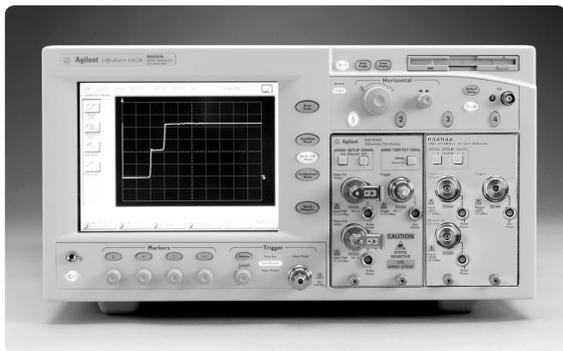
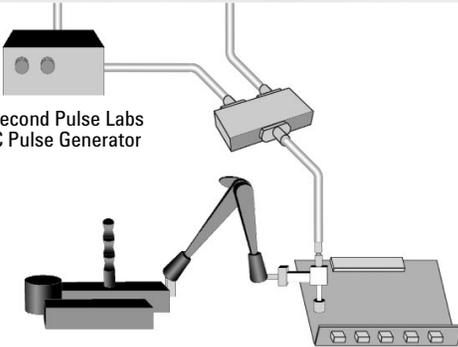


Faster Risetime for TDR Measurements

Using the PSPL 15 ps Pulse Generator
& Agilent 86100A Infiniium DCA
Product Note 86100-4



PicoSecond Pulse Labs
4015C Pulse Generator



Increased resolution TDR test
setup using the 86100A to
measure ≤ 15 ps risetime pulses



Agilent Technologies

This product note demonstrates how to make time domain reflection (TDR) measurements on electrical networks with better than 40 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 faster risetime TDR measurements are the Agilent 86100A Infiniium DCA 50 GHz digital sampling oscilloscope and the PicoSecond Pulse Labs (PSPL) model 4015, 9 V, 15 ps pulse generator.

Agilent 50 GHz Oscilloscope

The Agilent 54750A, 83480A, and 54120A high speed sampling oscilloscopes have been discontinued and replaced by the 86100A Infiniium DCA (digital communication analyzer). The 86100A can be viewed as three high-performance instruments in one. It's a general purpose 50 GHz oscilloscope, a digital communications analyzer, and a time-domain reflectometer. The 86100A provides a touch-screen, easy to use Windows®-based graphical user interface and a faster microprocessor.

Two plug-ins for the 86100A mainframe are compatible for TDR measurements. The 54753A dual-channel, 20 GHz, single-ended TDR plug-in or the 54754A dual-channel, 18 GHz, differential TDR module. The 83484A dual-channel 50 GHz electrical module is recommended for the 50 GHz electrical channel that is required for a 15 ps setup. The TDR modules have 18 or 20 GHz bandwidth, 17 ps risetime, and 50 ohm samplers with APC-3.5 mm connectors. The 50 GHz module has a selectable 50 GHz or 26 GHz bandwidth, 9 ps risetime, and 50 ohm inputs with APC-2.4 mm connectors. The TDR modules include a built-in TDR pulse generator(s) which produces a 200 mV, nominal 40 ps risetime step pulse.

Agilent high-speed sampling oscilloscopes such as the 86100A include built-in software for doing "Normalized" TDR measurements. Normalization is Agilent's term for deconvolution. Deconvolution is the mathematical operation of removing the input signal from an output signal and sets the reference plane to the device under test

(DUT). This is done by using transforms between the time and frequency domain and then applying digital filtering. Agilent oscilloscopes use the Bracewell transform licensed from Stanford University. By altering the bandwidth of the digital filter, test pulses are created 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. Imperfections are caused by cables and connectors attached to the DUT. The resultant normalized test pulse is a very clean, Gaussian impulse response. For more information on normalization, refer to application note 1304-5, Improving TDR/TDT Measurements Using Normalization.

PSPL 15 ps Pulse Generator

The Picosecond Pulse Labs (PSPL) model 4015C pulse generator produces a -9 volt, 15 ps risetime step pulse. It is used as a TDR pulse amplifier and improves the TDR risetime of the 86100A from 40 ps to 15 ps. The 4015C is triggered by the 54753/4A 200 mV, 40 ps TDR pulse and creates a much larger 9 volt, much faster 15 ps pulse. This 15 ps pulse is generated in a pulse head that 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 delivered directly to the DUT with no intermediate, risetime slowing, coaxial cables. The 4015C can be triggered externally and also includes a built-in repetition rate generator, trigger output and delay circuit.

TDR Measurements

Using the built-in 200 mV, 40 ps TDR test pulse, the 86100A will give good normalized results for risetimes as low as 10 ps by using the 4015C pulse generator. For faster normalized risetimes, the digital filter ringing becomes very objectionable. The 20 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.

The top trace in Figure 2 is the 17.5 ps 4015C pulse measured by the Agilent 50 GHz, 9 ps sampler. The time window is 50 ps/div. The bottom trace is a normalized 15 ps pulse with a very nice Gaussian wave shape and is free from the overshoot and ringing seen on the input 4015C pulse. A detailed examination of the 15 ps pulse's baseline or top line will reveal a small amount of "digital filter ringing". This ringing will limit the ultimate TDR system resolution.

The waveform of the pulse would normally appear as a negative going pulse due to the -9V step pulse. In this case, when attaching a short to the TDR reference plane in place of the DUT, the step is inverted.

86100A Vertical Calibration

A vertical calibration should be performed before collecting any measurement data. Follow the instructions below, to perform an 86100A vertical calibration. Key stroke names surrounded by [] indicate hard keys located on the front panel, while key stroke names surrounded by <> indicate the icons or menu options located on the touchscreen display.

1. Select <Calibrate> from the drop-down menu
2. Then select <All Calibrations>
3. Press the <Vertical (Amplitude)> tab
4. Choose a module to calibrate by pressing either <Calibrate Left Module...> or <Calibrate Right Module...>
5. Follow the step-by-step instructions. Some modules may need a 50Ω (male) termination to complete the calibration process

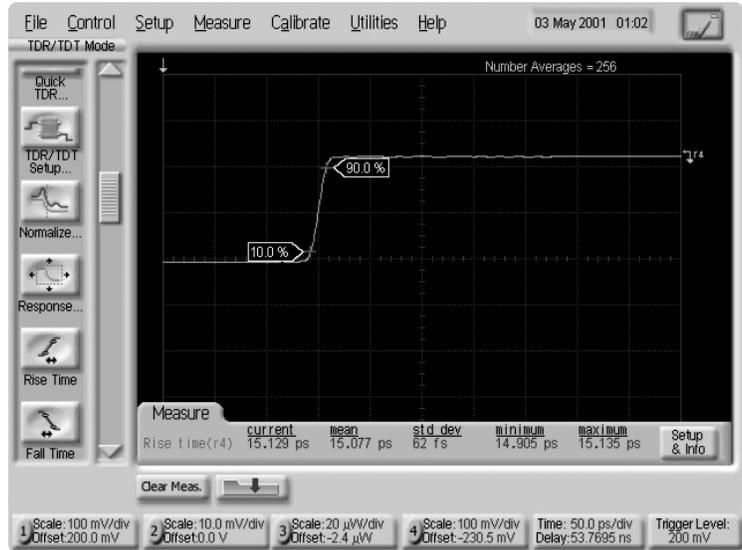


Figure 1. Normalized 15 ps waveform using the PSPL pulse generator.

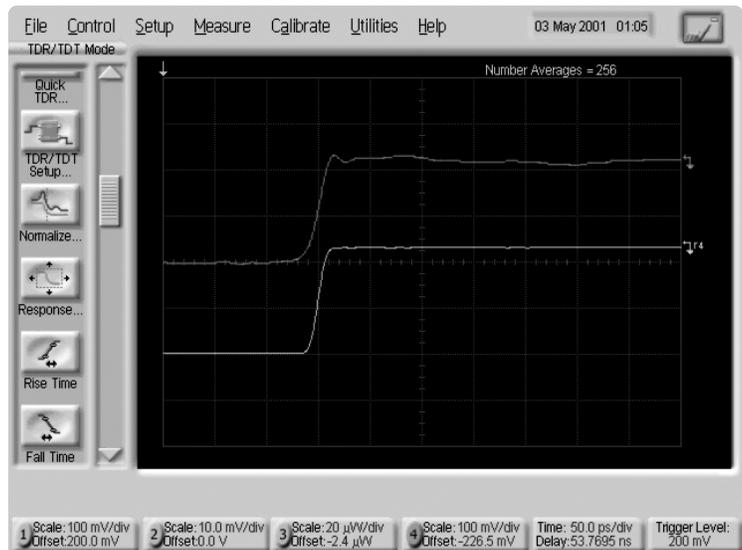


Figure 2. TDR input pulse. The top trace shows the 4015C "raw data" pulse. The bottom trace is normalized to a 15 ps risetime.

Note: A vertical calibration is recommended for the 83484A electrical module and the 54753/4A module. To do this, you must repeat the procedure for each module.

Detailed TDR Setup Procedure

The following procedure will assist the user in the setup of the Agilent 86100A and PSPL 4015C pulse generator for 15 ps risetime TDR measurements. A list of suggested accessories is shown at the end of this document. Always use electrostatic discharge (ESD) protective gear, such as a ground strap and an anti-static mat.

1. Install the 54753/4A TDR plug-in module into the 86100A's left slot. Install the 83484A dual 50 GHz plug-in module into the right slot. Refer to Figure 3 for the TDR test setup. Remove the 2.4 mm (f-f) barrel adapter from the channel 4 input of the 83484A. Attach one of the arms of the Agilent 11667C 50 GHz power splitter (2.4 mm, 6 dB) directly to the channel 4 input. *Note: The port on the power splitter labeled "Input" is the TDR reference port.* Attach an Agilent 8490D, 2.4 mm, 20 dB attenuator to the second arm of the power splitter. Attach a 2.4 mm/3.5 mm, coaxial adapter to the attenuator. Now, attach the PSPL model 4015RPH pulse head to the attenuator. Use a short, microwave quality SMA, coaxial cable to connect the 4015C pulse generator "Driver Output" to the pulse head. Use an ordinary SMA coaxial cable to connect the TDR output pulse from the channel 1 connector of the 54753/4A module to the 4015C pulse generator's SMA "Trigger Input" connector. If you are using the 4015C, then also set the repetition rate control to "EXT".

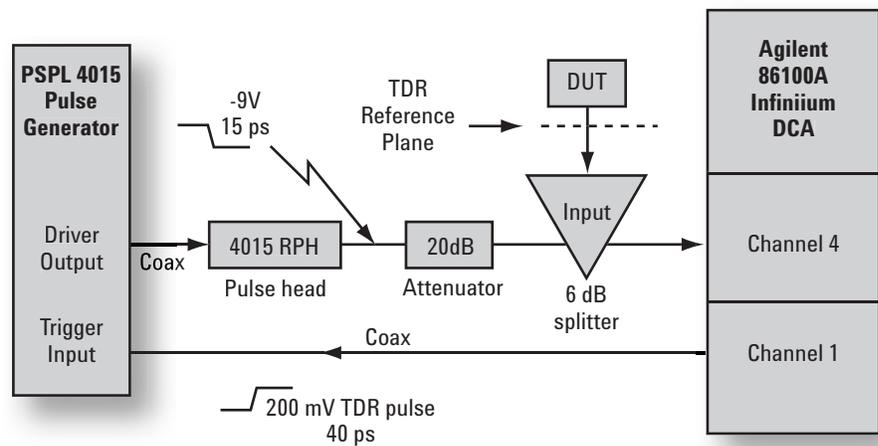


Figure 3. Block diagram setup for Agilent's 86100A with PSPL 4015.

2. Press the [Default Setup] button located near the top right corner of the 86100A front panel. Next press the [TDR/TDT Mode] button. Novice users may want to first select <Quick TDR> from the left tool bar. This will familiarize you with selecting a stimulus source and describe the settings used for basic TDR measurements. For additional information, you can also select <Help> from the menu options, then <Contents> for a wide range of information about the 86100A, measurements, glossary, and much more.

3. Select <Setup> from the 86100A menu and choose <Acquisition>. “Points/Waveform” should be on “Automatic” which is set at 1024 pts. Check the box next to “Enabled” and set the “Number of Averages” to a value of 256. “Best Flatness” should also be selected. Figure 4 illustrates this display.

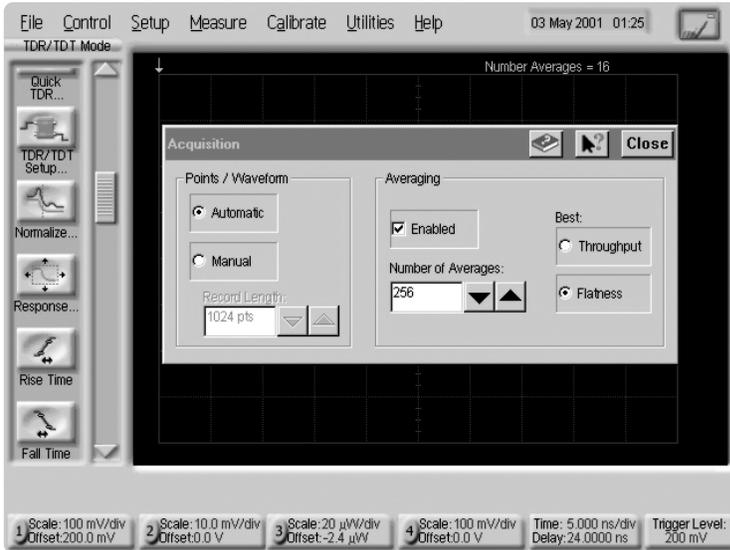


Figure 4. Acquisition dialog box for adjusting the number of averages.

4. To select an external stimulus for the 86100A, you need to select the <TDR/TDT Setup>. Then choose “External”. Under TDR destination for external stimulus, select Channel 4. Press the <Auto Setup> icon to prepare the instrument for making TDR/TDT measurements and close the dialog box. See Figure 5.

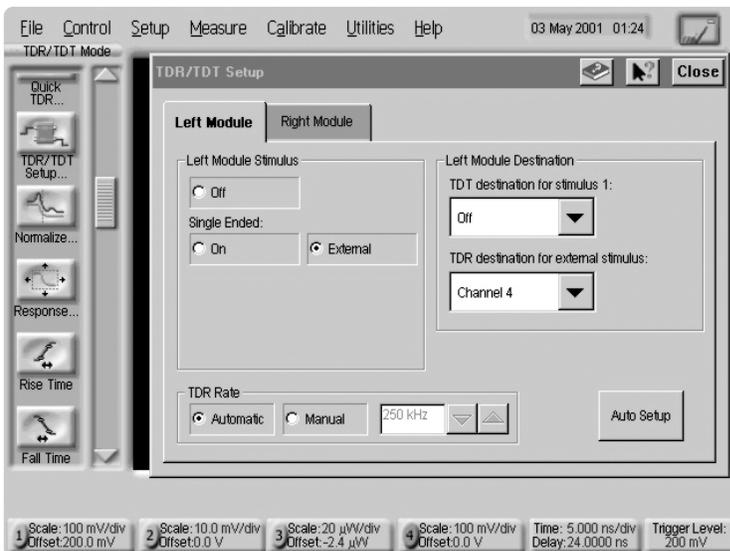


Figure 5. TDR/TDT Setup display for stimulus selection.

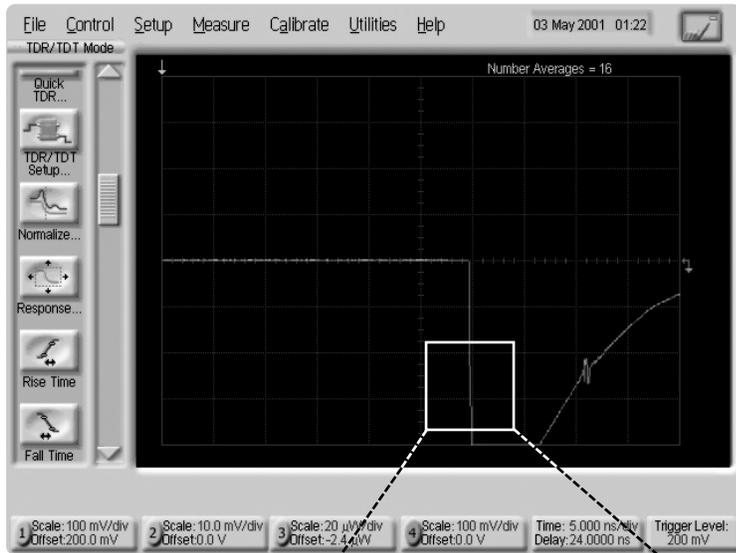


Figure 6. Screen shot after selecting external stimulus.

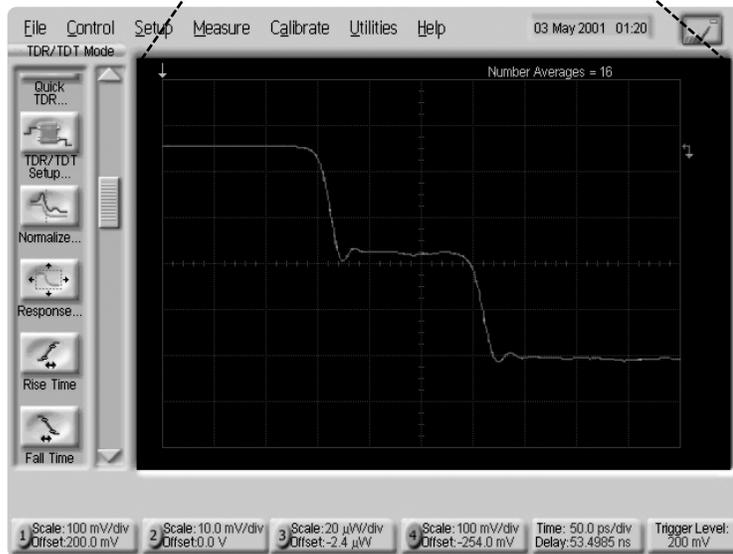


Figure 7. Inverted "open" step waveform after scale adjustment.

5. With an open circuit termination, you will see a sharp descending pulse edge followed by an exponential rising edge. Your screen should look similar to Figure 6. All of these changes occur in time at the TDR port reference plane.

6. Turn the larger "Horizontal knob" clockwise and the smaller "Position/Delay" knob counterclockwise to get a closer view of the step. Or you can press the <Time Delay> icon on the bottom of the screen and type a value that suits your setup. Also, press <4 Scale/Offset> on the front panel to adjust the scaling and offset. Refer to Figure 7 for an example, although values will vary depending on each individual setup.

7. Now attach a 50 Ω termination to the TDR reference port and watch what happens to the waveform. Next remove the termination and attach a short circuit termination to the reference port. Figure 8, illustrates how all three of the waveforms would appear if they were displayed simultaneously. This was constructed by saving each of the 50 Ω and open waveforms independently onto the display. The

waveforms are inverted compared to the normal reflections of the TDR step because the 4015C sends in an inverted pulse. The distance from the first descending edge and the reflections occurring at the TDR reference port will vary from one setup to another depending upon the length of coaxial adapters and/or coaxial cables attached to the power divider "input" port. If you don't see these changes, either shorten the length of the reference coaxial cable or change to a slower sweep speed.

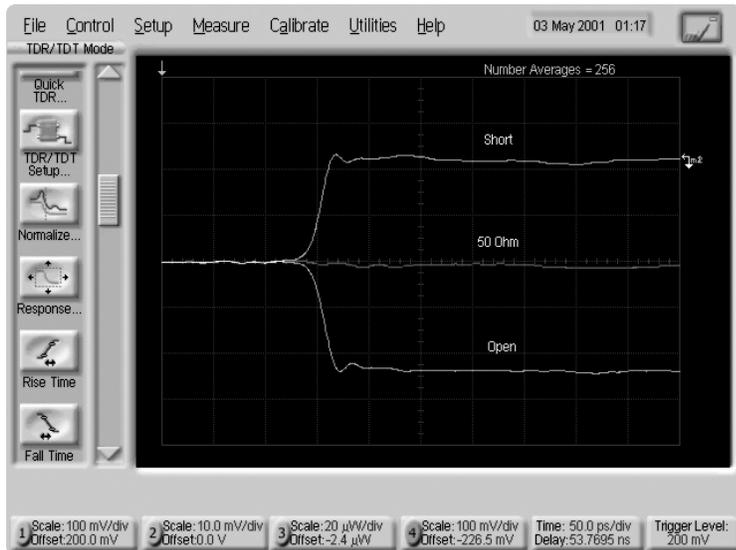


Figure 8. Multiple exposure showing short circuit, 50 Ω, and open circuit terminations.

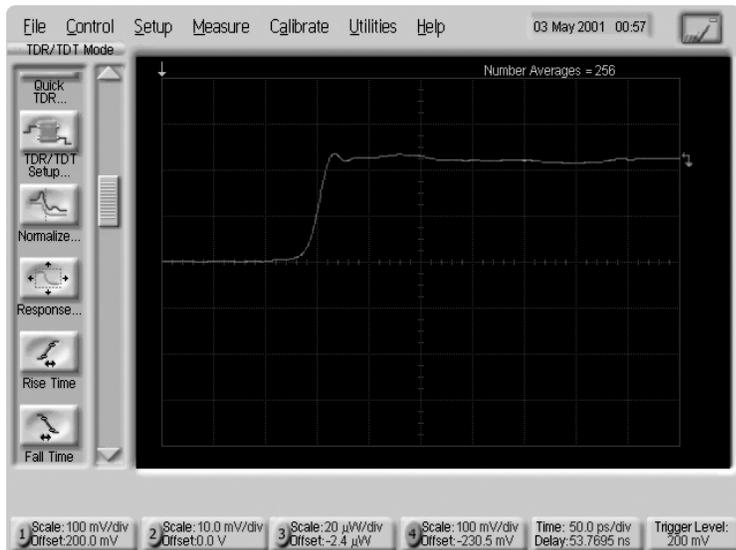


Figure 9. Expanded short circuit waveform.

8. Reattach the short circuit termination to the TDR reference port. You have now identified which edge in Figure 9 is affected by this short circuit. Now adjust the “Timebase” position/delay knob 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 horizontal scale to 50 ps/div. Reposition the positive edge reflection from the short circuit to the third division from the left on the graticule as shown in Figure 9.

9. Now you are ready to start the 86100A normalization procedure. Press the <Normalize> icon from the left toolbar. Choose the <TDR normalization> tab and select <Normalize Response 1>. Follow the step-by-step procedure instructed by the instrument. Make sure the falling edge does not get clipped from the screen, otherwise the normalization procedure will fail.

Note: The reference plane is the same as the reference port unless you attach a cable to the reference port and normalize at the end of the cable.



Figure 10. Standard waveform with discontinuities and fast risetime, normalized waveform with a slower default risetime.

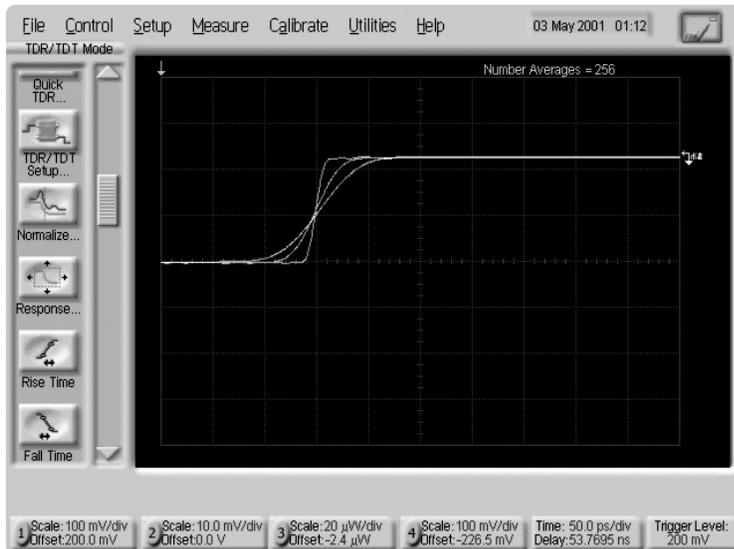


Figure 11. Normalized pulse waveforms with 15 ps, 45 ps, and 75 ps risetimes.

10. The measured, averaged TDR waveform data from the short circuit and $50\ \Omega$ termination will be stored in the 86100A's memory. After the normalization procedure has finished, the normalized waveform will be automatically displayed on the screen. The normalized waveform is also referred to as the "response" waveform. In this case it will be response 4, since channel 4 was normalized. The waveforms shown are the standard measured data and the normalized data. Figure 10 displays both waveforms of a short circuit after the normalization procedure.

11. The risetime of the response waveform defaults to a value depending on the timebase setting. You can adjust the risetime by pressing the <Response> icon. Select the response 4 tab or the response corresponding your normalized channel. Change the risetime by pressing the up/down arrows on the bottom of the tab or just type in a specific value.

12. Push the red channel 4 button above the TDR module. Now only the normalized results will be displayed. Experiment using different normalized risetimes. Figure 11 shows the results obtained for risetimes of 15 ps, 45 ps, and 75 ps. If the risetime is set too low, excessive ringing may occur.

Note: The timebase cannot be changed after performing normalization. If it is, the response waveform will disappear. However, the vertical scaling can be magnified until the waveform is clipped from the screen.

13. You are now ready to start making accurate measurements.

Suggestions to Obtain Optimum Performance

- Keep the Agilent 86100A and PSPL 4015C in a stable temperature environment. Avoid cyclic air conditioning and heating drafts. Allow both the 86100A and 4015C to operate for at least 30 minutes prior to performing high resolution 15 ps measurements. Perform a vertical calibration on the plug-in modules to be used prior to starting your normalization calibration. Note: A vertical calibration will be prompted automatically if one was not previously performed. To avoid multiple timebase and scaling adjustments, this should be performed as soon as the instrument is warmed up. Wait 30 seconds or more after turning on the channel 4 TDR pulse and triggering the 4015C before proceeding. These steps help minimize pulse timing drift.
- The TDR normalization calibration should be “fresh”. If something has changed in the system, the digital filtering done in the normalization procedure will no longer be as accurate and will cause an excessive amount of digital noise in the TDR response waveforms. If the signal-to-noise is excessive, then it is time to repeat the system normalization calibration.
- Use longer “Record lengths”. The normal default of 1024 points is usually sufficient, however, for 15 ps normalization on the widest time window of 5 ns (i.e. 500 ps/div), it will be necessary to use a 4096 record length and more than 16 averages.
- When doing the system normalization calibration, set the number of averages to a very, large number such as 1024. The 86100A 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 number, such as 32, for actual DUT measurements. After the 86100A has been calibrated, the number of averages selected becomes the number of normalized measurements that are averaged and then displayed.
- Perform a set of experiments to determine the optimum sweep speed, repetition rate and number of signal averages for your particular system and application to get the best signal to noise ratio (SNR) in the normalized waveforms. More averages is not always better because of long term drifts in the system. To determine the SNR examine the normalized baseline. The baseline can be expanded vertically using the <Response> icon. To measure the noise use the “Histogram” found in the <Measure> menu, then activate a vertical histogram.
- If the actual device under test has an electrical insertion delay time in excess of the scope’s time window, then the TDR 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 TDR destination channel’s position. “Horizontal Skew Adjust” is found in the <Calibrate> 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.
- 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 86100A to remote location. Use the 11898A plug-in extender module to position the 54753/4A TDR or 83484A electrical modules 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 they can usually be connected directly to the wafer probe station input coaxial connector.

15 ps TDR System Limitations

15 ps risetime measurements cannot be obtained for all possible settings of the 86100A time base. Their limitation is 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 maximum window is 500 ps (i.e. 50 ps/div). For 1024 points, the maximum window is 1 ns. For 2048 points, the maximum window is 2 ns. For 4096 points, the maximum 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 15 ps TDR testing in time windows up to 5 ns. At the extreme settings of 500 ps/div, 4096 record length and 64 averages, excellent 15 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 approach “real time” speeds. Normal “fast” operating conditions would use a 15 ps filter, 50 GHz bandwidth, 50 ps/div, 1024 point record length and 32 averages. Under these conditions, we found the residual digital filter noise was 0.9 mV rms. The attenuated 4015C test pulse amplitude into the sampler was 650 mV. The SNR is typically 67 dB for a normalized 15 ps risetime. The SNR can be improved using slower risetimes. With the 86100A 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.

List of Suggested Accessories for 10-15 ps TDR Measurements

Description	Part Number
20 dB Attenuator, 2.4 mm	Agilent 8490D option 020
6 dB Power Splitter, 2.4 mm	Agilent 11667C
50 Ω Termination, 2.4 mm, (m)	Agilent 00901-60003
50 Ω Termination, 2.4 mm, (f)	Agilent 00901-60004
Short Circuit, 2.4 mm, (m)	Agilent 85056-60020
Short Circuit, 2.4 mm, (f)	Agilent 85056-60021
Coaxial Adapter, 2.4 mm (m-m)	Agilent 11900A
Coaxial Adapter, 3.5 mm (f) to 2.4 mm (m)	Agilent 11901C

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