

Understanding Oscilloscope Bandwidth, Rise Time and Signal Fidelity



► Introduction

When an oscilloscope user chooses an oscilloscope for making critical measurements, banner specifications are often the only criterion used to make this choice. The top three oscilloscope banner specification categories are:

- Bandwidth
- Sample Rate
- Record Length

And of these banner specification categories, the number one asked for capability in an oscilloscope is bandwidth. After all, more bandwidth means higher performance, right? Well, not necessarily. This article will point out the pitfalls in this very simple assumption. Depending upon your expectation to see and analyze signals as they really are, more knowledge about the true performance of your oscilloscope will be needed.

BANDWIDTH – WHAT DOES THIS SPECIFICATION TELL US?

Bandwidth is a sine wave specification that simply defines the frequency at which the peak-to-peak amplitude of the sine wave on the screen is down by 3 dB from the actual sine wave amplitude. Figure 1 shows an idealized sine wave amplitude roll off error as the signal approaches the oscilloscope bandwidth frequency. At the rated bandwidth, the percent of error on screen is 29.3%!

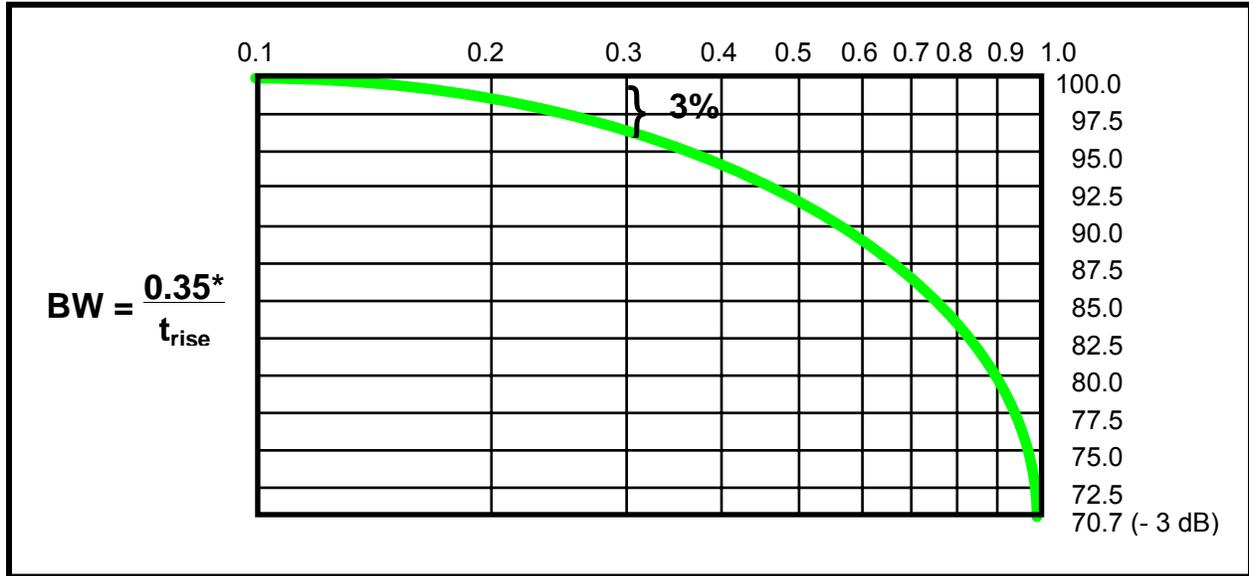


Figure 1. Oscilloscope Bandwidth vs. Frequency

If you want to make a 97% accurate measurement (actually a measurement that has only 3% error) you would want to have the sine wave input frequency be much less than the rated bandwidth of the oscilloscope. A general rule of thumb is to have an oscilloscope system that has 3 to 5 times the equivalent edge bandwidth (explained later in Figure 5) of the signal you intend to measure.

WHAT DOES BANDWIDTH NOT TELL US?

Most typical users choose an oscilloscope to display and measure complex signals, seen as a graph of signal amplitude over time. Bandwidth, the number one banner specification, is defined in the frequency domain, not the time domain. Complex signals, according to mathematics theory, can contain many spectral (sine wave) components, as shown in Figure 2.

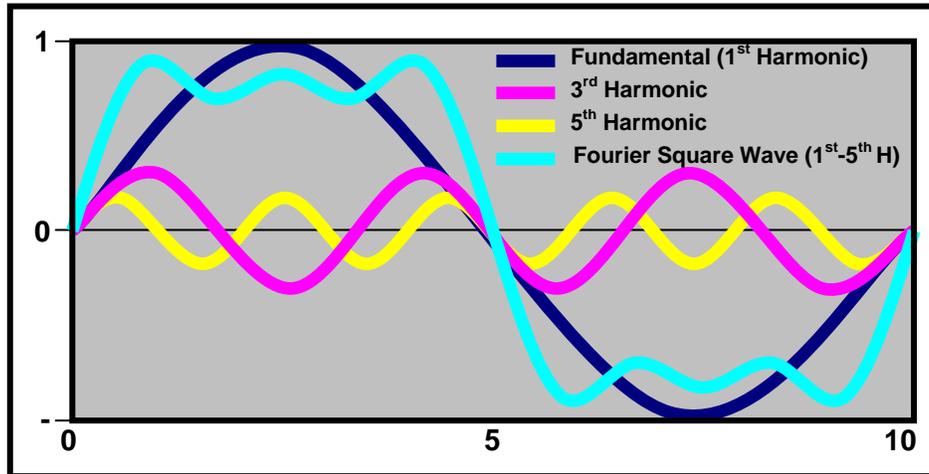


Figure 2. Digital Square Wave – Odd Fourier Sums

Spectrum analysis can tell us what these sine wave components are for a repeating signal. However, to fully characterize these components, we must know both the amplitude and phase of each of these sine wave components in the complex signal. Bandwidth tells us nothing about these details. We only know, for a sine wave, what the frequency is when the sine wave amplitude is down by 29.3%!

WHAT IS THE RELATIONSHIP BETWEEN BANDWIDTH AND RISE TIME?

Most people are interested in time measurements such as square wave rise time and fall time. Therefore, to estimate the oscilloscope system rise time from its specified bandwidth we must use a formula such as that shown below:

$$BW \times Tr = 0.35$$

$$0.35 / BW = Tr$$

This 0.35 relationship between bandwidth and rise time is based on a one-pole model for 10-90% rise time. The most commonly used model for a one-pole response is a resistor-capacitor (RC) low pass filter. By using this formula, it is easy to calculate Tr. However, the real world is not quite this simple.

Figure 3 is a table that illustrates the measurement system bandwidth requirements for various logic families when reasonable measurement accuracy is needed for rise time or other measurements. Keep in mind that all elements of your system will affect the rise time result on your oscilloscope display. These elements include your oscilloscope, probe, and signal source.

Logic Family	Typical Signal Rise Times	Calculated Signal Bandwidth = $\frac{0.35}{t_{rise}}$	Measurement Bandwidth for $\approx 3\%$ Rolloff Error
CMOS	500 ps	700 MHz	2.33 GHz
LV CMOS	200 ps	1.75 GHz	5.8 GHz
ECL	200 ps	1.75 GHz	5.8 GHz
GaAs	100 ps	3.5 GHz	11.6 GHz

Figure 3. Estimated Bandwidth Requirements for approximately 3% Rise Time Error

This table makes the assumption that the signal and the oscilloscope measurement system each has a one-pole roll off response characteristic. In reality, especially with today’s high-speed signals, this assumption is far from correct. For a maximum flat envelope delay response, the bandwidth times rise time constant of an oscilloscope can approach 0.45. And if spectral phase distortion is allowed, this constant can exceed 0.5.

So what does this really mean concerning the best oscilloscope to use? Two oscilloscopes that have the same bandwidth performance can have very different rise times! So, knowing the bandwidth of an oscilloscope will not reliably tell us its measurement rise time capability. A rise time specification that is calculated from bandwidth should be highly questioned. The only reliable way to know the rise and fall time response of an oscilloscope is to measure it with a step signal that is much faster than the oscilloscope!

WHAT IS STEP RESPONSE?

In reality, most oscilloscope users want an oscilloscope that has excellent overall step response. Bandwidth, as a specification, tells us next to nothing about how well an oscilloscope can reproduce a complex waveform shape. To verify step response performance, a very clean step generator is needed.

When an oscilloscope reproduces this clean (close to ideal) step signal on its screen, the displayed deviations are known as aberrations.

Figure 4 and Figure 5 show what step response aberrations and rise time might look like on an oscilloscope screen.

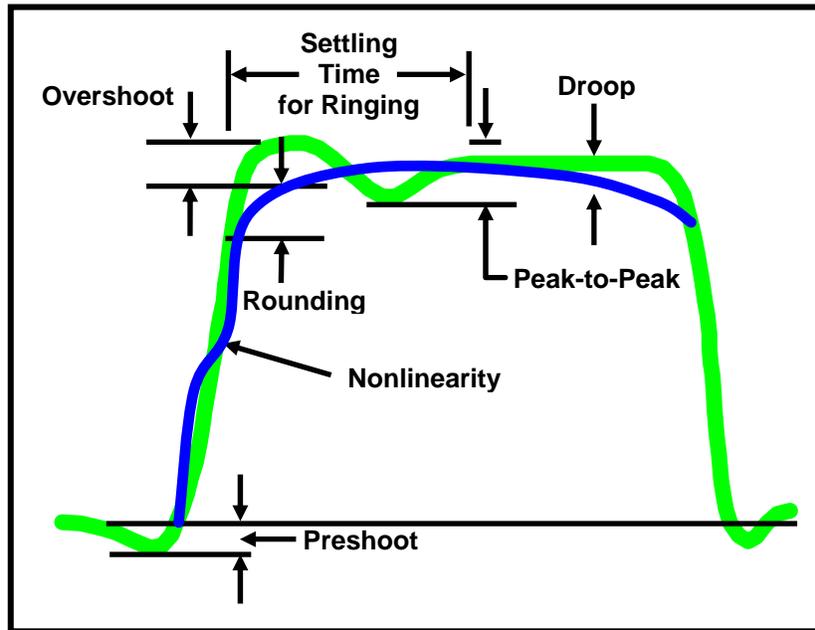


Figure 4. Step Response Aberrations

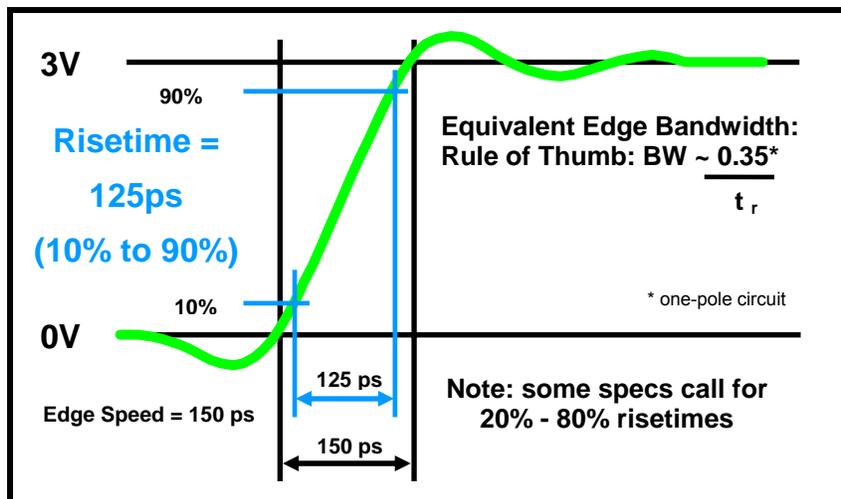


Figure 5. Step Response Rise Time

So how much deviation from an ideal step response are you willing to tolerate when using your oscilloscope? There can be four key contributing categories to these step response deviations:

- Base Oscilloscope Analog Performance
- Probing Effects
- Under Sample Alias Effects
- Digital Signal Processing Effects

WHAT DEFINES THE BASE ANALOG PERFORMANCE OF AN OSCILLOSCOPE?

True analog performance is defined by the analog oscilloscope circuitry leading up to the analog-to-digital (A/D) converter. This includes the vertical input attenuators, as well as the vertical amplifiers, position controls and trigger pick off circuitry in each channel of the oscilloscope. The following discussion will explain what you will need to consider in this circuitry when using your oscilloscope to look for signal details.

When you decide to “zoom” in on a detail of your waveform, you will quickly discover the limits of the traditional vertical position control. Each time you change the volts/div control to expand the trace, you must reposition the waveform. And when you wish to expand a portion of the waveform that is not close to the ground reference, the typical ± 12 divisions of vertical position range quickly limits the expansion. Also, when you reposition a vertically expanded trace, you may need to trigger on that detail. This requires that you also consider the range of your trigger level control. Figure 6 illustrates these analog limits.

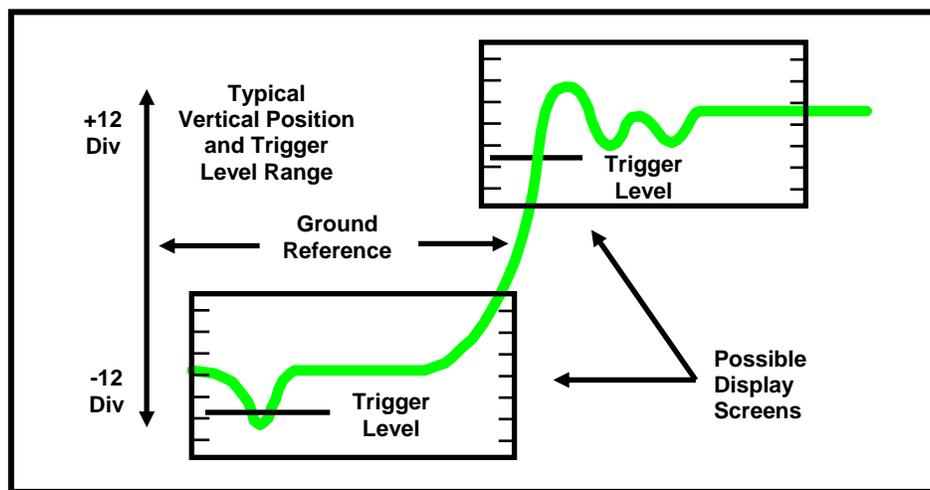


Figure 6. Dynamic Range for Vertical Position and Trigger Level

When you vertically reposition the trace, you also reposition the expansion reference, which is fixed at ground, as shown in Figure 7.

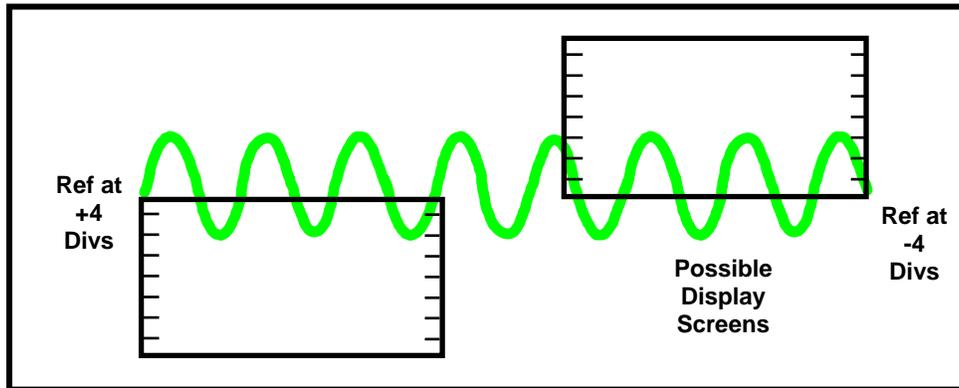


Figure 7. Vertical Position Moves the Volts/Div Zero Reference Point

If you want to “zoom” in on a waveform detail that is not at ground, consider specifying an offset control, illustrated in Figure 8.

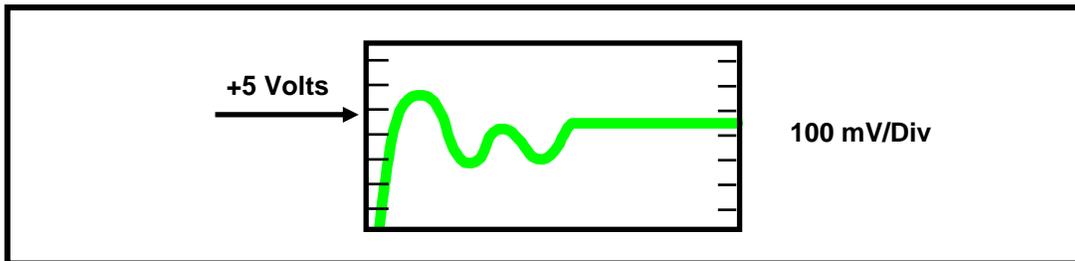


Figure 8. Vertical Offset Changes the Volts/Div Reference Point From Zero to Some Other Voltage

Vertical offset allows you to redefine the displayed reference for expansion. For example, if you want to zoom in on a waveform detail at the top of a pulse that is at +5 volts, simply set the offset control to +5 volts. Then change the volts/div to the needed sensitivity without the need to reposition the trace. Offset results in a tremendous increase in the vertical analog dynamic range of your oscilloscope.

One drawback to “zooming” in on vertical waveform details will be the overdrive recovery limit of your oscilloscope’s vertical system. When you drive a portion of your waveform off screen in order to expand on a particular detail, the vertical system will need to recover from that overdriven condition. A typical overdrive recovery specification could be “90% recovery in 10 nsec.” This would imply “99% recovery in

20 nsec.” Whatever your oscilloscope’s overdrive recovery performance might be, it will always be slower than the oscilloscope’s on screen rise time or fall time performance. Figure 9 illustrates this situation.

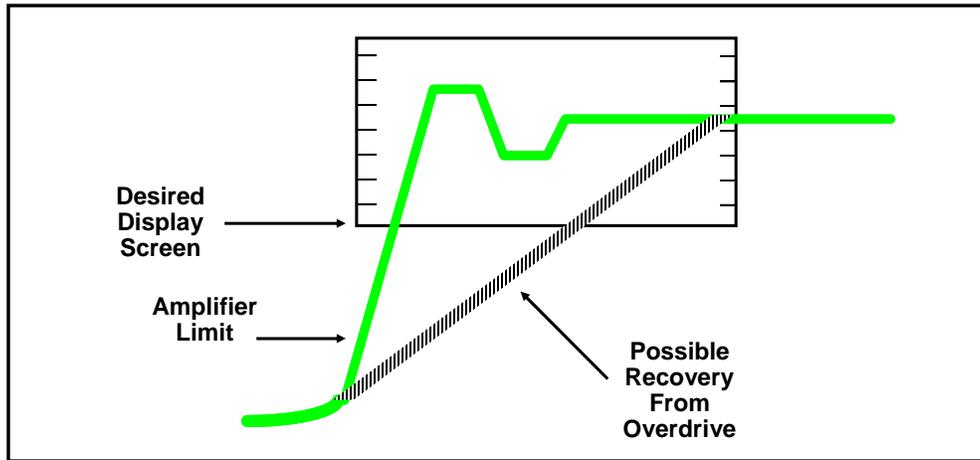


Figure 9. Overdrive Recovery Characteristics Can Cause High-speed Details to Disappear

True analog performance goes well beyond bandwidth. Step response aberrations, as well as rise time and fall time must be understood. Having the ability to zoom in on details requires both vertical position and offset controls that have adequate range for your applications. This implies that the oscilloscope vertical system also has adequate overdrive recovery characteristics for your measurement requirements.

And any time a part of the signal is taken out of the range of the analog-to-digital converter (as just described), digital signal processing of the signal can become more of a problem than a solution. This is true because the signal is no longer all available to the processing system. We will cover more on this topic at the end of this technical brief.

HOW CAN A PROBE AFFECT BANDWIDTH, RISE TIME AND STEP ABERRATIONS?

The load imposed on a high-speed circuit by a voltage probe can usually be represented by lumped inductance, capacitance, and resistance that the probe adds to the circuit-under-test. The resistance value is usually a function of the probe’s design. The capacitive and inductive elements arise from conditions such as probe tip geometry and ground lead length. The inductive element is the most variable impedance element depending on the addition of extra probe tip leads and ground leads. Added lead length on the signal tip is more likely to cause problems than added length on the ground lead.

The inductance of the probe's leads and circuit return combine with the probe's input and leads capacitance to create a series resonant circuit. This circuit can ring (resonate) at a frequency determined by the values of the total series L and C. As shown in Figure 10, the effect shows up as ringing on the rising edge of a pulse. For this example, a six-inch diameter ground loop, combined with 10 pF of capacitance from the typical 10X passive probe, will ring at about 50-70 MHz. A pulse with a 1 nanosecond rise time will have a bandwidth equivalent of 350 MHz, as defined by the one-pole model relationship between rise time and bandwidth discussed earlier. This pulse is more than fast enough to ring the 50-70 MHz resonant circuit in this example.

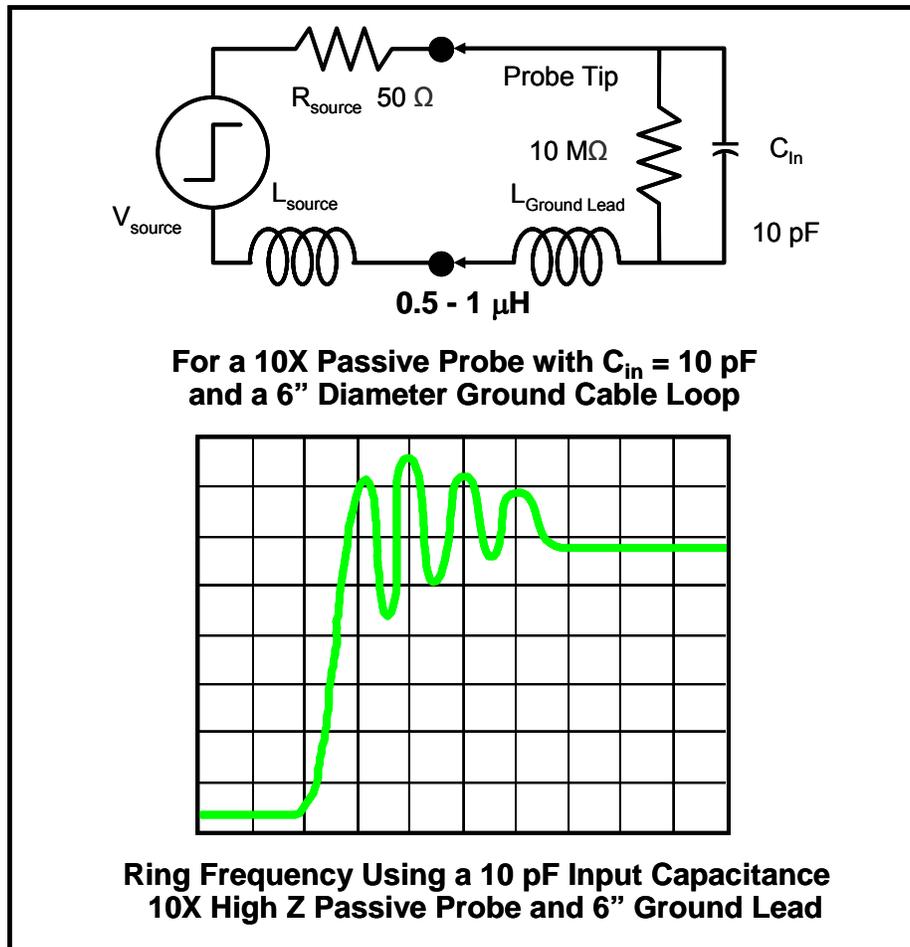


Figure 10. Source and Probe Inductance and Capacitance Causing 50-70 MHz Ring

In order to minimize the effects of inductive and capacitive loading from the probe, you must reduce L or C, preferably both. It is often not possible to reduce the probe leads and circuit return paths enough to resolve your measurement needs. For this situation, the only remaining answer is to reduce the probe's capacitance. This means that you will need to consider using an active probe that has both high input resistance and very low input capacitance.

$$\text{Resonant Frequency} = \frac{1}{2\pi\sqrt{LC}}$$

Figure 11. Formula for Calculating Resonance

In practice, the resonant frequency of the probe leads should be >5 times the signal's equivalent edge bandwidth, based on rise and/or fall times as previously described. Each inch of added lead length will add about 20 nanoHenries of inductance and between 1 and 2 picofarads of capacitance. This gives you general guidelines for determining the inductance (probe-connection loop) and capacitance of your probing situation.

There will always be a characteristic resonant frequency in any probe tip system based on the probe connection inductance and capacitance. The important thing is to keep this resonant frequency out of the range of the frequencies of interest, defined by the equivalent edge bandwidth of the signal to be measured (see Figure 5).

High-speed circuits today are really sending signals on transmission lines, often with impedance discontinuities, as shown in Figure 12.

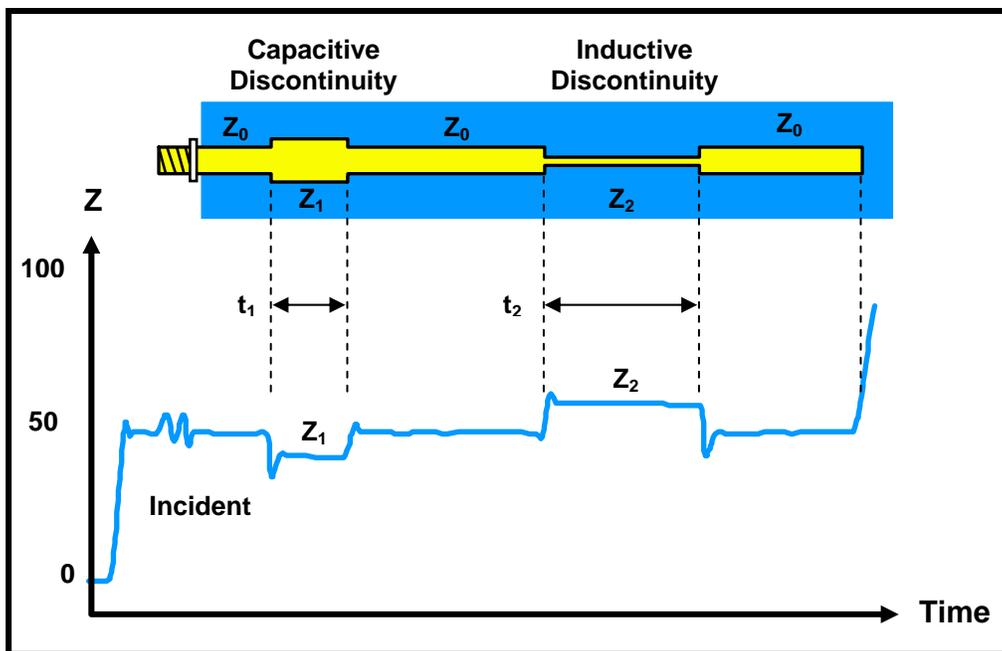


Figure 12. Signal Reflections along a Transmission Line From Inductive and Capacitive Discontinuities

Probes can add to these reflections, as a transmission line stub load, as shown in Figure 13.

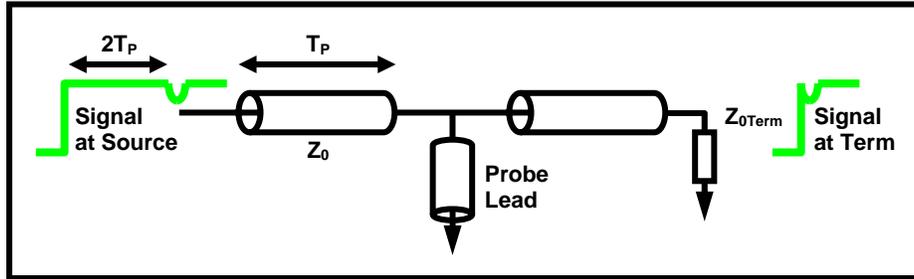


Figure 13. Probe Stub Load On a Transmission Line

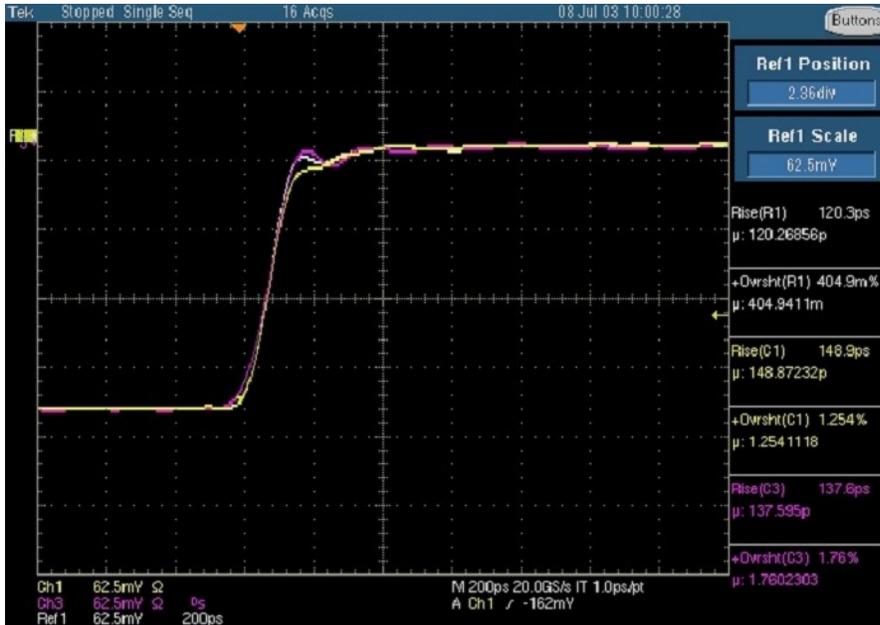
On a typical circuit board made of FR4 material, a signal will travel about six inches in one nanosecond. Impedance discontinuities will appear at the source and at the termination as reverse and forward reflections, traveling at this speed, as shown in Figure 13. So, whether you consider the probe as a lumped element RLC load, or as a transmission line element load, there will be an effect. The question is, how much can you afford to live with?

Figure 15 and 16 show what can happen when you add just 0.4 inches of square pin adapter to the leads of a high-speed differential active probe, connected to a 100 psec rise time signal on a 50 ohm transmission line. Figure 14 shows the probe tips without the adapter as used for the Figure 15 waveform displays. Also shown is the square pin probe adapter used for the Figure 16 waveform displays.



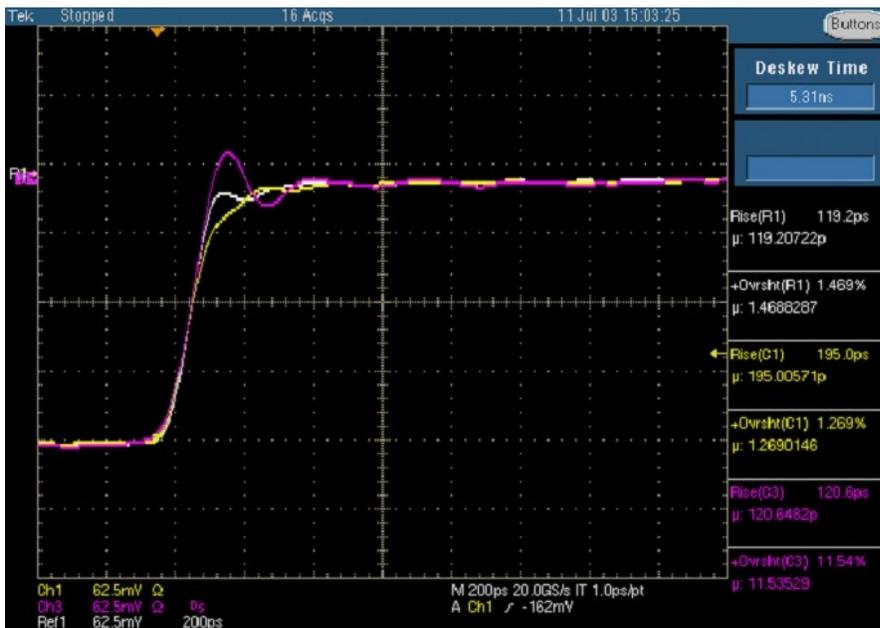
Figure 14. P7350 Differential Active Probe Plus Square Pin Adapter

Needless to say, it takes very little to cause large probe load distortions when measuring today's typical high-speed signals. And there are those who suggest that you can fix the ring distortions by adding series damping resistance at the probe tip. This can reduce the displayed ringing and actual signal loading effects, at the expense of increased measured rise time on the oscilloscope screen!



Unloaded Reference
 Loaded Signal
 Probe Response

Figure 15. TDS6604 and P7350 Differential Active Probe, Used to Measure 100 psec Rise Time Pulse With No Tip Adapters



Unloaded Reference
 Loaded Signal
 Probe Response

Figure 16. TDS6604 and P7350 Differential Active Probe, Used to Measure 100 psec Rise Time Pulse With Square Pin Adapter

As you can see, increased probe lead length can have significant and different effects on both the signal being tested and the probed waveform response.

WHAT ARE UNDER SAMPLE ALIAS EFFECTS?

For a complex waveform, the spectral sine waves that exist in the waveform can be determined with a spectrum analyzer, or a Fast Fourier Transform (FFT) of the waveform. Nyquist Theory states that, for a signal to be properly digitized, it needs to be sampled more than twice for each and every spectral sine wave cycle that is in the waveform. If the fastest sine wave in your signal is not sampled faster than this two times rate, then Nyquist Theory is violated and the signal will be reconstructed in a false way (aliased) that cannot be corrected. Figure 17 shows how under sampling can cause false waveform reconstruction.

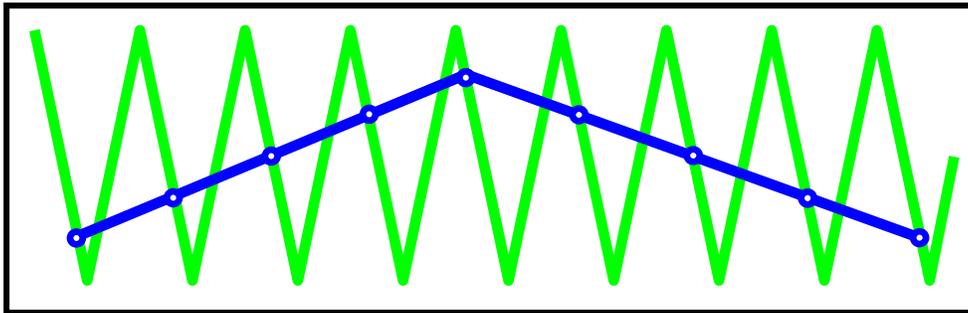


Figure 17. Under Sample Aliasing

If the signal present on the display seems to have an appearance of being not triggered, even though the trigger light is solidly lit, then under sampling is very likely to be the problem. If this is suspected, turn the sec/div control to a faster speed and you should eventually see a stable triggered display. This can be true for a repeating waveform. For single-shot conditions, it is not possible to have a hint about this type of aliasing (false waveform reconstruction) without some real initial knowledge about the waveform. The shape of a repeating waveform can appear to be correct, but can have the wrong timing. Or, the shape of fast moving waveform details can be incorrect, due to under sampling.

Perceptual aliasing is where your eyes can really be fooled when looking at a displayed waveform, even though you have satisfied Nyquist Theory. This means that you have more than two samples for every spectral sine wave component in your waveform, as previously described. Figure 18 shows this type of dots display.

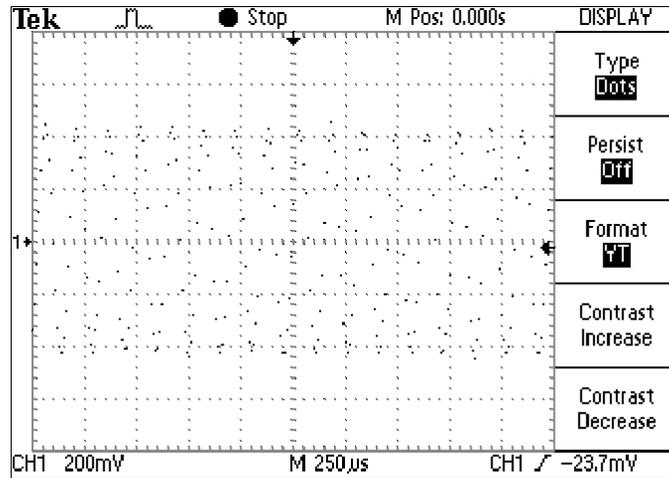


Figure 18. Dot Mode Does Not Show True Waveform Shape

Perceptual aliasing can appear as patterns of dots. The real waveform, of course, is still not visible. This type of displayed aliasing, or false waveform reproduction, can be significantly improved by joining the dots with various types of lines. This process of joining the dots is called interpolation, as shown in Figure 19, using the same dots used in Figure 18.

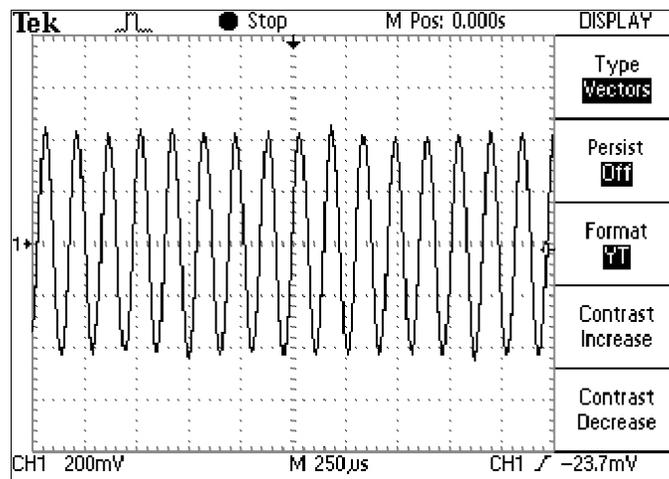


Figure 19. Vector Mode Improves Perceptual Aliasing

In order to truly remove the effects of perceptual aliasing, we must use the digital filter from Nyquist Theory, called $\text{sinc}(x)/x$. This mathematical filter allows truly correct intermediate points to be calculated between real samples on a waveform, provided that no “actual aliasing” is present. This means that more than 2 samples exist for each and every spectral (sine wave component) cycle in the signal that reaches the oscilloscope analog-to-digital converter.

So what will $\text{sine}(x)/x$ do to a step response that is under sampled? In Figure 20, the top waveform (R1) is not under sampled, and is displayed correctly with $\text{sine}(x)/x$ interpolation. The middle waveform (R2) is under sampled, with $\text{sine}(x)/x$ interpolation used for the display. The bottom waveform (1) is under sampled, with linear interpolation (straight lines between acquisition samples) used for the display.

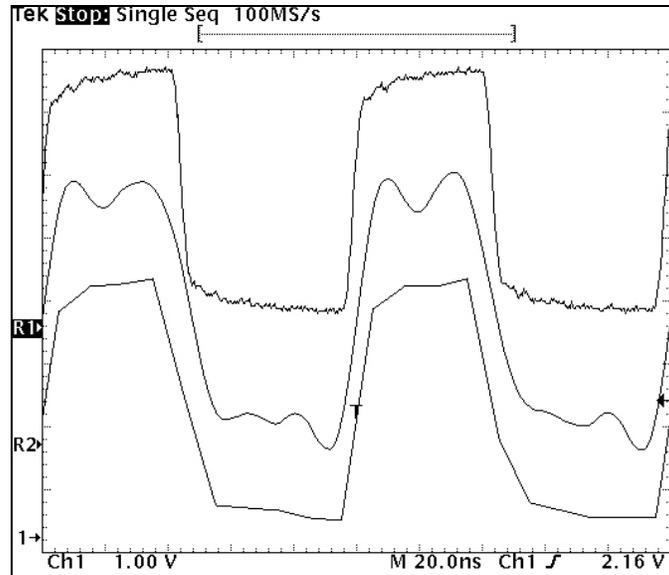


Figure 20. Under Sampling Can Produce Ring Aliasing When Using $\text{sine}(x)/x$ Interpolation

As you can see, under sampling combined with interpolation can give you very misleading information about a waveform. So be careful about your choice of sample rate and display interpolation to ensure the best measurement signal fidelity for your signals.

WHAT CAN DIGITAL SIGNAL PROCESSING DO TO RISE TIME, BANDWIDTH AND SIGNAL FIDELITY?

In reality, interpolation between real samples is a form of Digital Signal Processing (DSP). Processing waveforms can serve many purposes, including the following:

- Bandwidth Enhancement
- Rise Time Improvement
- Gain and Wave Shape Calibration
- Spectral Magnitude and Phase Correction
- Optical Reference Receiver Normalization
- Jitter Analysis of Waveform Deviations and Anomalies

In Figure 21, the blue trace is the uncorrected waveform through a less than perfect vertical amplifier system on an oscilloscope. The red trace shows DSP correction of shape, as well as enhanced bandwidth and improved rise time.

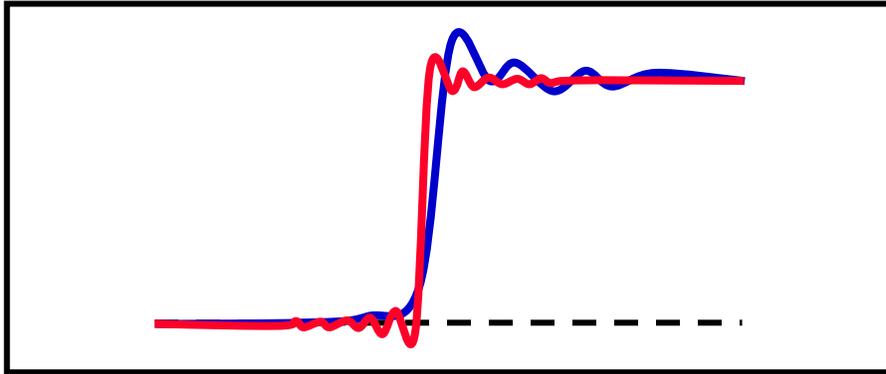


Figure 21. DSP Enhanced Shape, Rise Time and Bandwidth

A DSP filter can be used to improve the pass band magnitude and phase response of an oscilloscope acquisition channel. This filter can extend the bandwidth, flatten the oscilloscope channel frequency response, improve phase linearity, and provide a better match between channels. Fourier Series DSP filtering is most commonly used for bandwidth and rise time improvement.

When enhancing the rise time of a fast rise step, the Fourier Series DSP converges to the mid point of the step. On both sides of the step, the series will oscillate. The height of the peaks of the oscillation decreases away from the step, but the heights of peak1, peak2, etc. remain the same as the number of terms summed increases, making the amplitude and shape of the ring the same but at a higher frequency. The peak overshoot of each ring has a constant height (=18% of the step) and moves towards the step edge as the number of terms increases. This effect is referred to as the Gibbs Phenomenon.

So, according to Gibbs Phenomenon, pre and post ringing will occur on the step edge, when enhancing bandwidth to the limit with Fourier math. This is shown in Figure 21, where the oscilloscope channel response is low pass and linear in phase. The amount of Gibbs Phenomenon ringing will depend on the amount of rise time and bandwidth improvement being implemented with the DSP, as well as the speed of the signal being measured.

In order for DSP bandwidth enhancement to work consistently as described here, two conditions must be met. First, the sample rate must be kept high enough to ensure that no spectral frequency component at or above the Nyquist rate (half the sample rate) gets through to the oscilloscope's analog-to-digital

converter. If this condition is not met, under sampling will occur, and DSP will very likely destroy the integrity of the displayed waveform. Second, the total waveform must be kept within the range of the analog-to-digital converter. If you choose to zoom in on a detail of the waveform, and subsequently drive another part of the signal vertically off screen, digital signal processing is very likely to cause unwanted distortions.

SUMMARY

Bandwidth, as a banner specification, tells you very little about how well your oscilloscope will reproduce the true nature of your waveform. Step response rise time, fall time, and aberrations will tell you much more about the true fidelity of your measurement system. And when you want to zoom in on waveform details, remember that vertical offset and trigger level range, along with good overdrive recovery capability, will allow you to see these details as you expect. And don't forget probe loading effects, especially from signal tip and ground lead adapters.

Sample rate is another top banner specification. When you have the right amount of sample rate, combined with the correct interpolation between acquired samples, plus proper trigger-to-sample time correction, you can be less concerned about under sample aliasing effects. And make sure that digital signal processing enhancement of bandwidth and rise time, when used, delivers to you the signal fidelity that you expect.