

10 ps Risetime Network TDT and TDR Measurements using the PSPL 15 ps Pulse Generator and HP 50 GHz Oscilloscope

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This application note AN-5c demonstrates how to make Time Domain Transmission (TDT) and Time Domain Reflection (TDR) measurements on electrical networks with better than 10 ps resolution. This is made possible by advances in sampling oscilloscope bandwidths, ultra-fast risetime pulse generators, signal processing deconvolution mathematics, and high-speed microprocessors. The instruments used for 10 ps TDT are the Hewlett-Packard Model 54750A or 83480A 50 GHz, digital sampling oscilloscope and the PSPL Model 4015, 9 V, 15 ps pulse generator. PSPL's previous AN-5a (July, 1992) covered 10 ps TDR/TDT using the HP-54124A, 50 GHz oscilloscope.

HP 50 GHz OSCILLOSCOPE

The HP 54120 series of oscilloscopes has been discontinued and replaced by the 54750 series. The major changes made in the 54750 were repackaging and a much improved, faster microprocessor system. HP also offers a Model 83480A digital communications analyzer that is essentially identical to the 54750 main frame, but with a different set of internal software. If the optional TDR/TDT software is purchased from HP for the 83480A, then it will also do 10 ps TDR/TDT measurements.

Two HP plug-ins are required for 10 ps TDT measurements. One must be either the 54753A two-channel, 20 GHz, single TDR plug-in or the 54754A two-channel, 18 GHz, dual differential TDR plug-in. The other required plug-in is either the 54752B or 83484B single-channel 50 GHz plug-in or the 54752A or 83484A dual-channel 50 GHz plug-in. The TDR plug-ins have 18 or 20 GHz bandwidth, 17 ps risetime, 50 Ohm samplers with APC-3.5 mm connectors. The 50 GHz plug-ins have selectable 50 GHz or 26 GHz bandwidth, 9 ps risetime, 50 Ohm samplers with APC-2.4 mm connectors. The TDR plug-ins include a built-in TDR pulse generator(s) which produces a 200 mV, 45 ps risetime step pulse.

Both the original 54120 series and now the 54750 series (and 83480) include built-in software for doing "Normalized" TDR/TDT network measurements. "Normalization" is HP's term for deconvolution. Deconvolution is the mathematical operation of removing the input signal from an output signal to arrive at the actual step response of the Device Under Test (DUT). This is done by using transforms between the time and frequency domain and digital filtering. HP's scopes use the Bracewell transform. By altering the bandwidth of the

digital filter, one is able create test pulses with risetimes either slower or faster than the actual test pulse. Another advantage of "Normalization" is that it removes all of the imperfections in the original test pulse. The resultant normalized test pulse is a very clean, Gaussian-response step. See Figure 4.

PSPL 15 ps PULSE GENERATOR

The Picosecond Pulse Labs (PSPL) Model 4015 pulse generator produces a -9 Volt, 15 ps falltime step pulse. It was originally designed as a companion unit to the HP-54120 series sampling heads. It will also work with the newer HP 54750 or 83480 series of scopes. It is used as a TDR pulse amplifier and gives a 3:1 improvement in risetime, i.e., 15 ps vs. 45 ps. When used with the HP scopes for 10 ps TDT or TDR, it is triggered by the HP scope's 200 mV, 45 ps TDR pulse. The 4015 in turn generates a much larger, 9 Volt, much faster 15 ps pulse. This 15 ps pulse is generated in a Pulse Head which is about the size of a coaxial attenuator. The pulse head is connected to its pulse driver box using a microwave-quality coaxial cable. The remote pulse head concept allows the ultra-fast, 15 ps pulse to be connected directly to the DUT with no intermediate, risetime slowing, coaxial cables. Two 4015 models are available. The original 4015B must be triggered externally. The 4015C can be triggered externally, but also includes a built-in rep. rate generator, trigger output, and delay circuit.

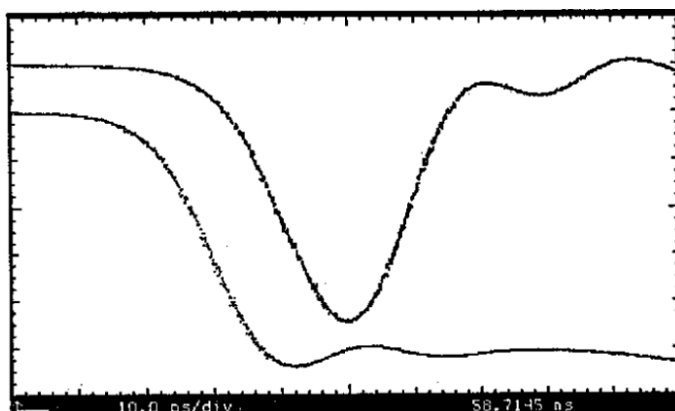


Figure 1: PSPL 4015 Pulse Generator Step and Impulse Waveforms

Top trace is impulse at 0.6 V/div. Bottom trace is step at 1.8 V/div. Horizontal scale is 10 ps/div.

Figure 1 shows two pulses generated by the 4015 Pulse Generators. The bottom trace is the -9 Volt, 15 ps falltime step pulse used for 10 ps TDT and TDR. The other trace is a -3 Volt, 22 ps duration impulse. The impulse is generated by adding a PSPL Model 5208 Impulse Forming Network on the output of the 4015 Pulse Head. The impulse is useful for driving laser diodes to obtain short light pulses. Other uses of the impulse are for impulse response tests and for making frequency domain, "S" parameter network measurements. This is done by measuring time domain waveforms with a scope and transferring data via the GPIB to a computer. The computer is then used to perform Fast Fourier Transforms (FFTs) on the time domain waveforms. For details, see PSPL's AN-4.

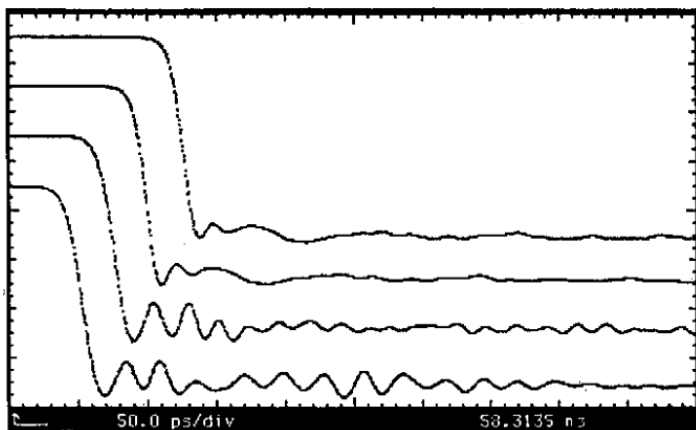


Figure 2: Waveguide Mode Effects in 30 dB Attenuators
75 mV/div. and 50 ps/div. Attenuators from bottom to top: PSPL Model 5510, 10 dB and 20 dB, 18GHz, SMA; HP Model 8493C, 30 dB, 26 GHz, APC-3.5; PSPL Model 5510-K, 10 dB and 20 dB, 40 GHz, 2.92 mm; and HP Model 8490D, 30 dB, 50 GHz, 2.4 mm.

BANDWIDTH AND CONNECTOR CONSIDERATIONS

The 15 ps edge from the 4015 pulse head is equivalent to a signal source with a -3 dB bandwidth of 23 GHz ($BW * Tr = 0.35$) and considerable spectral energy at even higher frequencies. SMA, 3.5 mm, 2.92 mm, and 2.4 mm connectors are rated for use up to 18 GHz, 26 GHz, 40 GHz, and 50 GHz, respectively. Above these frequencies, higher order waveguide modes can propagate. If a very fast pulse excites these waveguide modes, then "weird" waveforms will result. Figure 2 shows the results of the 4015, 9 V, 15 ps pulse being attenuated 30 dB by SMA, 3.5 mm, 2.92 mm, and 2.4 mm attenuators. The waveguide mode effects are obvious with the SMA and 3.5 mm attenuators as evidenced by the excessive ringing. Only the 2.92 mm and 2.4 mm attenuators provide acceptable performance. For the ultimate performance with the HP 50 GHz scope and PSPL 15 ps pulser, only 2.92 mm (40 GHz) or 2.4 mm (50 GHz) components should be used.

TDT NETWORK MEASUREMENTS

For pulse transmission TDT network measurements using an external pulse generator, the HP 54750 or 83480 uses the channel 1 TDR pulse as the external trigger signal, and the Device Under Test's (DUT) output signal is observed on either channel 3 or channel 4. Using the built-in 200 mV, 45 ps TDR test pulse and normalization, the HP scope will give good normalized results for risetimes down to 20 ps. For even faster normalized risetimes, the digital filter ringing noise becomes very objectionable. The risetime of the 50 GHz samplers is 9 ps and thus is not the limiting factor. The limitation is the slow, 45 ps risetime of the HP TDR pulse. To get below 20 ps requires that a faster risetime pulse source be used. This is where the 15 ps falltime of the 4015 pulser is needed. For 10 ps TDT, connect the scope and pulser as shown in Figure 3. The 23 dB of attenuation on the output of the pulse head is necessary to protect the scope's samplers. The 4015's 9 Volt pulse is sufficient to destroy the scope's sampling diodes. Depending upon the desired input signal amplitude to the DUT, the attenuators may be placed either before or after the DUT.

To start a 10 ps TDT measurement, first connect the instruments as shown in Figure 3 without a DUT. Put the HP scope into its TDR/TDT mode of operation. Position the test pulse in the desired location on the scope's screen. Next the scope must be calibrated for normalization. This is done by letting the scope measure and store in memory the actual input test signal. One then selects the desired normalized risetime. The scope then automatically proceeds to do the normalization and displays the results on the screen. Figure 4 shows the "before" and "after" results of normalization. The top trace is the 15 ps 4015 pulse as measured by the HP 50 GHz, 9 ps sampler. The time window is 100 ps (i.e., 10 ps/div). The bottom trace is after normalizing with a 10 ps risetime filter. The falltime is now in fact 10 ps, and the pulse has a very nice Gaussian waveshape and is free from the overshoot and ringing seen on the input 4015 pulse. A detailed examination of the 10 ps pulse's baseline or topline will reveal a small amount of "Digital Filter Ringing". This ringing will limit the ultimate TDT system resolution.

Next insert the DUT between the attenuators and the sampler. Push the "Clear Display" button on the scope to restart the normalization process. The resultant normalized waveform is the DUT's response to a perfect 10 ps falltime test pulse. Figure 5 shows the results obtained when a PSPL Model 5541A Bias Tee was inserted. The top graph shows the "raw" input and output waveforms. The bottom graph shows the 10 ps normalized input and output waveforms.

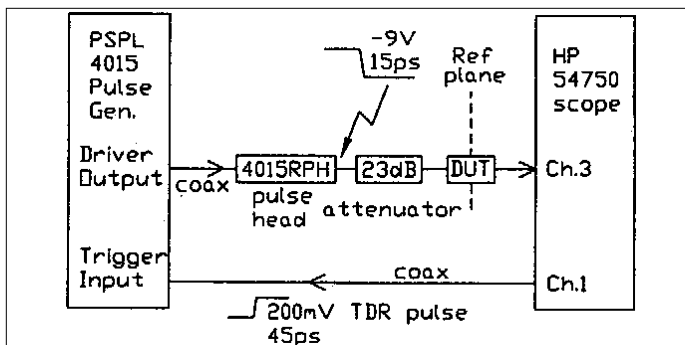


Figure 3: 10 ps TDT Measurement Setup

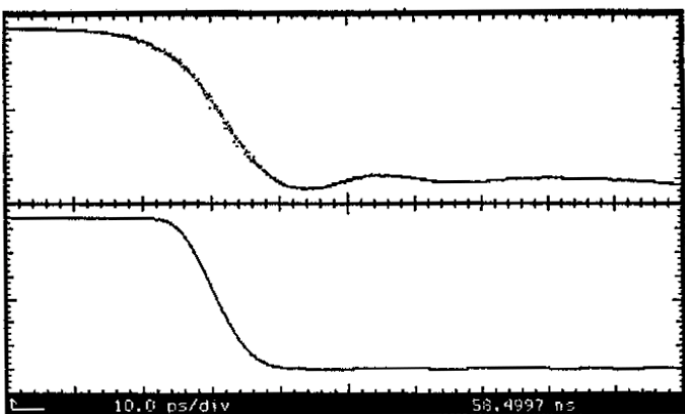


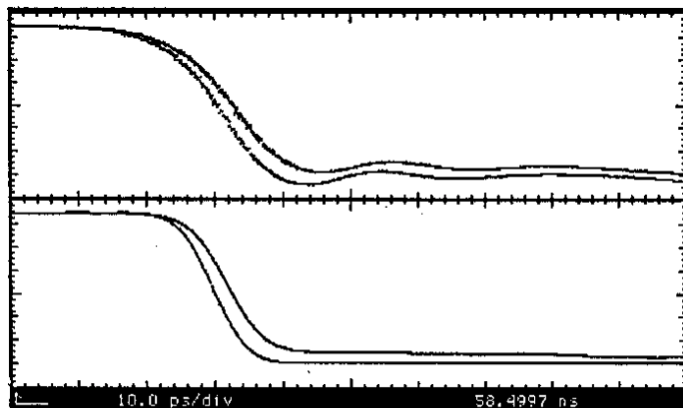
Figure 4: TDT Input Pulse. 100 mV/div and 10 ps/div. Top plot is "raw data" 4015 pulse. Bottom plot is after normalization to 10 ps falltime.

The HP scope's automatic pulse parameter measurement capability can be used to measure the falltimes of these various waveforms. For the 5541A Bias Tee's normalized waveforms, the input falltime was 9.99 ps, and the output falltime was 11.35 ps. The actual DUT's risetime can now be estimated using the root difference of squares equation.

$$Tr(DUT) = [Tr^2(out) - Tr^2(in)]^{1/2} = [11.35^2 ps - 9.99^2 ps]^{1/2} = 5.39 ps$$

10 ps TDT AND TDR SYSTEM LIMITATIONS

10 ps risetime measurements cannot be obtained for all possible settings of the HP scope time base. There are limitations imposed by the time window, number of data points in the record length, the Nyquist frequency, sampler bandwidth related noise, etc. For 512 points, the max. ps window is 500 ps (i.e., 50 ps/div). For 1024 points, the max. window is 1 ns. For 2048 points, the max. window is 2 ns. For 4096 points, the max. window is 5 ns (i.e., 500 ps/div). The flat top portion of the 4015C pulse is 5 ns (10 ns for the 4015B), which allows 10 ps TDT/TDR testing in time windows up to 5 ns. At the extreme settings of 500 ps/div, 4096 record



	current	mean	std dev
Falltime(m1)	15.280 ps	15.280 ps	0.0 s
Falltime(3)	16.579 ps	15.9912 ps	814.3 fs
Falltime(m2)	9.99 ps	9.99 ps	0.0 s
Falltime(r3)	11.48 ps	11.345 ps	213 fs

Figure 5: PSPL 5541A Bias Tee 10 ps TDT Test.

10 ps/div. Top is "raw" input and output waveforms. Bottom is input and output normalized to 10 ps.

length and 64 averages, excellent 10 ps normalized waveforms can still be obtained. The data acquisition and processing time will be quite slow. For narrower time windows, fewer data points, and less averaging, the results will appear to be much closer to "real time". Normal "fast" operating conditions would use a 10 ps filter, 50 GHz bandwidth, 50 ps/div, 1024 point record length, and 32 averages. In this condition we found the residual digital filter noise to be 0.9 mV rms. The attenuated 4015 test pulse amplitude into the sampler was 650 mV. Thus, the signal-to-noise ratio (s/n) was 57 dB. The s/n can be improved using slower risetimes. For a normalized 15 ps risetime, the s/n was 67 dB. With the 54750/83480 scope, one can examine in fine detail the normalized response by expanding both the vertical and horizontal scales. The horizontal scale can be expanded to 1 ps/div.

The fastest allowed normalized risetime is 10 ps. This is a software limitation within the HP scope. Based upon the excellent performance obtained at 10 ps, it is too bad that the HP scope programmers limited the minimum risetime to 10 ps in the software. There is another serious software limitation in the HP-54750/83480 oscilloscope. This deals with TDR. The previous 54120 series of scopes would allow the use of an external TDR pulse generator, such as the 4015, and performed both excellent 10 ps TDT and also 10 ps TDR. Due to a software "bug" in the 54750/83480 scope's TDR program, it will not correctly perform averaged normalization on the negative-going 4015 pulse. There is, however, a "work-around". The scope can be "fooled" into doing 10 ps normalized TDR measurements using its TDT

mode. Detailed setup procedures are given in the following sections for both TDT and also TDR. TDR markers are not functional.

DETAILED TDT SETUP PROCEDURE

The following procedure will assist the user in the first-time setup of the PSPL 4015B/C pulse generator and HP 54750A or 83480A oscilloscope for 10 ps TDT measurements.

1. Install a TDR plug-in module in the scope mainframe slots 1 and 2. Install a single-channel, 50 GHz plug-in module in slot 3 – or a dual-channel, 50 GHz plug-in module in slots 3 and 4.

2. Consult Figure 3 for the 10 ps TDT test setup. Attach a 2.92 mm / 2.4 mm (or 3.5/2.4 mm) coax adapter to the input of channel 3. Attach a 20 dB and 3 dB attenuator to the 3.5/2.4 mm adapter. PSPL Model 5510-K, 40 GHz, 2.92 mm attenuators are recommended. Attach the PSPL Model 4015RPH Pulse Head to the attenuators. Use a short, microwave-quality, coax cable to connect the 4015 pulse generator "Driver Output" to the Pulse Head. Use an ordinary, 3 ft., SMA coax cable to connect the TDR output pulse from the HP scope's channel 1 connector to the 4015 pulse generator's SMA "Trigger Input" connector. If you are using the 4015C, then also set the Rep. Rate control to "EXT".

3. Push "TDR/TDT Setup" button on the TDR plug-in to bring on screen the TDR/TDT menu. Select "Stimulus" = external, "TDT 1 dest" = channel 3, "TDR 1 dest" = channel 2 or 4, "TDR rate" = automatic (250 kHz). Push "Normalize Response" button to bring up another sub-menu. Select TDR. Set "TDR Normalize" to off. Select TDT. Set "TDT Normalize" to off. Push "Done" button.

4. Push "Preset TDR/TDT" button. You will get a screen set to 5 ns/div. and 22 ns sweep starting position. Push "Acquisition" button for menu. Set "Averaging" = off

5. Push "Setup - Chan 1" button for menu. Set "Display" = on, "Scale" = 100 mV/div, "Offset" = 200 mV. Channel 1's color is yellow. Push "Setup - Chan 3" button for menu. Set "Display" = on, "Scale" = 100 mV/div, "Offset" = -350 mV, "Bandwidth" = 50 GHz. Channel 3's color is violet. If either channel 2 (green) or channel 4 (magenta) is also displayed, then turn them off. Push "Setup - Chan 2 (or 4)" button for menu. Set "Display" = off

6. At this point you should see two waveforms displayed on the scope's screen. See Figure 6. The yellow trace (channel 1) is the scope's TDR pulse. The various spikes, etc., seen on the 200 mV TDR pulse yellow trace are the "kick-out"

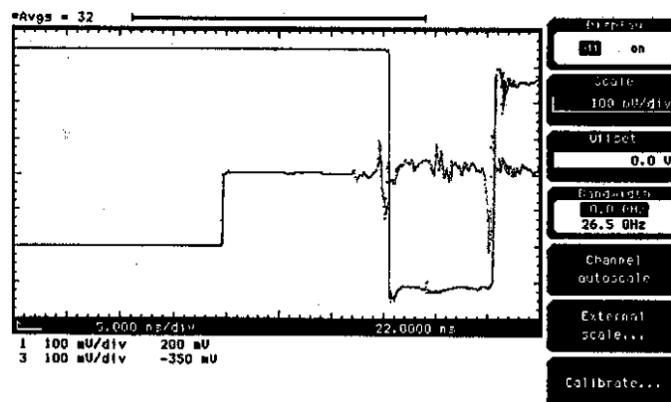


Figure 6: Initial Setup Waveforms

from the 4015's high-voltage pulse generator. If the 4015C rep. rate control is set to single pulse (or the cable is disconnected from the 4015B trigger input), then these spikes will disappear. The violet trace (channel 3) is the attenuated -9 V, 15 ps pulse from the 4015 pulse generator. If you are using a 4015B, this is a 10 ns wide rectangular pulse. If you are using a 4015C, then the pulse is flat at -9 V for 5 ns followed by a slow exponential decay. Figure 6 shows a 4015B pulse.

7. Push "Setup - Chan 1" button. Set "Display" = off. The yellow trace (channel 1) will disappear, but the TDR pulse will continue to be generated by the scope and trigger the 4015 pulse.

8. Push "Time Base" for menu. Set "Reference" = left. Adjust the "Position" control to set the leading edge of the 4015 pulse to the left side of the screen. Set "Scale" = 50 ps/div. Now readjust the "Position" control as necessary to set the leading edge of the pulse to 1.5 divisions from the left side. See Figure 7.

Caution: Be sure that the pulse leading edge does not cross a screen position that is an integer multiple of 4 ns. The HP scopes have very accurate time base sweeps, but they do have serious timing errors of a few ps that occur every 4 ns. These occur at $N \cdot 4\text{ns} + 2\text{ns}$, i.e., at 22 ns, 26 ns, 30 ns, 34 ns, etc. If the fast pulse edge is near one of these "4 ns glitches", then use a different length of coax cable between the channel 1 TDR pulse output and the 4015 trigger input.

9. Push "Acquisition" button for menu. Set "Averaging" = on, "# of averages" = 32, "Best" = flatness, "Record length" = 1024.

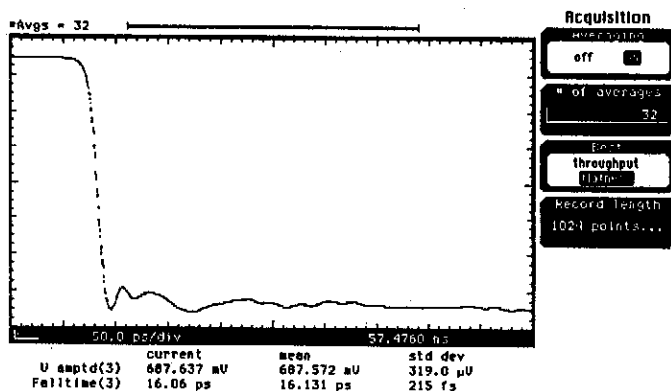


Figure 7: Attenuated 4015 Pulse 100 mV/div and 50 ps/div.

10. Now measure the 4015's attenuated pulse amplitude and falltime. Use the blue "measure" buttons "V amptd" and "Fall". Select "channel 3" for each and push "enter". See Figure 7. Clear these measurements.

11. On the TDR module, now push the "TDR/TDT Setup" button to again bring up the TDR/TDT menu. Push the "Normalize response" button for a sub-menu. Set "Risetime" = 50 ps, Select "TDR/TDT" = TDT. Set "TDT normalize" = on.

12. At this point you will sometimes get a warning message in red at the top of the screen. "Can't normalize: — re-cal". Don't worry about it. Move on to the next step.

13. Push the "Establish normalization and ref. plane" button. Follow the instructions in yellow at the top of the screen. It will say "Connect TDT source to Channel 3". You have already done this. Thus, go ahead and push the "Continue" button.

14. The scope will now take a few moments to signal average and measure the 4015 waveform on the screen. The measured, averaged waveform data will be stored in the scope's memory for later use in "normalizing" later measurements. After the scope has finished its measurement, it will then automatically start "normalizing" the waveform on the screen. The "normalized" waveform will then also be displayed on the screen as "response 3" (r3). See Figure 8.

15. Now measure the normalized, response 3 waveform pulse amplitude and falltime. Use the blue "measure" buttons "V amptd" and "Fall". Select "response 3" for each and push "enter". See Figure 8. Note that the measured falltime is very close to the selected 50 ps. Also note that the normalized

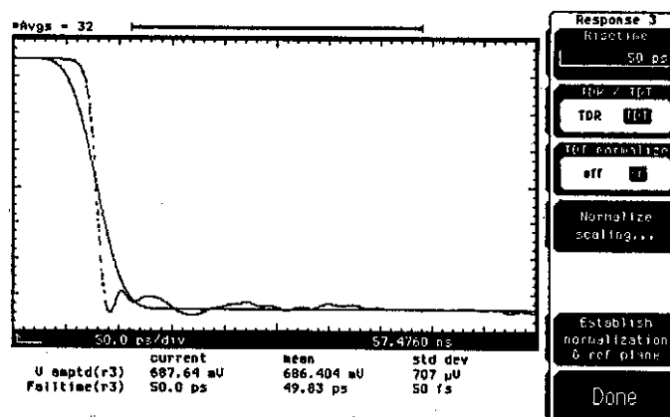


Figure 8: Channel 3, 4015 Pulse and Response 3, 50 ps Normalized Waveforms. 50 ps/div.

waveform is much cleaner than the original 4015 pulse. The normalization process has removed all of the bumps and wiggles from the 4015 waveform.

16. For further measurements, we can now eliminate the 4015 waveform from the screen. Push the "Setup Chan 3" button. Set "Display" = off. Now only the 50 ps falltime normalized waveform is displayed on the screen. The channel 3 sampler will still continue to function and measure the input signal.

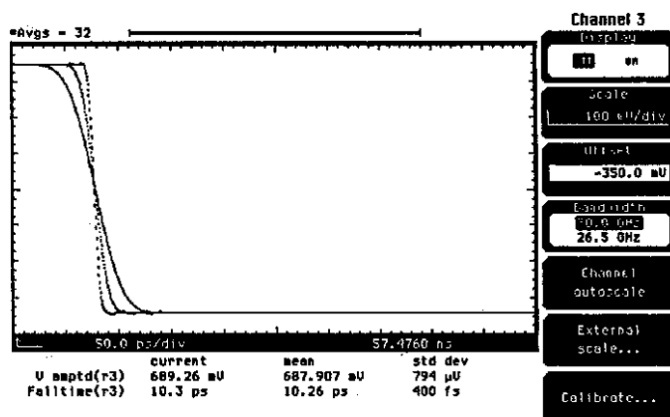


Figure 9: Normalized Pulse Waveforms with 50 ps, 25 ps and 10 ps Falltimes. 50 ps/div.

17. Push the "TDR/TDT Setup" button for a menu. Push "Normalized response". Now experiment with various "Risetime" settings, and note their effect on the normalized waveform. Figure 9 shows the results for risetime settings of 50 ps, 25 ps and 10 ps. The fastest allowed setting is 10 ps.

18. While still in the "TDR/TDT" menu, push "Normalize scaling" for a sub-menu. Select "Horizontal" = manual. Adjust "X position" to place the fast edge of the pulse in the center

of the screen. Now experiment with changing "X scale" to faster sweeps, i.e., 20 ps/div, 10 ps/div., etc. The fastest sweep available is 1 ps/div. At the faster sweeps you will start to see the individual dots in the trace. See Figure 10 for a plot at 5 ps/div. If you want a continuous trace, then select "connected dots" in the "Display" menu. Return the "Normalize scaling" setting to "track source".

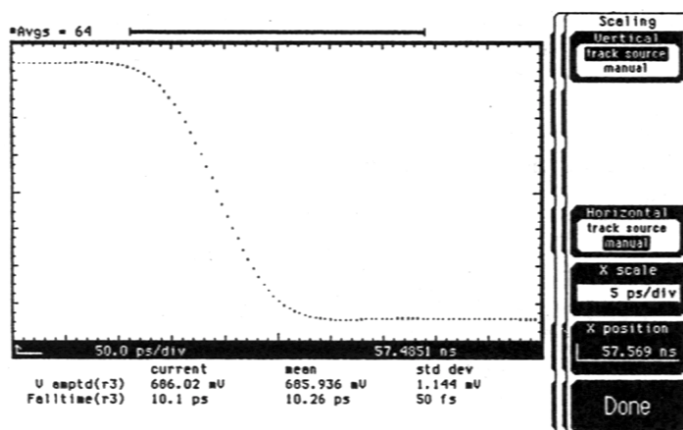


Figure 10: 10 ps Normalized Pulse on Expanded 5 ps/div Scale

19. At this point you can now proceed to test various coaxial components (DUTs). If you want to test the DUT with a -650 mV pulse, then insert it between the attenuators and the scope input. If you want to test with a -9 V pulse, then insert it between the pulse head and the attenuators. Intermediate test amplitudes can be obtained by inserting the DUT between the attenuators. The DUT's step response will now appear as "response 3" on the screen. If the insertion delay of the DUT is too large, this can be taken out of the measurement by "skewing" the channel 3 position. To do this, push the "Setup - Chan 3" button. Select "Calibrate" and then enter the desired amount of "skew". Figure 5 earlier showed the result of testing the response of a PSPL Model 5541A bias tee to a 10 ps pulse. For this measurement, adding skew was necessary.

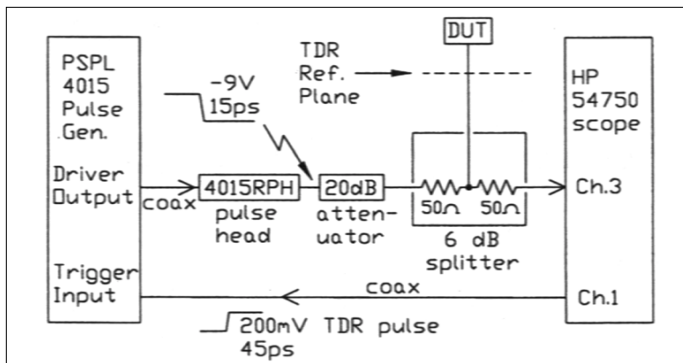


Figure 11: 10 ps TDR Measurement Setup

DETAILED TDR SETUP PROCEDURE

This is a way to work around the TDR software bug in the HP scope. We will instead use the TDT program, but use the reflected TDR pulse from a short circuit as the incident TDT test pulse. The procedure follows closely the previous TDT setup.

1. Install a TDR plug-in module in the scope mainframe slots 1 and 2. Install a single-channel, 50 GHz plug-in module in slot 3 – or a dual-channel, 50 GHz plug-in module in slots 3 and 4.

2. Consult Figure 11 for the 10 ps TDR test setup. Remove the 2.4 mm f/f barrel adapter from the channel 3 input connector. Attach one of the 50 Ohm arms of the HP-11667C, 2.4 mm, 6 dB power splitter directly to the channel 3 input. Note: The port on the power splitter labeled "Input" is the TDR reference port. Attach a 50 Ohm termination to the TDR reference port. Attach an HP-33340D, 2.4 mm, 20 dB attenuator to the other 50 Ohm arm of the power splitter. Attach a 2.4 mm / 2.92 mm (or 2.4/3.5 mm) coax adapter to the attenuator. Alternatively, a PSPL 5510-K20dB attenuator could be used. Now attach the PSPL Model 4015RPH Pulse Head to the attenuator. Use a short, microwave-quality, SMA, coax cable to connect the 4015 pulse generator "Driver Output" to the Pulse Head. Use an ordinary SMA coax cable to connect the TDR output pulse from the HP scope's channel 1 connector to the 4015 Pulse Generator's SMA "Trigger Input" connector. If you are using the 4015C, then also set the Rep. Rate control to "EXT".

3. Push "TDR/TDT Setup" button on the TDR plug-in to bring on screen the TDR/TDT menu. Select "Stimulus" = external, "TDT 1 dest" = channel 3, "TDR 1 dest" = channel 2 or 4, "TDR rate" = automatic (250 kHz). Push "Normalize Response" button to bring up another sub-menu. Select TDR. Set "TDR Normalize" to off. Select TDT. Set "TDT Normalize" to off. Push "Done" button.

4. Push "Preset TDR/TDT" button. You will get a screen set to 5 ns/div. and 22 ns sweep starting position. Push "Acquisition" button for menu. Set "Averaging" = off

5. Push "Setup - Chan 1" button for menu. Set "Display" = on, "Scale" = 100 mV/div, "Offset" = 350 mV. Channel 1's color is yellow. Push "Setup - Chan 3" button for menu. Set "Display" = on, "Scale" = 40 mV/div, "Offset" = -120 mV, "Bandwidth" = 50 GHz. Channel 3's color is violet. If either channel 2 (green) or channel 4 (magenta) is also displayed, then turn them off. Push "Setup - Chan 2 (or 4)" button for menu. Set "Display" = off

6. At this point you should now see two waveforms displayed on the scope's screen. See Figure 6. The yellow trace (channel 1) is the scope's TDR pulse. The various spikes, etc., seen on the 200 mV TDR pulse yellow trace are the "kick-out" from the 4015's high-voltage pulse generator. If the 4015C rep. rate control is set to single pulse (or the cable is disconnected from the 4015B trigger input), then these spikes will disappear. The violet trace (channel 3) is the attenuated -9 V, 15 ps pulse from the 4015 Pulse Generator. If you are using a 4015B, this is a 10 ns wide rectangular pulse. If you are using a 4015C, then the pulse is flat at -9 V for 5 ns followed by a slow exponential decay. Figure 6 shows a 4015B pulse.

7. Push "Setup - Chan 1" button. Set "Display" = off. The yellow trace (channel 1) will disappear, but the TDR pulse will continue to be generated by the scope and trigger the 4015 pulse generator.

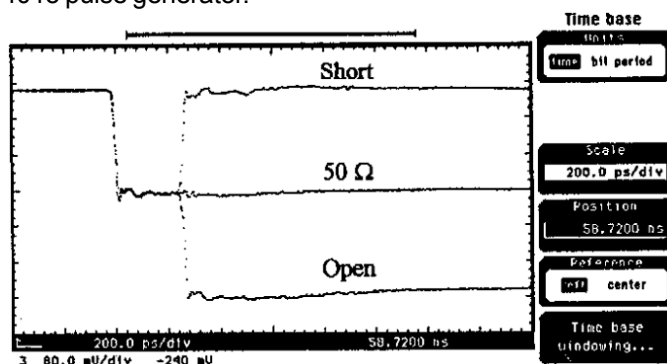


Figure 12: Attenuated 4015 TDR Pulse. Multiple exposure showing short circuit, 50 Ω and open circuit terminations attached at TDR test port. 80 mV/div and 200 ps/div.

8. Push "Setup - Chan 3" button. Set "Scale" = 80 mV/div, "Offset" = -240 mV.

9. Push "Time Base" for menu. Set "Reference" = left. Adjust the "Position" control to set the leading edge of the 4015 pulse to the left side of the screen. Set "Scale" = 200 ps/div. Now readjust the "Position" control as necessary to set the leading edge of the pulse to 2 divisions from the left side. See Figure 12.

10. Now remove the 50 Ω termination from the TDR reference port. With an open circuit termination, you should now see a two-hop descending staircase waveform. Now attach a short circuit termination to the TDR reference port. You should see a negative-going pulse edge followed later in time by a positive-going edge. All of these changes occur in time at the TDR port reference plane. All three cases are shown above in Figure 12. The distance from the first negative-going edge in Figure

12 and the reflections occurring at the TDR reference port will vary from one setup to another depending upon the length of coax adapters and/or coaxial cable attached to the power divider "input" port. If you don't see these changes, either shorten the length of your reference coax cable, or change to a slower sweep speed.

11. Leave the short circuit termination attached to the TDR reference port. You have now identified which edge in Figure 12 was due to this short circuit. Now adjust the time base position control to move the incident test pulse edge (i.e., the first negative edge) off of the screen to the left. Position the positive edge from the short circuit close to the left edge of the screen. Change the sweep to 20 ps/div. Reposition the positive edge reflection from the short circuit to the third division from the left. See Figure 13.

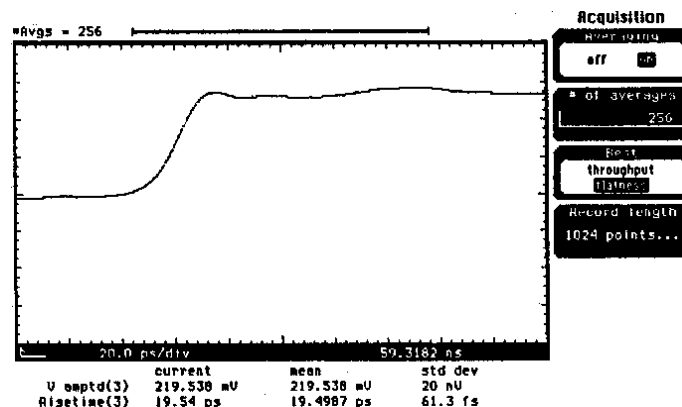


Figure 13: Reflection from short circuit at TDR test port. Used as system calibration waveform. 80 mV/div and 20 ps/div.

12. Push "Acquisition" button for menu. Set "Averaging" = on, "# of averages" = 256, "Best" = flatness, "Record length" = 1024.

13. On the TDR module, now push the "TDR/TDT Setup" button to again bring up the TDR/TDT menu. Push the "Normalize response" button for a sub-menu. Set "Risetime" = 50 ps, Select "TDR/TDT" = TDT. Set "TDT normalize" = on. At this point you will sometimes get a warning message in red at the top of the screen. "Can't normalize: — re-cal". Don't worry about it. Move on to the next step.

14. Push the "Establish normalization and ref. plane" button. Follow the instructions in yellow at the top of the screen. They will say "Connect TDT source to Channel 3". You have already done this. Thus, go ahead and push the "Continue" button. The scope will take a few moments to acquire this waveform.

15. The measured, averaged TDR waveform data from the short circuit will be stored in the scope's memory for later use in "normalizing" later measurements. After the scope has finished its measurement, it will then automatically start "normalizing" the waveform on the screen. The "normalized" waveform will then also be displayed on the screen as "response 3" (r3). See Figure 14. The waveforms shown are the "raw" measured data and the "normalized" data from the short circuit termination.

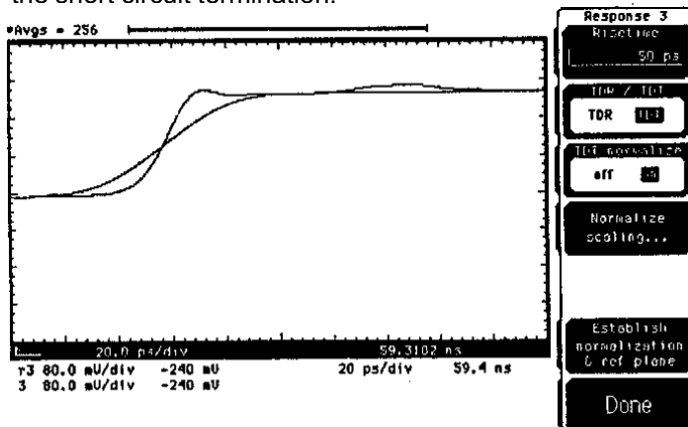


Figure 14: Reflection from Short Circuit Showing Both 4015 TDR Waveform and 50 ps Risetime Normalized Waveform. 20 ps/div.

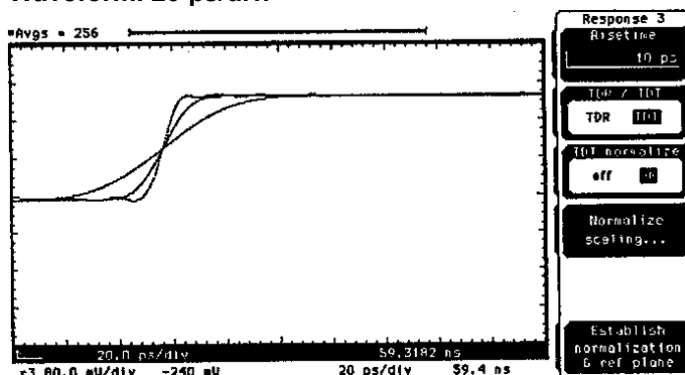


Figure 15: Reflection from Short Circuit Normalized to Risetimes of 50 ps, 20 ps and 10 ps. 80 mV/div and 20 ps/div.

16. Push "Setup - Chan 3" button. Set "Display" = off. Now only the normalized results will be displayed. Experiment using different normalization risetimes. The risetime control is contained in the TDR/TDT Setup menu and the "Normalize response" submenu. Figure 15 shows the results obtained for risetimes of 50 ps, 20 ps, and 10 ps.

17. Next test the normalization for various known terminations on the TDR reference port. Figure 16 shows the resultant 10 ps normalized waveforms for a short circuit, 50 Ohm, and open circuit termination. Press the "Clear

Display" button each time you change the connections at the TDR test port.

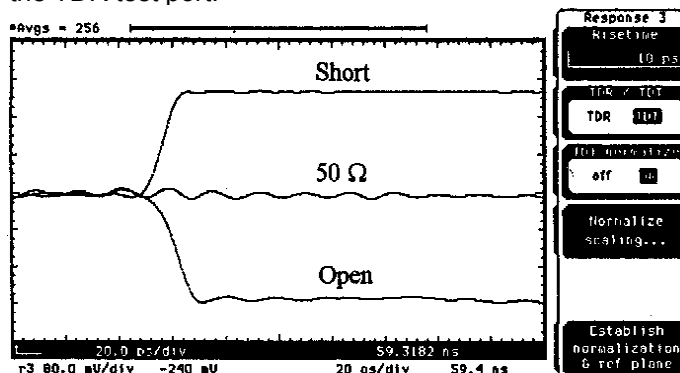


Figure 16: 10 ps Normalized TDR. Multiple Exposure Showing Short Circuit, 50 Ω , and Open Circuit Terminations. 20 ps/div.

SUGGESTIONS TO OBTAIN OPTIMUM PERFORMANCE

1. Keep the scope and pulser in a stable temperature environment. Avoid cyclic air conditioning and heating drafts. Allow both the scope and 4015 pulser to operate for at least 30 minutes prior to performing high resolution 10 ps measurements. Perform a vertical calibration of the plug-ins to be used prior to starting your normalization calibration. Wait 30 seconds or more after turning on the channel 1 TDR pulse and triggering the 4015 pulser before proceeding with normalization calibration and measurements. These steps help minimize pulse timing drift.

2. The TDT normalization calibration should be "fresh". If something has changed in the system, the digital filtering done in the normalization will "blow up" and cause an excessive amount of digital noise in the TDT (response 3) normalized waveforms. If the s/n is excessive, then it is time to redo the system normalization calibration.

3. Use longer "Record lengths". The normal "TDT preset" default is 1024. This is usually sufficient. For 10 ps normalization on the longest time window of 5 ns (i.e., 500ps/div), it will be necessary to use a 4096 record length and lots of averages.

4. When doing the system normalization calibration, set the number of averages to a very large number, such as 1024. The HP scope has a very fast data acquisition rate and will acquire the calibration data in a relatively short amount of time. Then set the number of averages to a lower amount, such as 32, for actual DUT measurements. After the scope has been calibrated, the number of averages selected becomes the number of normalized measurements that are averaged and then displayed. If you stick with 1024 points,

you will wait a very long time for your data.

5. Perform a set of experiments to determine the optimum sweep speed, rep. rate, and number of signal averages for your particular system and application to get the best signal to noise ratio (s/n) in the normalized waveforms. More averages are not always better because of long-term drifts in the system. To determine the s/n, examine the normalized baseline. The baseline can be expanded vertically using the "Normalize scaling" submenu. To measure the noise, use the "Histogram" menu and do a vertical histogram.

6. If the actual device under test has an electrical insertion delay time in excess of the scope's time window, then the TDT output pulse response will fall off the screen to the right. To move the response signal back onto the screen, you need to "skew" the TDT destination channel's position. Skew is found in the Channel Setup, "Calibrate" sub-menu. To obtain the best results, the skewed waveform should be positioned so that its leading edge coincides closely with the edge of the original test pulse. See Figure 5 for an example.

7. In some situations it is not physically possible to connect the DUT directly to the front of the oscilloscope. An example could be a semiconductor wafer probe station. The test ports must be moved from the scope main frame to the remote location. Use an HP plug-in extender cable to move the scope's plug-ins near the remote location. Then use a short network-analyzer-quality microwave cable to connect the wafer probe output to the scope. The PSPL pulse head and attenuators are small enough that they can usually be connected directly to the wafer probe station input coax connector.

Table 1: List of Suggested Accessories for 2.4 mm, 50 GHz, 10 ps TDT and TDR

Description	Part Number
Attenuator: 20 dB, 2.4 mm or 2.92 mm	HP 8490D-20dB PSPL 5510-K-20dB
Attenuator: 3 dB, 2.4 mm or 2.92 mm	HP 8490D-3dB PSPL 5510-K-3dB
6 dB Power Splitter, 2.4 mm	HP 11667C
50 Ω Termination, 2.4 mm, plug (m)	HP 00901-60003
50 Ω Termination, 2.4 mm, jack (f)	HP 00901-60004
Short Circuit, 2.4 mm, plug (m)	HP 85056-60020
Short Circuit, 2.4 mm, jack (f)	HP 85056-60021
Coax Adapter: 2.4 mm plug/plug (m/m)	HP 11900A
Coax Adapter: 3.5 mm jack (f) to 2.4 mm plug (m)	HP 11901C