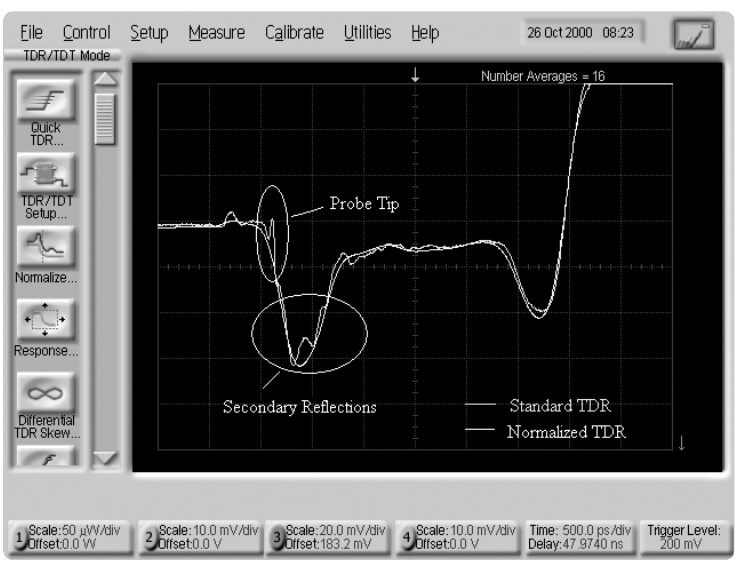
Improving TDR/TDT Measurements Using Normalization

Application Note 1304-5



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TDR/TDT and Normalization

Normalization, an error-correction process, helps ensure that time domain reflectometer (TDR) and time domain transmission (TDT) measurements are as accurate as possible. The Agilent 86100A wide-bandwidth oscilloscope includes normalization as a standard feature. With normalization software built into the oscilloscope, external controllers and multiple step generators or risetime converters are not needed. Normalization not only enhances measurement accuracy; it also simplifies the measurement process.

This application note discusses normalization and assumes the reader is familiar with basic TDR/TDT measurements. For background on TDR/TDT measurements, refer to the on-line Help function in the 86100A.

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 often make short work of designing 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 TDR/TDT 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 TDR/TDT measurements 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 TDR/TDT measurements: the cables and connectors, the oscilloscope, and the step generator.

Cables and Connectors Cause Loss 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.

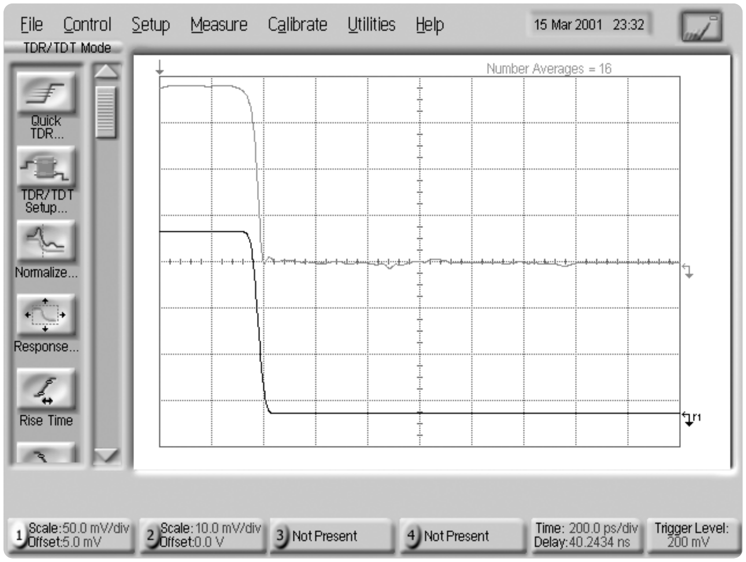


Figure 1. The top waveform shows distortions caused by cables and connectors. The bottom waveform shows how normalization corrects for these distortions.

Figure 1 illustrates how cables and connectors affect TDR/TDT 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.

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 less that 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 measurement waveform. They are generally small and so 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 TDR/TDT 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 TDR/TDT 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, you should test it at edge speeds similar to those it will actually encounter. Consider the example of a BNC connector (Figure 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.

In the case of the 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.

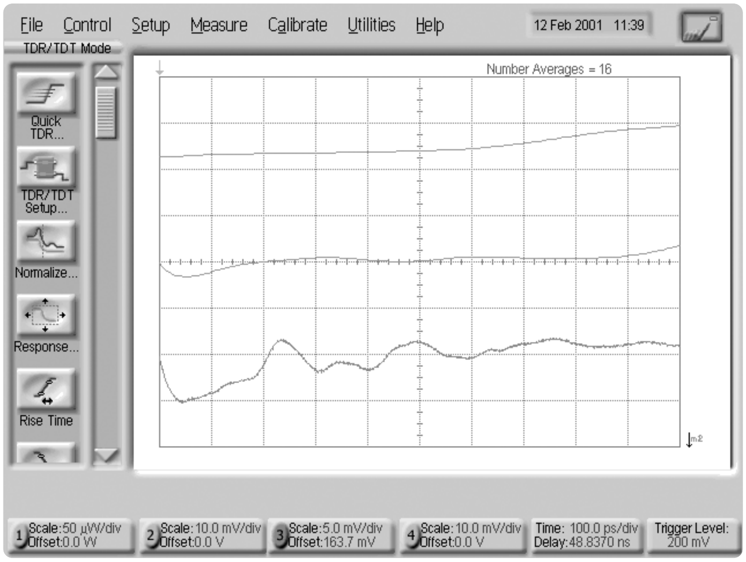


Figure 2. Variable edge speed helps determine the amount of reflection in actual applications. The top waveform (tested to 350 ps) shows less reflection than the middle waveform (tested at 100 ps) or the bottom waveform (tested to 50 ps).

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 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.

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 2 that as the risetime of the step stimulus is decreased, the true nature of the reflection from the DUT becomes more apparent.

$$\text{System risetime} = \sqrt{(\text{Step risetime})^2 + (\text{Scope risetime})^2 + (\text{Test setup-up risetime})^2}$$

Equation 1

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 the DUT waveforms, such as trigger coupling, channel crosstalk, and reflections from the 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 the 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 the above types of errors from TDR/TDT measurements. Taking full advantage of its powerful internal microprocessor, the Agilent 86100A Infiniium DCA (digital communications analyzer) is a wide-bandwidth oscilloscope that includes 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 calibration process are required. No risetime convertors are necessary, and the calibration standards are not related to the DUT.

Unlike a risetime convertor, 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 3.

Figure 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 4 is the unnormalized response of the system.

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.

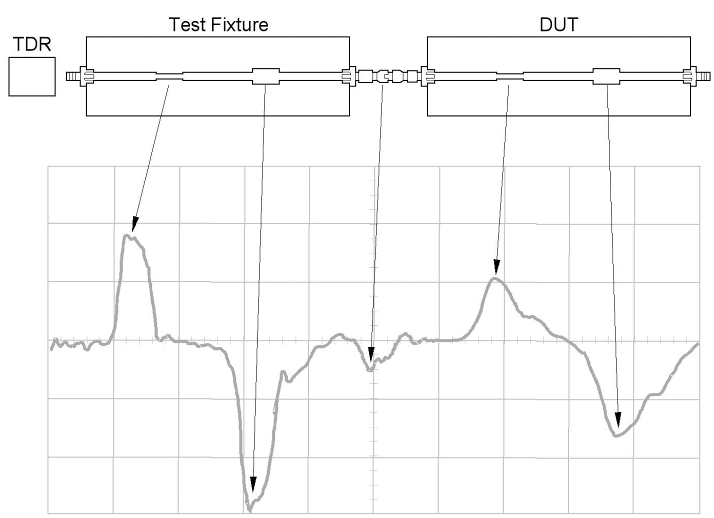


Figure 4. In an unnormalized measurement, the reflections from the DUT are masked by the imperfect test fixture.

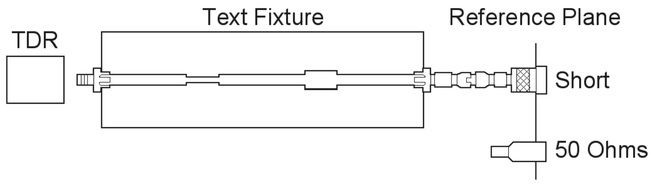


Figure 5. A normalized calibration uses first a short, then a 50 Ω termination to define a reference plane and generate a digital filter.

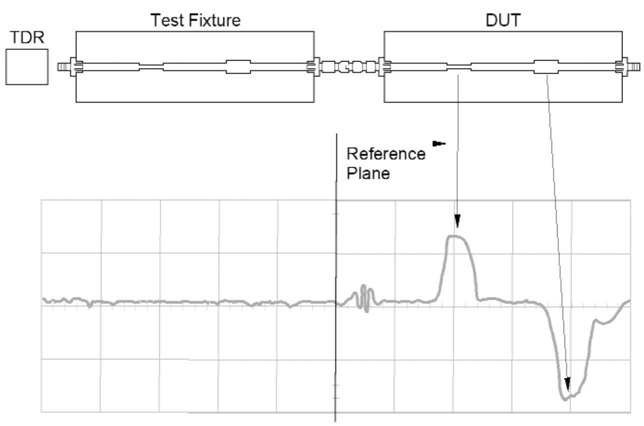


Figure 6. The normalized measurement corrects for the errors introduced by the test fixture.

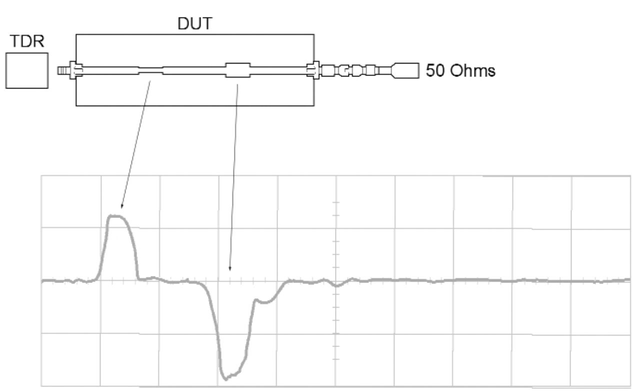


Figure 7. The unnormalized response of the DUT, measured without the test fixture.

By defining a reference plane to be at the end of the test fixture (first PCB) and then normalizing, the errors can be corrected.

Calibration 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) (Figure 6) now matches the response measured earlier of the nearly identical first PCB. (Figure 4)

To further verify the accuracy of the normalization, the response of the second PCB is measured without the first PCB. (Figure 7)

Example 2: Resolving two discontinuities separated by 2 mm.

Normalization can improve the TDR's ability to resolve adjacent discontinuities. Figure 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 90 ps, the two discontinuities appear to be one. By normalizing the response to a system risetime of 45 ps, both discontinuities can be seen.

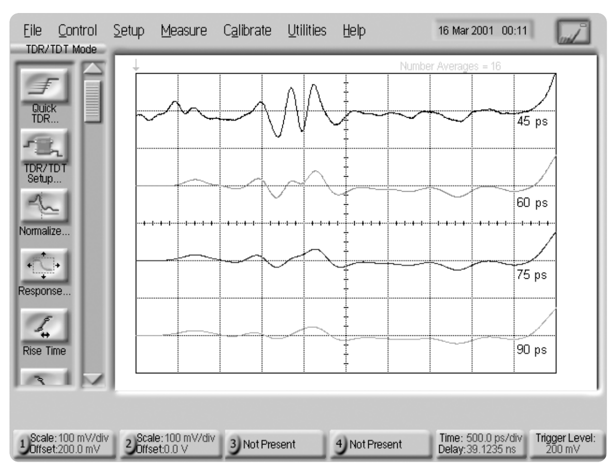


Figure 8. Normalization improves the ability to distinguish two discontinuities by decreasing the system risetime.

Calibration Characterizes the Test System

Calibration makes the normalization process possible. Calibration measurements, which characterize the test system, are made with all cables and connections in place but without the DUT.

TDR/TDT can be accomplished with an oscilloscope and step generator or with a frequency-domain network analyzer and swept sinewave source. Normalization may be applied in either case. However, the calibration process for the network analyzer/swept source solution requires three measurements whereas only two are required for the oscilloscope/step generator solution.

Removing Systematic Errors

The first part of TDR/TDT calibration removes systematic errors due to trigger coupling, channel crosstalk, and reflections from cables and connectors.

For TDR calibration, the DUT is replaced by a short circuit. The frequency response of the test system is derived from the measured short. 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. Therefore, it is important that a good quality short be used, because the calibration process assumes a perfect short circuit termination. Any non-ideal components in the measured short 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 that do not exist in the test system. By attempting to correct for errors that do not exist, the filter can actually add error terms into the normalized measurement results.

Generating the Digital Filter

The second part of the calibration generates the digital filter. Unlike the errors removed by subtracting the first calibration signal, the errors removed by the filter are proportional to the amplitude of the DUT response.

For TDR, this is done by replacing the DUT with a termination having an impedance equal to the characteristic impedance of the transmission line, typically 50Ω. 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.

In both cases, the measured waveforms are stored and subtracted directly from the measured DUT response before the response is filtered. Ideally, these calibration 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.

For TDT calibration, 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. With the oscilloscope/step generator TDR/TDT solution, airlines can separate the primary reflection from the secondary reflection. Time windowing can then be used to remove the secondary reflections. With the network analyzer/swept source solution, a third calibration 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 9 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 Agilent 86100A 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.

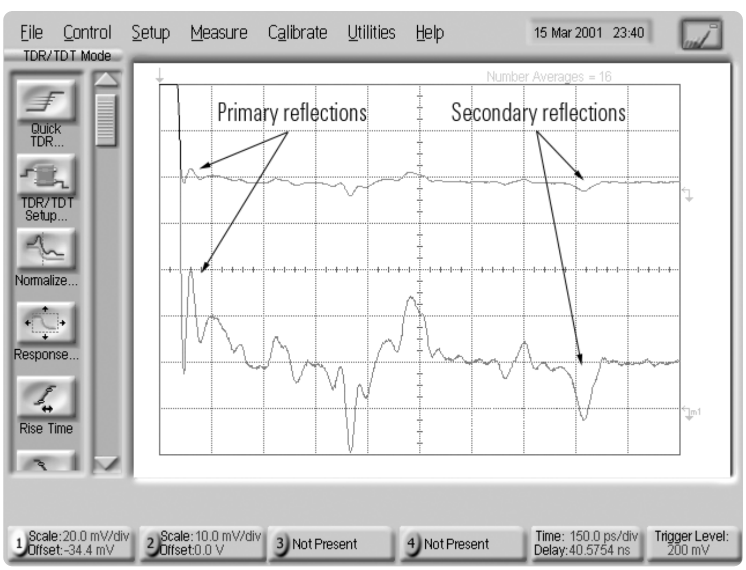


Figure 9. The lower waveform is a copy of the upper waveform with the voltage scale greatly expanded about the baseline to show more clearly the shape of the secondary reflection.

In TDR/TDT measurements made with an oscilloscope/step generator, 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 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.

After an adequate separation has been achieved, a time window can be selected which does not include the undesirable secondary reflections. Figure 11 illustrates the removal of secondary reflections from the measurement data using time windowing. The top waveform in Figure 11 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 TDR/TDT measurements made with a network analyzer/swept source, time windowing is cumbersome, thus a third calibration measurement is used.

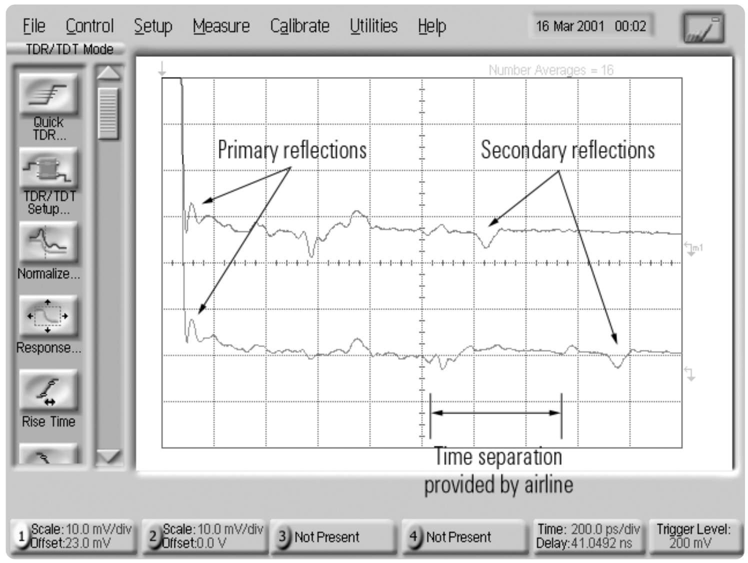
The Digital Filter Corrects the Measured Response

The digital filter describes how the frequency response of the test system varies from the ideal. If the calibration signal were 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 the 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.

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 consid-



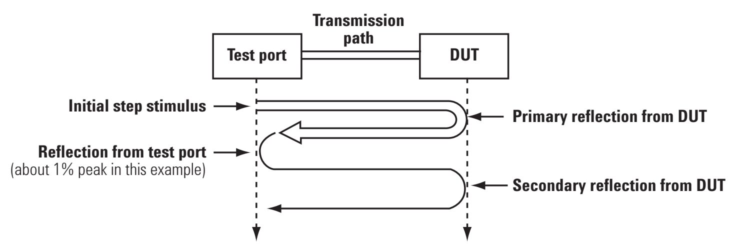


Figure 10. By adding a section of airline between the test port and the DUT, you can more clearly distinguish primary and secondary reflections.

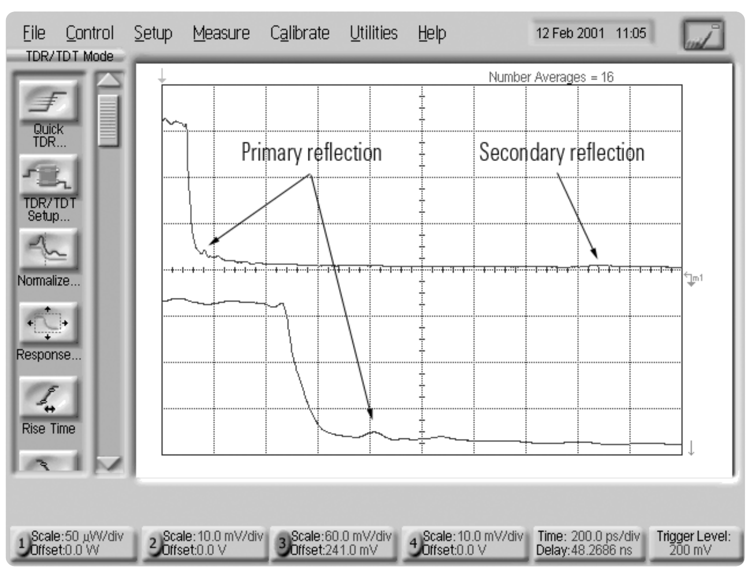


Figure 11. Decreasing delay in the bottom waveform removes the secondary reflection shown at the right end of the baseline in the top waveform.

$$W(f) = \sum_{k=0}^{3} a_k \cos(2\pi f k/L) \text{: for } \frac{-L}{2} < f < \frac{L}{2}$$
$$= 0 \text{ elsewhere}$$
$$\text{where: } a_0 + a_1 + a_2 + a_3 = 1$$

L = the full width of the window in hertz
f = frequency in hertz

Equation 2

$$F(f) = \frac{W(f)}{S(f)}$$

Equation 3

ered 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). Frequency response is the Fourier transform of the impulse response.

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 12). By carefully changing the –3 dB point in the frequency response, the bandwidth can be increased or decreased.

In the Agilent 86100A, 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 13). Increasing the bandwidth requires more consideration.

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 14).

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.

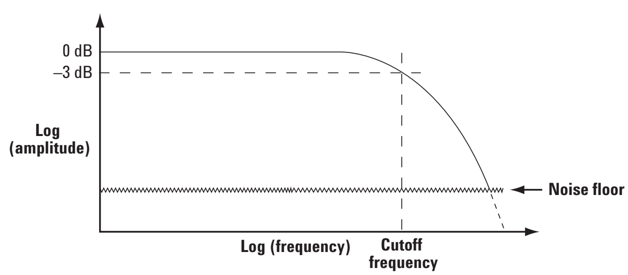


Figure 12. Basic system frequency response.

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

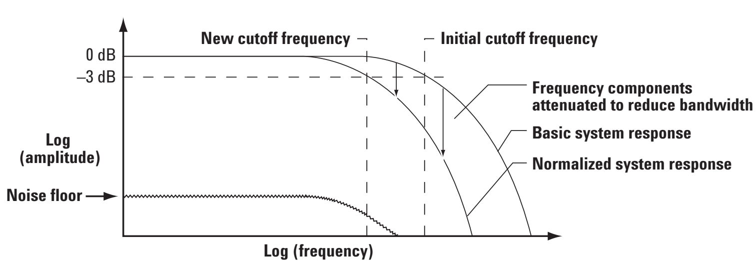


Figure 13. Normalized system frequency response (system bandwidth reduced).

normalized (filtered) frequency response of the DUT. Equation 5 describes the filtering process using the above definitions.

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,[1] the result is n_i (t), a normalized impulse response.

Because a step stimulus is used, a normalized step response, ns (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.

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 calibration 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

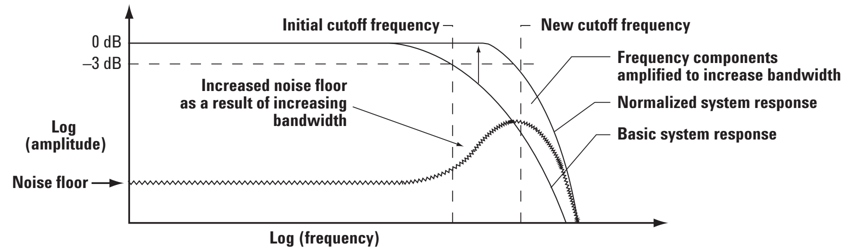


Figure 14. Normalized system frequency response (system bandwidth increased).

$$S(f) = W(f)\,E(f)$$

Equation 4

$$\begin{aligned} M(f) &= D(f)\,S(f) \\ N(f) &= M(f)\,F(f) \\ N(f) &= D(f)\,S(f)\,F(f) \\ N(f) &= D(f)\,W(f)\,E(f)\,\frac{W(f)}{W(f)\,E(f)} \\ N(f) &= D(f)\,W(f) \end{aligned}$$

Equation 5

$$\begin{aligned} n_i(t) &= d(t) * w(t) \\ n_s(t) &= n_i(t) * u(t) \\ n_s(t) &= d(t) * [w(t) * u(t)] \end{aligned}$$

Equation 6

[1] The Bracewell transform is under license from Stanford University.

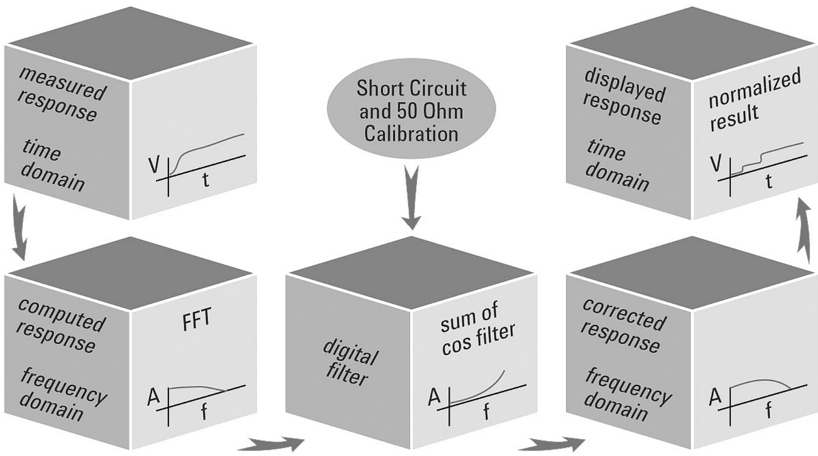


Figure 15. Block diagram of the normalization procedure.

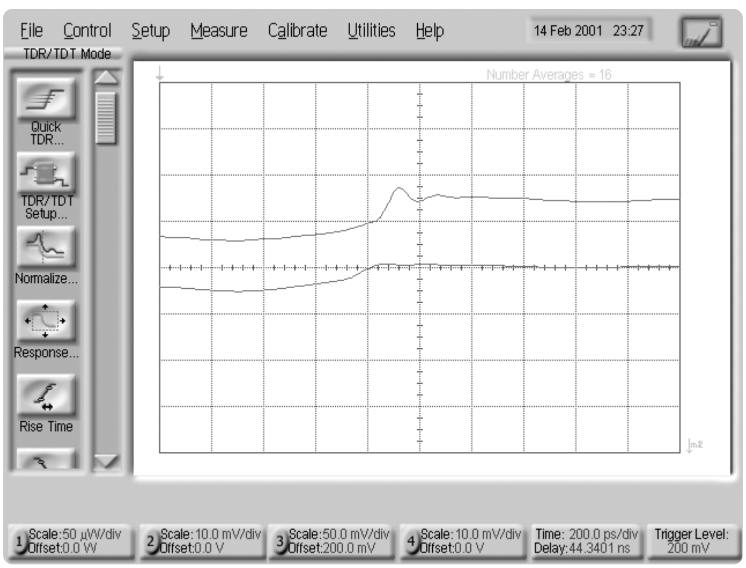


Figure 16. The top waveform is the same signal as the bottom waveform, except that it has been normalized. Normalization reveals that there are actually two inductive discontinuities, rather than one as shown in the bottom waveform.

of the DUT, normalized to an ideal step input with the user-specified risetime.

Figure 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 normalized to 20 ps risetime. Note that in the bottom waveform the inductive discontinuity is not clear. Using normalization, it becomes obvious that there is actually a prominent inductive discontinuity. Because it is difficult to built 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.

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