Understanding Oscilloscope

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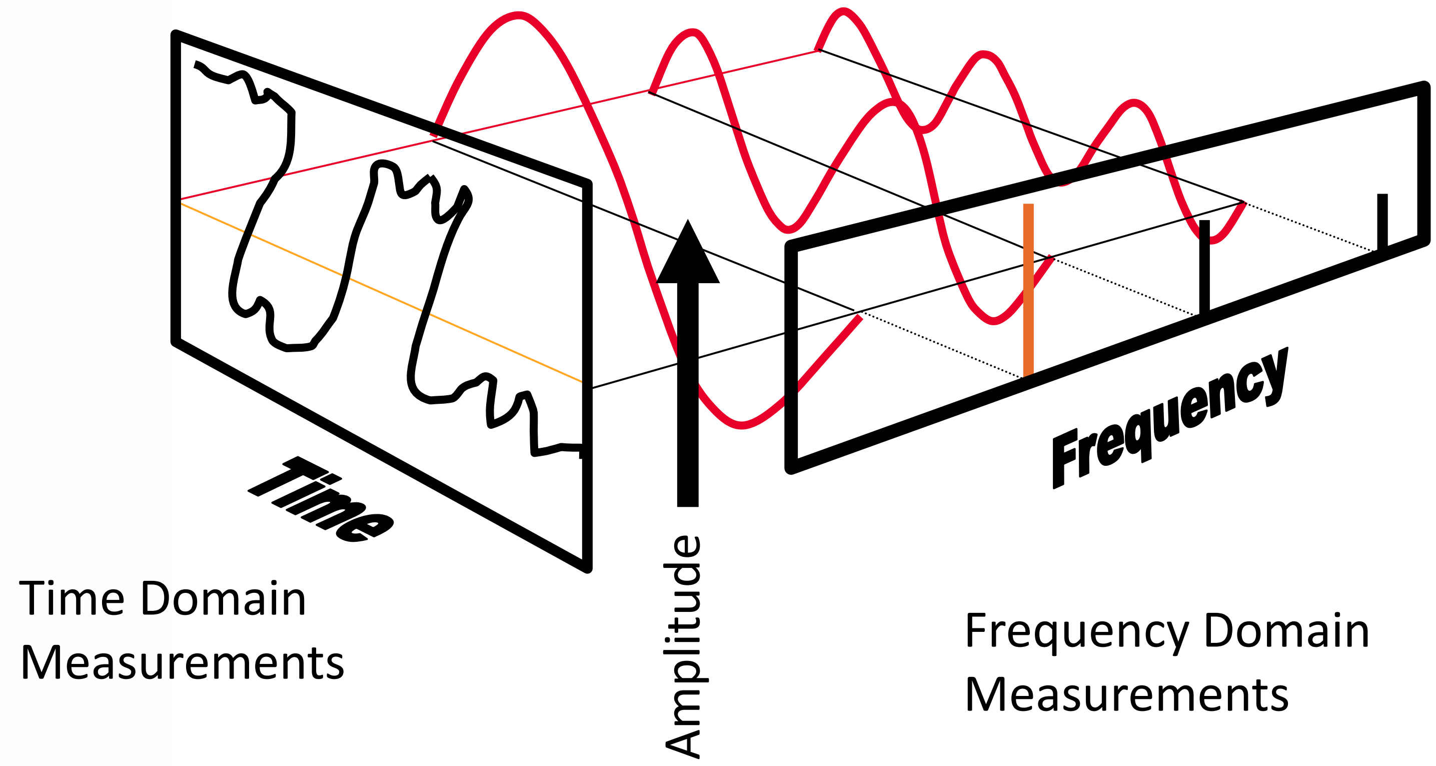
KEYSIGHT TECHNOLOGIES

Time Domain vs. Frequency Domain



Time Domain vs. Frequency Domain

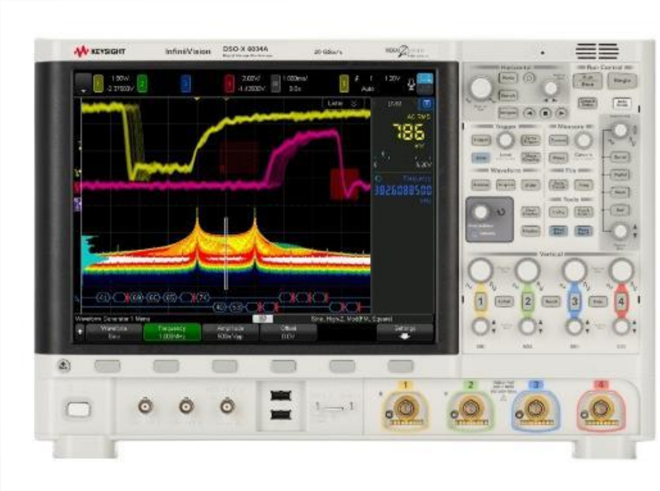
MEASUREMENT DEVICES

Time Domain Applications

Oscilloscope

Signal Analyzer

Network Analyzer



Frequency Domain Applications

Spectrum Analyzer

Network Analyzer

FFT Analyzer

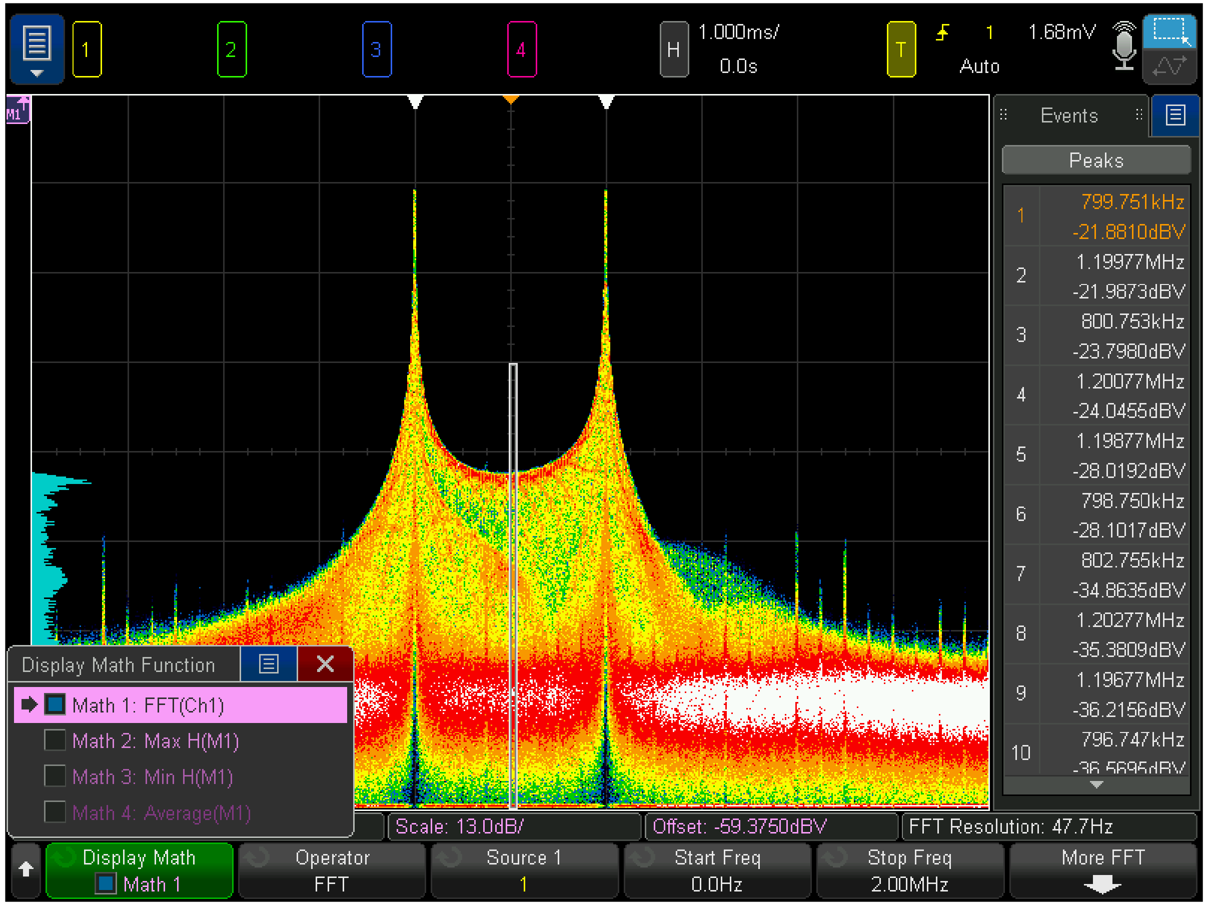
Signal Analyzer

FFT function on an Oscilloscope

Time Domain vs. Frequency Domain

HOW TO CONVERT BETWEEN THE TWO – OR HAVE BOTH!

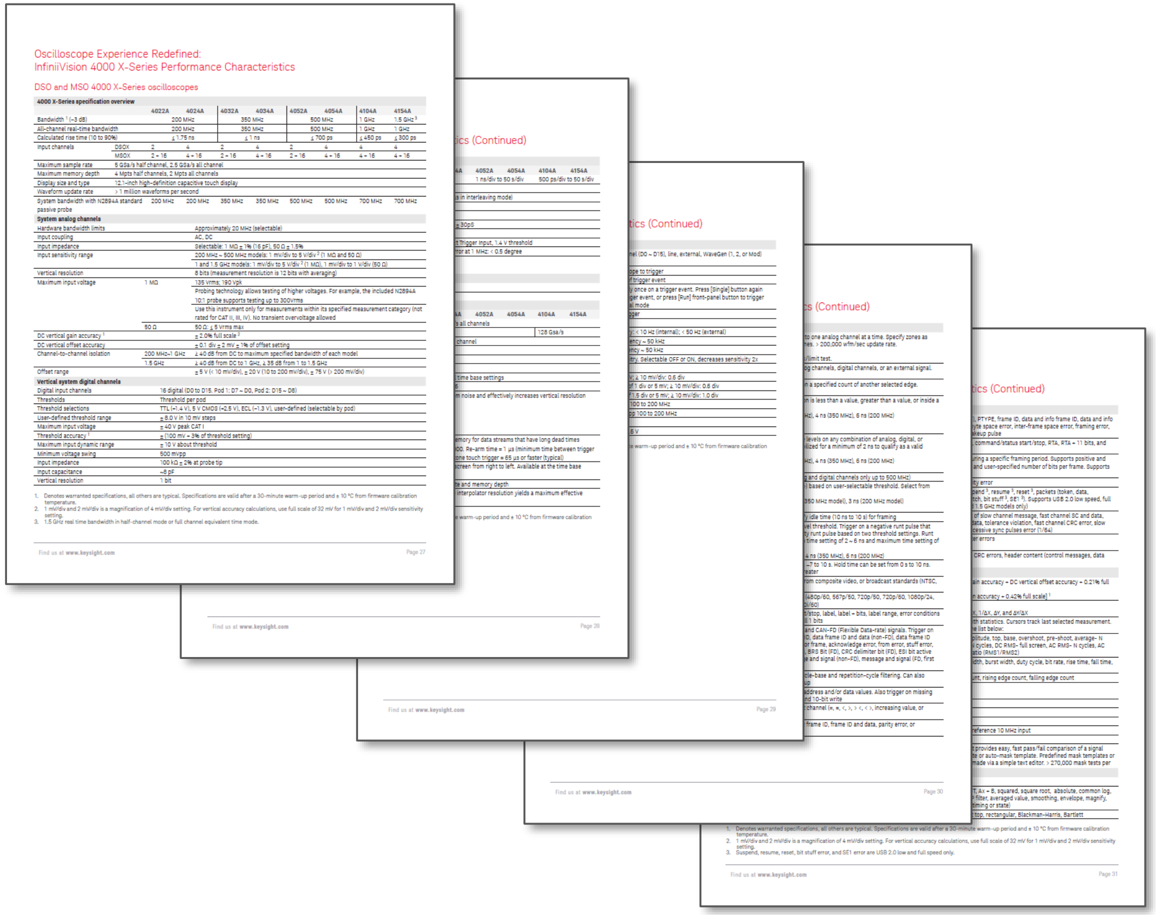
- A mathematical conversion between time and frequency domain can always be performed
- Fast Fourier Transform (FFT) – less calculations
- FFT - easily processed by a computer
- Alternative ways of representing the same signal
- Some behavior is seen easier in one domain



Objective

UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

Understanding and comparing oscilloscopes specifications and characteristics can be a daunting task. Which ones are important and which ones aren't so important? During this virtual seminar we will answer these questions along with many others you may have concerning oscilloscope specifications.

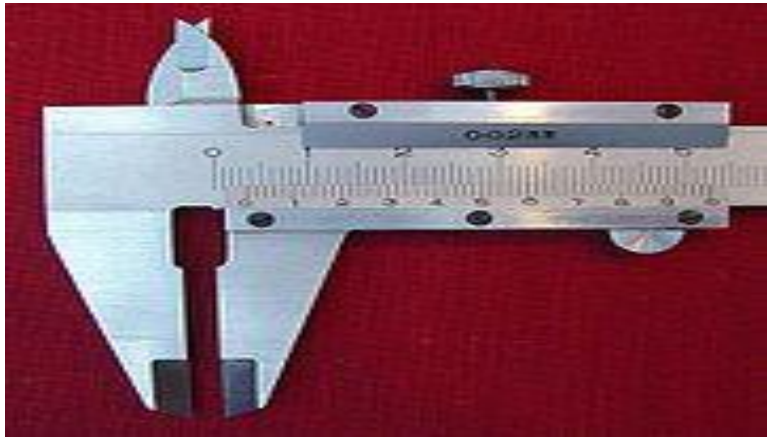


Specification versus Characteristic

UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

Specification:
A warranted and factory-tested technical standard of the oscilloscope based on NIST traceability. Examples include bandwidth, gain accuracy, and timebase accuracy.

Characteristic:
A non-warranted and non-tested capability of the oscilloscope. Examples include number of channels, number of ADC bits, and memory depth.



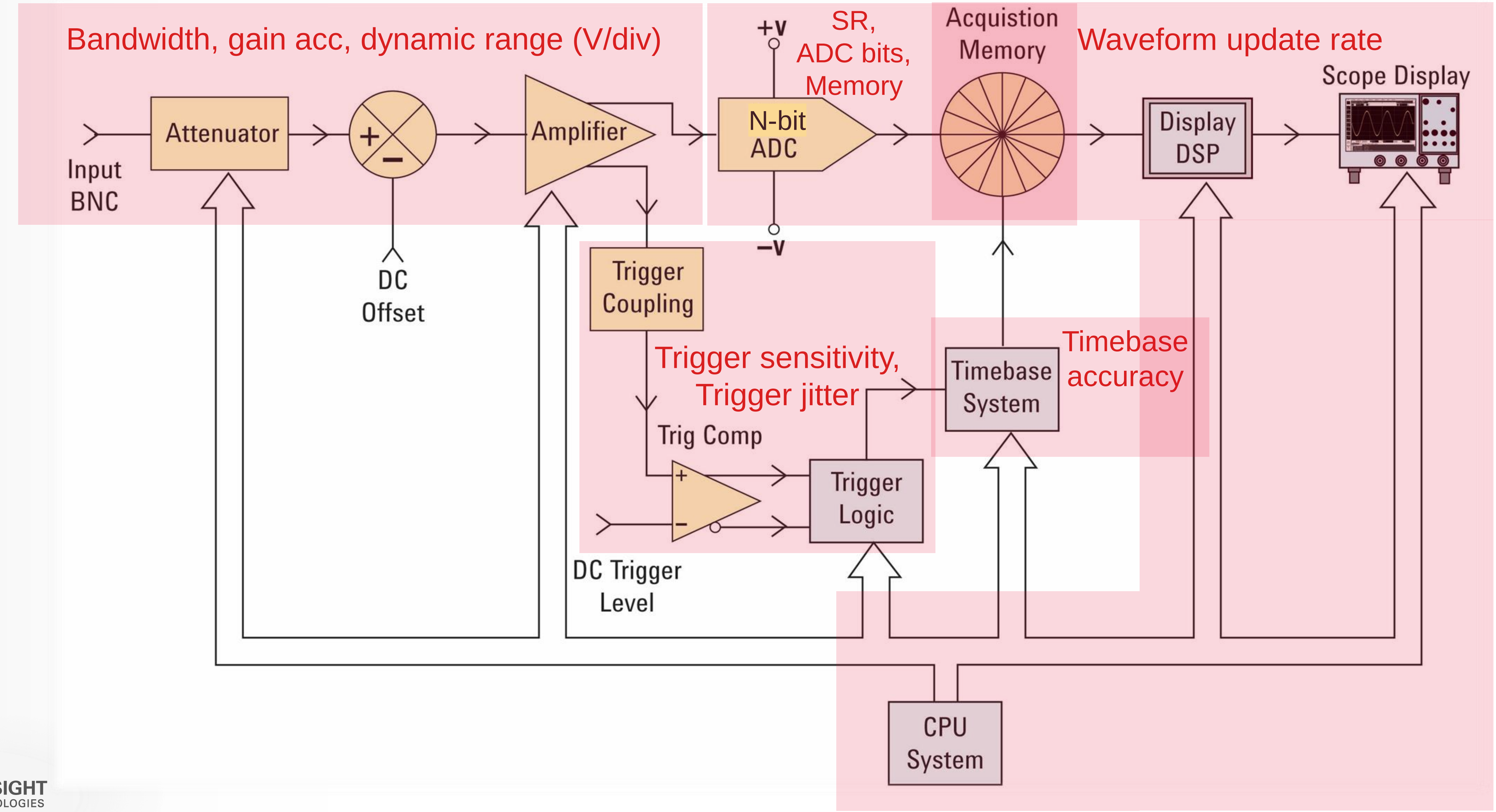
Agenda

UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

- Bandwidth and rise time
- Sample rate
- Memory depth
- Waveform update rate
- ADC bits of resolution, vertical noise, and ENOB
- Vertical sensitivity (V/div) and gain accuracy
- Timebase accuracy
- Trigger sensitivity and trigger jitter

Oscilloscope block diagram

FRONT-END SIGNAL CONDITIONING SCALES SIGNAL FOR ADC CONVERSION



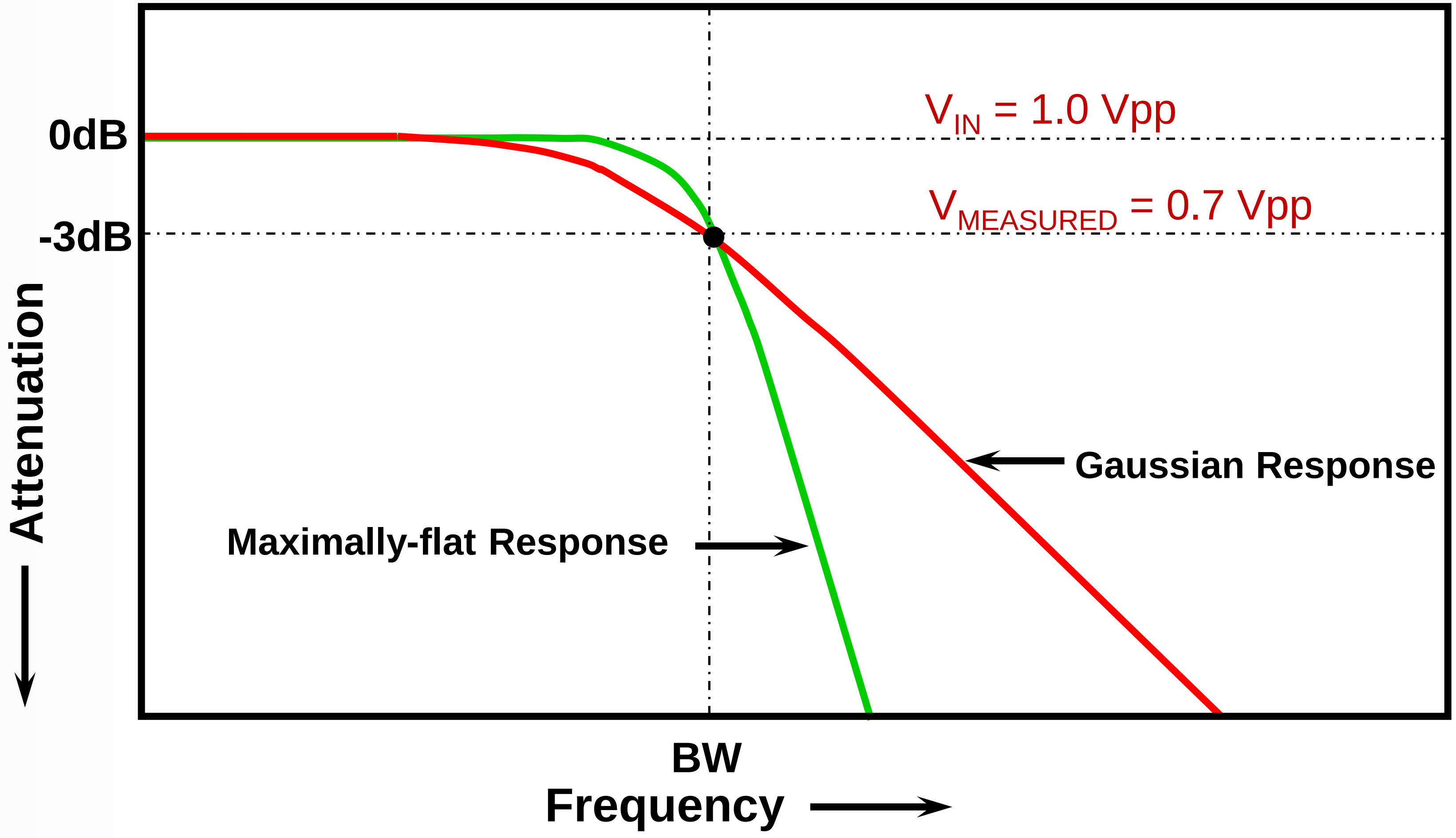
Bandwidth Basics

THE DEFINING CHARACTERISTIC OF AN OSCILLOSCOPE

- Defines the fastest signal the oscilloscope can capture. Any signals faster than the bandwidth of the scope will not be accurate, or may not even be shown at all.
- In datasheets, defined along with “rise time”.

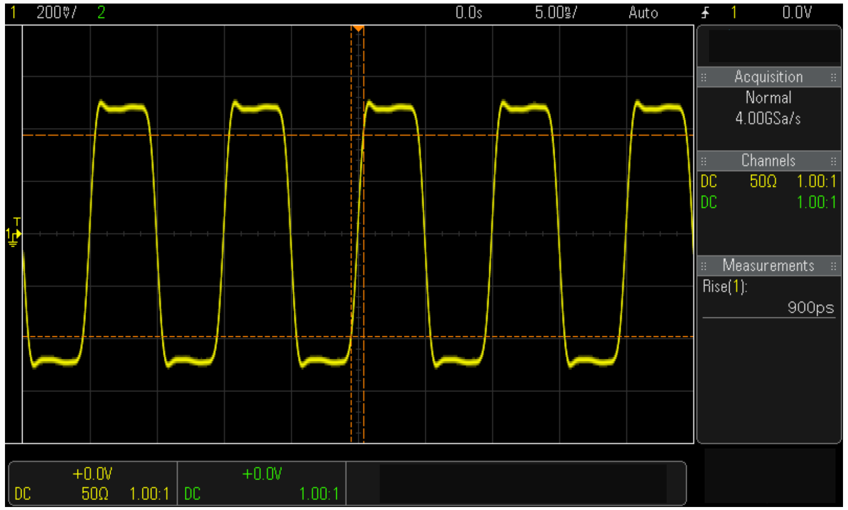
Oscilloscope Bandwidth

SPECIFIED AT FREQUENCY WHERE SIGNAL AMPLITUDE ATTENUATED BY 3dB

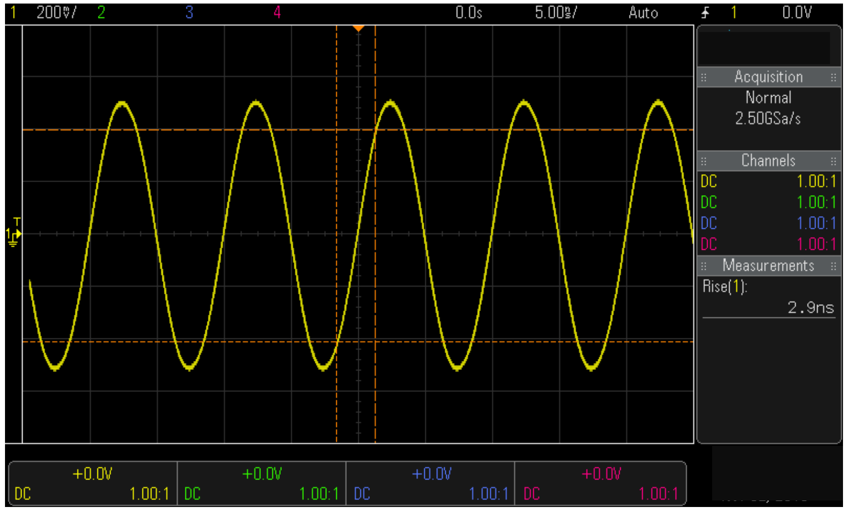


Selecting the right bandwidth

WHAT DOES A 100 MHZ CLOCK REALLY LOOK LIKE?



Response using a 500-MHz BW scope



Response using a 100-MHz BW scope

- Required BW for analog applications: ≥ 3X highest sine wave frequency.
- Required BW for digital applications: ≥ 5X highest digital clock rate.
- More accurate BW determination based on signal edge speeds.

Required bandwidth based on signal edge speed

HOW MUCH TIMING ACCURACY ARE YOU WILLING TO PAY FOR?

Step 1: Determine fastest rise/fall time of device-under-test

RT_{SIG} = 500 ps (10%-90%)

Step 2: Determine highest signal frequency content (f_{knee})

f_{knee} = 0.5/RT (10% - 90%)

f_{knee} = 0.4/RT (20% - 80%)

f_{knee} = 1.0 GHz

Step 3: Determine degree of required measurement accuracy

Let's see what we can afford

Step 4: Compute required bandwidth

Required Accuracy	Gaussian Respone	Maximally-flat Response
20%	BW = 1.0 x f_{knee}	BW = 1.0 x f_{knee}
10%	BW = 1.3 x f_{knee}	BW = 1.2 x f_{knee}
3%	BW = 1.9 x f_{knee}	BW = 1.4 x f_{knee}

BW = 1.0 GHz

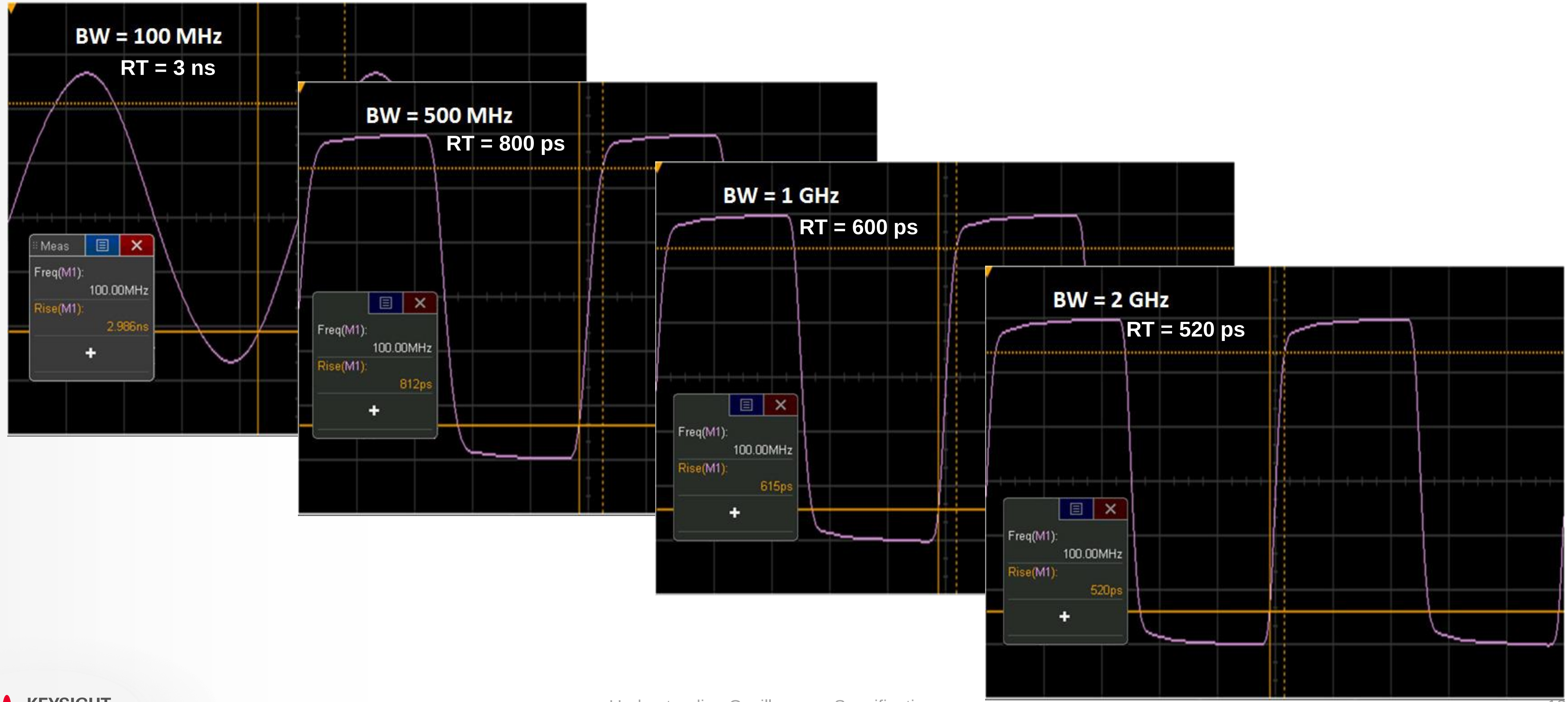
BW = 1.2 GHz

BW = 1.4 GHz

Source: Dr. Howard W. Johnson, "High-speed Digital Design – A Handbook of Black Magic"

Measurement accuracy versus bandwidth

INPUT = 100 MHZ CLOCK WITH 500 ps RISETIMES (10-90)



Direct relationship between bandwidth and risetime

RISETIME IS A THEORETICAL CHARACTERISTIC OF THE OSCILLOSCOPE

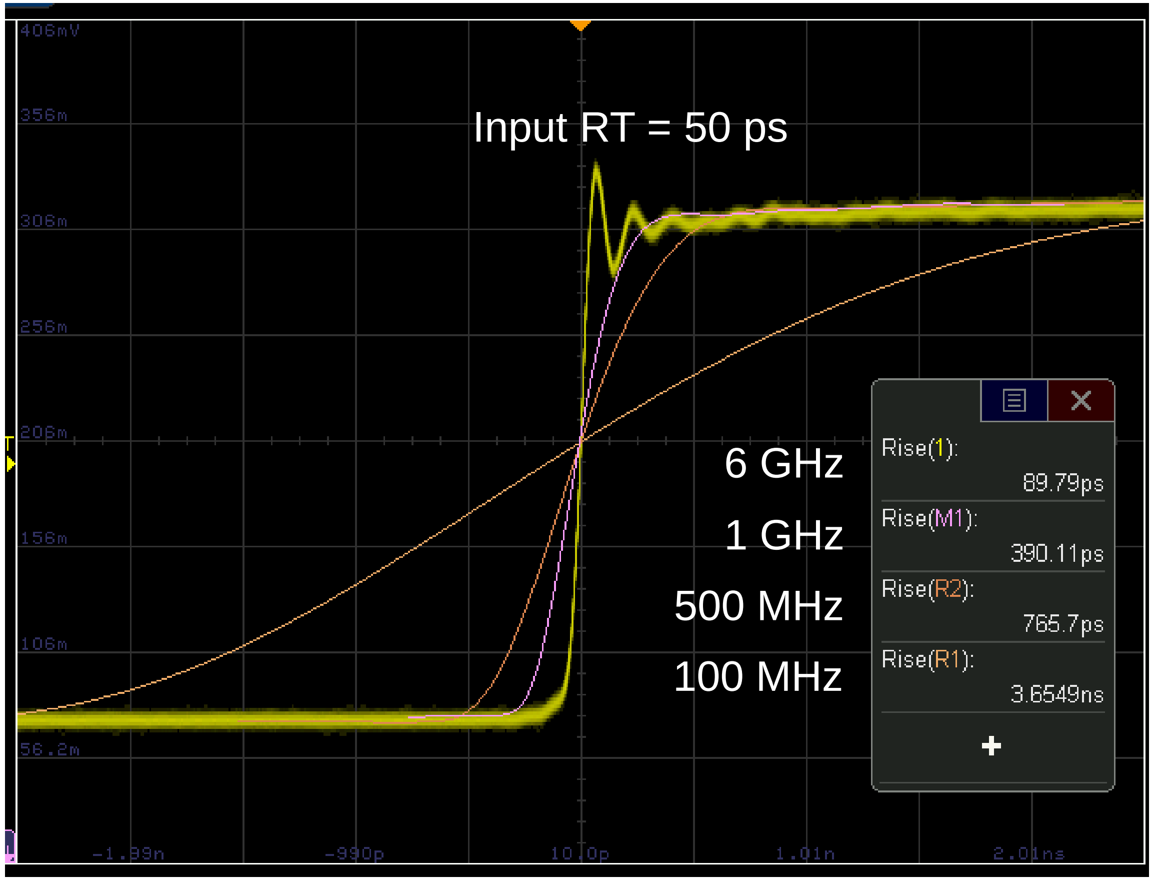
For a Gaussian system,

RT = 0.35/BW

For a maximally-flat system,

RT = ~0.45/BW

Oscilloscope risetimes are calculated and are non-verifiable (theoretical only)



$$RT_{measured} = \sqrt{(RT_{actual}^2 + RT_{scope}^2)}$$

$$BW_{system} = 1/(\sqrt{(1/BW_{probe}^2 + 1/BW_{scope}^2)})$$

Sampling Basics

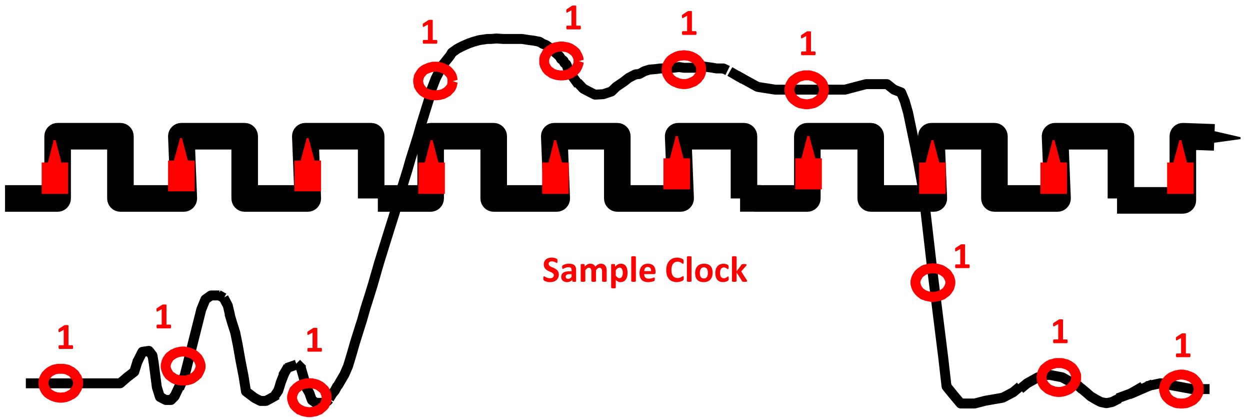
HOW OFTEN THE OSCILLOSCOPE MEASURES VOLTAGE – SAMPLE RATE

- The speed at which the oscilloscope samples the voltage of the input signal. Measured in samples per second (Sa/s)
- The signal you see on screen is actually a “connect the dots” image of up to billions of samples to create a continuous shape over time.
- The minimum sample rate varies from ~2.5x to 5x the oscilloscope bandwidth. E.g. 1 GHz needs 5 GSa/s

Sampling Basics

REAL-TIME SAMPLING

- All samples are taken on a single trigger event
- Pre-trigger acquisition is possible (data before trigger)
- Bandwidth depends on sampling frequency
- Sampling frequency is also called the digitizing rate
- Resolution of points on screen is 1/sample rate



Selecting the right sample rate

HOW MUCH SAMPLE RATE IS REQUIRED?

Professor Smart has total trust in Dr. Nyquist and says:

"2X over the scope's bandwidth."

Professor Wise doesn't trust Dr. Nyquist and says:

"10X to 20X over the scope's bandwidth."

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Selecting the right sample rate

HOW MUCH SAMPLE RATE IS REQUIRED?

Professor Smart has total trust in Dr. Nyquist and says:

"2X over the scope's bandwidth."

Professor Wise doesn't trust Dr. Nyquist and says:

"10X to 20X over the scope's bandwidth."

The truth lies somewhere in between!

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Nyquist's Sampling Theorem

NYQUIST ARTICULATED HIS SAMPLING THEOREM IN 1928

Dr. Harry Nyquist, 1889-1976

Nyquist's sampling theorem states that for a limited bandwidth (band-limited) signal with maximum frequency f_{max}, the equally-spaced sampling frequency f_s must be greater than twice of the maximum frequency f_{max}, i.e.,

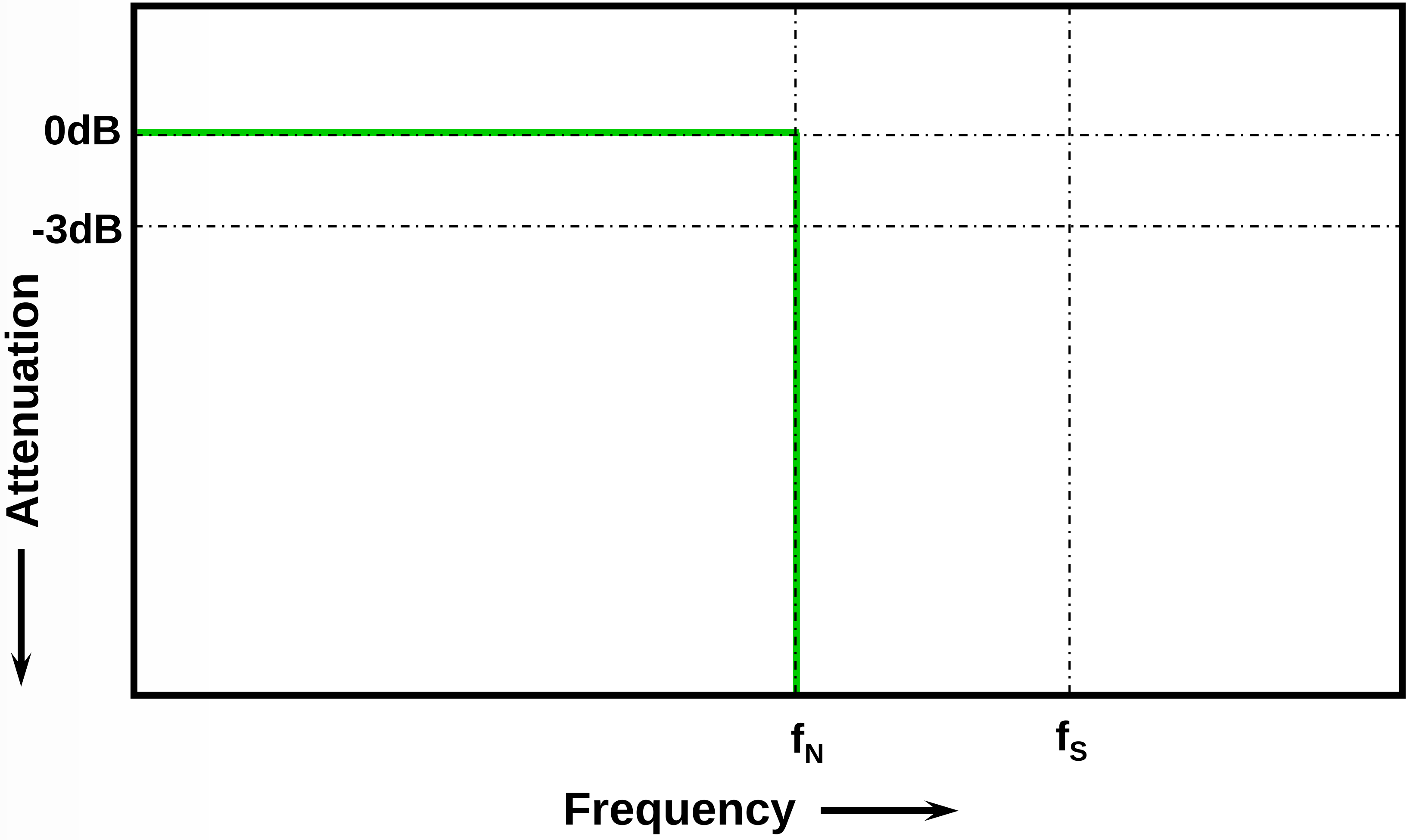
$$\mathbf{f_s > 2 \cdot f_{max}}$$

in order to have the signal be uniquely reconstructed without aliasing.

The frequency $\mathbf{2 \cdot f_{max}}$ is called the Nyquist sampling frequency (f_S). Half of this value, $\mathbf{f_{max}}$, is sometimes called the Nyquist frequency (f_N).

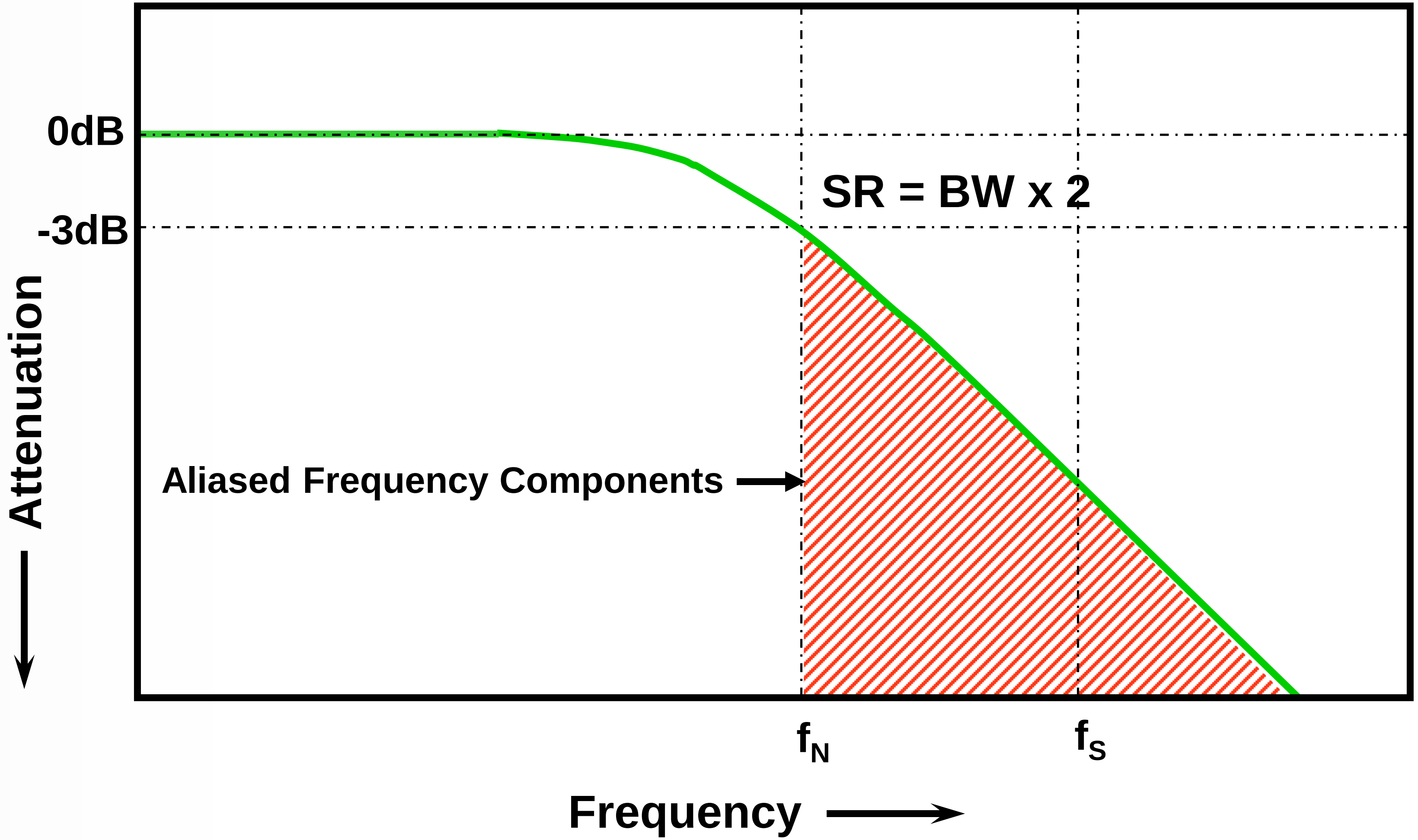
Ideal brick-wall frequency response

WITH BANDWIDTH AT NYQUIST FREQUENCY (f_N)



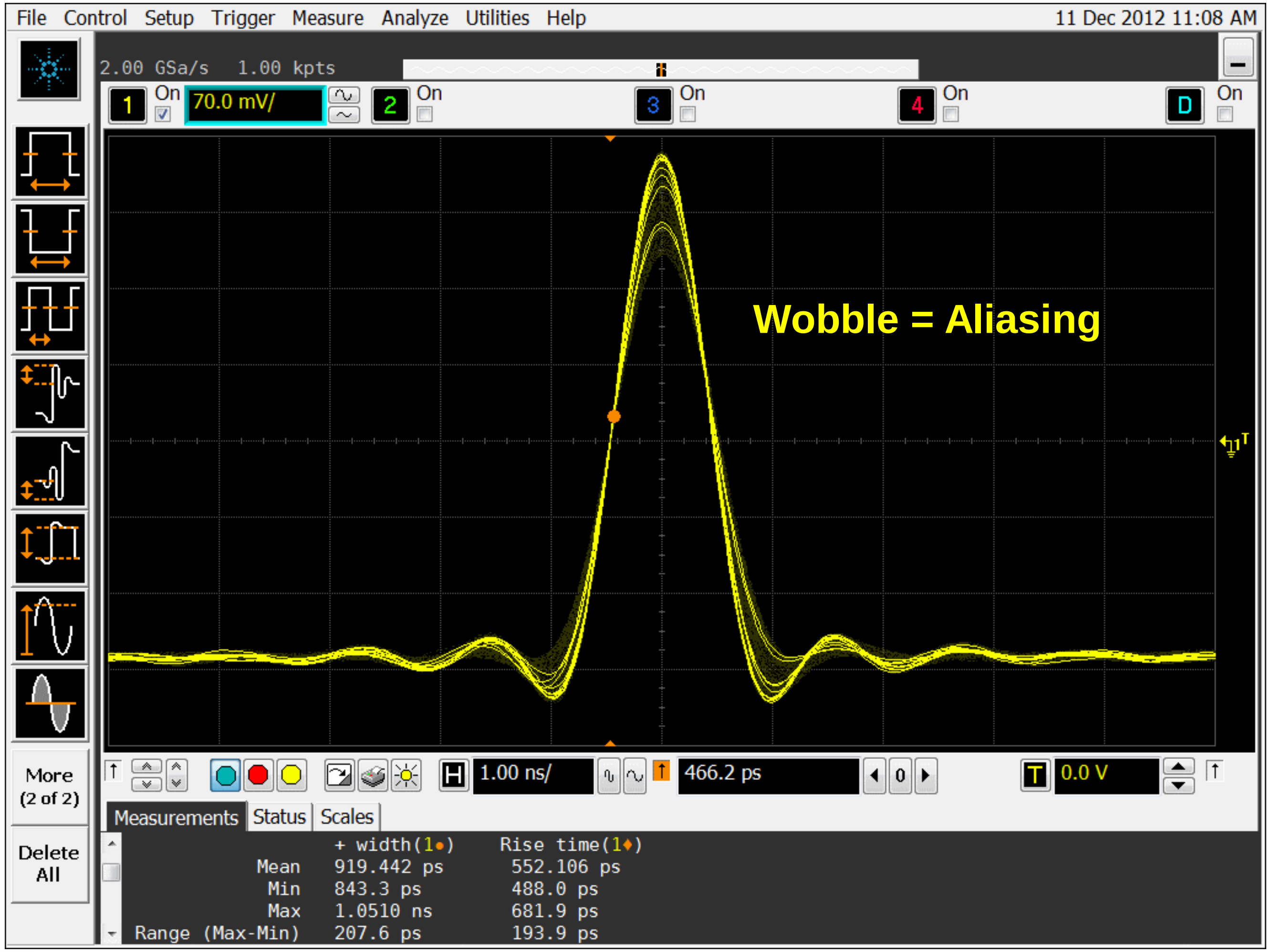
Typical Gaussian frequency response

WITH BANDWIDTH AT NYQUIST FREQUENCY (f_N)



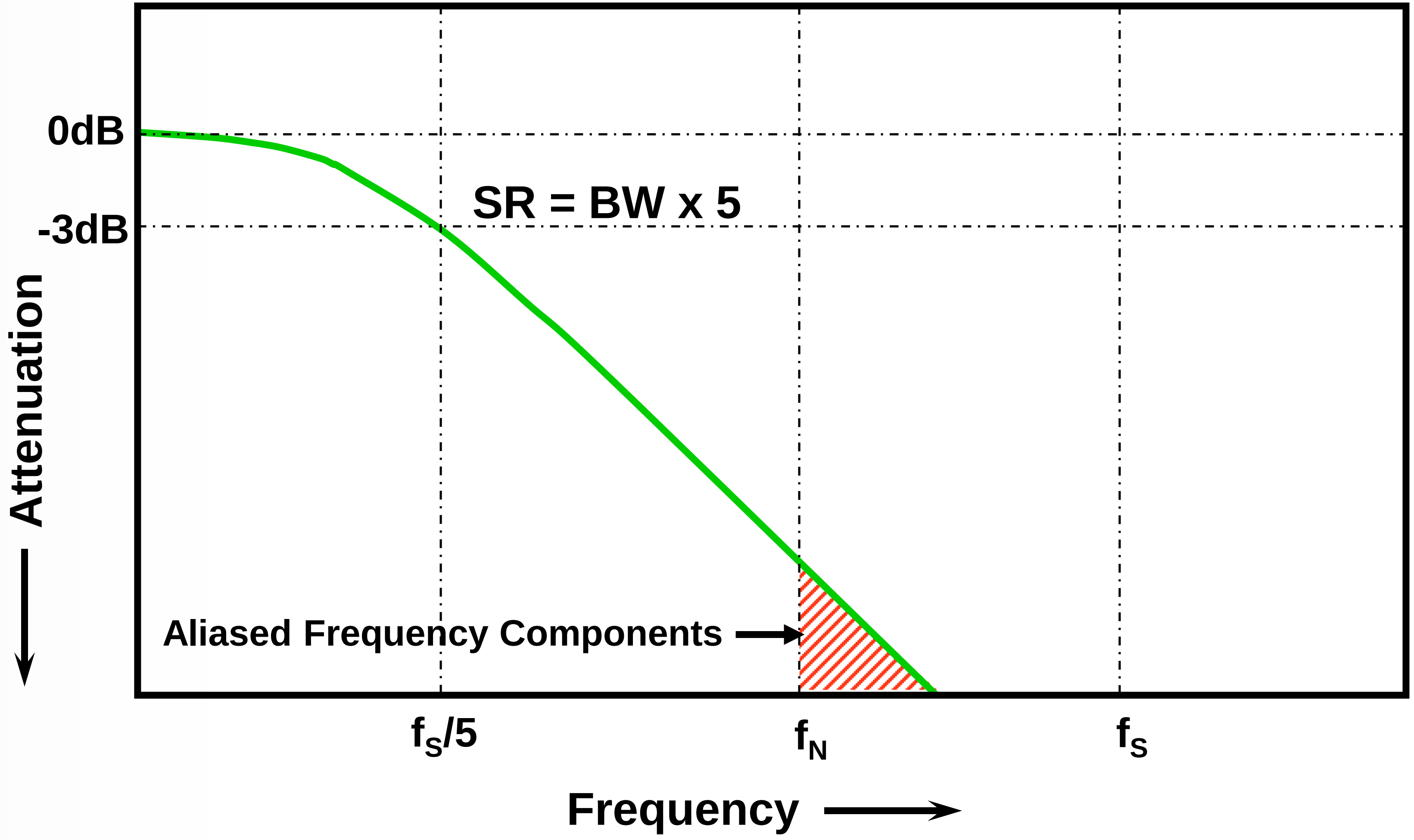
1-GHz bandwidth scope sampling @ 2 GSa/s

INPUT = 1 NS WIDE PULSE WITH VERY FAST EDGES



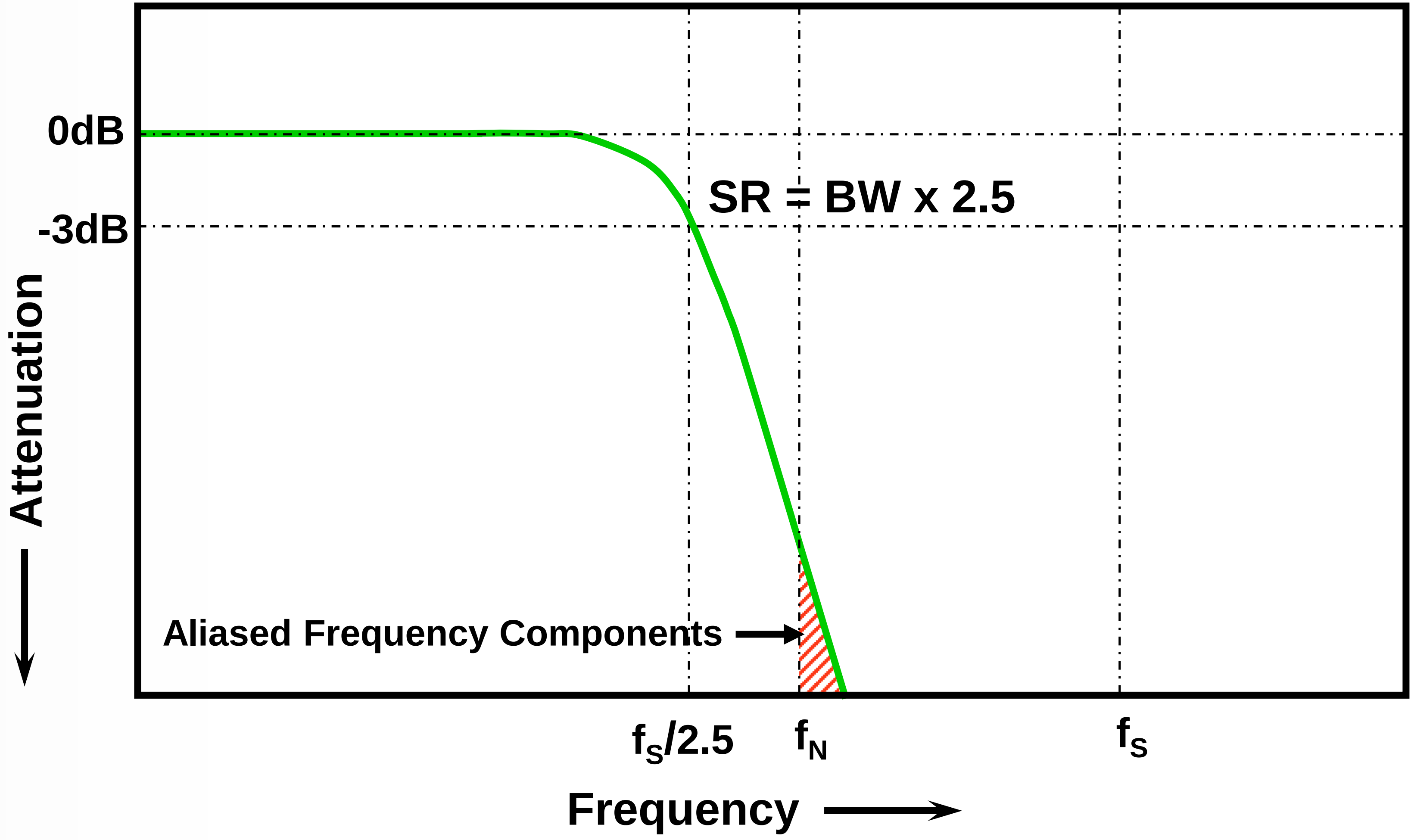
Gaussian frequency response

WITH BANDWIDTH @ $f_S/5$ ($f_N/2.5$)



Maximally-flat frequency response

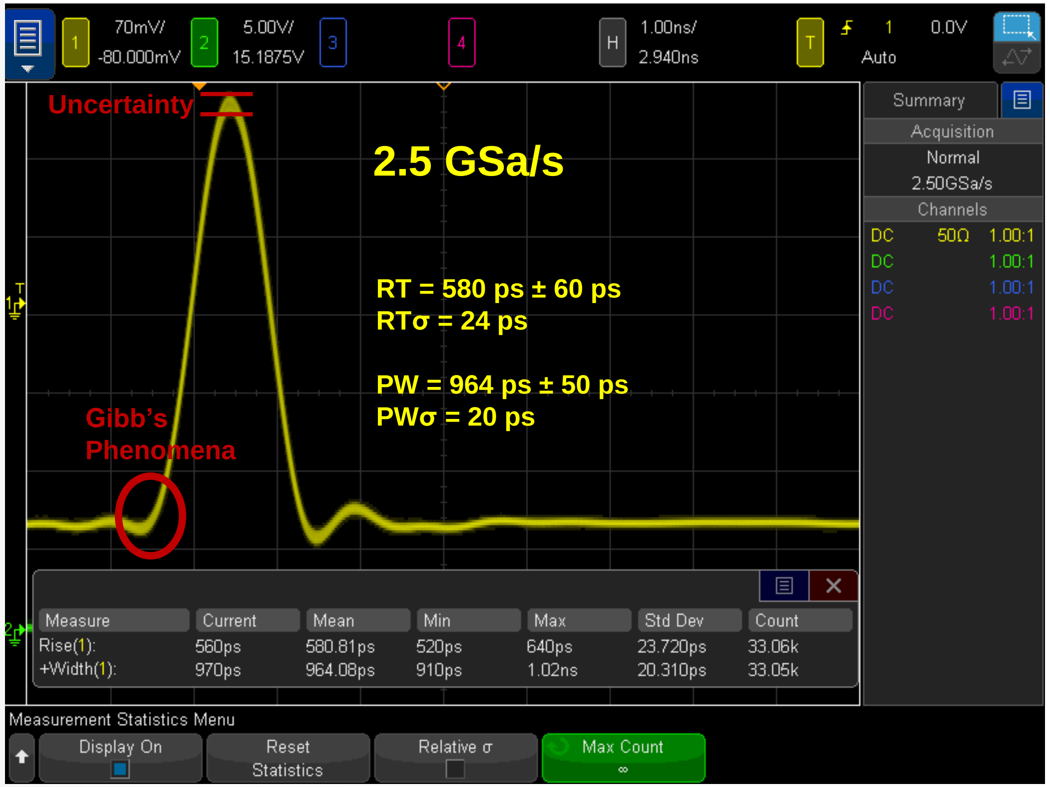
WITH BANDWIDTH @ $f_S/2.5$ ($f_N/1.25$)



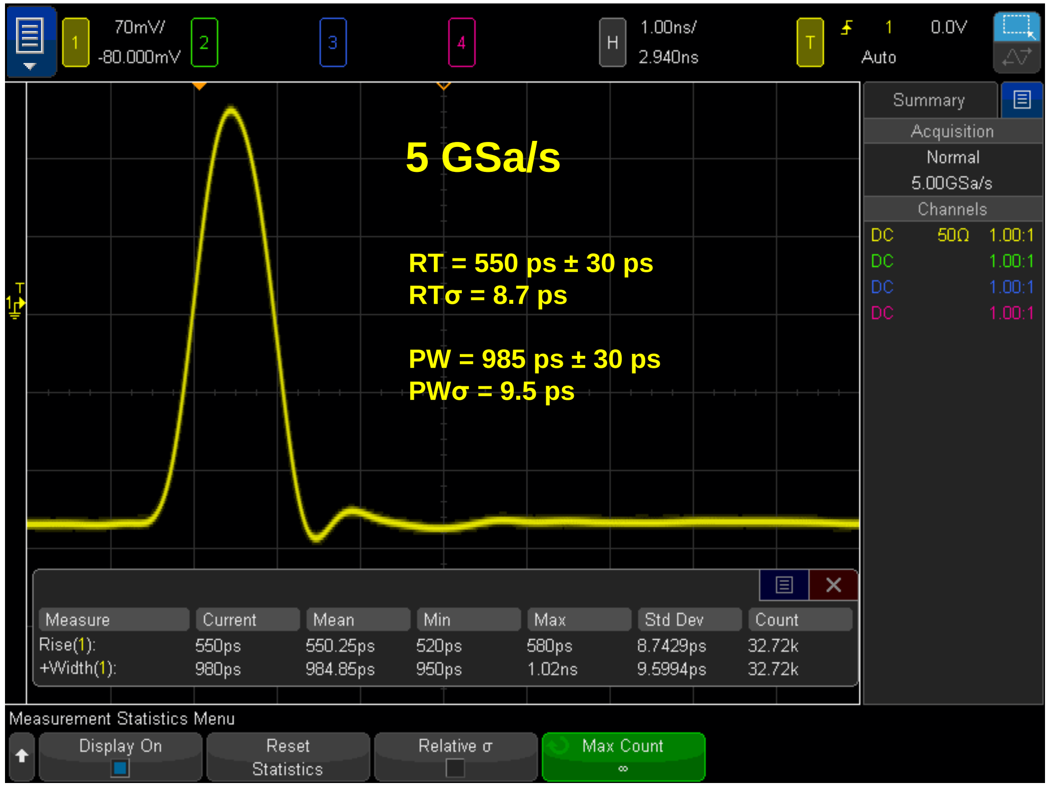
1-GHz bandwidth oscilloscope

INPUT = 1ns WIDE PULSE WITH 500ps RISE TIME

SR = BW x 2.5



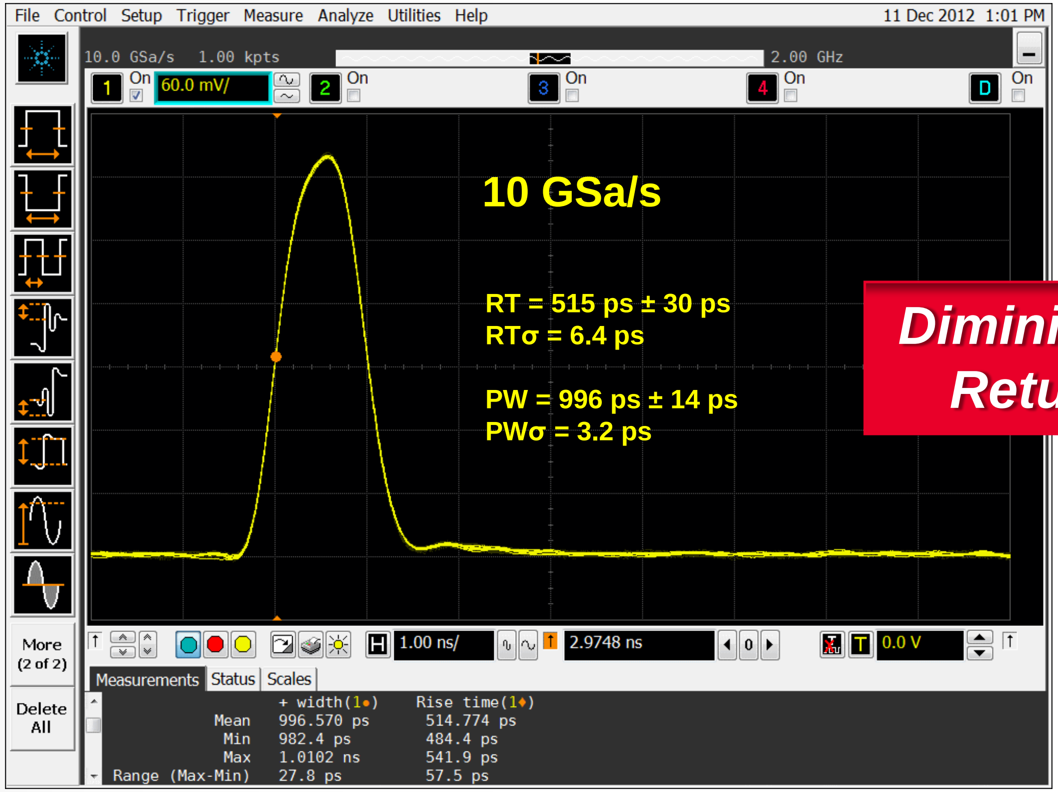
SR = BW x 5



2-GHz bandwidth oscilloscope

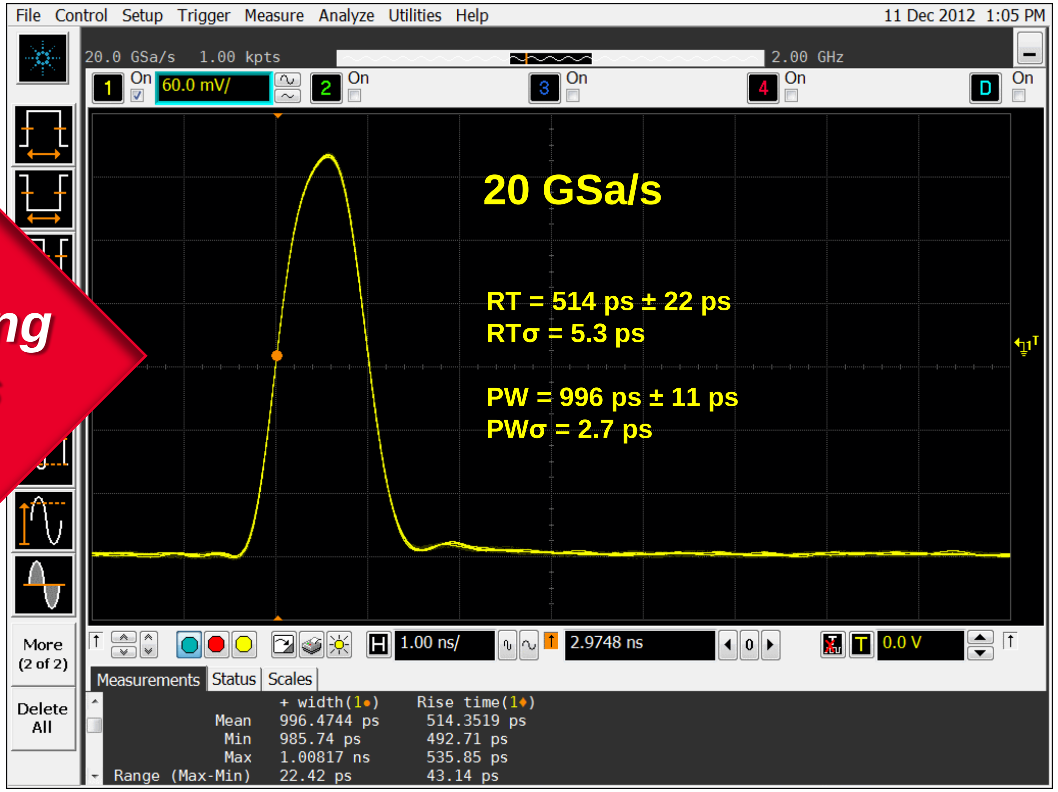
INPUT = 1ns WIDE PULSE WITH 500ps RISE TIME

SR = BW x 5



Diminishing Returns

SR = BW x 10



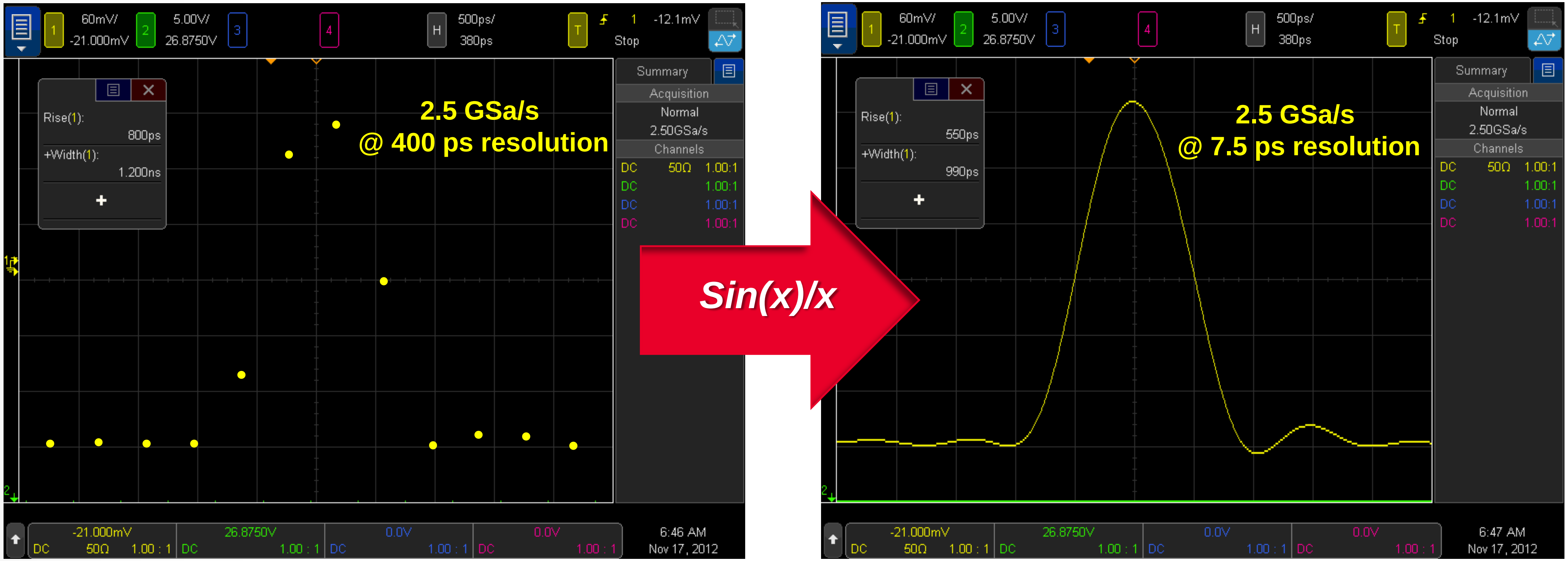
- Higher bandwidth = Improved measurement accuracy
- Higher sample rate = Slightly improved measurement resolution
- Higher bandwidth & sample rate = Higher price

KEYSIGHT TECHNOLOGIES

“Raw” sample data vs Sin(x)/x reconstruction

“Raw” sample data

Sin(x)/x waveform reconstruction



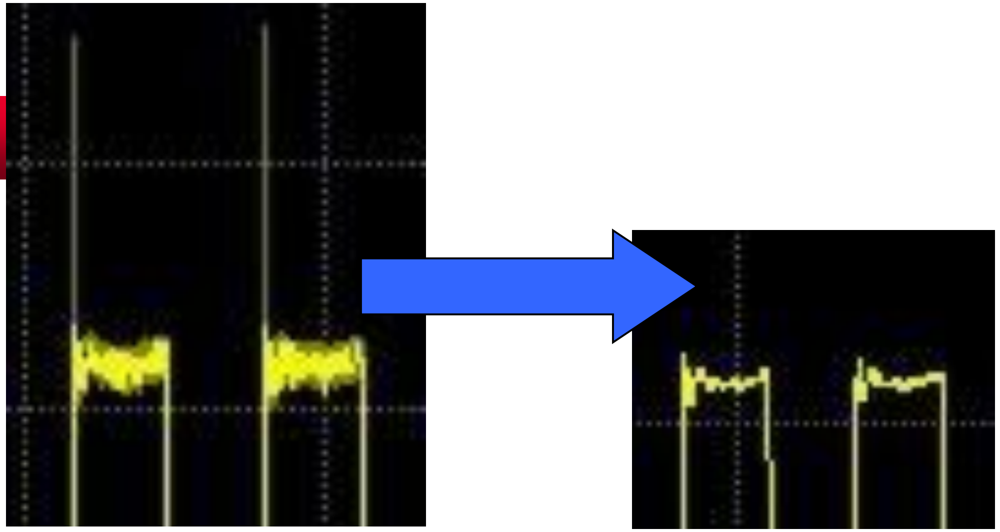
If Nyquist’s rules are observed:

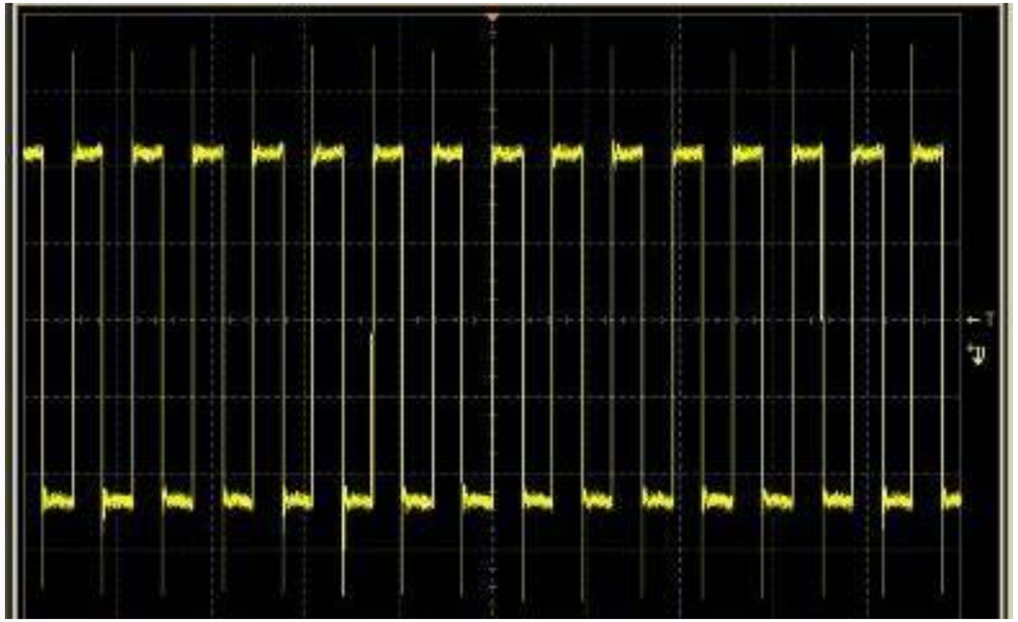
- 🙂 Sin(x)/x = Improved measurement accuracy & resolution
- 🙂 Sin(x)/x = Improved display quality (continuous waveform)
- ☹ Sin(x)/x = Reduced waveform update rates on most scopes
- 🙂 Sin(x)/x = Sustained fast waveform update rates on Keysight InfiniiVision X-Series scopes

Sampling Basics

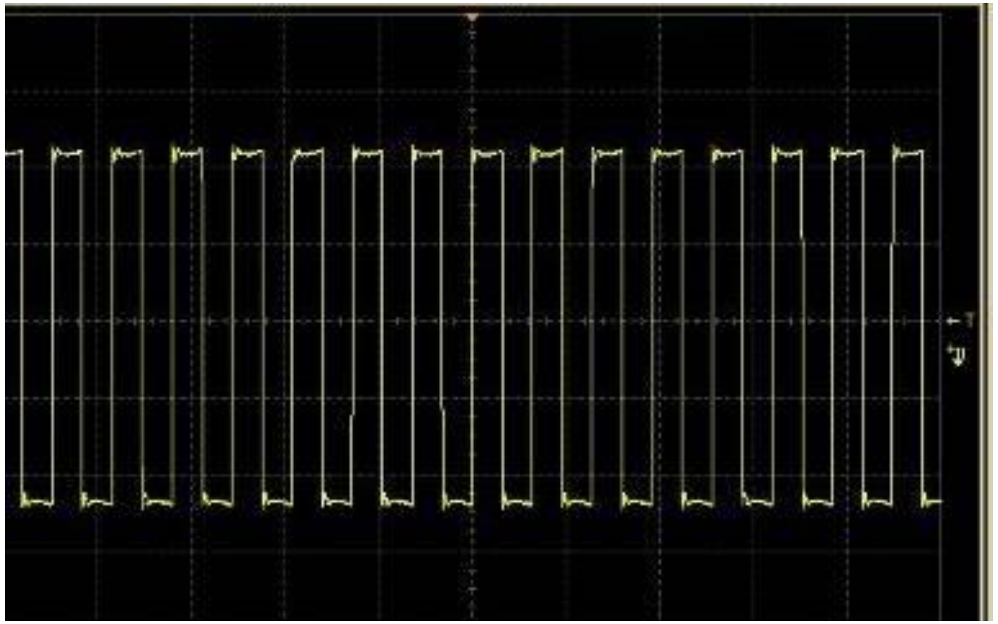
HIGH RESOLUTION MODE – REAL-TIME SCOPES

- Waveform is sampled at maximum rate
- Samples from the same trigger are averaged
- Reduces noise at the expense of bandwidth





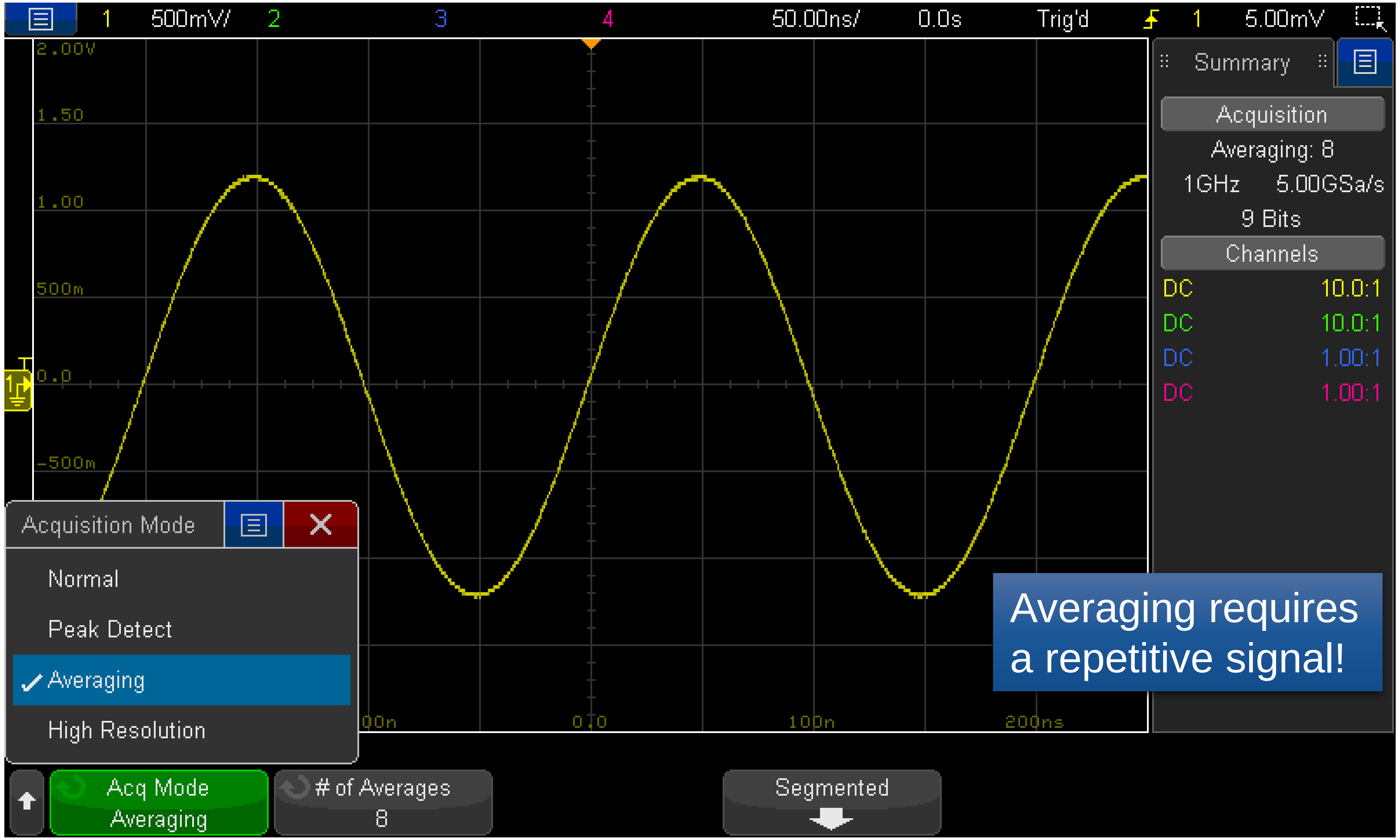
1.5MHz clock with Real-Time sampling



1.5MHz clock with High Resolution sampling

Sampling Mode

AVERAGING – REAL-TIME SCOPES



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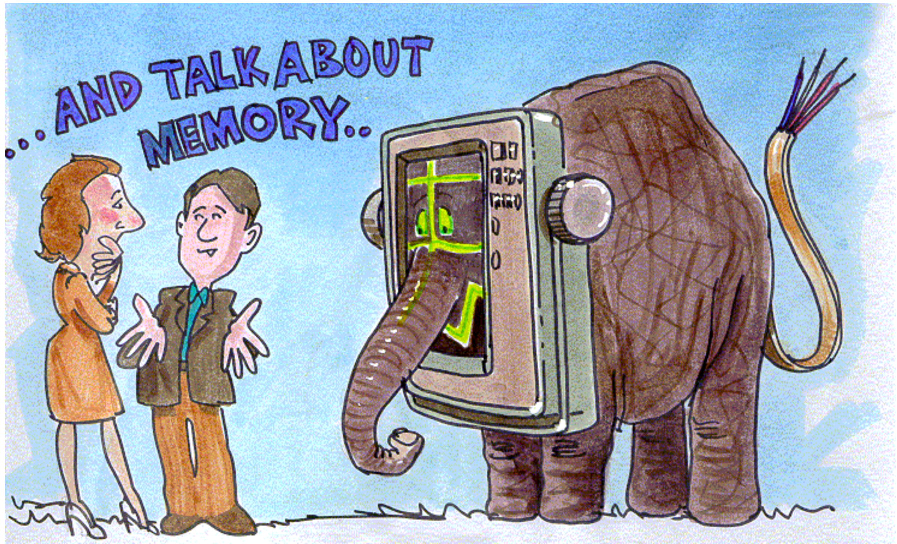
UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

- Bandwidth and rise time
- Sample rate
- Memory depth
- Waveform update rate
- ADC bits of resolution, vertical noise, and ENOB
- Vertical sensitivity (V/div) and gain accuracy
- Timebase accuracy
- Trigger sensitivity and trigger jitter

Memory depth

HOW DO SCOPES MANAGE THEIR MEMORY DEPTH

- Scopes with deeper memory can capture longer time-spans of data while still sampling at higher sample rates
- Scopes automatically adjust their sample rate based on timebase range and available memory
- Deep memory operation tradeoffs
  - Usually manually selected
  - Degrades scope's responsiveness and waveform update rate
  - Watch out for display decimation!
  - Often increases the price of the scope



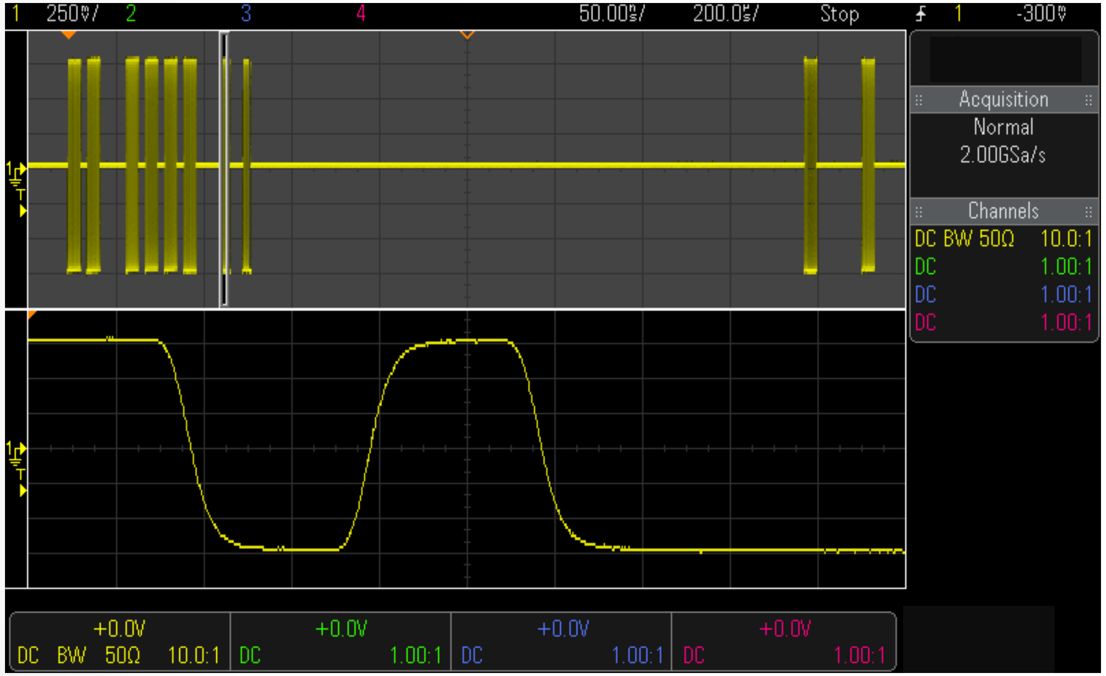
Memory depth

HOW MUCH MEMORY DO I NEED?

Step 1: Determine required bandwidth and sample rate

Step 2: Determine required time-span to be captured

Step 3: Required memory = Time-span/sample interval



Example:

Required sample rate = 2 GSa/s (500 ps / sample)

Required time-span = 2 ms (200 µs/div)

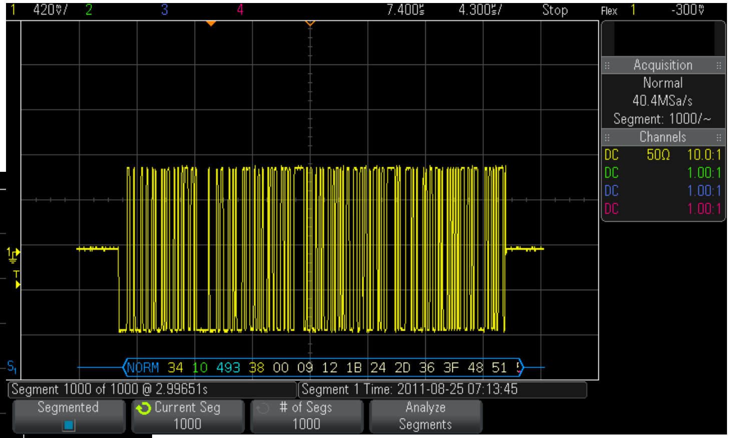
Required memory = 2 ms/500 ps = 4 M points

Memory depth

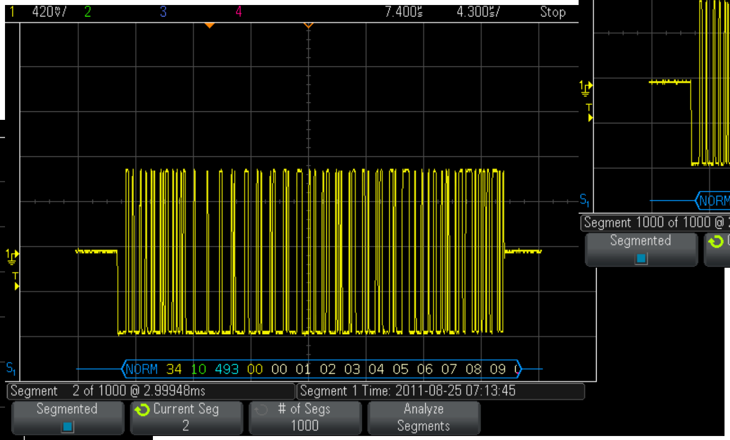
WHAT ABOUT SEGMENTED MEMORY?

Segmented Memory optimizes a scope’s available acquisition memory by only capturing important segments of an input signal. It is ideal for capturing bursts of signals such as packetized serial data that have long signal idle times between packets.

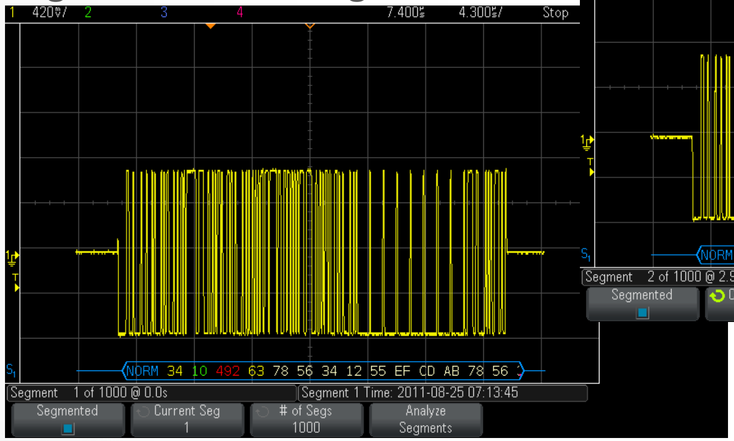
Segment #1000 time-tag = 2.99 s



Segment #2 time-tag = 2.99 ms



Segment #1 time-tag = 0.0 s



<u>Example:</u>

Number of segments = 1000

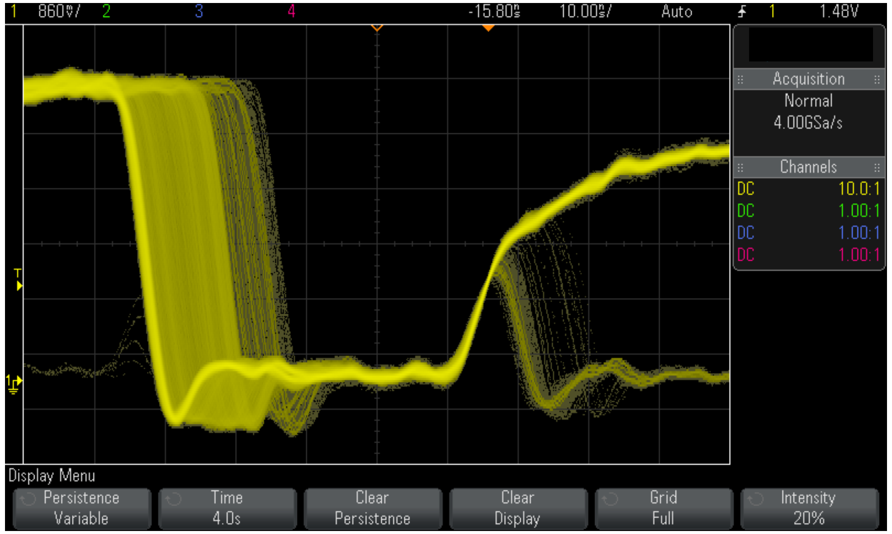
Time-tag of last segment = 3 seconds

Equivalent memory depth = 120 M points

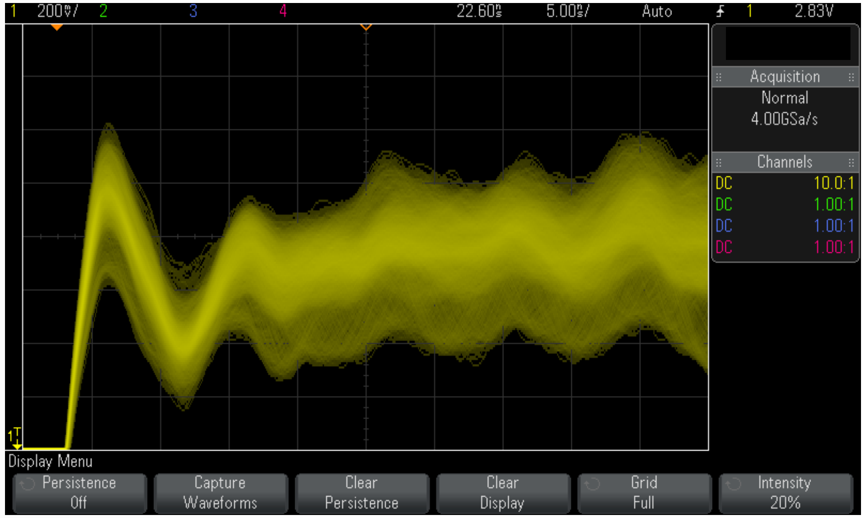
Waveform update rate

WHY ARE FAST WAVEFORM UPDATE RATE IMPORTANT?

Improves scope usability



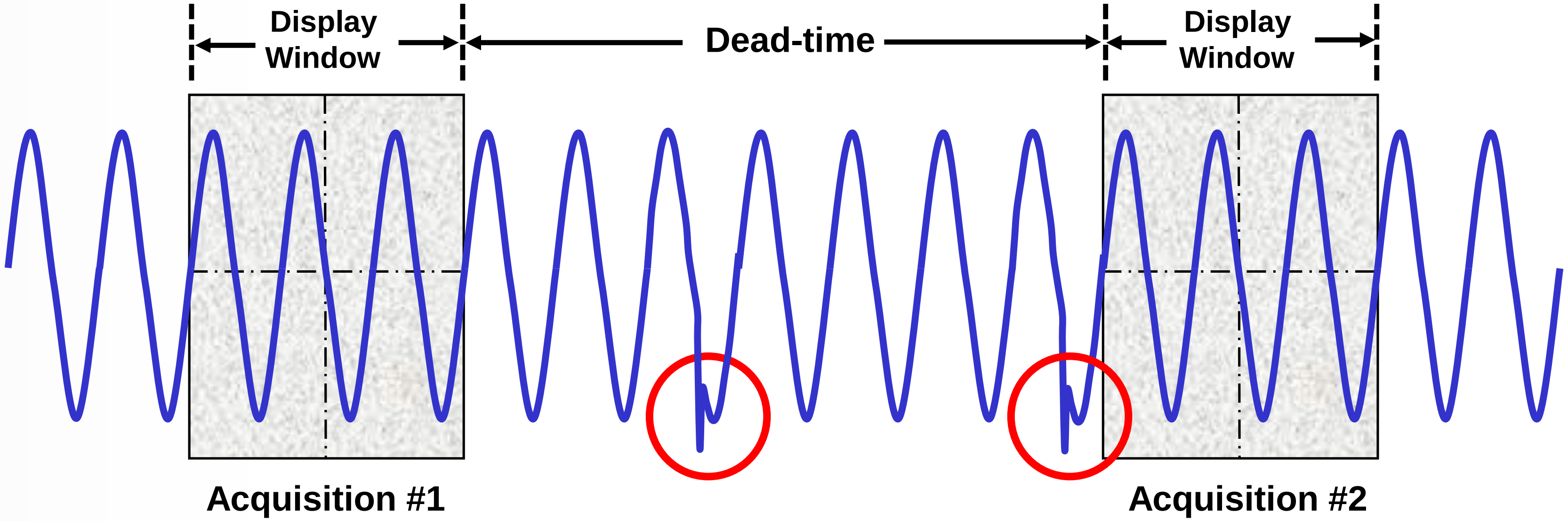
Improves scope's probability of capturing infrequent events



Improves scope display quality

Oscilloscope dead-time hides glitches

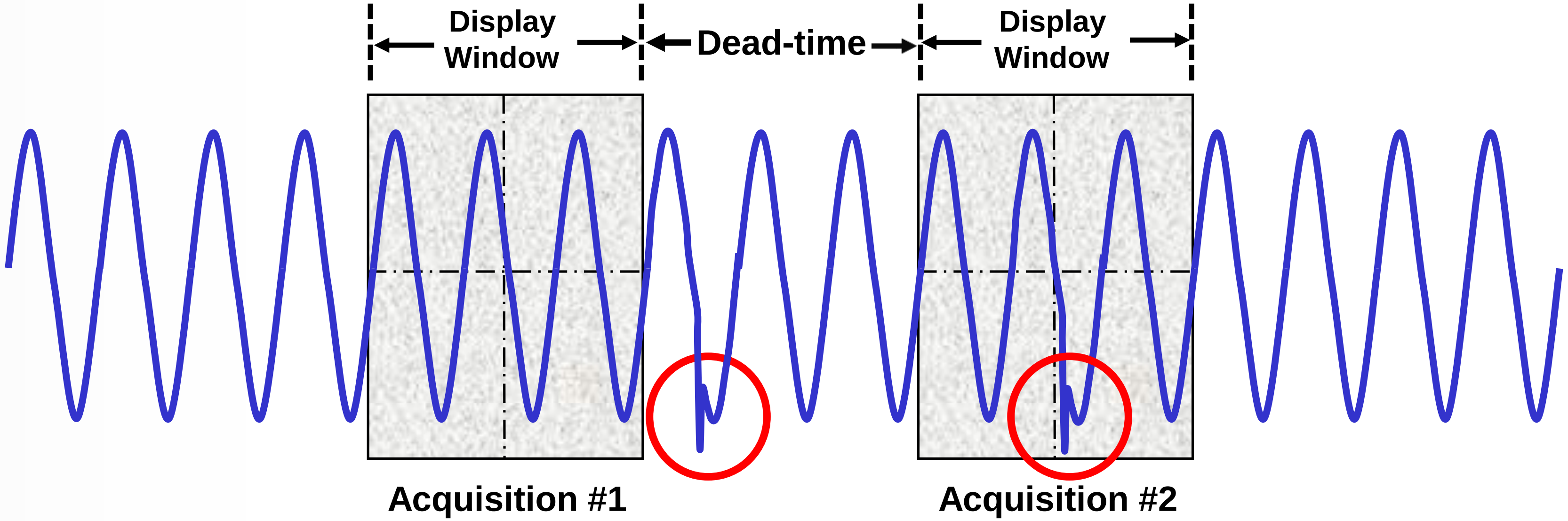
ALL SCOPES HAVE DEAD-TIME



- Dead-time is often orders of magnitude longer than acquisition time.
- Infrequent anomalies will usually occur during the scope's dead-time.

Faster waveform update rates help reveal glitches

REDUCED DEAD-TIMES = FASTER WAVEFORM UPDATE RATES

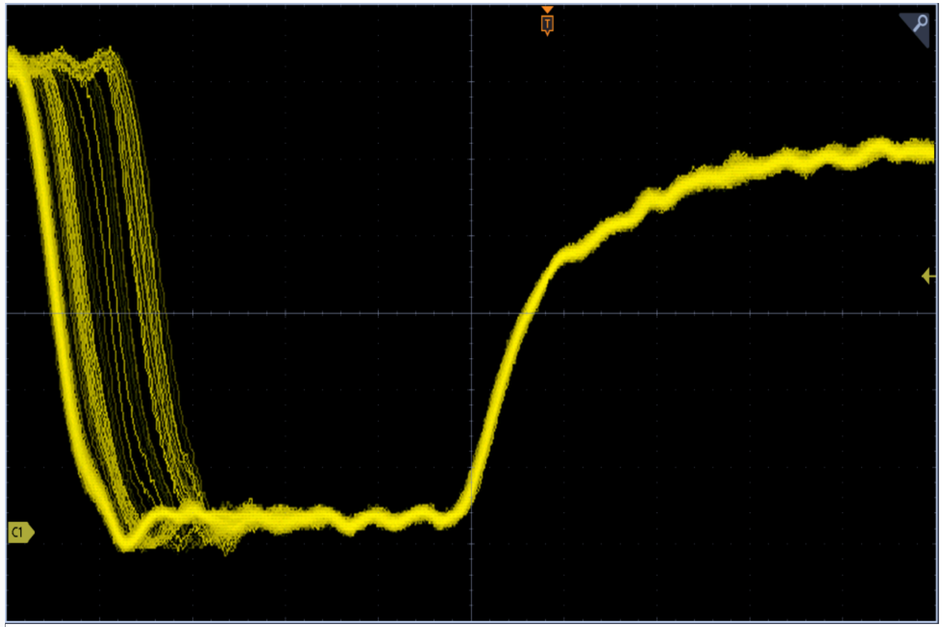


- Decreasing dead-time increases waveform update rates and thus improves probability of capturing and displaying infrequent anomalies/glitches

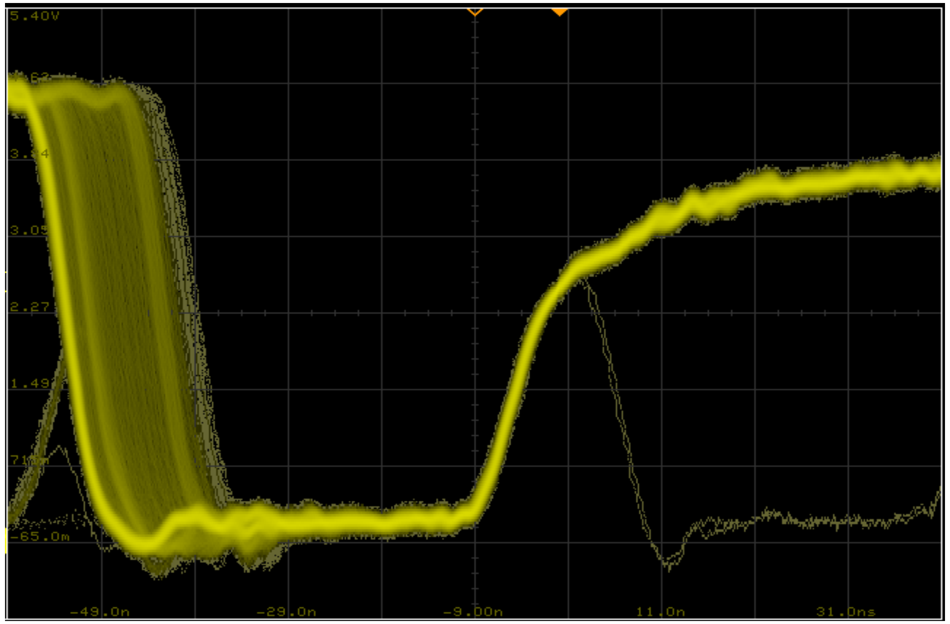
Capturing infrequent events

CAPTURING INFREQUENCY EVENTS BASED ON STATISTICAL PROBABILITIES

2,000 waveforms/sec



1,000,000 waveforms/sec



- Most under-rated and misunderstand specification/characteristic
- Watch out for special fast acquisition modes with tradeoffs
- Watch out for misleading specifications based on “non-viewing” modes

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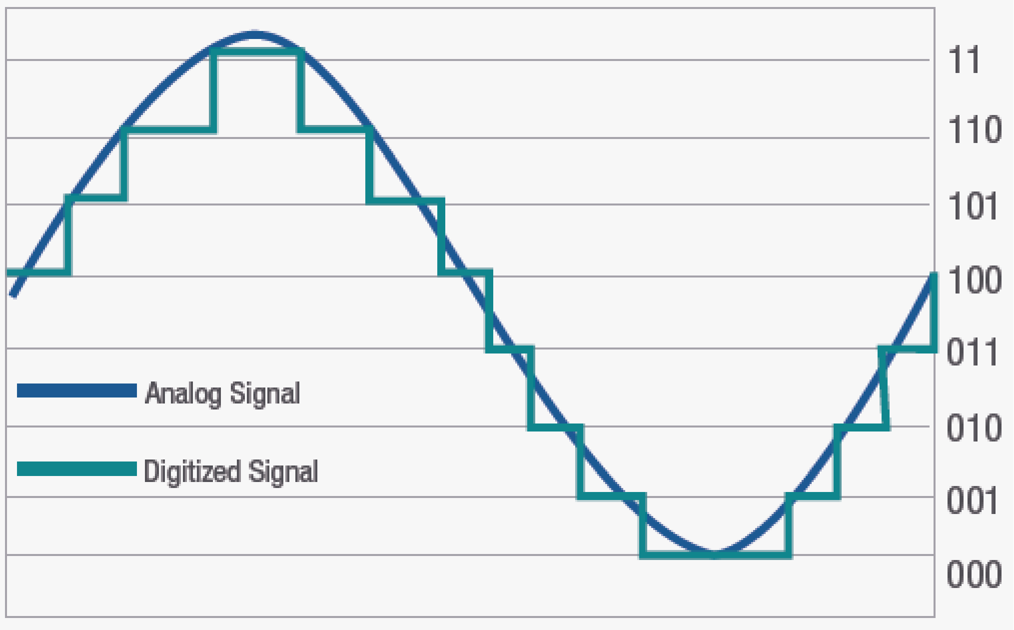
ADC bits of resolution

DO MORE BITS PROVIDE MORE ACCURACY?

The number of ADC bits is important because of quantization levels, or Q levels. The more bits there are, the more Q levels there can be. The more Q levels there are, the higher the accuracy because the oscilloscope can capture and display more of the true signal detail.



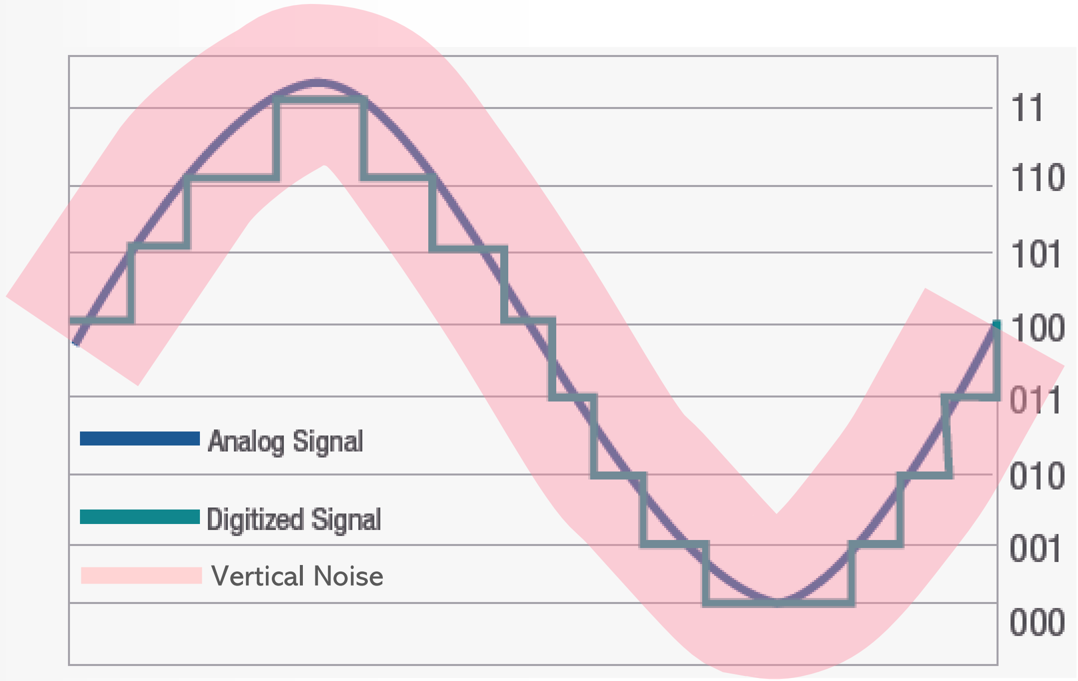
Visualization of a 3-bit ADC (8 quantization levels)

Number of ADC bits	Number of Q levels
6	$2^6 = 64$
8	$2^8 = 256$
10	$2^{10} = 1{,}024$
12	$2^{12} = 4{,}096$
14	$2^{14} = 16{,}384$

Vertical noise

HOW DOES VERTICAL NOISE EFFECT BITS OF MEASUREMENT RESOLUTION?

Vertical noise can “swamp out” ADC bits thereby providing less measurement resolution and accuracy



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Vertical noise specifications

HOW DOES VERTICAL NOISE EFFECT BITS OF MEASUREMENT RESOLUTION?

- Not always specified, and inconsistent when it is
- Sometimes only specified at the most sensitive V/div setting
- Noise is a function of bandwidth (higher bandwidth = higher noise)
- Should be specified in RMS units (peak-to-peak noise is theoretically unbounded)

Infiniium MXR-Series Noise Floor Specifications

	RMS noise floor ($V_{RMS\ AC}$) on 50 Ω inputs							
Vertical setting	20 MHz [1]	200 MHz [1]	500 MHz [1]	1 GHz [1]	2 GHz [1]	2.5 GHz	4 GHz	6 GHz
1, 2 mV/div	43 µV	59 µV	63 µV	73 µV	91 µV	100 µV	132 µV	193 µV
5mV/div	40 µV	61 µV	70 µV	81 µV	102 µV	112 µV	149 µV	216 µV
10 mV/div	46 µV	69 µV	81 µV	99 µV	131 µV	144 µV	189 µV	251 µV
20 mV/div	59 µV	99 µV	122 µV	156 µV	209 µV	233 µV	297 µV	401 µV
50 mV/div	210 µV	278 µV	328 µV	401 µV	520 µV	569 µV	719 µV	971 µV
100 mV/div	452 µV	582 µV	681 µV	821 µV	1.06 mV	1.17 mV	1.46 mV	2.03 mV
1 V/div	2.95 mV	4.10 mV	5.07 mV	6.33 mV	8.4 mV	9.31 mV	11.91 mV	16.26 mV

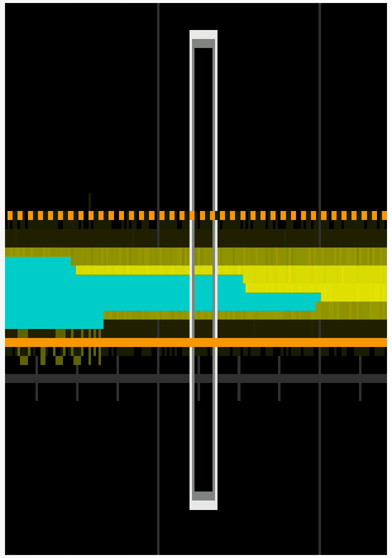
1. High-resolution is used for bandwidths 2 GHz and below.

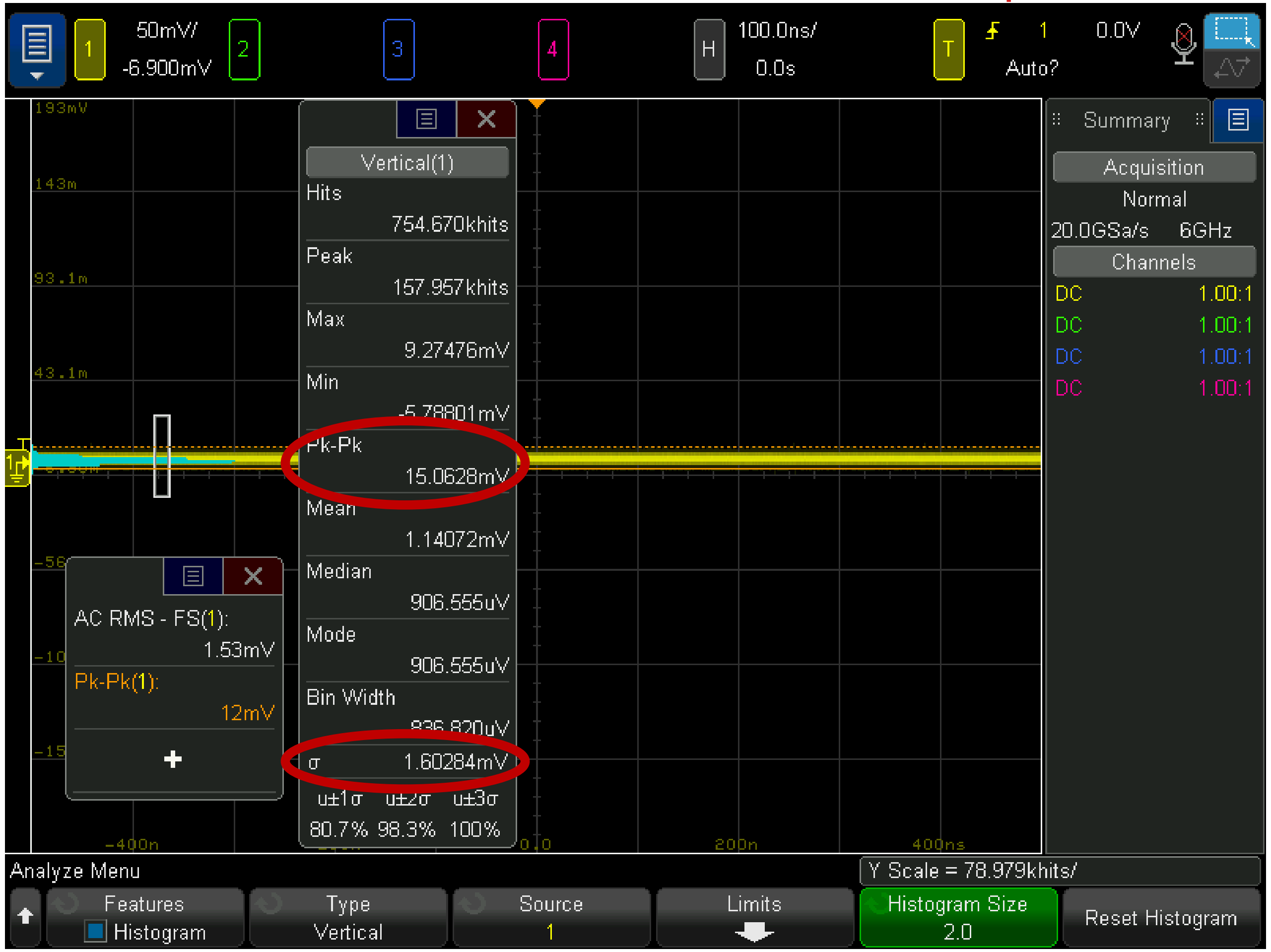
- At 100 mV/div, full-scale (8 div) = 800 mV (dynamic range of ADC)
- At 10-bit ADC resolution, quantization = 780 µV
- At 821 µV-rms noise (σ), peak-to-peak noise (6σ) ~5 mVp-p
- 5 mVp-p noise = 6.3 Q levels

Measuring vertical noise

AC-RMS, PEAK-TO-PEAK, VERTICAL HISTOGRAM

InfiniiVision 6000 X-Series oscilloscope





Effective number of bits (ENOB) of resolution

HOW DOES VERTICAL NOISE EFFECT BITS OF MEASUREMENT RESOLUTION?

- Accounts for ADC bits + scope noise + other system non-linearities
- Gain and offset errors are normalized out with best-fit sine wave analysis
- Equated with the RMS error of a theoretical noise-free sine wave digitized with a perfect ADC of "N" bits
- ENOB can vary based on bandwidth and input frequency
- Typically only specified in higher bandwidth oscilloscopes (>1 GHz)

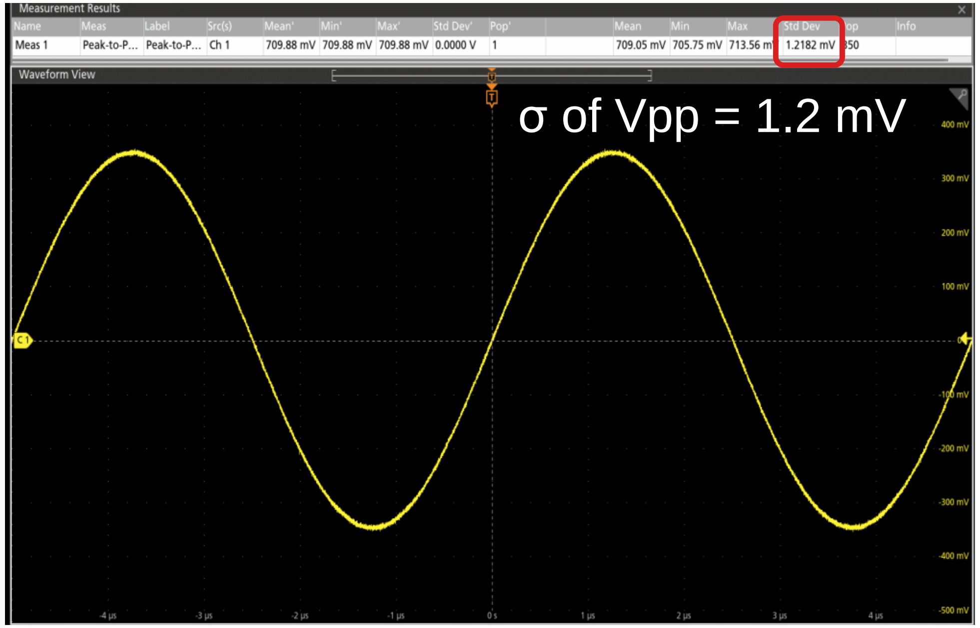
Infiniium MXR-Series ENOB Specifications (10-bit ADC)

ENOB on 50 Ω inputs, 50 mV/div											
20 MHz	200 MHz	250 MHz	350 MHz	500 MHz	1 GHz	2 GHz	2.5 GHz	3 GHz	4 GHz	5 GHz	6 GHz
9.0	8.5	8.4	8.3	8.2	8.0	7.6	7.5	7.4	7.2	7.1	6.8

Measurement resolution using *High-Res* acquisition

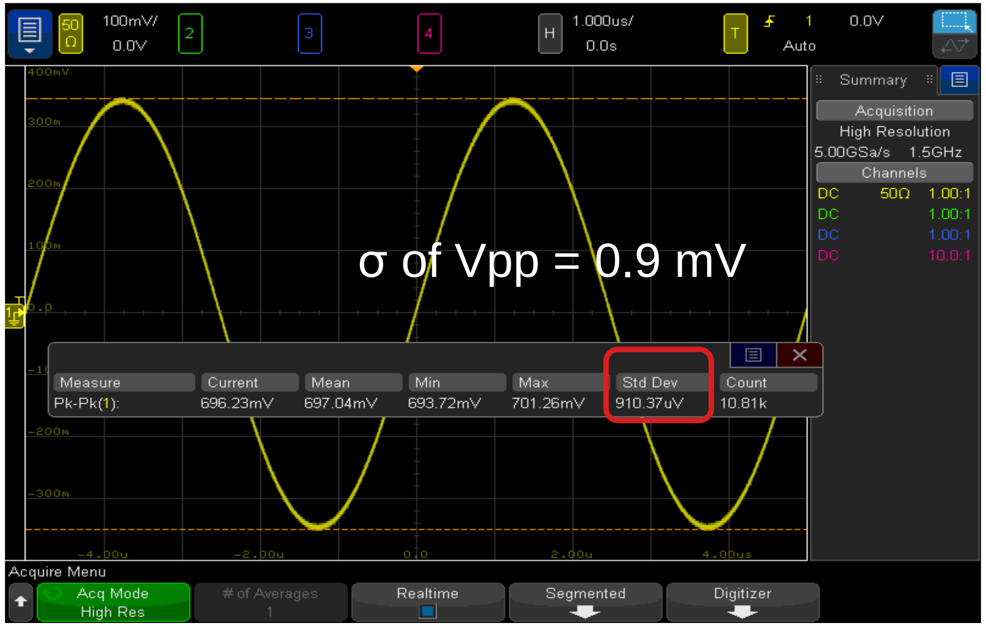
COMPARING STANDARD DEVIATION (σ) OF V_{P-P} MEASUREMENTS

Competitive oscilloscope



- 12-bits @ 1.0 GHz bandwidth @ 3.125 GSa/s

InfiniiVision 4000 X-Series



- 8-bits @ 1.5 GHz bandwidth @ 5 GSa/s
- Higher measurement resolution

WHEN 8-BITS IS BETTER THAN 12-BITS

Vertical sensitivity (V/div) and gain accuracy

VERTICAL DYNAMIC RANGE AND ACCURACY

- Vertical sensitivity (V/div) tells you the range of signals that can be captured and measured by the oscilloscope without divider probes
- More sensitive ranges are sometimes bandwidth limited or digitally magnified

Infiniium MXR-Series vertical sensitivity specifications

Input sensitivity [3]	50 Ω [1]	1 mV/div to 1 V/div
	1 MΩ	1 mV/div to 5 V/div

- Gain accuracy sometimes specified for major settings only (10 mV/div, 20 mV/div, etc.)
- "Typical" gain spec often highlighted with "guaranteed" spec hidden in fine print
- Gain accuracy only specified at DC. Non-flatness of frequency response further degrades vertical measurement accuracy

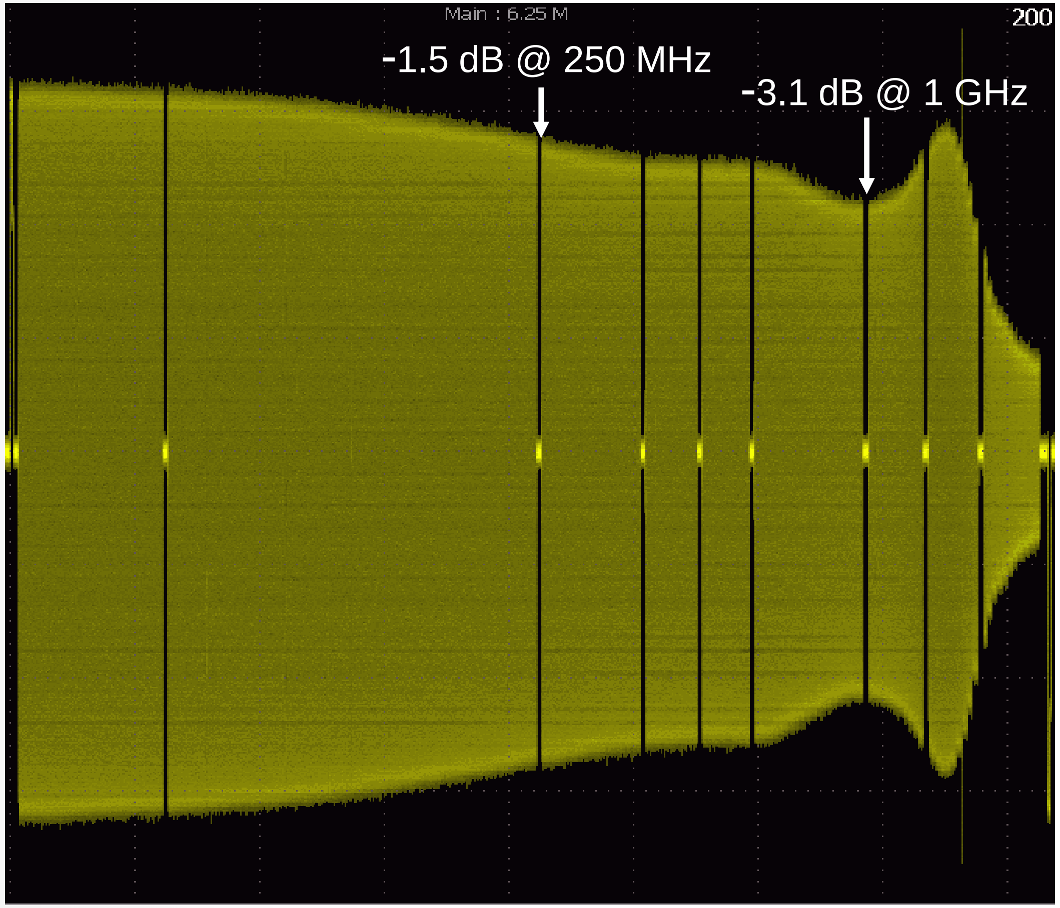
DC gain accuracy [1][2][3]		±2% full scale (±1% typical)

READ THE FINE PRINT AND SUB-NOTES

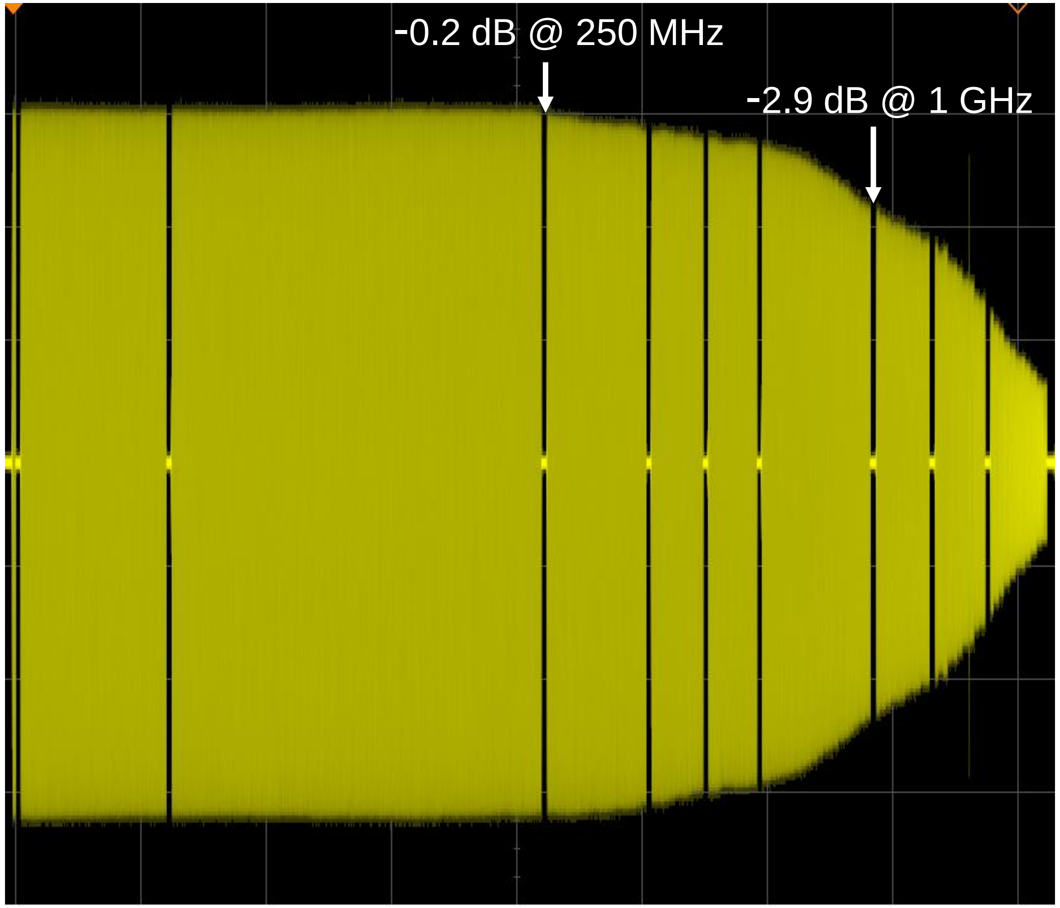
Non-flat frequency response degrades vertical accuracy

250 KHZ TO 2 GHZ SWEEP WITH LINEAR GAIN

Competitive 1-GHz oscilloscope



Keysight 1-GHz oscilloscope



Agenda

UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

- Bandwidth and rise time
- Sample rate
- Memory depth
- Waveform update rate
- ADC bits of resolution, vertical noise, and ENOB
- Vertical sensitivity (V/div) and gain accuracy
- Timebase accuracy
- Trigger sensitivity and trigger jitter

Timebase accuracy

HOW DOES TIMEBASE ACCURACY EFFECT ΔT MEASUREMENTS?

- Timebase error has minimal effect on *most* oscilloscope timing measurements
- Most over-rated specification (speaker's opinion)

Infiniium MXR-Series timebase accuracy specification

Timebase accuracy	8 parts per billion

Example #1 (5 ns Δt): Error due to timebase error = 40 atto seconds
Example #2 (longest Δt at 16 GSa/s and 400 M points (25 ms)): Max error = 200 ps

InfiniiVision 3000T X-Series timebase accuracy specification

Time base accuracy [1]	± 1.6 ppm + aging factor

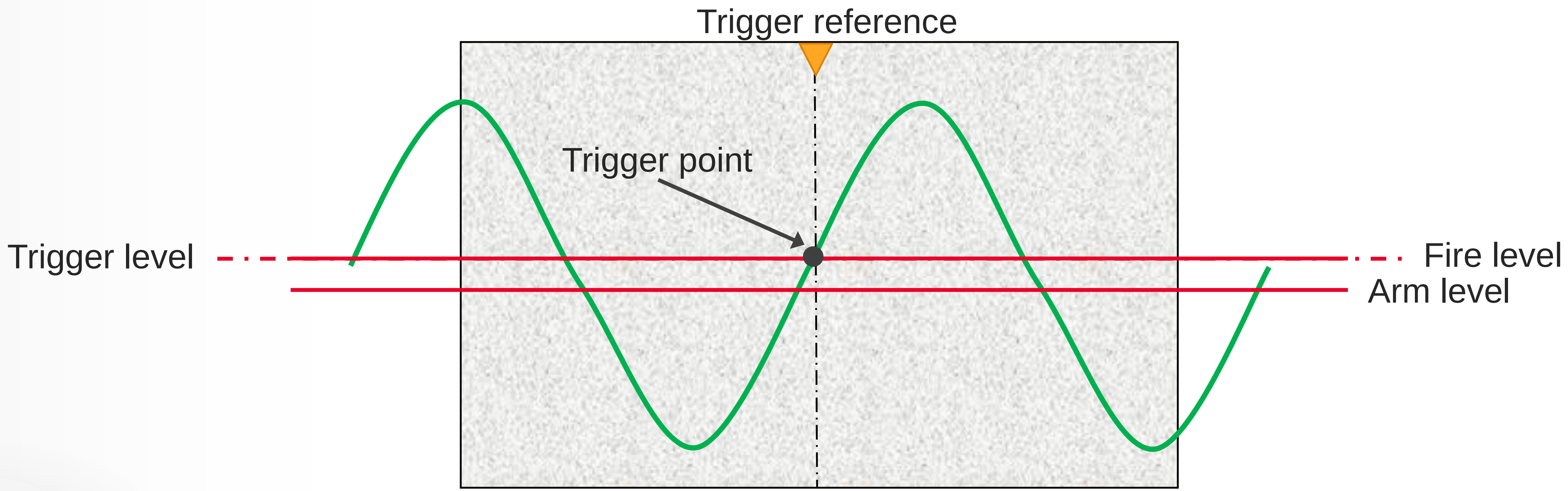
Example #1 (5 ns Δt): Error due to timebase error = 8 femto seconds
Example #2 (longest Δt at 5 GSa/sec and 4 M point (800 µs)): Max error = 1.38 ns

Trigger sensitivity

TRIGGER SENSITIVITY = TRIGGER HYSTERESIS = MINIMUM SWING

InfiniiVision 4000 X-Series trigger sensitivity specification

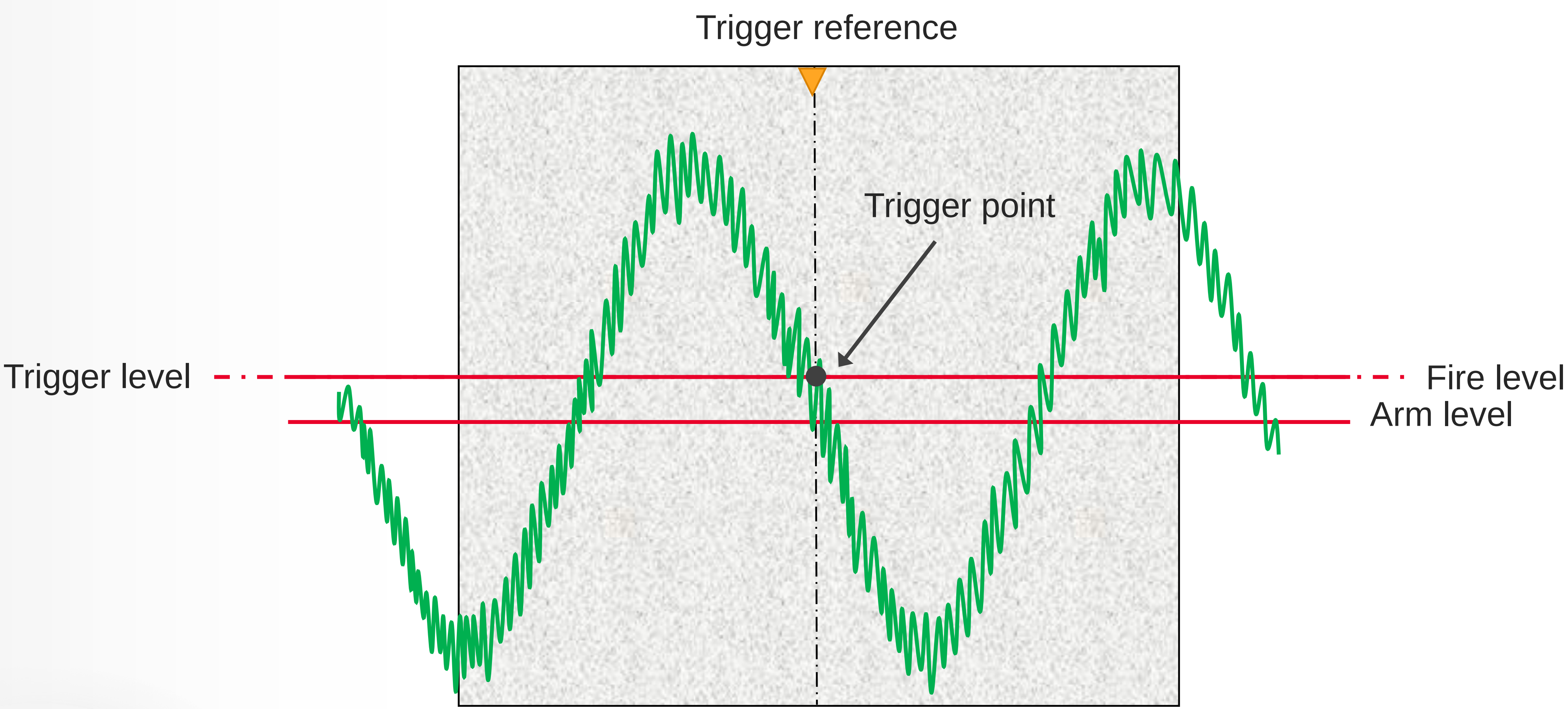
Trigger sensitivity (internal) [1]	200 MHz ~ 1 GHz	< 10 mV/div: greater of 1 div or 5 mV; ≥ 10 mV/div: 0.6 div
	1.5 GHz	DC to 1 GHz: < 10 mV/div: Greater of 1 div or 5 mV; ≥ 10 mV/div: 0.6 div
		1 to 1.5 GHz: < 10 mV/div: Greater of 1.5 div or 5 mV; ≥ 10 mV/div: 1.0 div



Higher sensitivity (lower swing) is not necessarily better

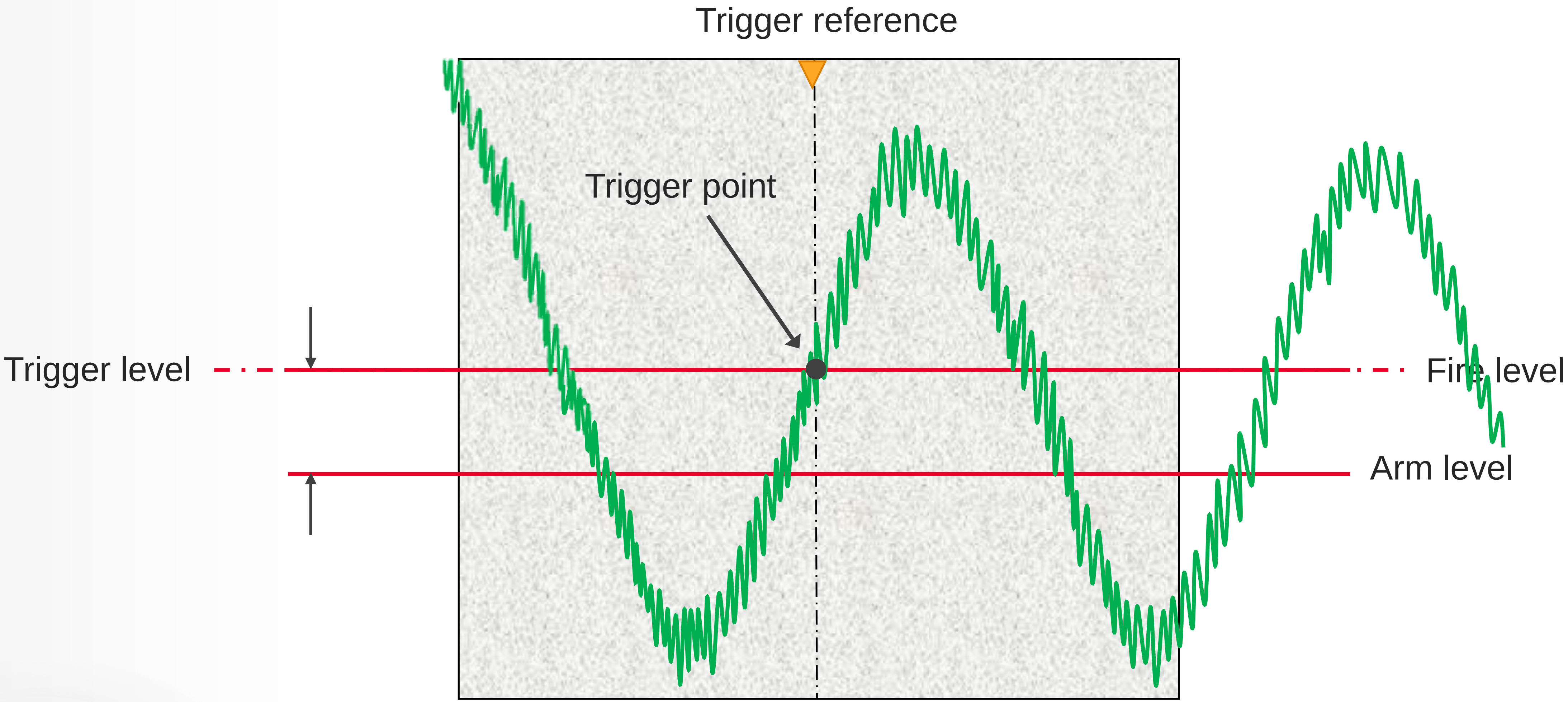
Trigger sensitivity

IF SENSITIVITY IS TOO LOW, SCOPE TRIGGERS ON RISING EDGE OF NOISE



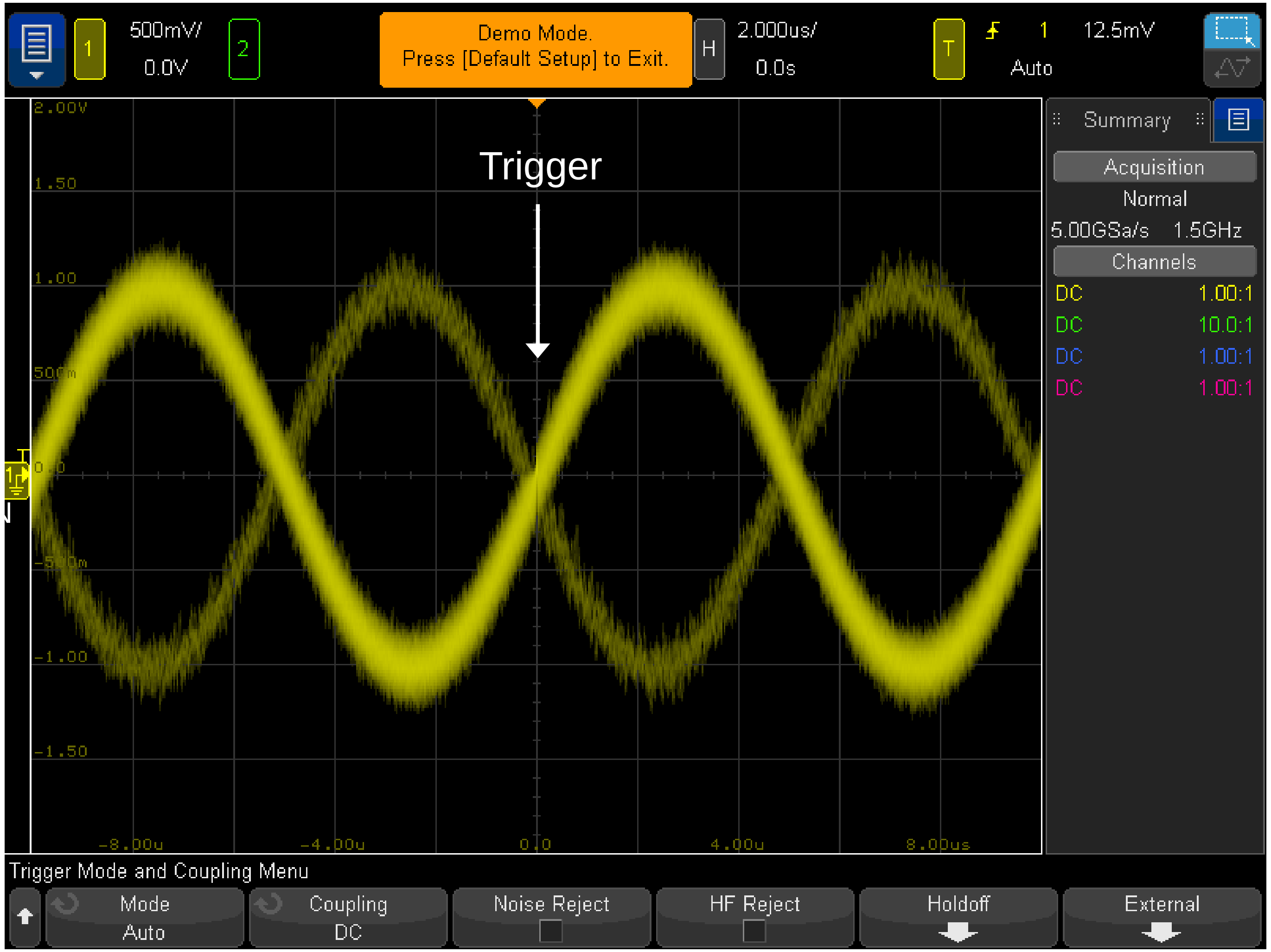
Trigger sensitivity

SENSITIVITY CAN BE REDUCED (MORE HYSTERESIS) WITH "NOISE REJECT"



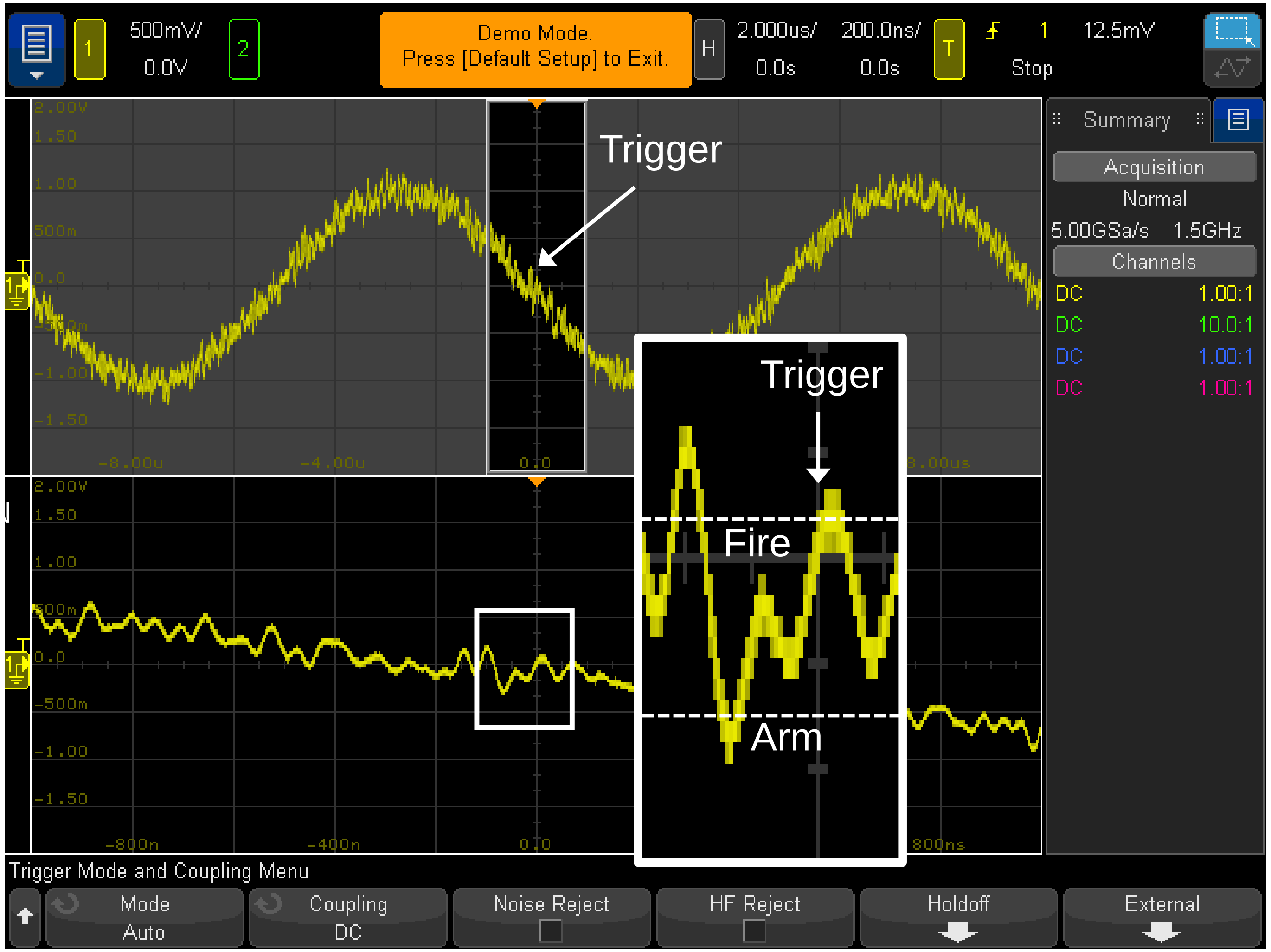
Triggering in a noisy environment

WITH RISING EDGE TRIGGER, SCOPE APPEARS TO TRIGGER ON EITHER EDGE



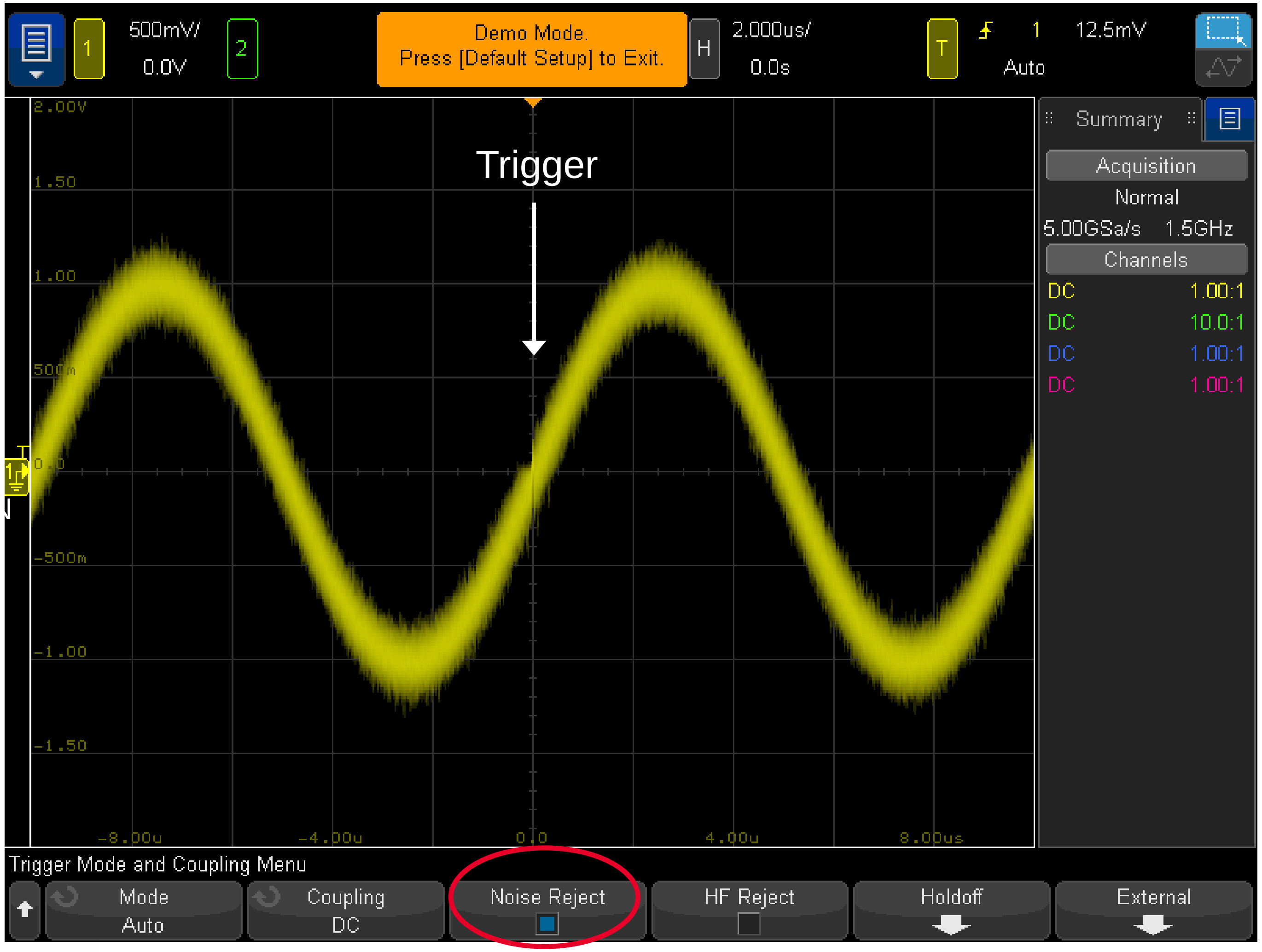
Triggering in a noisy environment

SINGLE-SHOT CAPTURE SHOWS THAT SCOPE TRIGGERED ON NOISE



Triggering in a noisy environment

WITH "NOISE REJECT", SCOPE ALWAYS TRIGGERS ON RISING EDGE OF SIGNAL

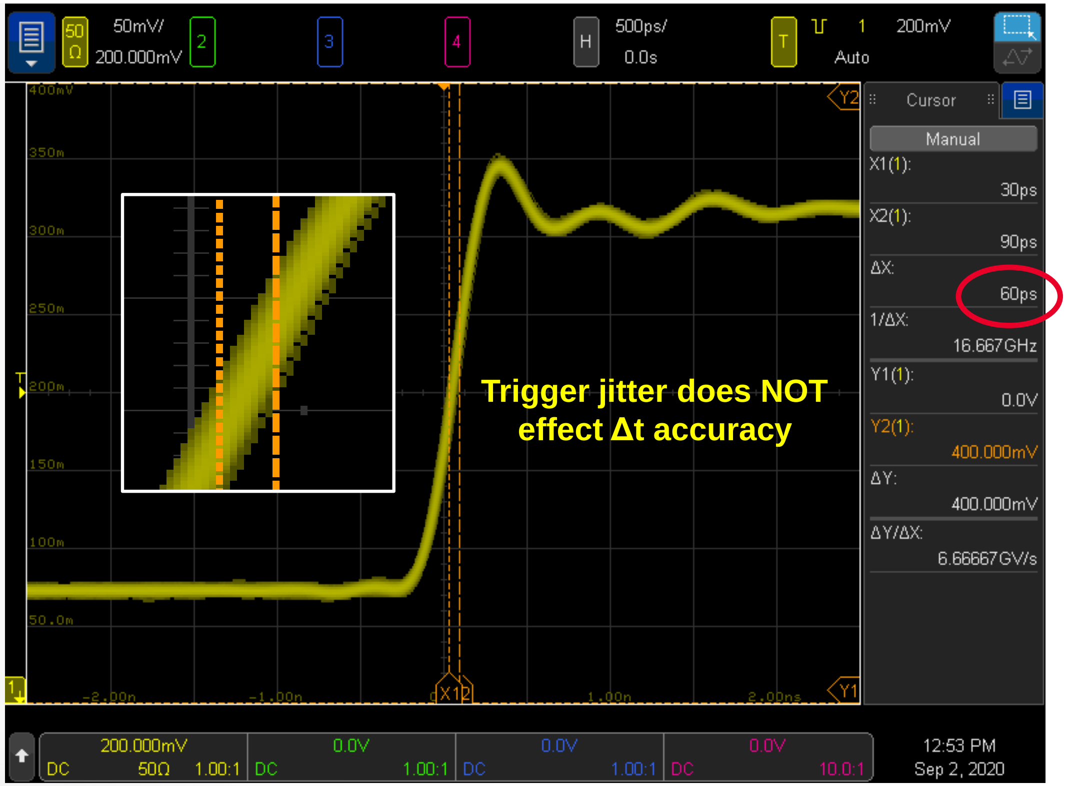


Triggering Jitter

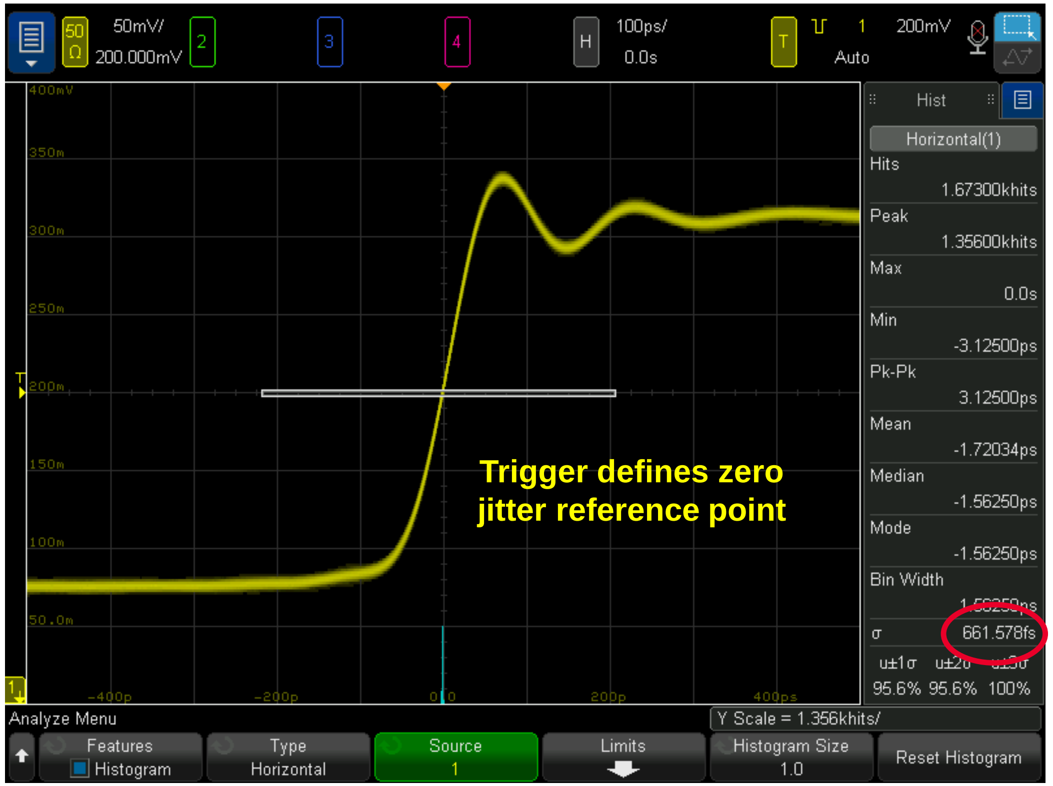
TRIGGER UNCERTAINTY – ONLY SPECIFIED ON HIGHER BANDWIDTH SCOPES

Trigger system	InfiniiVision 6000 X-Series
Trigger jitter	< 1.0-ps rms with the jitter-free trigger
	< 3.0-ps rms without the jitter-free trigger

InfiniiVision 4000 X-Series w/o jitter-free



InfiniiVision 6000 X-Series w/ jitter-free



What else is there to consider?

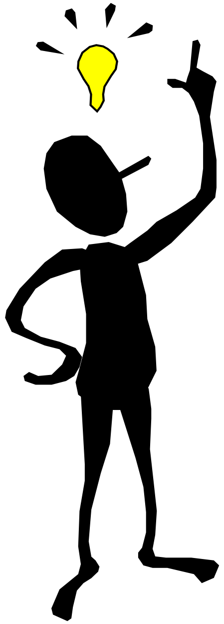
OSCILLOSCOPE FUNCTIONALITY IS OFTEN MORE THAN SPECIFICATIONS

- Automatic measurements
- Waveform math
- Industry-standard compliance testing
- Serial bus analysis
- Advanced triggering
- Jitter analysis
- Probing solutions
- User-interface/ease-of-use

Reviewing what we've learned today

UNDERSTANDING OSCILLOSCOPE SPECIFICATIONS

- Oscilloscopes have lots of specifications (and characteristics).
- Bandwidth and sample rate are usually the most important specifications to consider.
- Waveform update rate is the most under-rated specification.
- Timebase accuracy is the most over-rated specification.
- Oscilloscope functionality is often more important than specifications.
- Watch out for the fine print!



Keysight technical references & resources

InfiniiVision Oscilloscope Information: www.keysight.com/find/infiniivision
Keysight Probes & Accessories: www.keysight.com/find/scope_probes

Application Notes	Publication Number
How to Select Your Next Oscilloscope: 12 tips on what to consider	5991-2714EN
Evaluating Oscilloscope Bandwidths for Your Application	5989-5733EN
Evaluating Oscilloscope Sample Rates versus Sampling Fidelity	5989-5732EN
Can Your Oscilloscope Capture Elusive Events? Why Waveform Update Rate Matters	5992-3624EN
Understanding ADC Bits and ENOB	5952-3675EN
Understanding Oscilloscope Frequency Response and Its Effect on Rise Time Accuracy	5988-8008EN

Keysight Oscilloscopes

	Bandwidth	Number of channels	Sample Rate	Memory (max)	Update Rate	Jitter Analysis	Bode plot (FRA)	Entry-level Price
1000X	50 to 200 MHz	2 or 4	2 GSa/s	2M	200k/s	No	Std	$480
2000X	70 to 200 MHz	2 or 4 + 8 (digital)	2 GSa/s	1M	200k/s	No	No	$1,450
3000T	100 MHz to 1.0 GHz	2 or 4 + 16 (digital)	5 GSa/s	4M	1M/s	No	Option	$3,700
4000X	200 MHz to 1.5 GHz	2 or 4 + 16 (digital)	5 GSa/s	4M	1M/s	No	Option	$5,500
6000X	1 GHz to 6 GHz	2 or 4 + 16 (digital)	20 GSa/s	4M	500k/s	Option	Option	$15,300
MXR	500 MHz to 6 GHz	4 or 8 + 16 (digital)	16 GSa/s	400M	200k/s	Option	Option	$19,500

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