

Oscilloscopes and ENOB

Joel Woodward and Brig Asay, Agilent Technologies

6/15/2011 12:06 PM EDT

When oscilloscope users choose which oscilloscope to use for critical measurements, knowing the quality of the scope's measurement system is paramount. While banner specs like bandwidth, sample rate, and memory depth provide a basis of comparison, these specifications alone don't adequately describe oscilloscope measurement quality. Seasoned scope users will also compare a scope's update rate, intrinsic jitter, and noise floor, all of which enable better measurements. For scopes with bandwidth in the GHz range, another quality metric involves characterizing a scope's analog-to-digital converter (ADC) using effective number of bits (ENOB). When selecting which scope to use, how important is ENOB and how effective is ENOB at predicting a scope's measurement accuracy?

Designing oscilloscope architectures for measurement accuracy involves both front-end and ADC technology blocks. A scope's front end conditions a sampled signal so that the ADC can properly digitize the signal. The front end consists of attenuator, pre-amplifier, and path routing.

Engineers who design scopes spend significant effort designing front-ends that have flat frequency responses, low noise, and desired frequency roll-offs. Due to unique requirements for ADC technology, each scope vendor designs their own ADCs. Development of a new front end or ADC requires significant investment. Therefore, the resulting technology blocks will typically be used across multiple scope families and generations. Scope design teams maximize a scope's accuracy when these technology blocks induce the least change to the measurement of sampled signals.

While users can characterize the combination of the ADC and front-end, users can't easier characterize the technology blocks individually. There are many ways to measure an oscilloscope's front end measurement quality. Oscilloscope vendors typically will use noise measurements and ENOB as useful characteristic for determining how well a scope's front end and ADC are designed. It is often beneficial to consider the entire oscilloscope performance, instead of evaluating just ENOB or noise floor in isolation.

Characterizing an oscilloscope's noise floor at different vertical settings and offset provides an excellent criterion in determining a scope's measurement quality. These measurements tell the user how effective the scope's design team was in designing a quiet front-end and ADC converter. Oscilloscope noise adds unwanted jitter and erodes design margins. Typically the higher the bandwidth of the oscilloscope the more internal noise the oscilloscope produces as the scopes are accepting cumulative noise from higher frequencies that are rejected by the lower frequency roll-off of lower-bandwidth scope. A straightforward method of characterizing a scope's noise is to disconnect all inputs and see measurement the RMS voltage readings while varying both vertical sensitivity and offset.

IEEE defined a method for determining the goodness of ADCs using ENOB. Today's oscilloscopes typically will use to ADC architectures, pipelined or flash. Pipelined ADCs use two or more steps of sub-ranging to achieve higher sample rate, for instance the 90000A Series oscilloscope has a 20GSa/s ADC, which combines 80 sub-ranges of 256MSa/s to achieve the high sample rate. Interestingly and contrary to common wisdom, some scopes provide more accurate measurements when not running at fastest sample rate, due to additional interleaving distortion that can occur at the fastest sample rates and the addition of high frequency noise. Flash ADCs have a bank of comparators sampling the input signal in parallel, each firing for their decoded voltage range. The comparator bank feeds a logic circuit that generates a code for each voltage range* Each ADC technology has its own inherent

limitations, for instance flash ADCs are more prone to linearity errors, while pipelined ADCs typically will have more interleaving error. IEEE created the ENOB standard to help users determine the goodness of various ADCs.

Scope vendors will internally characterize standalone ADCs. They also characterize overall ENOB of a scope system. The resulting system ENOB will be lower than the ENOB of a standalone ADC. As a scope's ADC is part of an overall system, and can't be used independently, only ENOB results from the overall system are useful.

Users will generally use less than the full 8-bits of a scope's ADC. For example, to take advantage of the entire 8-bit vertical range, users would have to scale waveforms to consume the entire vertical range. This makes reading a signal more difficult, and the user runs the risk of driving the ADC into saturation, which causes undesired effects. For a signals that is scales to take 90% of the vertical range, the user reduces the scope's 8-bit converter to 7.2 bits (90%*8 bits). Front-end noise, harmonic distortion, and interleaving distortion will further reduce the effectiveness of the scope's ADC.

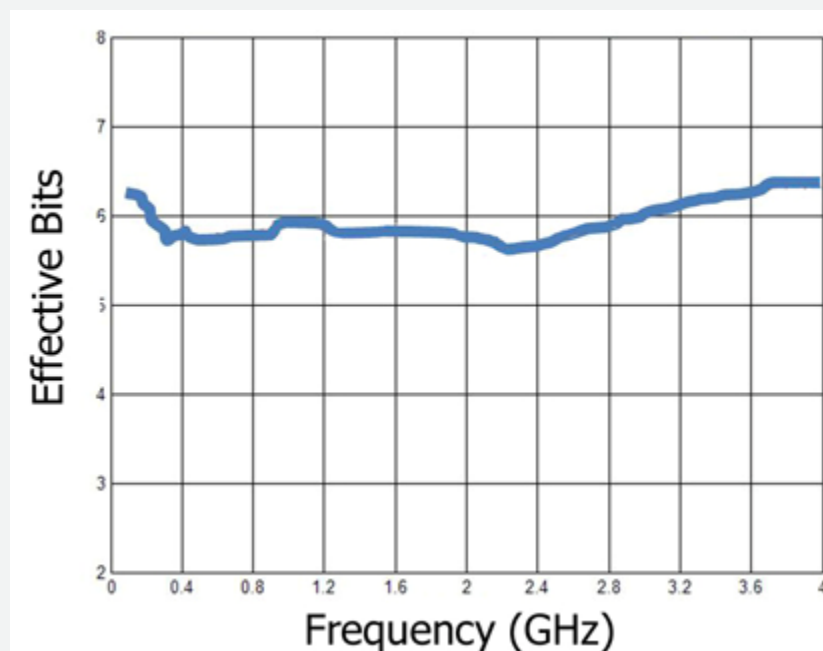


Fig 1. Sample ENOB plot for Agilent's Infiniium 9000 Series Oscilloscope. ENOB results will vary by frequency, and each scope model will have a unique ENOB plot. The ENOB plot is for the entire scope system and not just the scope's 8-bit ADC.

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What is ENOB and how is it measured?

ENOB is measured as a fixed amplitude sin wave is swept in frequency. The resulting voltage measurements are captured and evaluated. Using time-domain methods, ENOB is calculated from subtracting the theoretical best fit voltage versus time from what was measured. The difference is noise. This noise can come from the front-end of the scope from attributes such as phase non-linearities and amplitude variations over frequency sweeps. Noise can also come from interleaving distortion from ADCs. Evaluating the same signal in the frequency domain, ENOB is

calculated by subtracting the power associated with the primary tone from the entire broadband power. Both techniques provide the same result.

If you are making your ENOB measurements or analyzing ENOB measurements your scope vendor has previously made consider the following. ENOB results will be impacted by the spectral purity of the source being used. First, the source and accompanying filters should ensure that the sources ENOB is larger than the scope's ENOB. Second, ENOB values will be dependent of the amplitude ratio of the source signal to the scope's full screen amplitude. ENOB values will be different if the source was 75% of full screen or 90% of full screen. The JDEC standard uses 90% of full screen as their recommended amplitude for determine ENOB. Any comparisons of effective bits specifications or testing must take into account test signal amplitudes as well as frequency.

What does ENOB do well?

ENOB can be a good measure for determining the goodness of a scopes ADC. If a scope has a good ENOB, it will have minimal timing errors, frequency spurs (usually caused by interleaving distortion), and low broadband noise. If your application relies primarily on sin waves ENOB provides an effective criteria for scope selection.

What does ENOB exclude?

While ENOB is one measure of ADC and front-end "goodness," there are several attributes that it omits. ENOB does not account for offset, phase irregularities, nor frequency response distortion. Figure 2 shows an input signal, and display of this signal on two different scopes. Despite the fact that both scopes have the same ENOB, one scope displays a dramatically more correct representation of the input signal as shown in figure 2.

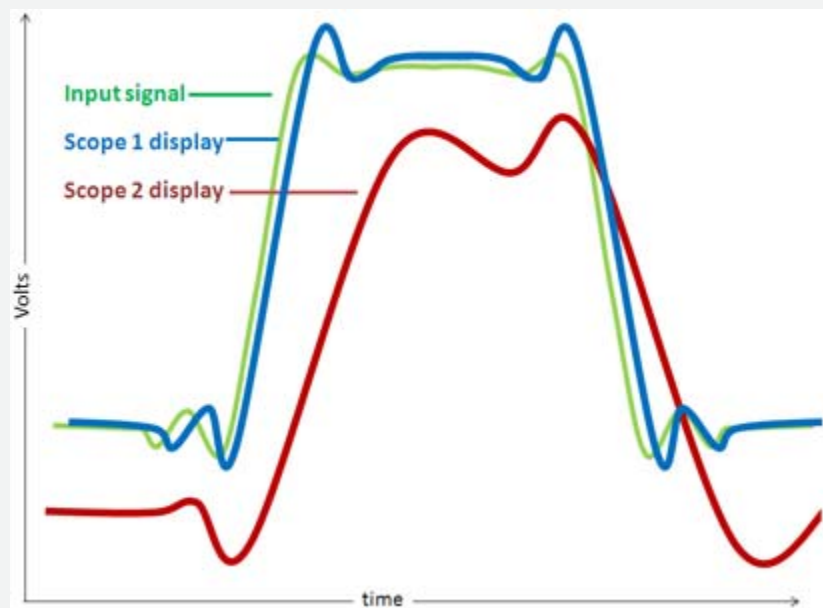


Fig 2: While ENOB provides one basis for scope evaluation, ENOB computations don't include the effect of magnitude or phase flatness. Both scope 1 and scope 2 have the same ENOB, but scope 2 has offset and phase distortion errors that limit its ability to correctly display the input signal.

ENOB doesn't take into account offset errors that the scope may inject. Two scopes with equal ENOB may show identical wave shapes offset by differences in absolute voltage. Adjusting offset and measuring noise or evaluating

DC gain specifications would provide a better evaluation metric.

To make it easier to select the right scope, ideally, all scopes would have a flat phase and frequency response and identical roll off characteristics. However, this isn't the case and phase and frequency response plots aren't generally found in vendor datasheets. As well, ENOB doesn't take into account frequency response flatness or phase irregularities. And, every scope model will have different frequency response and phase irregularities. For example, two scope models both rated to 6 GHz will produce different wave shapes when looking at a 2.1 GHz sine. One scope might have a slower bandwidth roll off and minimal phase correction algorithms, while the other scope may have a frequency response that peaks above 6 GHz before rolling off, and significant algorithms for phase correction. The scope with the higher ENOB isn't necessarily the scope that will show the most accurate representation of the input signal.

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How can I increase my scope's ENOB?

The obvious answer is to purchase an oscilloscope with higher ENOB to begin with. If asked, scope vendors will share overall ENOB values for each scope model. Most high-end oscilloscopes come with user-selectable bandwidth limit filters. Turning on a filter limits the bandwidth of the oscilloscope. This limits the high frequency content, including the interleaving errors and noise, which will make a higher ENOB. Finally oscilloscopes can also use averaging or high res mode for repetitive signals to reduce broadband noise. Using these modes can be a very effective tool for greater measurement accuracy.

How important is ENOB for selecting the right scope?

It will greatly depend on what you are trying to measure, as to whether or not the ENOB will affect your measurement outcome. Certainly ENOB plots should be viewed collectively with noise floor measurements. High speed serial data has harmonics at very specific frequencies, which may pass through the measurement system mostly unaffected by a decrease in effective bits. For these, the scope's noise floor may be a better indicator of measurement accuracy. If your signals are primarily fundamental sin waves, several defense applications come to mind, ENOB may be an excellent criteria. Ask your scope vendor for the ENOB plot of the specific scope model you are considering using. It is important that you know what the effective bits performance of the instrument you choose to measure with looks like across the full rated bandwidth of the instrument, as ENOB will vary with frequency.

About the authors:

Brig Asay is Product Manager High Performance Oscilloscopes in the Digital Test Division - Scopes, Electronic Measurements Group at Agilent Technologies. He manages product planning and strategic marketing for Agilent's high performance oscilloscope business.

Joel Woodward is Senior Product Manager, Oscilloscopes in the Digital Test Division, Electronic Measurement Group at Agilent Technologies. During his 21 years with Agilent Technologies, his career has focused on bringing new and innovative system verification and validation solutions to research and development engineers in the electronics industry. Within Agilent's electronic design automation and test and measurement businesses, He has

held several individual contributor and management positions. Instrumental in the creation of three start-up businesses within Agilent, and holds a patent in the area of field-programmable gate array debug.

Understanding the jitter specification in oscilloscopes

Brig Asay, Agilent Technologies

4/1/2011 12:28 PM EDT

Jitter remains one of the most important specifications when measuring the goodness of a device. Compliance packages specify random jitter, deterministic jitter, time interval error, and total jitter. Some technologies specify such measurements as bounded uncorrelated jitter and J2/J9 jitter specification. A low jitter measurement can be the difference between having to do a redesign versus shipping the product.

When it comes to jitter an oscilloscope has become a powerful tool for measuring it. Most oscilloscopes which have the Windows operating system installed on them provide many tools to measure jitter. However, oscilloscopes are inherently noisy and have a jitter measurement floor (meaning you can't measure jitter that is lower than the jitter measurement floor of the oscilloscope).

As a result, anyone who purchases an oscilloscope wants to know that they are getting the best oscilloscope for their money, especially when spending hundreds of thousands of dollars. Thus, it is important to understand the jitter specifications of the oscilloscope. The most important specification for jitter is the *jitter measurement floor*, which combines both oscilloscope *sample clock jitter* and *noise floor*. Oscilloscope vendors specify jitter measurement floor in different ways, therefore it is important to understand what each specification means. It's especially critical for looking at fast signals such as the 10 Gbase recovered clocks with intersymbol interference, **Figure 1**.

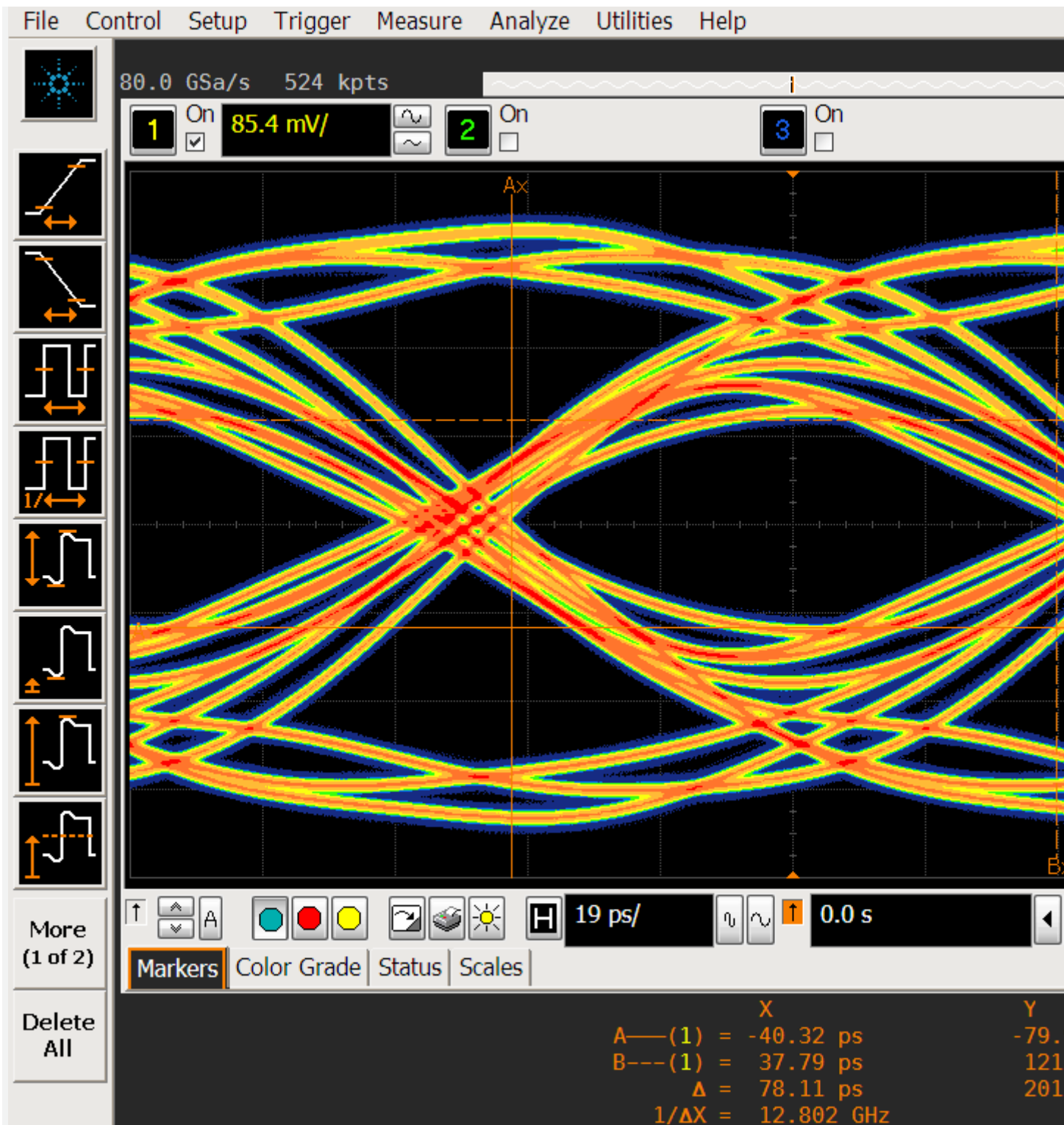


Figure 1: 10 Gbase KR signal with significant ISI

Intrinsic jitter or sample clock jitter

Real-time oscilloscopes sample data very fast, at up to 120 GSa/s, which means keeping data points in alignment is extremely important. All sample points must be aligned in time by the oscilloscope.

To align the sample points, an oscilloscope could use a chip or a system known as the time base, which provides the necessary tight time correlation needed between the sampled input signals delivered to analog to digital converter and the internal clock. The clock itself has a jitter specification, along with how well it is able to align the points of the oscilloscope through its time base. The jitter specification of the entire oscilloscope time base is known as the sample clock jitter, or also can be called the oscilloscope's *intrinsic jitter*.

Oscilloscope vendors differ in how they specify intrinsic jitter. For instance, the Agilent 90000 X-Series oscilloscope (**Figure 2**) specifies its intrinsic jitter at 150 femtoseconds (fs) as its sample clock jitter. Other vendors call this the jitter measurement floor (which will be discussed later). Intrinsic jitter is the absolute best an oscilloscope can do for its jitter measurement of time interval error. In other words, intrinsic jitter shows an absolute best-case jitter measurement for an oscilloscope.

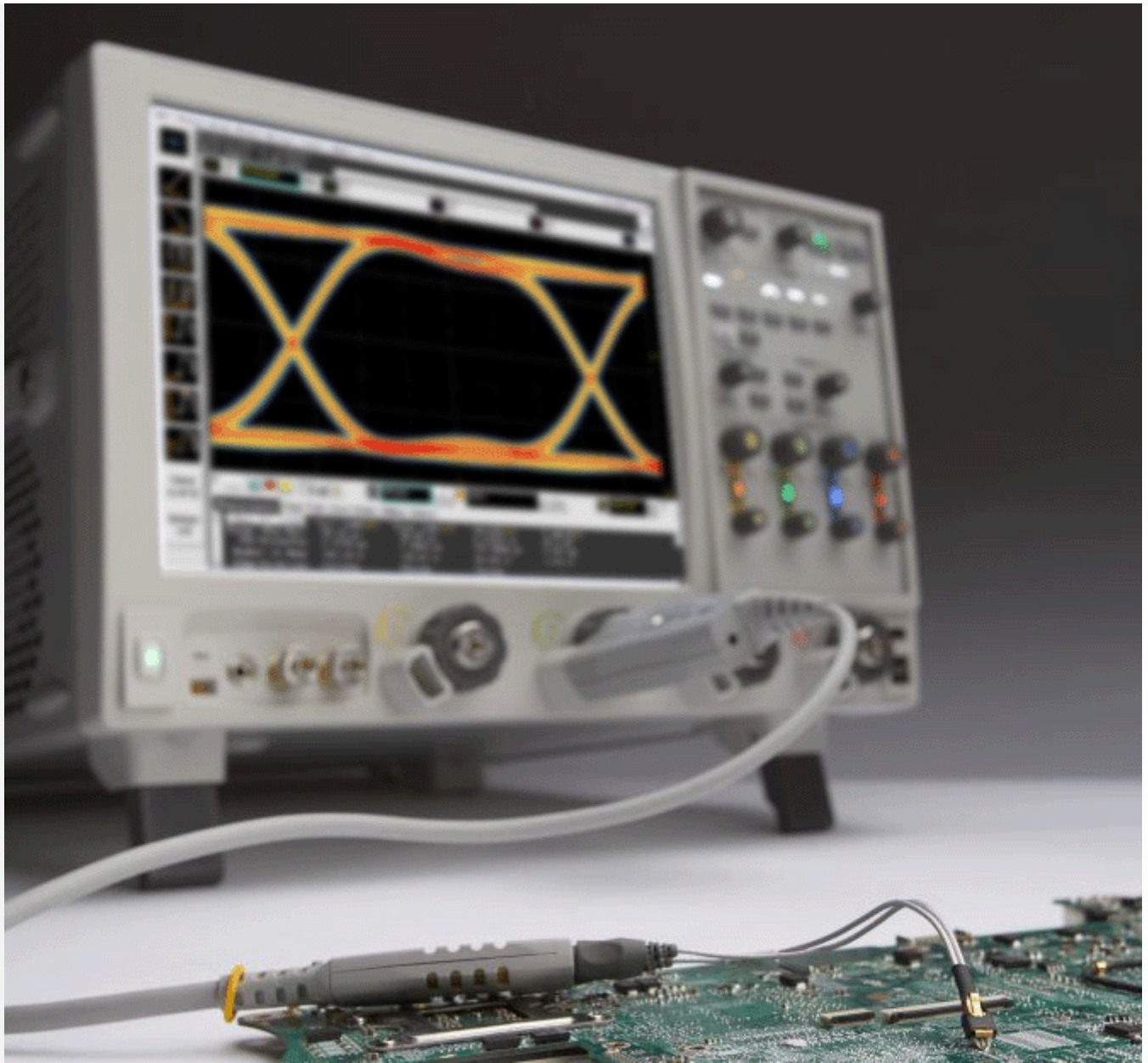


Figure 2: Infiniium 90000 X Series oscilloscope

Jitter measurement floor

While intrinsic jitter explains what is the theoretical best-case jitter of an oscilloscope (in other words, what the jitter would be, if there were no other variables present), the specification by itself will not allow the user to know how much jitter an oscilloscope will contribute to a measurement. One of the largest contributors to oscilloscope jitter is oscilloscope noise, which is unaccounted for using only the sample clock jitter specification. Jitter measurement floor (JMF) takes into account the oscilloscope noise floor. An example of the oscilloscope jitter measurement floor can be taken from the Agilent 90000 X-Series data sheet:

$$\sqrt{\left(\frac{\text{Noise}}{\text{SlewRate}}\right)^2 + \text{SampleClockJitter}^2}$$

Notice that the specification has three components, the aforementioned sample clock jitter, noise, and slew rate. It is important to have all three components in the specification. Oscilloscope data sheets which only give one number, such as 200 fs, are only specifying their best-case jitter or sample clock jitter, but are not properly representing their jitter measurement floor in their data sheet.

So why are the three specifications used into a single jitter measurement floor specification? Again, noise influences oscilloscope jitter. The slower the rise time or slew rate, the more oscilloscope noise influences the jitter contribution of the oscilloscope. While oscilloscope noise is not typically considered a horizontal specification, a slow rise time allows for noise to effect the horizontal measurement.

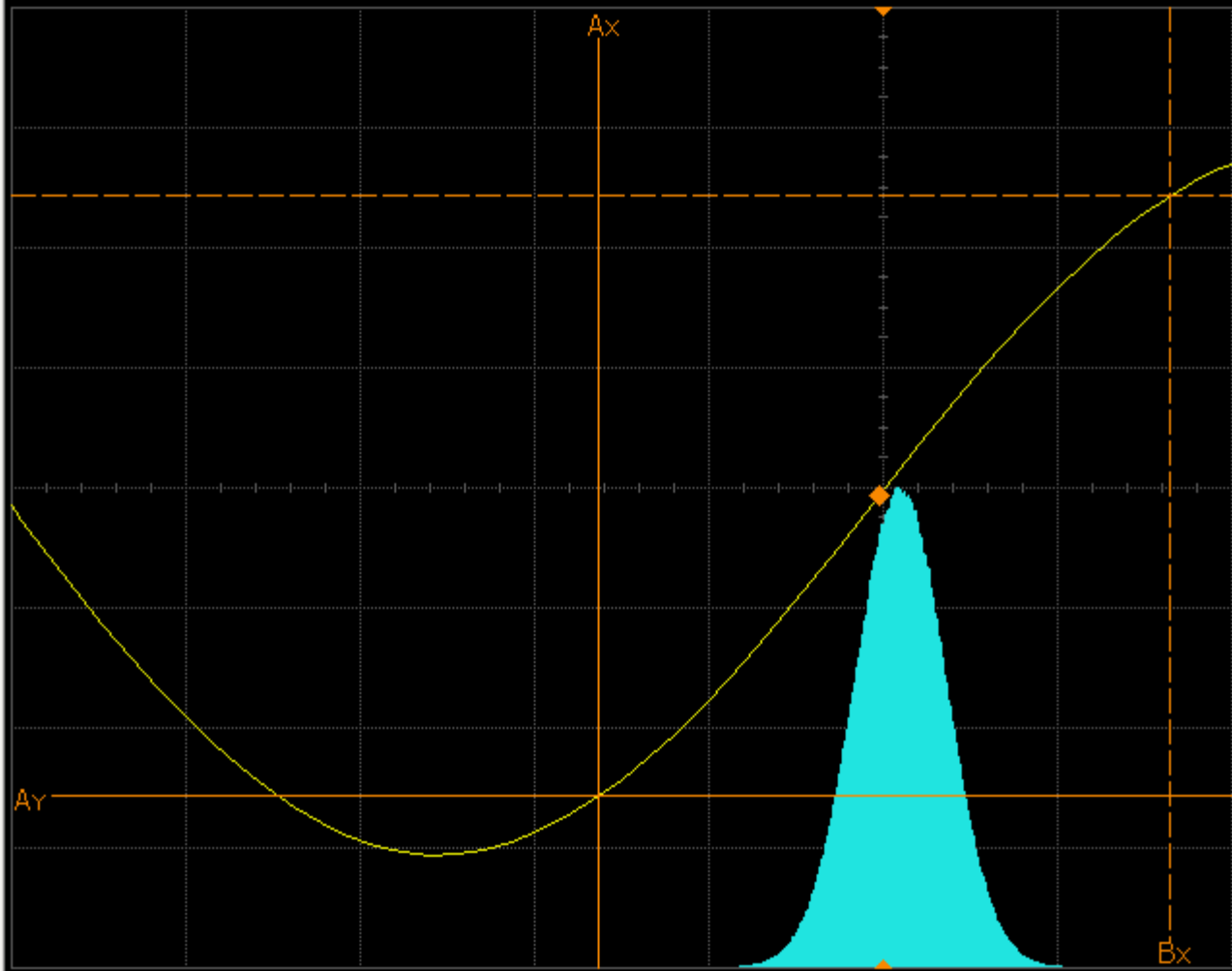
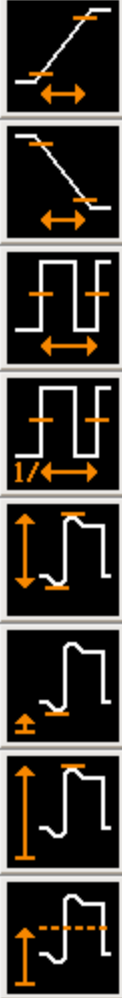
This phenomenon can be seen by looking at the time interval error of different sine wave frequencies.

Notice that for a 20 GHz sine wave, the oscilloscope has a time interval error of 190 fs (**Figure 3a**). Now the sine wave is slowed to 5 GHz and the time interval error is 400 fs (**Figure 3b**). The third mage (**Figure 3c**) shows an entire jitter versus frequency curve of the 90000 X-Series.



80.0 GSa/s 524 kpts

1 On 85.0 mV/ 2 On 3 On



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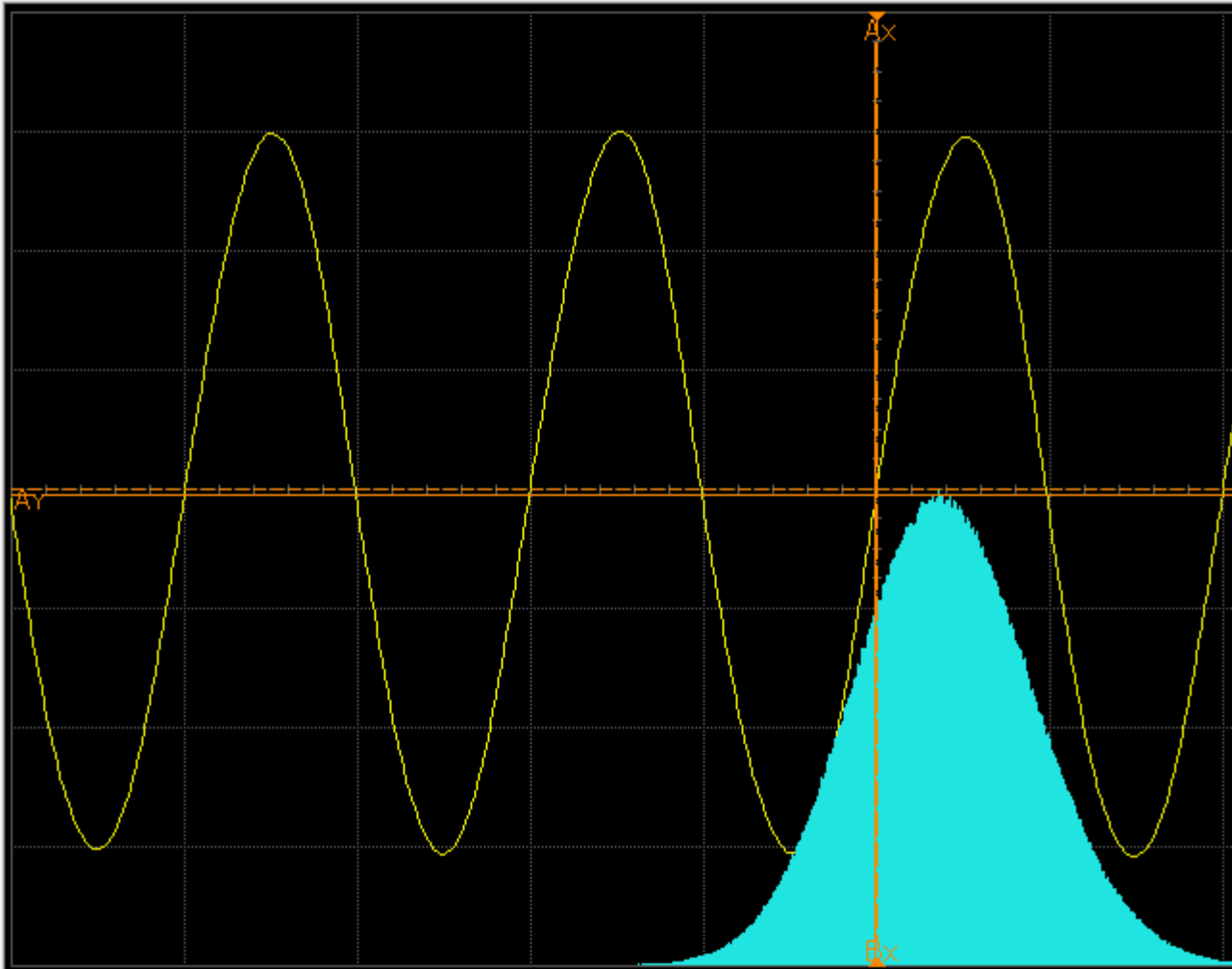
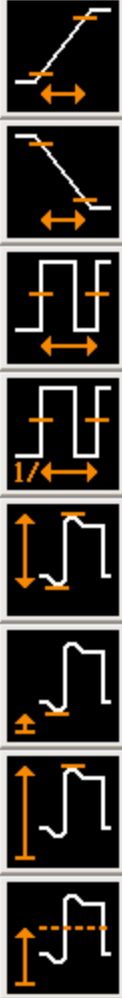
↑ **H** 5 ps/ 0.0 s

Measurements		Markers	Histogram	Status	Scales
Measurement	Clock TIE(1)		Mean	-964.59 as	p-p 1.37204
Y Scale	4.344 khits/		Std Dev	129.612 fs	Min -736.79 f
Y Offset	0 hits		$\mu \pm 1\sigma$	68.7%	Max 635.25 f
X Scale	500.00 fs/		$\mu \pm 2\sigma$	95.6%	Bin Width 1.94 fs
X Position	-50.09 fs		$\mu \pm 3\sigma$	99.7%	



80.0 GSa/s 524 kpts

1 On 85.0 mV/ 2 On 3 On



More (1 of 2)

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↑ [Zoom In] [Zoom Out] [Color Select] [Markers] [Histogram] [Status] [Scales] [H] 50 ps/ [Waveform] [Trigger] 0.0 s

Measurements		Markers	Histogram	Status	Scales
Measurement	Clock TIE(1)		Mean	-1.60422 fs	p-p 2.87757
Y Scale	3.689 khits/		Std Dev	256.267 fs	Min -1.63522
Y Offset	0 hits		$\mu \pm 1\sigma$	68.6%	Max 1.24235
X Scale	500.00 fs/		$\mu \pm 2\sigma$	95.5%	Bin Width 3.21 fs
X Position	-196.43 fs		$\mu \pm 3\sigma$	99.7%	

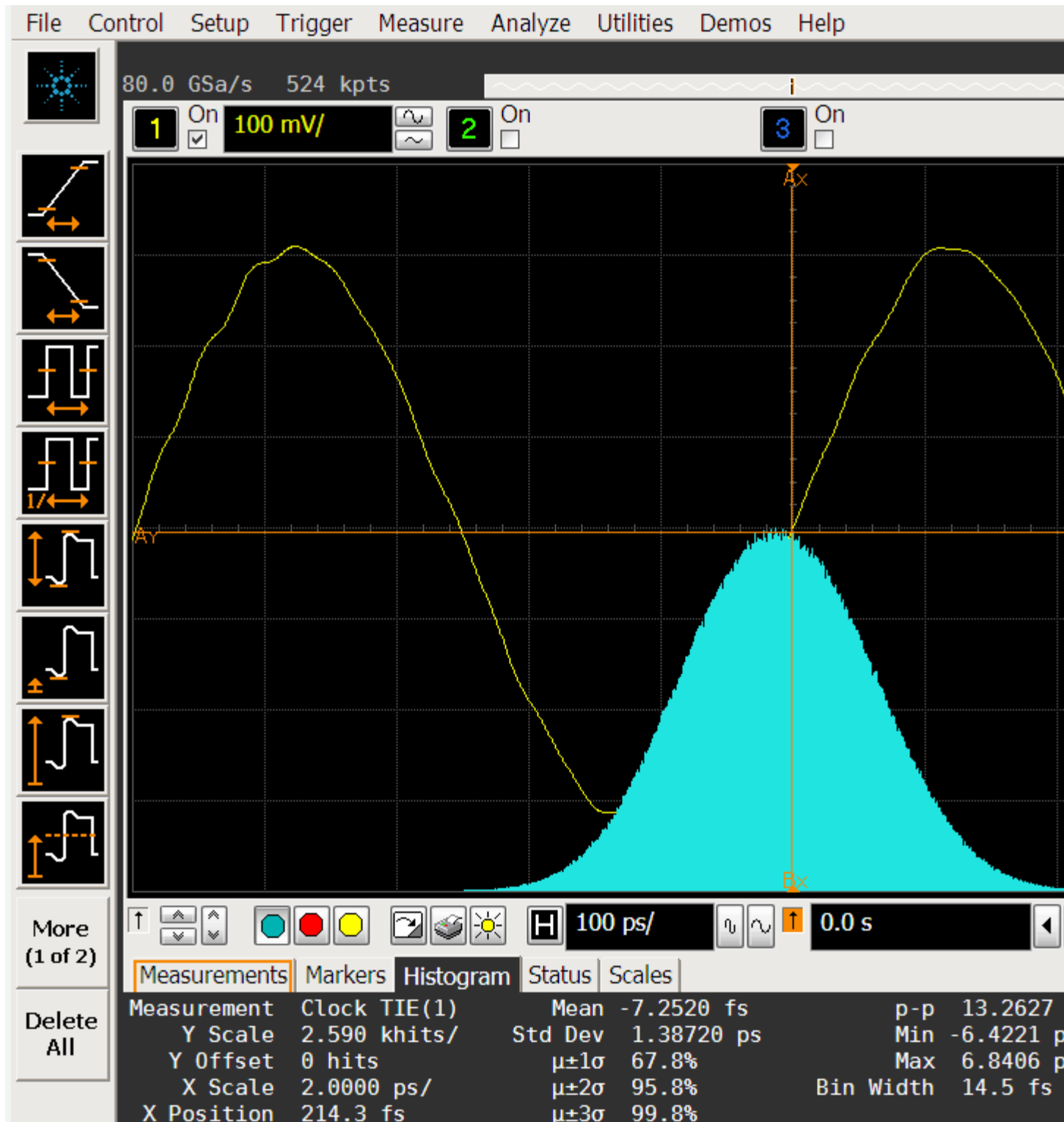


Figure 3: Notice how the jitter measurement increases as the frequency decreases; images show frequencies of a) 20 GHz, b) 10 GHz, and c) 2 GHz, top to bottom.

Notice that as the sine wave frequency increases to above 30 GHz, the jitter measurement floor approaches the sample clock jitter specification of 150 fs. Sine wave frequencies' slew rates become faster as the frequency increase. At 30 GHz, the slew rate is over ten times faster than a sine wave running at 5 GHz, which means significantly less oscilloscope noise contributing to the time interval error of the measurement.

Long term jitter

Another specification which affects jitter is the long-term jitter of the oscilloscope. As an oscilloscope's memory increases the time base must align even more sample points at extremely fast rates. This problem has been exasperated in recent years by oscilloscopes offering deeper memory.

In fact, now oscilloscopes offer up to 2 Gpts of data, which puts extreme stress on the oscilloscope's time base. In addition to deeper memory, chip manufacturers are separating jitter on longer patterns, such as PRBS23 or PRBS31. To properly separate random jitter from deterministic jitter on a PRBS23 pattern can require up to and beyond 500 Mpts of data. At these deep memory depths an oscilloscope's long-term jitter becoming vitally important.

Long-term jitter takes into account the effects of time-base drift that an oscilloscope will experience. A time base that was not designed for deep memory will experience significant drift and will result in very large jitter measurements.

What could be even worse is the fact that a jitter measurement taken with 2Mpts of data may show a completely different answer than one taken with 100Mpts of data--not because the device under test has any more jitter, but rather because of oscilloscope drift in the time base.

How to verify jitter

Verifying the jitter specification is actually relatively easy to do; however, each oscilloscope has some caveats that you need to consider as well.

Steps to Measure Jitter:

- 1: Find a very-low-jitter sine-wave source with as much, or more, bandwidth as the oscilloscope; for instance the Agilent's E8267D has greater than 30 GHz of bandwidth and very low jitter
- 2: Connect the sine-wave generator to one of the inputs of the oscilloscope.
- 3: Start with 1 GHz on the sine-wave generator; input the sine wave into the oscilloscope
- 4: Turn on the time interval error measurement of the oscilloscope, and note the measurement (clock recovery can be set to the oscilloscope's constant clock recovery setting).

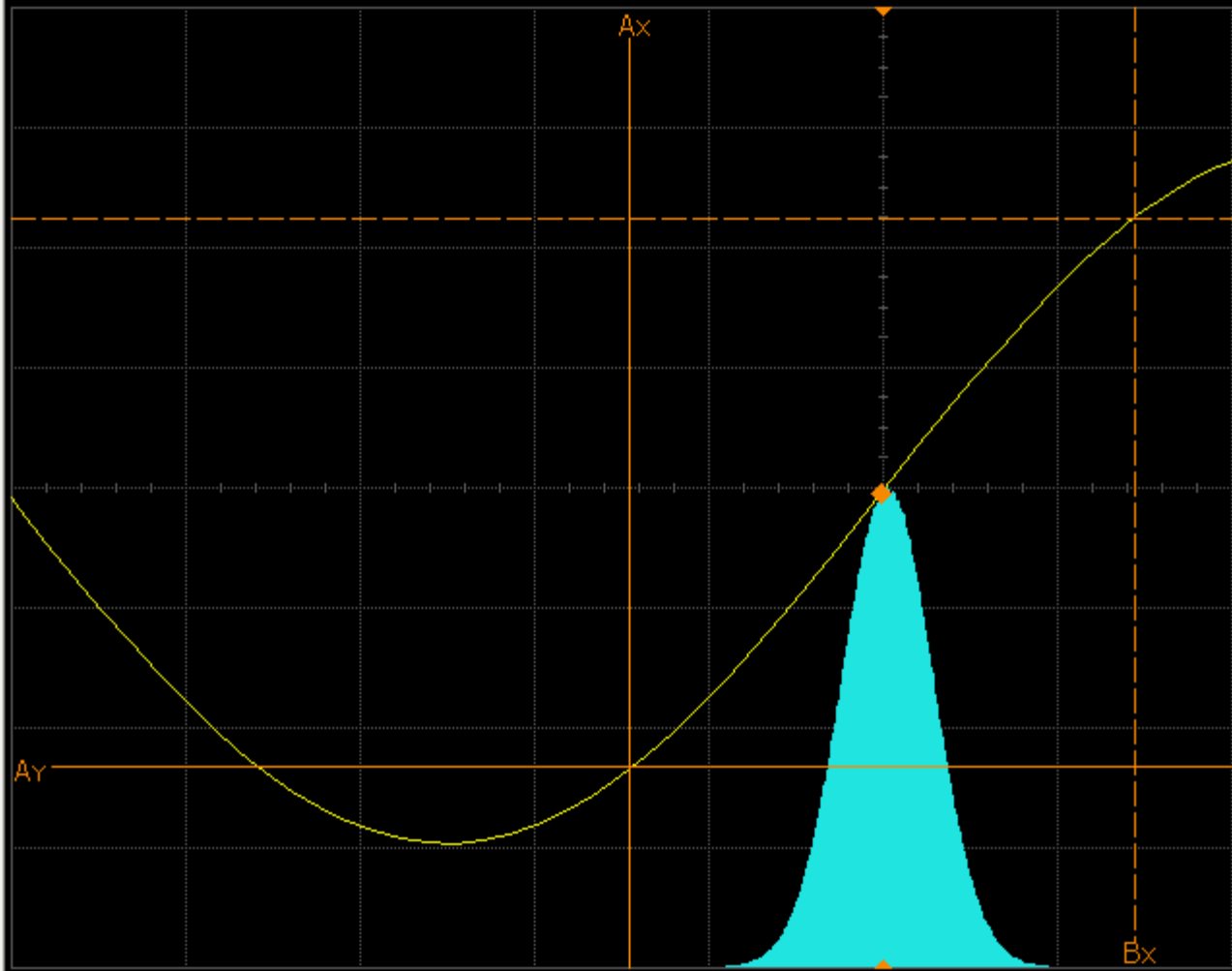
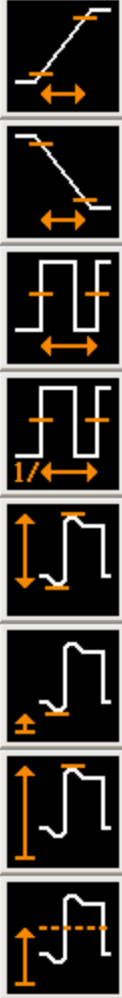
This is the first measurement of the jitter measurement floor curve; we now repeat Steps 2 to 4 in either 1 GHz or 500 MHz steps to the bandwidth of the oscilloscope.

Notice that the jitter measurement floor will decrease as the bandwidth of the sine wave increases. This is because the faster the rise time, the less noise that contributes to the jitter measurement floor, **Figure 4**.



80.0 GSa/s 524 kpts

1 On 85.0 mV/ 2 On 3 On



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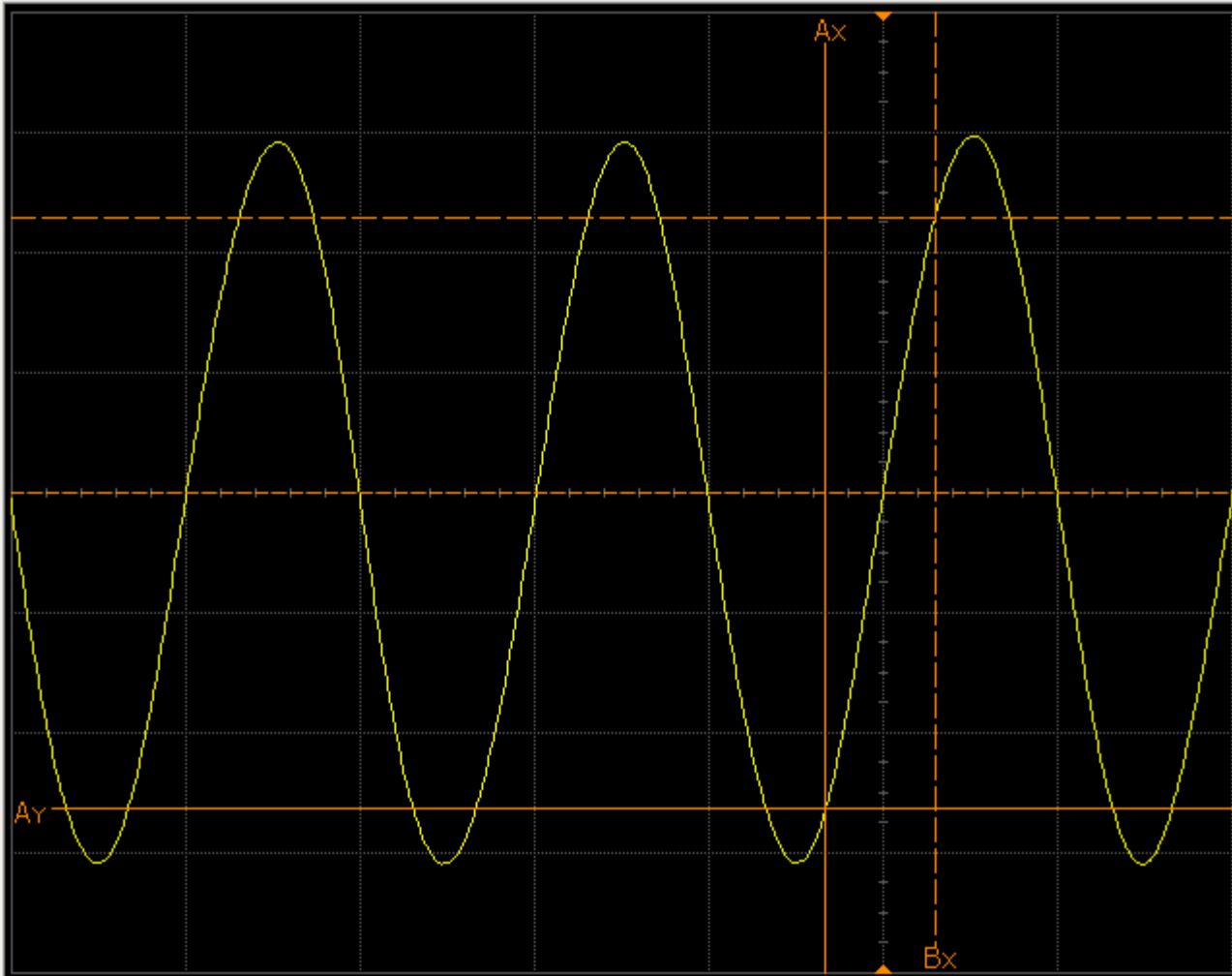
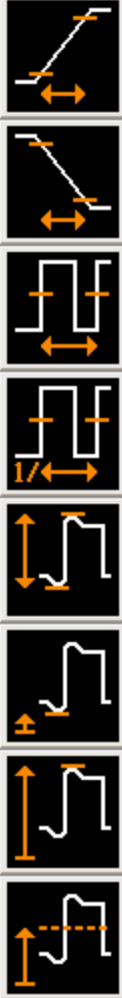
↑ H 5 ps/ 0.0 s

Measurements	Markers	Histogram	Status	Scales
Meas All Edges	Rise time(1♦)			Clock TIE(1)
Current	15.48 ps			70 fs
Mean	15.0466 ps			0.0 s
Min	12.20 ps			-740 fs
Max	18.40 ps			710 fs



80.0 GSa/s 524 kpts

1 On 85.0 mV/ 2 On 3 On



More (1 of 2)

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↑ [Zoom] [Color] [H] 50 ps/ [Waveform] [Trigger] 0.0 s

Measurements Markers Status Scales

Meas	All	Edges	Frequency(1)	Rise time(1)
	Current		10.010 GHz	34.73 ps
	Mean		10.000109 GHz	33.3784 ps
	Min		9.8413 GHz	29.53 ps
	Max		10.158 GHz	36.88 ps

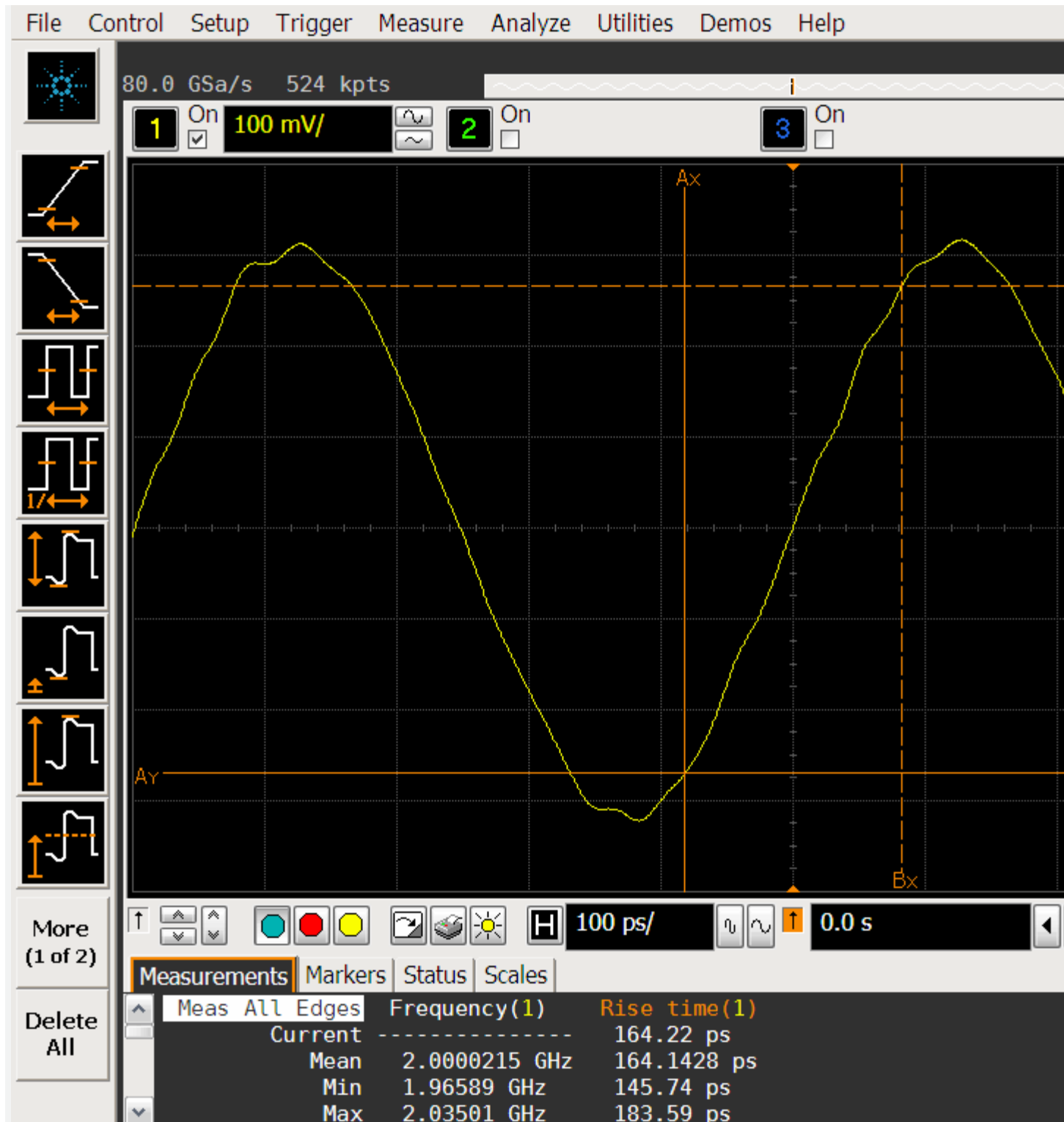


Figure 4: The rise times also increase as the frequencies decrease, which increases the oscilloscope noise contribution in the jitter measurement; images show frequencies of a) 20 GHz, b) 10 GHz, and c) 2 GHz, top to bottom.

If you are measuring rise times slower than 30 ps, than noise is actually the greater contributor to the jitter measurement floor than the sample clock jitter of the oscilloscope. Also, as the amplitude and offset of the sine wave are changed, the oscilloscopes will give different results. For instance, one brand of oscilloscope is very sensitive to offset changes and its jitters get significantly worse by adding offset to it. Another brand of oscilloscope is optimized with 75% of scale input, as you increase above 90% of scale the jitter measurement floor increases.

If time allows, it is a useful exercise to change variables such as amplitude, offset, and percentage of screen of input, and measure the same jitter measurement floor curve. Figure 4 also shows the jitter measurement floor of the 90000 X-Series. Notice that at sine wave frequencies of >20 GHz, it nears its intrinsic jitter of 150 fs.

Other considerations

Similar to the rise-time specification of an oscilloscope, if the jitter of the scope is close to the jitter of the measurement, the oscilloscope will actually contribute more jitter to your measurements. The only way to see the theoretical lowest jitter of the oscilloscope is to have significantly lower jitter on the device. For instance, if the jitter of the device is 150 fs and the scope's lowest jitter measurement floor is 150 fs, you can expect to have 30-40% error added to the jitter measurement. This means that, at best, you would see a jitter measurement of 200 fs from the real time oscilloscope.

Conclusion

The jitter specification is one of the most important specifications of the oscilloscope. Simply reading a data-sheet jitter measurement of 200 fs is not enough. The oscilloscope user needs to understand what the oscilloscope vendor is specifying.

Is the vendor only specifying sample clock jitter? In most cases, vendors will specify sample-clock jitter (intrinsic jitter), as opposed to the jitter measurement floor. Ultimately it is the jitter measurement floor that determines what the true jitter of the oscilloscope. Jitter measurement floor combines sample clock jitter and noise floor, by adding a slew rate component. The jitter measurement floor varies by slew rate, so it is important to find the needed slew rate and test the jitter measurement floor at that point.

While it takes additional to time to evaluate an oscilloscope in this way, the payoff is more accurate measurements with a lower total jitter measurement, which means faster time to market on designs.

About the author



Brig Asay is Product Manager, High Performance Oscilloscopes, in the Digital Test Division – Scopes of the Electronic Measurements Group at Agilent Technologies, where he manages product planning and strategic marketing for Agilent’s high performance oscilloscope business. Brig joined Agilent Technologies in 2005 as a Technical Support Engineer. During his 5 years with Agilent, he has been a Marketing Operations Manager, where he oversaw the marketing budget and managed the technical support and learning products teams, and a Technical Support Engineer, which he helped solve numerous customer problems. Previous to Agilent, Brig worked at Micron Technologies, Inc. as a Test Engineer. Brig graduated with an MBA from Northwest Nazarene University and BS Electrical Engineering from the University of Wyoming. He is a published technical author.