Understanding Oscilloscope Frequency Response and Its Effect on Rise-Time Accuracy

Application Note 1420

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Introduction

When you combine many circuit elements with similar frequency responses, you get a Gaussian response. Traditional analog oscilloscopes chain many analog amplifiers from the input to the cathode ray tube (CRT) display,[1] and therefore exhibit a Gaussian response. The properties of a Gaussian-response oscilloscope are fairly well understood in the industry.

Less familiar, though, is the flat-response that is now more commonly exhibited by modern, high-bandwidth digital oscilloscopes. A digital oscilloscope has a shorter chain of analog amplifiers, and it can use digital signal processing techniques to optimize the response for accuracy. More importantly, a digital oscilloscope can be subject to sampling alias errors,[2] which is not an issue with analog scopes. Compared to a Gaussian response, a flat response reduces sample alias errors, an important requirement in the design and operation of a digital oscilloscope.

This application note reviews the properties of both Gaussian- and flat-response oscilloscopes, then discusses rise-time accuracy for each response type. It shows that a flat-response oscilloscope gives more accurate rise-time measurements than a Gaussian-response oscilloscope of equal bandwidth, and how you can estimate the oscilloscope bandwidth you need.

This discussion refers to using a 1 GHz oscilloscope, but this analysis is scalable to other bandwidths with the same validity.

(1) Analog oscilloscopes use the input signal to directly deflect the electron beam in a CRT. This requires amplifying the input signal three orders of magnitude, and driving the large capacitive load that the CRT deflection plates present.
(2) Sampling alias errors occur when the signal has frequency content beyond half the sample rate, known as the Nyquist frequency.

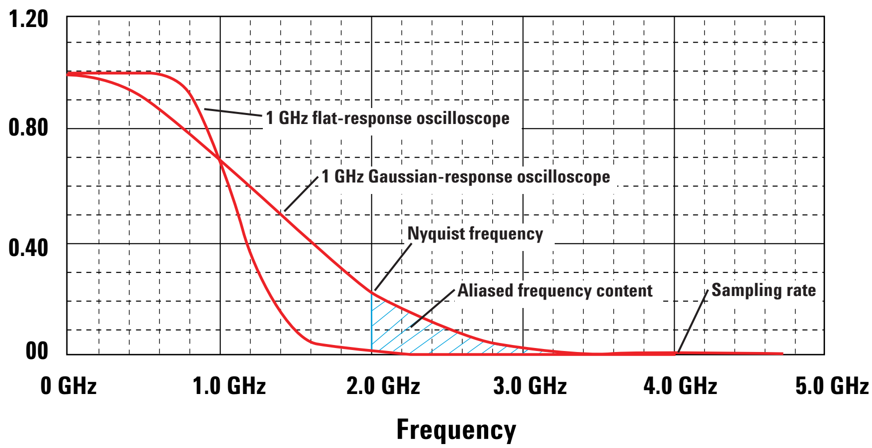

Figure 1. One GHz bandwidth oscilloscope frequency responses

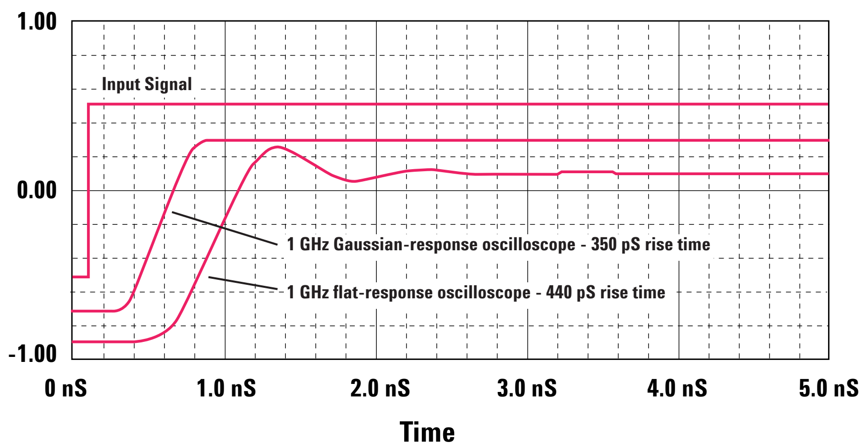

Figure 2. One GHz bandwidth oscilloscope pulse responses to fast step input

Properties of a Gaussian-Response Oscilloscope

Figure 1 depicts a typical Gaussian frequency response for a 1 GHz oscilloscope. A Gaussian-response offers good pulse response without overshoot, regardless of how fast the input signal is. Figure 2 shows the pulse response of a 1 GHz Gaussian-response oscilloscope to a fast step input.

In a Gaussian-response oscilloscope, the oscilloscope's rise time[3] is related to the oscilloscope's bandwidth[4] using the familiar formula:[5]

Rise time = 0.35/bandwidth

Another common property of Gaussian systems is that the overall system bandwidth[6] of the oscilloscope and its probe is the inverse root mean square (RMS) value of their individual bandwidths. The system bandwidth can be calculated using the familiar relationship:

$$\text{System bandwidth} = 1/(1/BW_{probe}{}^{2} + 1/BW_{oscilloscope}{}^{2})^{0.5}$$

Often oscilloscope probes are designed to have sufficiently higher bandwidth than the oscilloscope bandwidth, so you do not need the above formula for derating the system bandwidth. Inversely, the measured rise time is commonly related to the system rise time[7] and signal rise time using the formula:

$$\text{Measured rise time} = (RT_{signal}{}^{2} + RT_{system}{}^{2})^{0.5}$$

Sometimes this relationship is used to estimate the actual signal rise time when the oscilloscope's system rise time is not sufficiently faster than the signal's rise time to make an accurate measurement.

(3) Rise time is measured from the 10 to 90 percent amplitude points of the pulse edge.
(4) Bandwidth is the oscilloscope frequency, where the amplitude response is down -3 dB from its value at DC.
(5) The theoretical relationship for a Gaussian system is rise time = 0.339/bandwidth, but the industry has converged on 0.35/bandwidth as a practical formula.
(6) System bandwidth refers to the bandwidth achieved with a combination of an oscilloscope probe and oscilloscope.
(7) System rise time refers to the rise time achieved with a combination of an oscilloscope probe and oscilloscope.

Properties of a Flat-Response Oscilloscope

Figure 1 compares a flat response to a Gaussian response. Note that the frequency response is much flatter below the –3 dB bandwidth, but then drops off very rapidly above the –3 dB bandwidth. This response shape is sometimes referred to as a *maximally flat* or *brick wall* response.

There are a couple of advantages to a flat-response. First, the frequency content of the signal below the –3 dB bandwidth is less attenuated, and thus measured more accurately. Secondly, the steeper roll helps reduce sampling alias errors in digital oscilloscopes (more on this later).

In the time domain, a flat response results in a pulse response with overshoot and ringing when the oscilloscope input is driven with a fast step input, as depicted in Figure 2. Such overshoot and ringing is often perceived as an undesirable effect in an oscilloscope. However, this ringing only occurs if the signal rise time is significantly faster than the oscilloscope can measure accurately, in which case you should use a higher-bandwidth oscilloscope.

Unlike Gaussian systems, the system bandwidth of a flat-response oscilloscope is not determined by the inverse RMS value of the sub-system parts. *The commonly used bandwidth and rise-time formulas for Gaussian-response oscilloscope systems do not apply to flat-response oscilloscope systems!* Instead, you should rely on the oscilloscope vendor to specify the system bandwidth of an oscilloscope/probe combination.

In the case of a flat-response oscilloscope, the rise time is related to the bandwidth, as described in the formula:

Rise time = N/bandwidth
(where N = 0.4 to 0.5)

The larger N is, the steeper the frequency response is, or the more it approaches the "brick wall" configuration shown in Figure 1. The above relationship will sometimes be included in an oscilloscope's specifications, which can give you an indication of what type of response the oscilloscope has.

Measurement Accuracy

Which type of frequency response offers the best measurement accuracy? There are two issues to consider, the maximum signal frequency and the oscilloscope sampling alias errors.

Maximum signal frequency

Viewing the example in Figure 1, a flat response offers less signal attenuation below the –3 dB bandwidth (1 GHz) compared to a Gaussian response. It stands to reason, then, that for signals with frequencies primarily below the –3 dB bandwidth a flat-response oscilloscope would offer better measurement accuracy than a Gaussian-response oscilloscope.[8]

For example, let's compare the rise time measurement of a 700 pS rise time digital signal using both types of responses. You can determine the maximum signal frequency of this signal from its rise time:

Maximum signal frequency =
0.5/rise time (10%~90%)

Any system (including an oscilloscope) that can accurately measure frequencies up to and including the maximum signal frequency will reproduce the signal accurately.[9]

(8) Implied in this statement is the requirement that the phase response in the pass-band be linear.
(9) Johnson, Howard and Martin Graham, *High-Speed Digital Design: A Handbook of Black Magic,* page 2, Prentice Hall, 1993.

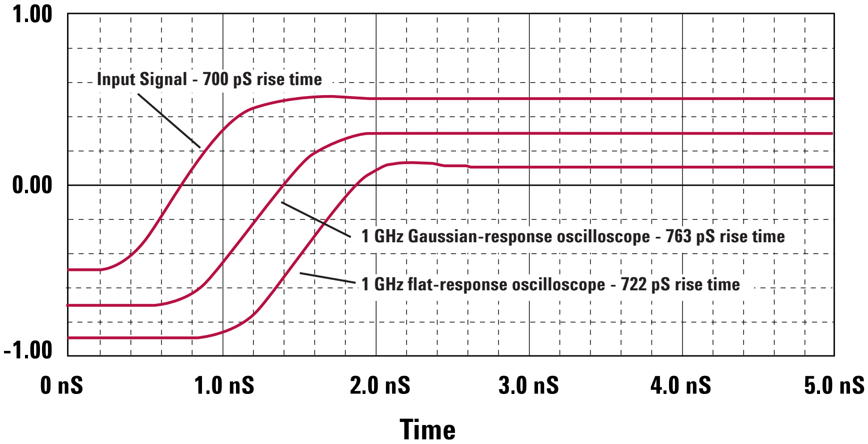

Figure 3. Pulse response accuracy

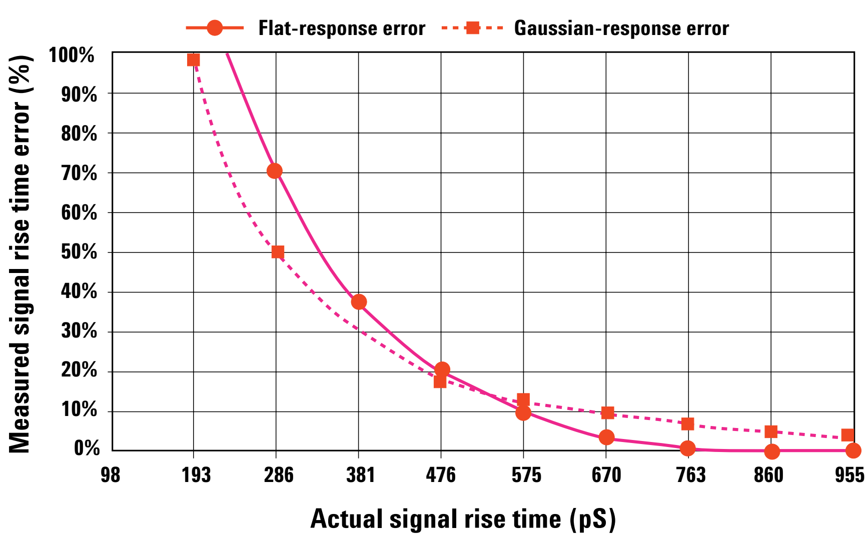

Figure 4. Rise time measurement accuracy for a 1-GHz bandwidth oscilloscope

Using this relationship, a signal with 700 pS rise times will be made up primarily of frequencies below 714 MHz. Viewing Figure 1, a flat-response scope offers less attenuation compared to that of a Gaussian-response instrument for frequencies up to 714 MHz. Indeed, a flat-response oscilloscope will measure the rise time of this 700 pS edge more accurately than a Gaussian-response oscilloscope, as depicted in Figure 3. A flat-response oscilloscope measures the rise time with 3 percent error, while a Gaussian-response oscilloscope has 9 percent error.

As the signal rise time decreases (as edges get faster), the rise-time measurement accuracy of a Gaussian-response oscilloscope eventually surpasses that of a flat-response oscilloscope. This happens because the frequency content of the signal increases above the –3 dB bandwidth, where a flat-response oscilloscope has less amplitude response than a Gaussian-response oscilloscope.

Figure 4 illustrates the rise-time measurement error for various signal rise times using the example oscilloscopes. Note that the rise-time measurement error is already 15 percent at the point where the Gaussian oscilloscope measurement becomes more accurate than the flat-response oscilloscope. Thus, *for accurate measurements (less than 15 percent error) of signal rise times, a flat-response oscilloscope is superior to a Gaussian-response oscilloscope of equal bandwidth.* This seems counter-intuitive, given that a Gaussian-response oscilloscope has a faster rise time than a flat-response oscilloscope to an ideal (fast) step input. Remember, an oscilloscope's rise-time specification alone does not indicate how accurately a rise time can be measured; you must also consider the oscilloscope response.

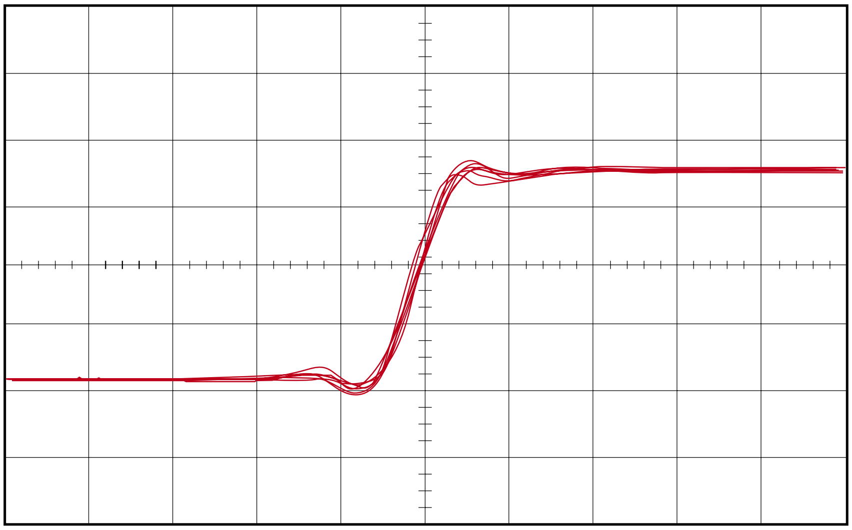

Figure 5. Waveform wobble due to sampling alias error

Sampling alias errors

Digital oscilloscopes use two basic sampling methods: repetitive and real-time. A repetitive-sampling scope samples the signal over many repetitions of the signal, and it is not subject to sampling alias errors. A real-time sampling oscilloscope samples and captures the signal in one pass or one occurrence of the signal. This discussion applies to the more common real-time sampling oscilloscopes, which offer many benefits over repetitive-sampling oscilloscopes.[10]

For a digital real-time oscilloscope to accurately measure a signal, the signal must not have significant frequency content above the Nyquist frequency, which is half the sampling frequency. Frequency content above the Nyquist frequency is folded back below the Nyquist frequency in the frequency domain. In the time domain, this error manifests itself as a pulse response with "wobbling" edges, as depicted in Figure 5. These "wobbling" edges result in inconsistent rise times and delta-time measurements.

For the example in Figure 1, the sample rate is 4 GHz,[11] so the Nyquist frequency is 2 GHz. A Gaussian-response oscilloscope allows you to sample frequency content beyond 2 GHz, which will result in sampling alias errors for signals with significant frequency content above 2 GHz. A flat-response oscilloscope, however, practically attenuates all frequency content above 2 GHz, and sampling alias errors do not exist.

To accurately measure the signal without sampling alias errors, your oscilloscope must have sufficient sample rate. For a Gaussian-response oscilloscope, you may need a sample rate up to six times the oscilloscope's bandwidth, although four times the bandwidth is more typical. On the other hand, a flat-response oscilloscope with a sharp filter may only need a sample rate 2.5 times the oscilloscope's bandwidth to avoid alias errors.

(10) Repetitive sampling oscilloscopes offer the benefit of higher bandwidths than real-time sampling oscilloscopes.
(11) It is typical for a digital oscilloscope to sample 4X the specified real-time bandwidth.
(12) Depending on your application, you may need additional bandwidth to capture noise and/or jitter beyond the maximum signal frequency.

Determine maximum signal frequency *(Fmax)*	0.5/Signal rise time (10%~90%) OR 0.4/Signal rise time (20%~80%)	
Determine oscilloscope response type	Gaussian-response	Flat-response
Rise time/bandwidth relationship	0.35/bandwidth	(0.4~0.5)/bandwidth
Rise time measurement error	Oscilloscope bandwidth	
20 %	1.0 *Fmax*	1.0 *Fmax*
10 %	1.3 *Fmax*	1.2 *Fmax*
3 %	1.9 *Fmax*	1.4 *Fmax*
Minimum sample rate[13]	4 x bandwidth	2.5 x bandwidth

Table 1. Oscilloscope bandwidth and accuracy

Determining How Much Bandwidth You Need

To estimate the necessary oscilloscope bandwidth to make accurate measurements, refer to the information in Table 1. First, determine the maximum signal frequency *(Fmax),* based on the signal's rise time.[12] Next, determine whether you are using a Gaussian- or flat-response oscilloscope. Then, depending on the accuracy you need, select the appropriate multiplier and multiply the maximum signal frequency (Fmax) by the multiplier to determine the required oscilloscope bandwidth. Finally, ensure that the oscilloscope has sufficient sample rate to achieve the required bandwidth without sampling alias errors.

For example, to measure a 100 pS rise-time signal (20 to 80 percent) with a flat-response oscilloscope to an accuracy of 10 percent would require a (0.4 /100 pS)1.2 = 4.8 GHz bandwidth oscilloscope, with a minimum sample rate of 4.8 GHz x 2.5 = 12 GSa/s.

This procedure is only a tool to estimate the bandwidth you need. It is prudent to verify actual rise-time accuracy with measurements, as frequency responses vary between oscilloscope models.

Summary

For accurate (less than 15 percent error) measurements of digital signal rise times, a flat-response oscilloscope offers better accuracy than a Gaussian-response oscilloscope of equal bandwidth. Another benefit of flat-response oscilloscopes is they typically have brick wall filters that reduce or prevent sampling alias errors.

The oscilloscope bandwidth needed is primarily determined by the rise time of the signals, not the signal's frequency. For accurate measurements, pick an oscilloscope that has accurate frequency response up to the maximum signal frequency, determined by 0.4/rise time (20 to 80 percent). In the case of a modern flat-response oscilloscope, an oscilloscope bandwidth that is 1.4 times the maximum signal frequency will usually suffice for accurate rise-time measurements.

(13) Typical values. Varies with oscilloscope models. Refer to the oscilloscope specifications.

Glossary

Brick wall response — the frequency response of an ideal low-pass filter, which would pass all frequencies below some cutoff frequency with no attenuation, and would not pass any frequencies above the cutoff frequency.

Flat-response oscilloscope — an oscilloscope with a response characteristic that approaches that of a brick wall response, using a combination of hardware and digital signal processing filter techniques.

Gaussian-response oscilloscope — an oscilloscope with an overall impulse response that is Gaussian due to the combination of many individual impulse responses in the oscilloscope's amplifier chain.

Maximally flat-response — a low-pass filter response that passes signals below the cutoff frequency with minimal attenuation, similar to the brick wall response.

Nyquist frequency —the highest bandwidth (fastest) signal that can be accurately digitized in a sampled system, where the Nyquist frequency is half the sample rate.

Real-time oscilloscope — a digital sampling oscilloscope that can capture a single occurrence of a signal using a high-speed digitizer capable of sampling and storing the signal.

Repetitive sampling oscilloscope — a digital sampling oscilloscope that digitizes different portions of a signal over many occurrences of the signal, eventually assembling a representation of the signal.

RMS value — root mean square value

Roll off — how quickly a low-pass filter attenuates frequencies beyond the cutoff frequency.

Related Literature

Infiniium 54800 Series Oscilloscopes
Product Overview 5988-3788EN

Infiniium 54800 Series Oscilloscope Probes, Accessories and Options
Selection Guide 5968-7141EN

Infiniium 54850 Series Oscilloscopes
InfiniiMax 1130 Series Probes
Data Sheet 5988-7976EN

Restoring Confidence in Your High-Bandwidth Probe Measurements
Application Note 1419-01 5988-7951EN

Improving Usability and Performance in High-Bandwidth Active Oscilloscope Probes
Application Note 1419-02 5988-8005EN

Performance Comparision of Differential and Single-Ended Active Voltage Probes
Application Note 1419-03 5988-8006EN

The Truth About the Fidelity of High-Bandwidth Voltage Probes
Application Note 1404 5988-6515EN

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