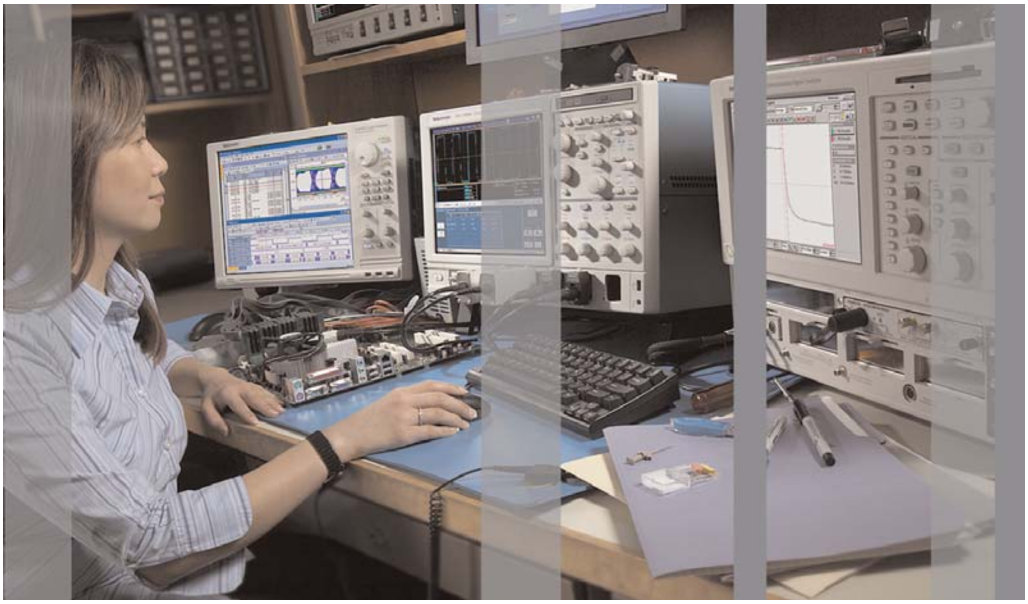
Technical Brief



# 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.

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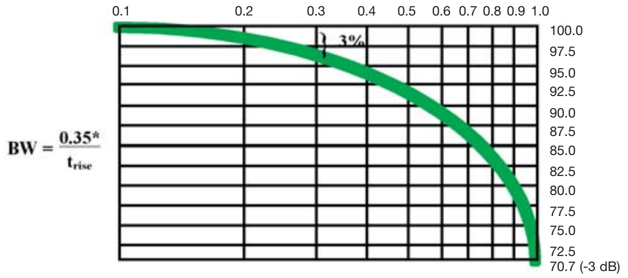

**Figure 1.** Oscilloscope Bandwidth vs. Frequency.

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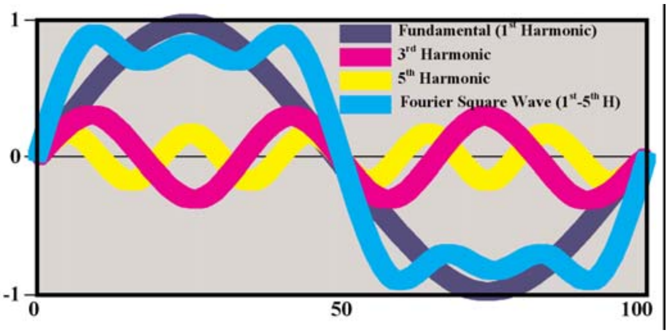


**Figure 2.** Digital Square Wave – Odd Fourier Sums.

# Bandwidth – What Does This Specification Tell Us?

Analog bandwidth is a measurement specification that simply defines the frequency at which the measured amplitude of a sinewave is 3 dB lower than the actual sinewave amplitude (see IEEE-1057). Figure 1 shows an idealized amplitude roll off error as a sinewave signal approaches the specified bandwidth frequency of a measurement device having a first order or single pole Gaussian response. At the rated bandwidth, the measurement error approaches 30%!

If you want to make a measurement on a sinewave that has only 3% error, you would only want to measure sinewaves much lower in frequency than the rated bandwidth of the oscilloscope, about 0.3 times the rated instrument bandwidth. Because most signals are more complex than sinewaves, it is a general rule of thumb is use a measurement device, like an oscilloscope, that has 5 times the bandwidth of the signal you intend to measure (explained later and shown in Figure 5).

# What Does Bandwidth Not Tell Us?

Most typical users choose an oscilloscope to display and measure complex electrical and optical signals, seen on the instrument display as a graph of signal amplitude versus time. Analog Bandwidth, a key oscilloscope specification, is defined by necessity in the frequency domain, not the time domain. Complex signals, according to sampling theory, will contain many spectral components (e.g., multi-tones that contain several discrete but harmonically related sinewave components), as shown in Figure 2.

Using spectral analysis, we can learn what these components are for a sampled signal. However, to fully characterize these components, we must know both the accurate amplitude and phase of each of these components making up the complex signal. In this case, the bandwidth specification tells us almost nothing about how the instrument will capture these details. From a bandwidth measurement alone, we only know that for a sinewave input, the measurement error approaches 30% at the specified bandwidth.

## What is the Relationship Between Bandwidth and Rise Time?

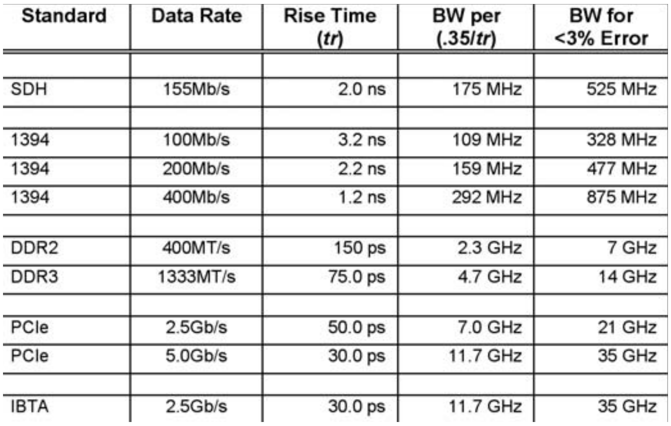
Beyond general purpose signal analysis, most engineers are also interested in time measurements such as a square wave rise time and fall time. Therefore, to estimate the oscilloscope system rise time from its specified bandwidth we can use an equation such as:

$$t_r = \frac{0.35}{BW}$$

This 0.35 factor between bandwidth and rise time is based on a simple 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 $T_r$. However, the real world is often not quite this simple.

Figure 3 is a table that illustrates the measurement system bandwidth suggestions for various types of common signaling standards when reasonable measurement accuracy is needed for rise time or other measurements. Keep in mind that many elements of your instrumentation system will affect the rise time result shown on your oscilloscope display. These elements include your signal source, probe, and oscilloscope.

Figure 3 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.



| Standard | Data Rate | Rise Time (*tr*) | BW per (.35/*tr*) | BW for <3% Error |
|---|---|---|---|---|
| | | | | |
| SDH | 155Mb/s | 2.0 ns | 175 MHz | 525 MHz |
| | | | | |
| 1394 | 100Mb/s | 3.2 ns | 109 MHz | 328 MHz |
| 1394 | 200Mb/s | 2.2 ns | 159 MHz | 477 MHz |
| 1394 | 400Mb/s | 1.2 ns | 292 MHz | 875 MHz |
| | | | | |
| DDR2 | 400MT/s | 150 ps | 2.3 GHz | 7 GHz |
| DDR3 | 1333MT/s | 75.0 ps | 4.7 GHz | 14 GHz |
| | | | | |
| PCIe | 2.5Gb/s | 50.0 ps | 7.0 GHz | 21 GHz |
| PCIe | 5.0Gb/s | 30.0 ps | 11.7 GHz | 35 GHz |
| | | | | |
| IBTA | 2.5Gb/s | 30.0 ps | 11.7 GHz | 35 GHz |

**Figure 3.** Bandwidth requirements for various high speed standards.

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, amplitude and phase response! So, knowing only the bandwidth of an oscilloscope will not reliably tell us its measurement capability or its ability to accurately capture complex signals like high speed serial data streams. Also, instruments that specify rise time as 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 an ideal step signal that is much faster than the oscilloscope!

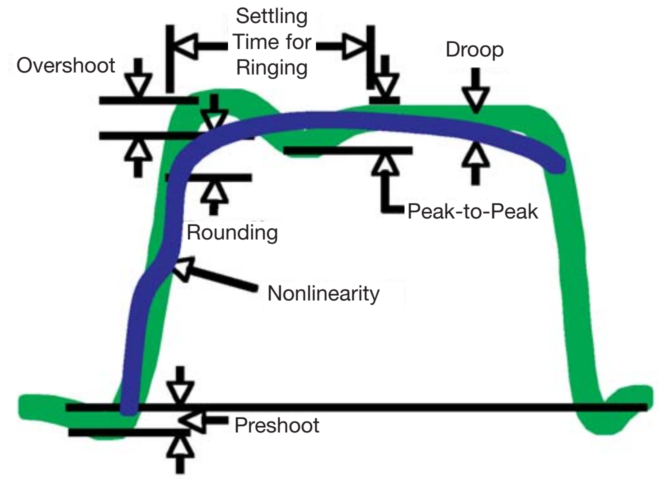


**Figure 4.** Step Response Aberrations.

## 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.

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

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 suble signal integrity details.

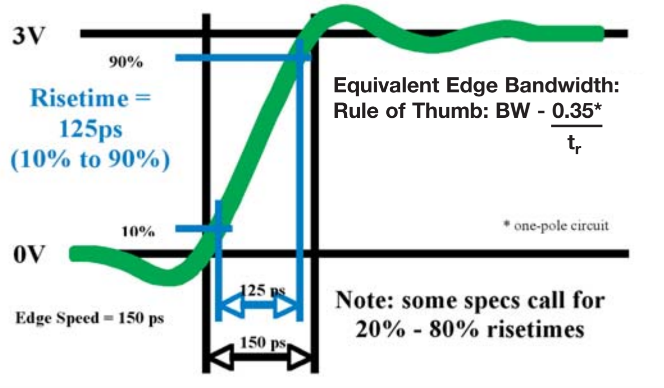


**Figure 5.** Step Response Rise Time.

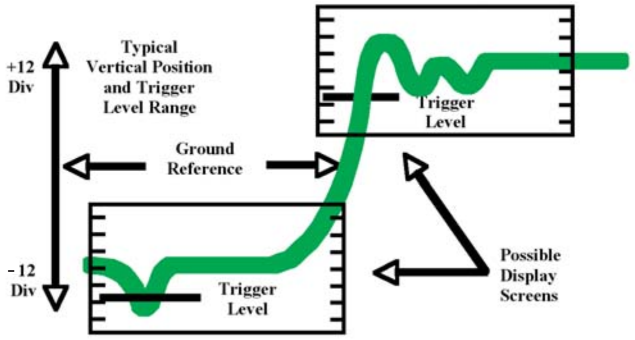


**Figure 6.** Dynamic range for vertical position and trigger level.

When you decide to explore a detail of your waveform, you will likely discover the limits of the traditional vertical position control quite quickly. 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 or zoom range you can use. Also, when you reposition a vertically expanded trace, you may also need to retain a trigger point or timing reference on that detail so that it remains on-screen. This requires that you also consider the range of your trigger level control. Figure 6 illustrates these analog limits.

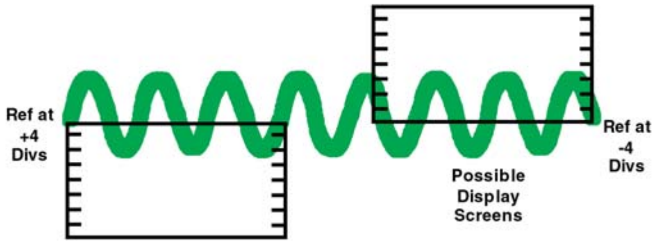


**Figure 7.** Vertical position moves the volts/div zero reference point.

**Figure 8.** Vertical offset changes the volts/div reference point from zero to some other voltage.

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

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

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 amplifiers and acquisition 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 1 nsec.” This would imply “99% recovery in 2 nsec.” On current models of Tektronix DPO/DSA Series oscilloscopes, overdrive recovery can be as low as 100ps for a 15 division overdrive.

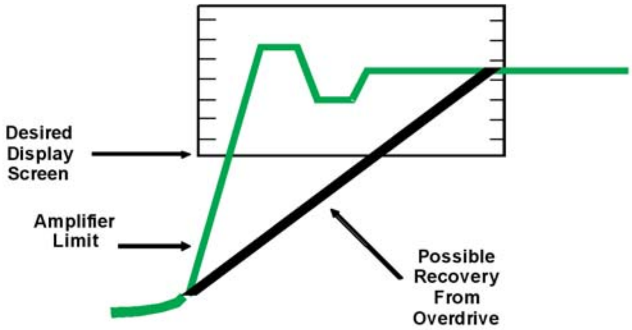


**Figure 9.** Overdrive recovery characteristics can cause high-speed details to disappear.

True analog performance goes well beyond bandwidth. Bandwidth, step response aberrations which affect in-band flatness and phase-response, 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, and having the ability to disable DSP is crucial to accurately evaluating regions of a waveform using the techniques mentioned above. This is true because the entire signal is no longer available to the processing system and DSP artifacts can swamp subtle signal features. We will cover more on this topic at the end of this technical brief.

## How Can a Probe Affect Bandwidth and Rise Time?

If you solder in a resistor, a capacitor, or even a piece of wire to a circuit, would you expect these components to affect the signals in that part of the circuit? Of course, you would. These components affect signal amplitude, slow down a signal, and influence signal shape. Likewise, every oscilloscope probe has some capacitance. Every oscilloscope probe has a resistance value. Every oscilloscope probe is going to affect the signals at the measurement point. It’s not a matter of if the probe will change the signal; it’s a matter of how much.

An ideal probe would capture any signal with perfect fidelity and would be non-invasive to the circuit under test. The requirements for the probe designer seem clear: extremely high bandwidth, broad dynamic range, and don’t affect the signal under test. We’ll consider the following topics and their impact on bandwidth, rise times, and the step response.

- Different Requirements. Different Probes.
- Probe Bandwidth and Rise Time
- Short Leads & Selecting the Right Accessories

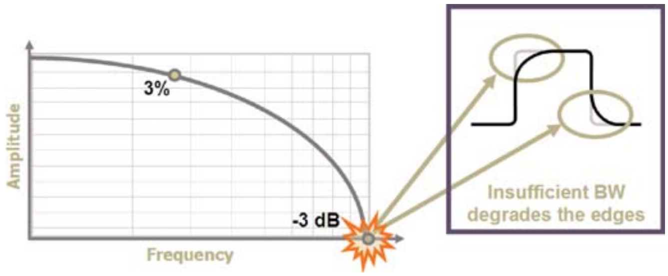


**Figure 10.** Frequency vs. Amplitude Bandwidth Plot.

### Different Requirements. Different Probes.

Probes are used in many different environments and are used in testing to numerous industry standards. For example, measuring high voltage in power applications requires adherence to safety certification standards. This type of measurement requires mechanically rugged probes with very large dynamic range, but these probes do not require high bandwidth. On the other hand, applications such as modern serial standards require measurement tools that use precision parts that are high bandwidth and have a low dynamic range.

It is important to realize that oscilloscope probes are designed for target markets that influence the probe’s design requirements. For varying measurement environments, probes have varying bandwidth capabilities. When determining the right probe for your measurement, make sure the probe has enough bandwidth. How much is enough? Let’s take a look.

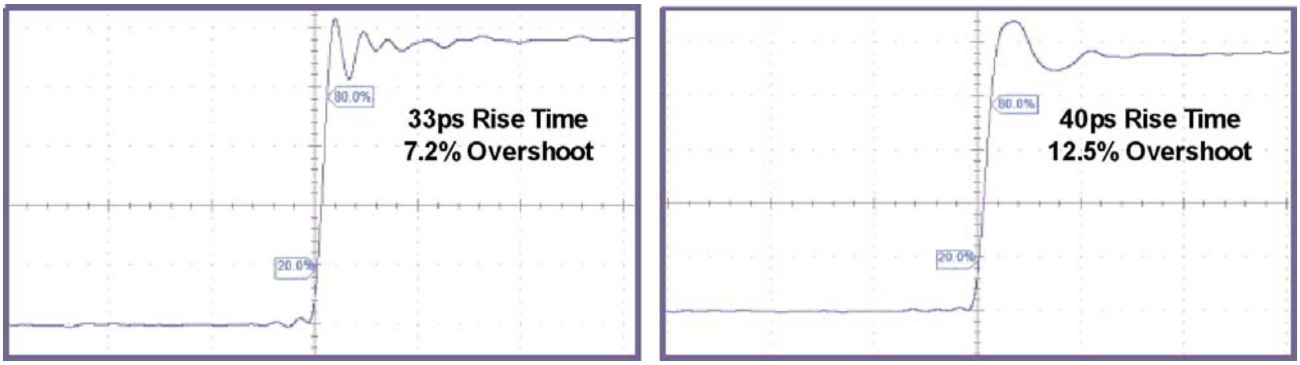


**Figure 11.** Keep Signal Leads Short.

## Probe Bandwidth and Rise Time

### Bandwidth

Bandwidth is the range of frequencies that an oscilloscope probe is designed for. For example, a 100 MHz oscilloscope probe is specified for measurements on all frequencies up to 100 MHz. However, the probe’s ability to capture signals changes across the specified frequency range. In fact, every probe manufacturer assumes that at the maximum specified bandwidth, the probe’s frequency response is down 3 dB. At frequencies beyond the 3 dB point, signal amplitudes are overly attenuated and measurement results may be unpredictable.

A general rule for accurate amplitude measurements is the bandwidth of the measurement system should be three to five times greater than the frequency of the measured waveform. This recommendation ensures adequate bandwidth for the higher-frequency components of non-sinusoidal waveforms, such as square waves. For example, a measurement system with 300 to 500 MHz bandwidth is suggested to capture the fifth harmonic of a 100 MHz square wave.

Consider the bandwidth plot in Figure 1. As the frequency increases, the amplitude of the signal decreases. As previously mentioned, probe manufacturers specify bandwidth out to the 3 dB point where amplitude losses have not significantly affected the test signal. At 3 dB down, the noticeable signal changes occur at the rising and falling edges where the corners of the square wave are rounded as the high frequency portion of the signal is attenuated. By selecting a probe that is three to five times faster than the signal under test, the amplitude error is considerably reduced from 30% at 3 dB to approximately 3%.

### Rise Time

Bandwidth describes frequency domain characterization but does not provide the complete picture of how the probe and scope will reproduce a complex waveform shape over time. To get the full story, the step response is essential in obtaining the time domain characterization. This characterization is provided through the probe’s rise time value where rise time is obtained by evaluating the response of a system to a step input that is faster than the capabilities of the test system. The general rule for evaluating the probe’s rise time capabilities is the probe’s rise time should be three to five times faster than the rise time of the signal under test.

## Short Leads & Selecting the Right Accessories

### Keep Signal Leads and Ground Leads Short

When a probe is attached to a measurement point, it will induce a load on the circuit. The capacitive and inductive elements typically come from the probe tip geometry and wire lengths. The inductive element is likely to have variation due to the addition of different probe tip accessories and varying wire lengths for signal and ground leads.

At times, connecting wire leads to the test point may be challenging. Users may compensate for this connectivity problem by making the signal or ground wires too long. As shown in Figure 11, lengthening the signal leads on a P7500 probe influences the measurement. The plot on the left has shorter leads whereas the plot on the right has much longer signal wires. The rise time and overshoot values change due to wire length.

### Selecting the Right Accessories

Oscilloscope probes are typically equipped with a number of different probe tip accessories. The different accessories are included with the probe to support the various design activities such as validation, debug, compliance testing, etc. Additionally, some probes are equipped with solder down solutions to enable a solid, hands-free connection.

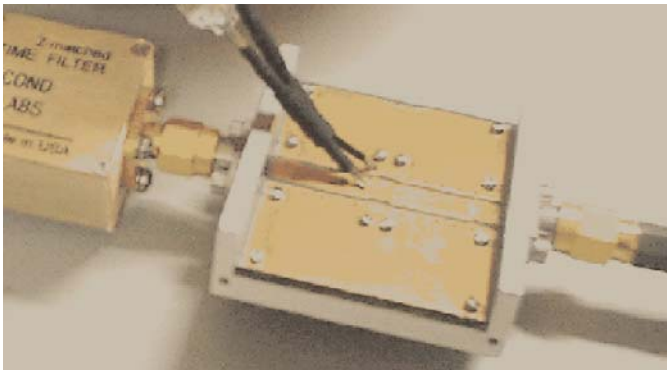


**Figure 12.** Make sure you understand how the probe tip accessory will affect your measurement.

Users should be aware that different probe accessory tips may have different measurement results. In an effort to make the connectivity to the device under test more convenient, some test leads have clips, some leads are longer, and some probe connectors have square pin sockets. Consider the connection in Figure 12. The probe in this picture has 1” signal and ground leads. Obviously, these longer leads will be more inductive and will cause effects such as ringing, aberrations or overshoot. The point is that there are a wide variety of connection methods and these varying methods may cause varying measurement results. Probe manufacturers will typically specify how the probe tip accessory will influence the measurement.

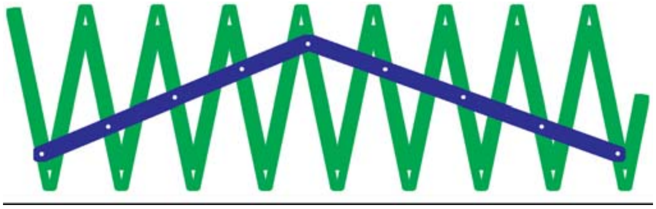


**Figure 13.** Under Sample Aliasing.

## 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 13 shows how under sampling can cause false waveform reconstruction.

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.

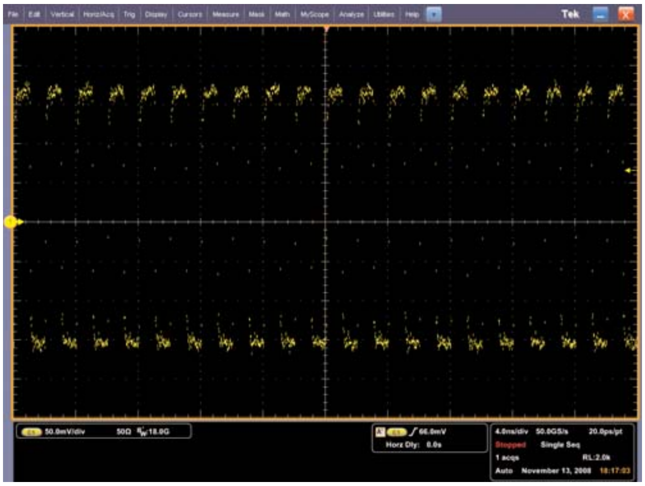
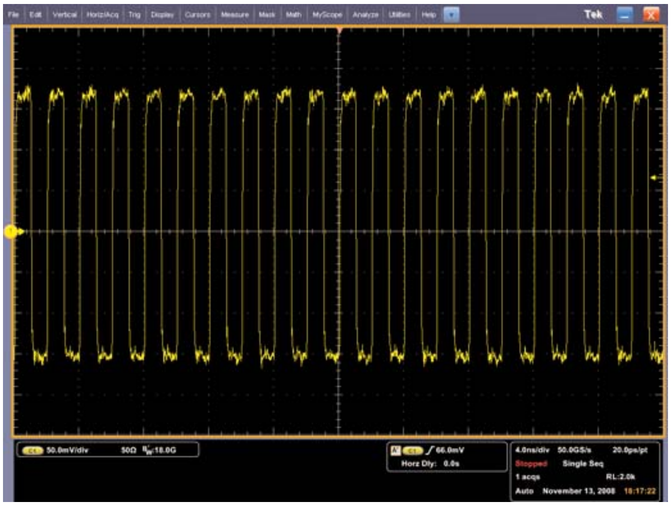


**Figure 14.** Dot mode does not show true waveform shape.

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 14 shows this type of dots display.



C1 50.0mV/div 50Ω BW:18.0G
C1 ∫ 66.0mV
Horz Dly: 0.0s
4.0ns/div 50.0GS/s 20.0ps/pt
Stopped Single Seq
1 acqs RL:2.0k
Auto November 13, 2008 18:17:22

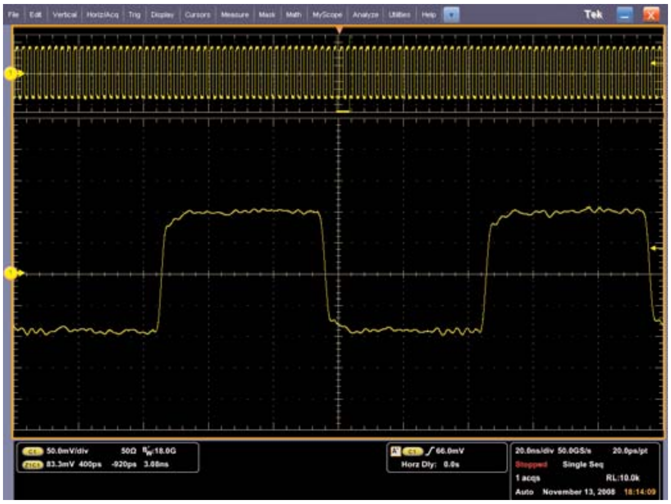
**Figure 15.** Vector Mode Improves Perceptual Aliasing.

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 15, using the same dots used in Figure 14.

In order to truly remove the effects of perceptual aliasing, we must use the digital filter from Nyquist Theory, called sine(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.

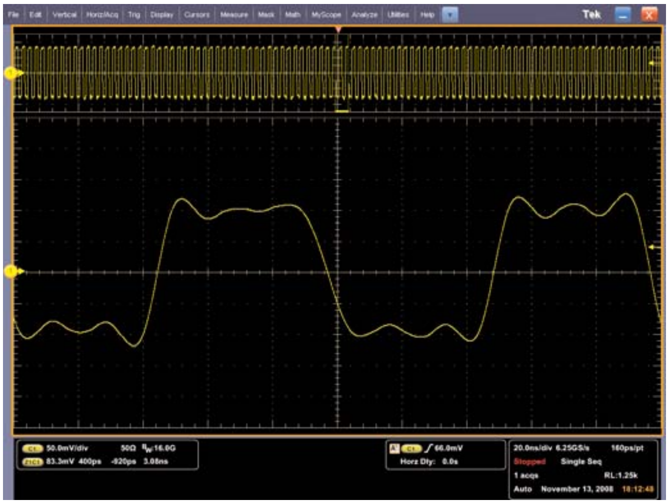
So what will sine(x)/x do to a step response that is under sampled? In Figures 16a the waveform is over sampled, and is displayed correctly with sine(x)/x interpolation. In Figure 16b the waveform is under sampled, with sine(x)/x interpolation used for the display, and results in ringing that isn't present on the original signal. In Figure 16c, the waveform is also under sampled, with linear interpolation (straight lines between acquisition samples) used for the display, and results in a better representation of the original signal.

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.



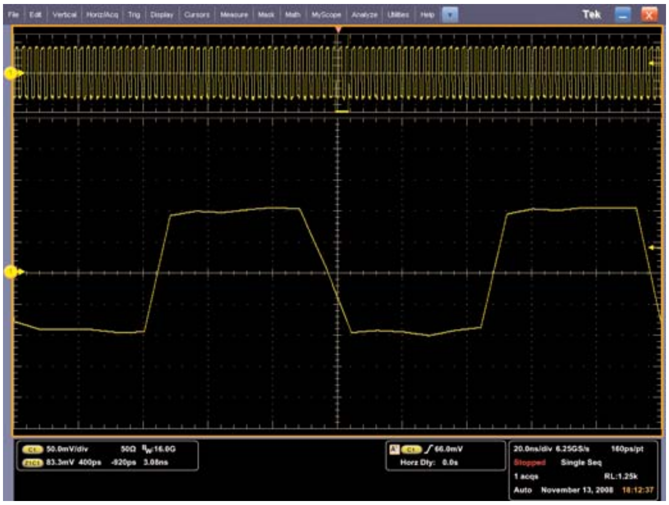
C1 50.0mV/div 50Ω BW:18.0G
Z1C1 83.3mV 400ps -920ps 3.08ns
C1 ∫ 66.0mV
Horz Dly: 0.0s
20.0ns/div 50.0GS/s 20.0ps/pt
Stopped Single Seq
1 acqs RL:10.0k
Auto November 13, 2008 18:14:09

**Figure 16a.** Oversampled waveform using sin(x)/x interpolation.



C1 50.0mV/div 50Ω BW:16.0G
Z1C1 83.3mV 400ps -920ps 3.08ns
C1 ∫ 66.0mV
Horz Dly: 0.0s
20.0ns/div 6.25GS/s 160ps/pt
Stopped Single Seq
1 acqs RL:1.25k
Auto November 13, 2008 18:12:48

**Figure 16b.** Undersampled waveform using sine(x)/s interpolation.



C1 50.0mV/div 50Ω BW:16.0G
Z1C1 83.3mV 400ps -920ps 3.08ns
C1 ∫ 66.0mV
Horz Dly: 0.0s
20.0ns/div 6.25GS/s 160ps/pt
Stopped Single Seq
1 acqs RL:1.25k
Auto November 13, 2008 18:12:37

**Figure 16c.** Undersampled waveform using linear interpolation.

## What can Digital Signal Processing do to Risetime, 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 17, 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.

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.

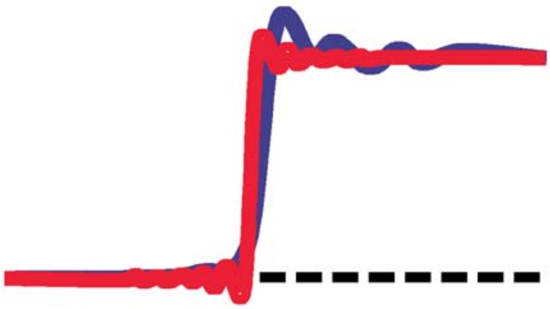


**Figure 17.** DSP enhanced shape, rise time and bandwidth.

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 17, 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 something about how well your oscilloscope will reproduce the true nature of your waveform, but not the entire story. Step response rise time, fall time, aberrations, and in-band flatness and phase response will tell you much more about the true fidelity of your measurement system. And when you want to explore 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.

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