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Oscilloscope Bandwidth Concerns

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presented by:

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Marketing

Welcome to today's NetSeminar on Oscilloscope Bandwidth Concerns by Agilent Technologies. My name is Bryan Kantack, and I will be your moderator. Before we begin our presentation, I have just a few announcements. This seminar is an on-demand event, and therefore, the slides will automatically advance as we progress through the presentation. At the end of the presentation, we will give you the opportunity to offer us your feedback on the content in today's presentation, and to submit any questions you may have directly to me for further comments and explanation. (next slide) Now let's get underway with our presentation.

Agenda

- System bandwidth concept
  - Connection Bandwidth
  - Probe and Scope Bandwidth
- Bandwidth Calculations
- Sample rate and aliasing

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Today's presentation will focus primarily on system bandwidth considerations. Specifically, the bandwidth and frequency response characteristics of the oscilloscope and probes used to connect to the device under test with emphasis on the physical connection to the target system. We will also briefly discuss classical calculations used to determine adequate test system bandwidth, and a new approach that is more suitable to today's wideband oscilloscope filters that have much steeper rolloff characteristics than previous generation, lower-bandwidth scopes. And, finally, (next slide) we will discuss the affects of aliasing due to undersampling.

System Bandwidth Concept

- **Lower bandwidth scopes have a Gaussian response**
  - **$BW = 1/\sqrt{(1/BW^2{}_{scope} + 1/BW^2{}_{probe} + \ldots}$**
- **Higher bandwidth scopes have a "maximally flat" response**
  - **BW = Weakest Leak$_{BW}$ (1st approximation)**

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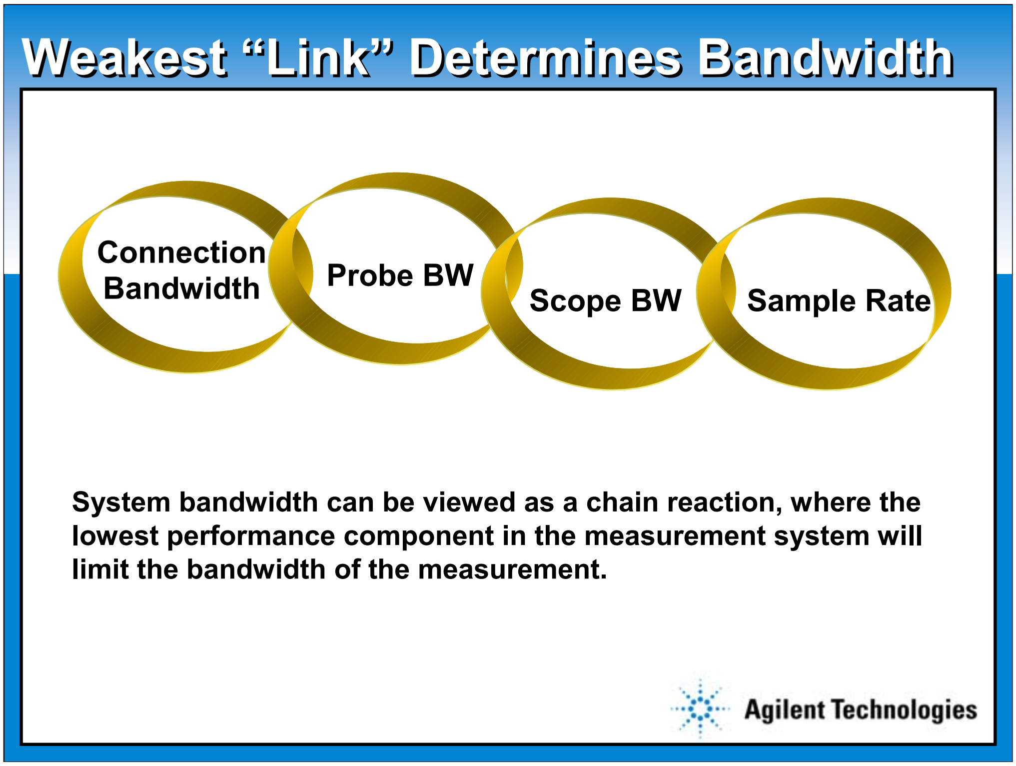
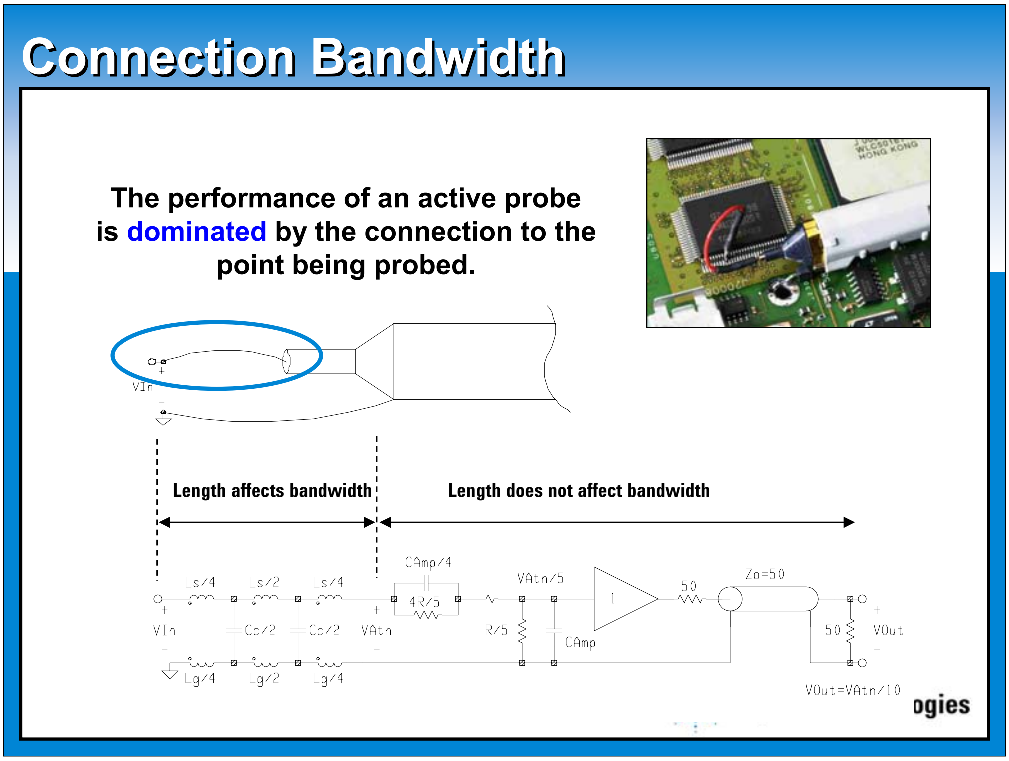
Lower bandwidth oscilloscope systems (<=1GHz) typically have a Gaussian frequency response. In a Gaussian-type system, bandwidth can be computed using the familiar square root of the sum of the squares formula, where the frequency response of the 'system' will behave as a series of cascaded low-pass filters with slow rolloff characteristics:

$$BW_{system} = 1/SQRT(1/scope_{BW}{}^2 + 1/probe_{BW}{}^2 + \ldots)$$

Today's higher bandwidth real-time oscilloscopes (>1GHz) typically have what is referred to as a "maximally flat" frequency response. This means that the system response is relatively flat out to the specified bandwidth, and then rolls-off very quickly, rather than gradually which is characteristic of a Gaussian system. As a first order approximation, the bandwidth of a "maximally flat" system is equal to the bandwidth (next slide) of the lowest frequency component in the chain.



As this chain illustrates, system bandwidth is a function of many factors including probe connection, the frequency response of the probe amplifier and oscilloscope, and the sample rate on each oscilloscope channel. In the past, probe system bandwidth has usually been the weakest "link" in this chain. Specifically, this is usually due to the physical connection of the probe tip to the device under test. It is usually customary for oscilloscope probe vendors to ship several short-wires or short, narrow, metal tips that can be used for connecting the probe to the target system. We will see that many of these short metal probe accessories may limit the performance of our system (next slide) to a much lower bandwidth than we expect.



If you need to probe your circuits with bandwidth performance in excess of 500MHz, you are probably using an active probe today to take advantage of higher input impedances magnitudes in the range of tens of thousands of ohms. Many vendors will emphasize their input specifications for network capacitance at the probe tip, but we illustrate here that it is often the inductance and capacitance of the ‘connection’ to the DUT, and not the probe’s input capacitance, that will limit the bandwidth of the system.

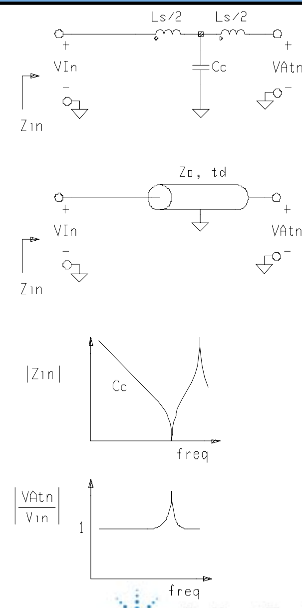
Even though a particular scope vendor’s active probe may have an impressive bandwidth specification which would seemingly produce excellent high frequency fidelity, the published specified performance may be under non-realistic probing conditions. In a real-world probing situation, which would include using probing accessories to attach to your signals, the traditional active probe’s performance may be very different than the published specified performance.

To put this in perspective, let’s take a closer look at a model of an active probe and it’s connection. Although we will not get into the details of this model, there is one section of the electrical model that you should focus your attention on. It’s the connection!. In most cases, the probe connection of a traditional active probe will determine the measurement bandwidth of the entire oscilloscope measurement system. The model for the probe connection is not just a zero Ohm, zero inductance, and zero capacitance wire. At high frequencies, the probe connection can be modeled as a transmission line, which is a series of parasitic lumped capacitors and inductors.

As you will see during this discussion, the real-world performance of an active probing system is dominated primarily by the connection. In other words, parasitic components to the left of the input to the probe will be the driving factors in determining the performance of a real-world active probing system in high frequency applications. (next slide)

Probe Input Model - Undamped

- **The connection can be modeled as an LC tank circuit or as a piece of transmission line**



- **Input impedance resonates low at 1/4 wave frequency of transmission line**
- **Transmitted response resonates high at same frequency**

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With the assumption of minimized ground lead connections, the model of our input connection begins to look like a single transmission line (as opposed to coupled lines). And that is exactly what it is! This model of the probe connection dominates the performance of the oscilloscope system. In most cases, you can assume that the model for the probe amplifier and oscilloscope are perfect (infinitely flat response).

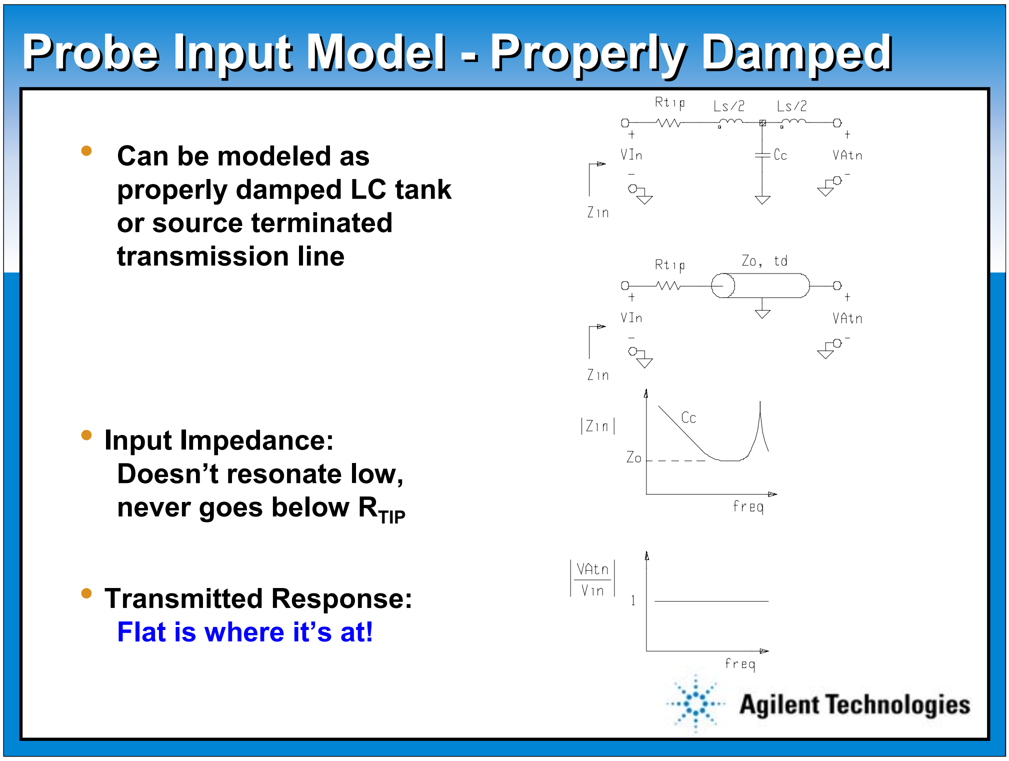
With good grounding techniques, the input probe connection can be modeled down into a simple L-C-L circuit. Or for engineers that are comfortable with the frequency/RF domain, we can model it as a simple transmission line. Unfortunately though, it is a relatively “uncontrolled” transmission line.

Question: So what happens to an L-C tank circuit, or a transmission line at its quarter-wave frequency?

Answer: For the L-C tank model, the input impedance will resonate low at it’s resonant frequency. -Or if you consider the transmission line model, the input impedance will resonate low at the quarter wave frequency of the transmission line. And the transmitted response will be peaked at this same frequency. With probe bandwidths available today, this first resonant frequency is the only one that we are concerned about. If we were to show the true structure of this input L-C network, it would have many more L and C components, and subsequently many more resonant points, but these are well outside of the bandwidths available today.

As we mentioned earlier, this first resonant frequency probably will occur within the –3dB bandwidth of your measurement system for high-frequency applications using a high bandwidth active probe. We call this “in-band resonance”, and it can potentially be the limiting element to our overall system bandwidth.

In addition to the in-band resonance problem caused by the connection, the bandwidth of the connection has a inverse relationship to the length of the connection. The longer the connection, the lower the bandwidth. Unfortunately, with traditional active probe technology, the only way to minimize bandwidth loss is to minimize the connection length. But there is a relatively easy technique to solve the in-band resonance problem. (next slide) Let’s see how we solve the in-band resonance problem.



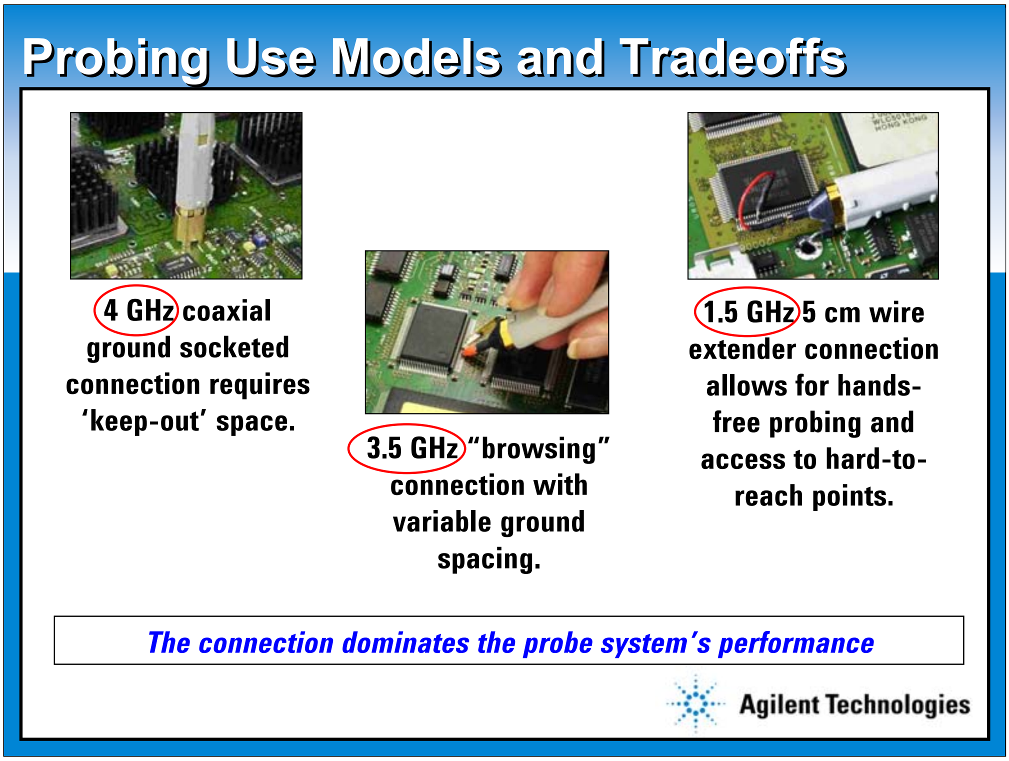
In the past the only way to keep the frequency of this resonance above the bandwidth of the probe was to use an ultra-short, stubby point at the input of the probe. Although this produces good high frequency fidelity, it is often difficult to connect such a short blunt point to the circuit.

A different method of limiting the loading effect of an L-C tank circuit is to simply properly damp the L-C tank with a small resistor on the front-end of the probing system. Or in transmission line terminology, source-terminate the transmission line. This allows for a longer, easier-to-use connection to be used at the input of a probe.

With a properly damped probe input, the loading/input impedance will never drop below the value of the damping resistor, which will be in the range of 100 to 250 Ω. (The actual value depends upon the length and geometry of the probing connection, as we mentioned in the previous slide.) The resultant transmitted response of this connection will no longer be peaked up, but will remain flat (ideally).

So practically speaking, how does Agilent properly damp the input connection? With our newest active probes, the user is provided with a variety of probe tip connection accessories with damping resistors physically positioned very close to the connection point. One of the accessories is an insertable browsing tip. This browsing tip basically consists of a resistor embedded within the body of the tip. Removable and replaceable probe heads now allow us to provide a high-frequency coaxial transmission line from the active probe amplifier out to the device under test, where the damping resistor is located.

Let's now look at various use models that have very different connections and associated parasitics.



Here we show that in order to obtain the full bandwidth with this 4GHz single-ended active voltage probe, we must mount it in a semi-permanent, coaxial ground socket on our device under test. This minimizes the ground length of the probe, and allows for the proper damping resistor to be placed at the point being probed (between the probe's input socket and the DUT). If the resistance is behind the probe's input socket, it does not provide proper damping for the parasitic L and C in the probe's socket.

Just by adding a short, low-inductance blade ground, we have reduced our usable bandwidth (less than +/- 3dB or 30% voltage error) to about 3.5GHz. We still use the proper value of R for the damping resistor at the tip, but the parasitic ground length is keeping us from obtaining full bandwidth.

Adding a short, 5cm (2 inch) wire accessory to our probe, which is a common practice in many labs, will further reduce our usable bandwidth to 1.5GHz, even though we are using properly calculated damping resistance. This is due to the lossy nature and low-bandwidth capability of unshielded wire. PLEASE NOTE: USING SHORT WIRE ACCESSORIES WILL ALWAYS REDUCE THE USABLE BANDWIDTH OF ANY VOLTAGE PROBE. THE LONGER THE WIRE IN THE CONNECTION PATH, THE LOWER THE USABLE BANDWIDTH.

Providing proper damping resistance will help to maintain a flat, non-resonant response from the probe tip to the oscilloscope screen, which allows you to see exactly what is at the tip of the probe. The damping resistance also protects the DUT from severe loading, which is typical of probes without proper damping resistance. Agilent provides all of the proper low-inductance damping resistors in their active voltage probe tips so that developers and designers don't need to worry about calculating these values.

Now that we have discussed the importance of a flat, non-resonant response in the probe's connection to the DUT, (next slide) let's look at the rest of the measurement system.

Probe and Scope Bandwidth

Measurement Concerns

- **Bandwidth will affect signal jitter**
- **Frequency response non-flatness will distort true signal qualities**
- **Insufficient sample rate will increase measurement error**
- **Aliasing will increase measurement error**

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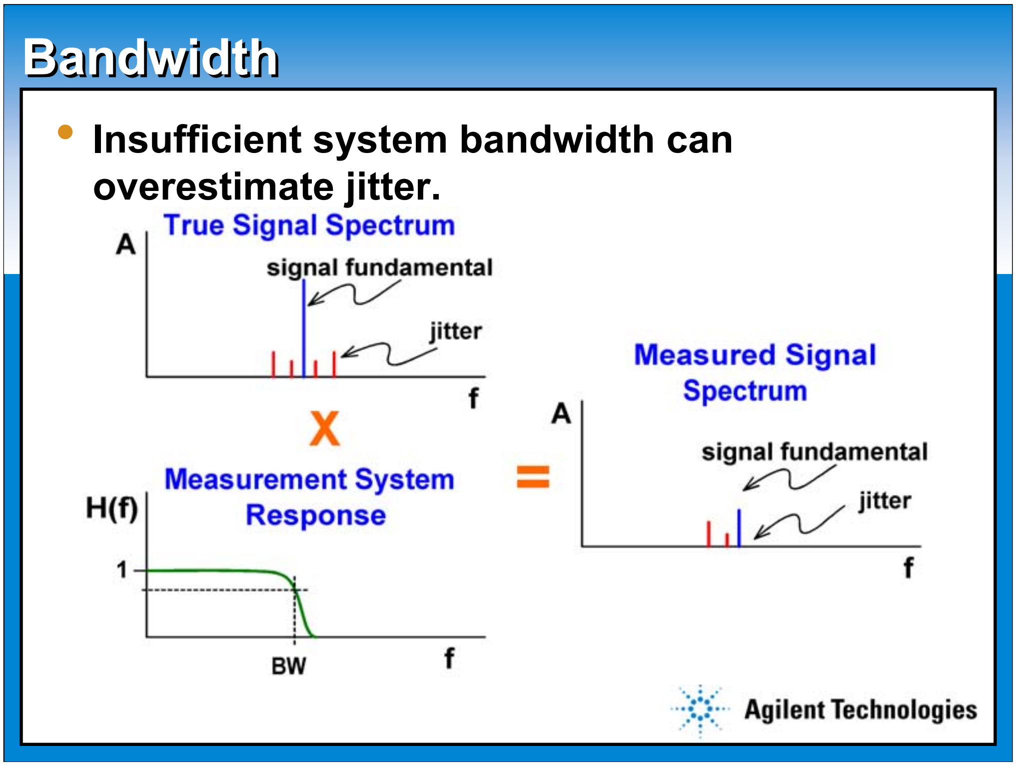
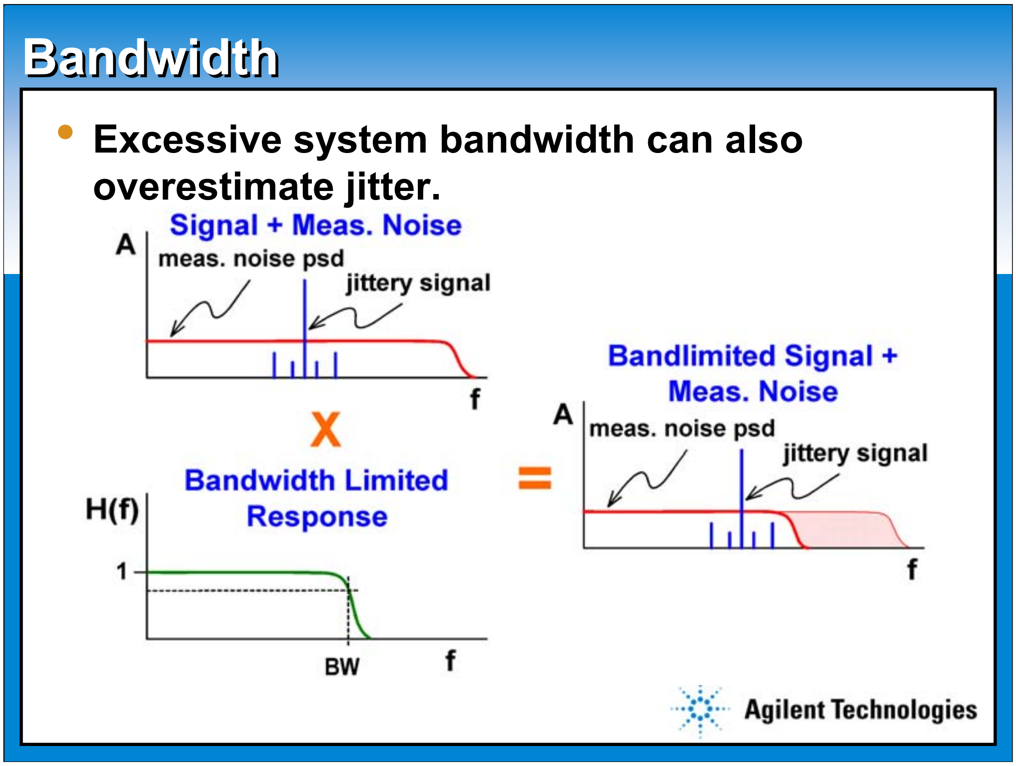
In this section, we will look at the effects of system bandwidth on jitter measurements and their relative accuracy. We will address the issues of flatness in the frequency response of the scope, probes and/or cabling used to connect to the target system, and insufficient sample rate that may cause aliasing of the target signal.



The effect of bandwidth on jitter measurement accuracy can be a complex issue. Just because the bandwidth of one measurement system, including probes or cables is higher than another one, doesn't mean it will always produce a more accurate answer.

If the measurement system bandwidth is too low, it will attenuate a clock's fundamental or harmonic frequency components relative to the jitter-producing components. A bandwidth that is too low will overestimate the true jitter. As I mentioned at the beginning of this presentation, many designers are 'edging out' the available scope bandwidths, and this may be a concern for them.



It is also possible for the measurement system bandwidth to be too high. If the measurement system noise floor dominates the error of a jitter measurement, and the measurement system has excessive bandwidth, then reducing the system bandwidth may produce a more accurate answer by reducing the jitter measurement floor.

Frequency Response Non-Flatness

- Frequency response non-flatness refers to the measurement system's ability to measure all signal frequencies with equal gain
- It is often overlooked
- Meas. system flatness is determined by:
  - Oscilloscope model
  - Oscilloscope settings
  - Probes
  - Cables

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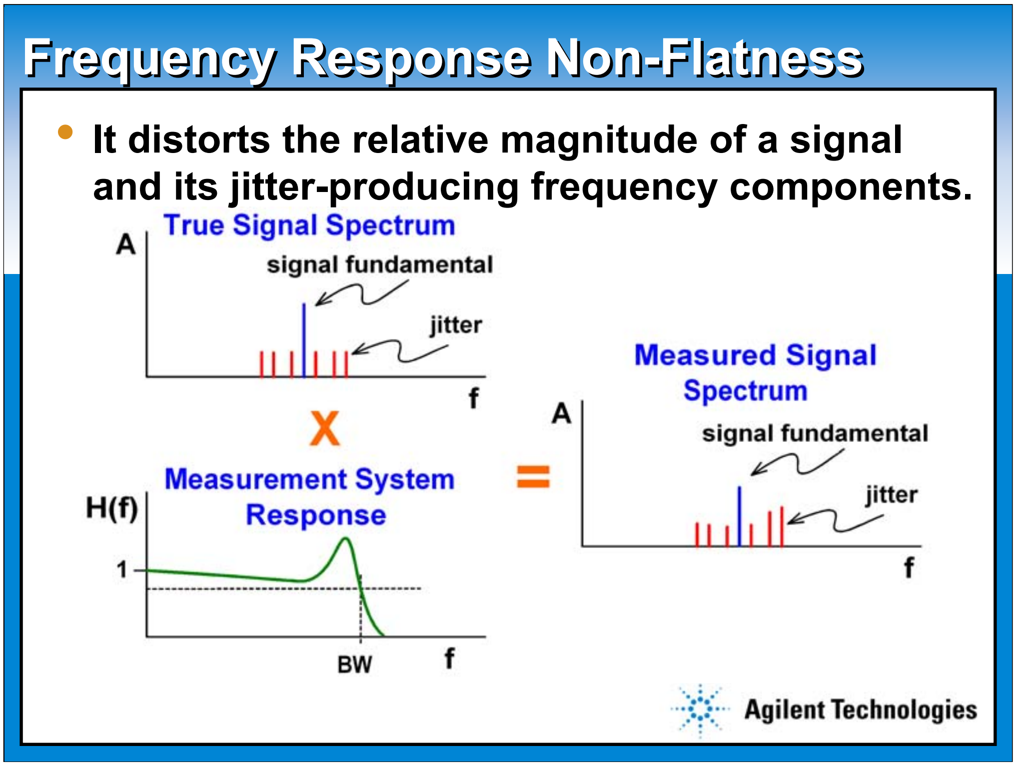
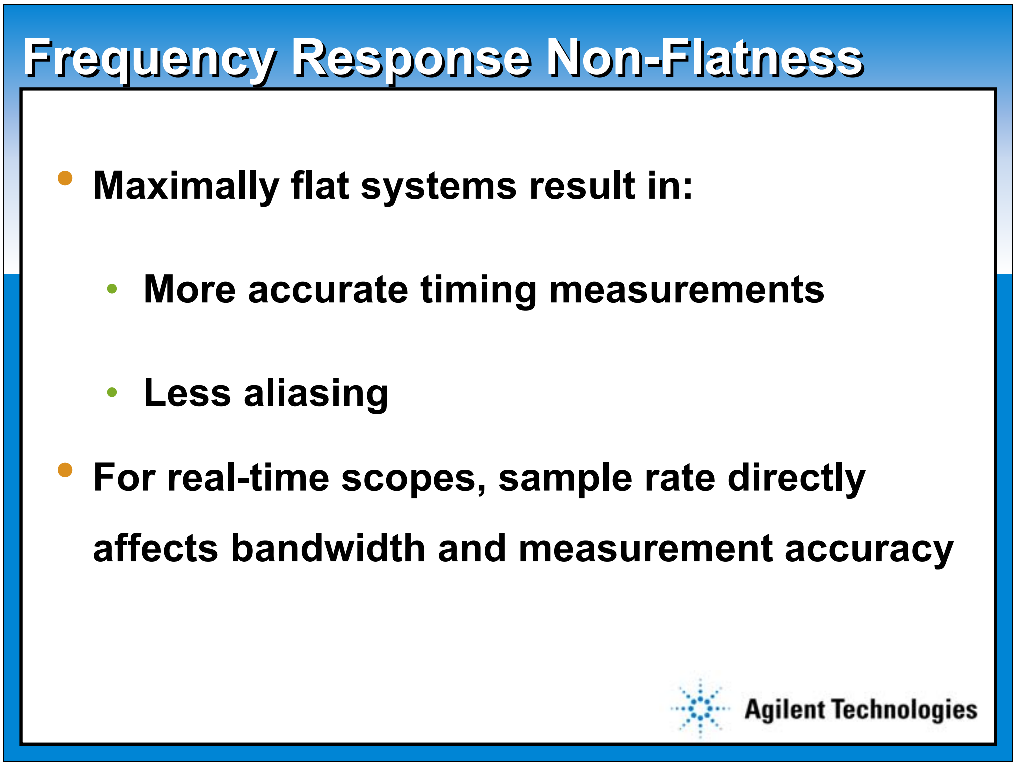
Here, I mention frequency response non-flatness separately from bandwidth because it is frequently overlooked. Measurement system flatness is determined by the frequency response of the oscilloscope and its voltage sensitivity setting, as well as the frequency response of any probes or cabling used to connect to the signal under test. Though frequency response flatness is usually not specified by oscilloscope or probe vendors, it is measurable using available high-frequency power meters. I note it here, because vertical noise is the largest contributor to horizontal jitter, and an accurate, flat gain of all frequency components in the signal relative to the true noise floor is imperative.



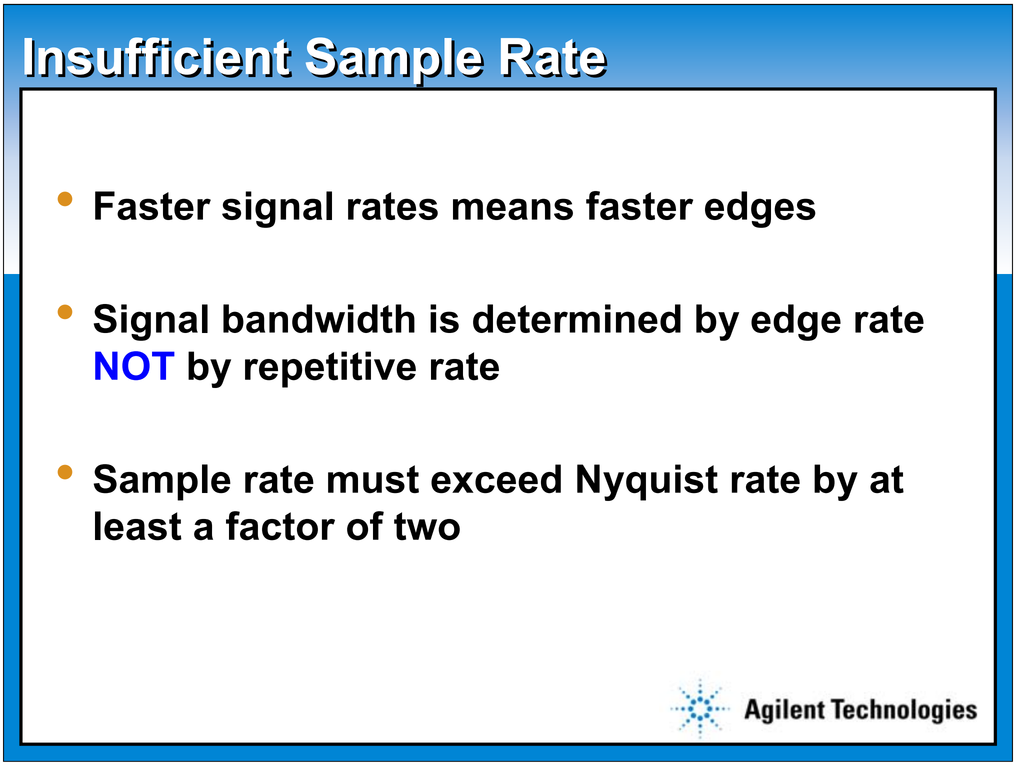
The 3dB bandwidth of a measurement system says nothing about the system's passband flatness. As I mentioned, most oscilloscope manufacturers do not specify this passband flatness. Distortions in the relative magnitude of a clock's fundamental or harmonic frequency components, with respect to the jitter-producing components, primarily noise, will corrupt a jitter measurement's accuracy. Non-flatness of up to 6 dB within a measurement system passband is not that uncommon, especially if you are using short wire accessories or long sockets to connect your probe to the target system.



Maximally flat systems typically result in better timing measurement accuracy. If the input signal under test is band limited, then the maximally flat systems captures more of the higher frequency components of the signal up to the bandwidth (-3dB). For high-speed signals in the 100ps edge range, this is the case.

Additionally, maximally flat systems will generate less aliased reconstruction error, which is exhibited as edge “wobble” on the oscilloscope. This is because maximally flat systems do a better job of attenuating frequency components of high-speed signals above the Nyquist rate.

Lastly, for real-time oscilloscopes, sample rate directly affects system bandwidth and measurement accuracy. Many real-time oscilloscopes have a “banner” sample rate specification that only applies to one or two channels of the scope. If the user is using all four channels, sample rate is often decimated which will result in lower bandwidth measurements. So be careful to note the sample rate per channel specification of a real-time oscilloscope, rather than just the maximum sample rate.



As signal speeds begin to increase, the respective edges of those signals are increasing at even faster rates to improve setup-and-hold times for clocking data. It is important to note that the signal's highest frequency content is determined by the speed of the edge, and not just by an nth harmonic of the fundamental frequency of the signal. The sample rate of the scope will need to be at least twice as great as the highest frequency component in the passband of the scope. With maximally flat oscilloscope frequency responses, this will typically be about 2.5 times greater than the –3dB specified bandwidth of the scope. My slide has a slight typo, here.

High-Speed Signaling Standards

Standard	Data Rate (Gb/s)	Driver Edge Rate (ps)	Receiver Sensitivity	Receiver Eye Opening or Setup/Hold
Serial		50ps to 140ps	200mVpp to 400mVpp	100ps to 140ps
PCI Express (3GIO)	2.5			
RapidIO Serial	3.125			
10GbE XAUI	3.125			
Fibre Channel 2125	2.125			
Infiniband	2.5			
Serial ATA	1.5			
Parallel				
RapidIO 8/16	2			
HyperTransport	1.6			

- **Edge rates are decreasing below 100ps**
- **Differential voltage swings are shrinking**

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The high-speed signaling standards listed in this table range from chip-to-chip interconnect buses, to backplane buses, to datacom links. Some of them are serial, where the clock is provided separately or embedded in the data. Some of them are parallel, with source synchronous clocking. Among these standards are several different signaling media as well: cables, multi-lane PCB traces, and even optical fiber. The common theme to these signaling standards, however, is that the minimum driver edge speeds are decreasing to at or below 100ps. Now, the risetime will be slower at the receiver, but if you are trying to verify your signals' risetimes to comply with a standard, you need to have a scope with at least 20GSa/s and 6GHz bandwidth on each channel you are measuring.

As receiver sensitivity margins and timing windows continue to shrink, it is important to have a measurement system with a low noise-floor and low timing jitter, as well as low probe loading, to ensure that you are truly measuring the error margins in your signals and not in your measurement system. In addition, differential probing is a MUST!

Edge Bandwidth Calculation

- **The oscilloscope bandwidth required for accurate measurements is primarily dependent on the signal's risetime, not its frequency.**

Oscilloscope Bandwidth and Accuracy		
Determine Maximum Signal Frequency (Fmax)	0.5 / Signal Risetime (10%-90%) OR 0.4 / Signal Risetime (20%-80%)	
Determine Oscilloscope Response Type	Gaussian Response	Flat Response
Risetime 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	4 x Bandwidth	2.5 x Bandwidth

- **Flat response oscilloscopes with a bandwidth that is 1.4 times the highest frequency content in the signal will make accurate risetime measurements.**

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Here is a calculation table that highlights the traditional calculations used to determine adequate system bandwidth and sample rate for gaussian response scopes, and the new calculations that can be used for maximally flat oscilloscope systems. Some vendors will use a different factor than 0.5 or 0.4 that better describes the particular rolloff characteristics of their scopes, but it will be very close to these numbers. The 0.35 numbers used in the past are actually derived from the RC time constant of a single-pole filter. This was an approximation, at best, even for gaussian scopes, and certainly does not apply to maximally flat scopes.

System Bandwidth Calculation

Example

- **Determine the minimum required bandwidth and sample rate of a flat frequency response oscilloscope to measure a 100ps risetime (20-80%) to an accuracy of 3%:**

F_{max} = (0.4/100ps) = 4.0 GHz

Required oscilloscope bandwidth = 1.4 * 4.0 GHz = 5.6 GHz

Minimum Sample Rate = 2.5 * 5.6 GHz = 14.0 GSa/s

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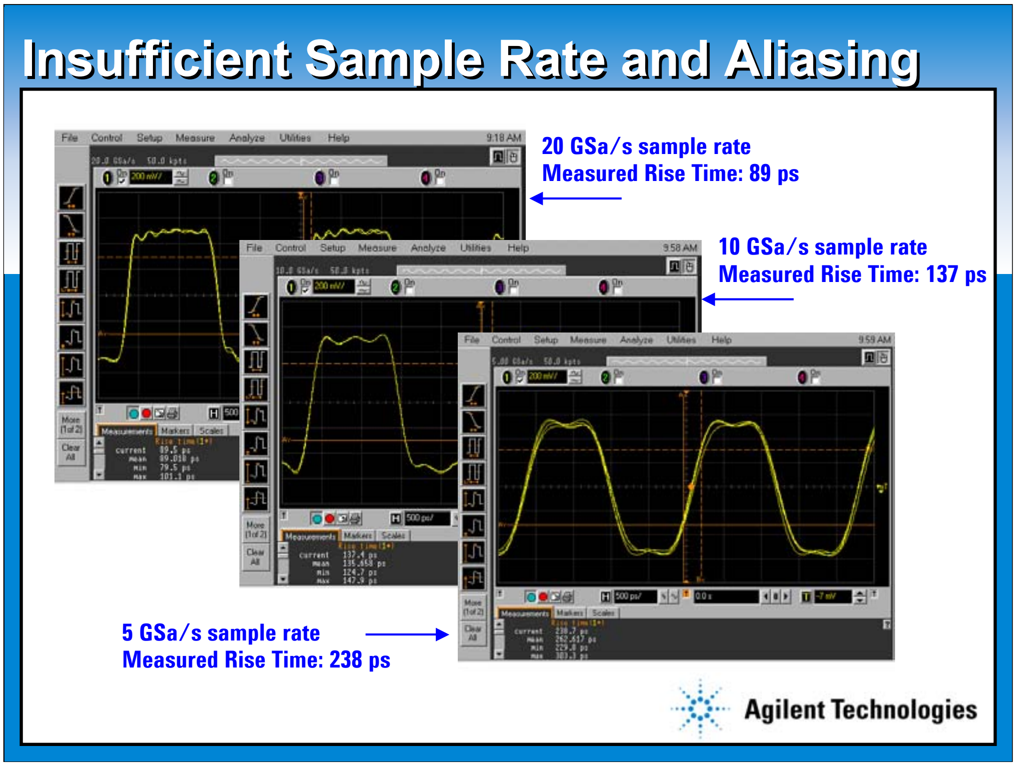
Many of today's high-speed buses and chip-to-chip signals have rise time specifications in the 100ps range (20% to 80%) as shown earlier. So, let's go walk through an example of accurately measuring a 100ps edge.

If the signal has an approximate rise time of 100ps, then the maximum practical frequency component (F_{max}) would be approximately 4GHz. For a rise time measurement accuracy of 3%, the minimum scope bandwidth should be at least 5.6GHz (assuming a maximally flat response). And then the minimum sample rate for a 5.6GHz maximally flat scope would be 14GSa/s.

Since scopes don't come with these odd numbered specifications, practically speaking you would need a 6GHz bandwidth scope with 20GSa/s sample rate. And if you needed to make simultaneous timing measurements on multiple channels, you should insure that the sample rate does not decimate in multi-channel operation.



To illustrate the point of better accuracy with higher sample rate, this slide shows the same high-speed signal captured at three different sample rates. The measured rise times of this signal vary significantly depending upon the sample rate. So the caution here is, watch out for scopes that trade-off sample rate for channels. Many high-bandwidth four channel scopes only sample at the highest specified rate (banner spec) when using just one or two of the acquisition channels.

Unfortunately, it is difficult to show the aliasing problem with a static slide. To view the "wobble" of a fast rising edge requires a live and interactive waveform display.

Aliasing

- **Aliasing applies to real-time oscilloscopes**
- **The quality of anti-aliasing filters affects accuracy**
- **Anti-aliasing filters don't help at reduced sample rates:**
  - **full channel count can reduce sample rate**
  - **insufficient record depth can reduce sample rate**

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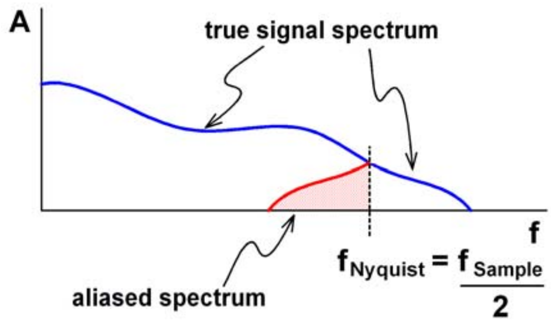
Most oscilloscopes employ fixed-bandwidth analog anti-aliasing filters in front of their analog-to-digital converters (ADCs). These filters reduce the magnitude of the signal spectra that can be aliased by the sampling process at the maximum sample rate. Some anti-aliasing filters provide better protection against aliasing than others, and this matters when the measured signals push the bandwidths and sample rates of the oscilloscopes.

Because the bandwidth of the anti-aliasing filters is fixed, they do not protect against aliasing at sample rates below the maximum sample rate. Sometimes measurements are performed using reduced sample rates in order to extend the time range of acquired waveforms when the record depth is limited. In some oscilloscopes the maximum sample rate is not available on all input channels simultaneously.

Aliasing

- **Aliasing corrupts waveforms by “folding” aliased spectral components down below the Nyquist frequency with random phase.**



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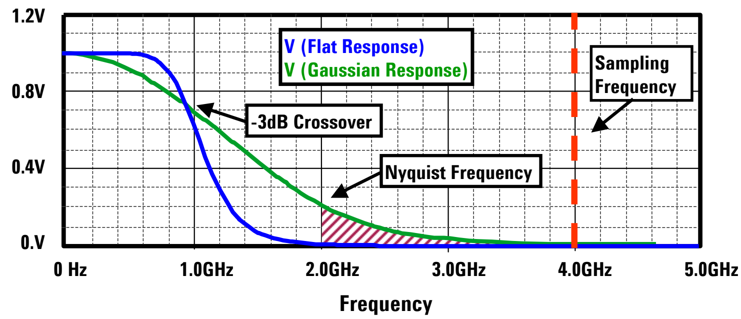
Aliasing occurs in real-time oscilloscopes if the measured signal contains spectral content above the Nyquist frequency, where the Nyquist frequency is one half of the oscilloscope’s sampling frequency. Aliasing distorts sampled waveforms by “folding” the aliased spectral components of the signal down below the Nyquist frequency with random phase.

Sampling Alias Error

- **Gaussian response oscilloscopes have a slow rolloff in their frequency response.**



- **Flat response oscilloscopes eliminate alias errors by quickly attenuating frequency content above the Nyquist sampling frequency.**

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A common problem associated with real-time digitizing oscilloscopes is aliasing. If a signal is "under-sampled", then the resultant waveform will exhibit aliased errors. A grossly under-sampled waveform (sample rate much slower than the fundamental frequency of the input signal) will appear as an untriggered waveform of a lower frequency. An input signal that is under-sampled on fast rising edges will appear as a "wobbling" waveform. This is all related to the Nyquist theorem that states that all frequency components within a signal must have at least two sampled points per period. If this is violated, then aliasing occurs.

An oscilloscope system with a maximally flat response will naturally attenuate more of the higher frequency components of an input signal (before sampling) than a system with a Gaussian response. This will result in less aliased error and better timing measurement accuracy.

Summary

- System bandwidth is often dominated by the connection to the signal
- Frequency response non-flatness can cause measurement inaccuracy and may hide probe loading
- Insufficient sample rate and aliasing will cause measurement error

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