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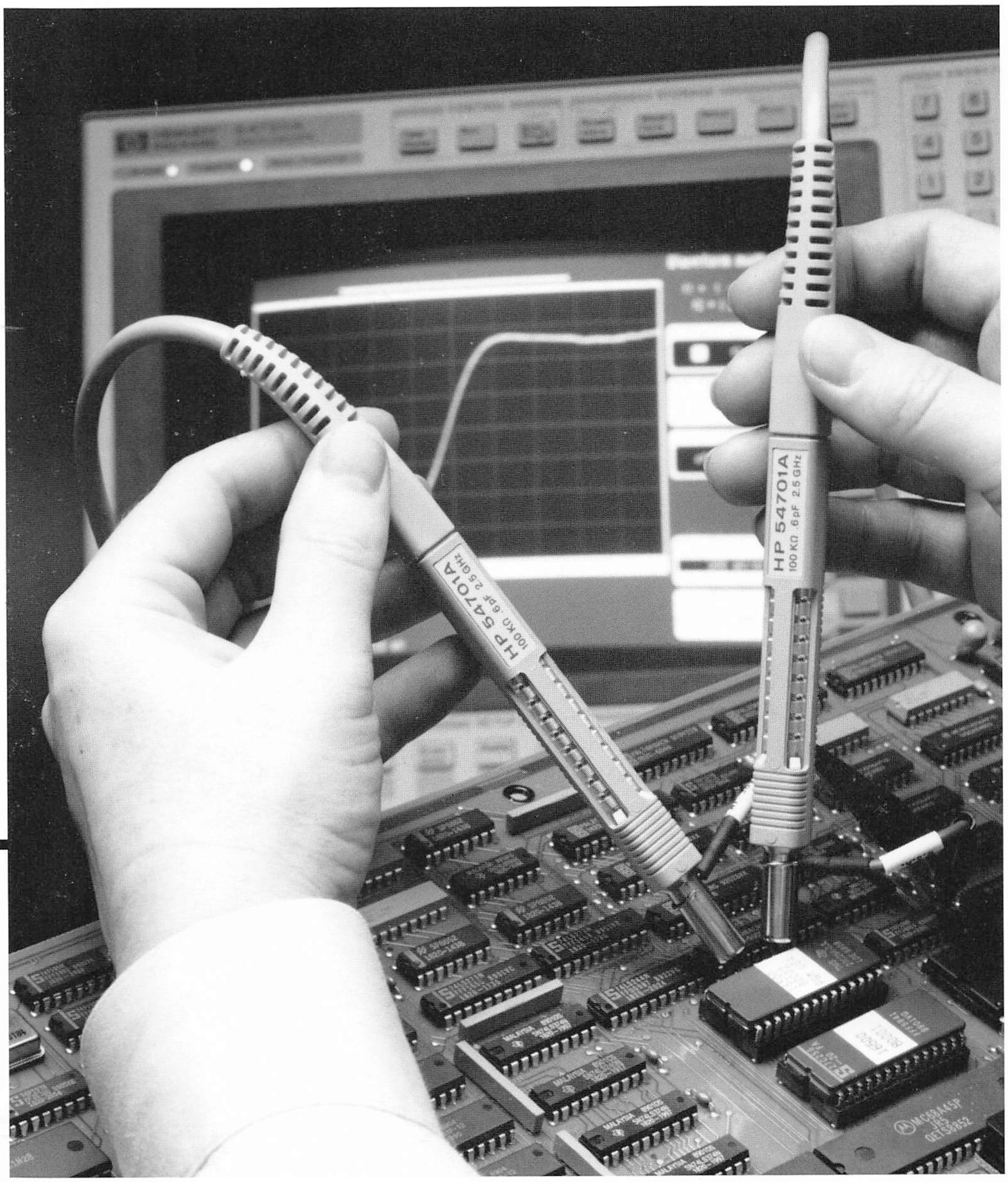
Differential Measurements on Wideband Signals

Application Note 1221



Introduction

This application note will describe the most accurate method to make differential waveform measurements on high-speed differential signals such as differential ECL. The HP 54720A oscilloscope and the HP 54701A active probe are used in the examples, but the general principles can be applied to many other digitizing oscilloscopes and probes. The primary requirement is that you must be able to deskew the oscilloscope channels. It is also critical to use probes and an oscilloscope that have sufficient bandwidth to accurately reproduce the signal; refer to “Bandwidth and Accuracy” on page 14.

Many high-speed ECL circuits use differential ECL logic. Oscilloscope measurements of these differential ECL signals must be made differentially to be valid. You cannot count on just measuring the signal on one side and assuming the other side is a mirror image. If there is any common-mode signal present, or if the two are not time-aligned, this assumption could mask the source of problems. See figure 1.

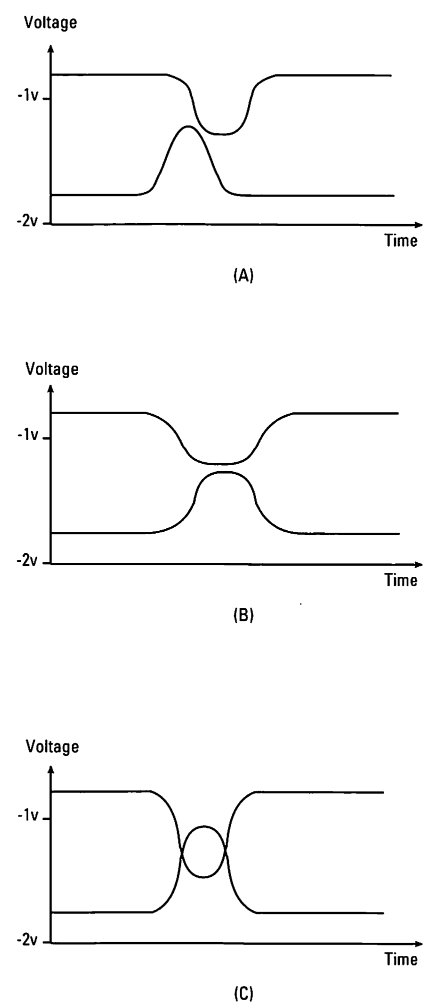


Figure 1. The waveforms shown in (a) and (b), if applied to the inputs of a differential ECL gate or flip-flop, will not cause its output to change state. The waveforms shown in (c) may cause the gate output to change state.

Procedure

Calibrate and Deskew the Probes

Calibrate the probe and channel gains

1. Install two plug-ins of the same model number in the HP 54720A oscilloscope. Referring to the HP 54720A User's Guide, perform a best calibration on each plug-in.

2. Connect two HP 54720A probes to the inputs of these two plug-ins. Referring to the HP 54720A User's Guide, perform a best calibration to the probe tip on each probe.

Deskew the probes and channels

1. Connect the two HP 54701A probes to the calibrator output on the HP 54720A as follows:

   a. Attach a BNC TEE adapter (HP part number 1250-0781) to the calibrator output.

   b. Connect a probe-tip-to-BNC adapter, HP 10218A, to each female port of the BNC TEE.

   c. Insert the tips of the HP 54701A probes into these adapters.

2. In the Acquisition menu, select the equivalent-time mode. Turn Averaging On. Set the number of averages to 16.

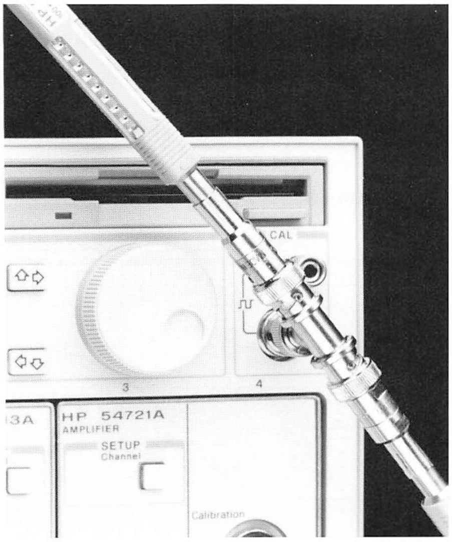


Figure 2. Test setup for deskewing channels

3. Turn on both channels. You will now adjust the skew on one of the two channels to match the two. If you are using one of the channels for the trigger source, adjust the skew on the other channel.

4. Press the Utility hardkey.

5. Press the Calibrate softkey.

6. Press the Output softkey.

7. Select the 500 kHz output.

8. Set the time base scale to 500 ps/div.

9. Set the vertical scale on each channel to 500 mV/div.

10. Set the vertical offset on each channel to 1 V.

11. Select one of the channels as the trigger source. Select edge trigger mode. Adjust the trigger level for a stable, triggered display (approximately 1 Vdc).

12. If necessary, adjust the vertical offset slightly on either channel to align the two traces vertically.

13. Press the Channel key on the plug-in for the channel you did not select as the trigger source in step 11.

14. Press the Calibrate softkey.

15. Press the Skew softkey.

16. Adjust the knob until the two traces overlay as close as possible on the fastest-slewing portion of the edge.

    Note that when the signals overlap, the color of the display changes to a third color. This is a handy visual indicator of exact overlap. See figure 3.

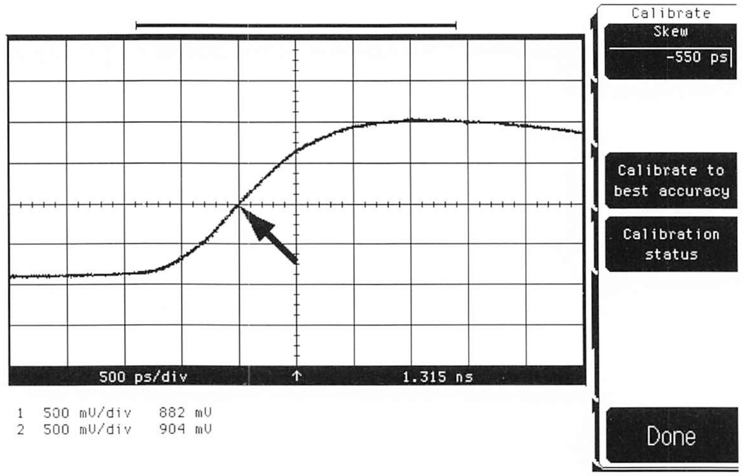


Figure 3. Match the two signals as closely as possible at the maximum dV/dt (arrow).

Match the probe gains for best CMRR

1. Connect both probes to only one of the differential signals you will make actual measurements on.

   You might want to practice the following procedure with the probes both hooked up to the calibrator output (as in the previous section), then repeat it on the signal you will make measurements on.

2. Set the scale and offset on each channel to be the same and to display the signal on the screen.

3. Adjust the offset on one channel slightly if needed to overlay the two signals.

4. Select the Channel menu for one channel.

5. Press the Probe softkey.

6. Press the Probe Atten softkey.

7. Adjust the probe attenuation to match the two signals as closely as possible.

   Note that to change the probe attenuation in small increments, you must use the keypad and the Enter hardkey. Set the time base scale to see two regions of the signal where the slope is zero or minimum, one where the signal is at its most positive level, one where the signal is at its most negative level. Concentrate on matching the gains at these levels, ignoring fast-changing regions of the signal. See figure 4.

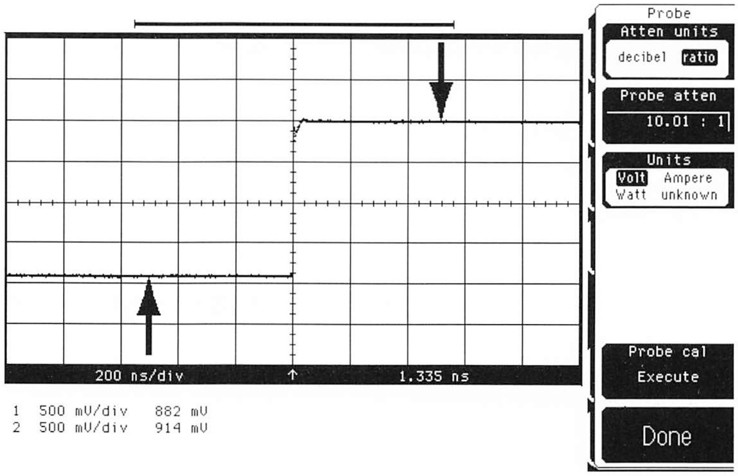


Figure 4. Adjust the probe attenuation to match the two signals as closely as possible in the regions of minumum dV/dt (arrows).

Note that when the gains are matched the display will switch to a third color, indicating overlapping signals.

8. Select the Math menu on the HP 54720A.

9. Press the Define function softkey.

10. Select "subtract" as the operator.

11. Assign the two channels as the operands.

12. Press the Done soft key.

13. Turn the function display on.

    You should now see the difference signal displayed on the scope screen. You may need to adjust the Offset of the function to bring the display on screen. If so, press the function scaling softkey in the math menu. Select manual vertical scaling.

14. Adjust the Scale factor for the function (located in the same menu) to be 1/10 the scale factor on the two channels.

15. Select the same channel menu in which you previously fine-tuned the probe attenuation ratio.

16. Readjust the probe attenuation ratio for minimum deflection in the function display. Concentrate on the areas where the signal derivative is zero, ignoring the fast-changing areas.

    Hint: turning on a manual marker will give you a convenient way to visually check for minimum deflection. See figure 5.

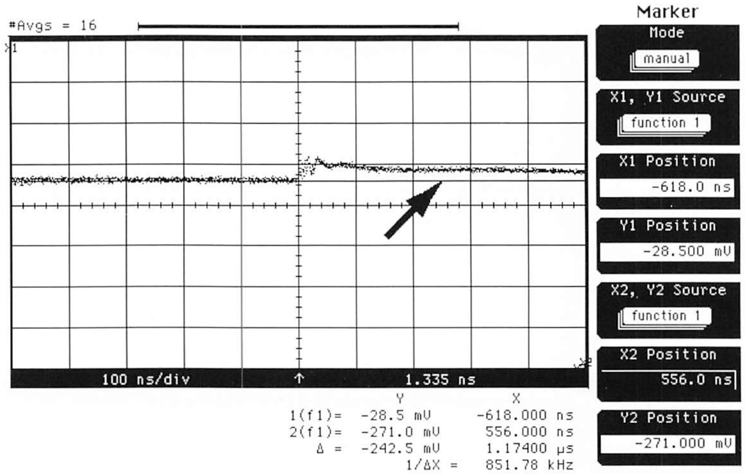


Figure 5. A voltage marker (arrow) can be used as an aid to visually matching the gains by adjusting the probe attenuation ratio for minimum vertical deflection.

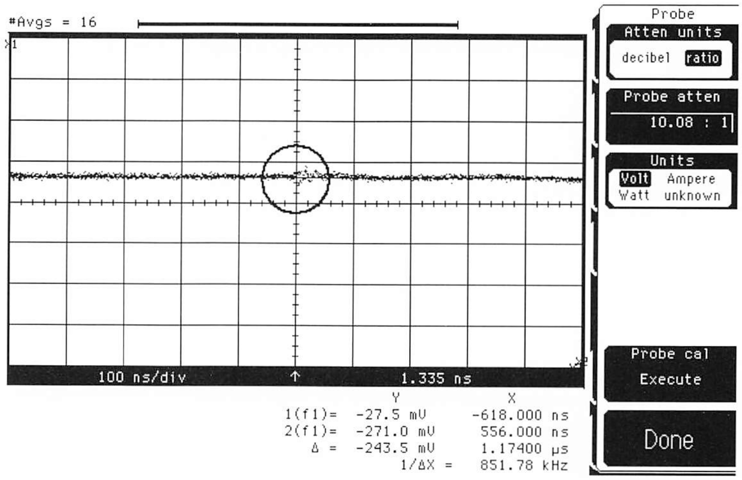


Figure 6. The probe attenuation ratio has now been adjusted to reduce the difference signal to a minimum, ignoring the fast-slewing portion (circled).

Making Measurements
Connect the probes

1. Connect the two 54701A probes to the two sides of the differential signal as shown in figure 7.

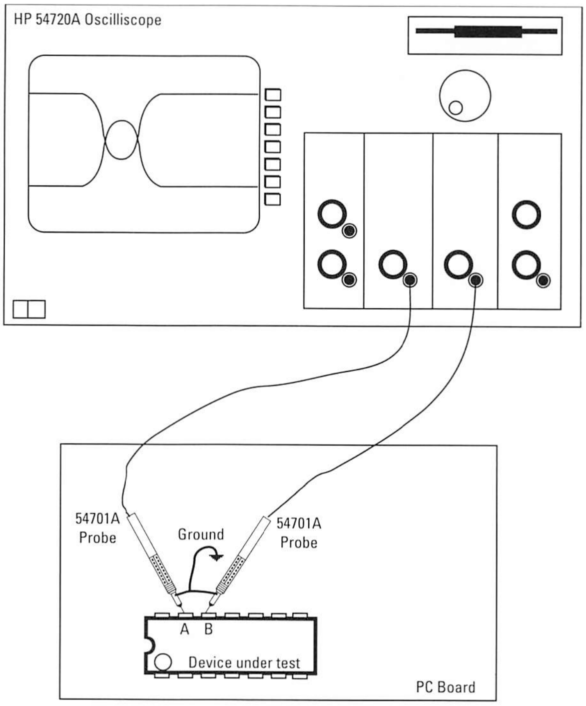


Figure 7. Points A and B are the true and complement sides of a differential ECL signal.

Note that it takes time for the signal to travel from one point to another along a conductor. The propagation velocity is equal to the speed of light in a vacuum divided by the dielectric constant of the insulator. For an FR4 epoxy-glass PC board, the delay is approximately 75 ps/cm. Therefore, you must be careful where you place the probe tips. Refer to figure 8.

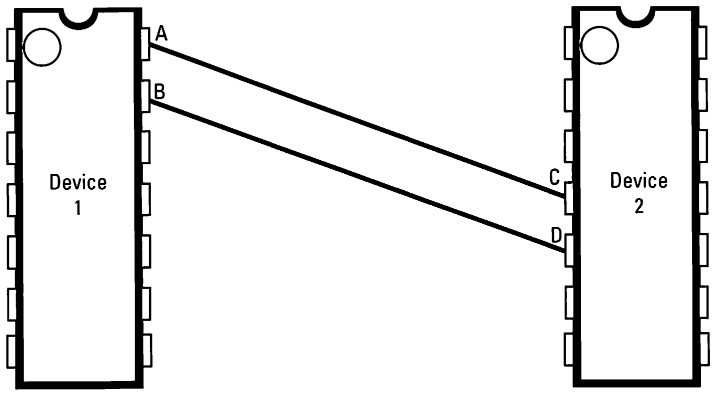


Figure 8A. A differential ECL signal propagates from points A and B at the ouput of device 1 to points C and D at the input of device 2. There will be a time delay between point A and point C, and likewise between point B and point D. For this reason, the probes must be connected at points A and B if you wish to observe the output of device 1, or at points C and D if you wish to observe the input of device 2.

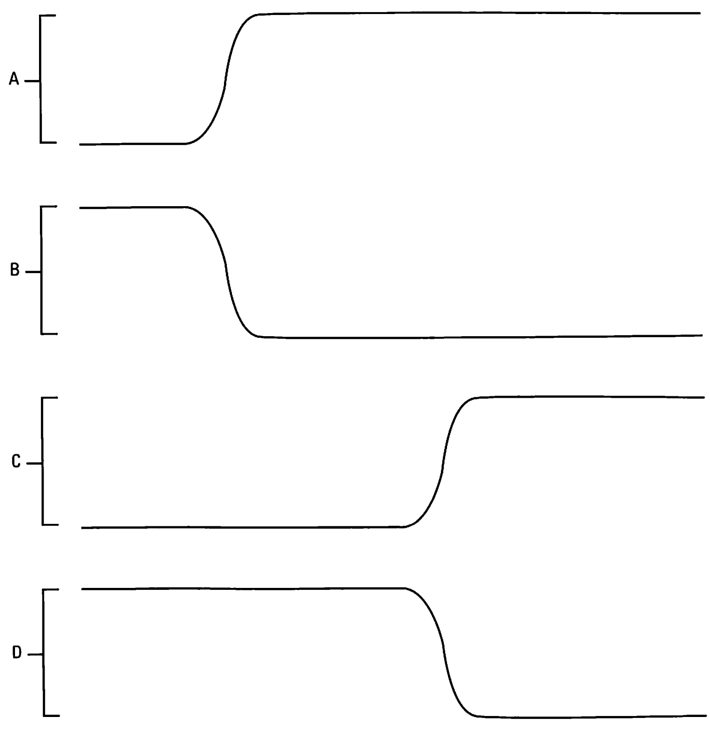


Figure 8B. The waveforms at points A, B, C, and D in figure 8A.

2. Connect the grounds of the two probes together with as short a lead as possible. Make just one ground connection to the device under test. See figure 9.

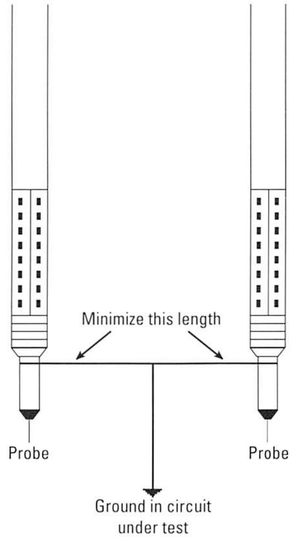


Figure 9. Connect the two probe grounds together. Connect them to ground at only one point in the circuit under test. Keep all ground connections as short as possible, especially the connection between the two probe grounds.

One way to do this is to use two of the probe grounding leads (HP part number 01123-61302, provided with the 54701A probe) and an alligator clip lead. Cut the alligator clip lead fairly short. Strip the insulation on the cut end. Attach both alligator clips of the probe grounding leads to the stripped end of the alligator clip lead. Attach the other ends of the probe clip leads to the probe ground sleeves. Attach the alligator clip lead to ground at a convenient point. See figure 10.

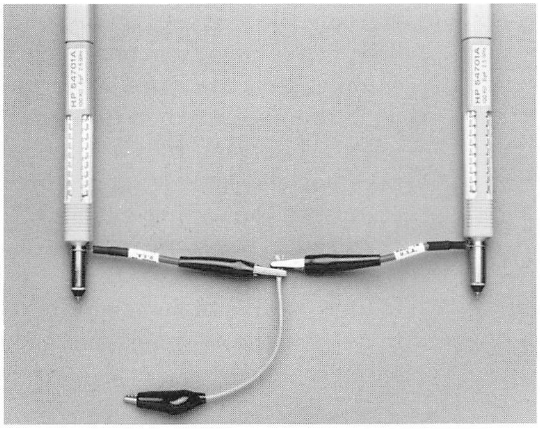


Figure 10. Recommended ground lead configuration and attachment.

Set up the scope to subtract the two channels

1. Set the vertical scale and offset on each channel so the signal is as large as possible but not clipped.

   The scale must be the same on each channel. For best accuracy, the channel gains must be matched for best common mode rejection at the same settings of scale and offset that will be used in the measurement. See "Match the probe gains for best CMRR," page 5.

2. Press the Math hardkey on the HP 54720A.

3. Press the Define function softkey.

4. Select "subtract" as the operator.

5. Assign the two channels as the operands.

6. Press the Done softkey.

7. Turn on the function display.

The difference signal will be displayed on the screen. You can turn off the display of the individual channels, if desired, to reduce the clutter on the display.

Making Differential Measurements on Noisy or Multi-valued Signals

If the signal has any noise on it and you want to measure the noise, or if the signal is an eye diagram or other signal that you expect to take on different values from one trigger to the next, then you should use real-time sampling. To select real-time sampling in the HP 54720A, use the Acquisition menu.

In the equivalent-time mode, deskewing the channels and then subtracting the samples is not valid except in the case where the signal does not change from one trigger to the next. This is because the samples that the scope subtracts in a particular time bucket may have been acquired on different trigger events and are therefore not valid to subtract. In real-time sampling mode, all the samples are taken on the same trigger. This makes it valid to subtract samples occupying the same time bucket after deskewing because they are acquired at the same instant.

If the signal is the same for all trigger occurrences, then it is valid to deskew the channels and subtract them in the equivalent-time sampling mode.

If you are using an oscilloscope that only has an equivalent-time sampling mode such as an HP 54120, you can use this general technique for making differential measurements. However, you must match the delays of the actual cables or probes if the signal is multi-valued. To do this, use the following procedure.

Hardware Deskew

1. Set the channel skews all to zero.

2. Insert a short piece of coaxial cable in series with one of the probes to add a fixed amount of delay.

   Use care to select a cable that is appropriate for the bandwidth needed. If you are using the HP 54006A 6-GHz resistive divider probe, you should use a cable which is rated up to at least 10 GHz. If you are using the HP 54701A active probe, the cable should be rated for operation up to at least 3 GHz.

3. Insert a variable coaxial delay line in series with the other probe. You may also need to insert a shorter piece of coaxial cable in series with the variable delay line to bring the adjustment range of the variable delay line into the correct range.

   Suppliers of variable delay lines (also known as phase shifters) are listed in table 1.

4. Connect both probes to the same source. A step with a fast rise time is needed such as an HP 8131A pulse generator.

5. Adjust the variable delay line until the rising edges on the two channels overlay as closely as possible on the display.

6. Use the waveform math feature to subtract the two channels and proceed as above.

Table 1. Suppliers of variable delay lines

Company name, address, and phone number	Model number
ARRA 15 Harold Court Bay Shore, NY 11706 516-231-8400	6426E
Microlab/FXR 10 Microlab Road Livingston, NJ 07039 201-992-7700	ST series SR series
Sage Laboratories 11 Huron Drive Natick, MA 01760-1314 508-653-0844	6708-2

An Example Measurement

Figures 11 and 12 illustrate a typical measurement on a differential ECL signal. Figure 11 shows the two signals displayed on the HP 54720A. Figure 12 shows the difference between the two sides, using the subtract function in the HP 54720A.

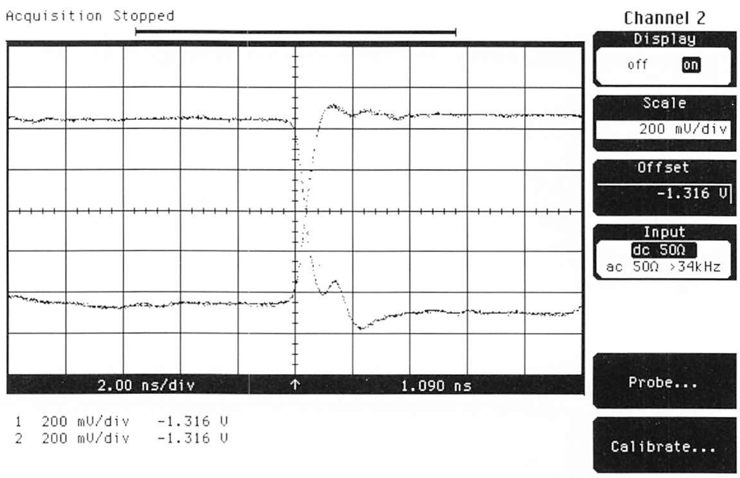


Figure 11. The signals on the two sides of a differential ECL output.

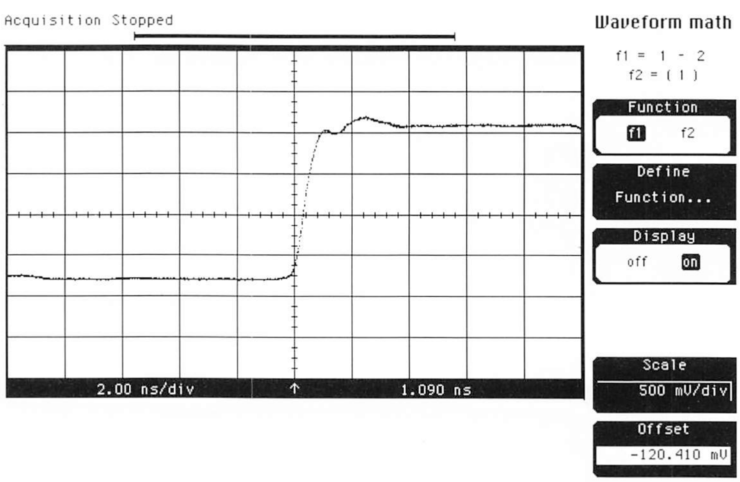


Figure 12. The same signals appearing in figure 11 are subtracted to view the differential mode signal.

Limitations

Scale Factor

When you use this technique to measure differential signals, the scale factor on each channel must be set so that the signal present on that channel is entirely on screen. This is because the subtraction is performed in firmware after the A/D conversion. If the signal exceeds the input dynamic range of the A/D converter on either channel, the subtraction is invalid.

Limit to Common Mode Rejection Ratio

The common mode rejection of this technique is limited by the resolution of the A/D converter. Therefore to achieve as much resolution as possible you should set the scale factor of the two channels to make the displayed signal as large as possible without exceeding the display area. The HP 54713A plug-in has continuously-variable hardware gain, so a signal of any amplitude can be optimally scaled to match the dynamic range of the A/D converters in the HP 54720A. Note: the scale factors on the two channels must be identical.

How about 1 MΩ or 10 MΩ probes?

For high-frequency measurements, the use of 1-MΩ or 10-MΩ divider probes is not recommended. With these probes there is too much uncertainty as to the gain at all frequencies. Any mismatch in the flatness of the two probes will lead to a reduction of common mode rejection as a function of frequency. For differential measurements with modest bandwidth requirements, a differential probe such as the HP 1141A will give much better results than two 1-MΩ or 10-MΩ probes.

No Differential Trigger

When you use this technique the scope can only be triggered on one of the two channels. Therefore the scope cannot trigger on the true difference signal. This is generally not a problem on signals such as differential ECL where the common mode signal is small compared to the differential signal.

Comparing the Two-Probe Technique to a Differential Probe

Differential probes, for example the HP 1141A, can be used for differential measurements up to 100 or 200 MHz. The advantages of the HP 1141A differential probe compared to the two-probe technique are:

- Higher common mode dynamic range
- Higher common mode rejection from dc up to approximately 50 MHz
- Does not require deskewing two probes and matching gains
- Lower resistive loading on the circuit under test
- Higher measurement sensitivity—the probe has a gain of one
- The scope can be triggered on the differential signal

The advantages of the two-probe method described in this application note compared to a differential probe are:

- Higher bandwidth
- Higher common-mode rejection at high frequencies
- Lower capacitive loading on the circuit under test

Bandwidth and Accuracy

The oscilloscope and probe must have sufficient bandwidth to measure the signals of interest or important information will be lost. Here are some handy rules to remember:

1. Bandwidth and rise time are inversely proportional as shown in the following equations:

$$\text{Bandwidth} \approx \frac{0.35}{\text{Rise Time}}$$

$$\text{Rise Time} \approx \frac{0.35}{\text{Bandwidth}}$$

2. The rise times of the oscilloscope and probe combine according to the following equation:

$$(\text{System rise time})^2 \approx (\text{Probe rise time})^2 + (\text{Oscilloscope rise time})^2$$

3. The measured rise time relates to the actual rise time and the oscilloscope and probe combined rise time as follows:

$$(\text{Measured rise time})^2 \approx (\text{Actual rise time})^2 + (\text{System rise time})^2$$

4. According to the approximation in rule (3), the accuracy of a rise time or pulse measurement relates to the ratio of actual signal rise time (or pulse width) to the system rise time as shown in the following table.

Table 2. Measurement error as a function of system rise time

Actual rise time or pulse width / System rise time	Error in rise time or pulse width measurement
3	5%
4	3%
5	2%
6	1.4%
7	1%

5. For rise time or pulse width measurement accuracy of less than 5%, the following table shows the bandwidth required and the recommended plug-in to use with the HP 54701A probe and HP 54720A oscilloscope.

Table 3. Recommended plug-in modules for a given rise time and bandwidth

Signal rise time	Bandwidth required	Recommended plug-in to use with HP 54720A oscilloscope and HP 54701A probe
800 ps	1.3 GHz	HP 54711A*
1 ns	1 GHz	HP 54721A or HP 54712A *
2 ns	500 MHz	HP 54713A

*Not recommended for real-time sampling. Use equivalent-time sampling to avoid aliasing.

For faster rise times, you can use either the HP 54006A resistive divider probe or the HP 54701A active probe with the HP 54121T oscilloscope. The table below shows the system bandwidth and the minimum rise time that can be measured to within 5% accuracy for these combinations.

Table 4. Probes to use for a given bandwidth and rise time

Probe used with HP 54121T	System bandwidth	Minimum recommended signal rise time
HP 54701A	2.5 GHz	400 ps
HP 54006A	6 GHz	170 ps

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