KEYSIGHT

Back to Basics: Oscilloscopes

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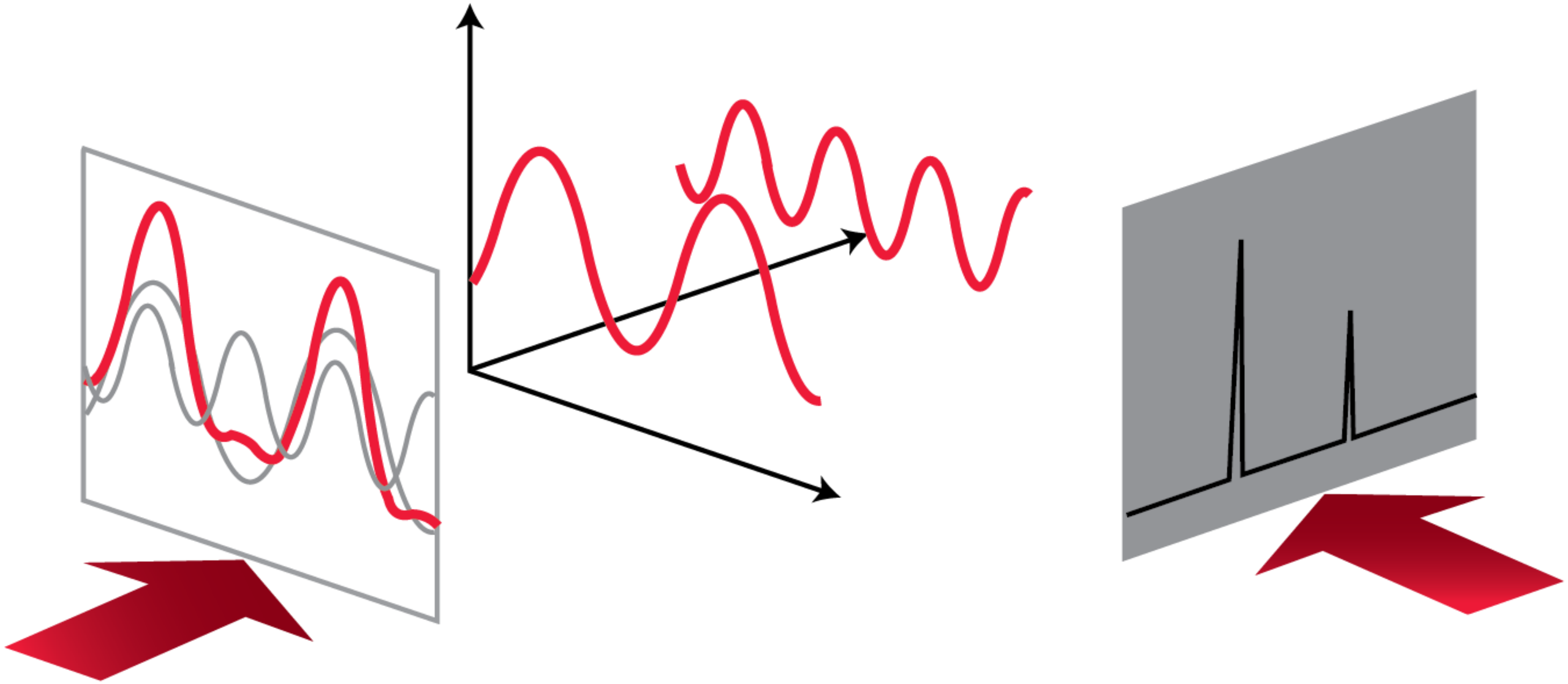
February 28th, 2025

Agenda

01

Time vs. Frequency Domain

Time Domain vs. Frequency Domain

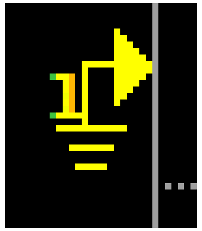


Time domain measurements

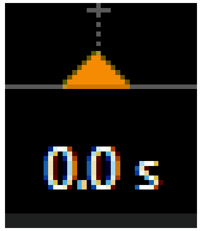
Frequency domain measurements

Time Domain vs. Frequency Domain

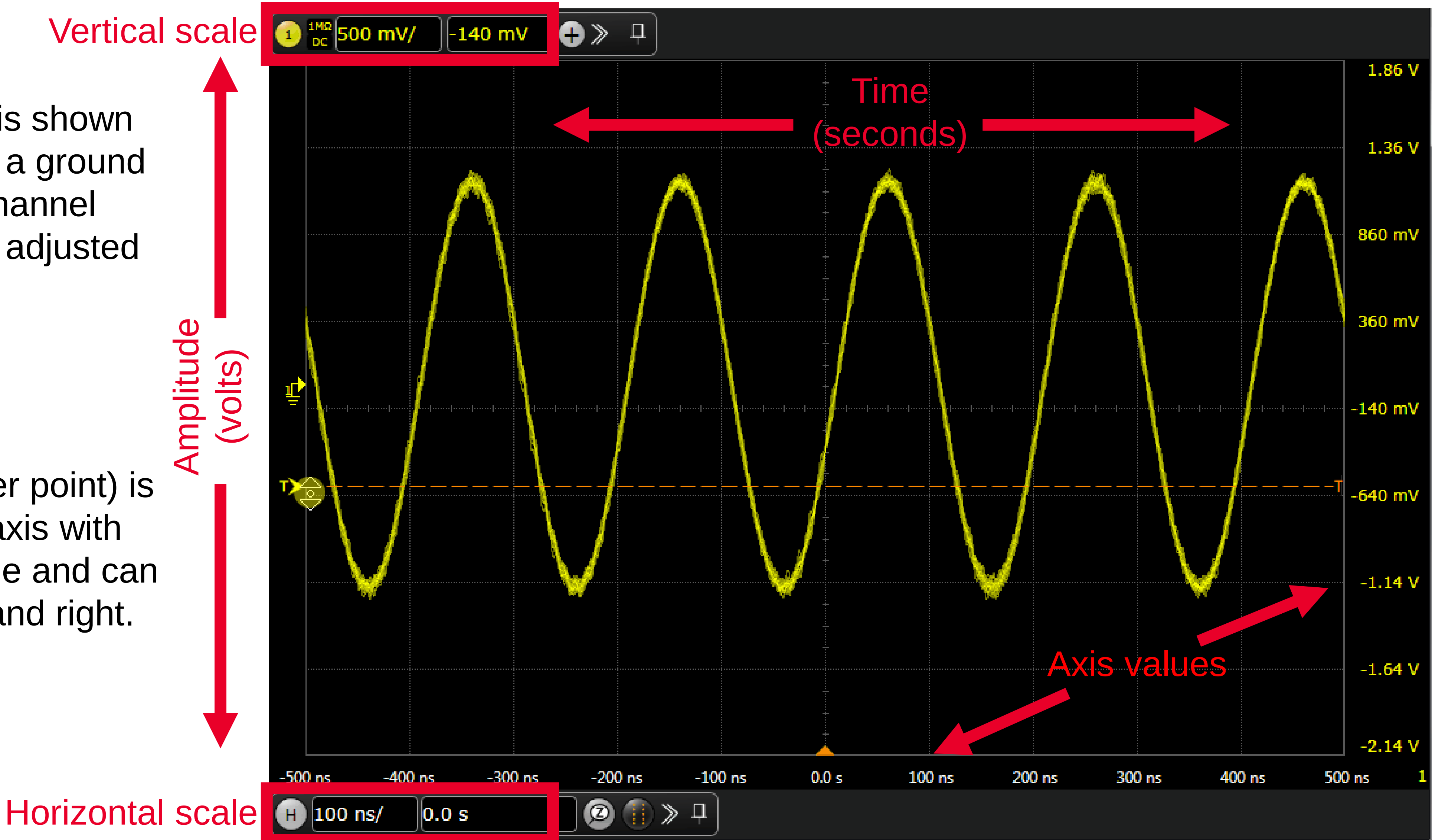
What is on the oscilloscope screen?



0 volts (or amps) is shown on the y-axis with a ground symbol and the channel number. It can be adjusted up and down.



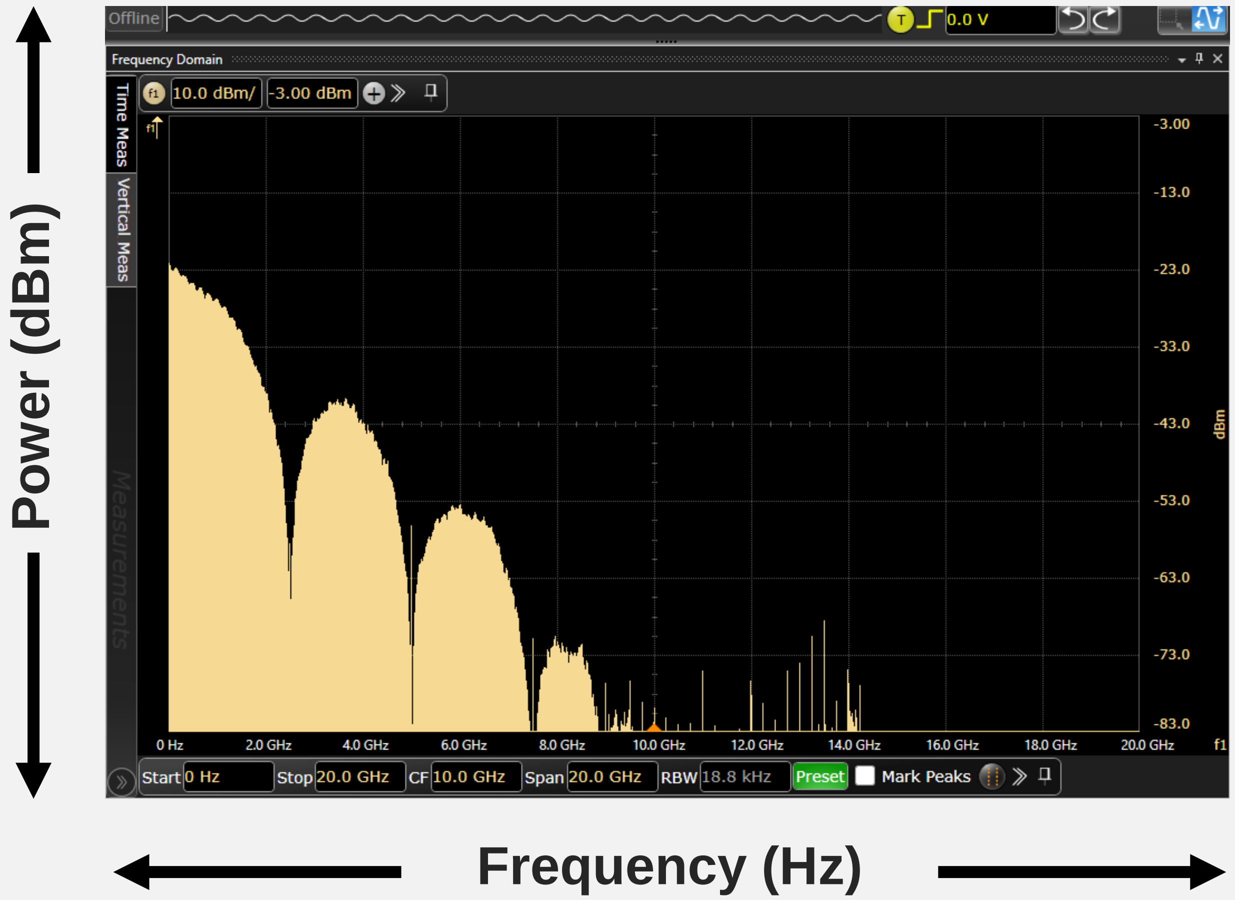
0 seconds (trigger point) is shown on the x-axis with an orange triangle and can be adjusted left and right.



Time Domain vs. Frequency Domain

How to convert between the two, or view both

- You can convert between the time and frequency domain using math.
- Fast Fourier Transform (FFT) - easily processed by a computer.
- Alternative ways of presenting the same signal.
- Some behavior is seen easier in one domain than the other.



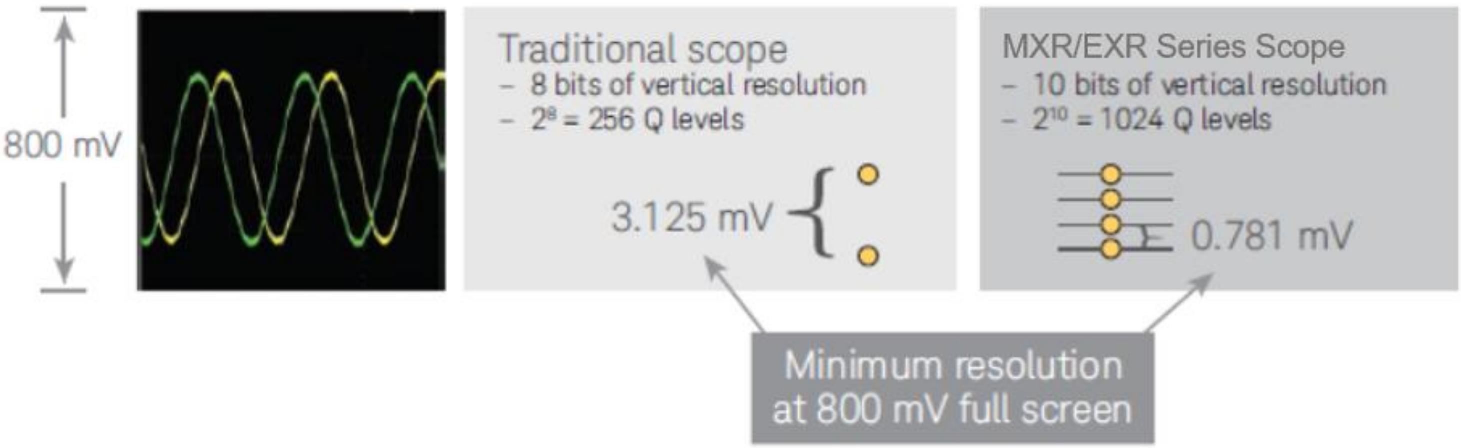
02

Oscilloscope Acquisition Basics

ADC Bits and ENOB

The vertical resolution of the oscilloscope

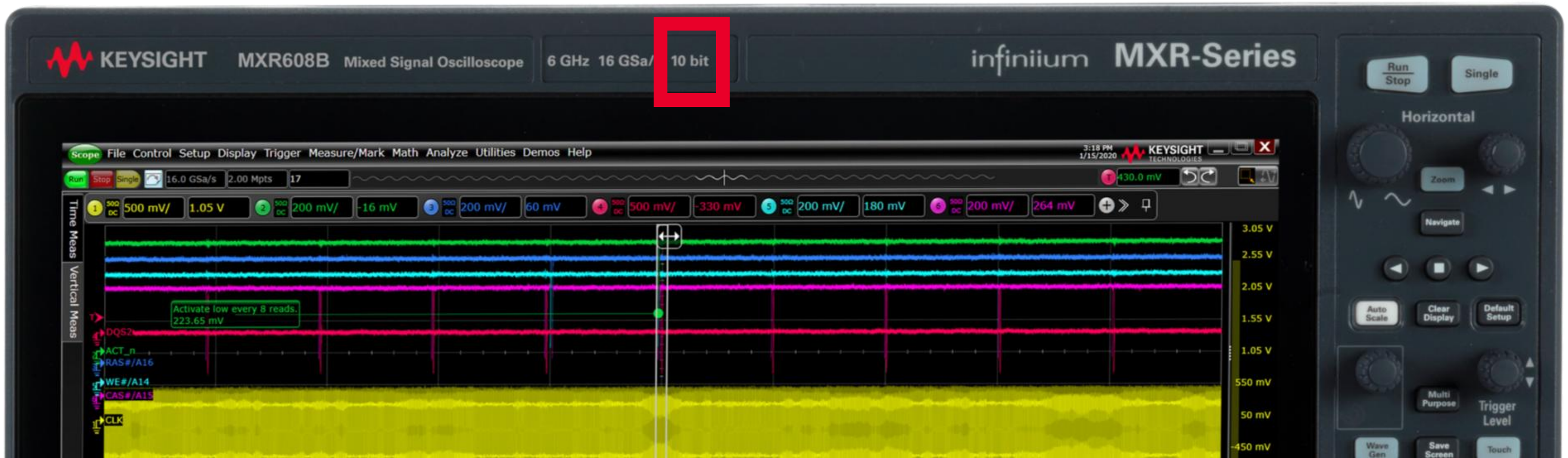
- The oscilloscope has an ADC with a specified number of bits. The number of bits (K) is equal to 2^K quantization levels. For example, an 8-bit ADC can encode an analog input to one in 256 different levels ($2^8 = 256$), while a 10-bit ADC would have 1024 Q levels ($2^{10} = 1024$).
- Therefore, a 10-bit ADC would theoretically have four times the vertical resolution of an 8-bit ADC. This is in a perfect world where no noise exists.



ADC Bits and ENOB

The vertical resolution of the oscilloscope

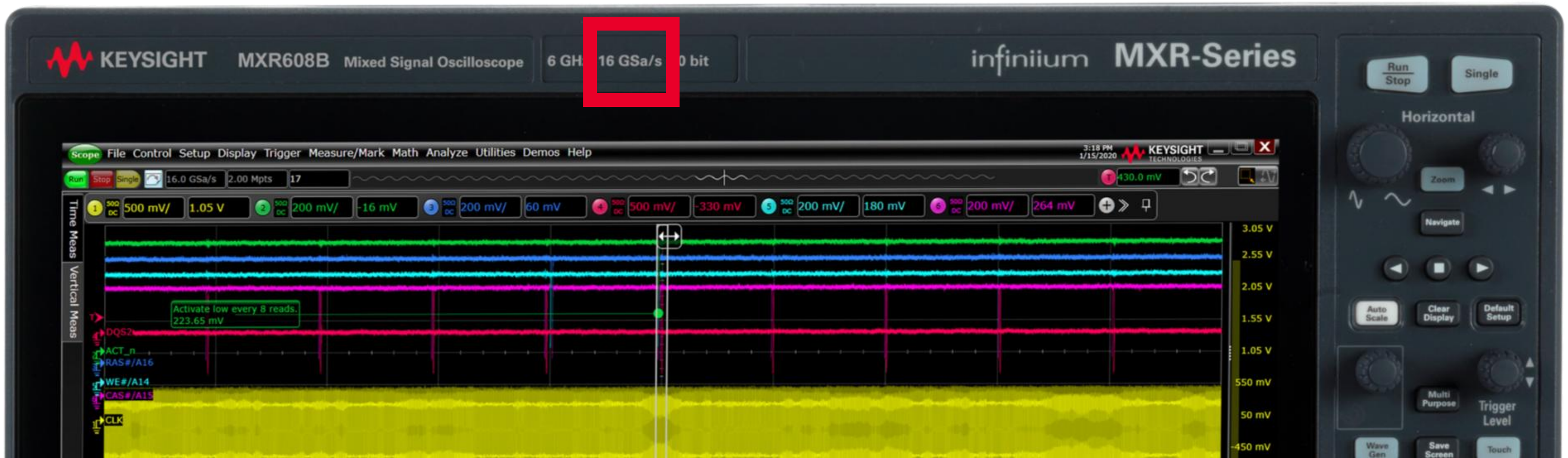
- Although an oscilloscope may have a higher ADC bit count than another scope, it may not have more vertical resolution when turned on and operating. Because noise is an inherent part of any electrical system, the oscilloscope’s ADC ends up using some bits to quantize noise of the system itself. Because of this, the oscilloscope will never reach the vertical resolution of the ADC while in operation.
- The effective number of bits (ENOB) of an oscilloscope is a better specification to use to understand a scope’s vertical resolution. It tells the actual number of bits available for digitizing the signal when the system is turned on.



Sampling Rate

How often the oscilloscope measures voltage

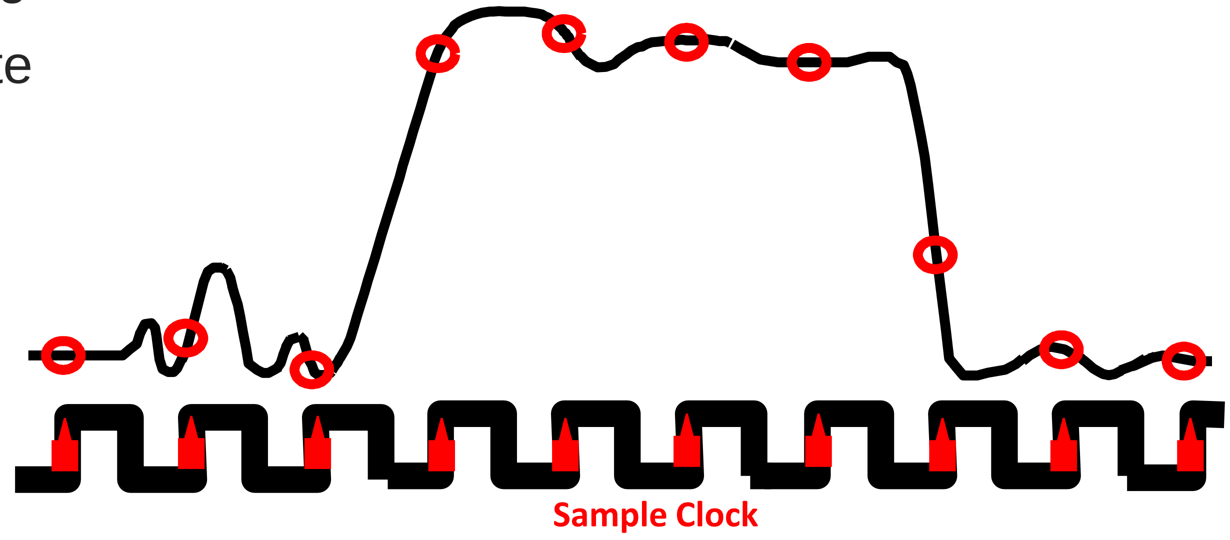
- The speed which the oscilloscope's ADC samples the voltage of the input signal. Measured in samples per second (Sa/s).
- The signal on the screen is an image created by connecting the dots between billions of samples to create a continuous shape over time.
- The minimum requirement is generally 2.5x the bandwidth, e.g. 6 GHz needs at least 15 GSa/s.



Sampling Basics

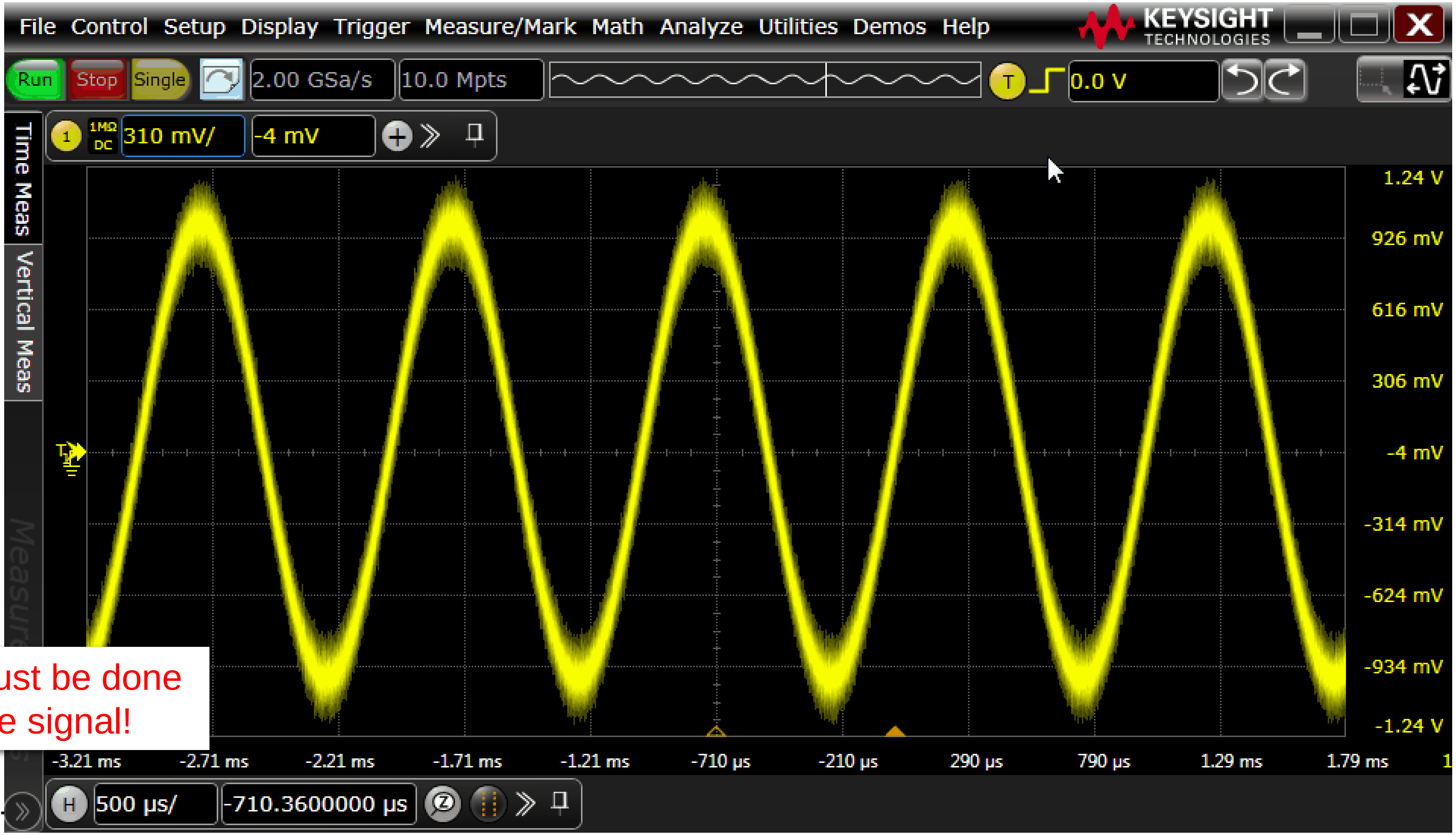
Real-time sampling

- All samples are displayed 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



Sampling Basics

Averaging



Averaging must be done on a repetitive signal!

Waveform Update Rate

Also known as trigger rate or capture rate

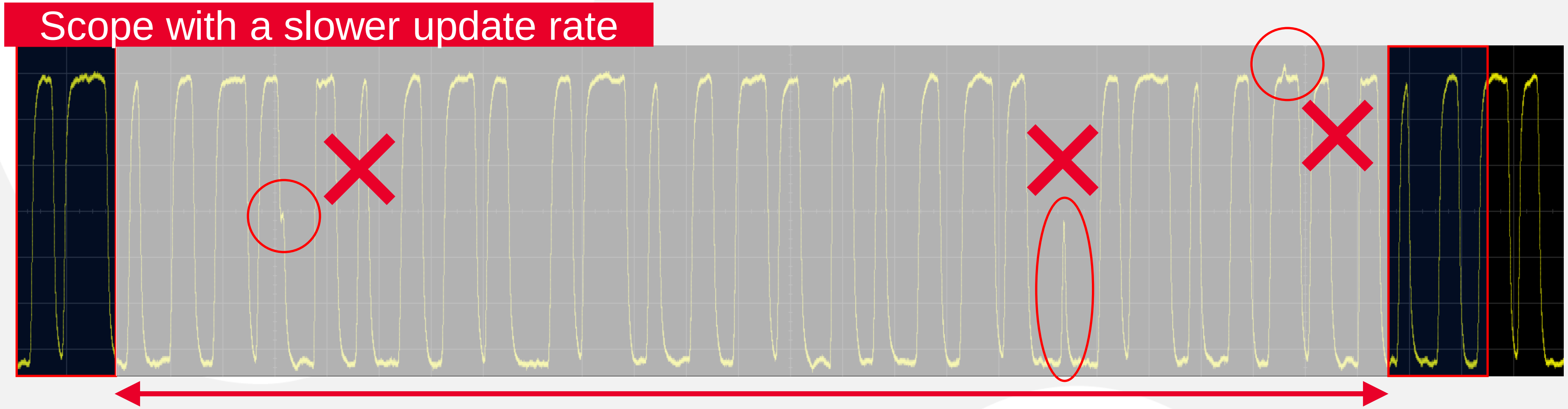
Waveform update rate refers to the number of waveforms an oscilloscope can acquire, process, and display per second. It’s usually expressed in waveforms per second (wfms/s).

Components of Capture Rate:

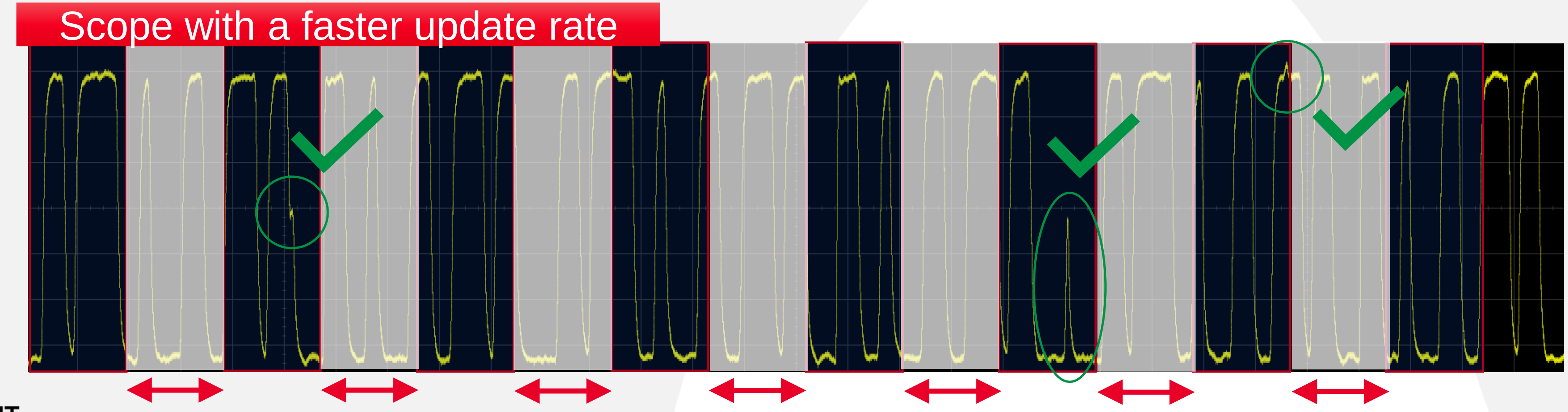
- **Acquisition system:** Captures the incoming signal.
- **Processing system:** Applies mathematical calculations or manipulations to the acquired data.
- **Display system:** Shows the final waveform on the screen.

Waveform Update Rate

Dead time



Long dead time = decreased chance of capturing rare events



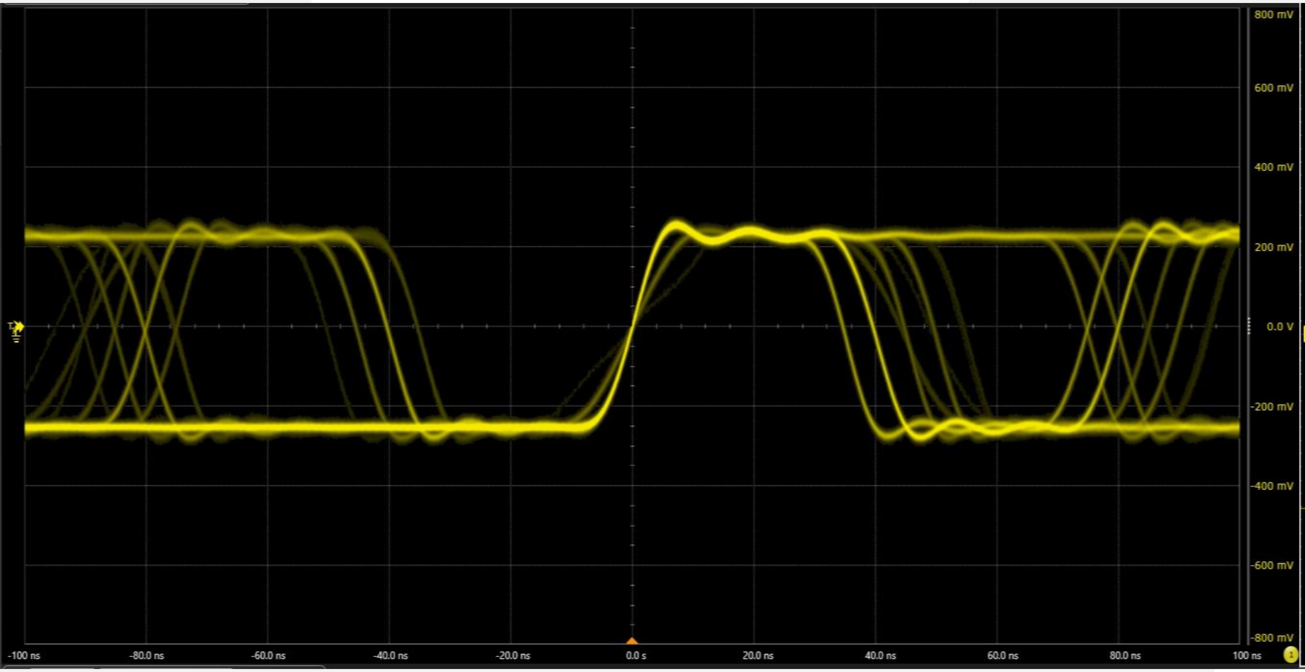
Short dead time = increased chance of capturing rare events

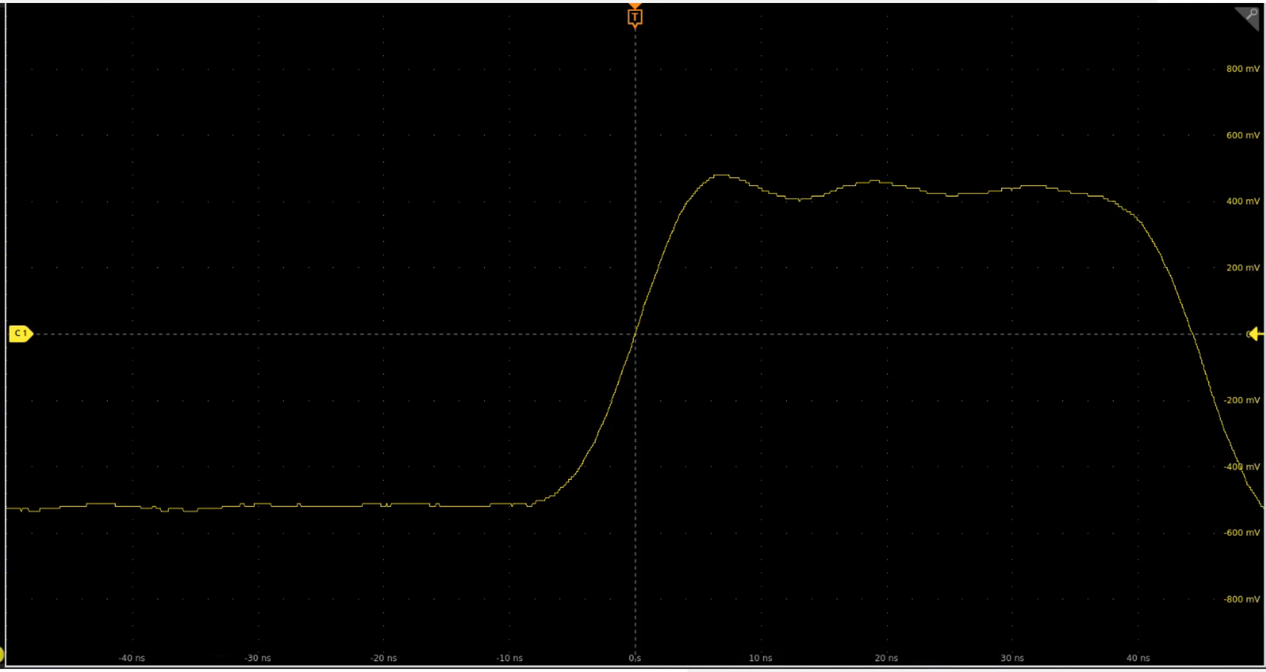
Waveform Update Rate

Competitive comparison

Fast waveform update rate
(Keysight scope)

Slow waveform update rate
(Competitive scope)





This is the same exact signal displayed on two different scopes!

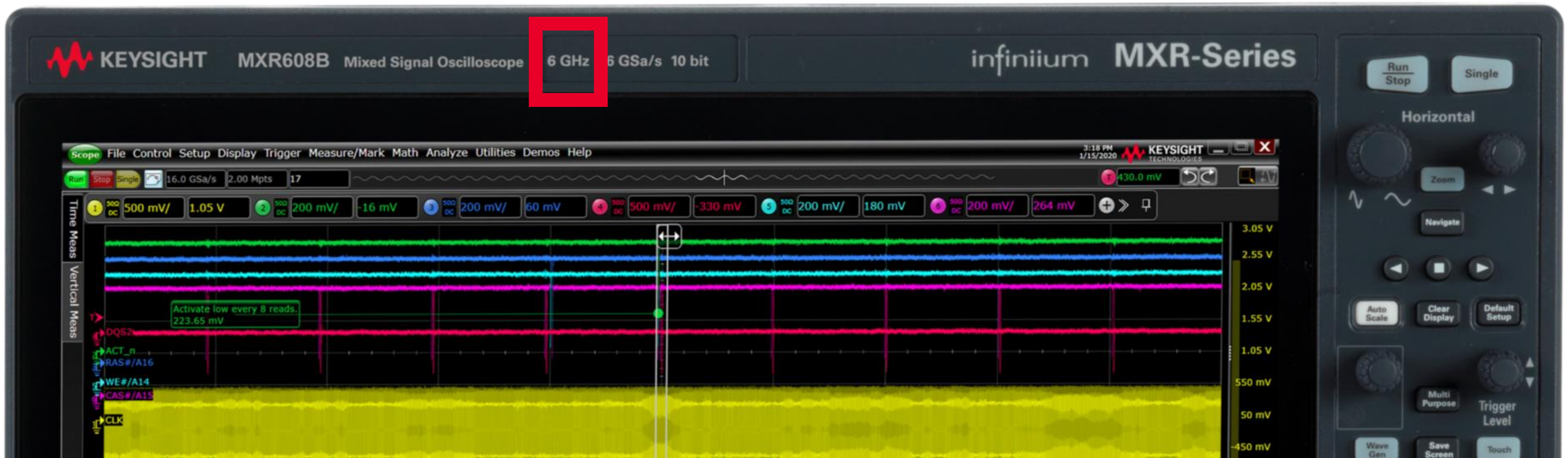
03

Bandwidth and Aliasing

Bandwidth Basics

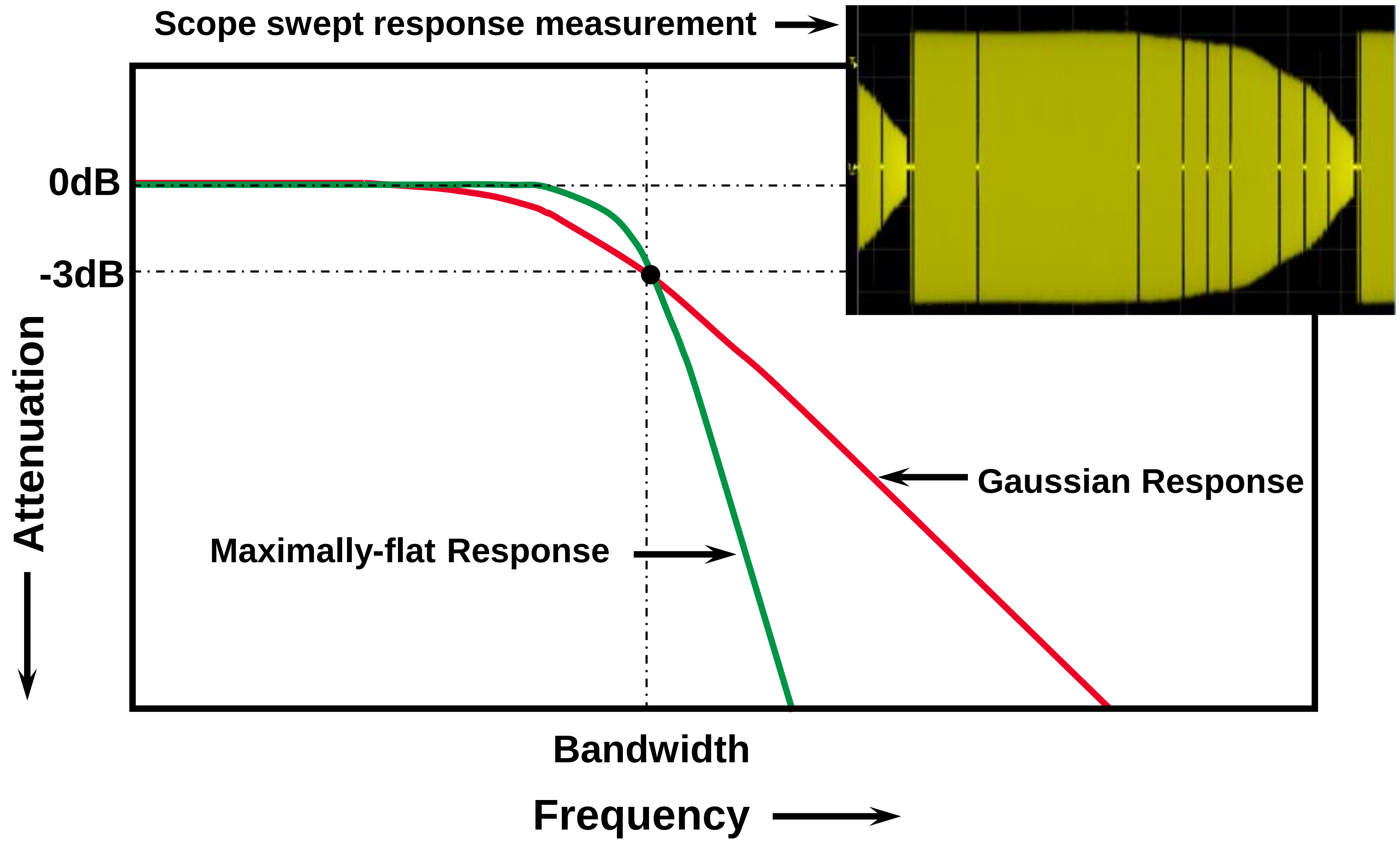
The defining characteristic of an oscilloscope

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



Bandwidth Basics

Also called the "3 dB down point"



Bandwidth Basics

Nyquist's Theorem

- **Nyquist's sampling theorem:**

for a limited bandwidth (band-limited) signal with maximum frequency f_{max}, the equally spaced sampling frequency f_s must be greater than twice f_{max} to reconstruct the signal uniquely and without aliasing.

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

f_s is called the Nyquist sampling frequency

f_{max} is sometimes called the Nyquist frequency (f_N)

- In other words, you need to have a sampling rate **AT LEAST** 2x the max frequency of your signal.

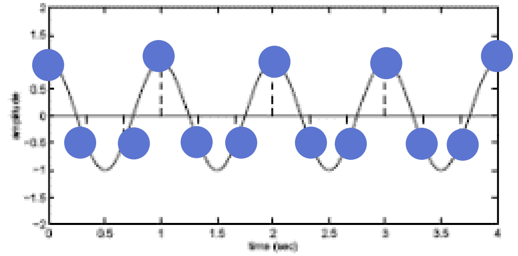
Dr. Harry Nyquist, 1889-1976, articulated his sampling theorem in 1928

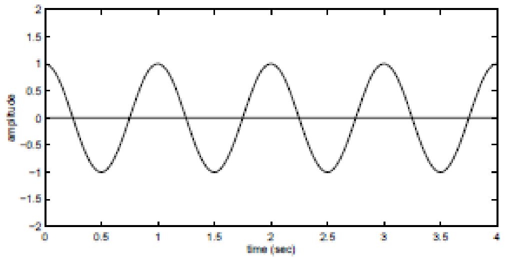
Nyquist / Sampling Theorem

$f_s \geq 2\, f_c$

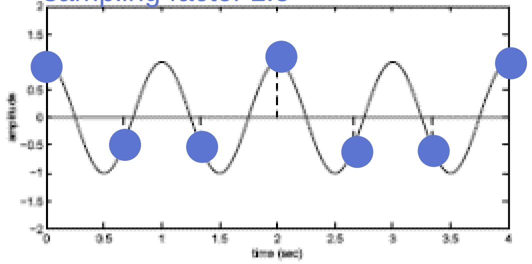
f_s sampling frequency
f_c highest frequency contained in the signal

sampling factor 3

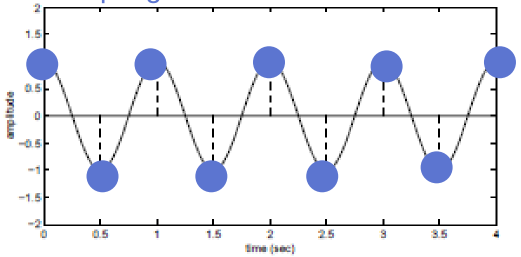




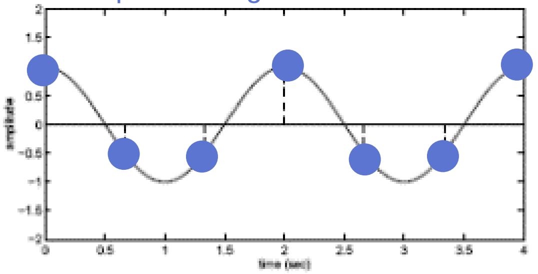
sampling factor 1.5



sampling factor 2



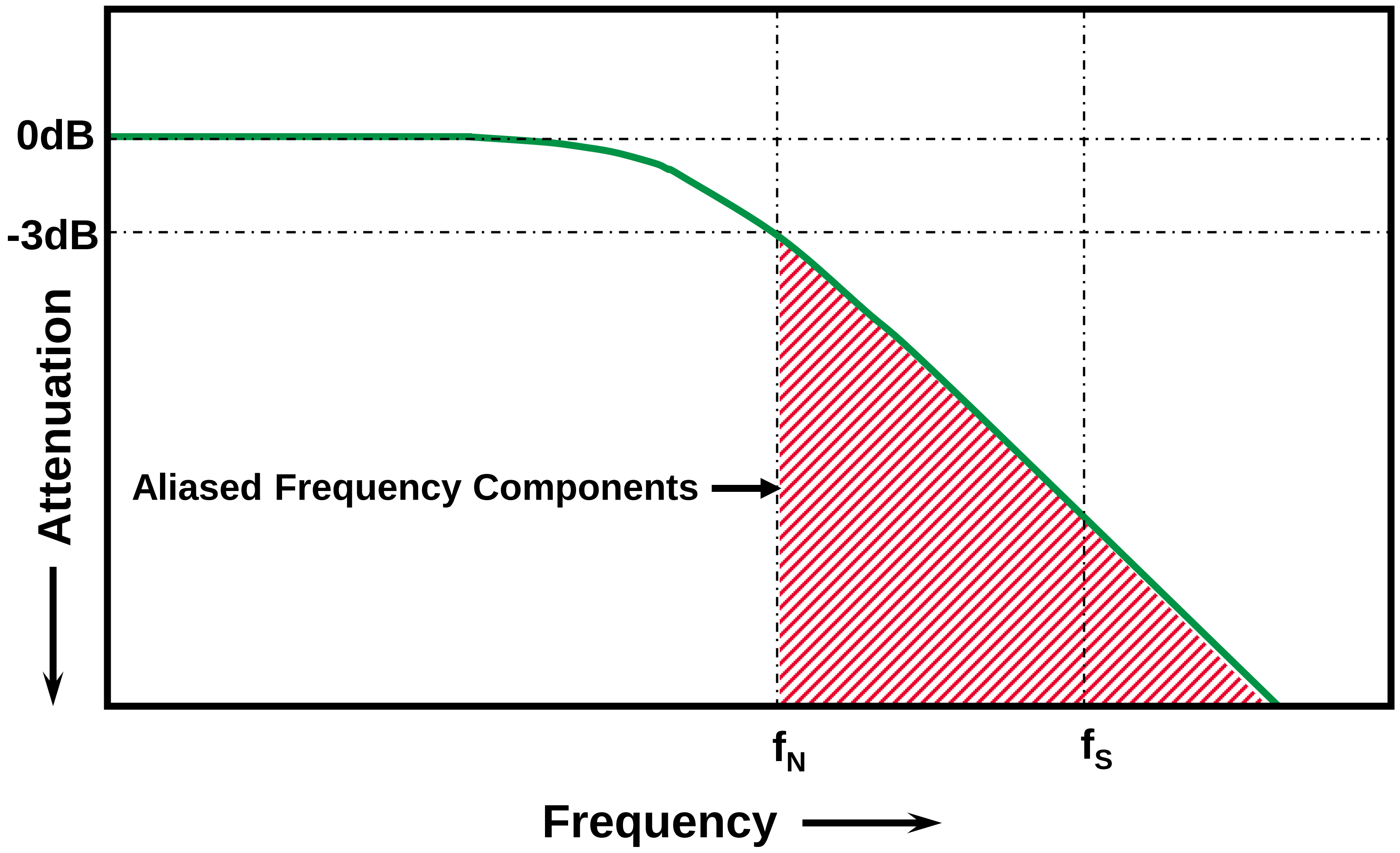
example aliasing



The sampling frequency should be at least twice the highest frequency contained in the signal

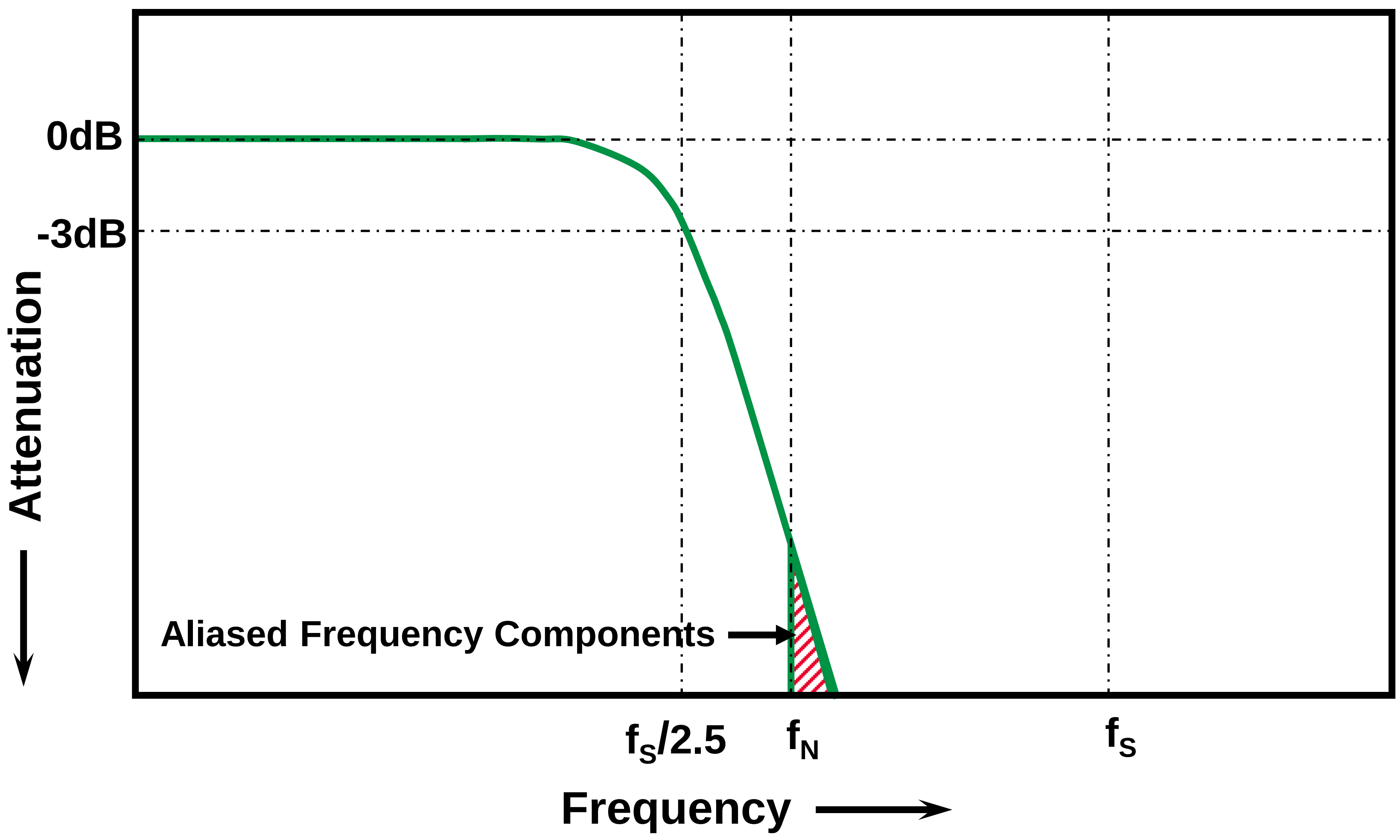
Gaussian Response With Bandwidth at 1/2 Sampling Rate (Nyquist Frequency)

A “Gaussian front end” has a typical 20 db/decade low pass filter response, and we’re at the limits of Nyquist’s theorem, meaning that content higher than f_N gets through easier. This causes aliasing.



Maximally-Flat Response With Bandwidth at $f_s/2.5$ (Sampling at 2.5 times Nyquist)

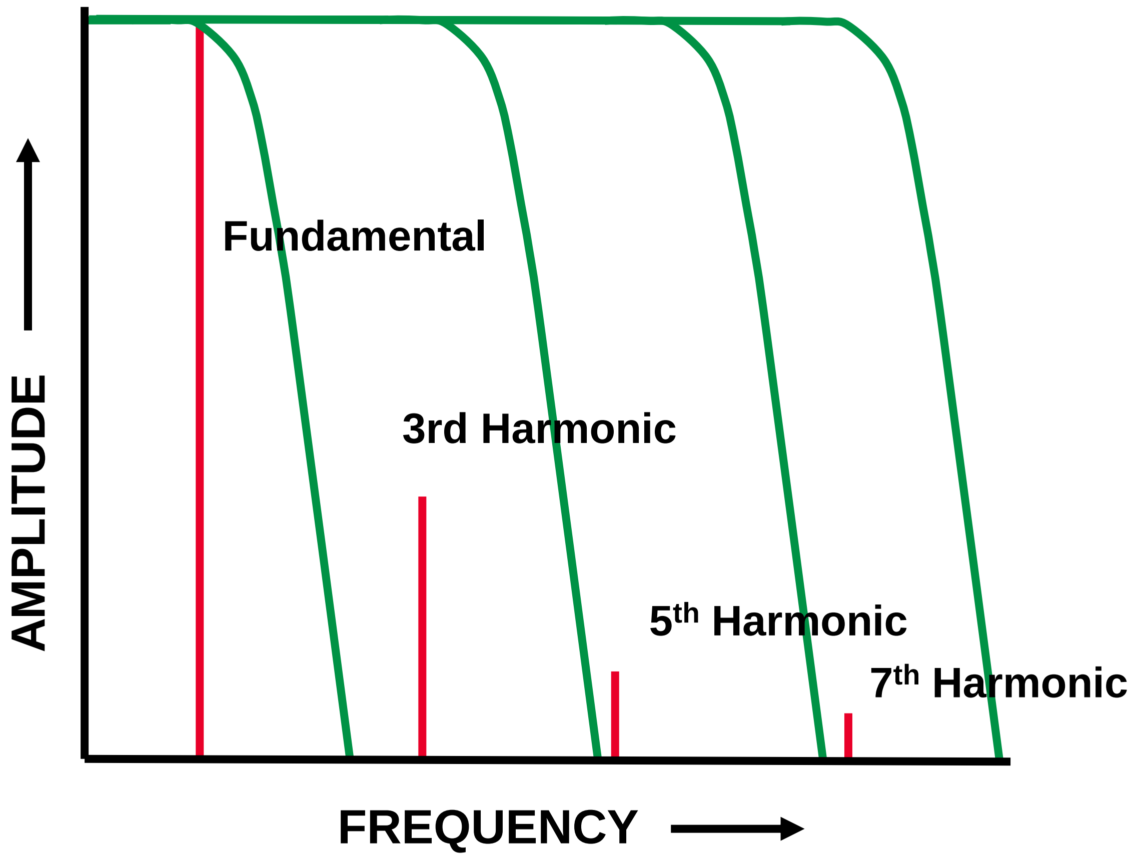
"Maximally flat front end" has a steeper low pass filter response, and we are sampling 2.5x of f_N, preventing most aliasing.



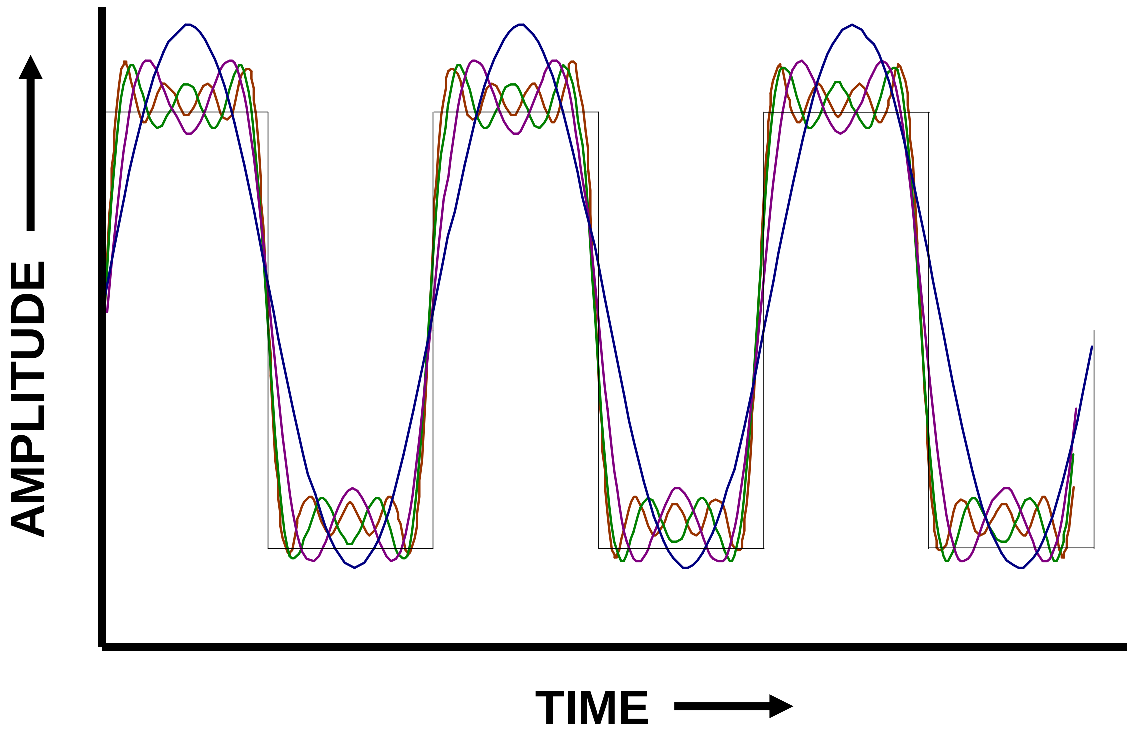
Bandwidth Basics

Every signal consists of a fundamental and its harmonics

Square wave in the frequency domain



Square wave in the time domain, as we increase sample rate and bandwidth



Bandwidth Basics

How much bandwidth do you need?

- **Step #1:** Determine the fastest rise/fall time of the device-under-test.
- **Step #2:** Determine the highest signal frequency content (f_{knee}).

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

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

- **Step #3:** Determine degree of required measurement accuracy.

- **Step #4:** Calculate required bandwidth.

Accuracy	Gaussian	Maximally-flat
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}

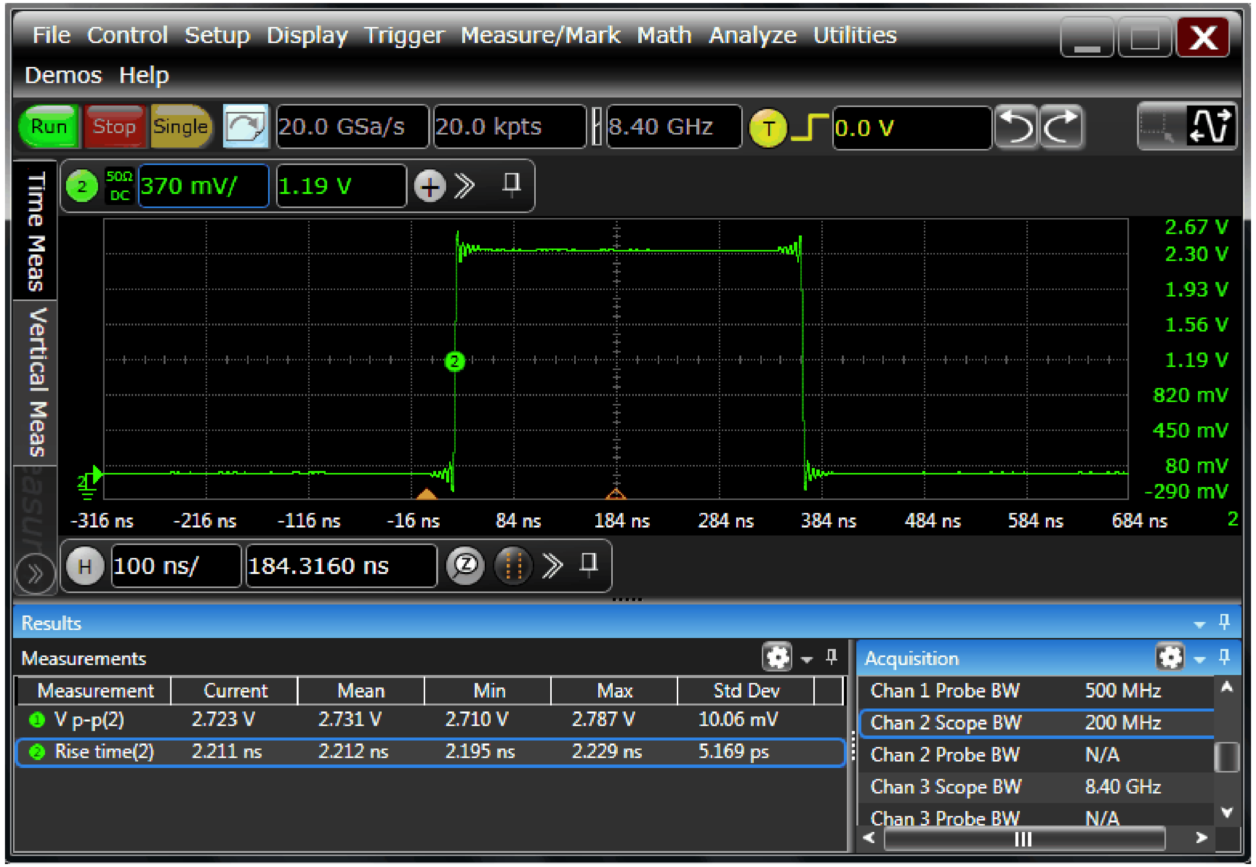
- Source: Dr. Howard W. Johnson, “High-speed Digital Design – A Handbook of Black Magic”

Bandwidth Basics

What happens if my oscilloscope is too slow?

Bandwidth Basics

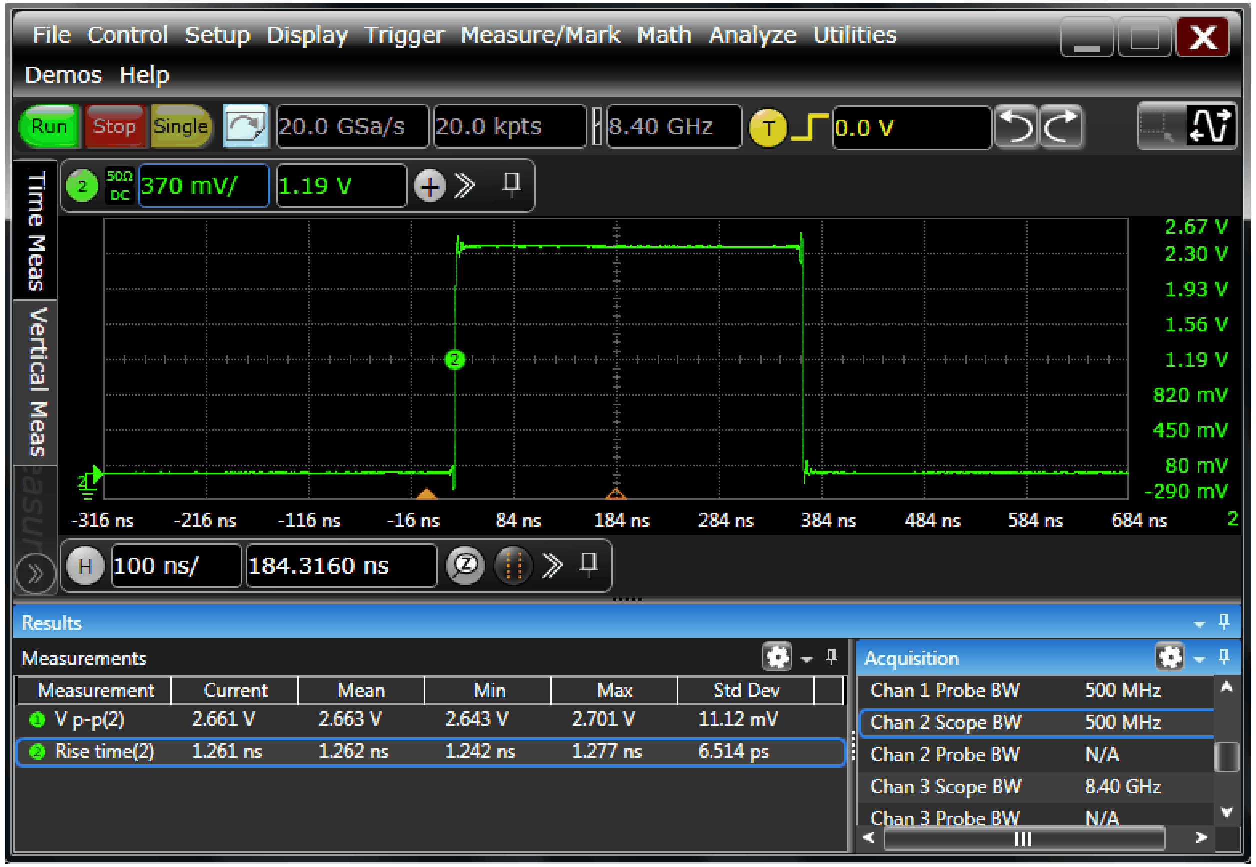
How measurement quality changes



200 MHz Bandwidth

V_{PP} = 2.73V

T_{RISE} = 2.21 ns



500 MHz Bandwidth

V_{PP} = 2.66V

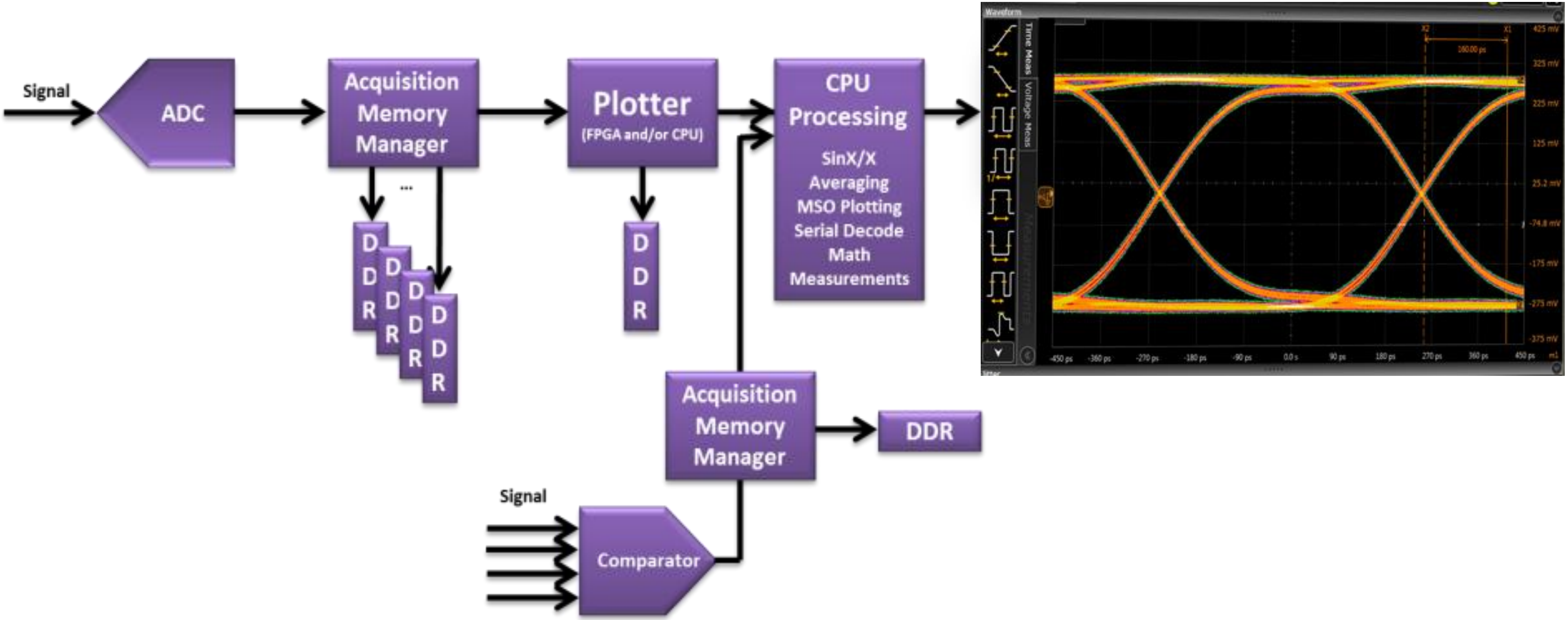
T_{RISE} = 1.26 ns

04

Oscilloscope Architectures

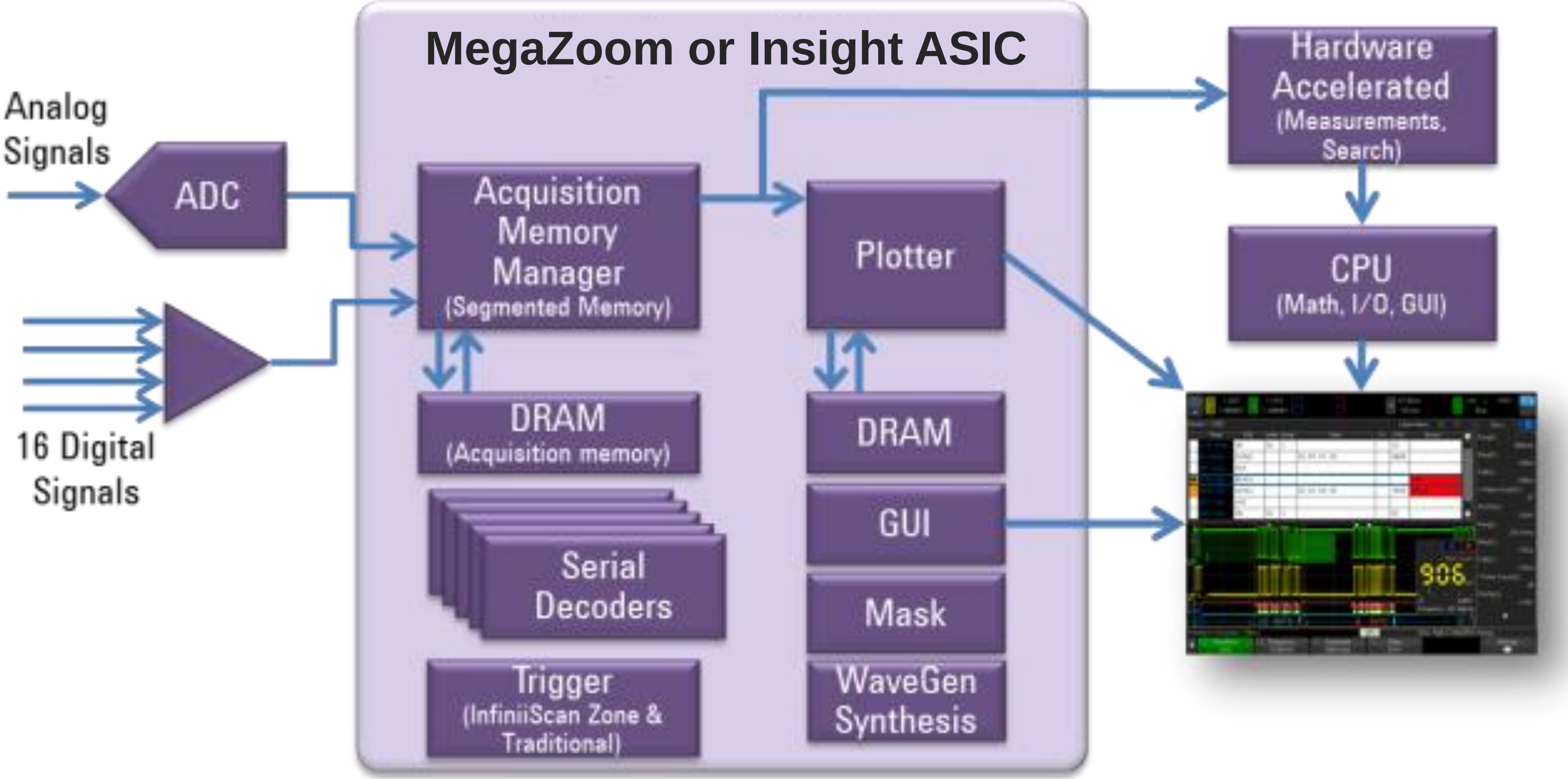
Oscilloscope Architectures

Traditional processing architecture



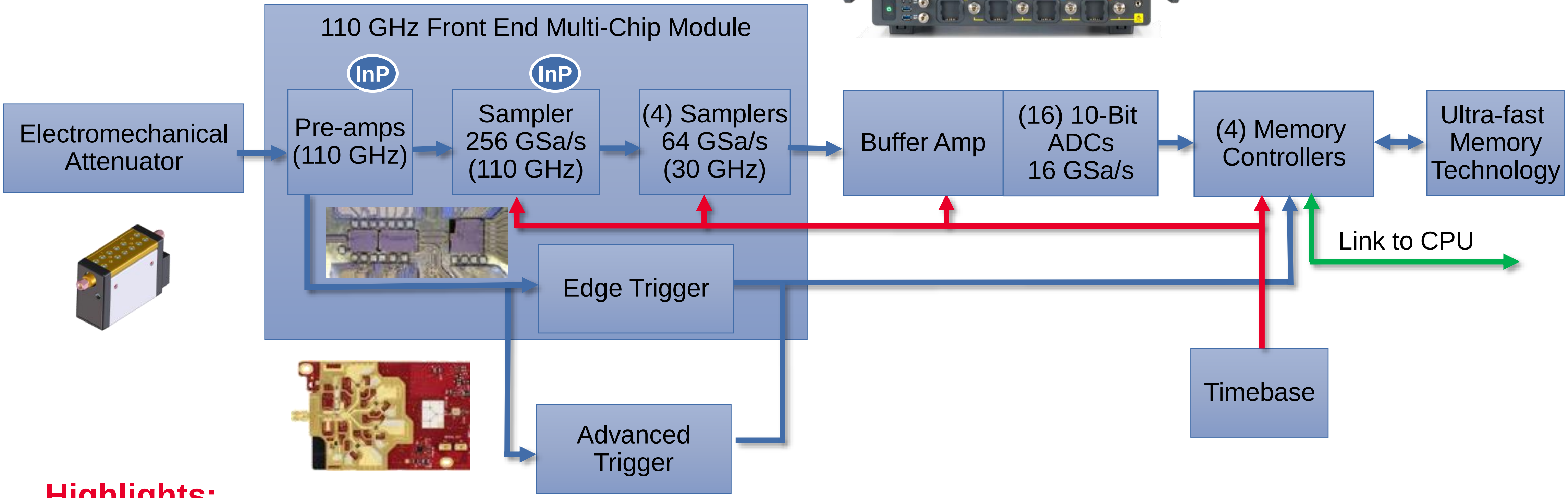
Oscilloscope Architectures

ASIC digital signal processing (DSP)



Oscilloscope Architecture

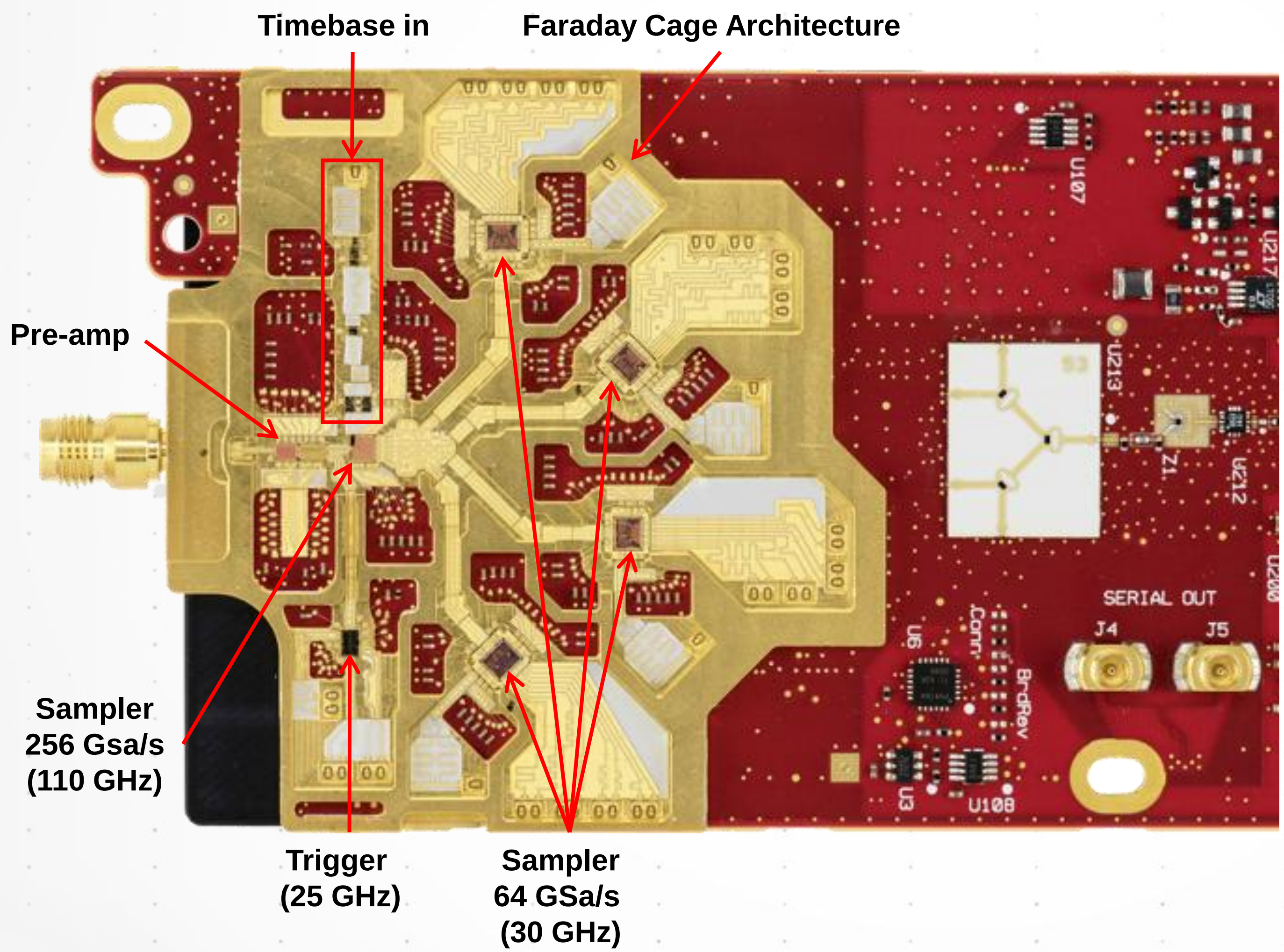
Modern time-interleave sampling

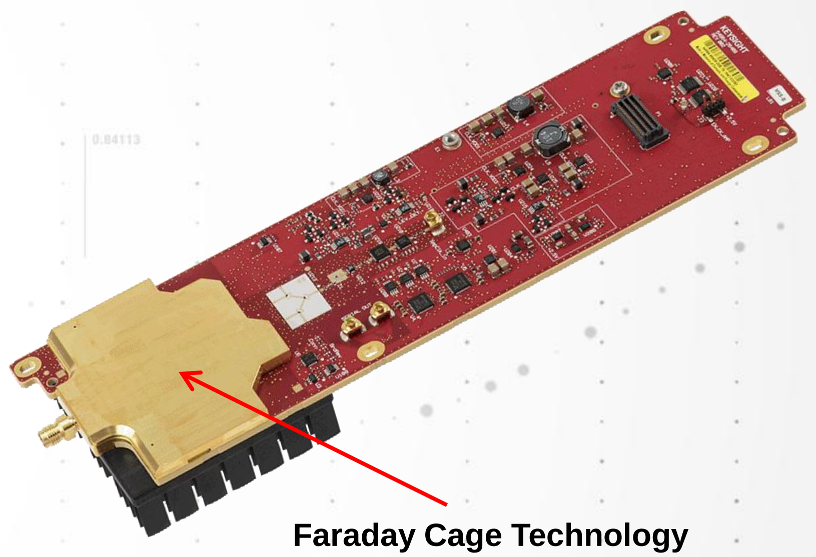


Highlights:

- Provides a full bandwidth, indium phosphide-enabled sampling system.
- Enables much higher frequency and more efficient data flow with less noise.
- Adapts to the latest technologies, including Hybrid Memory Cube (HMC) and Faraday Cage shielded, analog, Front-end Multi-Chip Modules (MCMs).

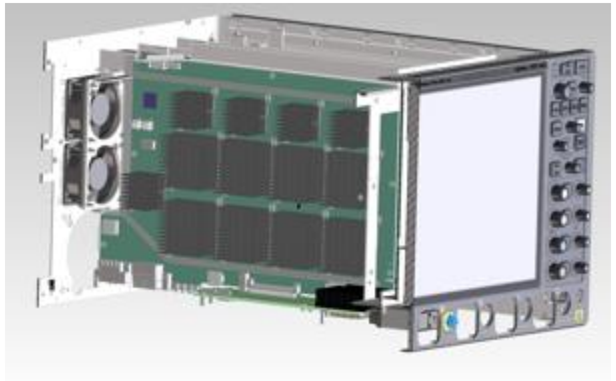
Front End Multi-Chip Module (1mm & 1.85mm models)



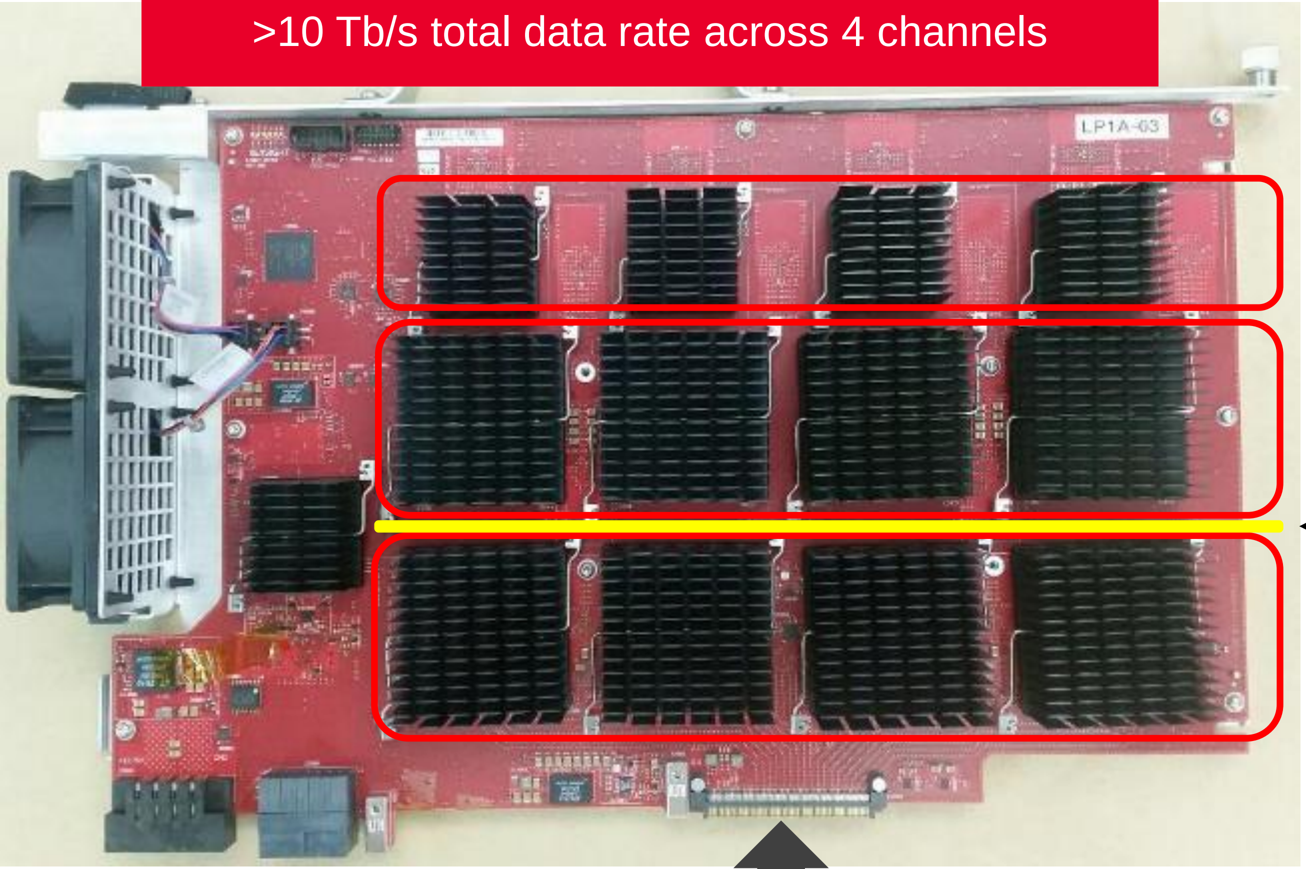


UXR Acquisition System

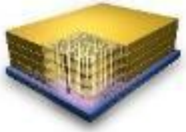
Sampling at 256 GSa/s on each channel (each sample is 10 bits)



>10 Tb/s total data rate across 4 channels



Hybrid Memory Cube



Advanced, ultra-fast 3D memory technology

New Data Processor

100M gate ASIC capable of 5 trillion integer operations per second

New Custom ADC

(4) 10-bit ADCs integrated into each chip

2.56 Tb/s at this interface

Multi-Chip Front End Modules connect here

Fun Facts About Infiniium UXR-series Oscilloscopes

ULTRA-PERFORMANCE FOR EVEN THE MOST DEMANDING ENGINEERING NEEDS

10Tb/s Acquisition system

- 272 - Full length DVDs
- 50 - 1080p Blu-ray movies
- 15 - 4K Ultra HD movies

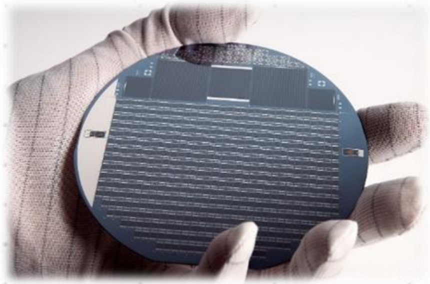
PER SECOND!!

OR streaming the entire Spotify music catalog of 30 million songs in less than 4 minutes

Each UXR chassis supports up to 4 Channels, each simultaneously sampling at 256 GSa/s, for a total of 1 Trillion samples per second

The Infiniium UXR is the first ever High-Definition 10-bit Ultra-performance Real-time Oscilloscope

8 new custom ASICs in InP, SiGe, and Si



- Up to 81 custom ASICs per oscilloscope
- 7 different custom ASIC processes

Plus

- 13 FPGAs per oscilloscope
- 38 thin films
- 9 unique MMICs

05

Triggering

Scope Trigger Modes

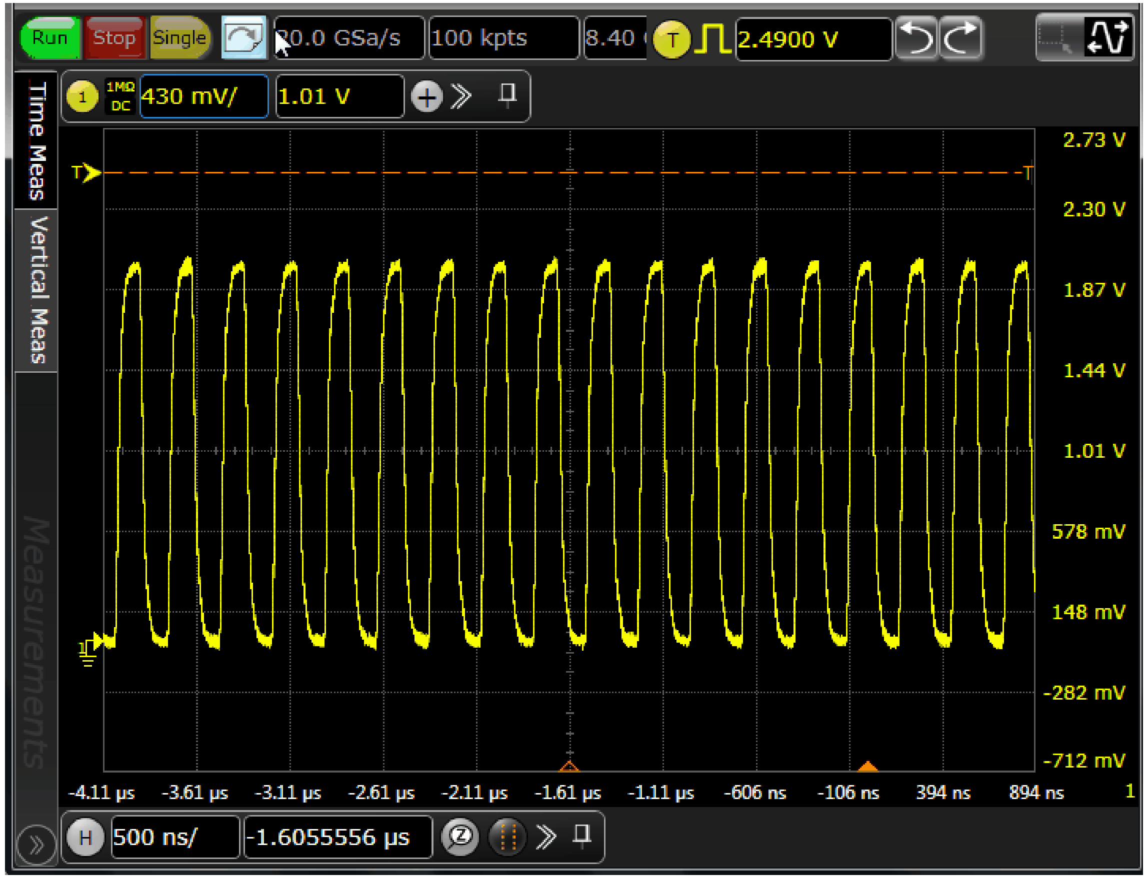
- **Auto** – Produce an automatic asynchronous trigger when a valid trigger is not present to display an untriggered waveform.

- **Triggered / normal** – Produces a trigger only if a valid trigger condition occurs. You must use this trigger mode if you have a low repetition rate trigger event.

- **Single** – Produces a one-time acquisition (single-shot) when a valid trigger condition occurs (based on normal trigger mode).

Scope Trigger Modes

Auto vs. triggered: what if the scope sees no trigger?



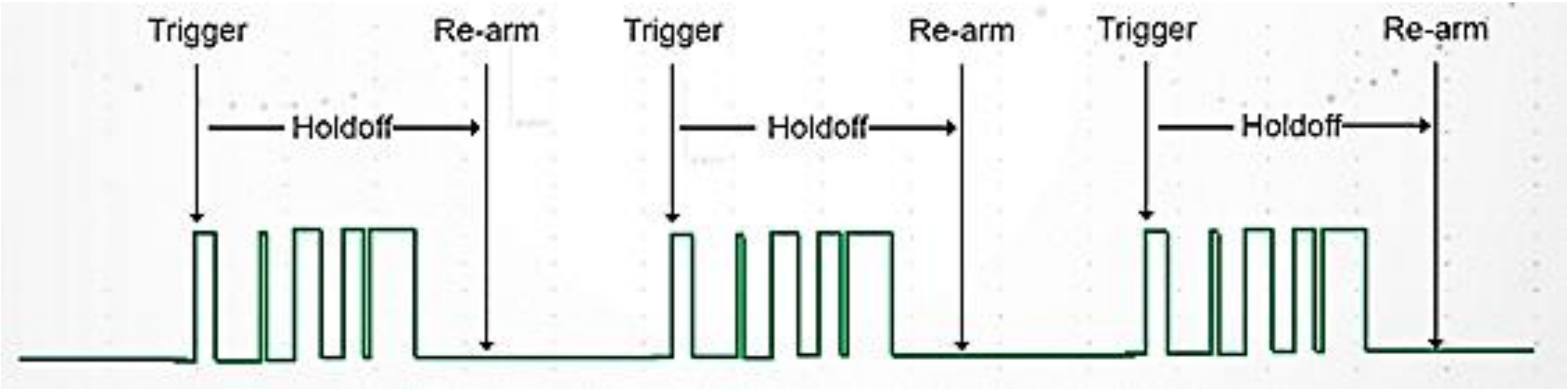
Auto: “I don’t see a trigger; I’ll trigger on my own.”

Triggered: “I don’t see a trigger; I’ll do nothing at all.”

Trigger Holdoff

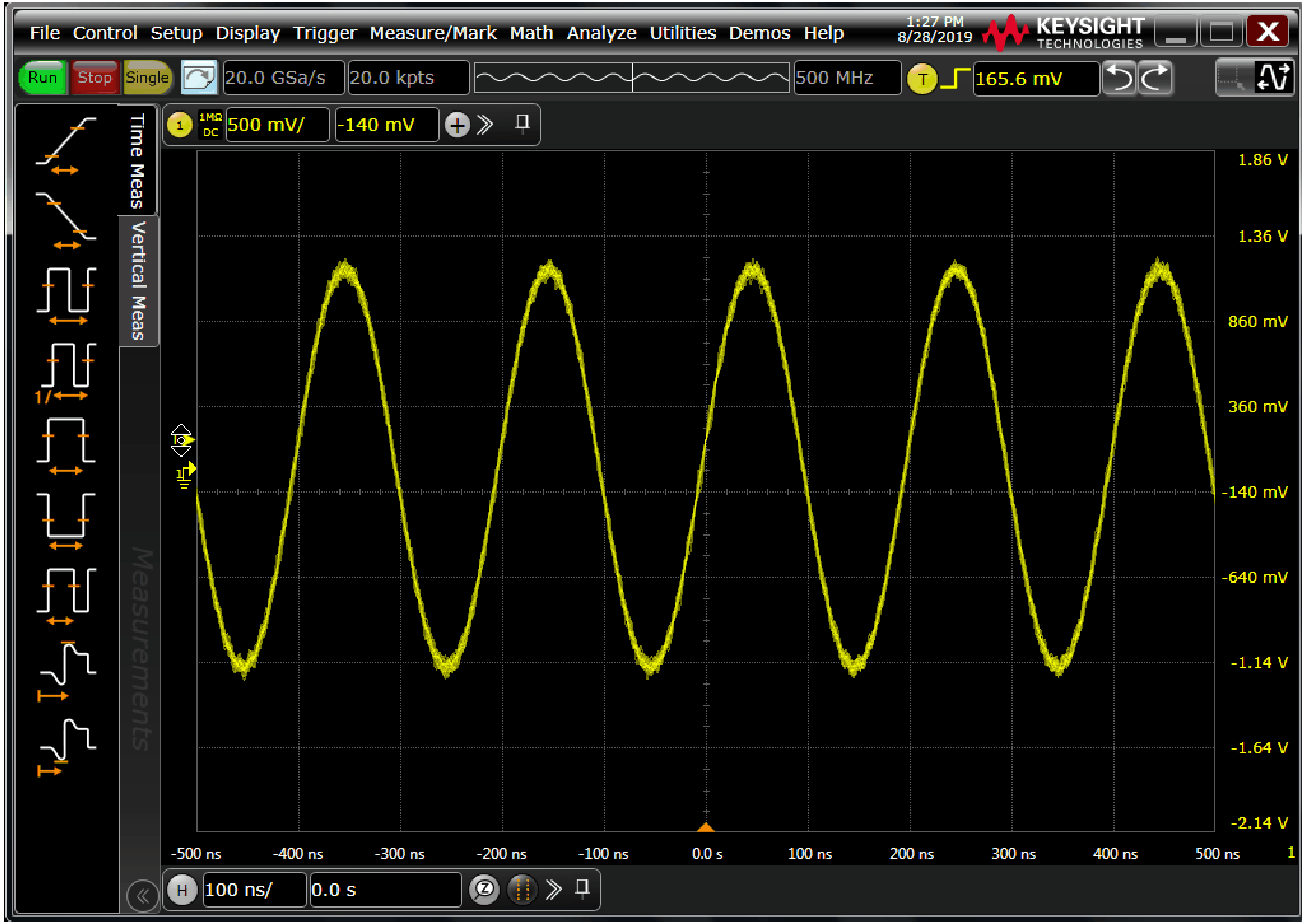
Delays re-arming of the trigger after trigger occurs

- After a trigger event occurs, trigger holdoff is a timer that delays re-arming the scope's trigger circuitry for a user-defined amount of time. Can be useful for triggering on the first event of a burst of events.
  - Use burst width to determine max and min of holdoff and lock onto the first pulse.



Trigger Types

Edge trigger (default)

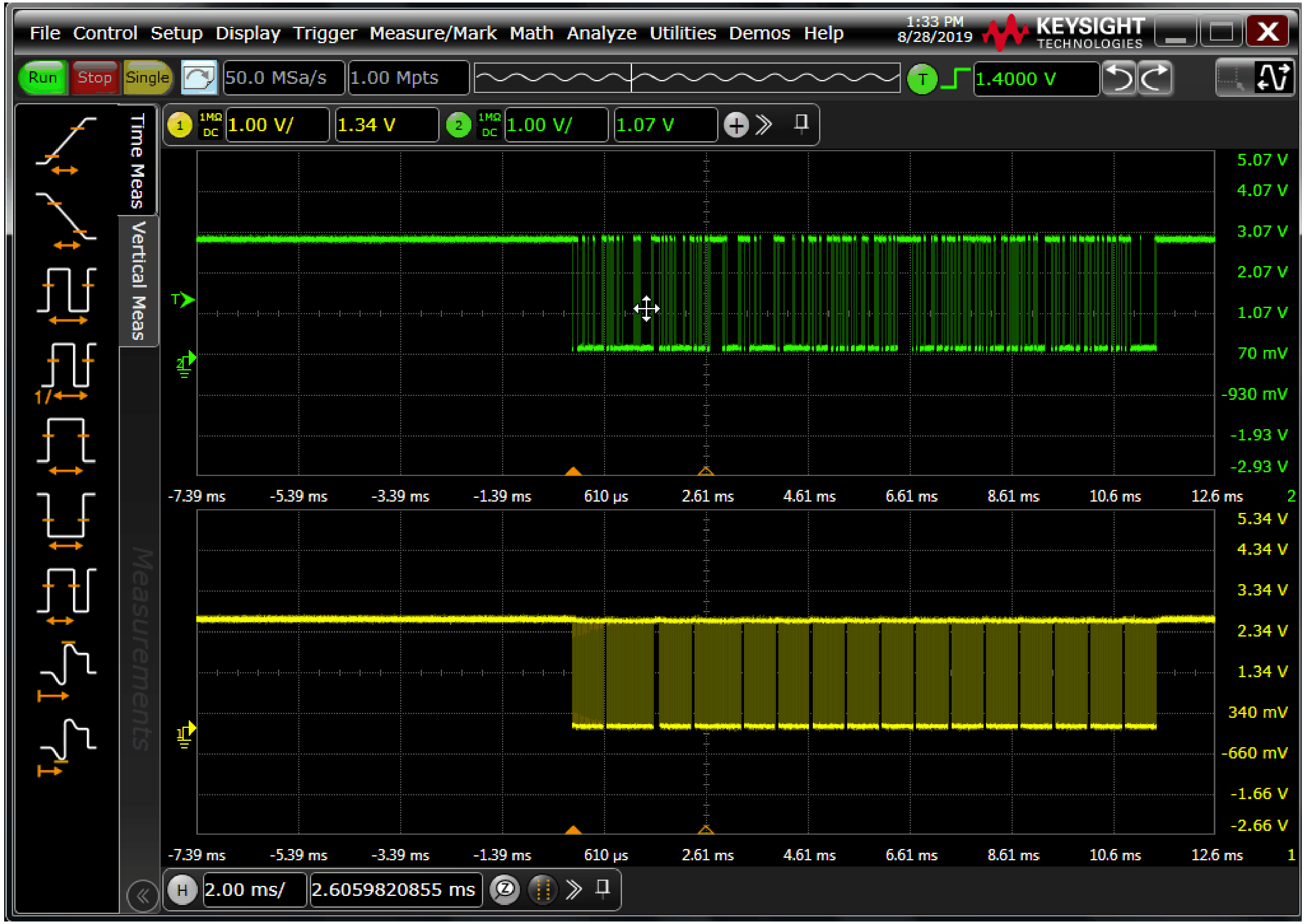


Trigger Types

Advanced triggers

Much of your oscilloscope use will only require standard “edge” triggering. Sometimes your signal is more complex, like this serial bus.

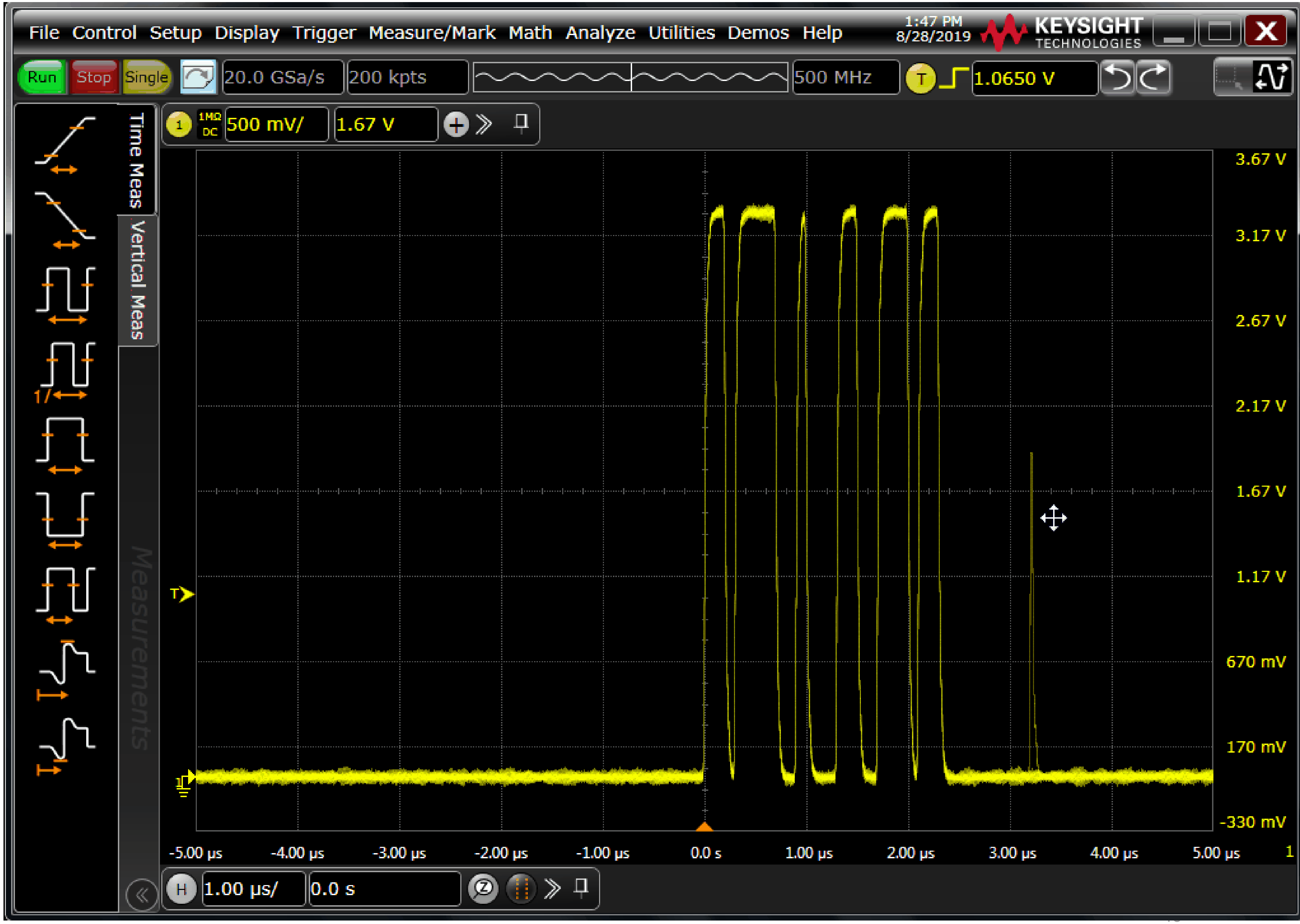
Triggering on more complex signals requires advanced triggering options.



Triggering

Advanced triggers

Advanced triggers are just more complex ways to describe the shape of a waveform, such as the pulse width trigger described in the video here.



Triggering

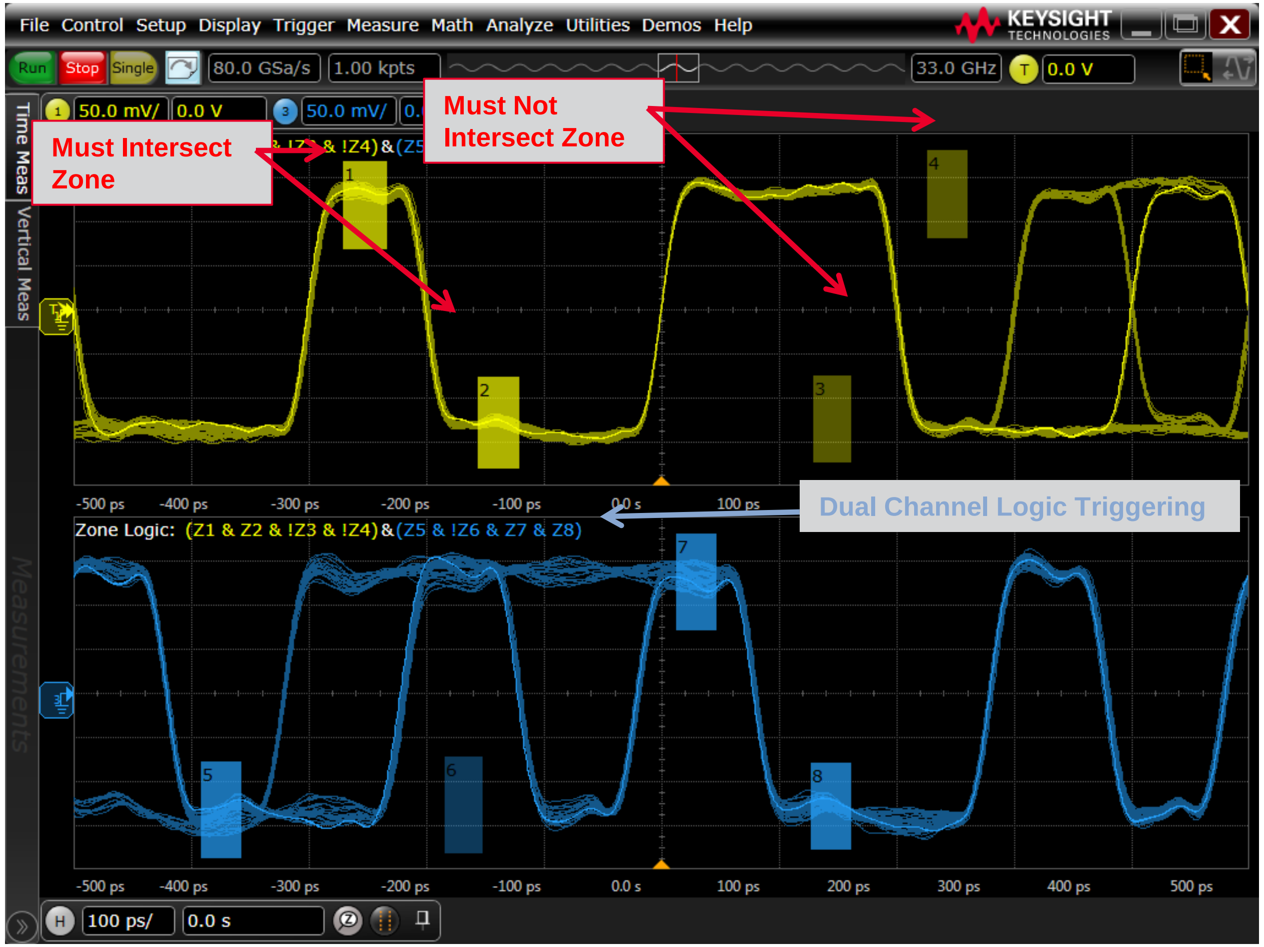
Visual triggering makes life easy

InfiniiScan trigger allows you to use a simple edge trigger and still trigger on complex waveform shapes. If you can see it, you can trigger on it by drawing up to 8 zones on multiple channel waveforms.

It can be used to create up to a three-stage trigger: Use A→B trigger, plus InfiniiScan, for two hardware triggers and the additional software InfiniiScan trigger for ultimate triggering control.

Complex Triggering with InfiniiScan Zone Qualify

- Qualify complex bus waveforms for analysis with flexible logic triggering



06

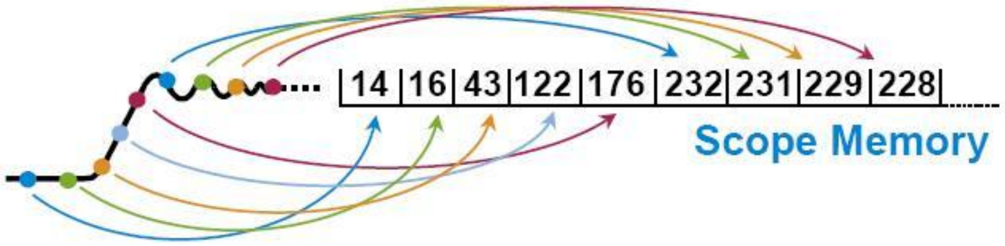
Memory

Memory Depth

How many samples the oscilloscope can take at one time

- Measured in samples or points. Modern scopes have millions or billions of samples in memory.
- Longer time captures mean more samples to store to maintain sample rate.
- Maintaining a higher sample rate means:
  - More accurate reproduction of signal
  - Better resolution between points
  - Better chance of catching glitches or anomalies

In this image, we see a waveform being sampled into memory as a value from 0 to 255 (8-bit ADC).



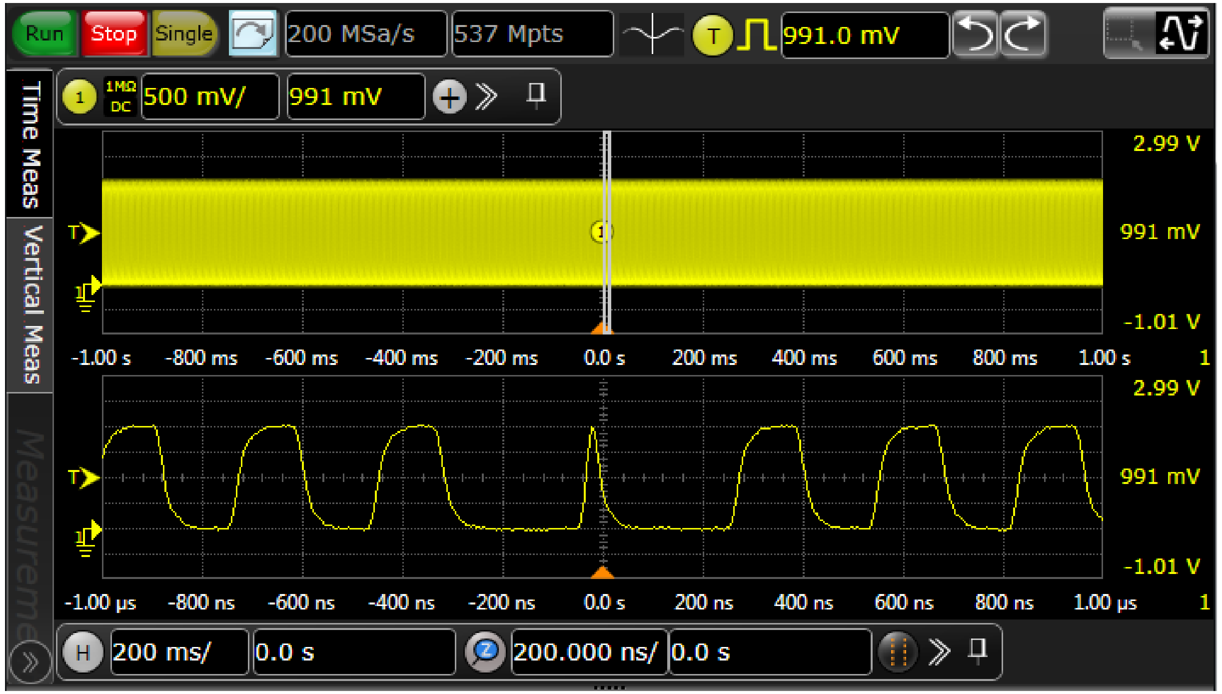
Takeaway: more memory is often better: better measurements, better at finding anomalies!

Memory Depth

How much memory do I need?

1. **Determine the required sample rate.**
   See Section 2 about determining the sample rate.
2. **Determine the longest acquisition time.**
   Based on the slowest analog signal or digital packets.

$$\text{Memory depth (Sa or pts)} = \text{sample rate}\left(\frac{\text{Sa}}{\text{s}}\right) * \text{time (s)}$$

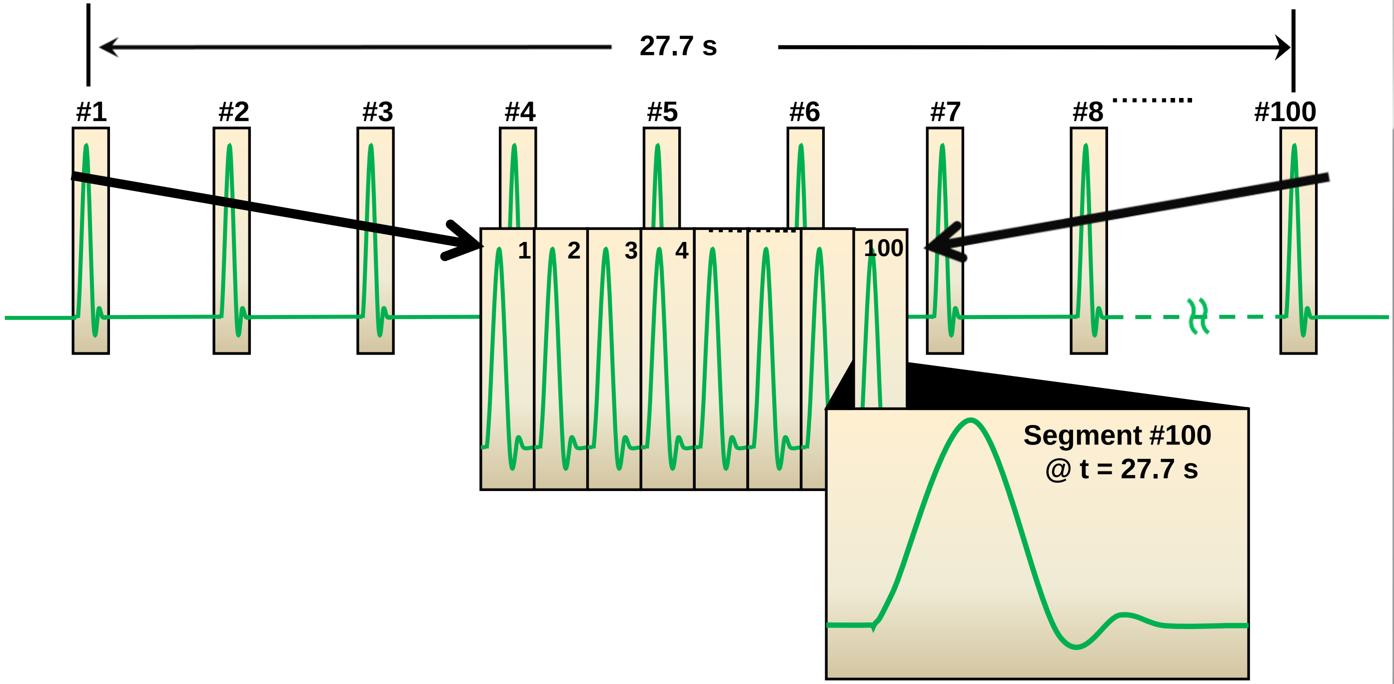


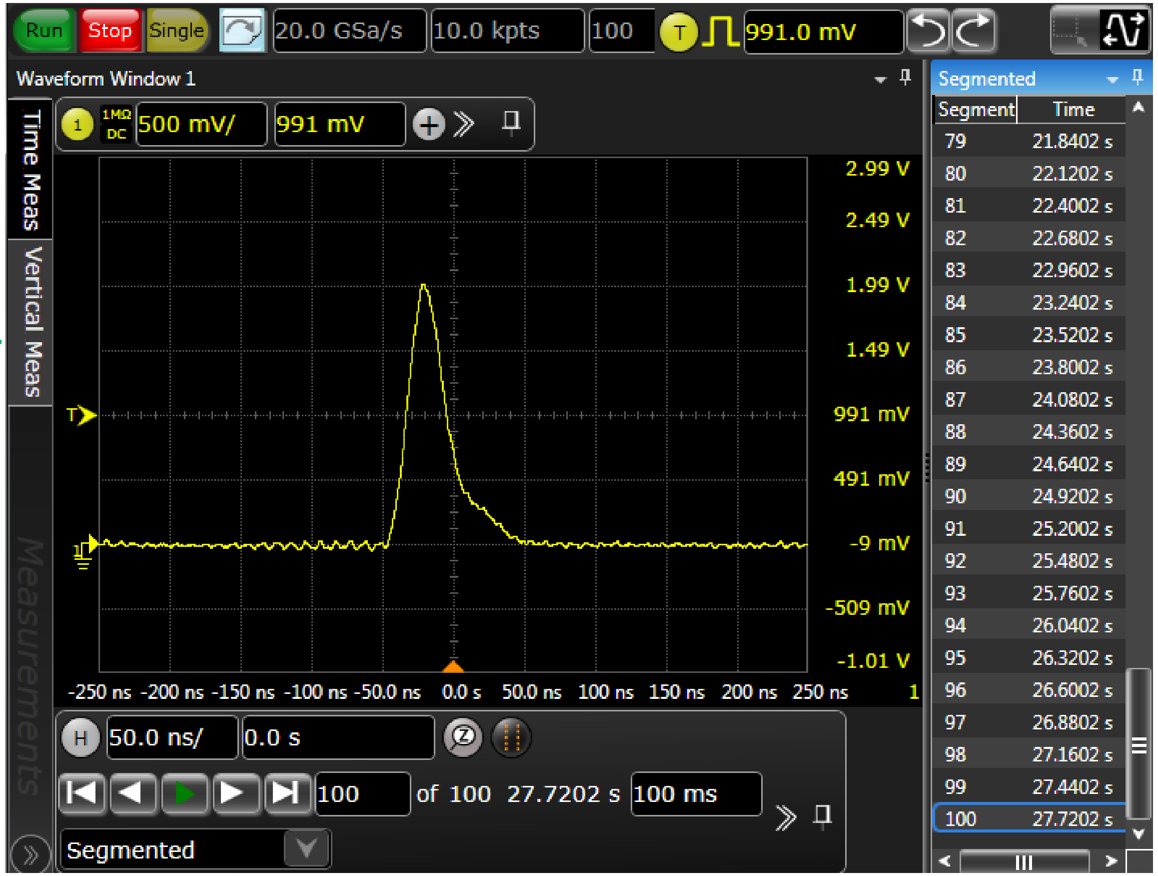
<u>Example:</u>
Required sample rate = 200 MSa/s
Longest acquisition time = 2 s (200 ms/div)
Required memory Depth = 2 s * 200 MSa/s = 400 MSa

Memory Depth

Segmented memory acquisition

Selectively captures more waveform data with precise time-stamps for each segment.





Equivalent memory = acquisition time x sample rate

554 GSa = 27.7 s x 20 GSa/s

07

Waveform Visualization Tools

Waveform Visualization Tools

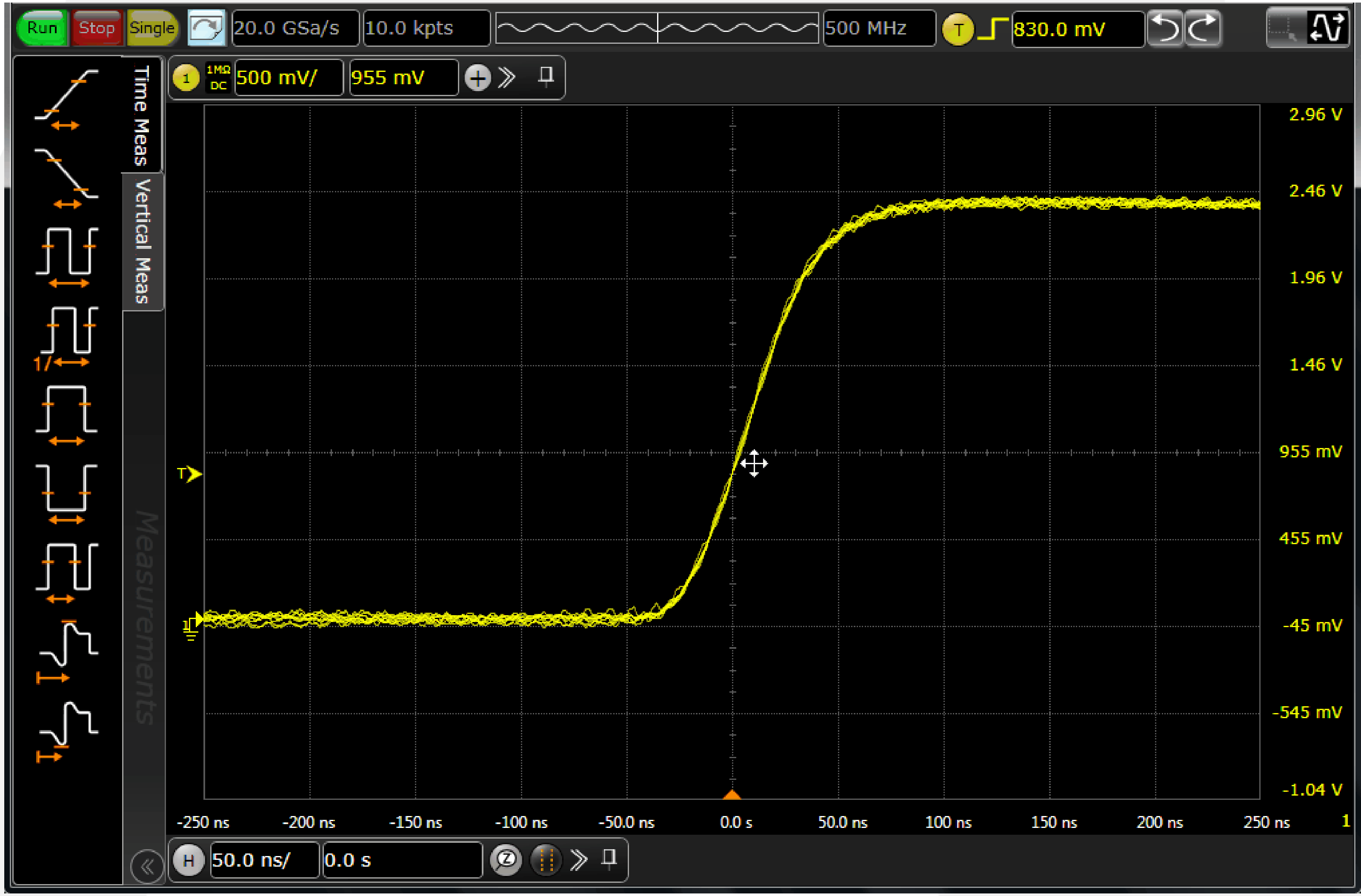
Getting more info from data

1. Persistence mode and color grade
2. Triggering on noisy signals
3. Averaging
4. Real-time eye diagrams
5. Jitter Analysis

Waveform Visualization Tools

Persistence and color grading

- View infrequent signals that may pop on/off screen quickly and increase the probability of that signal's occurrence.



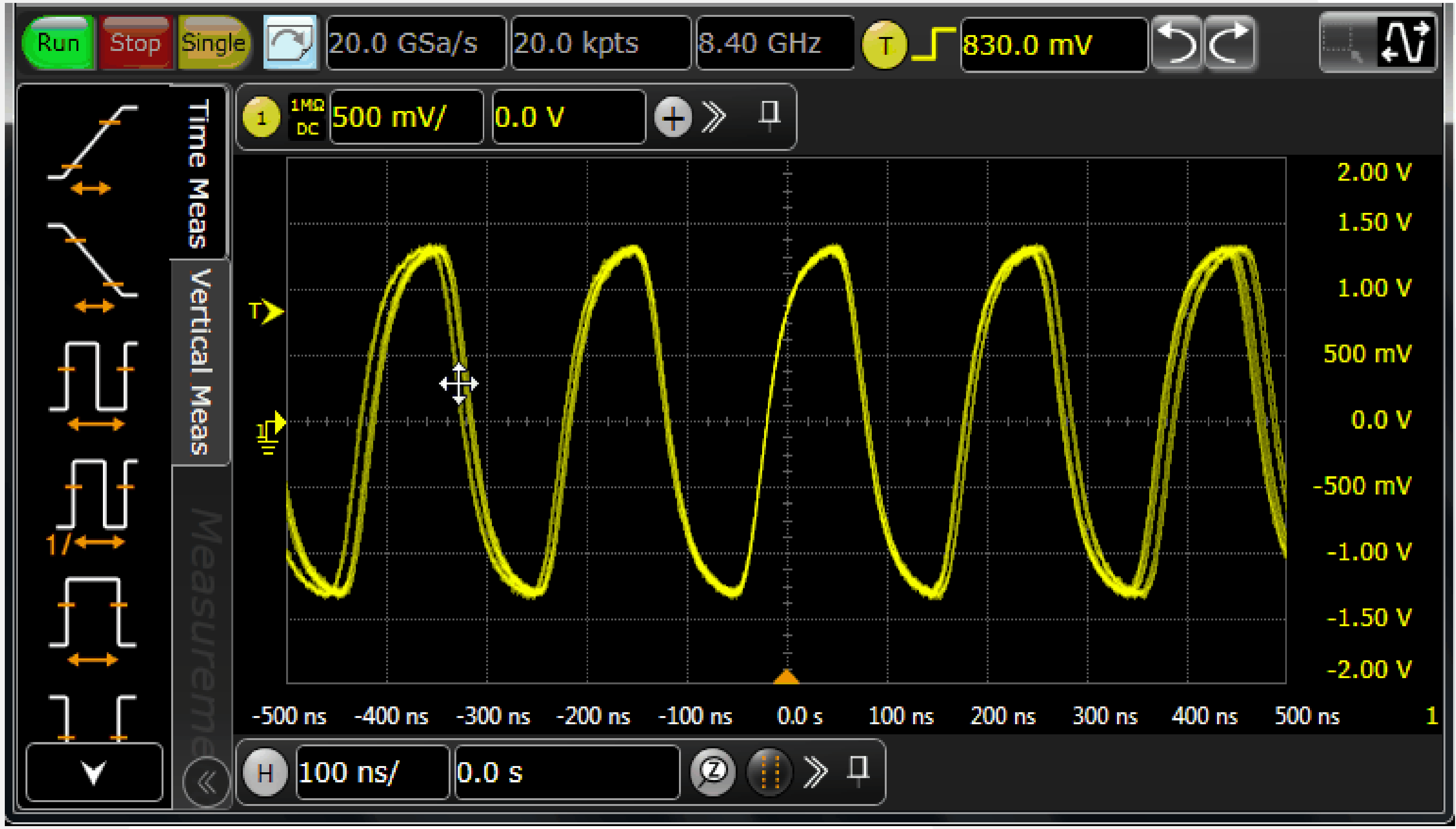
Waveform Visualization Tools

Histogram

- Distribution of a signal within a region on the screen.

OR…

- Distribution of measurement results (pictured).



Waveform Visualization Tools

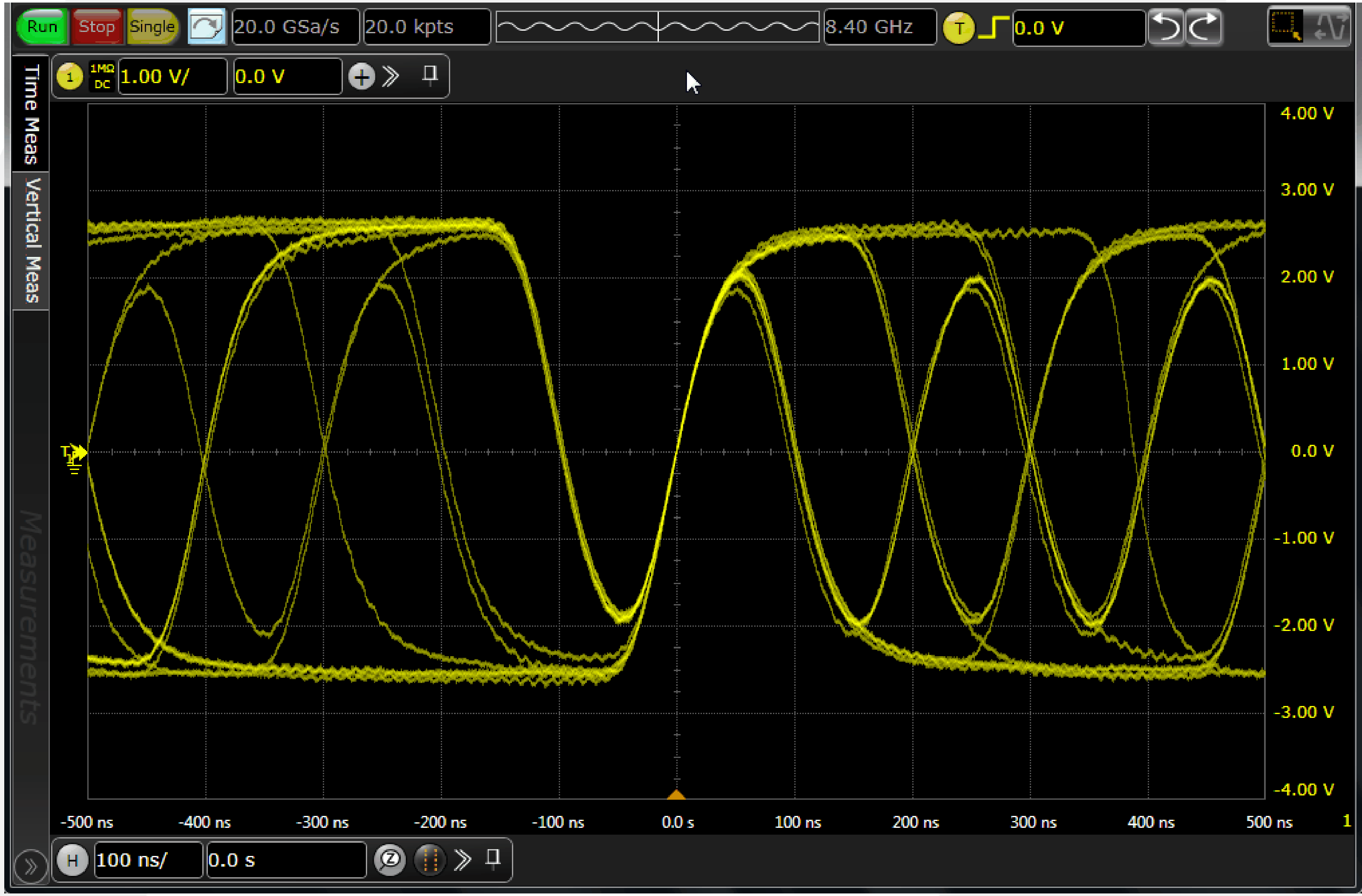
Measurement trends

- Show how a signal changes over time with respect to a particular measurement, such as frequency (pictured).

Waveform Visualization Tools

Real-time eye diagrams

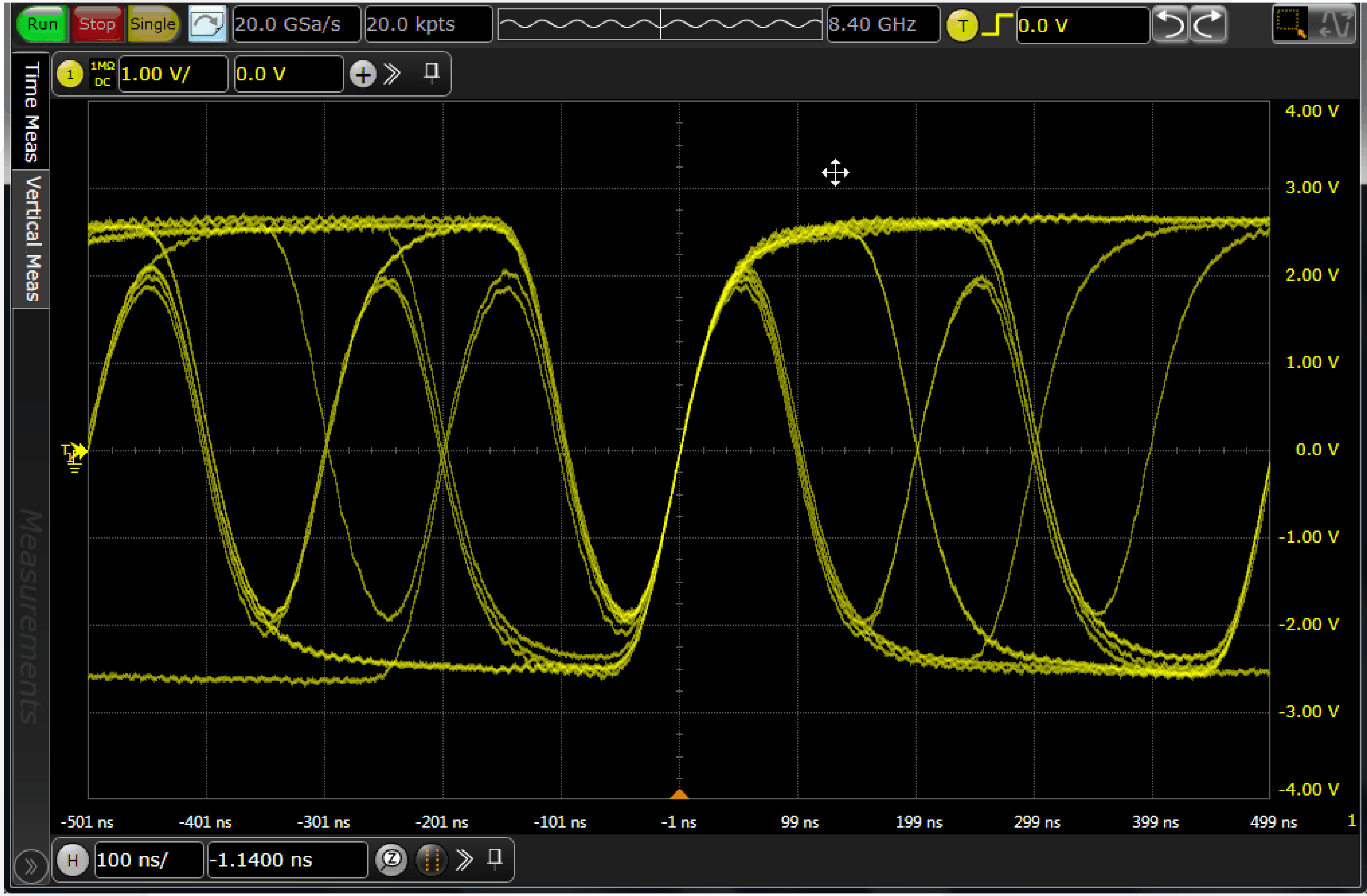
- Overlay bits on top of each other to detect physical layer issues in a serial data stream.



Waveform Visualization Tools

Jitter analysis

- Let the scope run dozens of automatic measurements and build plots, dissecting the details of your real time eye diagram, giving you information on where jitter is coming from in your design.



08

Probing

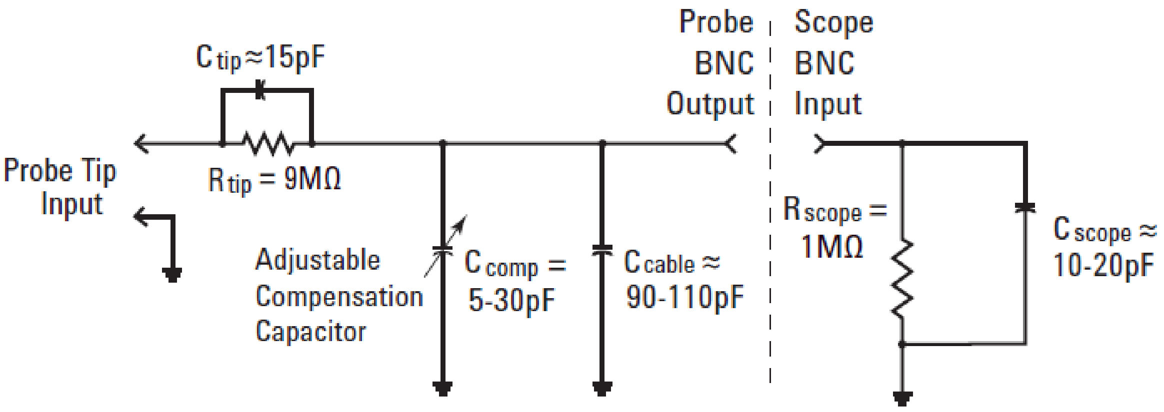
Probing

The other, equally important piece of the measurement puzzle

You can't visualize or measure your signal if you don't use the appropriate probe for your application!

Probing

Passive, resistor-divider probes

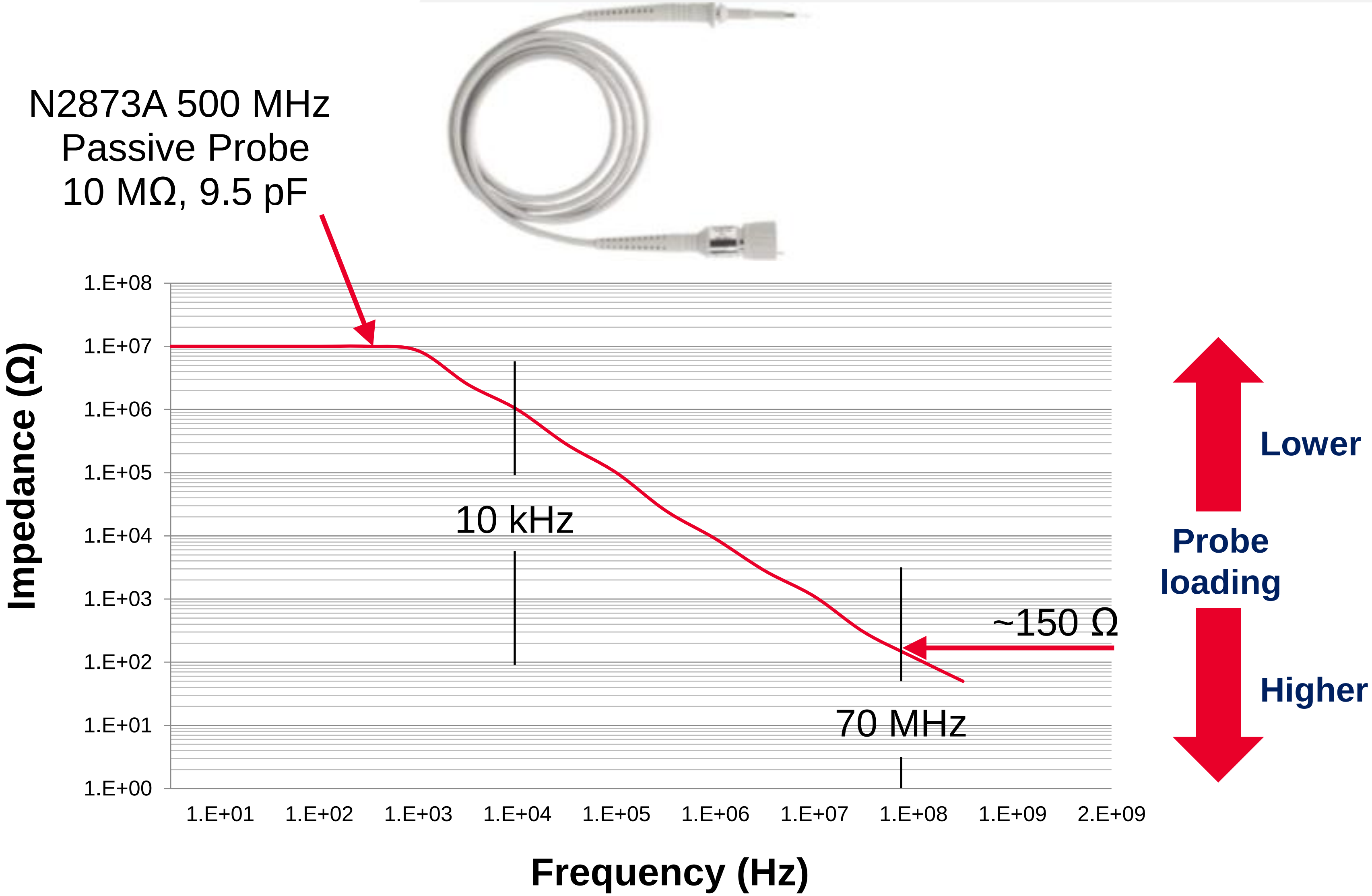


Passive 10:1 Probe Model

- Capacitors act as open circuits at low frequency.
- Inductors act as short circuits at low frequency.
- Simplifies to a 9-MΩ resistor in series with the scope's 1-MΩ input termination.

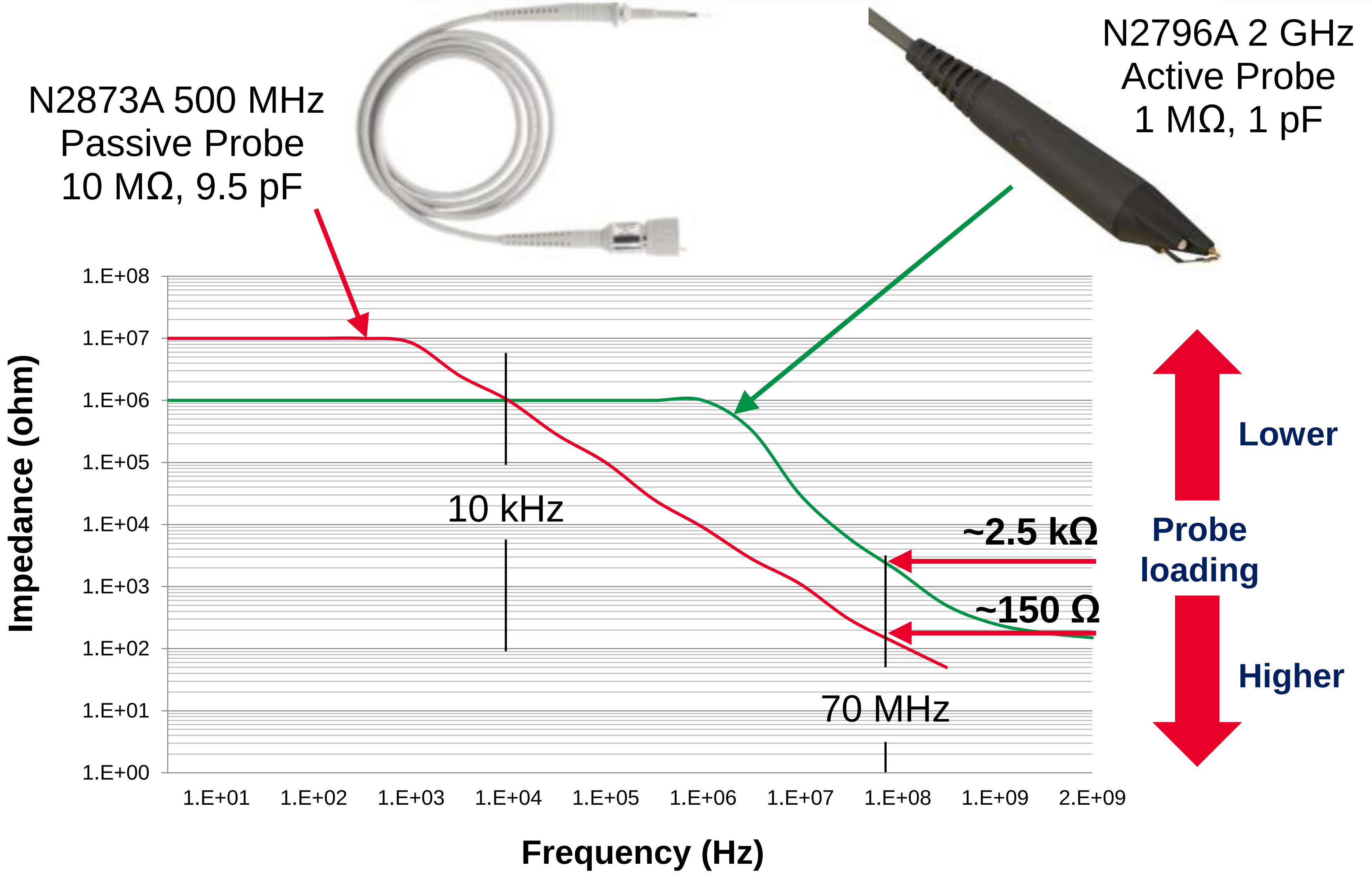
Probing

Passive, resistor-divider probe loading characteristics



Probing

Active probe loading is superior to passive



Probing

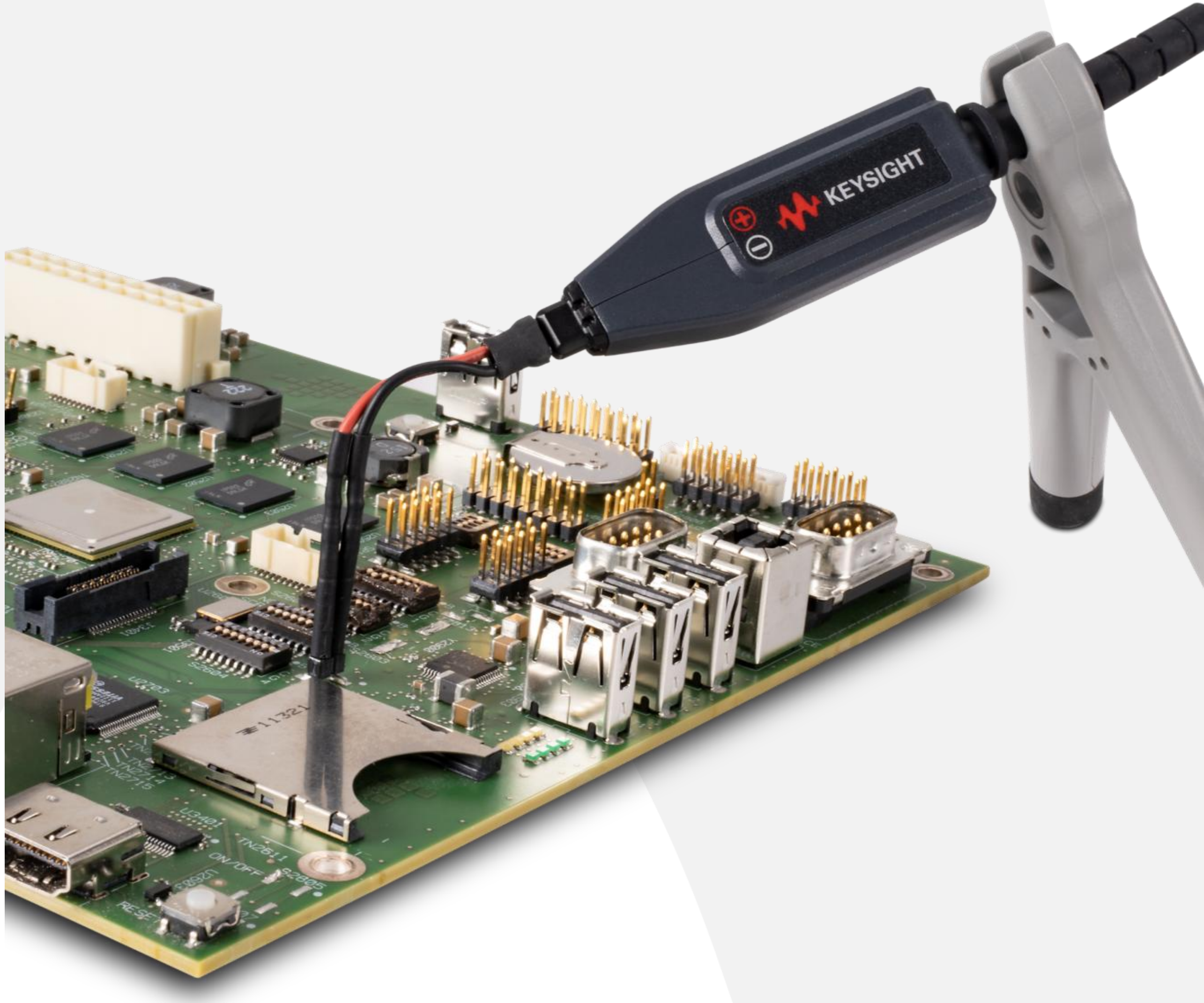
A probe can:

1. Change the signal shape on the screen.
2. Change the signal on the DUT itself !!

Probing

Differential probes – critical for floating measurements

- Perfect for floating measurements, even up to many kVs.
- Excellent common mode rejection even makes these a good all-purpose solution for single-ended measurements (up to -70 dB).
- Much more accurate than using two single-ended probes and waveform math to subtract.
- Accurately depict what your DUT is receiving in differential serial buses.



Keysight Probing Portfolio

An expansive portfolio for all your applications

InfiniiMax

- Up to 52 GHz
- Probe amp / head topology
- Variety of connections – browser, solder-in, socketed, SMA, ZIF tip, QuickTip
- S-parameter correction

Optical

- 33 GHz O/E converter for up to 28 Gbps optical signals
- Optical measurement software

InfiniiMode

- 1.5 – 6 GHz
- Making differential, SE, and common mode measurements with a single probe
- Multi-function scope control

Power Rail

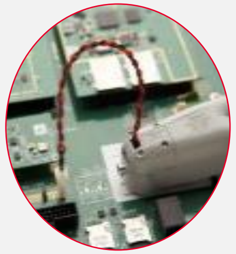
- Up to 6 GHz
- For making power integrity measurements
- Low noise
- Large offset range
- Low DC loading

SE Active

- Up to 2 GHz
- High input R and low C for low loading
- For high-speed ground referenced signal measurements

HV Diff

- Up to 800 MHz
- Up to 7 kV
- Ideal for power measurements
- High common mode rejection



Current

- DC to 100 MHz
- Clamp-on or high sensitivity
- 50 uA to 500 A

Passive

- Up to 6 GHz
- Low cost, rugged design
- Variety of accessories

Accessories

- InfiniiMax probe heads
- Compliance test fixtures
- TekProbe ® adapter
- BGA probe adapters
- Probe positioners
- Wedge adapters

09

Keysight Portfolio Overview

Keysight Infiniium Advanced Signal Analysis Tools

Most comprehensive application-specific measurement software

PAM-N

- Jitter and amplitude analysis on JP03 patterns

Power Integrity

- Analyze the adverse interactions between power supplies and digital lines

Infiniium Offline Software

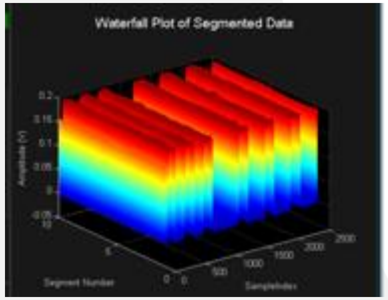
Serial Data Analysis

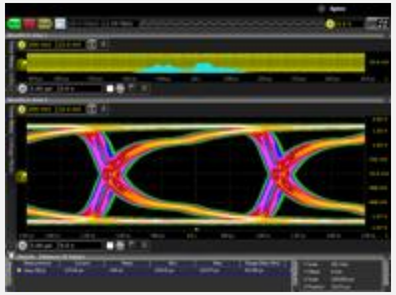
- Clock recovery and eye diagram analysis

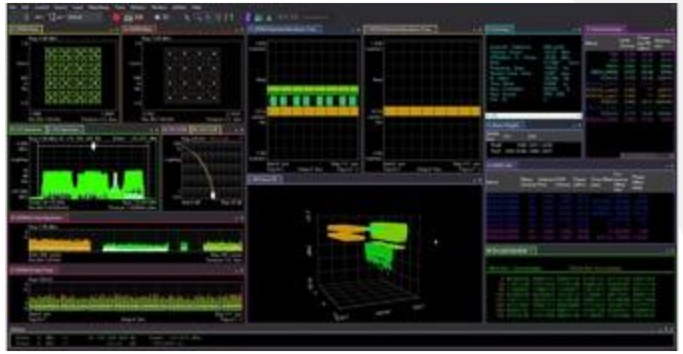
VSA

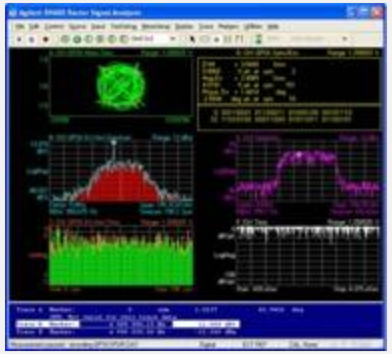
- Vector signal analysis, spectral, EVM

MATLAB integration







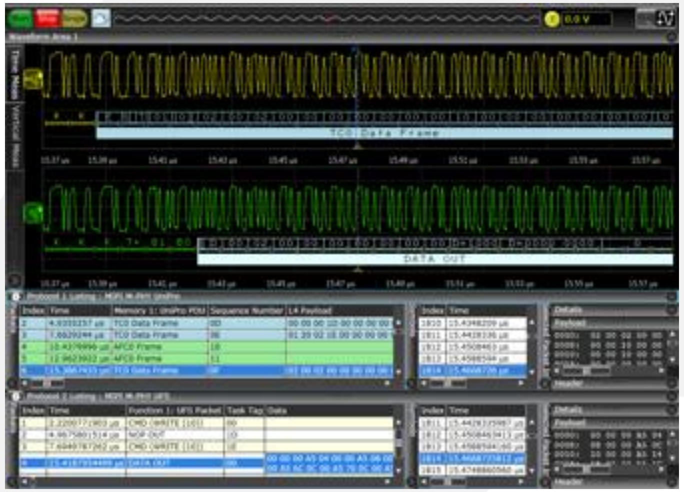


KEYSIGHT

Over 50 Protocol Debug Tools

Decode higher level protocols and debug CRC error Root Cause

- Run up to 4 protocol decoders at the same time.
- Decoded packets are shown on the waveform as well as the listing table
- Show payload and CRC information.
- Quickly and easily zoom into waveforms
- Automatically warns when computed CRC and embedded CRC do not match, indicating a CRC error.
- Quickly identify errors related to signal integrity or protocol issues.



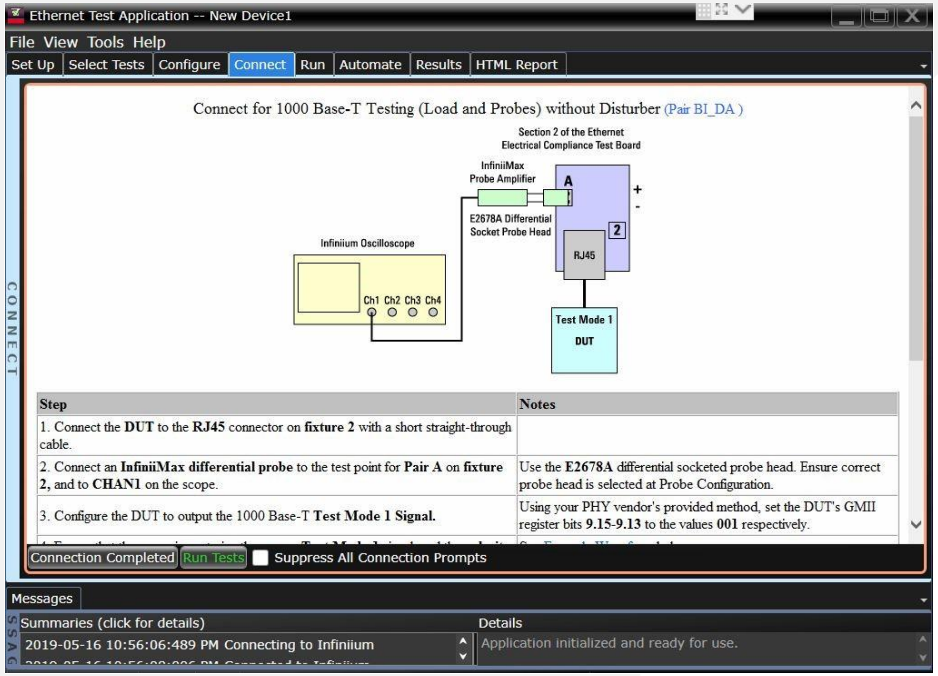
Supported protocols:

- SPI, eSPI, Quad eSPI
- RS232 / UART
- USB 2.0, 3.0, 3.1 Gen 1
- USB-PD, USB-HSIC
- USB 3.1, 3.2 (5 and 10 Gbps)
- Ethernet 10BaseT 8b/10b
- Ethernet 100Base-TX
- Ethernet 10GBase-KR 64b/66b
- Ethernet 100GBase-KR/CR 64b/66b
- CAN / CAN-FD / LIN / FlexRay / SENT
- SATA / SAS
- PCI Express Gen 1, 2, 3, 4
- I²C, I2S, JTAG (IEEE 1149.1)
- Manchester
- SVID
- ARINC 429, MIL-STD-1553, SpaceWire
- I3C / SPMI
- MIPI C-PHY, D-PHY, M-PHY
- MIPI DigRF v4, LLI, RFFE, UniPro
- UFS Universal Flash Storage
- Broad-R Reach / 100BASE-T1
- And more!

Most Comprehensive Compliance Applications

Ensure designs are compliant with industry-leading standards

- Keysight experts help define compliance requirements.
- Compliance applications are certified to test to the exact specifications of each technology standard.
- Setup wizards combined with intelligent test filtering give you confidence you are running the right tests.
- Comprehensive HTML reports with visual documentation and pass/fail results.



Supported Compliance Applications

BroadR-Reach	MIPI M-PHY
CAUI-4	MOST
DDR1 and LPDDR1	OIF-CEI 4.0
DDR2 and LPDDR2	ONFI
DDR3 and LPDDR3	PCI Express 1.0a/1.1 2.5G
DDR4 and LPDDR4	PCI Express Gen 3
DDR5	PCI Express Gen 4
DisplayPort 1.4	PCI Express Gen 5
eDP 1.4	SAS-4 / SCSI-4
eMMC	SATA 1.5, 3.0 and 6.0Gbps
Ethernet + EEE 10/100/1000Base-T	SD UHS-II
Ethernet 10GBase-T and MGBase-T	SD UHS-I
Ethernet 10GBase-KR	SFP+
Ethernet 100GBase-CR10	OIF-CEI 4.0
Ethernet 100GBase-CR4	CAUI-4
Ethernet 100GBase-KR4	Thunderbolt / TBT3
Ethernet 1000Base-T1	UHS-I
GDDR5	UHS-II
HDMI 1.4, TMDS/2.0, 2.1	User-defined application
HMC	USB 2.0
IEEE802.3bs/cd	USB 3.1 5 Gbps and 10 Gbps
MHL 3.0	USB HSIC
MIPI C-PHY	XAUI with 10GBASE-CX4, CPRI, OBSAI, and Serial RapidIO
MIPI D-PHY	

Keysight Oscilloscope Portfolio

InfiniiVision - Real Time

InfiniiVision
1000 X-Series

M924XA PXI

InfiniiVision
2000 X-Series

InfiniiVision
3000G X-Series

InfiniiVision
HD3 Series

InfiniiVision
4000 X-Series

InfiniiVision
6000 X-Series

Infiniium - Real Time

Infiniium
S-Series

Infiniium
MXR B-Series

Infiniium
V-Series

Infiniium
Z-Series

Infiniium
UXR B-Series

Digital Communication Analyzer – Sampling

N109x Optical Ref
Receiver and electrical
DCA-M series

N1000A DCA-
X Mainframe
Series

N1055A 50 GHz
TDR DCA
Plug-in Series

N1045A
60 GHz DCA
Plug-in
Series

N1060A >90 GHz
DCA Plug-in with
CDR Series

N1046A 122
GHz DCA
Plug-in Series

N107xA 64
GBd electrical
& optical CDR
Series

10

Additional Resources

Additional Resources

- [Keysight Oscilloscopes]
- [Keysight Probe Selection Guide]
- [Keysight Probe Resource Center]
- [Keysight Labs YouTube Channel]
- [Keysight Learn]
- [Basic Oscilloscope Fundamentals] Application Note
- Understanding Oscilloscope Probe Specifications Application Note

Thank you