impedance of the differential line.

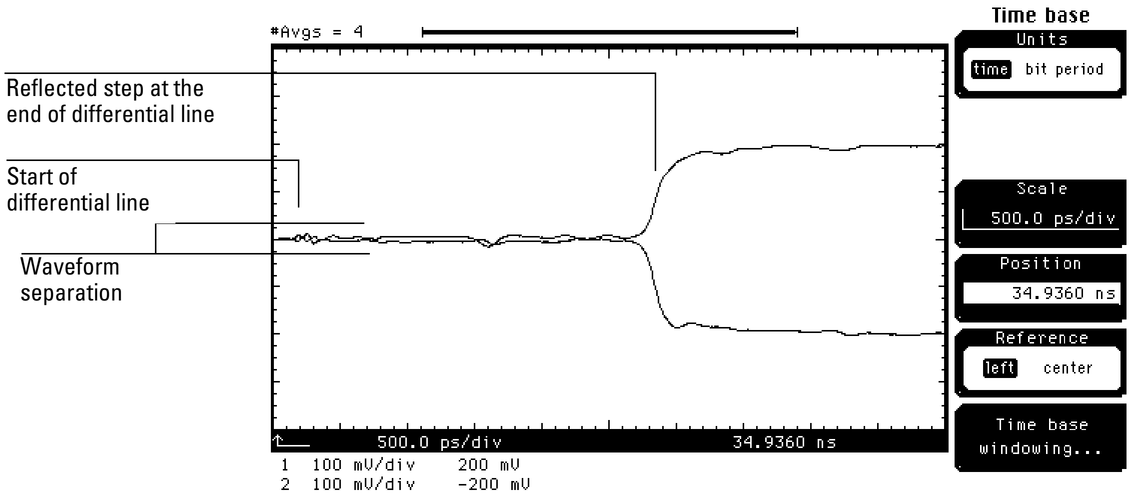
1 Connect the channel 1 cable to the differential line closest to the edge of the board.
2 Connect the channel 2 cable to the other differential line (Figure 8-5).

Figure 8-5



1 Make sure that the switch on the demo board is in the off position (toward the outside edge of the board away from the differential line).
2 Press the **blue** key followed by the **Clr** key.
3 Press the **SETUP Time base** key.
4 Change the *Scale* to 500 ps/div.
5 Change the *Position* until the reflected steps are in the middle of the display (Figure 8-6).

Figure 8-6



The portion of the waveforms starting at the left-hand of the display is where the cables are connected to the differential line. The positive and negative going steps are the reflected steps from the end of the differential line. The waveform separation seen is due to the difference in impedance along the differential line. The differential mode impedance for two 50 ohm uncoupled lines is 100 ohms.

Before performing the next step, be sure to wear a grounding strap connected to the mainframe ground.

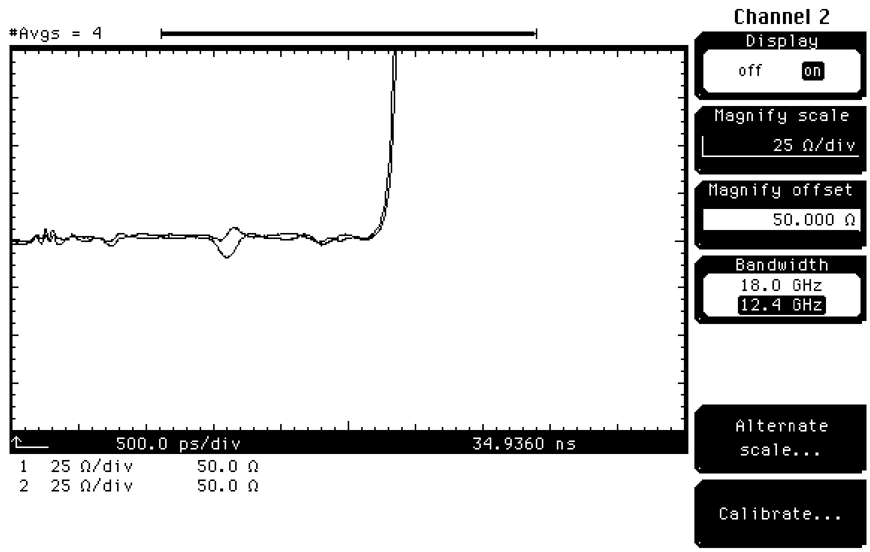
To verify which part of the waveform represents a certain part of the differential line, touch the differential line with your finger. A bump in the waveform will appear which represents the location of your finger along the differential line.

To measure the impedance of the differential line, use the following procedure.

1. Press **SETUP Channel 1/3** key.
2. Press the *Alternate scale . . .* softkey.
3. Press the *Units* softkey and select `Ohm`.
4. Press the *Enter* softkey.
5. Press the *Done* softkey.
6. Press **SETUP Channel 2/4** key.

7 Press the *Alternate scale . . .* softkey.
8 Press the *Units* softkey and select `Ohm`.
9 Press the *Enter* softkey.
10 Press the *Done* softkey (Figure 8-7).

Figure 8-7

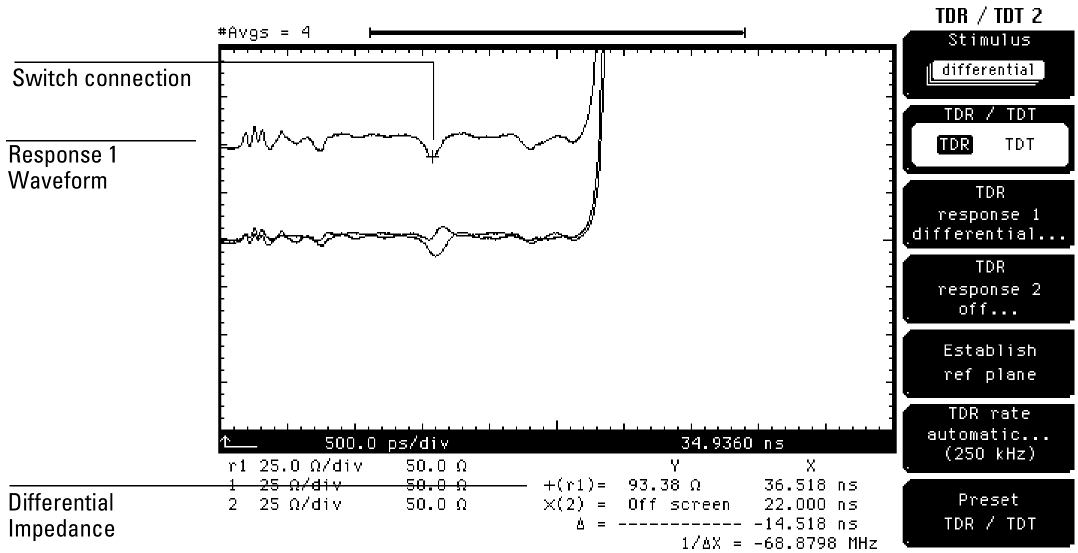


Both channel waveforms have positive going steps because ohms is always positive in a passive system.

We will now measure the differential line impedance.

1 Press the **TDR/TDT Setup** key.
2 Press the *TDR response 1 off . . .* softkey.
3 Press the *Response* softkey and select `differential`.
4 Press the *Enter* softkey.
5 Press the *Done* softkey (Figure 8-8).

Figure 8-8



1 Press the **SETUP Marker** key.
2 Press the *Mode* softkey and select `TDR/TDT`.
3 Press the *Enter* softkey.
4 Press the *+ Source* softkey and select `response 1`.
5 Press the *Enter* softkey.
6 Change the *+ Position* until the + marker is on screen.

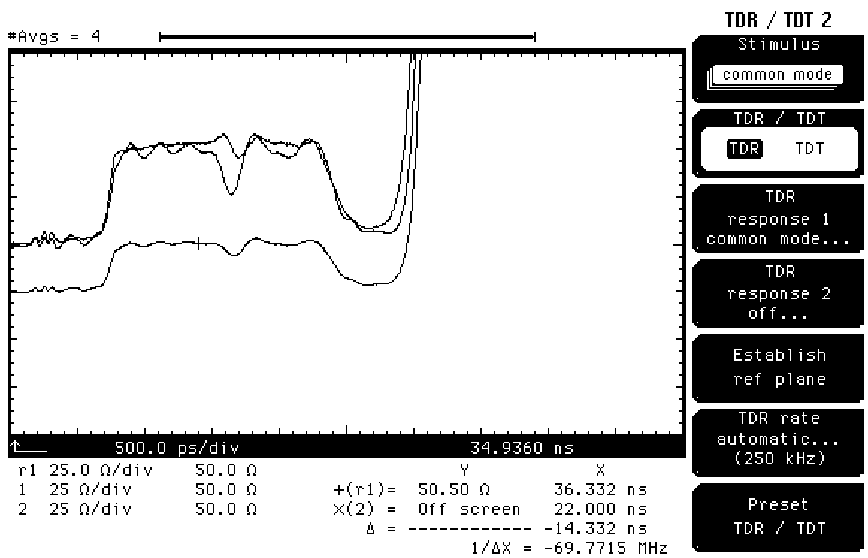
As the + marker moves along the waveform, the differential impedance at the current + marker is shown at the bottom of the display. If you move the + marker to the portion of the waveform representing the cable response, the impedance is the sum of the two cable impedances (approximately 100 ohms depending on the quality of the cable). The negative bump where the + marker is located in Figure 8-8 is the parasitic capacitance due to the leg of the switch connected to the trace.

Measuring Common Mode Impedance

We are now ready to measure the common mode impedance of the differential line. This section assumes that the differential mode impedance section has been completed and that the oscilloscope settings have not been changed.

1. Press the **TDR/TDT Setup** key.
2. Press the *Stimulus* softkey and select common mode.
3. Press the *Enter* softkey.
4. Press the *TDR response 1 differential . . .* softkey.
5. Press the *Response* softkey and select common mode.
6. Press the *Enter* softkey.
7. Press the *Done* softkey (Figure 8-9).

Figure 8-9



The common mode impedance of two 50 ohm uncoupled lines is 25 ohms.

Making Differential TDT Measurements

This section will show how to deskew the TDR step generators, establish the reference planes, and make differential and common mode TDT measurements. To perform the tasks in this section, you need the following:

- 4 good quality SMA cables one meter in length, such as the Agilent 8120-4948 cable.
- 2 female-to-female SMA adapters.
- 1 each demo board (54754-66503) supplied with the TDR plug-in.
- 1 SMA short.
- 1 SMA 50 ohm load.
- 1 Agilent 54754A TDR Module.
- 1 two channel electrical plug-in module, for example, an Agilent 54751A or Agilent 83483A 20 GHz Module.

Deskewing Differential TDR Step Generators

> If you have just completed the *Measuring Differential and Common Mode Impedance* section, set the stimulus to differential and go to the *Deskewing the TDT Channels* section.

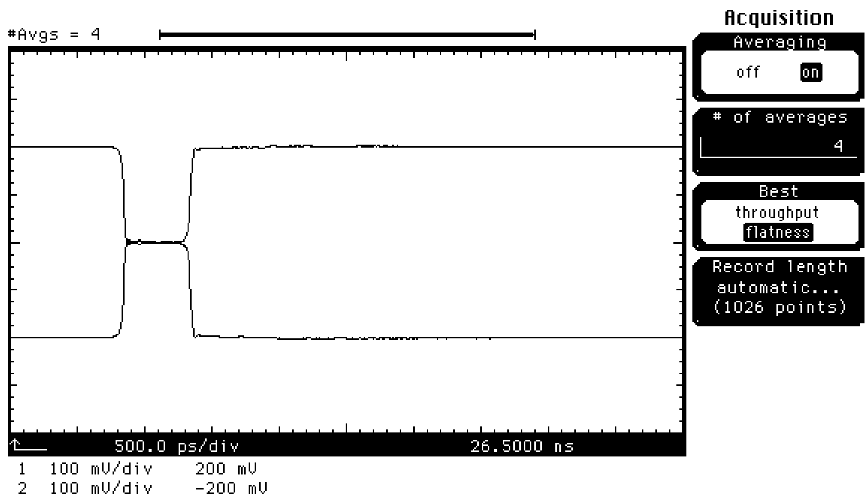
The first thing that must be done before you can make differential TDT measurements is to deskew the TDR step generators to the end of the cables. The following steps describe the deskewing process.

1. Press the **STORAGE Setup** menu key above the display.
2. Press the *Default setup* softkey.
3. Press **TDR/TDT Setup** on the TDR plug-in module.
4. Press the *Stimulus* softkey and select `differential`.
5. Press the *Enter* softkey.
6. Press the *Preset TDR/TDT* softkey.
7. Press the **SETUP Acquisition** menu key below the display.
8. Change the *# of averages* from 16 to 4.

These steps set the oscilloscope to a known condition and activates the TDR steps on channel 1 and channel 2. You should see a display similar to Figure 8-10.

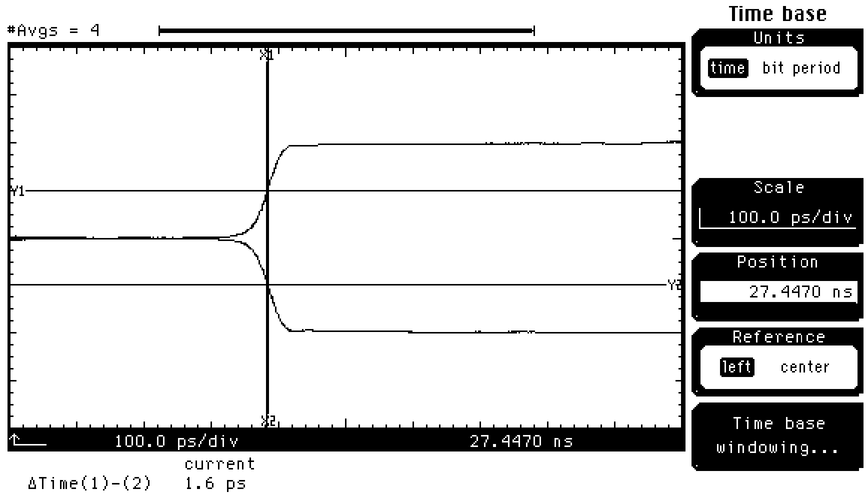
> Channel skew is set to 0.0 s for both channels. It is important to set these controls to 0.0 s before adjusting the TDR skew otherwise the TDR step generator skew will be incorrectly set.

Figure 8-10



1. Press the **SETUP Time base** key.
2. Change the *Scale* to 100 ps/div.
3. Change the *Position* until the incident edge is off screen to the left.
4. Press the **blue** key followed by the **milli** key to turn on the ΔTime measurement.
5. Press the *Stop src* softkey and select `channel 2`.
6. Press the *Enter* softkey (Figure 8-11).

Figure 8-11



1 Press the **SETUP Channe**l key for the channel whose reflected step is the right-most step on the display.

2 Press the *Calibrate....* softkey.

3 Change the *TDR Skew* until the remaining ΔTime is approximately 0. You will need to move the control slowly as it takes a short amount of time for the waveform to settle.

Deskewing Differential Cables

The next thing that must be done before you can measure differential impedance is to deskew the TDR step generators to the end of the cables. The following steps describe the deskewing process.

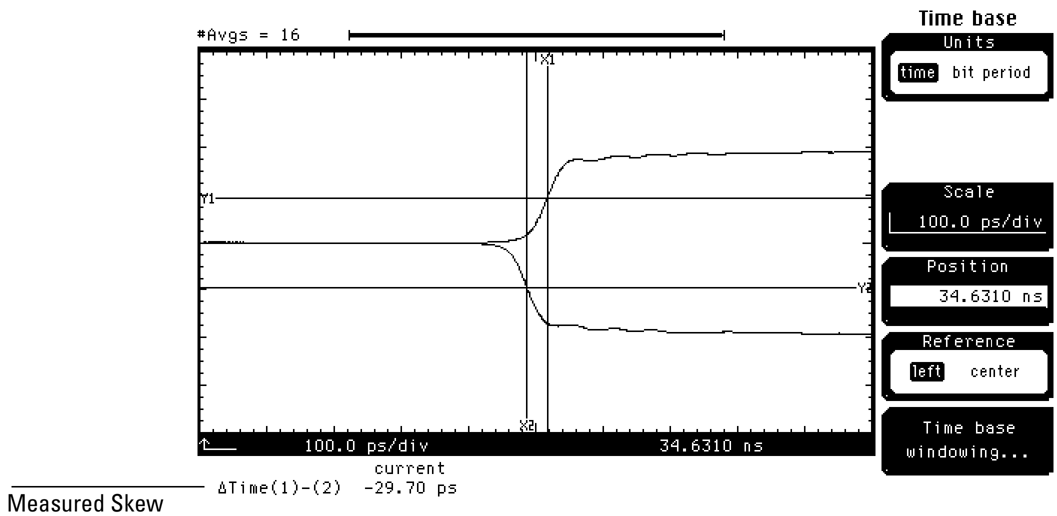
1 Connect an SMA cable to the TDR plug-in channel 1.

2 Connect an SMA cable to the TDR plug-in channel 2.

3 Press the **SETUP Time base** key.

4 Change the *Position* until the reflected edge is approximately centered in the display (Figure 8-12).

Figure 8-12



A Δtime (skew) value of 7 ps (one fifth the TDR step risetime of 35 ps) or less is small enough that the skew will not introduce errors into TDR measurements. However, for the purposes of demonstration, the following process shows how to deskew the cables.

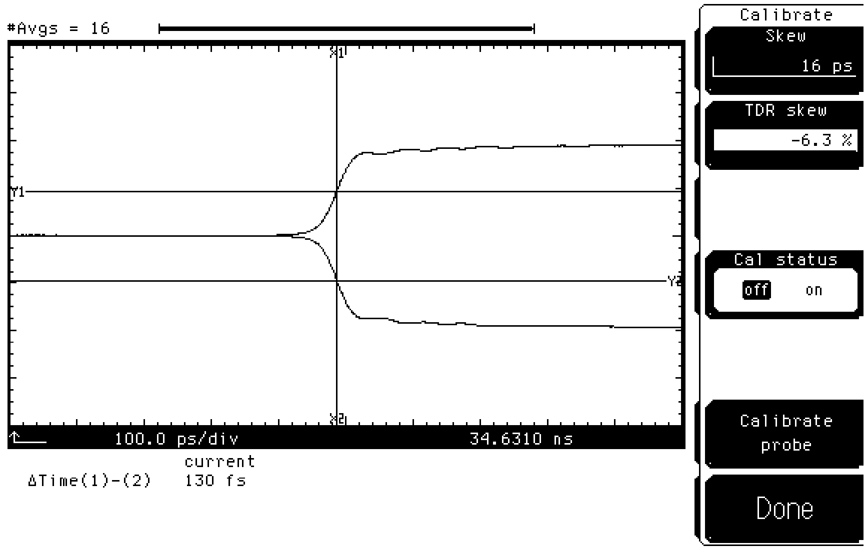
1 Press the **SETUP Channel** key for the channel whose reflected step is the right-most step on the display.

2 Press the *Calibrate....* softkey.

3 Change the *Skew* until the ΔTime is ½ its initial value.

4 Change the *TDR Skew* until the remaining ΔTime is approximately 0. You will need to move the control slowly as it takes a short amount of time for the waveform to settle (Figure 8-13).

Figure 8-13



Establishing the Reference Plane

Since we want to measure the impedance of a differential line, we must establish the reference plane so the scope can measure the height of TDR step height.

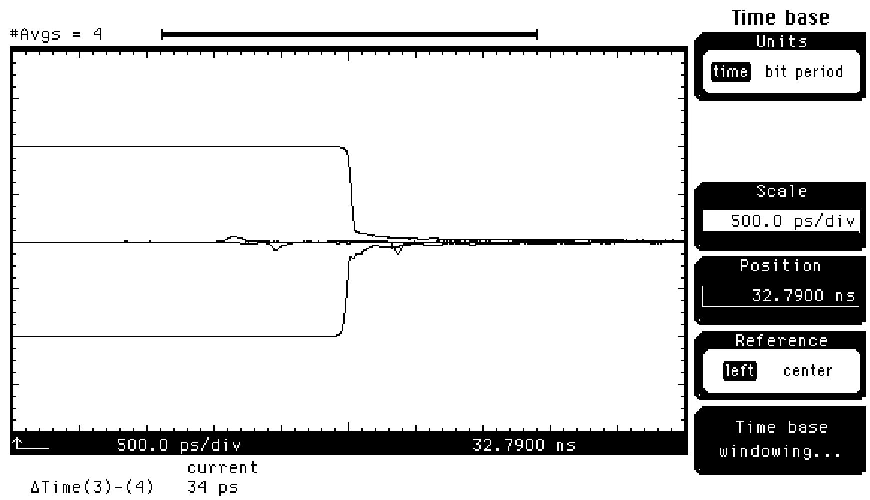
1. Press the **TDR/TDT Setup** key.
2. Press the *Establish ref plane* softkey.
3. Connect an SMA short to the end of the cable on channel 1.
4. Press the *Continue* softkey.
5. Remove the SMA short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
6. Press the *Continue* softkey.
7. Remove the SMA 50 load from the end of the cable.
8. Connect an SMA short to the end of the cable on channel 2.
9. Press the *Continue* softkey.
10. Remove the SMA short from the end of the cable and connect an SMA 50 ohm load to the end of the cable.
11. Press the *Continue* softkey.
12. Remove the SMA 50 load from the end of the cable.

Deskewing the TDT Channels

In addition to the TDR step generators requiring deskewing the two TDT destination channels require deskewing. Use the following procedure to deskew the TDT destination channels.

1. Connect an SMA cable to channel 3 of the electrical plug-in module.
2. Connect another SMA cable to channel 4 of the electrical plug-in module.
3. Press the *TDR/TDT* softkey to select TDT.
4. Press the *Preset TDR/TDT* softkey.
5. Connect one end of a female-to-female SMA adapter to the end of the channel 1 cable and the other end of the adapter to the channel 3 cable.
6. Connect one end of a female-to-female SMA adapter to the end of the channel 2 cable and the other end of the adapter to the channel 4 cable.
7. Press the **Time base** key.
8. Change the *Position* until positive going TDT step is in the middle of the display.
9. Press the **blue** key followed by the **milli** key.
10. Press the *Start src* softkey and select channel 3.
11. Press the *Enter* softkey.
12. Press the *Stop src* softkey and select channel 4.
13. Press the *Enter* softkey.
14. Press the *Enter* softkey (Figure 8-14).

Figure 8-14



1 Press the electrical plug-in module's **SETUP Channel** key whose waveform is closest to the right side of the display. (For the example shown in Figure 8-14, channel 4 is chosen.)

2 Press the *Calibrate . . .* softkey.

3 Change the *Skew* until the ΔTime is reduced to approximately 0 ps.

4 Press the *Done* softkey.

This completes the deskewing process for the TDT channels.

TDT Response Analysis

Analyzing TDT responses can help determine problems in differential lines. The following procedure will show how to use TDT find a problem on the demo board.

1 Remove the female-to-female adapters from both cable pairs.

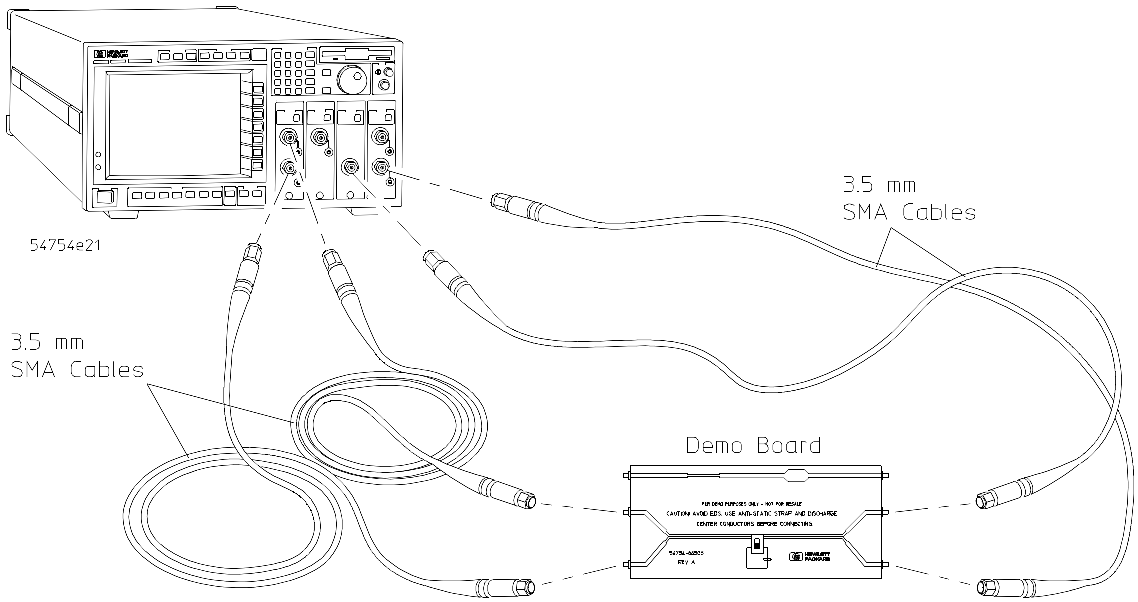
2 Connect the channel 1 cable to the differential line closest to the single transmission line on the demo board.

3 Connect the channel 3 cable to the other end of the differential line closest to the single transmission line on the demo board.

4 Connect the channel 2 cable to the differential line closest to the edge of the demo board.

5 Connect the channel 4 cable to the other end of the differential line closest to the edge of the demo board(Figure 8-15).

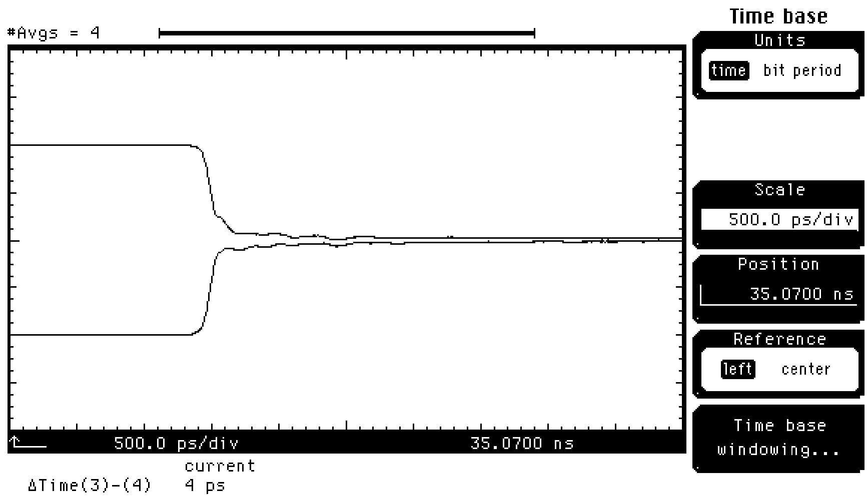
Figure 8-15



1 Press the **SETUP Channel 1/3** key.
2 Press the *Display* softkey to turn off the display of channel 1.
3 Press the **SETUP Channel 2/4** key.
4 Press the *Display* softkey to turn off the display of channel 2.
5 Press the **SETUP Time base** key.
6 Change the *Position* until the positive and negative going steps are on the third graticule from the left side of the display.

The transmitted steps' edges, seen on channels 3 and 4, nearly overlay one another (Figure 8-16).

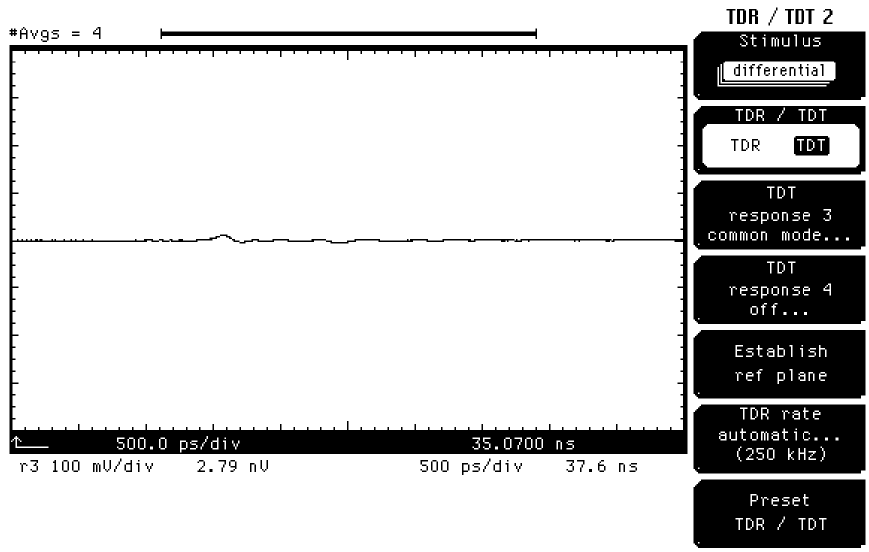
Figure 8-16



1. Press the **blue** key followed by the **Clr** key.
2. Press the **SETUP Channel 3** key of the electrical plug-in module.
3. Press the *Display* softkey to turn off the channel 3 display.
4. Press the **SETUP Channel 4** key of the electrical plug-in module.
5. Press the *Display* softkey to turn off the channel 4 display.
6. Press the **TDR/TDT Setup** key.
7. Press the *TDT response 3 off....* softkey.
8. Press the *Response* softkey and select `common mode`.
9. Press the *Enter* softkey.
10. Press the *Done* softkey.

You should see a response similar to that in Figure 8-17. The response is nearly flat, as should be expected from a balanced differential line.

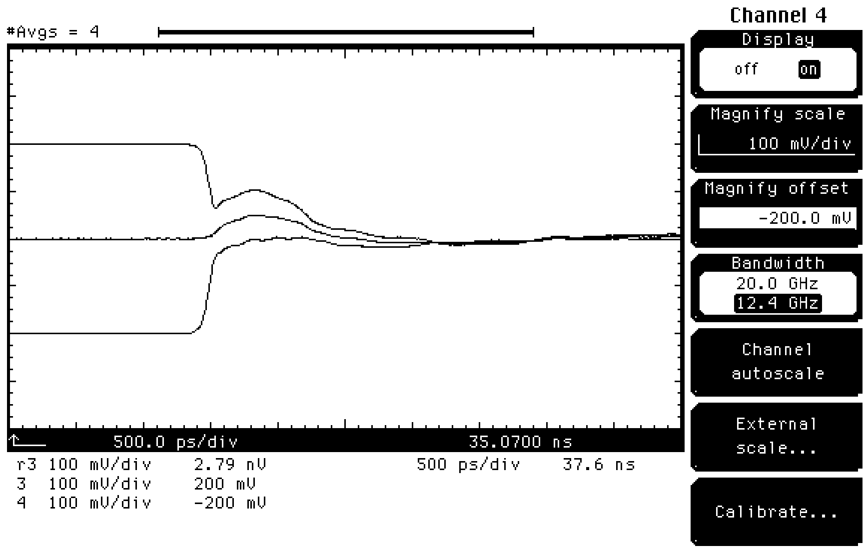
Figure 8-17



1. Press the **SETUP Channel 3** key of the electrical plug-in module.
2. Press the *Display* softkey to turn on the channel 3 display.
3. Press the **SETUP Channel 4** key of the electrical plug-in module.
4. Press the *Display* softkey to turn on the channel 4 display.
5. Change the demo board switch position to on.

   This places a 10 pF capacitive load on one of the differential lines. Note that the response waveform is no longer flat and the transmitted steps on channels 3 and 4 no longer overlay each other (Figure 8-18). This is due to the fact that the differential lines are unbalanced.

Figure 8-18



This situation might occur on a clock distribution line of a digital PC board where an input pin of a gate connected one side of line has an excess capacitance of 10 pF. The gate receiving the differential signal might produce a glitch or might not switch properly.

Even though the extra capacitance was connected to only one of the differential lines, the waveforms for both differential lines were affected. This shows that the differential lines are coupled. If the differential lines were separated by a greater distance, the capacitive load would only affect one side and not both sides of the differential line.

While both differential lines show the effects of the capacitive load, the differential line connected to the capacitive line shows the most change. Knowing this allows you to find the differential line which has the problem.

9

TDR Fundamentals

Introduction

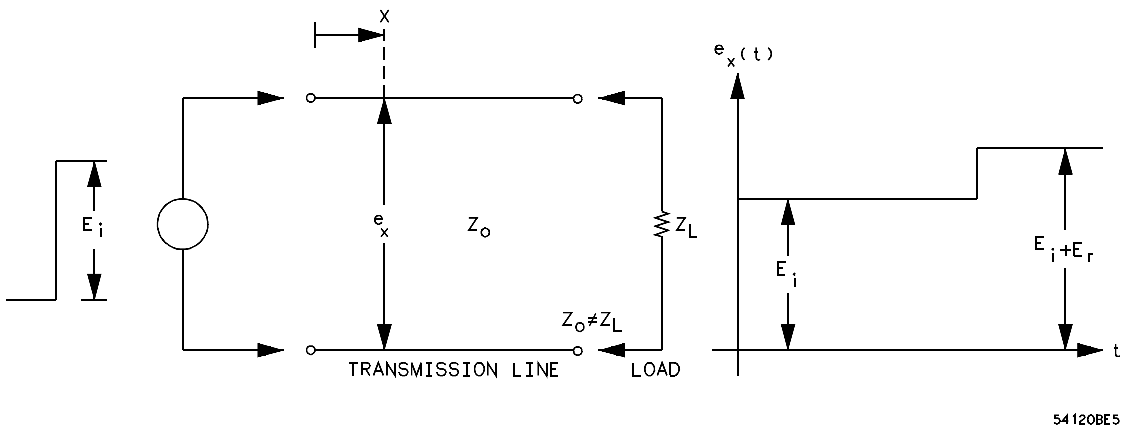
The most common method for evaluating a transmission line and its load has traditionally involved applying a sine wave to a system and measuring waves resulting from discontinuities on the line. From these measurements, the standing wave ratio (SWR) is calculated and used as a figure of merit for the transmission system. When the system includes several discontinuities, however, the SWR measurement fails to isolate them. Consider a case where the load is well matched to the transmission line (i.e., $Z_L = Z_o$) but several connector joining segments of the line act as minor discontinuities. This is a realistic situation since BNC connectors, for example, will typically look like small inductors in series with the line. The SWR measurement does not single out the component or components causing the discontinuity; it only indicates their aggregate effect. Any attempt to improve the system, becomes a trial and error method of component substitution. In addition SWR techniques fail to demonstrate whether one discontinuity is generating a reflection of the proper phase and magnitude to cancel (at a particular frequency) the reflection from a second discontinuity. When the broadband quality of a transmission system is to be determined, SWR measurements must be made at many frequencies, and this method soon becomes very time consuming and tedious.

TDR avoids all of these disadvantages of the SWR method. TDR employs a step generator and an oscilloscope in a system best described as "closed- loop radar." A voltage step is propagated down the transmission line under investigation, and the incident and reflected voltage waves are monitored by the oscilloscope at a particular point on the line.

This echo technique (see Figure 9-1) reveals at a glance the characteristic impedance of the line, and it shows both the position and the nature (resistive, inductive, or capacitive) of each discontinuity along the line. TDR also demonstrates whether losses in a transmission system are series losses or shunt losses. All of this information is immediately available from the oscilloscope's display. TDR also gives more meaningful information concerning the broadband response of a transmission system than any other measuring technique.

Since the basic principles of time domain reflectometry are easily grasped, even those with limited experience in high frequency measurements can quickly master this technique. This chapter attempts a concise presentation of the fundamentals of TDR and then relates these fundamentals to the parameters that can be measured in actual test situations. Before discussing these principles further we will briefly review transmission line theory.

Figure 9-1

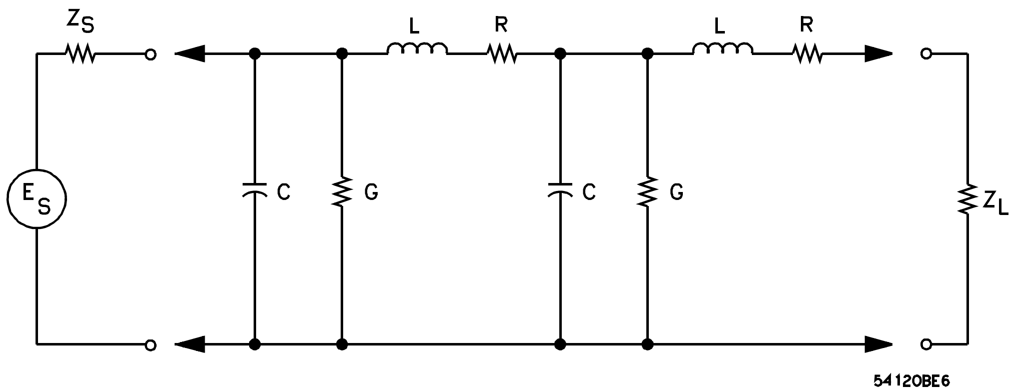


Voltage vs Time at a Particular Point on a Mismatched Transmission Line Driven with a Step of Height E_i

Propagation on a Transmission Line

The classical transmission line is assumed to consist of a continuous structure of resistors (R), inductors (L) and capacitors (C), as shown in Figure 9-2. By studying this equivalent circuit, several characteristics of the transmission line can be determined.

Figure 9-2



The Classical Model for a Transmission Line.

If the line is infinitely long and R, L, G, and C are defined per unit length, then

$$Z_{in} = Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega L}}$$

where Z_o is the characteristic impedance of the line. A voltage introduced at the generator will require a finite time to travel down the line to a point x. The phase of the voltage moving down the line will lag behind the voltage introduced at the generator by an amount β per unit length. Furthermore, the voltage will be attenuated by an amount α per unit length by the series resistance and shunt conductance of the line. The phase shift and attenuation are defined by the propagation constant γ,where

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

where α = attenuation in nepers per unit length
β = phase shift in radians per unit length

The velocity at which the voltage travels down the line can be defined in terms of β where:

$$v_p = \frac{\omega}{\beta} \text{ unit length per second}$$

The velocity of propagation approaches the speed of light, v_c, for transmission lines with air dielectric. For the general case where ε_r is the dielectric constant.

$$v_p = \frac{v_c}{\sqrt{\varepsilon_r}}$$

The propagation constant γ can be used to define the voltage and the current at any distance x down an infinitely long line by the relations

$$E_x = E_{in}e^{-\Upsilon x}$$

$$I_x = I_{in}e^{-\Upsilon x}$$

Since the voltage and the current are related at any point by the characteristic impedance of the line

$$Z_o = \frac{E_{in}e^{-\Upsilon x}}{I_{in}e^{-\Upsilon x}} = \frac{E_{in}}{I_{in}} = Z_{in}$$

When the transmission line is finite in length and is terminated in a load whose impedance matches the characteristic impedance of the line, the voltage and current relationships are satisfied by the preceding equations.

If the load is different from Z_O, these equations are not satisfied unless a second wave is considered to originate at the load and to propagate back up the line toward the source. This reflected wave is energy that is not delivered to the load. Therefore, the quality of the transmission system is indicated by the ratio of this reflected wave to the incident wave originating at the source. This ratio is called the voltage reflection coefficient, ρ, and is related to the transmission line impedance by the equation:

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

The magnitude of the steady-state sinusoidal voltage along a line terminated in a load other than Z_O varies periodically as a function of distance between a maximum and minimum value. This variation called a standing wave, is caused by the phase relationship between incident and reflected waves. The ratio of the maximum and minimum values of this voltage is called the voltage standing wave ratio, σ, and is related to the reflection coefficient by the equation

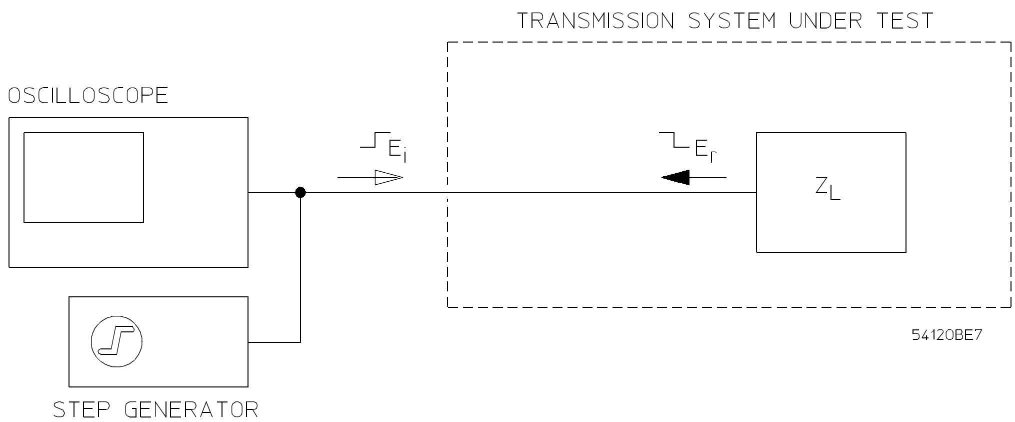
$$\sigma = \frac{1 + |\rho|}{1 - |\rho|}$$

As has been said, either of the above coefficients can be measured with presently available test equipment. But the value of the SW*R* measurement is limited. Again, if a system consists of a connector, a short transmission line and a load, the measured standing wave ratio indicates only the overall quality of the system. It does not tell which of the system components is causing the reflection. It does not tell if the reflection from one component is of such a phase as to cancel the reflection from another. The engineer must make detailed measurements at many frequencies before he can know what must be done to improve the broadband transmission quality of the system.

Step Reflection Testing

A time domain reflectometer setup is shown in Figure 9-3.

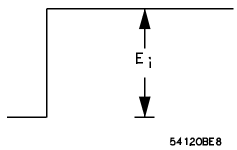
Figure 9-3



A Time Domain Reflectometer

The step generator produces a positive-going incident wave that is applied to the transmission system under test. The step travels down the transmission line at the velocity of propagation of the line. If the load impedance is equal to the characteristic impedance of the line no wave is reflected and all that will be seen on the oscilloscope is the incident voltage step recorded as the wave passes the point on the line monitored by the oscilloscope. Refer to Figure 9-4.

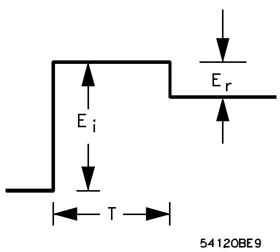
Figure 9-4



Oscilloscope Display When $E_r = 0$

If a mismatch exists at the load, part of the incident wave is reflected. The reflected voltage wave will appear on the oscilloscope display algebraically added to the incident wave. Refer to Figure 9-5.

Figure 9-5



Oscilloscope Display When $E_r \neq 0$

Locating Mismatches

The reflected wave is readily identified since it is separated in time from the incident wave. This time is also valuable in determining the length of the transmission system from the monitoring point to the mismatch. Letting D denote this length:

$$D = v_p \bullet \frac{T}{2} = \frac{v_p T}{2}$$

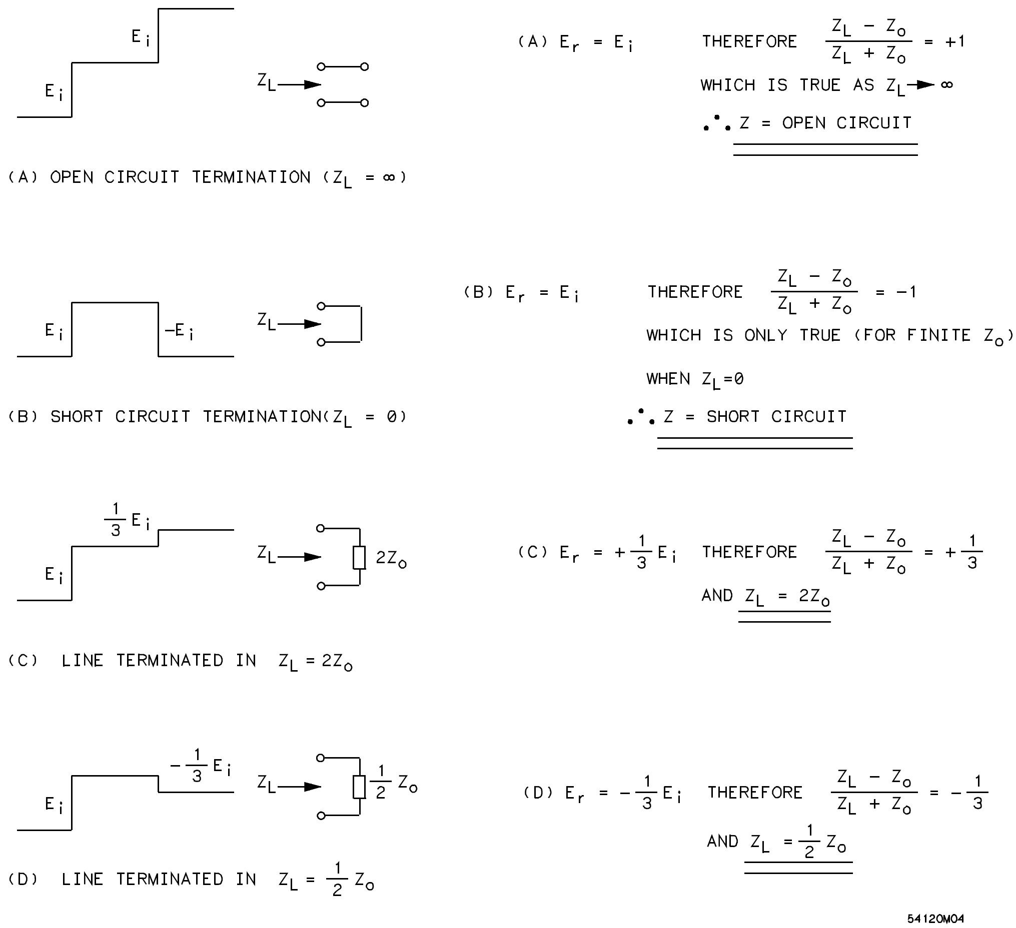
where v_p = velocity of propagation
T = transit time from monitoring point to the mismatch and back again, as measured on the oscilloscope (Figure 9-5)

The velocity of propagation can be determined from an experiment on a known length of the same type of cable for example, the time required for the incident wave to travel down and the reflected wave to travel back from an open circuit termination at the end of a 120 cm piece of RG-9A/U is 11.4 ns resulting in a v_p = 2.1 x 10 cm/sec. Knowing v_p and reading T from the oscilloscope determines D. The mismatch is then located down the line.

Analyzing Reflections

The shape of the reflected wave is also valuable since it reveals both the nature and magnitude of the mismatch. Figure 9-6 shows four typical oscilloscope displays and the load impedance responsible for each.

Figure 9-6



TDR Displays for Typical Loads

These displays are easily interpreted by recalling this equation:

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_o}{Z_L + Z_o}$$

Knowledge of E_i and E_r, as measured on the oscilloscope, allows Z_L to be determined in terms of Z_o, or vice versa. In Figure 9-6, for example, we may verify that the reflections are actually from the terminations specified.

Assuming Z_o is real (approximately true for high quality commercial cable), it is seen that resistive mismatches reflect a voltage of the same shape as the driving voltage, with the magnitude and polarity of E_r determined by the relative values of Z_o and R_L.

Also of interest are the reflections produced by complex load impedances. Four basic examples of these reflections are shown in Figure 9-7.

These waveforms could be verified by writing the expression for $\rho(s)$ in terms of the specific Z_L for example:

$$Z_L = R + sL,\ \frac{R}{1 + RCs}, \text{ etc.}$$

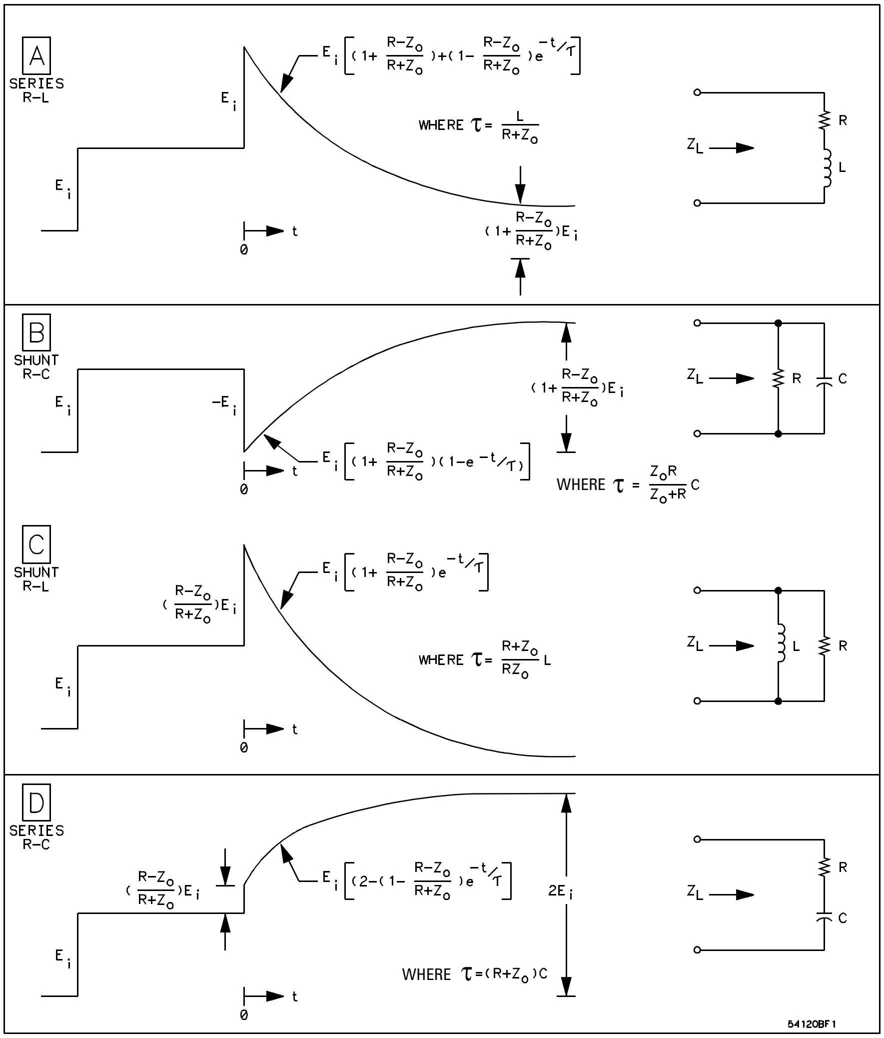
multiplying $\rho(s)$ by E_i/s the transform of a step function of E_i, and then transforming this product back into the time domain to find an expression for $e_r(t)$. This procedure is useful, but a simpler analysis is possible without resorting to Laplace transforms. The more direct analysis involves evaluating the reflected voltage at time t = 0 and at time t = ∞ and assuming any transition between these two values to be exponential. (For simplicity, time is chosen to be zero when the reflected wave arrives back at the monitoring point.) In the case of the series R-L combination, for example, at t = 0 the reflected voltage is $+E_i$. This is because the inductor will not accept a sudden change in current; it initially looks like an infinite impedance, and $\rho = +1$ at t = 0. Then current in L builds up exponentially and its impedance drops toward zero. At t = ∞, therefore $e_r(t)$ is determined only by the value of R.

$$\rho = \frac{R - Z_o}{R + Z_o} \text{ when } \iota = \infty$$

The exponential transition of $e_r(t)$ has a time constant determined by the effective resistance seen by the inductor. Since the output impedance of the transmission line is Z_o, the inductor sees Z_o in series with R, and

$$\Upsilon = \frac{L}{R + Z_o}$$

Figure 9-7



Oscilloscope Displays for Complex Z_L

A similar analysis is possible for the case of the parallel R-C termination. At time zero, the load appears as a short circuit since the capacitor will not accept a sudden change in voltage. Therefore $\rho = -1$ when $t = 0$. After some time, however, voltage builds up on C and its impedance rises. At $t = \infty$, the capacitor is effectively an open circuit:

$$Z_L = R$$

$$\therefore \quad \rho = \frac{R - Z_o}{R + Z_o}$$

The resistance seen by the capacitor is Z_o in parallel with R, and therefore the time constant of the exponential transition of $e_r(t)$ is:

$$\frac{Z_o R}{Z_o + R} C$$

The two remaining cases can be treated in exactly the same way. The results of this analysis are summarized in Figure 9-7.

Measuring the Time Constant of the Reflected Wave from Complex Loads

When one encounters a transmission line terminated in a complex impedance, determining the element values comprising Z_L involves measuring two things:

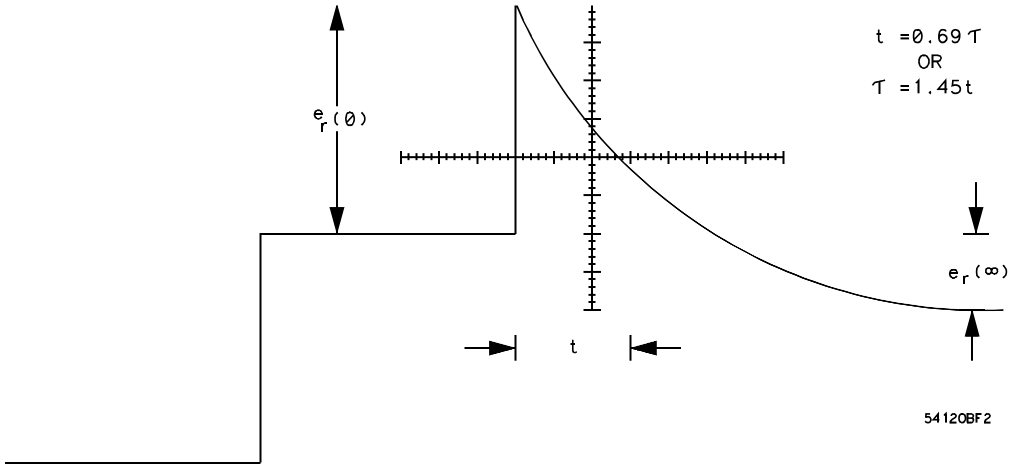
1. Either $e_r(t)$ at $t = 0$ or at $t = \infty$

and

2. The time constant of the exponential transition from $e_r(0)$ to $e_r(\infty)$.

Number 1 is a straight forward procedure from the information given in Figure 9-7. Number 2 is most conveniently done by measuring the time to complete one half of the exponential transition from $e_r(0)$ to $e_r(\infty)$. The time for this to occur corresponds to 0.69 t, where t denotes the time constant of the exponential. Adjusting the vertical sensitivity of the oscilloscope in the TDR system so that the exponential portion of the reflected wave fills the full vertical dimension of the graticule makes this measurement very easy (Figure 9-8).

Figure 9-8

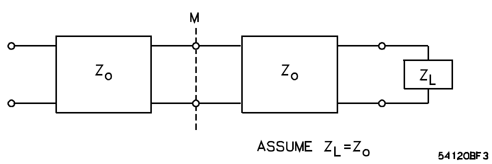


Determining the Time Constant of a Reflected Wave Returning from a Complex Z_L

Discontinuities on the Line

So far, mention has been made only about the effect of a mismatched load at the end of a transmission line. Often, however, one is not only concerned with what is happening at the load, but also at intermediate points along the line. Consider the transmission system in Figure 9-9.

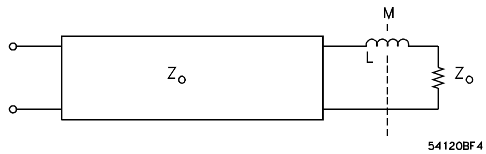
Figure 9-9



Transmission System

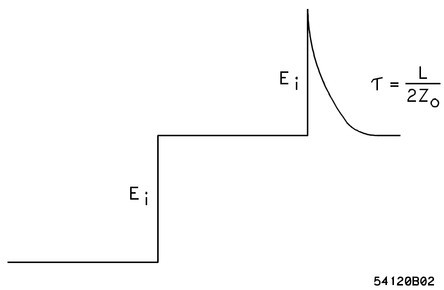
The junction of the two lines (both of characteristic impedance Z_o) employs a connector of some sort. Let us assume that the connector adds a small inductor in series with the line. Analyzing this discontinuity on the line is not much different from analyzing a mismatched termination. In effect, one treats everything to the right of M in the figure as an equivalent impedance in series with the small inductor and then calls this series combination the effective load impedance for the system at the point M. Since the input impedance to the right of M is Z_o, an equivalent representation is shown in Figure 9-10. The pattern on the oscilloscope is merely a special case of Figure 9-7A and is shown on Figure 9-11.

Figure 9-10



Equivalent System

Figure 9-11



Evaluating Cable Loss

Time domain reflectometry is also useful for comparing losses in transmission lines. Cables where series losses predominate, reflect a voltage wave with an exponentially rising characteristic, while cables where shunt losses predominate, reflect a voltage wave with an exponentially-decaying characteristic. This can be understood by looking at the input impedance of the lossy line.

Assuming that the lossy line is infinitely long, the input impedance is given by:

$$Z_{in} = Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Treating first the case where series losses predominate, G is so small compared to ωC that it can be neglected:

$$Z_{in} = \sqrt{\frac{R + j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}}\left(1 + \frac{R}{j\omega L}\right)^{\frac{1}{2}}$$

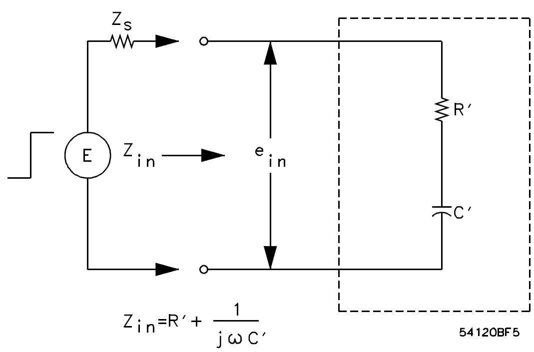
Recalling the approximation $(1 + x)^a \cong (1 + ax)$ for x<1, Z_{in} can be approximated by:

$$Z_{in} \cong \sqrt{\frac{L}{C}}\left(1 + \frac{R}{2j\omega L}\right) \text{ when } R < \omega L$$

Since the leading edge of the incident step is made up almost entirely of high frequency components, R is certainly less than ωL for $t = 0^+$. Therefore, the above approximation for the lossy line which looks like a simple series R-C network, is valid for a short time after t = 0. It turns out that this model is all that is necessary to determine the transmission line's loss.

In terms of an equivalent circuit valid at $t = 0^+$, the transmission line with series losses is shown in Figure 9-12.

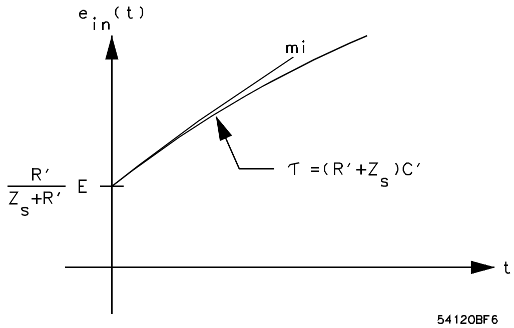
Figure 9-12



A Simple Model Valid at t = 0⁺ for a line with series losses

The response to a step of height E appears as shown in Figure 9-13, where Z_s = source impedance, and assumed resistive.

Figure 9-13



Transmission Line with Series Losses

In the case where $Z_s = R'$, and $\tau = 2Z_sC'$ and the initial slope of $e_{in}(t)$ is given by:

$$m_i = \frac{E}{4R'C'} = \frac{E}{8L}R$$

The series resistance of the lossy line (R) is a function of the skin depth of the conductor and therefore is not constant with frequency. As a result, it is difficult to relate the initial slope with an actual value of R. However, the magnitude of the slope is useful in comparing cables of different loss.

A similar analysis is possible for a cable where shunt losses predominate. Here the input admittance of the lossy cable is given by:

$$Y_{in} = \frac{1}{Z_{in}} = \sqrt{\frac{G + j\omega C}{R + j\omega L}} = \sqrt{\frac{G + j\omega C}{j\omega L}}$$

Since R is assumed small, re-writing this expression for Y_{in}:

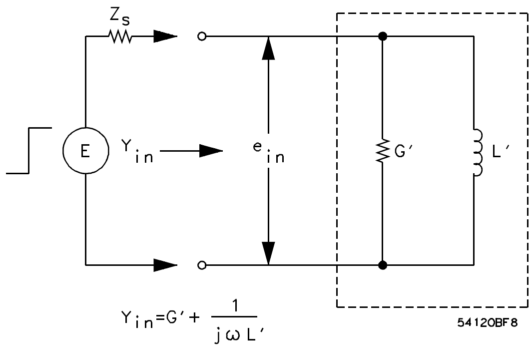
$$Y_{in} = \sqrt{\frac{C}{L}}\left(1 + \frac{G}{j\omega C}\right)^{\frac{1}{2}}$$

Again approximating the polynomial under the square root sign:

$$Y_{in} \cong \sqrt{\frac{C}{L}}\left(1 + \frac{G}{2j\omega C}\right) \text{ when } G < \omega C$$

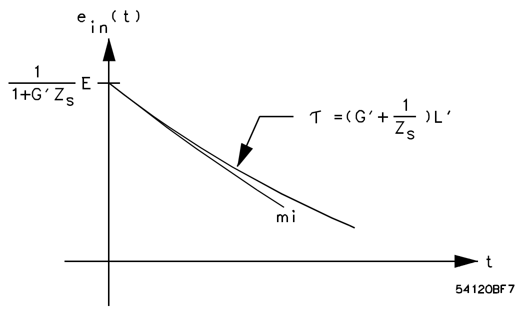
Going to an equivalent circuit () valid at $t = 0^+$, $e_{in}(t)$ will look like Figure 9-15.

Figure 9-14



A Simple Model Valid at 0+ for a Line with Shunt Losses

Figure 9-15



Assuming $G' = \frac{1}{Z_s}$, $\tau = 2G'L'$ and the initial slope of $e_{in}(t)$ is given by:

$$m_i = -\frac{E}{4G'L'} = -\frac{E}{8C}G$$

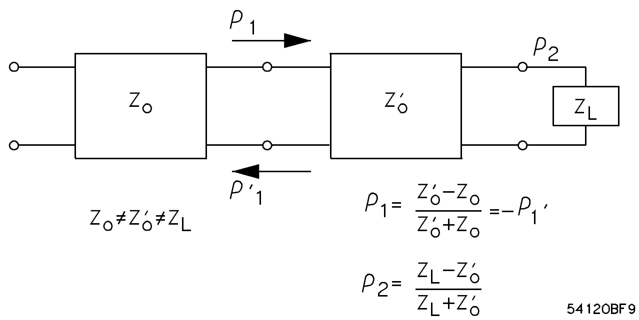
Again G depends on frequency, but relative loss can be estimated from the value of m_i.

A qualitative interpretation of why $e_{in}(t)$ behaves as it does is quite simple in both these cases. For series losses, the line looks more and more like an open circuit as time goes on because the voltage wave traveling down the line accumulates more and more series resistance to force current through. In the case of shunt losses, the input eventually looks like a short circuit because the current traveling down the line sees more and more accumulated shunt conductance to develop voltage across.

Multiple Discontinuities

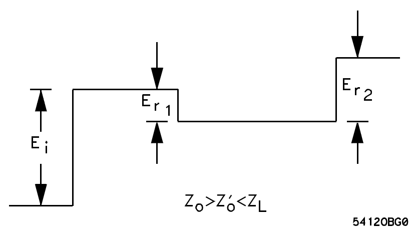
One of the advantages of TDR is its ability to handle cases involving more than one discontinuity. An example of this is Figure 9-16.

Figure 9-16



The oscilloscope's display for this situation would be similar to the diagram in Figure 9-17 (drawn for the case where $Z_L > Z_o > Z'_o$):

Figure 9-17



It is seen that the two mismatches produce reflections that can be analyzed separately. The mismatch at the junction of the two transmission lines generates a reflected wave, E_{r1}, where

$$E_{r1} = \rho_1 E_i = \left(\frac{Z_o' - Z_o}{Z_o' + Z_o}\right) E_i$$

Similarly, the mismatch at the load also creates a reflection due to its reflection coefficient

$$\rho_2 = \frac{Z_L - Z_o'}{Z_L + Z_o'}$$

Two things must be considered before the apparent reflection from Z_L, as shown on the oscilloscope, is used to determine ρ_2. First, the voltage step incident on Z_L is $(1 + \rho_1)\ E_i$, not merely E_i: Second, the reflection from the load is

$$[\rho_2(1+\rho_1)E_i] = E_{rL}$$

but this is not equal to E_{r2} since a re-reflection occurs at the mismatched junction of the two transmission lines. The wave that returns to the monitoring point is

$$E_{r2} = (1+\rho_1')E_{rL} = (1+\rho_1')[\rho_2(1+\rho_1)E_i]$$

Since $\rho_1' = -\rho_1$, E_{r2} may be re-written as:

$$E_{r2} = [\rho_2(1-\rho_1^2)]E_i$$

The part of E_{rL} reflected from the junction of Z_o' and Z_o, such as $\rho_1' E_{rL}$, is again reflected off the load and heads back to the monitoring point only to be partially reflected at the junction of Z_o', and Z_o. This continues indefinitely, but after some time the magnitude of the reflections approaches zero.

Practical Handling of Multiple Discontinuities.

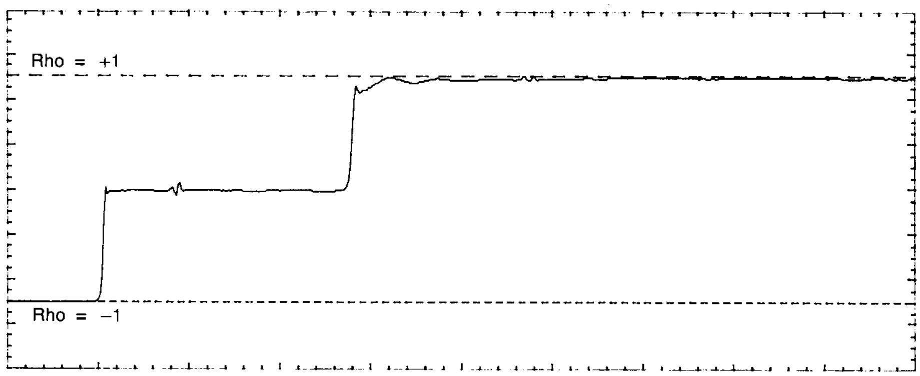
It is now seen that although TDR is useful when observing multiple discontinuities, one must be aware of the slight complication they introduce when analyzing the display. It is fortunate that most practical measuring situations involve only small mismatches (e.g., $Z_o \cong Z_o'$) and the effect of multiple reflections is almost nil. Even in this situation, however, it is advisable to analyze and clean up a system from the generator end. The reflection from the first of any number of discontinuities is unaffected by the presence of others. Therefore if it is remedied first and one then moves on to the second discontinuity, the complications introduced by re-reflections will not exist.

Matching Source Impedance to Transmission Line Impedance

Until now nothing has been said concerning reflections that may have occurred at the generator end of the transmission line. In general, the source impedance of the step generator may not be equal to the characteristic impedance of the transmission line it drives. When this is the case, voltage waves returning from a mismatch or discontinuity in the system under test will be re- reflected at the generator end and will complicate the analysis of the display. Referring to Figure 9-18 and Figure 9-19, it is almost essential that the source impedance of the step generator match the cable it drives. When this is the case, all re-reflections returning from the system under test pass the oscilloscope's monitoring point only once and are then absorbed in the source impedance of the step generator.

Figure 9-18 is the oscilloscope display of a TDR system investigating a transmission line terminated into an open circuit. The source impedance of the step generator matches the characteristic impedance of the line under test ($Z_S = Z_O = 50\ \Omega$).

Figure 9-18

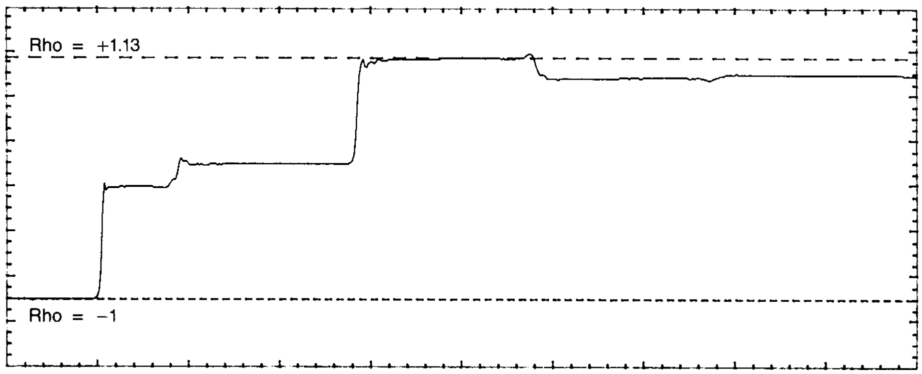


A 50 Ω TDR System Testing a 50 Ω Line Terminated With an Open Circuit.

In Figure 9-19 this was not the case. Here the source impedance of the step generator is 50 Ω and the line impedance is 75 Ω. The jump from a 50 Ω to a 75 Ω cable is evident and follows TDR rules. But the step from the 75 Ω cable to the open circuit does not. Instead of jumping to a +1 reflection coefficient for an open circuit, the trace actually exceeds that value.

The 50 Ω to 75 Ω mis-match caused the reflected wave returning from the open circuit to be re-reflected at the source, thus launching a second incident wave down the line. This second wave travels back to the monitoring point. The second reflected wave, in turn, launches a third incident wave, down the line. This process continues indefinitely, but unless the reflection coefficient at each end is equal to ±1, the reflections decrease in magnitude and only the first few are noticeable.

Figure 9-19

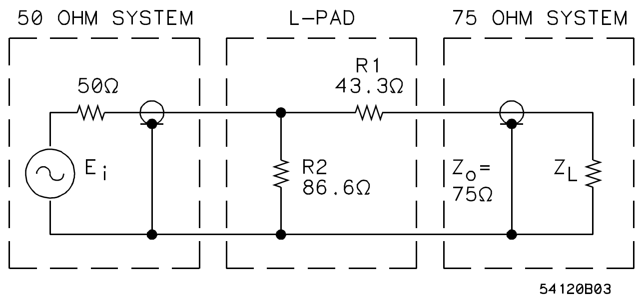


A 50 Ω TDR System Testing a 75 Ω Line Terminated With an Open Circuit Yields a Display That is More Difficult to Interpret

Balun For measurements of transmission lines in the 200 Ω to 300 Ω region, a balun is the best solution. A good balun will permit a 200 Ω line to be tested without the danger of re-reflections from the 50 Ω source. A broadband balun should be used so that the incident step is not appreciably affected by sag or loss of risetime.

Matching L-Pad To completely eliminate the effect of multiple reflections in a non 50 Ω system, use a simple matching L-pad. Refer to Figure 9-20 and Figure 9-21.

Figure 9-20



L-Pad Matching 50 Ω Source to 75 Ω System Impedance

for $Z_o > 50\ \Omega$:

Resistance in series with Z_o, $R_1 = \sqrt{Z_o(Z_o - 50)}$

Shunt resistance, $R_2 = \sqrt{\frac{50Z_o}{R_1}}$

for $Z_o < 50\ \Omega$:

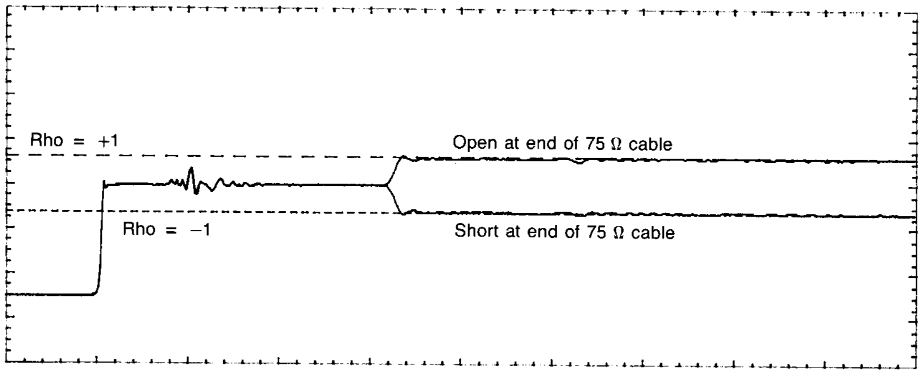
Resistance in series with source, $R_2 = \sqrt{50(50 - Z_o)}$

Shunt resistance, $R_2 = \sqrt{\frac{50Z_o}{R_1}}$

The incident step and the reflections will be attenuated considerably. Refer to Figure 9-21. The sacrifice made to achieve the reflectionless connection is sensitivity, and a loss of calibration. It is a good rule of thumb to use the L-pad technique when major discontinuities are to be encountered and a tapered section when small discontinuities are present (such as in cable testing).

The ±100% reflection points may be determined with the voltage markers and by using a short and open at the transmission line's end.

Figure 9-21



A 50 Ω **TDR System with a Matching L-Pad to the 75 Ω cable. The Amplitude Corresponding to Rho = ±1 is Reduced Using the Matching L-Pad**

Instrument Configuration

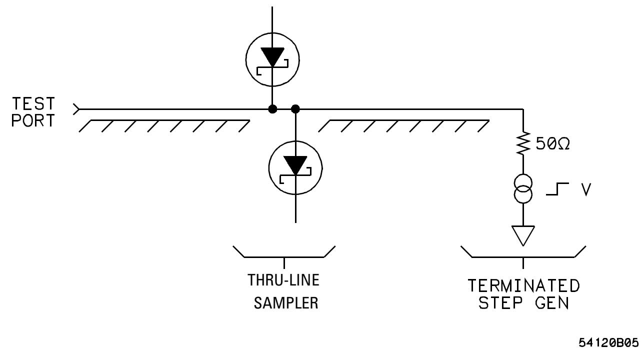
In the proceeding sections little consideration was given to the effects of the configuration of the oscilloscope and step generator on the measurement. Now lets examine this important part of the TDR measurement.

There are several different architectures for accomplishing a TDR measurement. They are:

- Terminated step generator and through-line sampler.
- Terminated sampler and through-line step generator.
- Terminated sampler, terminated step generator, and power splitter.

Traditionally, TDR systems have used the terminated step generator and through-line sampler architecture shown in Figure 9-22.

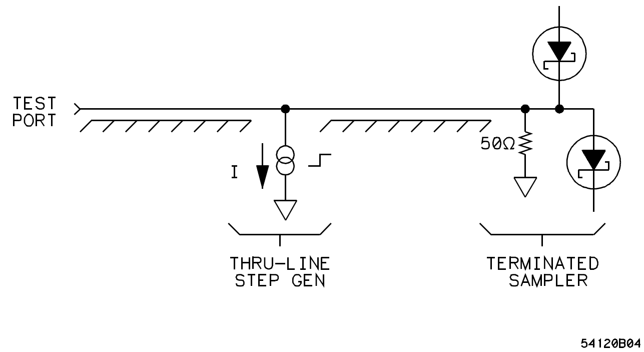
Figure 9-22



The step generator was implemented using a tunnel diode. Because a tunnel diode is a low impedance device, it lends itself to a terminated configuration. The major drawback of this architecture is that small reflections from the terminated step generator are measured directly by the through-line sampler.

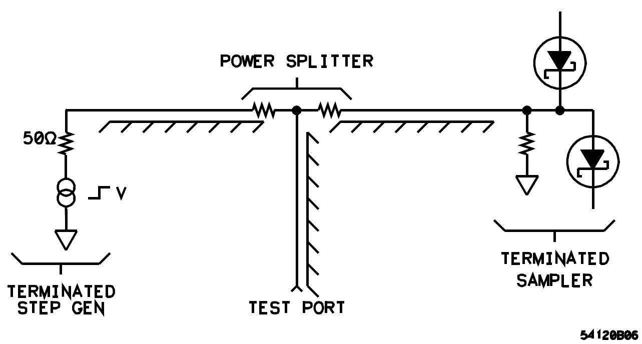
In the Agilent 54750 Series TDR systems, the terminated sampler and through-line step generator architecture in Figure 9-23 is used. In this case step generation is accomplished using a switched current source driven from a step recovery diode. This configuration is advantageous because small reflections from the terminated sampler propagate back to the through-line step generator where only a small portion of the already small reflection is sent back to the terminated sampler and measured. None of the reflections from the step generator or the sampler are measured directly, thus improving the system performance.

Figure 9-23



The terminated sampler, terminated step generator, and power splitter architecture in Figure 9-24 is usable but is typically not used because both the incident and reflected step are attenuated when they pass through the power splitter. This decreases the system signal-to-noise ratio.

Figure 9-24



Risetime and Distance Resolution

The examples shown so far have assumed that the TDR step has zero risetime. Practical TDR systems have a finite risetime for both the step generator and the sampler. The effect of the finite risetime of the TDR system is to low-pass filter the ideal (zero risetime) response of a given discontinuity with a filter that has a risetime equal to the combined risetime of the step generator, sampler, and test setup which is approximated by:

$$t_{r\ \text{system}} \cong \sqrt{(t_{r\ \text{step gen}})^2 + (t_{r\ \text{sampler}})^2 + (\text{test setup})^2}$$

The distance or time resolution of a Time Domain Network Analysis (TDNA) system is related to the system risetime. The distance to a discontinuity is given by:

$$d = \upsilon t$$

so that

$$d = \frac{c}{\sqrt{\varepsilon_r}}\frac{t_o}{2}$$

where c is the speed of light, t_o is the Delta time between the incident step and the reflected signal, and ε_r is the relative dielectric constant of the dielectric of the transmission line. Therefore the distance that separates two discontinuities is given by:

$$\Delta d = \frac{c}{\sqrt{\varepsilon_r}}\frac{t_2 - t_1}{2}$$

where t_1 is the two way travel time to one discontinuity and t_2 is the two way travel time to second discontinuity. These two discontinuities become indistinguishable when separated by a time (t_2 - t_1) of less than half the system risetime. Therefore the minimum distinguishable distance between two discontinuities is given by:

$$d_{min} = \frac{c}{\sqrt{\varepsilon_r}}\frac{t_r}{4}$$

This means that with the Agilent 54750 Series TDR system risetime of 45 ps, two discontinuities merge together and become indistinguishable at 3.5 mm for an air dielectric. For practical systems the Agilent 54750 Series TDR systems define the distance resolution to be twice this number, or 7 mm in air.

An example of how risetime affects distance resolution is an airline with two washers (capacitive discontinuities) placed 2 mm apart on the center conductor. The risetime needed to distinguish these as separate discontinuities is given by:

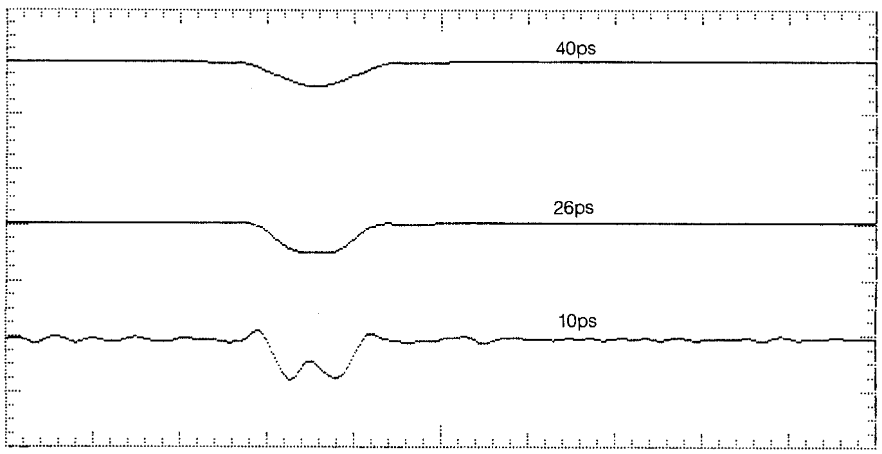
$$d_{min} = \frac{c}{\sqrt{\varepsilon_r}}\frac{t_r}{4}$$

or

$$t_r = \frac{4d_{min}\sqrt{\varepsilon_r}}{c} = 26.7 \text{ ps}$$

The results of a TDR measurement, using normalization to decrease the system risetime, on this airline at three different risetimes (40, 26, and 10 ps) is shown in Figure 9-25. At 40 ps it is not possible to distinguish each discontinuity. At 26 ps the separate discontinuities begin to show. Finally, at 10 ps risetime both discontinuities are clearly discernible.

Figure 9-25



Two Discontinuities 2 mm Apart can be Distinguished with a System Risetime of 10 ps

Small L's and C's

Figure 9-26 is an example of risetime effects for a series L discontinuity in a 50 Ω line. If the combined step generator and sampler risetime, $t_{r\ system}$, is much less than the risetime of the low-pass filter, $t_{r\ lpf}$, created by the discontinuity (where $t_{r\ lpf} \sim 2.2 \times T$ where $T = L \div 100\ \Omega$), the result approaches the ideal as shown in Figure 9-26 Plot A. If $t_{r\ system} \sim t_{r\ lpf}$, the result is as shown in Figure 9-26 Plot C. If $t_{r\ system} > t_{r\ lpf}$, the result is as shown in Figure 9-26 Plot D.

Plot A: $t_{r\ lpf} = 100 \times t_{r\ system}$ = approaches ideal

Plot B: $t_{r\ lpf} = 10 \times t_{r\ system}$

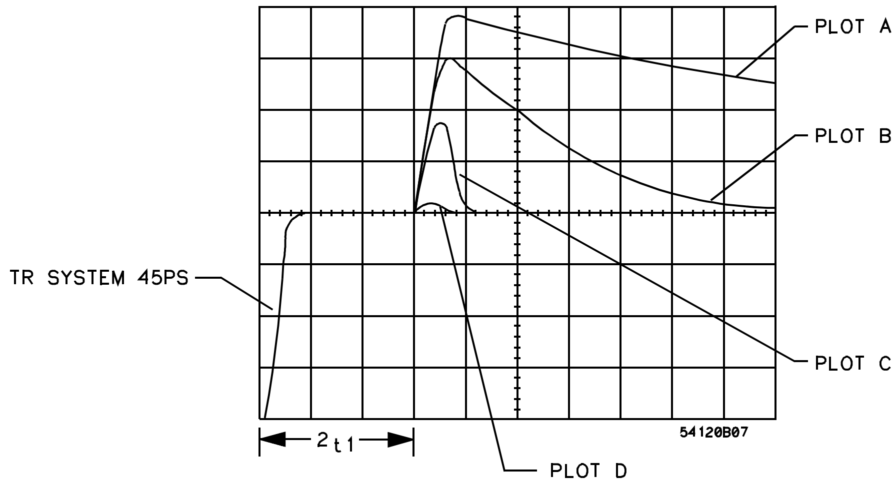
Plot C: $t_{r\ lpf} = t_{r\ system}$

Plot D: $t_{r\ lpf} = 1/10 \times t_{r\ system}$

$t_{r\ system}$ = Combined risetime of the step generator and sampler.

$t_{r\ lpf}$ = Risetime of the low pass filter created by the discontinuity.

Figure 9-26



System Risetime Affects the TDR Results

In analyzing TDR results so far, we have assumed that the time constant and therefore risetime ($t_{r\ lpf}$) created by a discontinuity were known and therefore the value of the inductor L or capacitor C was also known. In most TDNA measurements, only the combined step generator and sampler risetime ($t_{r\ system}$) and the reflected waveform are known. From this information, you may want to derive the value of the discontinuity L or C. Again three cases exist in this analysis. If $t_{r\ system} << t_{r\ lpf}$, then, as stated earlier, the TDR response approaches the ideal result and a value for the L or C can be calculated (as in Figure 9-7) from the measured time constant of the exponential decay or rise to the final value. If $t_{r\ system}$ is of the same order of magnitude as $t_{r\ lpf}$, then calculating the L or C discontinuity becomes much more difficult due to the interaction of the time constants.

One way to find the value of the L or C in this case is to use a SPICE simulation program to model the response and vary the L or C value until the maximum reflection on the SPICE simulation program and the TDR waveform match. Accuracy depends on using realistic waveforms in the SPICE simulation. When $t_{r\ system} >> t_{r\ lpf}$, such as small reflections, it is possible to relate the reflected signal to the value of the L or C by assuming the L or C is driven by a current or voltage source. This is equivalent to saying that for the frequencies contained in the step, the impedance of a discontinuity does not significantly alter the impedance of the circuit loading it. Using this approximation, we can relate the maximum slope of the step to the maximum reflection from the discontinuity. If the TDNA step is Gaussian (or can be normalized to an approximately Gaussian step), then it can be shown that the maximum slope of the step is 27%

higher than the slope of a line through the 10% and 90% risetime points. For reflections less than 10%, the error resulting from this method is less than 3%, not including measurement error of the TDR system.

For a series inductive discontinuity, the relationship between the reflected signal and the inductor, L, is found as follows:

1 Since $\omega L << 100\ \Omega$ for frequencies of interest.

$i_L \sim v_{step} / 100\ \Omega$ where i_L is the current through L and v_{step} is the open circuit step amplitude

2 The voltage across the inductor therefore is:

$$v_L = L\frac{di_L}{dt} = \frac{L}{100}\frac{dv_{step}}{dt}$$

where v_L is the voltage across the inductor, and

$$v_{Lmax} = \left(\frac{L}{100}\frac{dv_{step}}{dt}\right)_{max}$$

3 As discussed above the max slope is

$$\left(\frac{dv_{step}}{dt}\right)_{max} = \frac{(0.8)(v_{step})(1.27)}{t_{rL}} = \frac{1.016v_{step}}{t_{rL}}$$

4 If the incident voltage at the inductor is v_{iL} and the reflected voltage at the inductor is v_{rL} then

$v_{iL} = 0.5v_{step}$ or $v_{step} = 2v_{iL}$

and

$v_{rL} = 0.5v_L$ or $v_L = 2v_{rL}$

5 Combining steps 2, 3 4 above produces

$$v_{Lmax} = \frac{L}{100}\left(\frac{v_{step}}{dt}\right)_{max}$$

$$v_{Lmax} = \frac{L}{100}\frac{1.016v_{step}}{t_{rL}}$$

$$2v_{rLmax} = \frac{L}{100}\frac{2v_{iL}}{t_{rL}}$$

$$L = \frac{100(v_{rL})(t_{rL})}{1.016v_{iL}}$$

Since

$$\rho = \frac{v_{rL}}{v_{iL}}$$

then

$$L = 98.4 \rho t_{r \text{ system}}$$

For a series L discontinuity ±3% when $\rho \leq$ to 10%

Using a similar derivation for a shunt C interline discontinuity, the relationship between shunt C and the reflection is:

$$C = 0.0303 \rho t_{rL}$$

For a shunt C discontinuity ±3% when $\rho \leq 10\%$

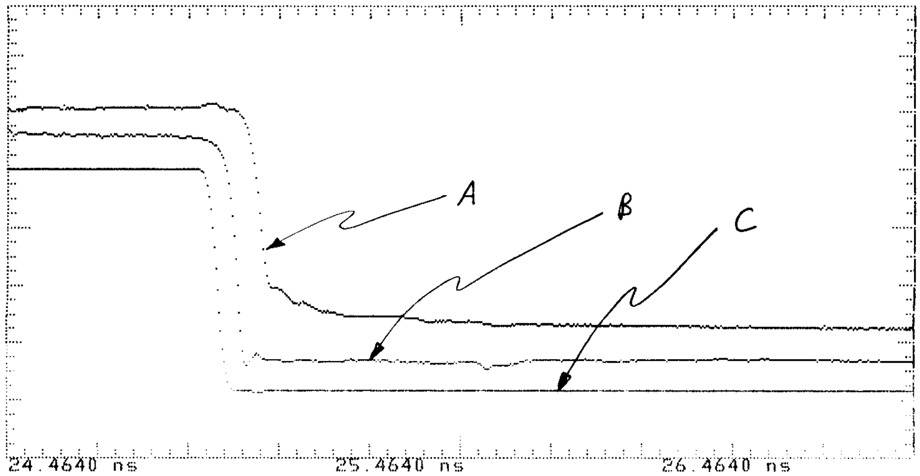
Cable Loss

As a step travels down a non-ideal transmission line, the higher frequencies are attenuated by skin effect losses and dielectric losses. This distorts the step, and is called cable loss. The effect of cable loss is shown in Figure 9-27 Plot A, which shows the reflection of a short at the end of a 1 meter cable. Since cable loss degrades the risetime of the TDR step, it can limit the distance resolution and the accuracy of reflection measurements made at the end of a cable.

If fast risetime TDR measurements are needed, short interconnecting cables should be used to reduce the effects of cable loss. The same reflection off a short is shown in Figure 9-27 Plot B except now it is at the end of a very short cable (approximately 5 cm).

Another way to reduce cable loss effects is to use normalization, if the TDR system has this capability. Normalization to an ideal (approximating a Gaussian) step removes the effects of cable loss to the point in the cable where a calibration is done which establishes the reference plane from which TDR measurements can be made without suffering effects from the cable. Calibration typically involves connecting a 50 Ω termination and a short termination at the reference plane. Figure 9-27 Plot C shows the results of normalizing the reflection of a short at the end of a 1 meter cable. Normalization can also be used to remove cable loss effects from transmission measurements.

Figure 9-27



Short Cables (B) and Normalization (C) can Reduce the Effects of Cable Loss Seen in (A)

Multiple Discontinuities

Multiple discontinuities are another source of error in TDR measurements. A discontinuity that occurs before the discontinuity of interest will cause a degradation of risetime and accuracy of reflection measurements similar to cable losses. Typically in a TDR system, if high accuracy and resolution are needed to examine a particular discontinuity on a transmission line, the reflections due to discontinuities that are before the one of interest must be small. One example involves a transmission line with two discontinuities on it. The first one has a maximum reflection coefficient of ρ_1 and the second of ρ_2. The percent error in ρ_2 due to ρ_1 is:

ρ_1	% error in ρ_2
0.01	<0.25%
0.05	~2%
0.10	~6%

These results are computed values and are useful for estimating errors in measurements. As with cable loss, you can remove the effects of multiple discontinuities using normalization up to the point in the transmission line where a calibration is done.

Using TDR to Test Interconnects

One of the largest applications of TDR measurements is optimizing and testing transmission line systems. An example of this involves the interface from a PC board 50 Ω line to a thickfilm hybrid 50 Ω line. If the connection was made with a 3 mm wire bond, then this would introduce a series inductive discontinuity into the line. Where L_{wb} is the inductance of the wire bond. Refer to Figure 9-28. A wire bond in free space would have an inductance of about 1.26 nH/mm but since it is located near the ground planes of the transmission lines the inductance is somewhat lower. A measured inductance for typical wire bonds on hybrids is about 1 nH/mm. If we assume this number, then the inductance of the 3 mm wire bond is 3 nH. This then says that the low-pass filter created by L_{wb} in the 50 Ω line has a risetime given by:

$$t_r = 2.2T$$

where T = time constant = L_{wb}/100 Ω = 2.2 × 3 nH/100 Ω = 66 ps

Therefore the risetime of the signal that is to pass through this discontinuity should be greater than 66 ps if it is not to be significantly degraded. If the signal to be transmitted through the discontinuity was a 350 ps risetime logic signal, then the risetime degradation would be small. Even though the risetime degradation is small there will be a significant reflection off the wire bond. Assuming the reflection is less than 10%, then an equation predicts a maximum reflection of:

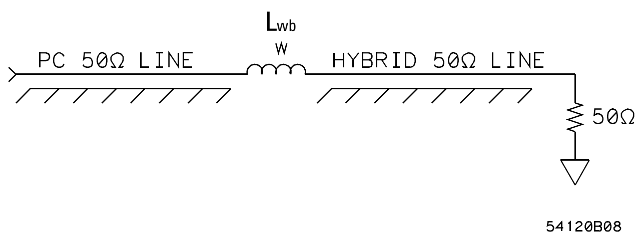
$$L = 98.4\rho t_{r\ \mathrm{system}}$$

or

$$\rho = \frac{L}{98.4 t_{r\ \mathrm{system}}} = \frac{3\ \mathrm{nH}}{(98.4)(350\ \mathrm{ps})} = 8.7$$

if the edge was an ideal Gaussian step.

Figure 9-28



If the step is not ideal, this gives an approximate answer. This reflection may or may not be a problem. If the circuit driving the 50 **Ω** line is source-terminated in 50 **Ω** then this will not be a problem, but if it is driven from a current source such as an open collector of a transistor, then it could. If it is desired to minimize reflections of this discontinuity, then there are methods to do this. Refer to Figure 9-28. If a TDR system is used to measure the transmission line, a response would be seen as shown in Figure 9-30 which is an inductive response with a max reflection of about 8.7% as predicted before. If the capacitance along the wire bond could be increased, this would reduce the maximum reflection since the wire bond section is moving towards a 50 **Ω** line. While it may not be possible to do this, it is possible to increase the capacitance at the two ends of the wire bond by widening the 50 **Ω** lines there. The circuit would now resemble the circuit shown in Figure 9-29. When the value of *C1* and *C2* are chosen properly, the TDR response of the system would now be as shown in Figure 9-31. The value of *C1* and *C2* which minimizes the maximum reflection is 0.6 pF which can be calculated from the equation.

$$Z_o = 50\Omega = \frac{L}{C}$$

where

$$C = C1 + C2$$

therefore

$$C1 = C2 = \frac{L}{Z_o^2} = 0.6 \text{ pF}$$

The resultant circuit is actually a third order Butterworth filter. Refer to Figure 9-31. The bandwidth of the resultant Butterworth filter has the same bandwidth as the initial single pole filter. Since the risetime of the step to be transmitted is much greater than the risetime of either the single pole or Butterworth filter there will be little effect on the transmitted step.

Figure 9-29

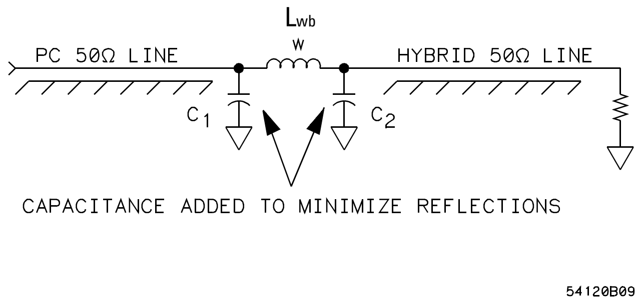
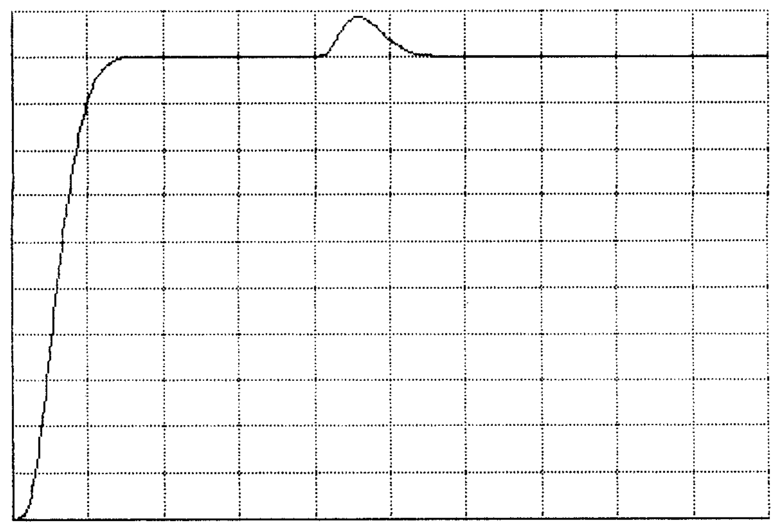
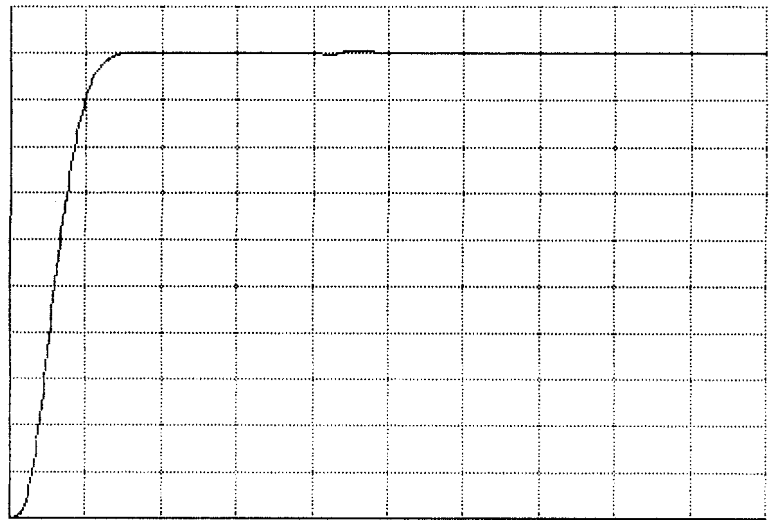


Figure 9-30



Inductance of the Wirebond Causes a Reflection

Figure 9-31



Extra Capacitance can Compensate for the Wirebond's Inductance, Reducing the Reflection

10

Improving Time Domain Network Measurements

Time Domain Network Analysis and Normalization

Normalization, an error-correction process, helps ensure that time domain network analysis measurements are as accurate as possible. The Agilent 54750A Series digitizing oscilloscopes with TDR capability include normalization as a standard feature. With normalization software built into the oscilloscope, external controllers and variable edge speed step generators or risetime converters are not needed. Normalization not only enhances measurement accuracy, it simplifies the measurement process.

Time domain network analysis (TDNA), includes both time domain reflectometry (TDR) and time domain transmission (TDT) measurements. TDNA measurement accuracies can be improved using normalization techniques. This chapter discusses normalization and assumes the reader is familiar with basic TDNA measurements.

Time domain reflectometry (TDR) sends a very fast edge down a transmission line to a test device and then measures the reflections from that device. The measured reflections can help to design signal path interconnects and transmission lines in IC packages, PC board traces, and coaxial connectors.

Time domain transmission (TDT) measurements are made by passing an edge through the test device. Parameters typically measured are gain and propagation delay. Transmission measurements also characterize crosstalk between traces.

Imperfect connectors, cabling, and even the response of the oscilloscope itself can introduce errors into TDNA measurements. Understanding the effects of these errors, and more importantly, how to remove them, will result in more accurate and useful measurements.

Normalization can be used in TDNA to remove the oscilloscope response, step aberrations, and cable losses and reflections so that the only response measured is that of the device under test (DUT). In addition, normalization can be used to predict how the DUT would respond to an ideal step of any arbitrary risetime.

Sources of Measurement Error

There are three primary sources of error in TDNA measurements: the cables and connectors, the oscilloscope, and the step generator.

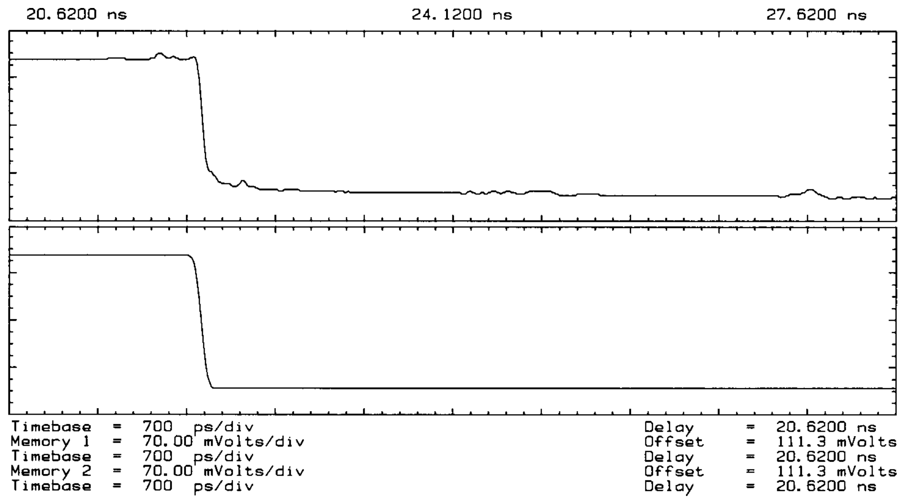
Cables and Connectors Cause Losses and Reflections

Cables and connectors between the step source, the DUT, and the oscilloscope can significantly affect measurement results. Impedance mismatches and imperfect connectors add reflections to the actual signal being measured. These can distort the signal and make it difficult to determine which reflections are from the DUT and which are from other sources.

In addition, cables are imperfect conductors that become more imperfect as frequency increases. Cable losses, which increase at higher frequencies, increase the risetime of edges and cause the edges to droop as they approach their final value.

Figure 10-1 illustrates how cables and connectors affect TDNA measurements. The upper waveform is the reflection of a step from a short circuit. Connections cause the reflections at the peak of the step and along the baseline. Cable loss yields the rounded transition of the step to its baseline level. Normalization can correct the measured data, resulting in the lower waveform.

Figure 10-1



The top waveform shows distortions caused by cables and connectors. The bottom waveform shows how normalization corrects for these distortions

The Oscilloscope as an Error Source

Oscilloscopes introduce errors into measurements in several ways. The finite bandwidth of the oscilloscope translates to limited risetime. Edges with risetimes that approach the minimum risetime of the oscilloscope are measured slower than they actually are. When measuring how a device responds to a very fast edge, the oscilloscope's limited risetime may distort or hide some of the device response.

The oscilloscope can also introduce small errors that are due to the trigger coupling into the channels and channel crosstalk. These errors appear as ringing and other non-flatness in the display of the measurement channel baseline and are superimposed on the measured waveform. They are generally small and are only significant when measuring small signals.

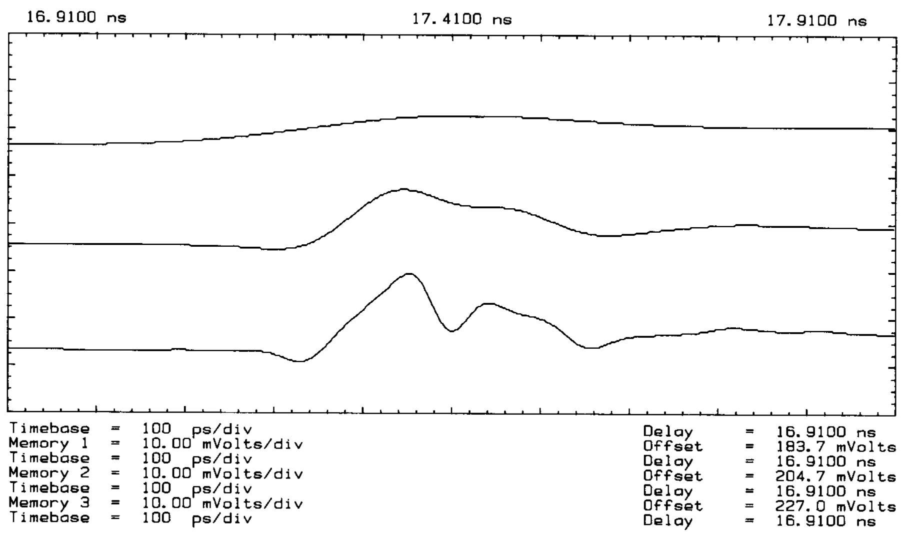
The Step Generator as an Error Source

The shape of the step stimulus is also important for accurate TDNA measurements. The DUT responds not only to the step, but also to the aberrations on the step such as overshoot and non-flatness. If the overshoot is substantial, the DUT's response can be more difficult to interpret.

The risetime of the step is also extremely important. In most cases the step generator used for TDNA will have a fixed risetime. A hardware filter known as a risetime convertor can be used in some systems to change the risetime.

To determine how the DUT will actually respond in it's intended application, you should test it at edge speeds similar to those it will actually encounter. Consider the example of a BNC connector (Figure 10-2). Only about 3% of a 350 ps risetime edge (top waveform) is reflected by a BNC connector whereas 6% of a 100 ps risetime edge (middle waveform) is reflected and about 8% of a 50 ps risetime edge (bottom waveform) is reflected.

Figure 10-2



Variable edge speed helps determine the amount of reflection in actual applications. The top waveform (tested to 350 ps) shows less reflection than the middle waveform (tested to 100 ps) or the bottom waveform (tested to 50 ps)

In the case of this measurement, the results obtained using a 50 ps risetime step stimulus do not apply for a connector that sees edges that are always slower than 350 ps. The connector might be acceptable for 350 ps edges but not for 50 ps edges. Measurements made at inappropriate risetimes can yield invalid conclusions.

Edge speed is also critical when using TDR to locate the source of a discontinuity along a transmission line. Just as the limited risetime of the oscilloscope can limit the accuracy of this kind of measurement, the risetime of the step source can also limit accuracy.

The edge speed also affects the spatial resolution of a TDR measurement or its ability to resolve discontinuities along a transmission line. This can be important when trying to extract models for an interconnect.

The risetime of the measurement system is limited by the combined risetimes of the oscilloscope and the step generator. It can be approximated by equation 1.

$$\text{System risetime} = \sqrt{(\text{Step risetime})^2 + (\text{Scope risetime})^2 + (\text{Test setup risetime})^2} \quad (1)$$

In a system with zero minimum risetime, the response of a discontinuity would not be attenuated at all. A real system has a limited risetime, which acts as a lowpass filter. If the step stimulus used is too slow, the true nature of the discontinuity may be disguised or may not even be visible. The cause may be more difficult to physically locate. Notice in Figure 10-2 that as the risetime of the step stimulus is decreased, the true nature of the reflection from the DUT becomes more apparent.

Removing Measurement Errors

Waveform Subtraction has Limitations

In the past, waveform subtraction was used to reduce the effects of some of the errors discussed above. It was convenient because many digitizing oscilloscopes provided this feature without the aid of an external controller. A known good reference device was measured and the reference waveform stored in memory. The reference waveform could then be subtracted from the waveform measured from the DUT. The result showed how the DUT response differed from the reference response. This technique removed error terms common to both the reference and DUT waveforms, such as trigger coupling, channel crosstalk, and reflections from cables and connectors.

Waveform subtraction has, however, several shortcomings. First, it requires that a known good reference DUT exists and is available to measure. In some cases a good DUT may not be readily available or may not exist at all. Second, the waveform which results from the subtraction process is a description of how the DUT response differs from the reference response. Hence, there is no way to view the actual DUT response without the errors introduced by the test system.

Finally, the most significant shortcoming is that measurements are limited to the risetime of the test system. Determining the DUT response at multiple risetimes is cumbersome. Either multiple step generators or multiple risetime convertors are necessary and a separate reference waveform is required for each risetime.

Normalization Improves on Error Correction

A digital error-correction method known as normalization can significantly reduce or remove all of the above types of errors from TDNA measurements. Taking full advantage of its powerful internal microprocessor, the Agilent 54750A Series digitizing oscilloscopes with TDR capability include normalization as a standard feature.

Normalization can predict how the DUT will respond to an ideal step of the user-specified risetime. Only one step generator and one normalization process are required. No risetime convertors are necessary, and the normalization standards are not related to the DUT.

Unlike a risetime converter, normalization can also increase the bandwidth (i.e., decrease the risetime) of the system by some amount depending on the noise floor. This means that when more bandwidth is critical, such as when trying to locate a discontinuity along a transmission line, the waveform data acquired by the oscilloscope can be "squeezed" for every bit of useful information it contains.

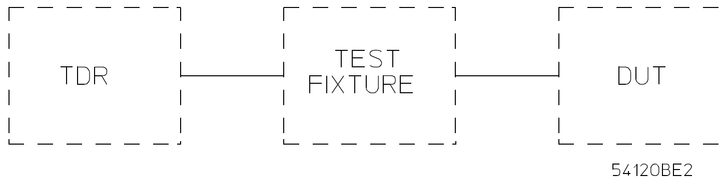
Examples of What Normalization Can Do

The following two examples illustrate what normalization can accomplish:

Example 1 Correcting for the TDR measurement errors introduced by connecting hardware.

Consider trying to model a device at the end of some imperfect test fixture as in Figure 10-3.

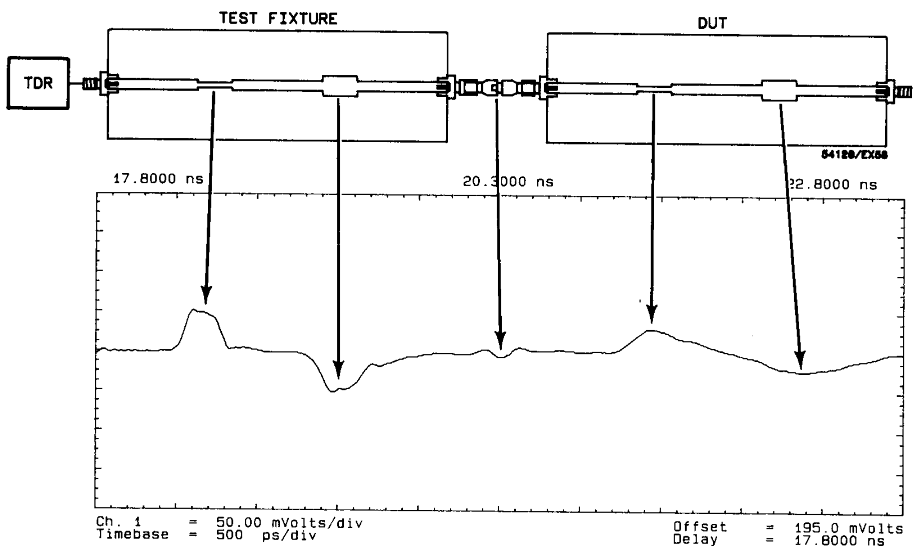
Figure 10-3



Test system with the device at the end of an imperfect test fixture

This example uses two identical printed circuit boards (PCBs) to model this measurement. The PCBs have a 50 Ω trace on them with two discontinuities. The first PCB represents the test fixture, and the second PCB represents the DUT. The goal is to accurately measure the reflections caused by the DUT (second PCB). Figure 10-4 is the unnormalized response of the system.

Figure 10-4

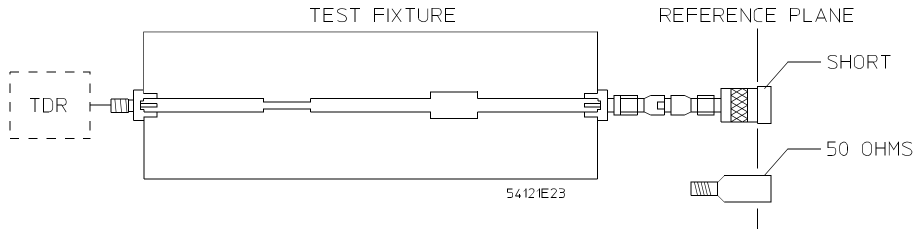


In an unnormalized measurement, the reflections from the DUT are masked by the imperfect test fixture

The TDR response shows the reflections of the second PCB to be different from the first PCB. TDR accurately measures the first discontinuity. But TDR measures each succeeding discontinuity with less accuracy, as the transmitted step degrades and multiple reflections occur. Thus the two identical boards show different responses.

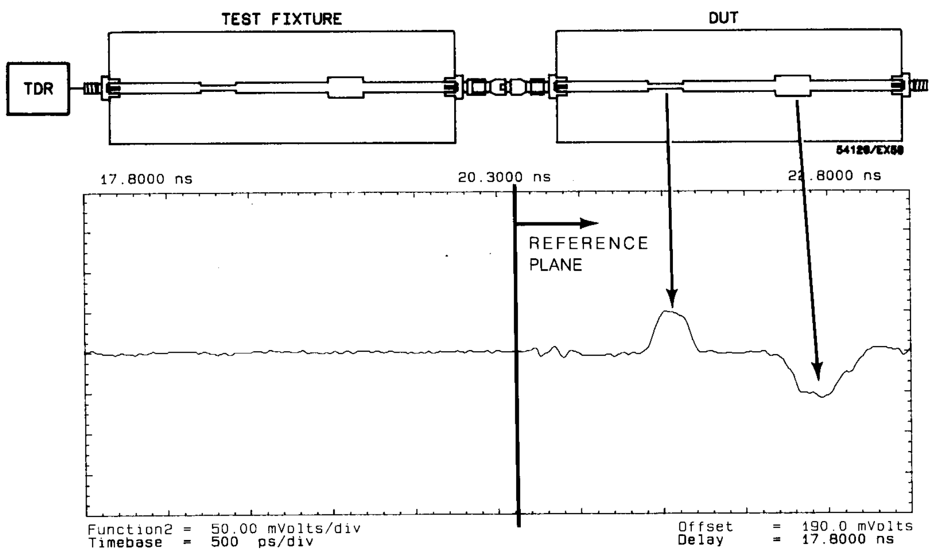
By defining a reference plane to be at the end of the test fixture (first PCB) and then normalizing, the errors can be corrected.

Figure 10-5



Normalization uses a short, then a 50 Ω termination to define a reference plane and to generate a digital filter

Figure 10-6

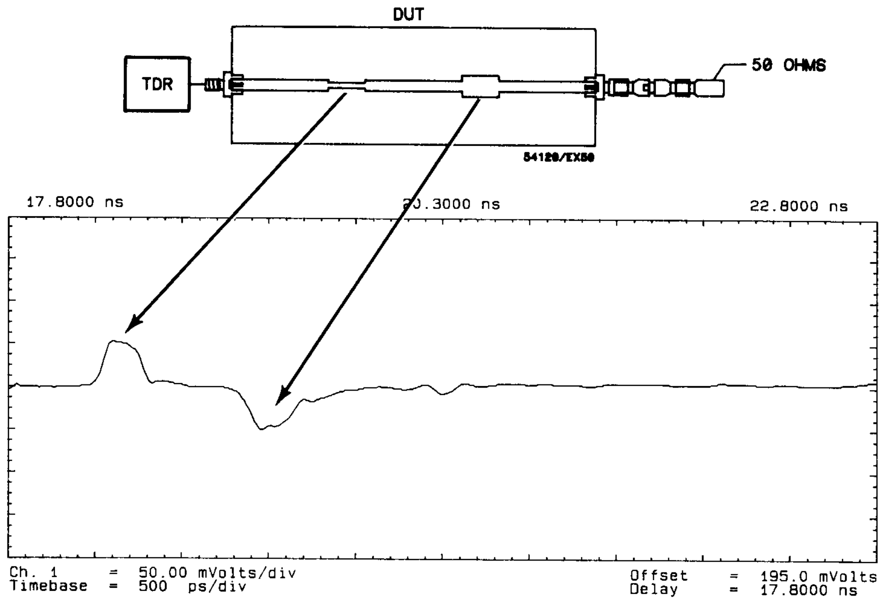


The normalized measurement corrects for the errors introduced by test fixture.

normalization first defines a reference plane and generates a digital filter. The normalizing measurement then corrects for the errors introduced by the test fixture. Notice how the normalized response of the second PCB (DUT) now matches the response measured earlier of the nearly identical first PCB.

To further verify the accuracy of the normalization, the response of the second PCB is measured without the first PCB.

Figure 10-7

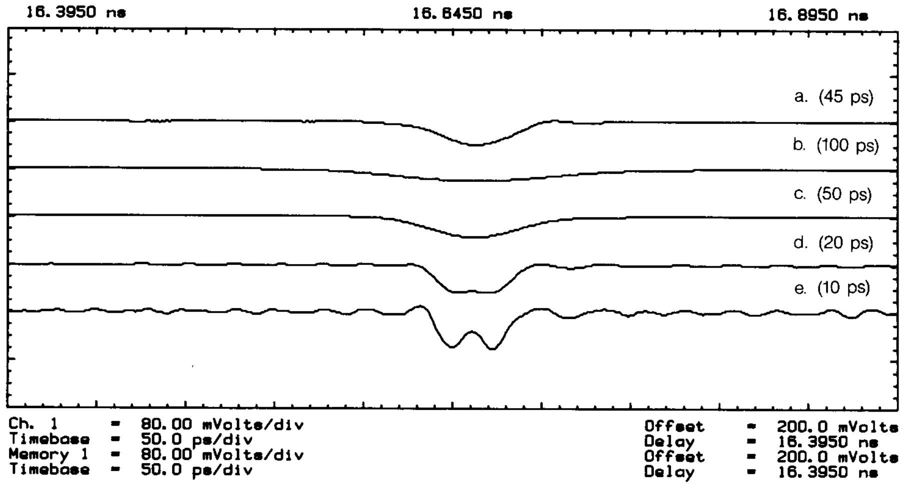


The unnormalized response of the DUT, measured without the test fixture

Example 2 Resolving two discontinuities separated by 2 mm.

Normalization can improve the TDR's ability to resolve adjacent discontinuities. Figure 10-8 shows the TDR measurement results of two capacitive discontinuities 2 mm apart in an air dielectric. Note that at a system risetime slower than 45 ps, the two discontinuities appear to be one. By normalizing the response to a system risetime of 10 ps, both discontinuities can be seen.

Figure 10-8



Normalization improves the ability to distinguish two discontinuities by decreasing the system risetime.
a. System risetime = 45 ps.
b. System risetime = 100 ps.
c. System risetime = 50 ps.
d. System risetime = 20 ps.
e. System risetime = 10 ps

Normalizing the Test System

The normalization process characterizes the test system and is made with all cables and connections in place but without the DUT.

Removing Systematic Errors

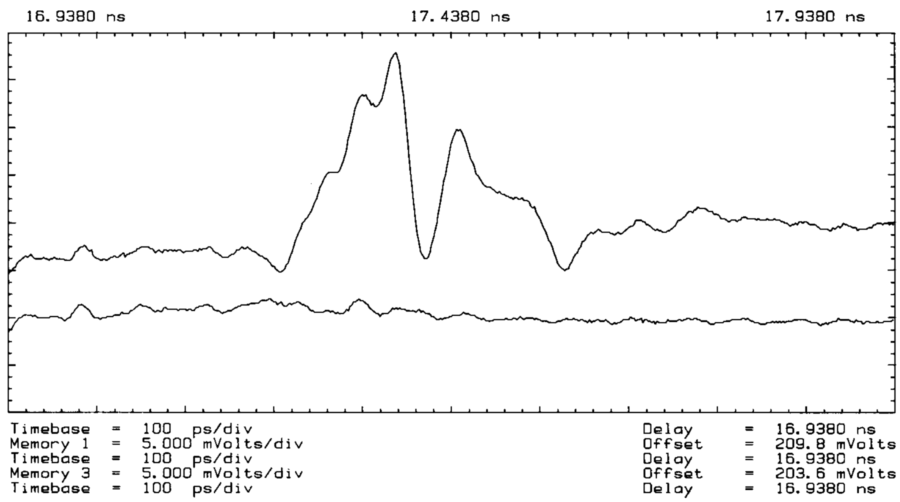
The first part of TDNA normalization removes systematic errors due to trigger coupling, channel crosstalk, and reflections from cables and connectors.

For TDR, this is done by replacing the DUT with a termination having an impedance equal to the characteristic impedance of the transmission line. If the termination is properly matched, all of the energy that reaches it will be absorbed. The only reflections measured result from discontinuities along the transmission line.

For TDT, this normalization step is done with nothing connected to the oscilloscope input.

In both cases, the measured waveforms are stored and subtracted directly from the measured DUT response before the response is filtered. Ideally, these normalization waveforms are flat lines. Any non-flatness or ringing is superimposed on the measured DUT response and represents a potential measurement error source. These errors are not related to the magnitude of the response of the DUT. Therefore, it is valid to subtract them directly. Notice in Figure 10-9 that the errors present in the TDR normalization waveform (bottom) are also visible in the measured DUT waveform (top), particularly at the left side of the figure.

Figure 10-9



Errors present in the TDR normalization waveform (bottom) are visible in the measured waveform (top)

Generating the Digital Filter

The second part of the normalization process generates the digital filter. Unlike the errors removed by subtracting the first normalization signal, the errors removed by the filter are proportional to the amplitude of the DUT response.

For the second part of the TDR normalization process, the DUT is replaced by a short circuit. The frequency response of the test system is derived from the measured short cal signal. Note that a short circuit should be used rather than an open circuit. When a step hits an open circuit at the end of a real-world transmission line, some of the energy is lost due to radiation rather than being reflected. Of course there is no such thing as a perfect short either, but the energy lost due to resistance in the short has a much smaller effect.

It is important that a good quality short be used, because the normalization process assumes a perfect short circuit termination. Any non-ideal components in the measured short cal signal are attributed to the test system. If any of the non-ideal components are, in reality due to the short itself, the filter will attempt to correct for error terms which do not exist in the test system. By attempting to correct for errors which do not exist, the filter can actually add error terms into the normalized measurement results.

In the second part of the TDT normalization process, the transmission through-path is connected without the DUT. The frequency response of the test system is then measured with the aid of the step stimulus. With this information, a digital filter can be computed that will compensate for errors due to anomalies in the frequency response of the test system.

Correcting for Secondary Reflections

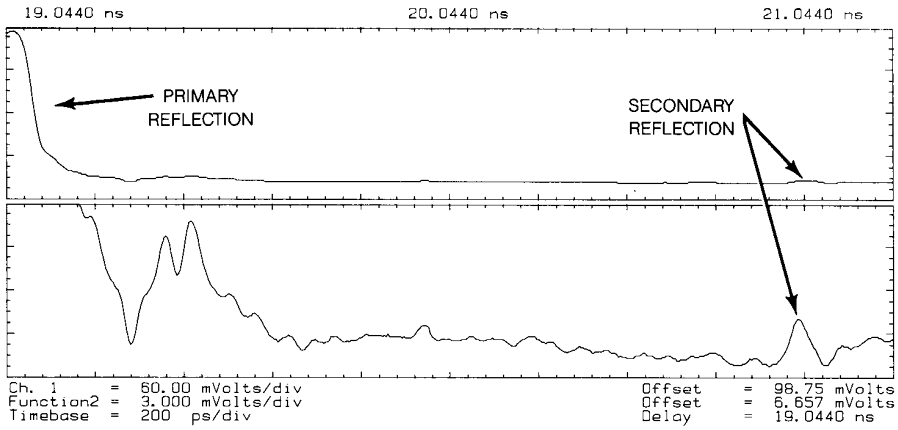
Secondary reflections caused by the impedance mismatch between the test port and the transmission media can also be corrected. In step TDNA, airlines can separate the primary reflection from the secondary reflection. Time windowing can then be used to remove the secondary reflection. In CW TDNA, a third normalization is used.

The impedance mismatch between test port and transmission media reflects a portion of the primary reflection back towards the DUT. A secondary reflection from the DUT may then be measured. Secondary reflections are usually very small.

Figure 10-10 shows the relative size of primary and secondary reflections. The lower waveform is a copy of the upper waveform with the voltage scale greatly expanded about the baseline to show more clearly the shape of the secondary reflection. The DUT is a short circuit connected to the oscilloscope through a

BNC connector. A secondary reflection from the DUT is visible at the right end of the baseline. Notice that the secondary reflection is indeed quite small. It has a peak voltage value of about 1.5 mV at 40 ps risetime, which is about 0.75% of the 200 mV incident step.

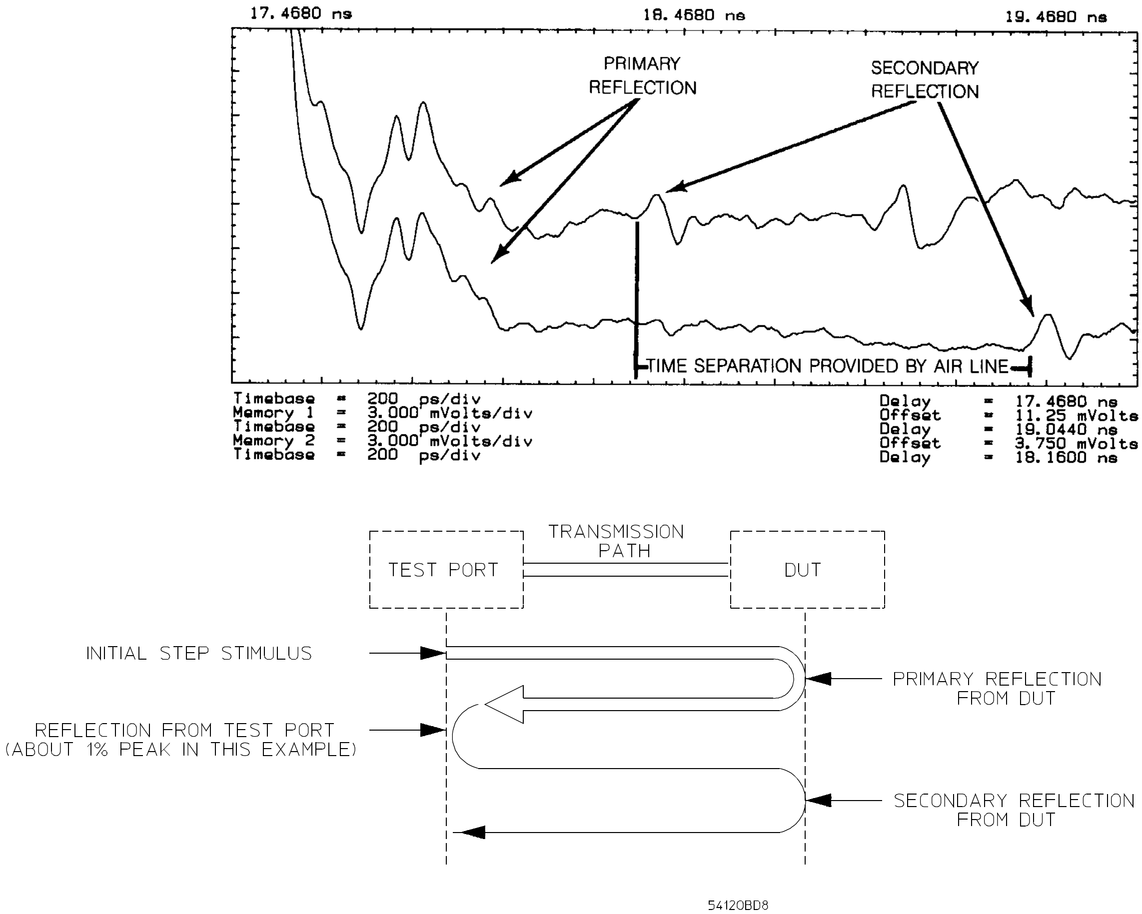
Figure 10-10



The lower waveform is a copy of the upper waveform with the voltage scale greatly expanded about the baseline to show more clearly the shape of the secondary reflection

In step TDNA, a section of airline may be placed between the test port and the DUT to provide time separation between the primary reflection and secondary reflections. Figure 10-11 illustrates the use of this technique. A secondary reflection is visible very close to the primary reflection in the top waveform. It is difficult to tell them apart. A short section of airline was placed between the DUT and the test port, resulting in the lower waveform. Note that the primary and secondary reflections are clearly separated. When the primary and secondary reflections are close together, the shapes of both may be distorted. If they are adequately separated in time, as is the case in the lower waveform, they no longer have a significant effect on each other.

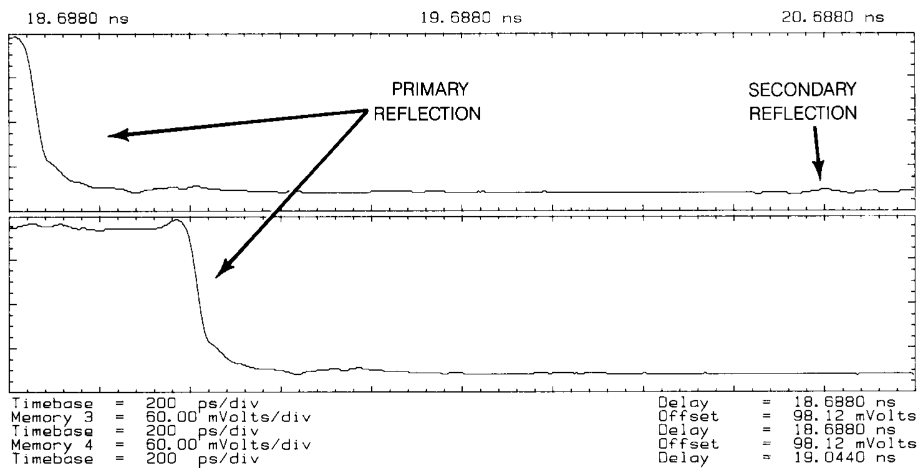
Figure 10-11



By adding a section of airline between the test port and the DUT, you can more clearly distinguish primary and secondary reflections

After an adequate separation has been achieved, a time window can be selected which does not include the undesirable secondary reflections. Figure 10-12 illustrates the removal of secondary reflections from the measurement data using time windowing. The top waveform in Figure 10-12 contains a secondary reflection visible at the right end of the baseline. Note that moving the time window to the left (less delay after the trigger) removes the secondary reflection from the measurement without losing any of the primary reflection data. In CW TDNA, time windowing is cumbersome, thus a third normalization measurement is used.

Figure 10-12



Decreasing delay in the bottom waveform removes the secondary reflection shown at the right end of the baseline in the top waveform.

The Digital Filter Corrects the Measured Response

The digital filter describes how the frequency response of the test system varies from the ideal. If the signal was passed through the filter, the result would be the ideal response. The filter removes errors by attenuating or amplifying and phase-shifting components of the frequency response as necessary.

Consider, for example, overshoot on the step stimulus. The frequency response of a DUT will include unwanted response to the overshoot. During normalization, the filter will phase-shift the frequencies responsible for the overshoot and thus attenuate the DUT response to the overshoot. The filter works similarly to correct for cable losses due to attenuation of high frequencies. It compensates for cable losses by boosting high frequency components in the DUT response back up to their proper levels.

The digital filter defines an ideal impulse response. A good basis for a normalization filter is a four-term, frequency-domain sum of cosines window, *W(f)* (see equation 2) with the appropriate coefficients.

$$W(f) = \sum_{k=0}^{3} a_k \cos\left(\frac{2\pi fk}{L}\right), \text{ for } \left(\frac{-L}{2} < f < \frac{L}{2}\right) \qquad (2)$$

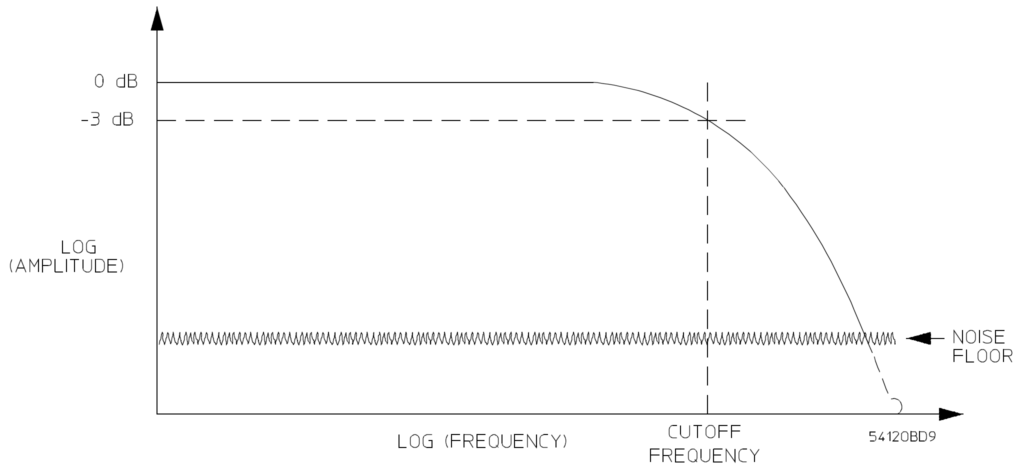
where : $a_0 + a_1 + a_2 + a_3 = 1$
L = the full width of the window in hertz
f = frequency in hertz

A window of this form may be selected that rolls off quickly and has an almost Gaussian impulse response. The impulse response of the window defines the ideal response. The Gaussian response is considered ideal because it has a minimum settling time after a transition from one voltage level to another. Minimizing the settling time minimizes the interference between closely-spaced discontinuities, thus making them easier to see and analyze. The filter's bandwidth, and therefore risetime, is determined by the choice of L, the width of the sum of the cosines window. The actual normalization filter, $F(f)$, is computed by dividing the sum of cosines window by the frequency response of the test system, $S(f)$ (see equation 3). The frequency response is the Fourier transform of the impulse response.

$$F(f) = \frac{W(f)}{S(f)} \qquad (3)$$

By varying the bandwidth of the filter, normalization can predict how the DUT would respond to ideal steps of various risetimes. The bandwidth of the test system is the frequency at which the frequency response is attenuated by 3 dB. The response beyond the cutoff frequency is not zero; it is only attenuated (Figure 10-13). By carefully changing the - 3 dB point in the frequency response, the bandwidth can be increased or decreased.

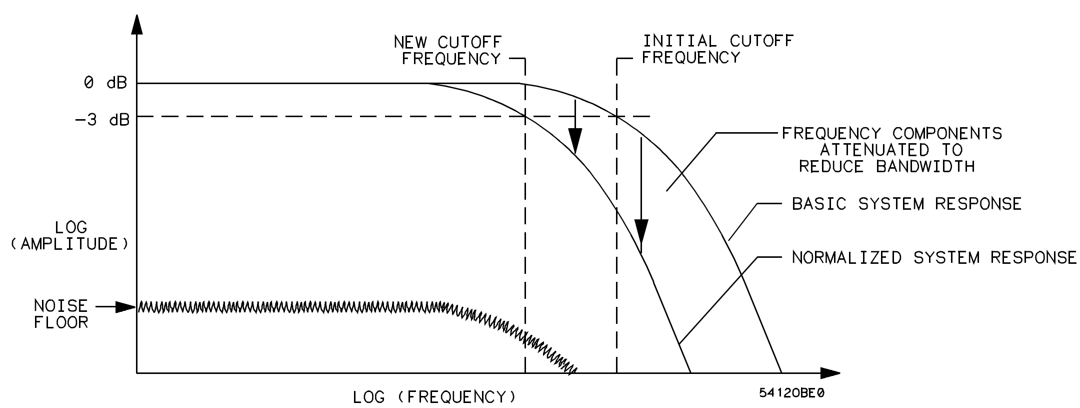
Figure 10-13



Basic system frequency response

In the Agilent 54750A Series digitizing oscilloscopes with TDR capability, the user-specified risetime determines the bandwidth of the filter. Decreasing the bandwidth is accomplished by attenuating the frequencies that are beyond the bandwidth of interest (Figure 10-14). Increasing the bandwidth requires more consideration.

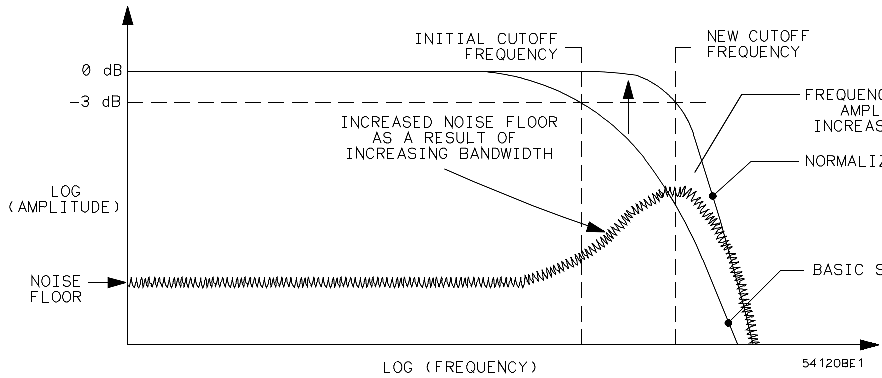
Figure 10-14



Normalized system frequency response (system bandwidth reduced)

To increase the bandwidth, the response beyond the initial -3 dB frequency needs to be amplified. While this is a valid step, it is important to realize that the system noise at these frequencies and at nearby higher frequencies is also amplified (see Figure 10-15).

Figure 10-15



Normalized system frequency response (system bandwidth increased)

The limit to which the risetime of real systems may be extended is determined by the noise floor. In real systems, there is a point beyond which the amplitude of the frequency response data is below the noise floor. Any further increase in bandwidth only adds noise.

Because waveform averaging reduces the initial level of the noise floor, WAVEFORM AVERAGING SHOULD BE USED WHEN NORMALIZING.

An equation can be used to describe the filtering process. The test system frequency response, $S(f)$, can be thought of as the ideal frequency response defined by the sum of cosines window, $W(f)$ multiplied by an error frequency response, $E(f)$ (see equation 4). Further, the measured response of the DUT, $M(f)$, can be thought of as the DUT frequency response, $D(f)$, multiplied by the test system frequency response, $S(f)$. Filtering is accomplished by multiplying the measured frequency response of the DUT by the filter, $F(f)$. $N(f)$ is the normalized (filtered) frequency response of the DUT. Equation 5 describes the filtering process using the above definitions.

$$S(f) = W(f)E(f) \tag{4}$$

$$\begin{aligned} M(f) &= D(f) \\ S(f)N(f) &= M(f)F(f) \\ N(f) &= D(f)S(f)F(f) \\ N(f) &= D(f)W(f)E(f)\frac{W(f)}{W(f)E(f)} \\ N(f) &= D(f)W(f) \end{aligned} \tag{5}$$

The normalized response is the DUT frequency response multiplied by the frequency response of an ideal impulse. Note that the error response has been removed, and that *N(f)* is an impulse response.

When *N(f)* is converted to the time domain, the result is $n_i(t)$, a normalized impulse response.

Because a step stimulus is used, a normalized step response, $n_s(t)$, is desired. An ideal step can be defined in the time domain by convolving $w(t)$, the ideal impulse response, with $u(t)$, the unit step function. Given this modification, equation 6 further describes the effect of the filtering process.

$$\begin{aligned} n_i(t) &= d(t)w(t) \\ n_s(t) &= n_i(t)u(t) \\ n_s(t) &= d(t)[w(t)u(t)] \end{aligned} \tag{6}$$

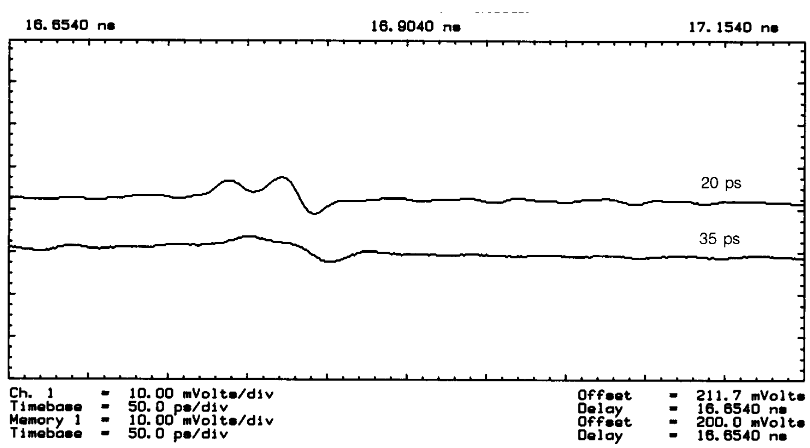
The normalized response, $n_s(t)$, is the impulse response of the DUT convolved with the ideal step defined by the convolution of $w(t)$ with $u(t)$. The result of normalization is, therefore, the response of the DUT to an ideal step of risetime determined by $w(t)$. By varying the width, L, of *W(f)*, normalization can predict the response of the DUT at multiple risetimes based on a single-step response measurement.

Putting It All Together

The actual normalization of a DUT response is accomplished in two steps. A stored waveform, derived in the normalization and which represents the systematic errors, is subtracted from the measured DUT waveform. This result is then convolved with the digital filter to yield the response of the DUT, normalized to an ideal step input with the user-specified risetime.

Figure 10-16 illustrates the power of normalization. It shows discontinuities in a transmission path measured using TDR. The bottom waveform was measured in a test system with an approximate risetime of 35 ps. The top waveform is the bottom waveform normalized to 20 ps risetime. Note that in the bottom waveform there appears to be only one inductive discontinuity. Using normalization, it becomes obvious that there are actually two inductive discontinuities. Because it is difficult to build a 20 ps risetime step stimulus with a clean response and a test system with adequate bandwidth to measure it, this measurement probably could not have been made without normalization.

Figure 10-16



The top waveform is the same signal as the bottom waveform, except that it has been normalized. Normalization reveals that there are actually two inductive discontinuities, rather than one as shown in the bottom waveform

11

Transmission Line Theory Applied to Digital Systems

Introduction

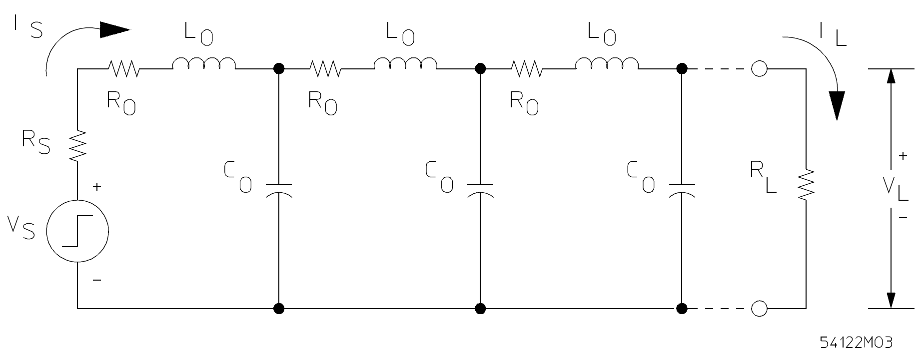
Understanding the operation of transmission lines used in conjunction with high speed MECL circuits is necessary in order to be able to completely characterize system operation. This Chapter describes transmission lines with respect to both line reflections and propagation delay times. Also discussed will be the use of the Time Domain Reflectometer (TDR) for measuring transmission line characteristics.

Transmission Line Design

A transmission line, as used with high speed MECL, is a signal path that exhibits a characteristic impedance. Coaxial cables and twisted pairs have a defined characteristic impedance and are commonly referred to as transmission lines. Equally important, printed circuit fabrication of microstrip and stripline results in closely-controlled transmission-line impedance.

Transmission lines may be approximated by the lumped constant representation shown in Figure 11-1. The effect of the line resistance R_o, of the line on characteristic impedance, Z_o, is negligible, but it will cause some loss in voltage at the receiving end of long lines. The inductance and capacitance of the line in the presence of a ground plane are a function of the dielectric medium, the thickness and width of the line, and the spacing from the ground plane. The inductance and capacitance of the line can be measured using an LC meter.

Figure 11-1



Equivalent Circuit of a Transmission Line

Microstrip and strip lines may be treated as operating in the transverse electromagnetic (TEM) mode. Although microstrip propagation is not purely TEM because of non-uniform dielectrics, for all practical purposes it can be treated as TEM. The characteristic impedance of the line is:

$$Z_o = \sqrt{L_o / C_o}$$

and the propagation delay is:

$$t_{pd} = \sqrt{L_o C_o} = Z_o C_o$$

For a homogeneous medium the propagation delay is also equal to:

$$t_{pd} = \sqrt{\mu\varepsilon} = \sqrt{\mu_o \mu_r \varepsilon_o \varepsilon_r}$$

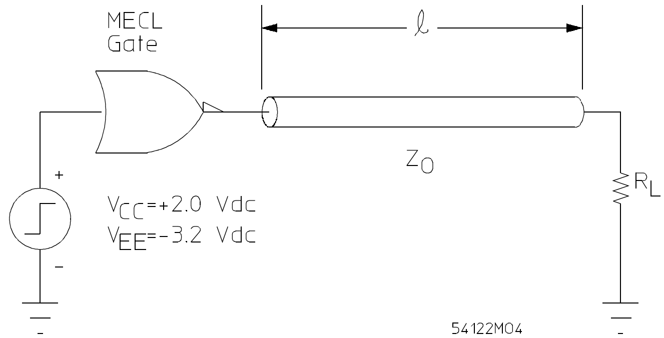
Where μ is the permeability and ε is the permittivity of the medium. In transmission lines, the relative permeability (μ_r) is unity, $\mu_o = 4\pi \times 10^{-7}$ henries/metre, and $\varepsilon_o = 8.85 \times 10^{-12}$ farads/metre.

Therefore, $t_{pd} = 1.017$ ns/ft, ε_r is the relative dielectric constant. For microstrip lines on glass epoxy boards $\varepsilon_r = 3.0$, and for strip lines $\varepsilon_r = 5.0$.

From transmission line theory for a lossless line, it can be shown that a signal sent down a line of constant characteristic impedance will travel along the line without distortion. However, when the signal reaches the end of the line, a reflection will occur if the line is not properly terminated. Proper termination requires the terminator value to be equal to the characteristic impedance of the line.

Figure 11-2 shows a MECL gate driving a transmission line terminated in a load resistor, R_L. A negative-going transition on the input to the gate will result in a positive-going transition at the NOR output. The MECL gate is essentially a VHF linear differential amplifier with a bandwidth of $0.37 \div t_r$ (MHz), where t_r is the risetime of the gate in nanoseconds. The effect of the capacitance of the transmission line will not decrease the bandwidth or affect the risetime at the MECL gate output. However, the signal at the end of a long transmission line may be attenuated due to bandwidth limitations in the particular type of transmission line used. For the purposes of this discussion, a long line is defined as a line having a propagation delay larger than the risetime of the driving circuit divided by two: $T_D > t_r \div 2$.

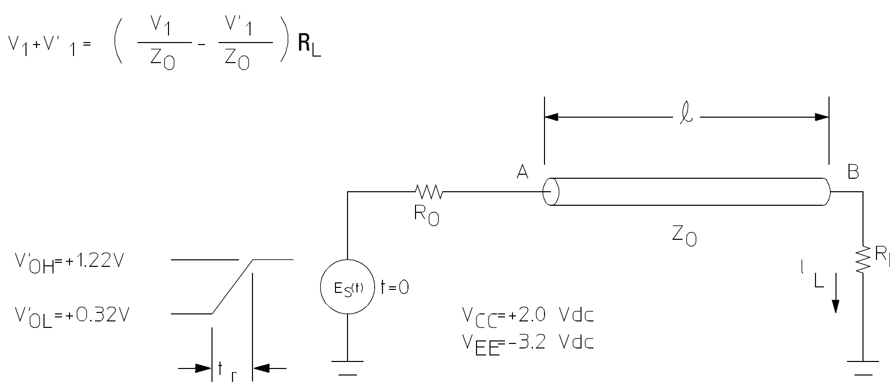
Figure 11-2



MECL Gate Driving a Transmission Line

The circuit of Figure 11-2 can be redrawn as shown in Figure 11-3 to include the equivalent circuit of the MECL gate. The resistor, R_o, is the output source impedance (for MECL 10K/10KH it is 7 Ω, and MECL III it is 5 Ω). According to theory, the risetime of the driving voltage source is not affected by the capacitance of the transmission line. Except for skin effect and dielectric losses, the signal will remain undistorted until it reaches the load.

Figure 11-3



Equivalent MECL Gate Output, Driving a Transmission Line

The equation representing the voltage waveform going down the line as a function of distance and time can be written as:

$$v_1(x,t) = v_A(t) \bullet u(t - xt_{pd}), \text{ for } t < T_D \qquad (1)$$

where:

$$v_A(t) = E_s(t)\left(\frac{Z_o}{Z_o + R_o}\right)$$

$v_A(t)$ = voltage at point A,

x = the distance to an arbitrary point on the line,

l = the total line length,

t_{pd} = the propagation delay of the line in ns/unit distance,

$T_D = l\ \ t_{pd}$,

$u(t)$ = a unit step function occurring at $t = 0$, and

$E_S(t)$ = the source voltage at the sending end of the line.

When the incident voltage v_1 reaches the end of the long line, a reflected voltage v'_1 will occur if $R_L \neq Z_o$. The reflection coefficient at the load, ρ_L, can be obtained by applying Ohm's Law.

The voltage at the load is $v_1 + v'_1$ which must be equal to $(i_1 + i'_1)\ R_L$. But $i_1 = v_1/Z_o$, and $i'_1 = -v'_1/Z_o$ (the minus sign is due to v'_1, travelling toward the source). Therefore,

$$v_1 + v'_1 = \left(\frac{v_1}{Z_o} - \frac{v'_1}{Z_o}\right)R_L \qquad (2)$$

By definition

$$\rho_S = \frac{\text{reflected voltage}}{\text{incident voltage}} = \frac{v'_1}{v_1}$$

Solving for $v'_1 + v_1$ in equation 2, and substituting in the relation for ρ_L results in:

$$\rho_L = \frac{R_L - Z_o}{R_L + Z_o} \qquad (3)$$

Similarly, the reflection coefficient at the source is:

$$\rho_S = \frac{R_o - Z_o}{R_o + Z_o} \tag{4}$$

By summing the incident voltage v_1 (equation 1), together with similar voltage contributions from the various orders of reflection (due to ρ_L and ρ_S), a general equation for total line voltage can be written, and used to develop practical design information:

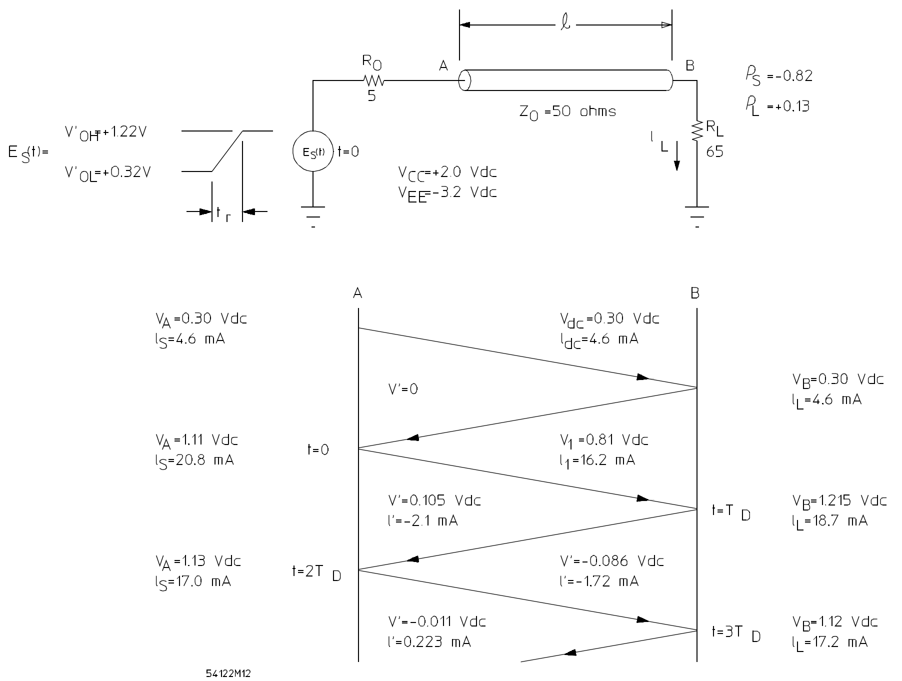
$$\begin{aligned} v(x,t) = {} & v_A(t)[u(t - t_{pd}x) + \rho_L u(t - t_{dp}(2l - x)) + \rho_L \rho_S u(t - t_{pd}(2l + x)) \\ & + \rho_L 2\rho_S u(t - t_{pd}(4l - x)) + \rho_L 2\rho_S 2u(t - t_{pd}(4l + x)) + \ldots] + V_{dc} \end{aligned} \tag{5}$$

Note that as time progresses, the unit step function (u) brings successively higher order reflection coefficient terms into $v(x,t)$. Successive terms may be positive or negative, depending on the resulting sign and so damped ringing can occur. Equation 5 expresses the voltage at any point, x, on the line for any time, t. The equation can be used graphically with a lattice diagram to find $v(x,t)$.

Example 1

Figure 11-4 will be used to illustrate the lattice diagram method for finding $v(x,t)$ and the use of equation 5. The source impedance of the MECL III gate is 5 Ω, resulting in a reflection coefficient at the source of - 0.82 for a line impedance of 50 Ω.

Figure 11-4



Latice Diagram for a Typical Reflection Example

The load resistor is arbitrarily chosen to be 30 percent greater (65 Ω) than the characteristic impedance (50 Ω) so that reflections will occur. The resulting reflection coefficient at the load is $\rho_L = + 0.13$. Two vertical lines are drawn to represent the input of the line, point A, and the output of the line, point B. A line is drawn from point A to point B before $t = 0$ to represent the steady state conditions. Note that for $V_{CC} = 2$ V and $V_{EE} = - 3.2$ V, the nominal logic levels are approximately logic 0 = 0.3 V, and logic 1 = 1.14 V. (These power supply conditions are used to permit convenient measurements when output resistors are returned directly to ground). For steady state conditions, the line looks like a short line with a resistance equal to R_{dc}. It can be assumed that R_{dc} is negligible for this example.

The voltage and current at points A and B are the same initially, as shown in Figure 11-4. At t = 0, the voltage at the source switches from a logic 0 to a logic 1 level. The voltage term, $v_A(t)$, in equation 1 is:

$$v_A(t) = (V'_{OH} - V'_{OL})\left(\frac{Z_o}{Z_o + R_o}\right) = v_1 = 0.81 \text{ volts,}$$

where: $(v'_{OH} - v'_{OL}) = E_S(t)$ = internal voltage swings in the circuit = ΔV_{INT}

Therefore, at time t = 0 a voltage waveform, V = 0.81 V, and a current, I = 16.2 mA, travel down the line as shown in Figure 11-4 by the line from t = 0 to $t = T_D$ (T_D is the time it takes for the wavefront to travel down the length of the line). A line is drawn from $t = T_D$ to $t = 2T_D$. Voltage and current values are as indicated. Note that the reflected current is negative, indicating the current is flowing back toward the source; the reflection coefficient for the current is a minus one times the reflection coefficient for the voltage.

To find the voltage at point B for $t = T_D$ all the voltages entering and leaving this point are summed. The same is done to determine the load current. The process continues until the voltage at the load approaches the new steady state condition in the example. This condition occurs when $t = 3T_D$. (The steady state logic 1 voltage is actually 1.13 V).

This example indicates that for a case in which the load resistor is 30% higher than the characteristic impedance, 85 mV of overshoot and 10 mV of undershoot would occur. Generally, as far as noise immunity is concerned, only the undershoot need be considered. The typical noise immunity (or noise margin) for a MECL circuit is greater than 200 mV. Since the undershoot in this example was 10 mV, the typical noise immunity would exceed 190 mV. In actual system design, typically more than 100 mV of undershoot can be tolerated. Regarding overshoot, 300 mV can be tolerated, except in some early ac coupled flip-flops (MECL I and II). This restriction insures that saturation of the input transistor does not occur (if it did, the gate would slow down). If a 100 Ω load resistor were used in Figure 11-4, the resulting overshoot would be about 220 mV and the undershoot, about 80 mV. If the load resistor is twice the characteristic impedance, the noise margin is typically 120 mV which is more than acceptable for MECL circuits.

A slightly different situation can exist when the output of the MECL gate switches from a logic 1 to a logic 0. The output of the MECL gate will turn off if the termination resistor, R_L, is somewhat larger than the characteristic impedance of the line. For the conditions in Figure 11-4, the output transistor of the MECL gate will turn off at $t = 0$ for the negative going transition, when $R_L > 70\ \Omega$.

An equation for the value for R_L at which the gate will turn off can be derived as follows. The maximum voltage change at point A in Figure 11-4, (due to turning off the output transistor) is the product of the dc current in the line and the characteristic impedance of the line:

$$\Delta V_A = I_{LINE}(Z_o) = \frac{V'_{OH}}{R_o + Z_o}(Z_o)$$

The voltage at point A is also dependent on the internal resistance of the driving gate R_o and the internal logic swing.

$$\Delta V_A = \frac{Z_o}{R_o + Z_o}(\Delta V_{INT})$$

Equating the two and solving for R_L:

$$R_L = \frac{V'_{OH}(R_o + Z_o)}{\Delta V_{INT}} - R_o \tag{6}$$

Thus for the conditions given in Figure 11-4, the output transistor will turn off at

$$t = 0 \text{ when } R_L = \frac{1.22(5 + 50)}{0.9} - 5 = 70\Omega \text{ is exceeded.}$$

The case for which the MECL output turns off is not in itself a serious problem, although it makes a thorough analysis more difficult. Two reflection coefficients must be used at the sending end and a piecewise approach used in determining the voltage reflections.

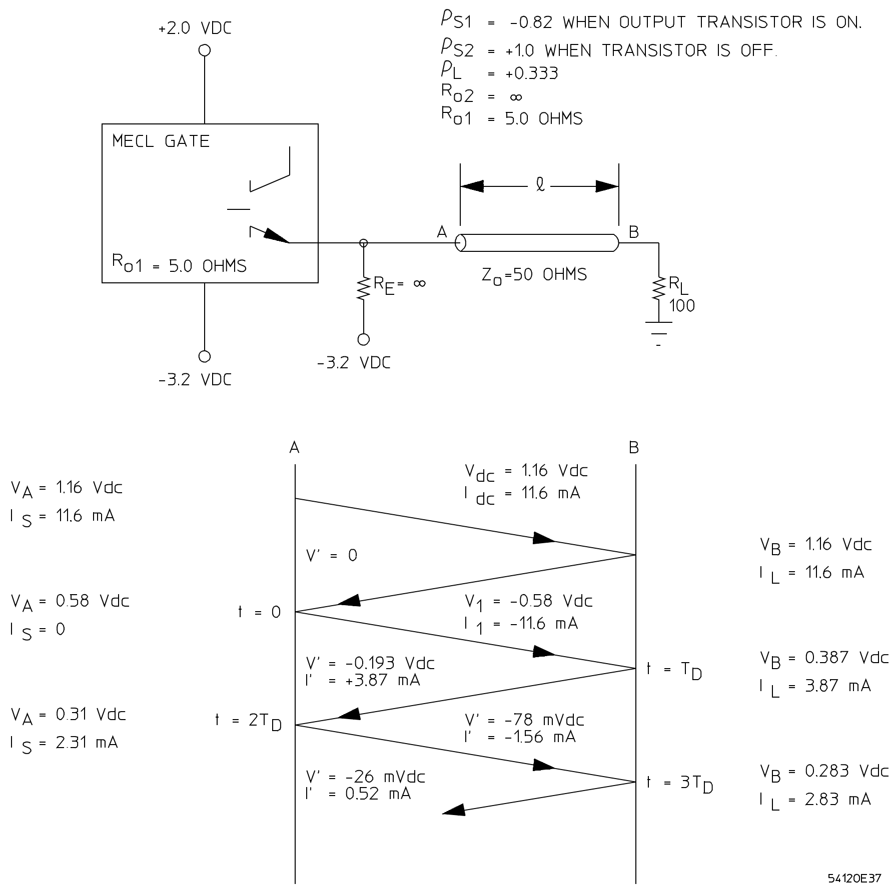
Example 2

The condition for a negative-going transition will now be analyzed. Refer to Figure 11-5. The steady state high logic level current is:

$$I_{dc} = \frac{V'_{OH}}{R_o + Z_o} = 11.6 \text{ mA}$$

For the conditions shown in Figure 11-5, the use of equation 6 shows that the load resistor is indeed larger than required to turn off the output transistor during a negative transition.

Figure 11-5



Lattice Diagram for Negative-Going Voltage Transition

To determine the voltage V_1 at $t = 0$, the following equation results from the application of Ohm's Law to the circuit:

$$V_1 = \left(I_{dc} + \frac{V_A + 3.2 + V_1}{R_E}\right)Z_o \qquad (7)$$

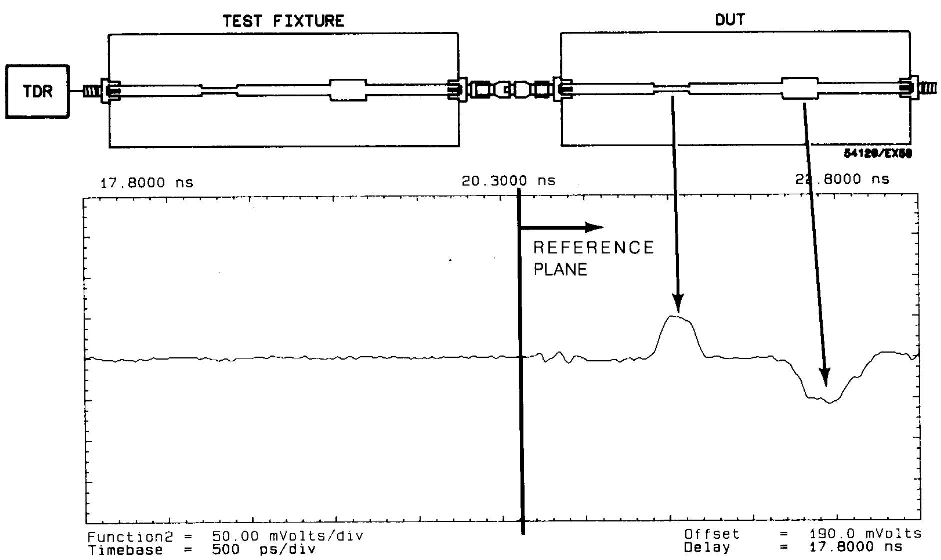
For the example shown, let $R_E = \infty$, then:

$$V_1 = (-I_{dc})Z_o \tag{8}$$

Solving equation 8, V_1 = 0.58 V. The implication of this result is that stubbing off the line with gate loads in a distributed fashion is not recommended, due to the reduced initial voltage swing. However, it would be acceptable to lump the loads at the end of the line.

Since the value of the load resistor is greater than the characteristic impedance, the voltage swing at the load resistor is greater than $v1$ by the amount of $\rho_L V_1$, (in this example, 193 mV). When $t = T_D + T_1$, the voltage at B is equal to 0.387 V; so 82 mV of undershoot occurs. Undershoot on the falling edge is defined as the amount of voltage step above the nominal logic 0 level of 0.305 V. Overshoot in the low logic state is defined as the amount of voltage change below the logic 0 level.

Figure 11-6



Voltage Waveforms for Points A and B in Example 2

In Figure 11-6, the voltage waveforms at points A and B of this example are shown as a function of time. To be more realistic, the waveform in the figure is shown to be a negative-going ramp rather than an abrupt step function. The term, T_1, is the amount of time it takes for the waveform at A to switch to the level at which the output transistor turns off. The fall time of the signal would have been longer by an amount equal to:

$$T'_1 = \frac{(1.16 - 0.305)}{(1.16 - 0.58)} T_1$$

if the termination resistor had been 70 Ω or less.

The reflected voltage waveform leaving point B at $t = T_D$ arrives at point A at $t = 2TD$. The source impedance is very high initially ($\rho_S = +1.0$), with the output transistor being in the off condition until the voltage at A falls to 0.32 V. Then, the source impedance changes to 5 Ω ($\rho_S = -0.82$).

The following formula may be used to determine the point at which the transistor turns on:

$$\Delta V_{source} = V_1 + \rho_S V_1 = 2V_1 \qquad (9)$$

where V_1 is now the incident voltage approaching the source and ΔV_{source} is the change in voltage at the source necessary to turn the transistor on.

In this example the actual voltage change for this conduction to occur is $\Delta V_{source} = 0.32 - 0.58 = -0.26$ V. Therefore, the voltage waveform approaching the source (193 mV) can be broken into two signals $V_{11} = -0.13$, and $V_{12} = -0.063$ V. The reflected voltage due to V_{11} is $V'_{11} = -0.13$ V, and for V_{12}, the reflected voltage is $V'_{12} = (-0.82)(-0.063) = 0.052$ V. The two reflected voltages of opposite polarity at point A going toward point B are the reason for the increased overshoot of short duration at point B, when $t = 3T_D + (0.13 \div 0.193)\,T_1$. Refer to Figure 11-6.

The steady state voltage reflection that occurs after $t = 2T_D + T_1$ is the sum of -0.13 V and +0.052 V, equal to -78 mV as shown in Figure 11-5. The steady state voltage reflection can be calculated using the relation:

$$V' = \rho_{S2} \Delta V_{source} \left(\frac{1 + \frac{Z_o}{R_{o2}}}{2} \right) + \rho_{S1} \left[V_1 - \Delta V_{source} \left(\frac{1 + \frac{Z_o}{R_{o2}}}{2} \right) \right] \qquad (10)$$

Equation 10 may be illustrated by solving for the steady state reflection voltage at $t = 2T_D + T_1$:

$$V' = (1.0)(0.32 - 0.58)\left(\frac{1 + \frac{50}{\infty}}{2}\right) + (-0.82)\left[-0.193 - (0.32 - 0.58)\left(\frac{1 + \frac{50}{\infty}}{2}\right)\right] = 78 \text{ mV}$$

From the analysis of Figure 11-5, it is concluded that the MECL gate can safely drive the transmission line ($Z_o = 50\ \Omega$) with a 100 Ω load resistor and with the gate loads lumped at the end of the line, since less than 100 mV of undershoot occurs. The remaining noise margin will be typically greater than 100 mV.

Signal Propagation Delay for Microstrip and Strip Lines with Distributed or Lumped Loads

The propagation delay, t_{pd}, has been shown to be 1.77 ns/ft for microstrip lines and 2.26 ns/ft for strip lines, when a glass epoxy dielectric is the surrounding medium. The propagation delay time of the line will increase with gate loading and the altered delay can be derived as follows. The unloaded propagation delay for a transmission line is:

$$t_{pd} = \sqrt{L_o C_o}$$

If a lumped load, C_d, is placed along the line, then the propagation delay will be modified to t'_{pd}:

$$t'_{pd} = \sqrt{L_o(C_o + C_d)} = \sqrt{L_o C_o}\sqrt{1 + \frac{C_d}{C_0}} = t_{pd}\sqrt{1 + \frac{C_d}{C_o}} \qquad (11)$$

where L_o and C_o are the intrinsic line inductance and capacitance per unit length.

Therefore, the signal propagation down the line will increase by the factor of:

$$\sqrt{1 + \frac{C_d}{C_o}}$$

A MECL gate input should be considered to have 5 pF of capacitance for ac loading considerations (includes stray capacitance). If 4 gate loads are placed on a 1 foot signal line, then the distributed capacitance, C_d, is equal to 20 pF/ft or 1.67 pF/in. As an example, a propagation delay increase is to be found for a 50 Ω microstrip line on a glass epoxy board. Given a line width of 25 mils, the dielectric material would have a thickness of 15 mils to yield Z_o = 50 Ω and a capacitance of 35 pF/ft. Therefore, the modified propagation delay would be:

$$t'_{pd} = 1.77\text{ ns/ft}\sqrt{1 + \frac{20}{35}} = 2.21\text{ ns/ft}$$

For a 50 Ω strip line on a glass epoxy board with a 15 mil spacing between the strip line and ground plane, a 12 mil width would be required, and the strip line would exhibit a capacitance of 41 pF/ft. The modified propagation delay for such a strip line would be:

$$t'_{pd} = 2.26 \text{ ns/ft } \sqrt{1 + \frac{20}{41}} = 2.75 \text{ ns/ft}$$

Notice that the propagation delay for the strip line and the microstrip line change by approximately the same factor when the separation between the line and ground plane, and the characteristic impedance are the same. However, the line width of the strip line is less (by a factor of 2) than the microstrip line for the same characteristic impedance.

It should be noted that to obtain the minimum change and lowest propagation delay as a function of gate loading, the lowest characteristic impedance line should be used. This will result in the largest intrinsic line capacitance. With MECL 10K/10KH the lowest impedance that can be used is about 35 Ω (V_{TT} = - 2.0 V and R_{TT} = 35 Ω).

According to theory, when an open line (stub) is driven by a pulse, the resultant undershoot and ringing are held to about 15 percent of the logic swing if the two way delay of the line is less than the risetime of the pulse. The maximum line length, l_{max} may be calculated using the equality:

$$l_{max} = \frac{t_r}{2t'_{pd}} \text{ (inches)}$$

where t_r is the risetime of the pulse in nanoseconds, and t'_{pd} is the modified propagation delay in nanoseconds/inch from equation 11.

A quadratic equation for maximum line length for G-10 fiber glass epoxy microstrip conductors may be written in terms of C_D, C_o, and t_r as

$$l^2_{max} + \frac{C_D}{C_o} l_{max} - 11.1 t^2_r = 0 \text{ (for microstrip lines)} \quad (12)$$

where C_D is the total gate capacitance.

An equation for maximum open line length for a strip line (using G-10 fiber glass epoxy material) can be written in a similar fashion as follows:

$$l^2_{max} + \frac{C_D}{C_o} l_{max} - 7.1 t^2_r = 0 \text{ (for strip lines)} \qquad (13)$$

Using the lattice diagram, it has been found that the rule of thumb used to derive equations 12 and 13 should be modified for an open line because the incident voltage doubles at the end of the line. This results in a faster risetime at the receiving end of an unloaded line than at the driving end. An approximate value of maximum open line length can be generated from equations 12 and 13 if the risetime that is substituted into the equations is multiplied by an adjustment factor, 0.75. This maintains an approximate overshoot and undershoot of less than 35% and 12% respectively.

To demonstrate how equations 12 and 13 may be used, the maximum open line length will be computed for a 50 Ω line with a fanout of one MECL 10K gate. Using the equation $t_{pd} = Z_o C_o$, the line capacitance, C_o, is found to be C = 2.96 pF/in for microstrip, and C_o = 3.76 pF/in for strip line. For a fanout of one, C_D is equal to 5 pF when the device is in a socket. The risetime for MECL 10K is 3.5 ns which means that a value of t_r = 0.75 X 3.5 = 2.6 ns should be used in the equations. Solving equations 12 and 13, l_{max} for a 50 Ω microstrip line and l_{max} = 6.2 inches for a 50 Ω strip line.

Equations 12 and 13 can be very useful in finding the approximate maximum line length under various conditions. Suggested maximum open line lengths for MECL 10K/10KH and MECL III are tabulated in tables Table 11-1, Table 11-2, and Table 11-3 for various fanouts and line impedances. For these tables, line lengths are chosen to limit overshoot to 3.5% of logic swing and undershoot to 12%. Note that the tables give the maximum line lengths for fanouts of 1, 2, 4, and 8 for various types of lines with a wide range of characteristic impedances.

Table 11-1

Maximum Open Line Length for MECL 10,100 (Gate Rise Time = 3.5 ns)

	Z_o (OHMS)	FANOUT = 1 (2.9pF) l_{MAX} (IN)	FANOUT = 2 (5.8pF) l_{MAX} (IN)	FANOUT = 4 (11.6pF) l_{MAX} (IN)	FANOUT = 8 (23.2pF) l_{MAX} (IN)
MICROSTRIP (Propagation Delay 0.148 ns/in.)	50	8.3	7.5	6.7	5.7
	68	7.0	6.2	5.0	4.0
	75	6.9	5.9	4.6	3.6
	82	6.6	5.7	4.2	3.3
	90	6.5	5.4	3.9	3.0
	100	6.3	5.1	3.6	2.6
STRIPLINE (Propagation Delay 0.188 ns/in.)	50	6.5	5.9	5.2	4.5
	68	5.6	4.9	3.9	3.2
	75	5.3	4.7	3.6	2.8
	82	5.2	4.4	3.3	2.6
	90	5.1	4.3	3.1	2.4
	100	4.9	4.0	2.8	2.1
BACKPLANE (Propagation Delay 0.140 ns/in.)	100	6.6	5.4	3.8	2.8
	140	5.9	4.3	2.8	1.9
	180	5.2	3.6	2.1	1.3

Table 11-2

Maximum Open Line Length for MECL 10,200, MECL 10H100, 10H210, 10H211 (Gate Rise Time = 2 ns)

	Z_0 (OHMS)	FANOUT = 1 (3.3pF) l_{MAX} (IN)	FANOUT = 2 (6.6pF) l_{MAX} (IN)	FANOUT = 4 (13.2pF) l_{MAX} (IN)	FANOUT = 8 (26.4pF) l_{MAX} (IN)
MICROSTRIP (Propagation Delay 0.148 ns/in.)	50	3.5	2.8	1.9	1.2
	68	3.2	2.3	1.5	0.8
	75	3.0	2.2	1.3	0.7
	82	2.9	2.0	1.2	0.6
	90	2.8	1.9	1.0	0.5
	100	2.6	1.8	0.9	0.4
STRIPLINE (Propagation Delay 0.188 ns/in.)	50	2.8	2.2	1.5	1.0
	68	2.5	1.9	1.2	0.6
	75	2.4	1.7	1.1	0.6
	82	2.3	1.6	0.9	0.5
	90	2.2	1.5	0.8	0.4
	100	2.0	1.4	0.7	0.3
BACKPLANE (Propagation Delay 0.140 ns/in.)	100	2.8	1.8	0.9	0.4
	140	2.4	1.4	0.5	0.3
	180	2.0	1.0	0.3	0.1

Table 11-3

Maximum Open Line Length for MECL III, MECL 10H209 (Gate Rise Time 1.1 ns)

	Z_0 (OHMS)	FANOUT = 1 (3.3pF) l_{MAX} (IN)	FANOUT = 2 (6.6pF) l_{MAX} (IN)	FANOUT = 4 (13.2pF) l_{MAX} (IN)	FANOUT = 8 (26.4pF) l_{MAX} (IN)
MICROSTRIP (Propagation Delay 0.148 ns/in.)	50	1.6	1.1	0.7	0.6
	68	1.4	0.8	0.5	0.4
	75	1.3	0.8	0.4	0.3
	82	1.2	0.7	0.4	0.2
	90	1.1	0.6	0.3	0.2
	100	1.0	0.5	0.2	0.1
STRIPLINE (Propagation Delay 0.188 ns/in.)	50	1.2	0.8	0.6	0.5
	68	1.1	0.7	0.4	0.3
	75	1.0	0.6	0.3	0.2
	82	0.9	0.6	0.3	0.2
	90	0.9	0.5	0.2	0.1
	100	0.8	0.4	0.2	0.1
BACKPLANE (Propagation Delay 0.140 ns/in.)	100	1.1	0.6	0.2	0.1
	140	0.8	0.3	0.0	0.0
	180	0.6	0.2	0.0	0.0

The maximum line lengths are also given for various characteristic impedances in the backplane. The characteristic impedance of the backplane should be between 100 Ω and 180 Ω if a ground screen is used. For MECL 10K from Table 11-1, 5.9 inches of open backplane wiring can be driven for a fanout of one.

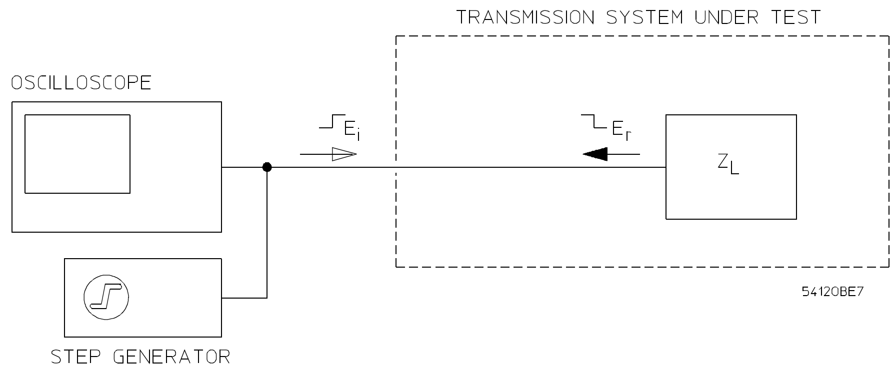
It should be remembered that these line lengths are based on 100 mV maximum undershoot, and are not absolute maximum lengths with which MECL circuits will operate. It is possible to use longer unterminated lines than shown — the tradeoff being an associated loss of noise immunity due to increased ringing.

From these calculations, it can be concluded that lower impedance lines result in longer line lengths before termination is required. The lower impedance lines are preferred over higher impedance lines because longer open lines are possible, and the propagation delay down the line is reduced. In addition, more stubbed-off gate loads can be driven with a terminated line due to its higher capacitance per unit length.

Microstrip Transmission Line Techniques Evaluated Using TDR Measurements

The time domain reflectometer (TDR) employs a step generator and an oscilloscope in a system which might be described as "closed-loop radar. Refer to Figure 11-7. In operation, a voltage step is propagated down the transmission line under investigation. Both the incident and reflected voltage waves are monitored on the oscilloscope at a particular point on the line.

Figure 11-7



Time Domain Reflectometer

For the examples the incident voltage setup, E1, is a positive edge with an amplitude of 1 V and a risetime of 30 ps. It is generated from a source impedance of 50 **Ω**. Also, the output edge has very little overshoot (less than ±5%).

This TDR technique reveals the characteristic impedance of the line under test. It shows both the position and the nature (resistive, inductive, or capacitive) of each discontinuity along the line, and signifies whether losses in a transmission system are series losses or shunt losses. All of this information is immediately available from the oscilloscope's display. An example of a microstrip line evaluated with TDR techniques is shown below:

TDR Example 1

Given the following:

Board material:	Norplex Type G-10
Dielectric thickness:	h = 0.062 inch;
Copper thickness:	t = 0.0014 inch;
Dielectric constant:	ε_r = 5.3.

The formula for the characteristic impedance is:

$$Z_o = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right) \tag{14}$$

For a line width, w = 0.1 inch, the characteristic impedance of the line is calculated to be 51 Ω. A board was fabricated as shown in Figure 11-8 to the dimensions specified above. Figure 11-8 and Figure 11-9 show the incident and reflected waveforms observed with the TDR. The vertical scale is calibrated both in terms of the voltage and the reflection coefficient, ρ. Equation 3 can be rearranged to determine the characteristic impedance of the line:

$$Z_{line} = \left(\frac{1 + 0.01}{1 - 0.01}\right) \bullet Z_{reference} \tag{15}$$

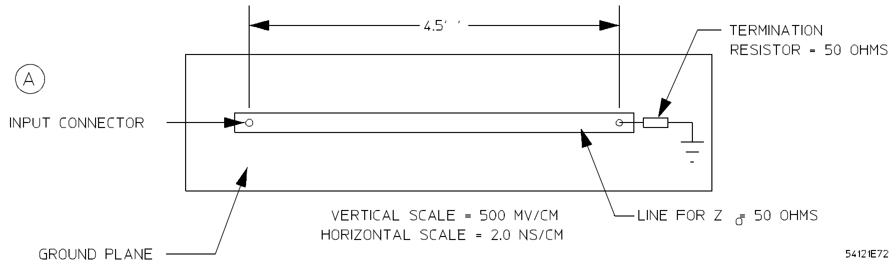
where: Z_{line} = characteristic impedance of the line under test
and $Z_{reference}$ = impedance of the known line.

The 50 Ω reference point is shown in Figure 11-9. The mean level of the reflected waveform due to the line has a ρ = + 0.01. Substituting values into equation 15 permits calculation of the line impedance:

$$Z_{line} = \left(\frac{1 + 0.01}{1 - 0.01}\right) \bullet 50 \text{ ohms} = 51 \text{ ohms}$$

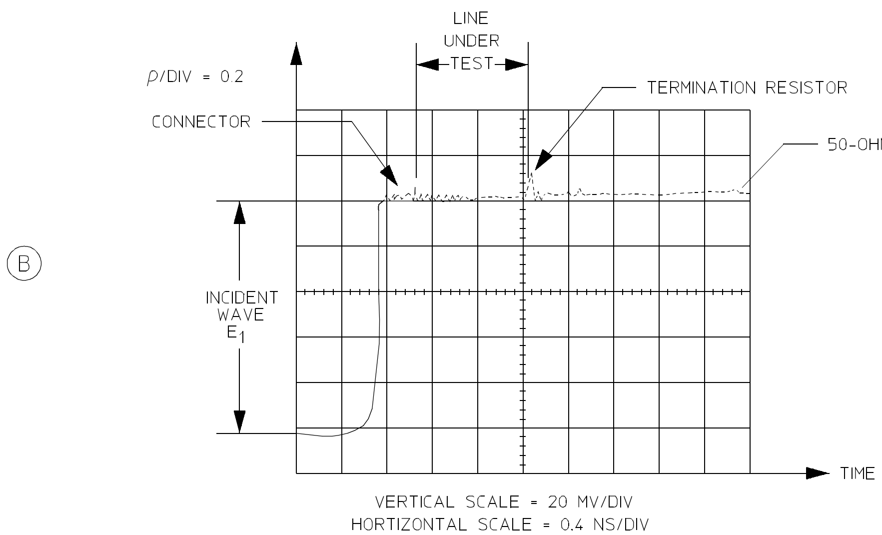
which agrees closely with the calculated value.

Figure 11-8



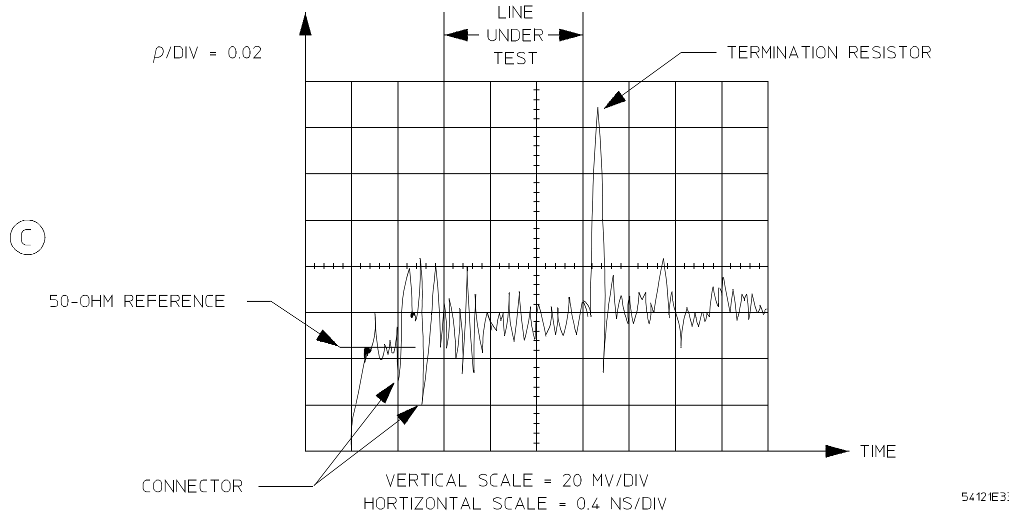
TDR Determination of Line Characteristic Impedance

Figure 11-9



TDR Determination of Line Characteristic Impedance (Continued)

Figure 11-10



TDR Determination of Line Characteristic Impedance (Continued)

The reflected voltage due to the connector is ±40 mV. The line reflects a voltage of ±25 mV due to variations in the characteristic impedance of the line. The reflection of 88 mV shown for the termination resistor ($\rho = 0.088$) is due to the inductance of the resistor. It can be calculated that the inductance of the resistor is less than 0.9 nH.

In these experiments, the input waveform comes from a generator which has a risetime of 28 ps. There is some attenuation of the signal noticeable as it reaches the termination resistor ($t_r = 80$ ps at the load). When driving the line with a MECL III gate with a risetime of 1 ns, the reflection due to the inductance of the resistor would be much less (about 10 mV).

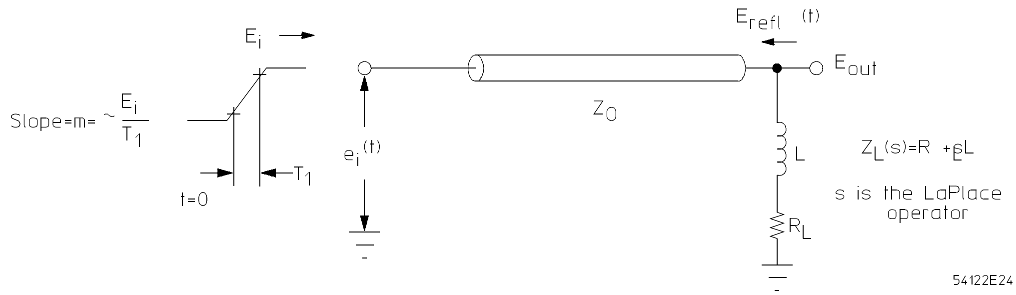
TDR Example 2

An equation can be derived to determine the maximum reflection voltage due to the inductance of the resistor leads. The circuit shown in will be used in the derivation.

The reflection coefficient at the load is:

$$\rho_L(s) = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{(R_L + sL) - Z_o}{(R_L + sL) + Z_o} = \frac{s + \frac{R_L - Z_o}{L}}{s + \frac{R_L + Z_o}{L}} \qquad (16)$$

Figure 11-11



Circuit for Determining the Maximum Reflected Voltage Due to the Inductance of the Resistor Leads

where s is the LaPlace operator for $j\omega$. The driving voltage will be represented as:

$$e_i(t) \;=\; mtu(t) - m(t - T_1)u(t - T_1) \tag{17}$$

where $u(t)$ is a step function occurring at $t = 0$. Taking the LaPlace transform of equation 17 gives:

$$E_i(s) \;=\; \frac{m}{s^2}(1 - e^{-T_1 s}) \tag{18}$$

The reflected voltage at the load is then the product of the driving voltage and the reflection coefficient (both in the transformed plane):

$$E_i(s) \;=\; E_i(s)\rho_L(s) \;=\; \frac{s + \frac{R_L - Z_o}{L}}{s^2\left(s + \frac{R_L + Z_o}{L}\right)} \bullet m(1 - e^{(-T_1)s}) \tag{19}$$

Taking the inverse LaPlace transform yields:

$$E_{ref1}(t) \;=\; \left[\frac{2Z_oL}{(R_L + Z_o)^2} + \left(\frac{R_L - Z_o}{R_L + Z_o}\right)t - \left(\frac{2Z_oL}{(R_L + Z_o)^2}\right)e^{-\frac{(R_L + Z_o)t}{L}}\right]mu(t) - \left[\frac{2Z_oL}{(R_L + Z_o)^2} + \left(\frac{R_L - Z_o}{R_L + Z_o}\right)(t - T_1) - \left(\frac{2Z_oL}{(R_L + Z_o)^2}\right)e^{-\frac{(R_L + Z_o)(t - T_1)}{L}}\right]mu(t - T_1) \tag{20}$$

The maximum reflection voltage occurs at $t = T_1$. Then, for $R = Z_o$:

$$T_{ref1}(t = T_1) = E_{ref1max} = \frac{mL}{2Z_o}\left(1 - e^{-\frac{2Z_o}{L}T_1}\right) \tag{21}$$

This equation relates the maximum reflected voltage, which can be measured by TDR, and the inductance, which can then be calculated for the circuit of Figure 11-11.

TDR Example 3

This example indicates how to measure the effect of resistor leads using the TDR. Figure 11-12A shows the construction of a microstrip board used for determining the effects of a resistor with 1" lead lengths. The reflected voltage determined from the TDR measurement is 480 mV (see Figure 11-12B). The risetime at the input to the line is 28 ps but it is lengthened to about 80 ps as the wavefront reaches the termination resistor.

The time, T_1, associated with the slope of the input voltage rise at the terminating resistor can be approximated as:

$$T_1 \approx \frac{t_r}{0.80} = 100ps \tag{22}$$

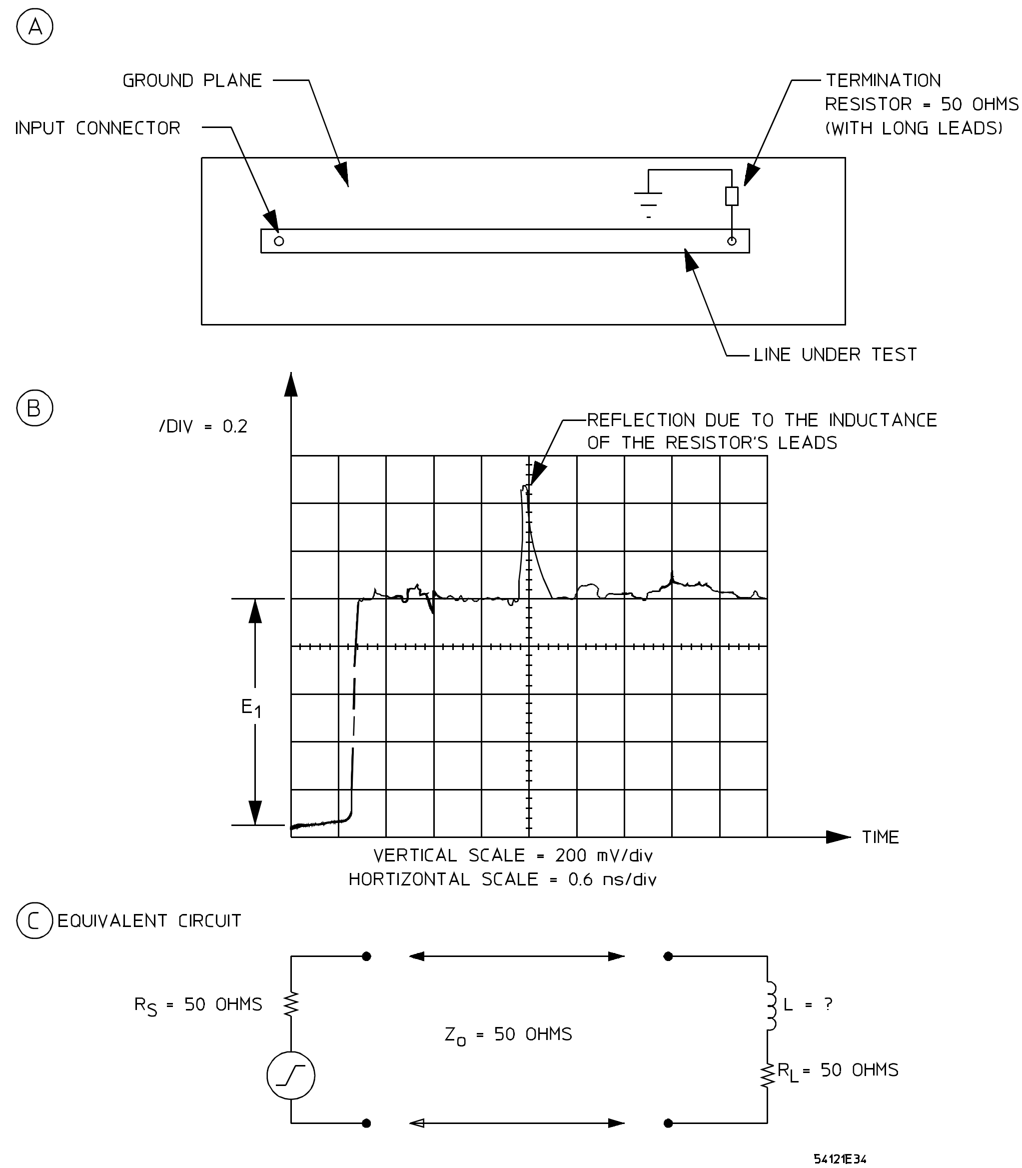
The inductance can be computed by using equation 21, giving L = 6 nH. Additional information can be obtained from the decay of the reflection shown in Figure 11-12B. The decay lasts about 0.3 ns implying a time constant of about 0.3 ns/5 = 60 ps (using 5 time constants as decay time). The calculated time constant for an inductance of 6 nH is:

$$\frac{L}{2Z_o} = 60ps$$

The two results agree closely.

When driving the line with a MECL III gate risetime = 1 ns the reflection would be only 50 mV. Most carbon resistor types will have less than 10 nH of inductance. This inductance gives a reflection of less than 75 mV when the line is driven by a MECL III gate. Note that the reflection is positive, indicating that the noise immunity of a MECL gate connected at the load would be unchanged.

Figure 11-12



Effects Due to Termination Resistor Leads

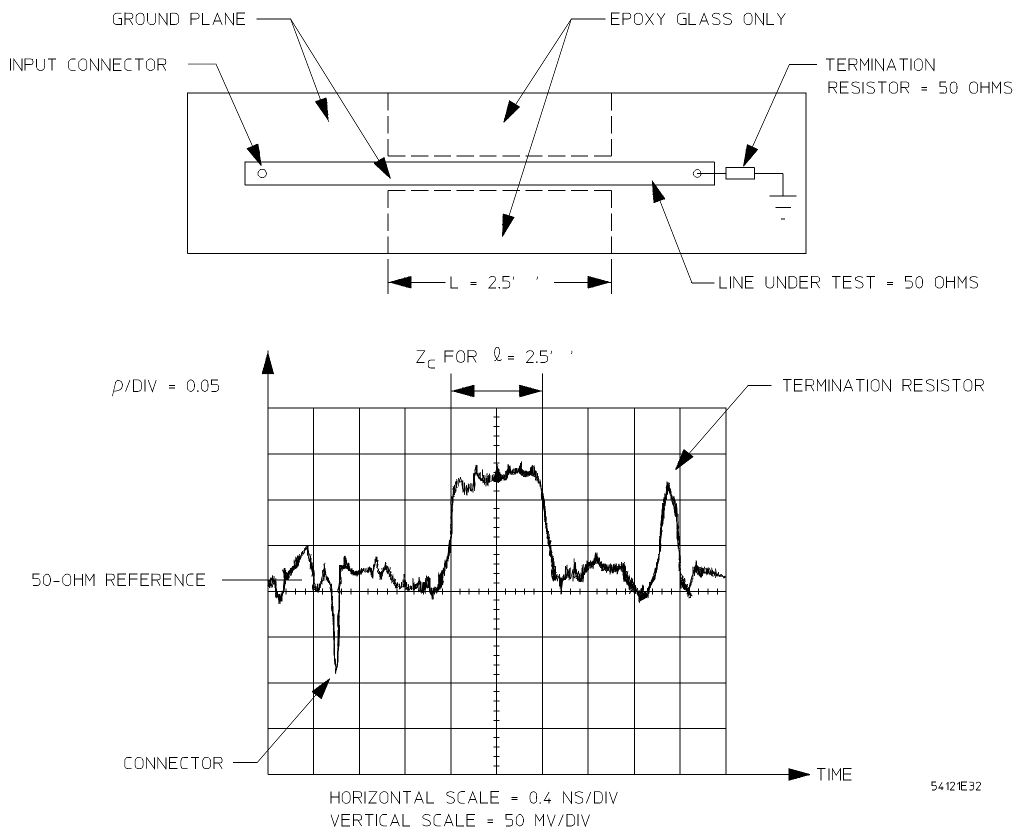
TDR Example 4

Experiments have also been performed to determine the effects of a ground plane on the characteristic impedance of microstrip lines. Figure 11-13 illustrates what happens when the ground plane width under the transmission line abruptly drops to the width of an active line. The TDR waveform shows that a 12% reflection occurs due to this discontinuity in the ground plane.

Using equation 15 the impedance of the 2½ inch-long strip can be calculated as:

$$Z_{line} = \frac{1 + 0.12}{1 - 0.12} \bullet 50 = 68 ohms$$

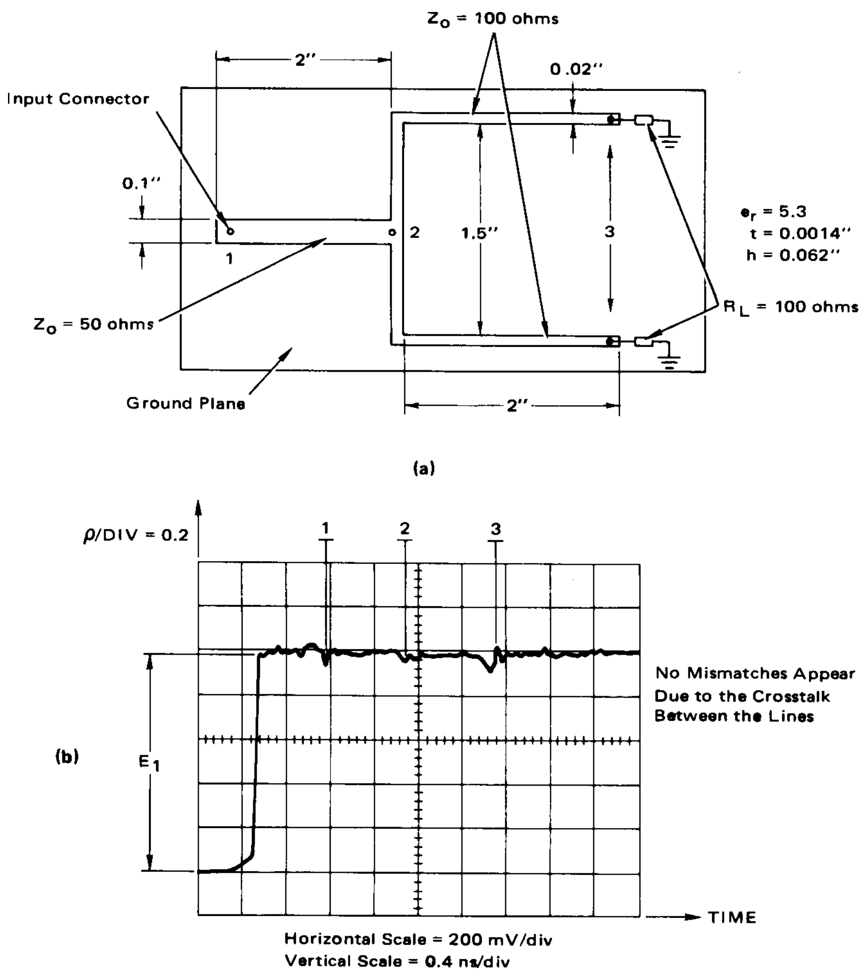
Figure 11-13



Effects of Ground Plane Discontinuities.

Figure 11-14 shows a curve that approximates the change in the characteristic impedance of the line for various ratios of ground plane width to active line width. Note that when the ground width is greater than 3 times the line width, the characteristic impedance is constant according to equation 14.

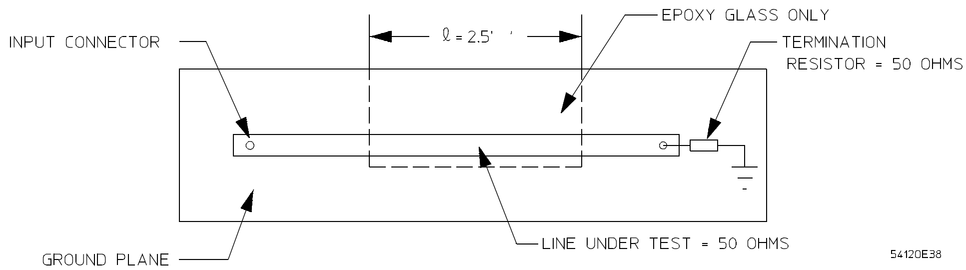
Figure 11-14

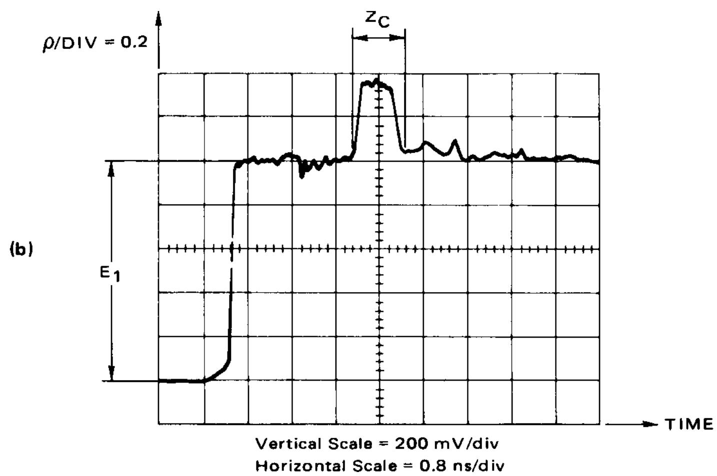


Variation of Microstrip Impedance as a Function of Ground Width - Line Width

A related experiment was performed to find the reflection due to a ground plane near the active line, but not directly under it. The test configuration and test results are shown in Figure 11-15.

Figure 11-15





Effects of Ground Plane Discontinuity

As indicated by the TDR measurement, the reflection is about 36%. Again using equation 15, the impedance of the 2½ inch strip can be calculated:

$$Z_{line} = \frac{1 + 0.36}{1 - 0.36} \bullet 50 = 106 ohms$$

The reason for the reflection is the change in the characteristic impedance along with the line resulting from the ground plane not being under part of the active line. In such a region, capacitance of the line to ground decreases while the inductance of the line increases, the net result being a higher characteristic impedance.

It must be remembered that the TDR input waveform has a risetime of 28 ps. Consequently, in a real logic circuit situation where perhaps, a MECL III gate with a 1 ns risetime is driving the line the reflection would actually be less than 27%, not 36% as in this example.[1] This can be determined by scaling the value of ρ found with the TDR waveshape in Figure 11-15B, with a 1 ns risetime. When the length of the ground plane discontinuity is less than the distance travelled by the signal during its risetime, then the reflection coefficient can also be calculated as:

$$\rho' = \frac{2lt_{pd}}{t_r} \bullet \rho, \quad \text{for} \left(\frac{2lt_{pd}}{t_r} < 1\right) \qquad (23)$$

where: t_{pd} = the propagation delay time of the line in ns / in.
t_r = the risetime of the signal in ns
l = the length of the discontinuity in inches
ρ = the reflection coefficient for $2l_{pd} / t_r \geq 1$
(in this case the value found with the TDR waveshape with t_r = 28 ns).

For a discontinuity in the ground plane of 2.5 inches length, a propagation delay of the line of 0.15 ns / in, and a MECL III gate with 1 ns risetime, the percent reflected voltage can be calculated. From Figure 11-15B, ρ is found to be 0.36. Using equation 23

$$\rho' = \frac{2(0.36)2.5(0.15)}{1} = 0.27$$

Therefore, the reflection would be 27%. For a MECL 10K series gate with a risetime of 3.5 ns, the reflection would only be 7.7%, and a MECL 10KH gate with a rise time of 1.8 ns, the reflection would be 15%.

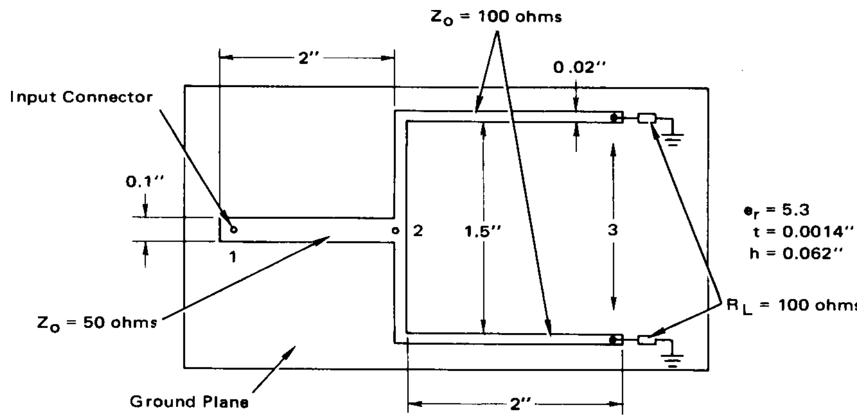
TDR Example 5

Another measurement was performed to observe the reflections due to the use of a hybrid divider. The construction of the microstrip board used is shown in the Figure 11-16. Note that the 50 Ω line branches out into two 100 Ω lines. A reflection of 4% is observed at point 2 where the junction occurs. Notice that the resistor exhibits a reflection of - 8%, due to capacitance of the resistor.

[1]The Agilent 54753A and Agilent 54754A TDR plug-ins' normalization allows the user to change the risetime of the measurement system to simulate actual circuit risetimes.

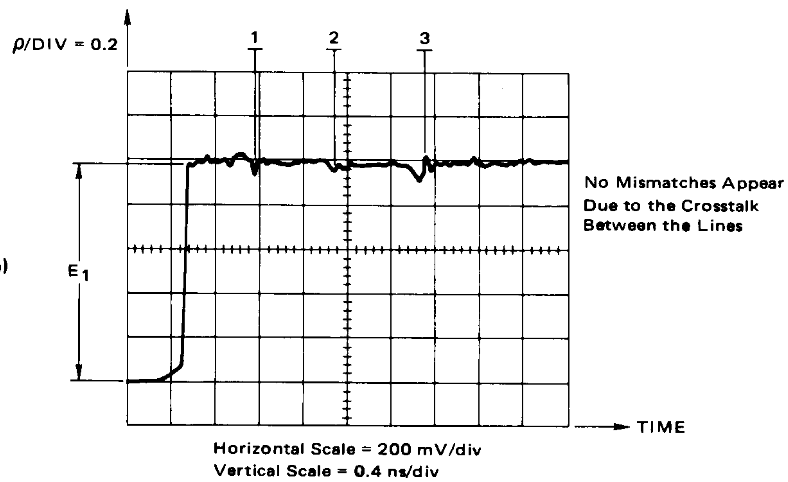
Previously it was found that the 50 Ω resistor was inductive. The lower values of resistors (< 75 Ω) exhibit inductance, while the higher values behave capacitively. No mismatch appears due to the crosstalk between the two 100 Ω branches, because of their wide separation.

Figure 11-16



(a)

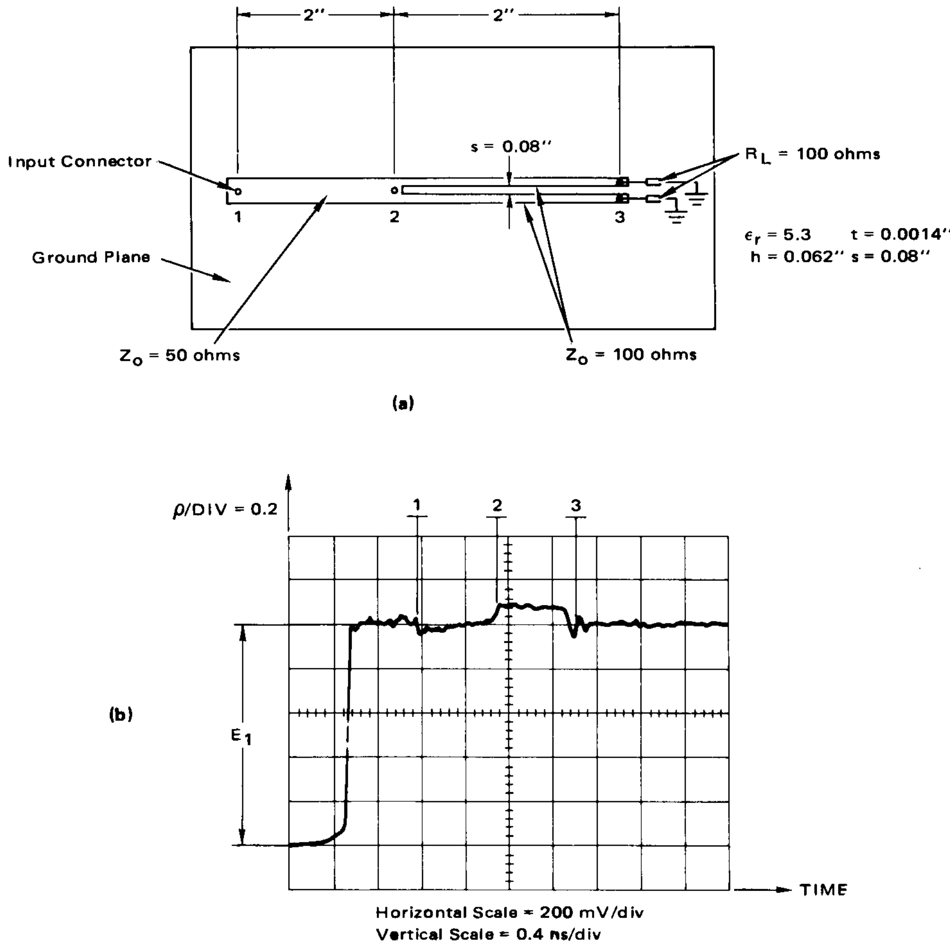
(b)



Hybrid Divider

Figure 11-17B shows the reflection due to the construction of Figure 11-17A where the two 100 Ω lines have been brought close together. The reflection at point 2 is now equal to 8% because the two lines are cross coupled.

Figure 11-17



Hybrid Divider with Crosstalk Problem

Even mode or odd mode characteristic impedance (Z_{oe} or Z_{oo}) can be considered to exist in a circuit with crosstalk. One, Z_{oe}, is due to the strips being at the same potential and carrying equal currents in the same direction. The other, Z_{OO}, is due to the strips being at equal but opposite potentials and carrying equal currents in opposite directions. The backward crosstalk voltage, V_B, on a passive line is:

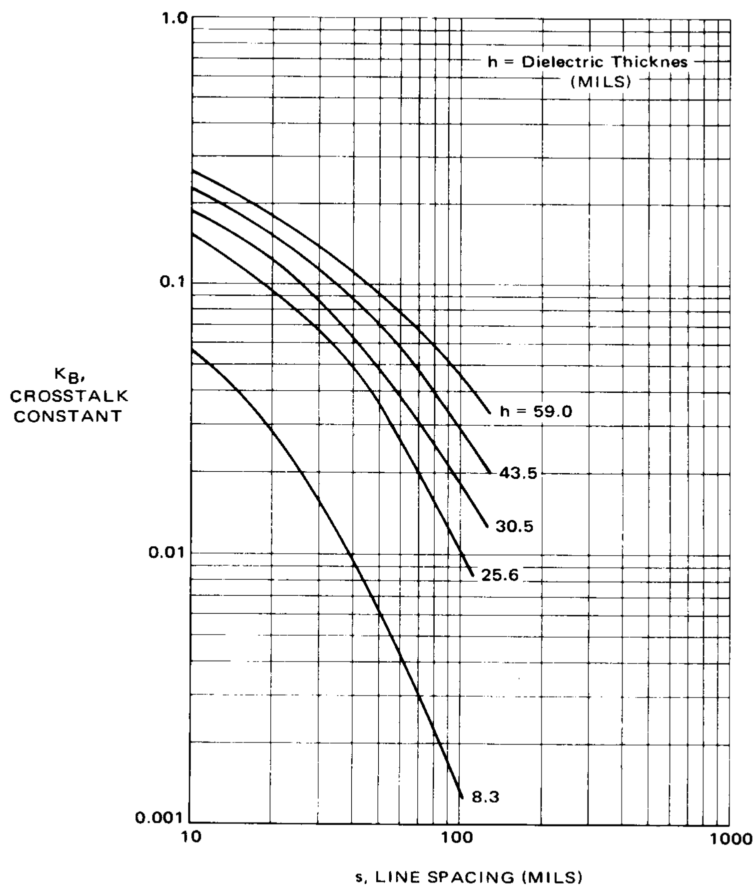
$$V_B = \left(\frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}}\right) E_1 \tag{24}$$

where E_1 is the signal propagating down the active line. The backward crosstalk voltage shown in Figure 11-17B at point 2 is equal to 8% of the incident voltage E_1. Since both lines are active, the crosstalk due to one active line is 4% of E_1 for a spacing of 80 mils.

Crosstalk is not ordinarily a problem when using MECL III on microstrip or strip line circuit boards, when line spacings are greater than 30 mils. The mutual inductance and capacitance between two lines are used to determine the crosstalk coefficient. Forward crosstalk is normally much smaller than the backward crosstalk on microstrip lines except for very long lines (> 5 feet). Forward crosstalk does not exist at all on strip lines, since they are made with a homogeneous medium, so that the inductively and capacitively induced currents cancel.

The backward crosstalk coefficients for various types of microstrip lines on glass epoxy boards are shown in Figure 11-18.

Figure 11-18



Backward Crosstalk Coefficient for Microstrip Lines on Glass Epoxy Boards (G-10 Material)

The backward crosstalk coefficient is equal to:

$$K_B = \frac{1}{4t_{pd}}\left(\frac{L_M}{Z_o} + C_M Z_o\right) \qquad (25)$$

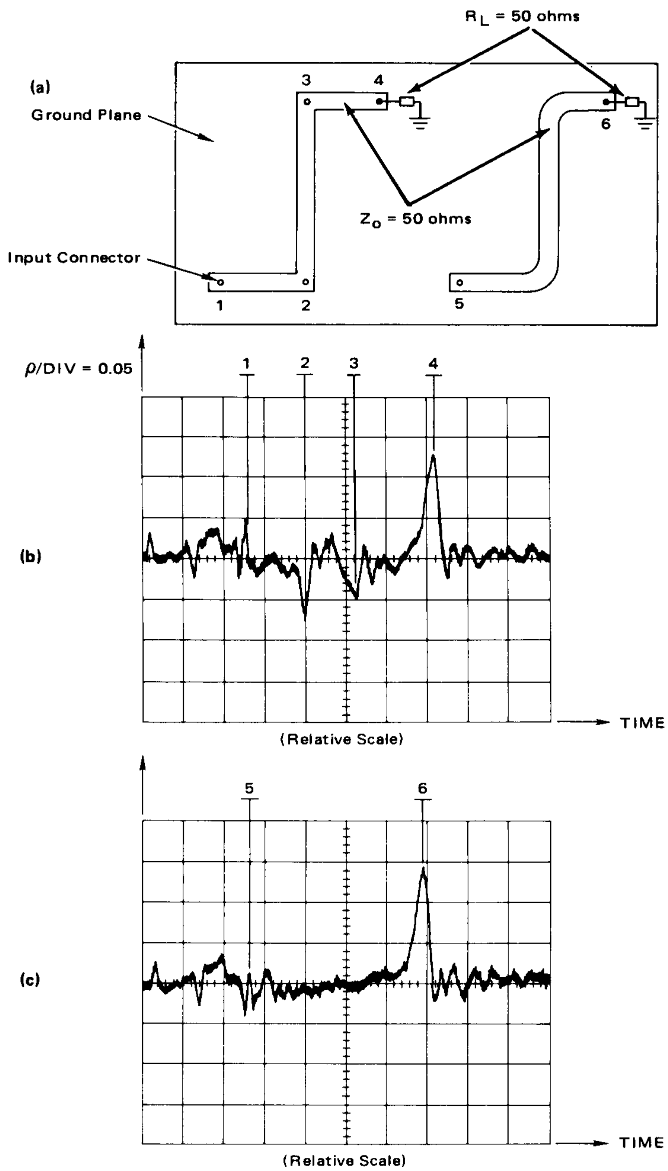
where: L_M = the inductive coupling
C_M = the capacitive coupling
t_{pd} = the propagation delay of the line per unit length

TDR Example 6

The graph data in Figure 11-18 will be used to determine the percent of crosstalk coupling for the circuit of Figure 11-17. From the dimensions of the lines given in Figure 11-17 (a), K_B is found to be 0.055 from the graph. This means that if one line (the active line) were driven with a signal, the other line (passive) would have a coupled signal of 5.5% of the amplitude on the active line, in a direction opposite to that of the driving signal. Since both 100 Ω lines are active simultaneously, the reflection observed on the TDR is twice as much, or 11%. From Figure 11-17, the actual crosstalk can be seen to be about 8%.

In very high speed systems, the exact shape of a line can be important, if reflections are to be kept to a minimum. The arrangement shown in Figure 11-19A has been used to investigate the behavior of two different line shapes. For one line, corners are sharp. This permits the width of the line to be larger at corners than elsewhere. Figure 11-19B shows that a -7.5% reflection occurs at point 6 due to the lowered characteristic impedance at the corner. For the other line, the corners are rounded to produce a constant line width. Figure 11-19C shows that a constant line impedance exists for the second line. Note that an inductive reflection, as discussed before, occurs at the end of the line due to the inductance of the resistor. In conclusion, it is desirable to have smooth, rounded line edges and constant line widths when designing transmission lines for high speed systems. Resistor leads should be kept short to minimize termination inductance.

Figure 11-19



Reflections Caused by Signal-Line Shape Variations

References

1 Kaupp, H. R., "Characteristics of Microstrip Transmission Lines", IEEE Transactions on Electronic Computers, Vol. EC-16 No. 2, April 1967, pp. 185-193.

2 Cohn, S. B., "Characteristic Impedance of the Shielded Strip Transmission Line", Transactions IRE, Vol. MTT-2, July 1954, pp. 52-57

3 Springfield, W. K., "Designing Transmission Lines into Multilayer Circuit Boards". Electronics, November 1, 1965 pp. 90-96.

4 Skilling, H. H., "Electric Transmission Lines", New York McGraw-Hill, 1951.

5 DeFalco, J. A., "Reflections and Crosstalk in Logic Circuit Interconnections", IEEE Spectrum. July 1970, pp. 44-50.

6 Millman, J., and Taub, H., "Pulse, Digital and Switching Waveforms", New York, McGraw-Hill, 1965, pp. 83-106

7 "Time Domain Reflectometry", Hewlett-Packard[2] Application Note 62, 1964.

8 Botos, Bob, "Nanosecond Pulse Handling Techniques in I/C Interconnections", Motorola Application Note AN-270.

9 Schwarzmann, A., "Microstrip Plus Equations Adds Up to Fast Designs", Electronics, October 2, 1967, pp. 109-112

10 Catt, I., "Crosstalk (Noise) in Digital Systems". IEEE Transactions on Electronic Computers, Vol. EC-16, No. 6 December 1967, pp. 743-763.

11 Feller, A., H. R. Kaupp. J. J. Digiacoma. "Crosstalk and Reflections in High-Speed Digital Systems". Proceedings, Fall Joint Computer Conference, 1965, pp. 511-525.

12 Cohn, S. B., "Shielded Coupled-Strip Transmission Line", IRE Transactions-Microwave Theory and Techniques, October 1955. pp. 29-38.

13 Gabbard, O. G., "High-Speed Digital Logic for Satellite Communications", Electro-Technology, April 1969, pp. 59-65.

14 Henschen, I. E. and E. M. Reyner II, "Adapting PC Connectors for Impedance Matching", Proceedings, NEPCON, 1970.

[2] Hewlett-Packard and HP are U.S. registered trademarks of Hewlett-Packard Company.

12

Specifications and Characteristics

Specifications and Characteristics

What you'll find in this chapter

This chapter lists the system specifications and characteristics of the Agilent 54753A, 54754A TDR plug-in module when it is combined with either the Agilent 83480A or Agilent 54750A mainframes. The specifications and characteristics for the mainframe are in the *Agilent 83480A, 54750A User's Guide*.

All specifications, unless otherwise noted, require a 60 minute warm-up period.

Definitions of terms

The distinction between specifications, *characteristics*, typical performance, and nominal values is described as follows:

- Specifications describe warranted performance over the temperature range +15° C to +35° C (unless otherwise noted). All specifications apply after the instrument's temperature has been stabilized after 60 minute continuous operation. Unless otherwise noted, corrected limits are given when specifications are subject to minimization with error-correction routines.
- *Characteristics* provide useful, but nonwarranted information about the functions and performance of the instrument. *Characteristics are printed in italics*.
- Typical Performance, where listed, is not *warranted*, but indicates performance which most units will exhibit. *Typical performance is printed in italics*.
- Nominal Value indicates the expected, but not *warranted*, value of the parameter.

Specifications

The following are specifications used to test the Agilent 54753A, 54754A plug-in modules. Specifications are valid after a 60 minute warm-up period. See the *Agilent 54701A Active Probe Service Guide* for complete probe specifications.

Vertical Specifications

Channels (Vertical)[1]	dc to 12.4 or 18.0 GHz, user selectable dc to 12.4 or 20.0 GHz, user selectable[2]
Bandwidth (–3 dB)	dc to 12.4 or 18.0 GHz[3], user selectable dc to 12.4 or 20.0 GHz, user selectable[2]
dc Accuracy—single marker[4 5]	
12.4 GHz bandwidth	±0.4% of full scale ±2 mV ±0.6% of reading-channel offset[6] ± (1%/°C) (ΔT_{cal}) (reading) [7]
18 GHz bandwidth	±0.4% of full scale ±2 mV ±1.2% of reading-channel offset[6] ± (1%/°C) (ΔT_{cal}) (reading) [7]
20 GHz bandwidth[2]	±0.4% of full scale ±2 mV ±1.2% of reading-channel offset[6] ± (1%/°C) (ΔT_{cal}) (reading) [7]
dc Difference—two marker accuracy on same channel [5]	
12.4 GHz bandwidth	±0.8% of full scale ±0.6% of delta reading[6] ± (1%/°C) (ΔT_{cal}) (delta reading) [7]
18 GHz bandwidth	±0.8% of full scale ±1.2% of delta reading[6] ± (1%/°C) (ΔT_{cal}) (delta reading) [7]
20 GHz bandwidth[2]	±0.8% of full scale ±1.2% of delta reading[6] ± (1%/°C) (ΔT_{cal}) (delta reading) [7]
Transition Time (10%–90%) characteristic, calculated from T=0.35/BW, electrical	
12.4 GHz bandwidth	28.2 ps
18 GHz bandwidth	19.4 ps
20 GHz bandwidth [2]	17.5 ps
RMS Noise Typical	
12.4 GHz	0.25 mV
18 GHz	0.5 mV
20 GHz [2]	0.5 mV

Maximum	
12.4 GHz	0.5 mV
18 GHz	1.0 mV
20 GHz[2]	1.0 mV
Scale Factor	full scale is eight divisions
Minimum	1 mV/div
Maximum	100 mV/div
Display Resolution	256 points
dc Offset Range[8]	±500 mV
Nominal Input Impedance	50 [ohm]
Connectors	3.5mm (m), channel and trigger
Input Reflection/Return Loss	≤5% for 30 ps rise time
Number of Channels	2
Dynamic Range/Maximum Specified Input Power	±400 mV relative to channel offset
Maximum Safe Input	±2V + peak ac (+16 dBm)

1 When operated within ±5°C (±9°F) of the temperature of the last plug-in calibration.

2 For the Agilent 54753A channel 2 only

3 The input sampler is biased differently for increased bandwidth in the 18 GHz bandwidth mode.

4 When driven from a 0 ohm source.

5 It is recommended that a user vertical calibration be performed after every 10 hours of continuous use or if the temperature has changed by greater in 2°C from the previous vertical calibration.

6 When operated within ±2°C (±3.6°F) of the temperature of the last plug-in calibration. When operated within ±5°C (±9°F) of the temperature of the last plug-in calibration, the final term in the dc accuracy specification is 2.5 times higher.

7 Where ΔT_{cal} represents the temperature change in Celsius from the last user vertical calibration.

8 An effective offset of ±900 mV can be achieved using the ±500 mV of channel offset and adding ±400 mV of offset using the waveform math offset scaling function.

Environmental Specifications

Temperature	
Operating	15 °C to +35 °C
Non-operating	–40 °C to +70 °C

Humidity	
Operating	up to 90% relative humidity at 35 °C
Non-operating	up to 90% relative humidity at 35 °C

Power Requirements

Supplied by mainframe.

Weight

Net	approximately 1.1 kg (2.4 lb.)
Shipping	approximately 2.0 kg (4.4 lb.)

Characteristics

The following characteristics are typical for the Agilent 54753A and 54754A TDR plug-in modules. See the *Agilent 54701A Active Probe Service Guide* for complete probe characteristics.

Trigger Input Characteristics

Nominal Impedance	50 [ohm]
Input Connector	3.5 mm (m)
Trigger Level Range	±1 V
Maximum Safe Input Voltage	±2 Vdc + ac peak (+16 dBm)
Percent Reflection	≤10% for 200 ps rise time

Refer to the *Agilent 83480A, 54750A User's Guide* for Trigger specifications.

Product Regulations

Safety

IEC 1010
UL 3111
CSA Standard C22.2 No. 1010.1-92

EMC

This product meets the requirement of the European Communities (EC) EMC Directive 89/336/EEC.

Emissions

EN55011/CISPR 11 (ISM Group 1, Class A equipment)

Immunity

EN50082-1

	Code[1]	Notes[2]
IEC 801-2 (ESD) 4kV CD, 8kV AD	2	
IEC 801-3 (Rad.) 3V/m	2	
IEC 801-4 (EFT) 1kV	2	

[1] Performance Codes:
1 PASS - Normal operation, no effect.
2 PASS - Temporary degradation, self recoverable.
3 PASS -Temporary degradation, operator intervention required.
4 FAIL - Not recoverable, component damage.

[2] Notes:
(None)

13

In Case of Difficulty

In Case of Difficulty

What you'll find in this chapter

This chapter provides a list of suggestions for you to follow if the plug-in module fails to operate. A list of messages that may be display is also included.

For complete service information, refer to the optional *Agilent 54753A, 54754A Service Guide*.

CAUTION

Electrostatic discharge (ESD) on or near input connectors can damage circuits inside the instrument. Repair of damage due to misuse is *not* covered under warranty. Before connecting any cable to the electrical input, momentarily short the center and outer conductors of the cable together. Personnel should be properly grounded, and should touch the frame of the instrument before touching any connector.

If You Have Problems

Review the procedure being performed when the problem occurred. Before calling Agilent Technologies or returning the unit for service, a few minutes spent performing some simple checks may save waiting for your instrument to be repaired.

If the Mainframe Does Not Operate

Please make the following checks:

1. Is the line fuse good?
2. Does the line socket have power?
3. Is the unit plugged in to the proper ac power source?
4. Is the mainframe turned on?
5. Is the rear-panel line switch set to on?
6. Will the mainframe power up *without* the plug-in module installed?

   If the mainframe still does not power up, refer to the optional *Agilent 83480A, 54750A Service Guide* or return the mainframe to a qualified service department.

If the Plug-in Does Not Operate

Make the following checks:

1 Is the plug-in module firmly seated in the mainframe slot?

- Are the knurled screws at the bottom of the plug-in module finger-tight?
- Is a trigger signal connected to a trigger input?
- If other equipment, cables, and connectors are being used with the plug-in module are they connected properly and operating correctly?
- Review the procedure for the test being performed when the problem appeared. Are all the settings correct? Can the problem be reproduced?

2 Perform the following procedures:

- Make sure the instrument is ready to acquire data by pressing *Run*.
- Find any signals on the channel inputs by pressing **Autoscale**.
- See if any signals are present at the channel inputs by pressing:

  Trigger
  Sweep
  freerun

After viewing the signal, press *triggered*.

- Make sure Channel Display is on by pressing:

  Channel
  Display on off on

- Make sure the channel offset is adjusted so the waveform is not clipped off the display.
- If you are using the plug-in module only as a trigger source, make sure at least one other channel is turned on.
- If all of the channels are turned off, the mainframe will not trigger.
- Make sure the mainframe identifies the plug-in module by pressing:

  Utility
  System config...

The calibration status of the plug-in modules is listed near the bottom of the display, in the box labeled "**`Plug-ins`**". If the model number of the plug-in module is listed next to the appropriate slot number, then the mainframe has identified the plug-in.

If "**~known**" is displayed instead of the model number of the plug-in module, remove and reinsert the plug-in module in the same slot. If "**~known**" is still displayed, then the memory contents of the plug-in module are corrupt. Refer to the optional *Agilent 54753A, 54754A Service Guide* or contact a qualified service department.

If all of the above steps check out okay, and the plug-in module still does not operate properly, then the problem is beyond the scope of this book. Refer to the optional *Agilent 54753A, 54754A Service Guide* or return the plug-in module to a qualified service department.

Error Messages

The following error messages are for the plug-in module. Typically, the error messages indicate there is a problem with either the plug-in or the mainframe.

This section explains what the messages mean and offers a few suggestions that might help resolve the error condition. If the suggestions do not eliminate the error message, then additional troubleshooting is required that is beyond the scope of this book. Refer to the optional *Agilent 54753A, 54754A Service Guide* and *Agilent 83480A, 54750A Service Guide* for additional troubleshooting information.

Additional error messages are listed in the *Agilent 83480A, 54750A User's Guide* for the mainframe.

`Memory error occurred in plug-in _ : Try reinstalling plug-in`

The mainframe could not correctly read the contents of the memory in the plug-in.

1 Remove and reinstall the plug-in module.
2 Each time a plug-in is installed, the mainframe rereads the plug-in module's memory.
3 Verify the plug-in module is firmly seated in the mainframe slot.
4 Verify the knurled screws at the bottom of the plug-in module are finger-tight.
5 Install the plug-in in a different slot in the mainframe.

`Busy timeout occurred with plug-in _: Try reinstalling plug-in`

The mainframe is having trouble communicating with the plug-in module. Make sure there is a good connection between the mainframe and the plug-in module.

1. Remove and reinstall the plug-in module.
2. Verify the plug-in module is firmly seated in the mainframe slot.
3. Verify the knurled screws at the bottom of the plug-in module are finger-tight.
4. Install the plug-in in a different slot in the mainframe.

`Communication failure exists at slot _: Service is required`

An illegal hardware state is detected at the mainframe to plug-in module interface of the specified slot.

If the slot is empty, there is a mainframe hardware problem. Refer to the *Agilent 83480A, 54750A Service Guide*.

If a plug-in is installed in the slot, there is a plug-in module hardware problem. Refer to the optional *Agilent 54753A, 54754A Service Guide*.

`ID error occurred in plug-in _: Service is required`

The information read from the plug-in module's memory does not match the hardware in the plug-in module. This can be caused by a communication problem between the mainframe and the plug-in module. Make sure there is a good connection between the mainframe and the plug-in.

1. Remove and reinstall the plug-in module.
2. Verify the plug-in module is firmly seated in the mainframe slot.
3. Verify the knurled screws at the bottom of the plug-in module are finger-tight.

Index

Numerics

R

S

T

U

V

W

Document Warranty

The information contained in this document is subject to change without notice.

Agilent Technologies makes no warranty of any kind with regard to this material, including, but not limited to, the implied warranties of merchantability or fitness for a particular purpose.

Agilent Technologies shall not be liable for errors contained herein or for damages in connection with the furnishing, performance, or use of this material.

Safety

This apparatus has been designed and tested in accordance with IEC Publication 61010-1, Safety Requirements for Measuring Apparatus, and has been supplied in a safe condition. This is a Safety Class I instrument (provided with terminal for protective earthing). Before applying power, verify that the correct safety precautions are taken (see the following warnings). In addition, note the external markings on the instrument that are described under "Safety Symbols."

Warning

• Before turning on the instrument, you must connect the protective earth terminal of the instrument to the protective conductor of the (mains) power cord. The mains plug shall only be inserted in a socket outlet provided with a protective earth contact. You must not negate the protective action by using an extension cord (power cable) without a protective conductor (grounding). Grounding one conductor of a two-conductor outlet is not sufficient protection.

• Only fuses with the required rated current, voltage, and specified type (normal blow, time delay, etc.) should be used. Do not use repaired fuses or short-circuited fuseholders. To do so could cause a shock of fire hazard.

• Service instructions are for trained service personnel. To avoid dangerous electric shock, do not perform any service unless qualified to do so. Do not attempt internal service or adjustment unless another person, capable of rendering first aid and resuscitation, is present.

• If you energize this instrument by an auto transformer (for voltage reduction), make sure the common terminal is connected to the earth terminal of the power source.

• Whenever it is likely that the ground protection is impaired, you must make the instrument inoperative and secure it against any unintended operation.

• Do not operate the instrument in the presence of flammable gasses or fumes. Operation of any electrical instrument in such an environment constitutes a definite safety hazard.

• Do not install substitute parts or perform any unauthorized modification to the instrument.

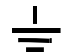
• Capacitors inside the instrument may retain a charge even if the instrument is disconnected from its source of supply.

• Use caution when exposing or handling the CRT. Handling or replacing the CRT shall be done only by qualified maintenance personnel.

Safety Symbols

Instruction manual symbol: the product is marked with this symbol when it is necessary for you to refer to the instruction manual in order to protect against damage to the product.

Hazardous voltage symbol.



Earth terminal symbol: Used to indicate a circuit common connected to grounded chassis.

WARNING

The Warning sign denotes a hazard. It calls attention to a procedure, practice, or the like, which, if not correctly performed or adhered to, could result in personal injury. Do not proceed beyond a Warning sign until the indicated conditions are fully understood and met.

CAUTION

The Caution sign denotes a hazard. It calls attention to an operating procedure, practice, or the like, which, if not correctly performed or adhered to, could result in damage to or destruction of part or all of the product. Do not proceed beyond a Caution symbol until the indicated conditions are fully understood or met.

Agilent Technologies
Lightwave Division
1400 Fountaingrove Parkway
Santa Rosa, CA 95403-1799, USA
(707) 577-1400

Product Warranty

This Agilent Technologies product has a warranty against defects in material and workmanship for a period of one year from date of shipment. During the warranty period, Agilent Technologies will, at its option, either repair or replace products that prove to be defective. For warranty service or repair, this product must be returned to a service facility designated by Agilent Technologies. For products returned to Agilent Technologies for warranty service, the Buyer shall prepay shipping charges to Agilent Technologies and Agilent Technologies shall pay shipping charges to return the product to the Buyer. However, the Buyer shall pay all shipping charges, duties, and taxes for products returned to Agilent Technologies from another country. Agilent Technologies warrants that its software and firmware designated by Agilent Technologies for use with an instrument will execute its programming instructions when properly installed on that instrument. Agilent Technologies does not warrant that the operation of the instrument software, or firmware will be uninterrupted or error free.

Limitation of Warranty

The foregoing warranty shall not apply to defects resulting from improper or inadequate maintenance by the Buyer, Buyer- supplied software or interfacing, unauthorized modification or misuse, operation outside of the environmental specifications for the product, or improper site preparation or maintenance.

No other warranty is expressed or implied. Agilent Technologies specifically disclaims the implied warranties of merchantability or fitness for a particular purpose.

Exclusive Remedies

The remedies provided herein are the buyer's sole and exclusive remedies. Agilent Technologies shall not be liable for any direct, indirect, special, incidental, or consequential damages, whether based on contract, tort, or any other legal theory.

Assistance

Product maintenance agreements and other customer assistance agreements are available for Agilent Technologies products. For any assistance, contact your nearest Agilent Technologies Sales Office.

Certification

Agilent Technologies certifies that this product met its published specifications at the time of shipment from the factory. Agilent Technologies further certifies that its calibration measurements are traceable to the United States National Institute of Standards and Technology, to the extent allowed by the Institute's calibration facility, and to the calibration facilities of other International Standards Organization members.

About this edition

This is the second edition of the Agilent 54753A and Agilent 54754A TDR Plug-in Modules User's Guide.

Publication number 54753-97015

Printed in USA.

New editions are complete revisions of the manual. Update packages, which are issued between editions, contain additional and replacement pages to be merged into the manual by you. The dates on the title page change only when a new edition is published. A software or firmware code may be printed before the date. This code indicates the version level of the software or firmware of this product at the time the manual or update was issued. Many product updates do not require manual changes; and, conversely, manual corrections may be done without accompanying product changes. Therefore, do not expect a one-to-one correspondence between product updates and manual updates.

The following list of pages gives the date of the current edition and of any changed pages to that edition.

All pages original edition