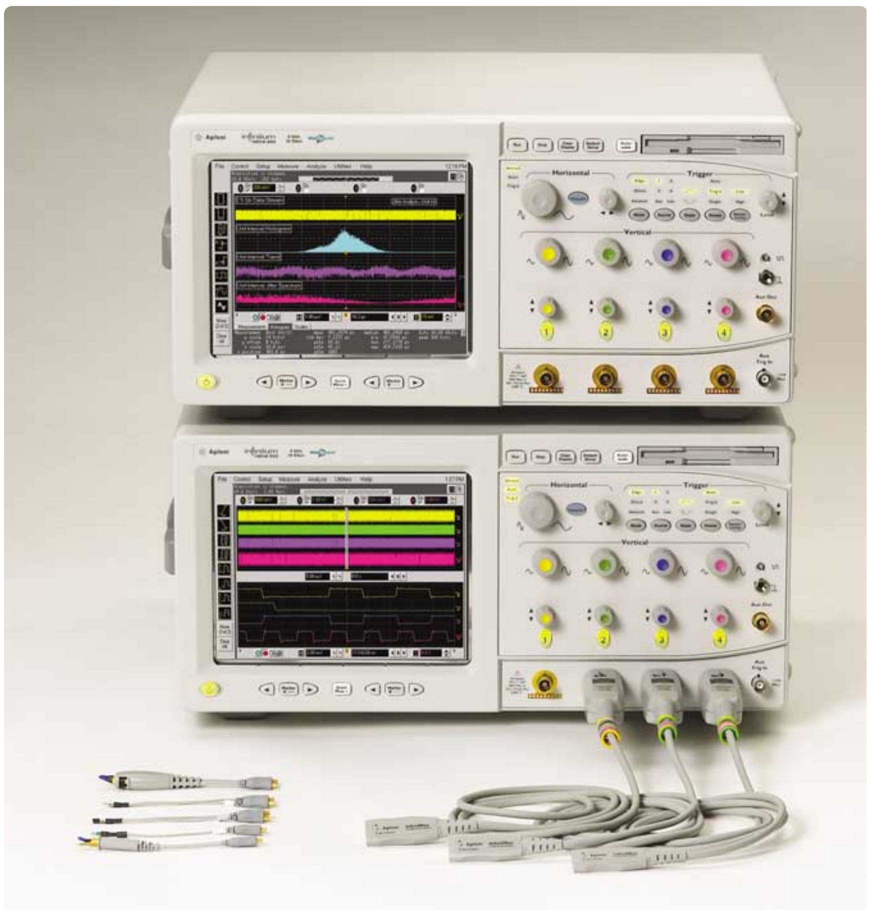
Time-Domain Response of Agilent InfiniiMax Probes and 54850 Series Infiniium Oscilloscopes

Application Note 1461

Who should read this document?

Designers have looked to time-domain response characteristics to determine the accuracy of high-performance oscilloscopes and probes for reproducing the signal present at the probe tip. Yet these characteristics can be misleading if not interpreted correctly. This application note will show measurements of the time-domain response of the Agilent Technologies InfiniiMax probes and 54855A 20 GSa/s real-time oscilloscopes. We will also introduce a new technique for accurately characterizing the time-domain response of oscilloscope probes.



Agilent Technologies

Time-domain response characteristics

High-performance oscilloscopes typically are used to measure the time-domain characteristics of fast digital signals. Consequently, the time-domain response characteristics of oscilloscopes and probes are important. Rise time and bandwidth traditionally have been 'banner specs' on oscilloscope data sheets because they both help indicate how faithfully the oscilloscope and probe system reproduce the signal present at the probe tip. However, some caution must be used in interpreting these specifications. An oscilloscope or probe with significant overpeaking may have a stellar rise time and bandwidth but will not accurately represent the signal at the probe tip.

At Agilent the philosophy is that the oscilloscope and probe system should reproduce the signal at the probe tip as accurately as possible for signals whose frequency content falls within the scope's bandwidth. The only specification that Agilent warrants for its oscilloscope and probe systems is the frequency-domain magnitude response because it is the only measurement with standards and test methods that are traceable to the National Institute of Standards and Technology (NIST). NIST does not provide traceable reference standards or methods for time-domain response measurements; therefore, the time-domain response is not specified.

Even if a 'reference standard' step generator were available to help determine true time-domain response, its output waveform would be affected by the termination. For example, if a probe were connected to the step generator to measure the response, the probe's reactive load would change the waveform. The change in the waveform due to probe loading can be accounted for by measuring the waveform at the input of the probe. To characterize the probe, we need to measure the waveform at the output of the probe as well. In the time domain, the response of the probe can then be calculated by using convolution. In the frequency domain, the response of the probe can be calculated by using complex division to calculate Vout (s)/Vin(s). In either case, determining the response of the probe requires measuring the signals at both the input and the output of the probe.
Note that a specification of the frequency-domain magnitude response says nothing about the phase response. Linear phase is also important to accurate reproduction of signals in the time domain.

Today, typical high-bandwidth oscilloscopes have a 'maximally-flat' response instead of the traditional Gaussian response (see Application Note 1420 in Related Literature at the end of this document). This means you cannot assume a simple 0.35 inverse relationship between rise time and bandwidth. Furthermore, it is not a simple matter of adding rise times in quadrature to arrive at total system response or to estimate errors in rise-time measurements. As you will see in this application note (Figure 23), an oscilloscope with a maximally-flat response is capable of measuring rise times less than twice its own rise time with a very small error. For oscilloscopes with a more traditional Gaussian response, such a small ratio between the measured rise time and the rise time of the scope and probe would result in much larger errors.

Probe response

All measurements in this section are made on an Agilent 1134A, 7 GHz InfiniiMax probe with various probe heads.

Measuring the true step response of a high-bandwidth voltage probe is not as easy as just connecting the probe to a fast step and looking at the probe output. The reason for this lies in the definition of step response. Step response is defined as the output response of a device under test (DUT) when the input to the device is stimulated with a step that is perfectly flat and infinitely fast (tr ~= 0). If the DUT has a flat frequency response and linear chase, it will produce at its output a flat step whose bandwidth is limited by the passband of the DUT.

In order to measure the step response of a probe, you must drive it with a perfectly flat, infinitely fast step. Obviously this is not practically possible, so instead we'll drive the input with the fastest, flattest step available and then use correction techniques to derive the true step responses.

The test equipment includes:

- Agilent 54750A sampling oscilloscope (or any Agilent sampling scope with a time-domain reflectometer (TDR) and normalization)
- Agilent E2655A probe deskew/performance verification fixture
- Agilent 1143A probe power supply
- Agilent N1022A AutoProbe interface adapter
- Agilent 5062-1247 outside thread 3.5 mm adapter
- Short, high-quality 3.5 mm or sma coax cable
- Agilent 909D 50 ohm termination

Procedures for the test equipment setup are:

- Connect a E2655A to a sampling scope channel using high-quality adapters
- Connect a TDR channel to the other side of a E2655A fixture using a short, high-quality cable
- Connect a 1143A power supply, N1022A adapter, and 5062-1247 adapter to the 1134A probe to be tested

Set up the sampling scope so that the TDR step is "on" on the proper channel and the measuring channel is being viewed. Figures 1 and 2 show the block diagrams for the equipment setup. The waveform seen when this setup is done properly should be very similar to the waveform in Figure 4.

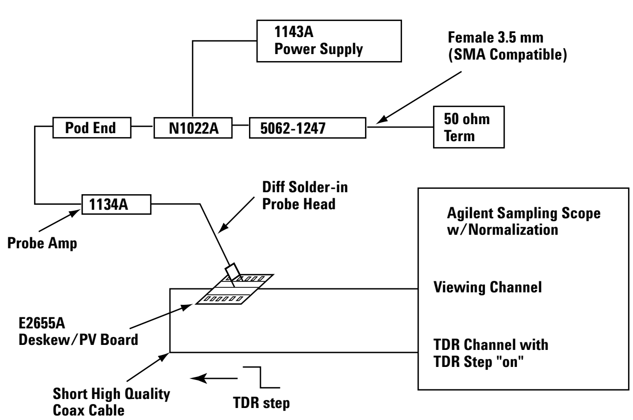


Figure 1. Setup for measuring the probe input step

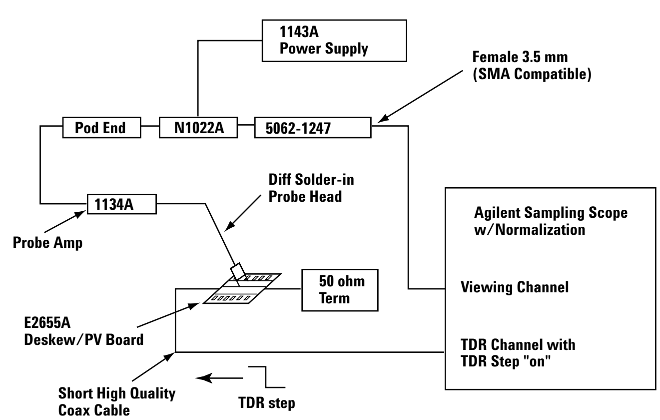


Figure 2. Setup for measuring the probe output step

The E2655A probe performance verification (PV) and deskew fixture allows us to connect the probe tip to a 50 ohm transmission line, as shown in Figure 3.

Figure 4 shows the TDR step from channel 4, as viewed on channel 3, through the test setup. Notice that it is somewhat slowed down from the nominal 35 ps, 10 to 90 percent step of the TDR step generator due to the loss through the test setup.

Connect the Agilent E2677A differential solder-in probe head to both the 1134A probe amp and the E2655A fixture. Align the + side to the center conductor on the E2655A and the – side to either ground conductor under the retainer clip. Release the clip and lift slightly to make sure good contact is made. Once the probe input impedance is loading the through line on the E2655A, we should see the loading effects on this edge. These are seen in Figure 6.

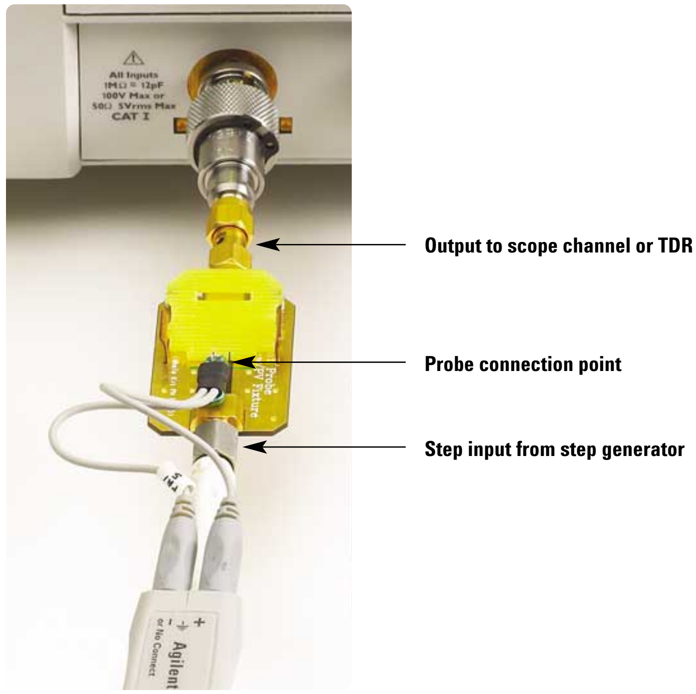


Figure 3. Probe deskew fixture E2655A

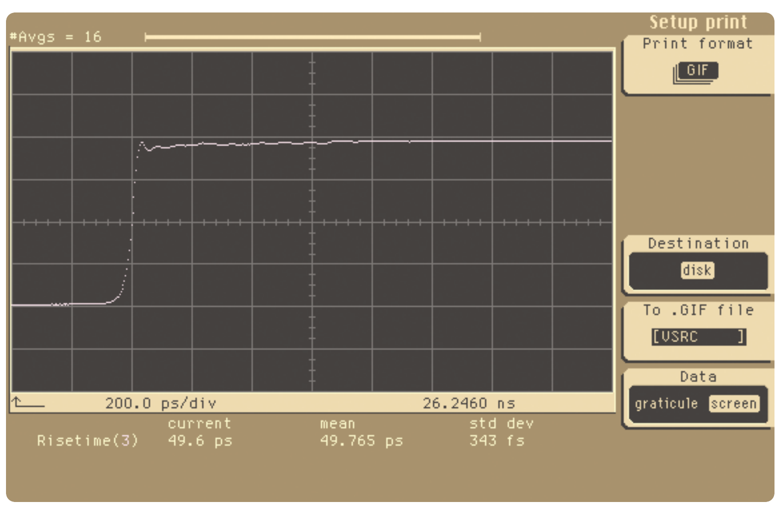


Figure 4. TDR step response

With the probe loading the line, we will perform a time-domain transmission (TDT) normalization in the sampling scope (see Application Note 1304-5 in Related Literature at the end of this document). This normalization takes the step that is applied to the probe input, propagates forward on the transmission line into channel 3, and constructs a digital filter that, when applied to the input step, produces a "perfect" 31 ps step. This step is shown in Figure 6 as Response 3 or "r3." Note that its 10 to 90 percent rise time is 31.26 ps. Now we have a filter that can correct the actual input step to a fast, flat input step. If we apply this filter to the output of the probe, then we will be able to view the step response of the probe to this 31 ps step. To view the output, we disconnect the E2655A from the sampling channel and terminate it with a 50 ohm termination, then connect the output of the probe to the sampling channel (see Figure 2). The result is seen in Figure 7.

Because the input and output steps do not have excessive overshoot, we can use the square root of the sum of the squares to approximate the rise time of the probe only. Note that even if we did not do this, the 10 to 90 percent output rise time is already ~67 ps. If we approximate the rise-time probe only, the result is:

tr probe only ~=
$\sqrt{66.67 \text{ ps**2} - 31 \text{ ps**2}}$ =
59 ps 10-90%

This confirms the typical characteristic stated in the E2677A data sheet of 61 ps.

Figure 5. Differential solder-in probe head E2677A

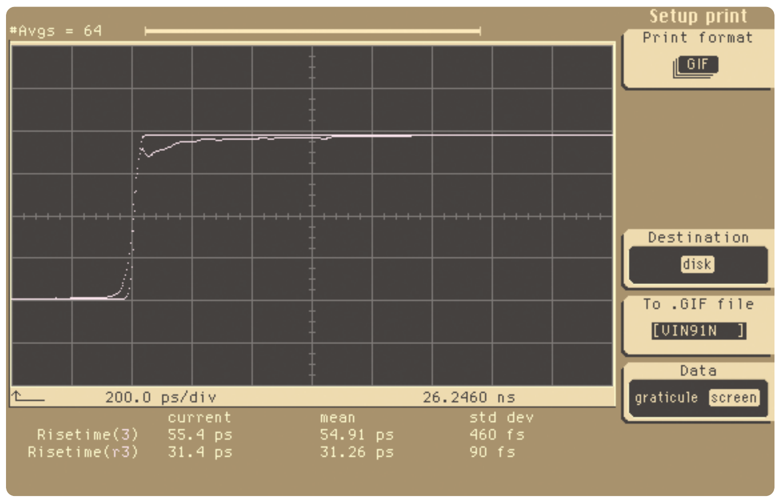


Figure 6. Differential solder-in probe head E2677A connected to probe fixture

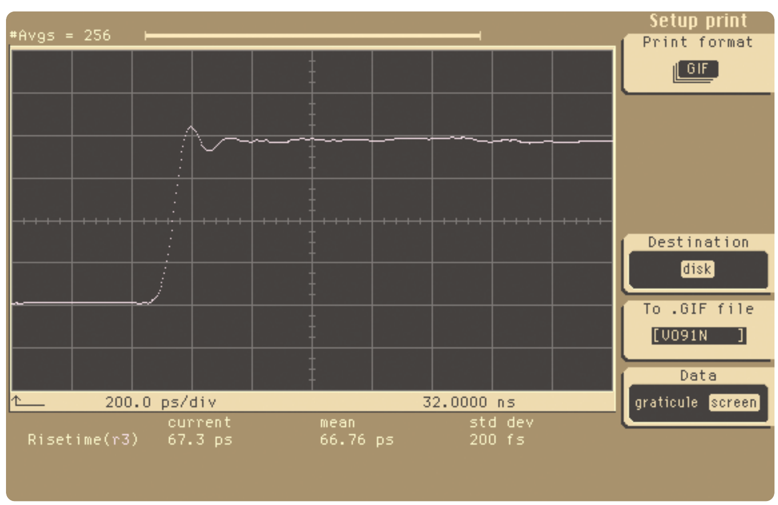


Figure 7. Measured response of E2677A differential solder-in probe head

Step response of other probe heads and configurations

The same methods described above can be used to determine the step response of virtually any combination of probe and accessories. Figures 8 through 14 are plots of the step response for other InfiniiMax probe heads alone and with other accessories. In each plot, the actual input waveform on the probe and the corrected input waveforms are shown in blue. The corrected output of the probe is shown in purple. Rise times for the corrected input and output are shown on the plots.

E2675A differential browser probe head

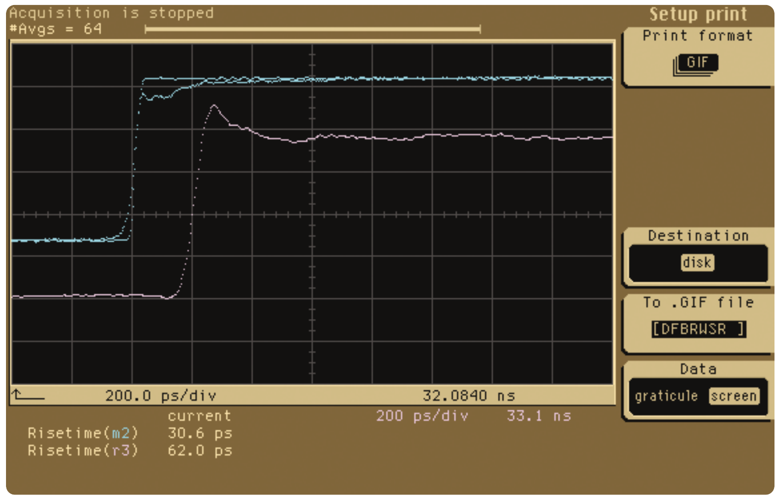


Figure 8. Differential browser probe head E2675A with 7 GHz 1134A probe amp

E2678A differential socketed probe head

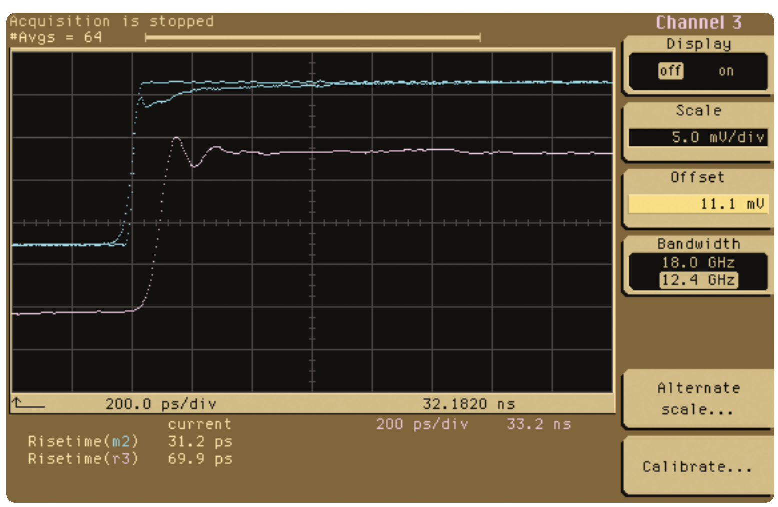


Figure 9. Differential socketed probe head E2678A with 7 GHz 1134A probe amp

E2676A single-ended browser probe head

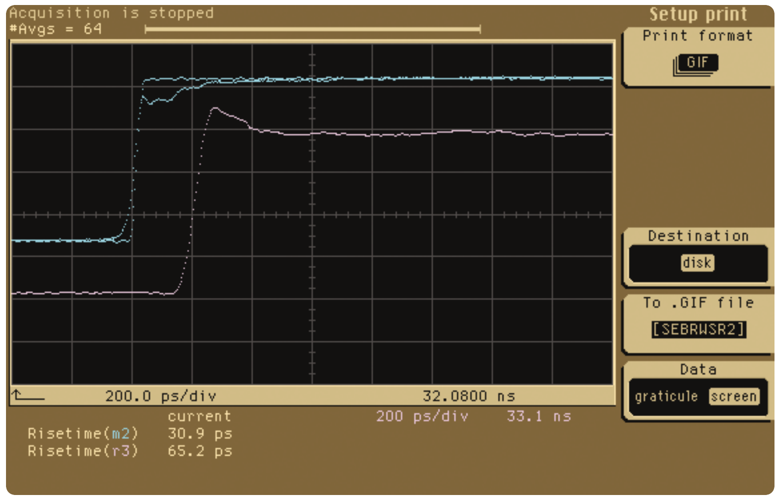


Figure 10. Single-ended browser probe head E2676A with 7 GHz 1134A probe amp

E2676A single-ended browser probe head

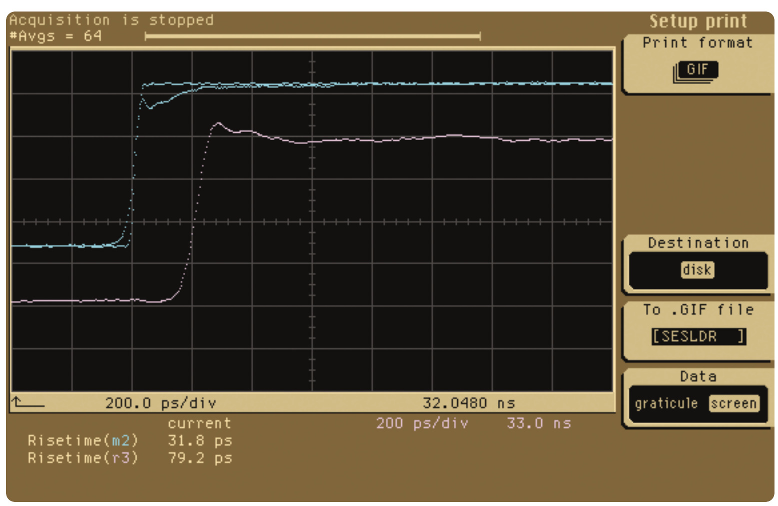


Figure 11. Single-ended solder-in probe head E2679A with 7 GHz 1134A probe amp

Figures 12 through 14 illustrate solutions for situations where the points to be probed are separated by a greater distance. Obviously there is some compromise of performance in these situations.

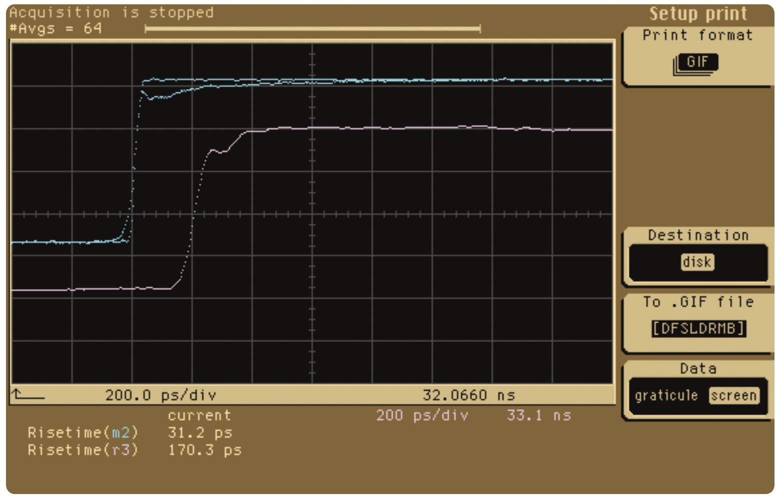


Figure 12. Differential solder-in probe head E2677A with 7 GHz 1134A probe amp (using longer span mid-bandwidth 150 ohm tip resistors)

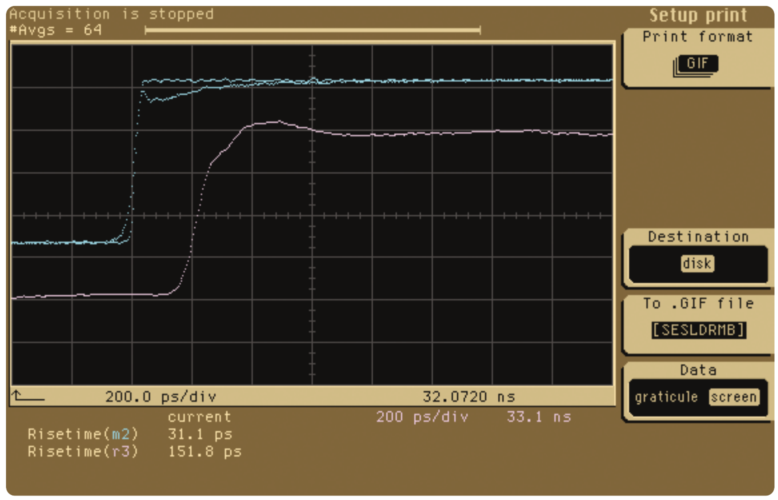


Figure 13. Single-ended solder-in probe head E2679A with 7 GHz 1134A probe amp (using longer span mid-bandwidth 150 ohm tip resistors)

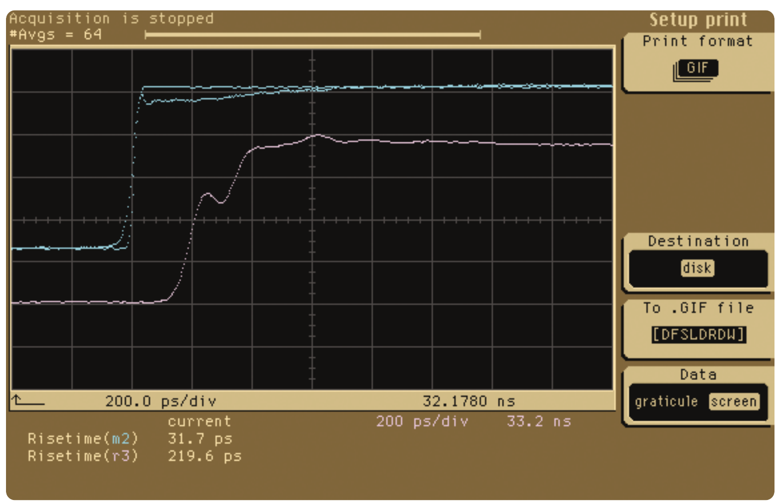


Figure 14. Differential socketed probe head E2678A with 7 GHz 1134A probe amp (using wide span damped wire accessories with 160 ohm tip resistors)

Note: The ringing in the edge of this step response is due to the long damped wire accessories. This ringing is out of band and not visible when a slower, more in-band step is applied.

Probe and scope system response

Now we will turn our attention to the response of the entire measurement system. This, by definition, includes everything from the points on the user's circuit to the oscilloscope display. It includes probe connection accessories, the probe itself, and the scope. In this case, normalization software is not available, so the strategy will be to use an "as-flat-as-possible" step and to compare the step response of the scope and probe to that of a very wideband sampling scope.

In this section, the system being measured consists of the following Agilent Technologies products:

- InfiniiMax probe heads, including connection accessories
- InfiniiMax 1134A 7 GHz probe amplifier
- Infiniium 54855A 6 GHz oscilloscope

Measured with an "as-flat-as-possible" Vin step, the InfiniiMax probe heads, 1134A InfiniiMax 7 GHz probe amplifier, and 54855A 6 GHz Infiniium scope have the time-domain characteristics shown in Table 1. Again, the sum of squares approximation is used based on the measured rise times of Vin and Vdisplay.

The equipment used to make these measurements includes:

- PicoSecond Pulse Labs 4015D with 10 ps step generator head
- Agilent 54750A sampling scope with 54752A 50 GHz sampling plug-in to measure Vin
- Agilent E2655A probe de-skew fixture modified for flat Vin, (see discussion following)
- Agilent 2.4 mm attenuators and 2.4 to 3.5 mm adapters

Probe accessories	Vin	VDisplay	System derived
1134A probe amp with differential solder-in head	35 ps	90 ps	83 ps
1134A probe amp with differential socketed head	33 ps	90 ps	84 ps
1134A probe amp with differential browser head	34 ps	76 ps	68 ps
1134A probe amp with single-ended solder-in head	34 ps	95 ps	89 ps
1134A probe amp with single-ended browser head	36 ps	81 ps	73 ps

Table 1. Time-domain characteristics

The first step is to experimentally create a fast step that is as flat as possible while the probe is attached. To do this, we use an Agilent 54750A high-bandwidth sampling scope to monitor the step. The equipment is connected as shown in Figure 15.

Note that the Picosecond Pulse Labs generator produces A fast step on the falling edge of its output, so all the measurements in this section are fall time measurements on falling edges. An E2677A differential solder-in probe head is attached to the E2655A probe fixture.
The values for the added compensation circuit were experimentally chosen to optimize the flatness of the step while the probe is attached.

In Figure 16, the blue trace is the step arriving at the input of the sampling scope without the probe attached. The red trace shows the change in the step when the probe is attached.

After adding the 200 ohms in series with 18 nH between the probe attachment point and ground, the step arriving at the input of the sampling scope is as shown in Figure 17. This is the stimulus for the following measurements. When you're viewing the responses of the various probe head, probe amplifier, and scope combinations in the remainder of this section, compare them to Figure 17, which is "Vin".

Vin with each probe head is measured with the 50 GHz sampling scope. The results are all fairly flat, with rise (fall) times ranging from 33 to 36 ps.

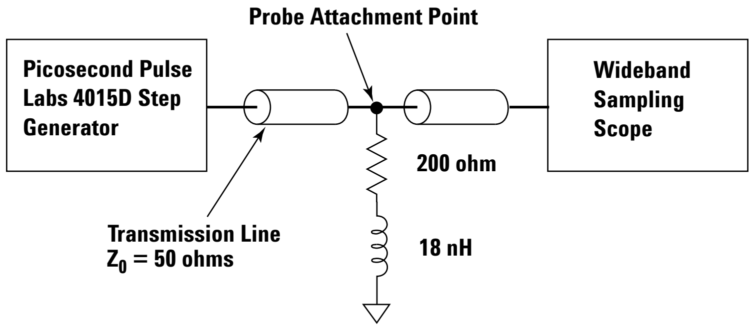


Figure 15. Setup for measuring system step response

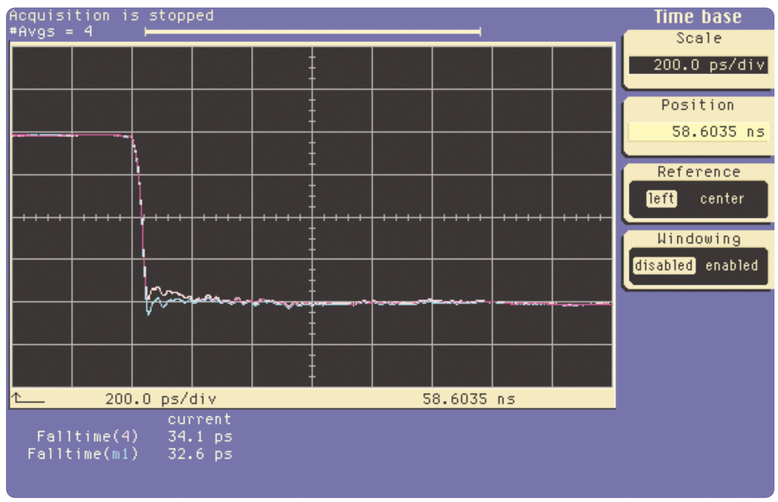


Figure 16. Unmodified step, with and without probe

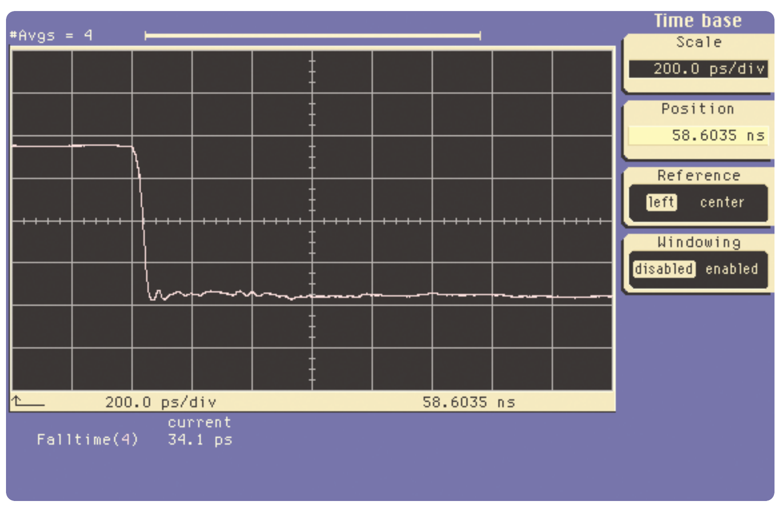
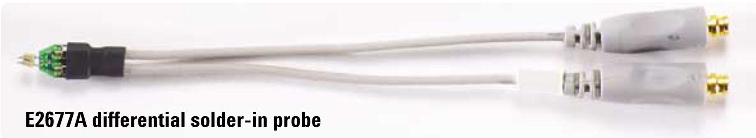


Figure 17. Step with probe attached and with compensation circuit in place



E2677A differential solder-in probe

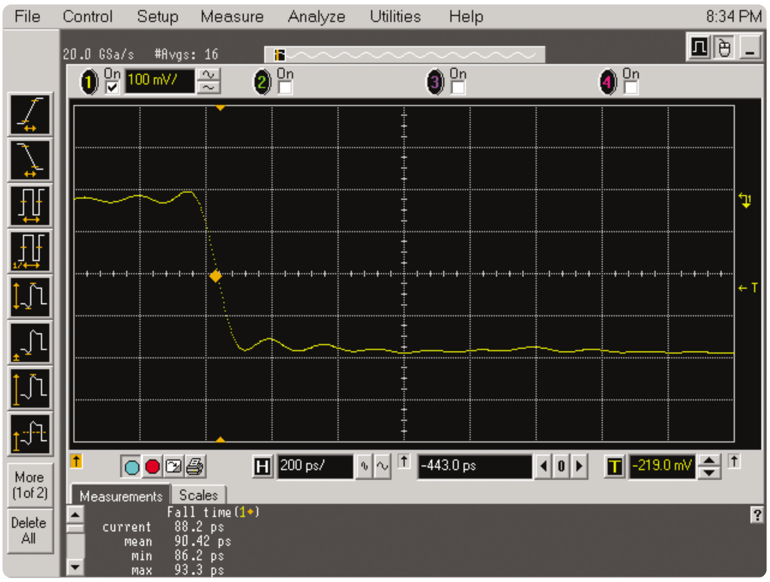
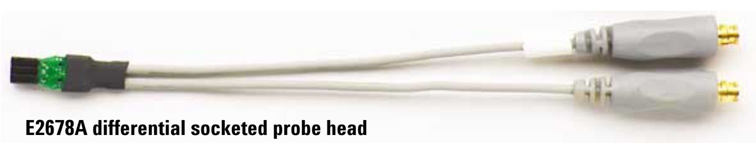


Figure 18. System step response of E2677A differential solder-in probe and 54855A oscilloscope



E2678A differential socketed probe head

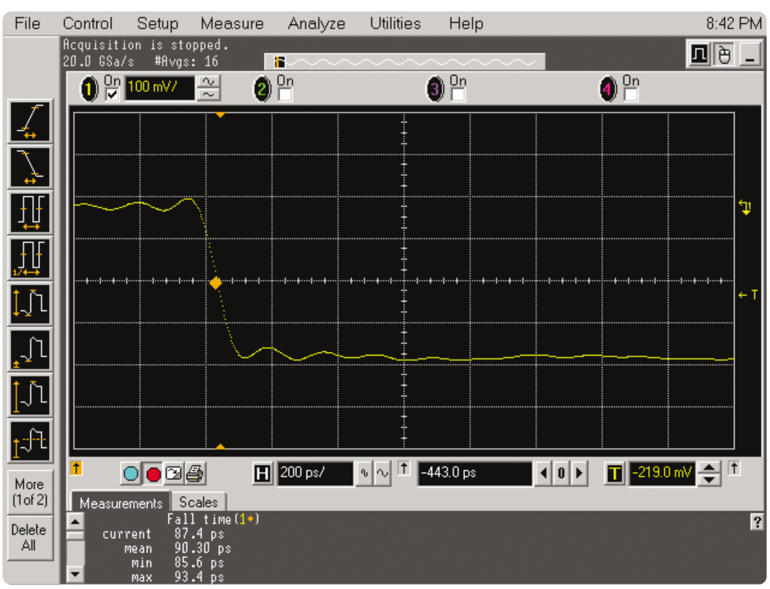


Figure 19. System step response of E2678A differential socketed probe head, 1134A probe amp, and 54855A oscilloscope

E2675A differential browser probe head

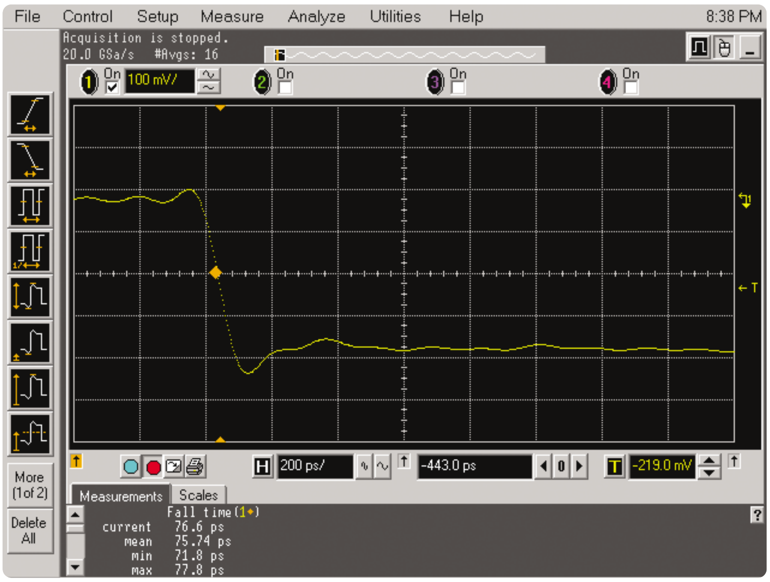


Figure 20. System step response of E2675A differential browser probe head, 1134A probe amp, and 54855A oscilloscope

E2679A single-ended solder-in probe head

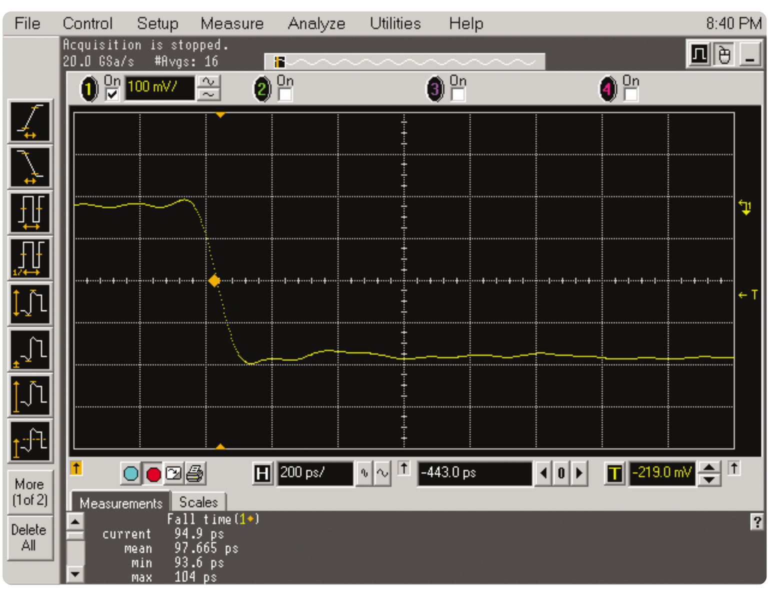


Figure 21. System step response of E2679A single-ended solder-in probe head, 1134A probe amp, and 54855A oscilloscope

E2676A single-ended browser probe head

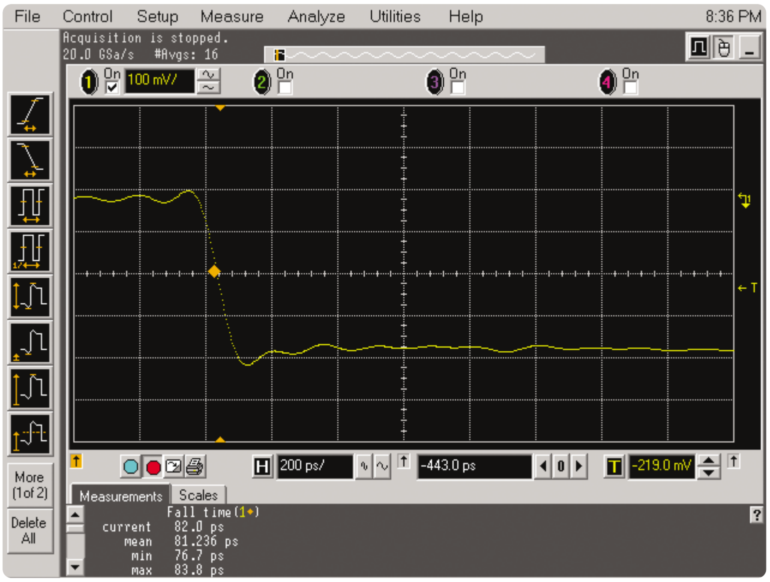


Figure 22. System step response of E2676A single-ended browser probe head, 1134A probe amp, and 54855A oscilloscope

E2675A differential solder-in probe

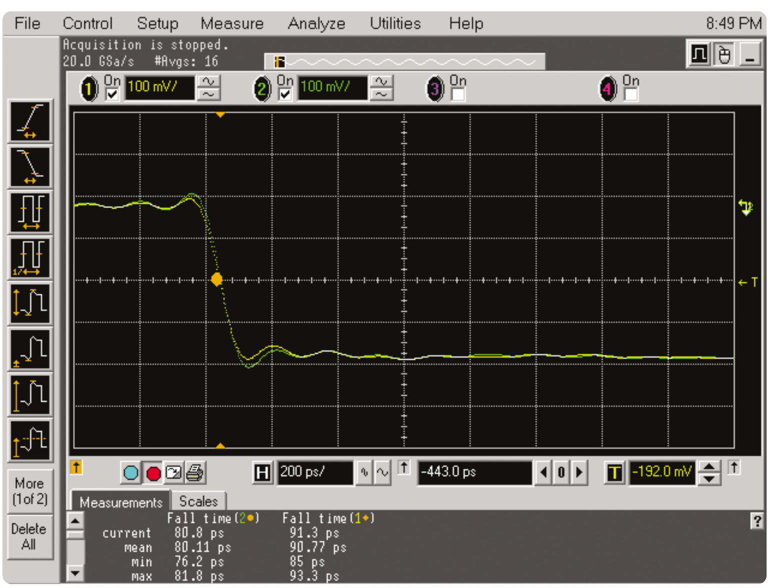


Figure 23. The step at the probe input (green trace), as measured on channel 1 of the scope, compared to the step seen through the E2675A differential solder-in probe head and 1134A probe amp, as seen on channel 2 (yellow trace)

In Figure 23, the step at the input of the probe, which is measured at the output of the fixture by the scope, is compared to the step response measured through the E2675A differential solder-in probe head, the 1134A probe amp, and the scope.

Scope and probe response to various rise time inputs, comparison to sampling scope response

An alternative method to evaluate the performance of the scope and probe system is to compare the response to inputs of various rise times to that of an Agilent 86100B wideband sampling oscilloscope. In these measurements we are not determining the step response of the probe and scope system. Instead these measurements characterize how accurately the scope and probe track and measure input signals with various rise times. We will determine the actual measurement error for each rise time.

For the measurements in this section, a TDR step generator is modified to produce a step that is flat in the frequency domain and has linear phase out to >6 GHz. The step has some overshoot in the time domain, as can be seen in Figure 27. Following this initial overshoot, the step is quite flat. The step is applied to the input of an Agilent 86100B digital communication analyzer (DCA) oscilloscope with an 86112A 18 GHz electrical module, and to the input of a 54855A oscilloscope and probing system (Figures 28 and 29). The waveform, as measured by the 86100B, is saved in a waveform memory. The waveform data is then imported into a waveform memory in the 54855A. This allows us to display both responses on the screen of the 54855A at the same scale factors to facilitate a visual comparison and to make comparative measurements on both. Slower rise times are generated by passing the fast-rising step through Agilent rise-time converters with a Gaussian response. This allows us to evaluate the scope's step response at various input rise times of interest.

In all the figures, the yellow trace is the response of the 54855A, 6 GHz, 20 Gsa/s oscilloscope. The blue trace is the response of the 86100B DCA.

NOTE: All the rise times quoted in this section are 20 to 80 percent

As you can see in Figure 23, the responses of the two oscilloscopes are indistinguishable at a 20 to 80 percent rise time of 210 ps. The measured rise times agree within 3 percent.

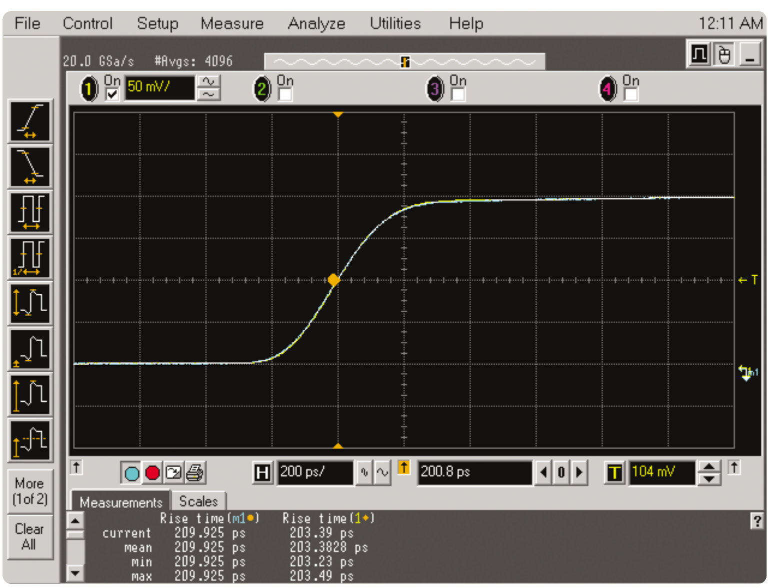


Figure 24. Response comparison of 54855A oscilloscope and 86100B DCA at 210 ps

At a 20 to 80 percent rise time of 140 ps, the two responses agree well. The rise-time measurements agree within 3 percent.

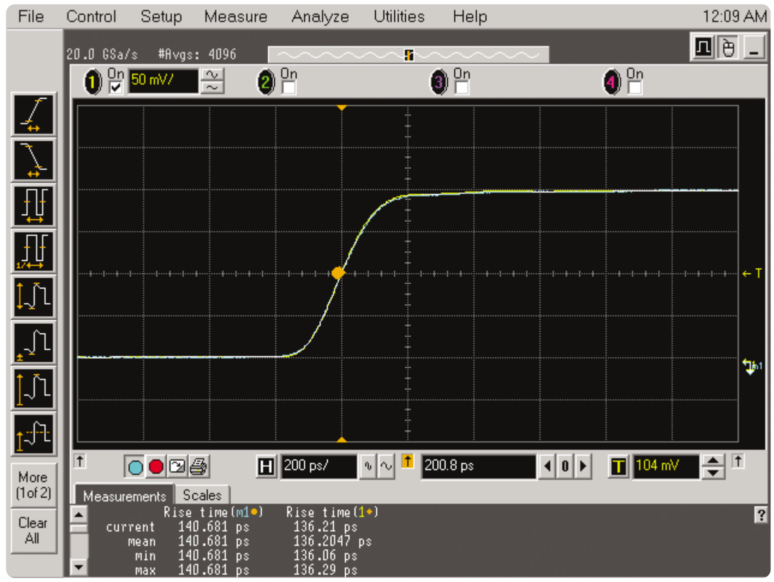


Figure 25. Response comparison of 54855A oscilloscope and 86100B DCA at 140 ps

At a 20 to 80 percent rise of 88 ps, the agreement is still quite good, though you can begin to detect a slight deviation right at the upper corner of the rising edge. The rise-time measurements agree within 1 ps. Note that the rise time of the measured signal is less than twice the scope's rise time, yet the measurement error is still quite small.

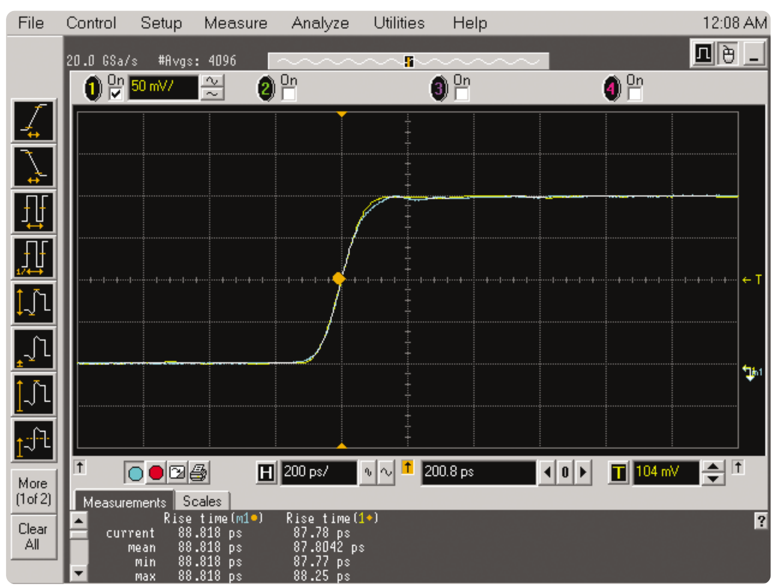


Figure 26. Response comparison of 54855A oscilloscope and 86100B DCA at 88 ps

At a 20 to 80 percent rise time of 49 ps, the responses begin to diverge noticeably, but the rise-time measurements still agree quite closely. At this speed, you begin to see some ‘pre-ripple’ in the step response.

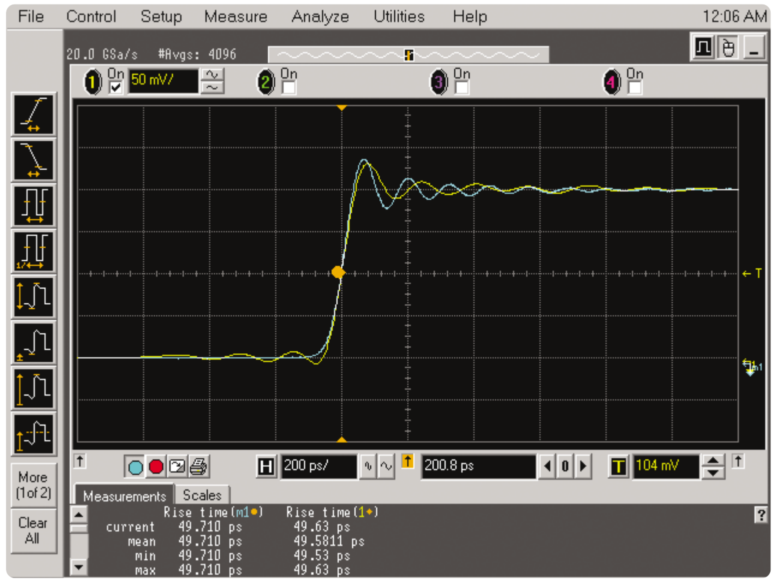


Figure 27. Response comparison of 54855A oscilloscope and 86100B DCA at 49 ps

Figures 28 and 29 show measurements made on an Agilent 54855A oscilloscope combined with an 1134A 7 GHz probe amp and an E2677A differential solder-in probe head.

At a 20 to 80 percent rise time of 220 ps, the oscilloscope and probe track the response of the 86100B quite well visually. The measured rise time agrees within 2 percent.

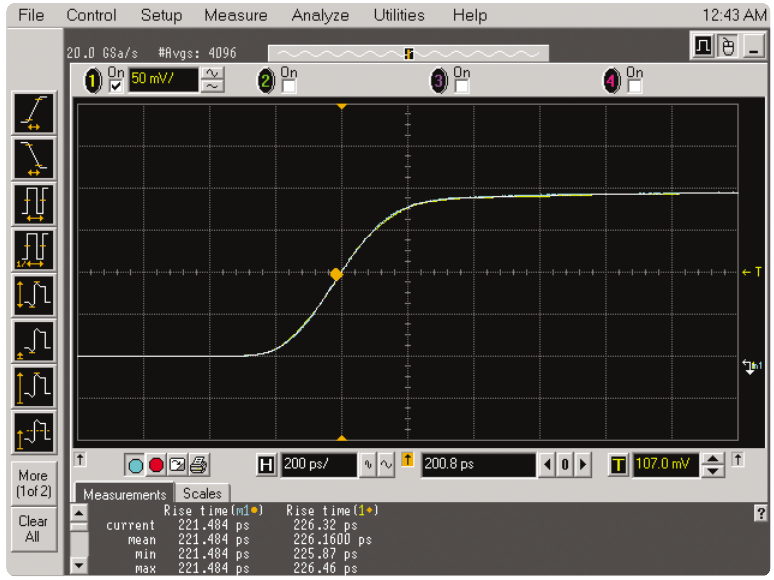


Figure 28. Response of 54855A oscilloscope combined with an 1134A 7 GHz probe amp and an E2677A differential solder-in probe head at 220 ps

At a 20 to 80 percent rise time of 100 ps, the response agrees well with the 86100B DCA. The rise-time measurement agrees within 6 percent.

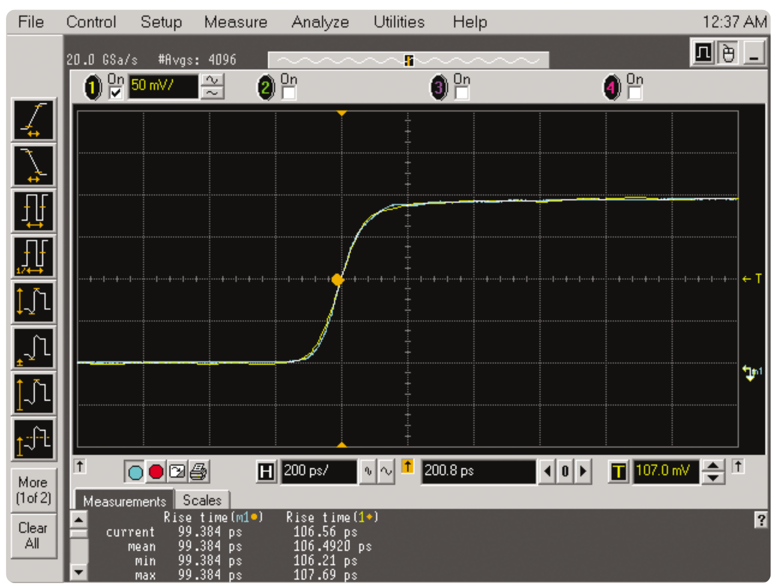


Figure 29. Response of a 54855A oscilloscope combined with an 1134A 7 GHz probe amp and an E2677A differential solder-in probe head at 100 ps

Frequency-domain measurements

For completeness, Figure 30 is the measured frequency-domain magnitude response of a 54855A Infiniium 6 GHz oscilloscope.

Figure 31 shows the frequency-domain response of the entire measurement system, including probe connection accessories, an 1134A probe amp, and a 54855A oscilloscope. The green plot is the response of the E2677A differential solder-in probe head. The blue plot is the response of the E2678A differential socketed probe head. The red plot is the response of the E2675A differential browser probe head. The brown plot is the response of the E2679A single-ended solder-in probe head. The yellow plot is the response of the E2676A single-ended browser probe head.

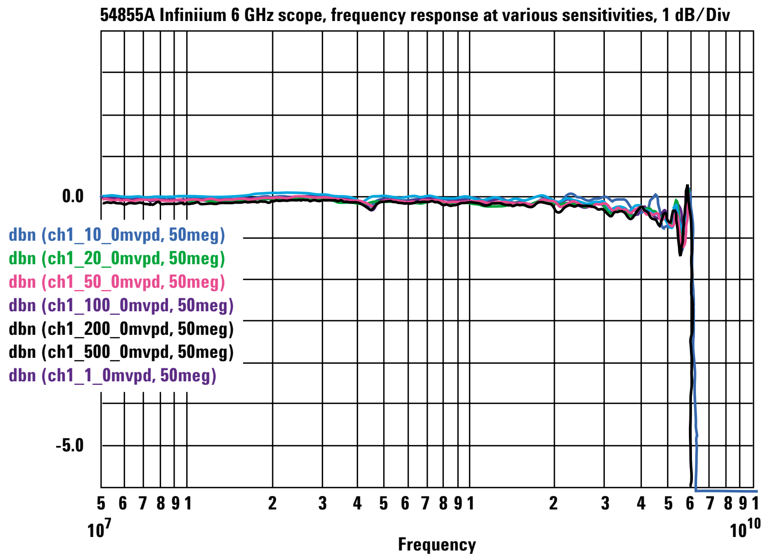


Figure 30. Frequency response of a 54855A oscilloscope

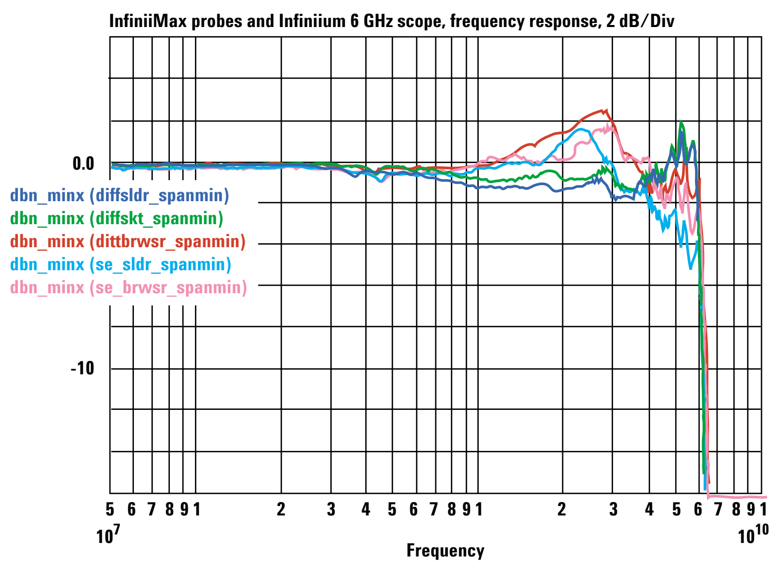


Figure 31. Frequency response of a 54855A oscilloscope, 1134A probe amp, and probe connection accessories

Conclusion

In this application note we have shown measurements of the time-domain response of the Agilent 54850 Series oscilloscopes and InfiniiMax probes. Knowledge of the time-domain response is important in selecting oscilloscopes and probes for critical measurement applications.

Related Literature

Publication Title	Publication Type	Publication Number
Improving TDR/TDT Measurements Using Normalization	Application Note 1304-5	5988-2490EN
Understanding Oscilloscope Frequency Response and its Effect on Rise Time Accuracy	Application Note 1420	5988-8008EN
Infiniium 54850 Series Oscilloscopes Infiniimax 1130 Series Probes	Data Sheet	5988-7976EN

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Printed in USA May 31, 2003

5988-9608EN

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