High-Speed Oscilloscope Fundamentals

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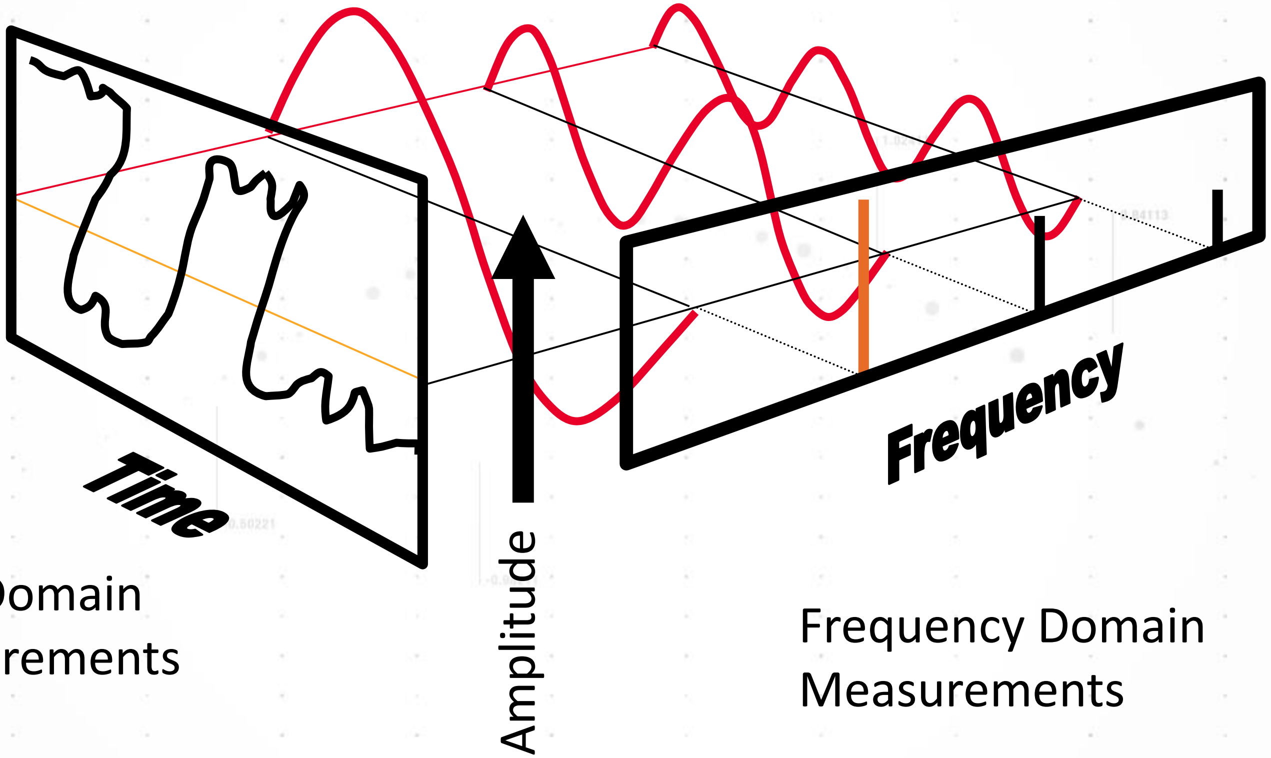
Oscilloscope Fundamentals

AGENDA SLIDE

- Time Domain vs. Frequency Domain
- Sampling Rate and Modes
- Bandwidth and Aliasing
- Oscilloscope Architectures
- Waveform Update Rate
- Memory Depth and Methods
- Triggering: Basics and Advanced
- Waveform Visualization Tools
- Probing Architecture, Tips and Tricks

Time Domain vs. Frequency Domain



Time Domain Measurements

Frequency Domain Measurements

Time Domain vs. Frequency Domain

MEASUREMENT DEVICES

Time Domain Applications

Oscilloscope

Signal Analyzer

Network Analyzer

Frequency Domain Applications

Spectrum Analyzer

Network Analyzer

FFT Analyzer

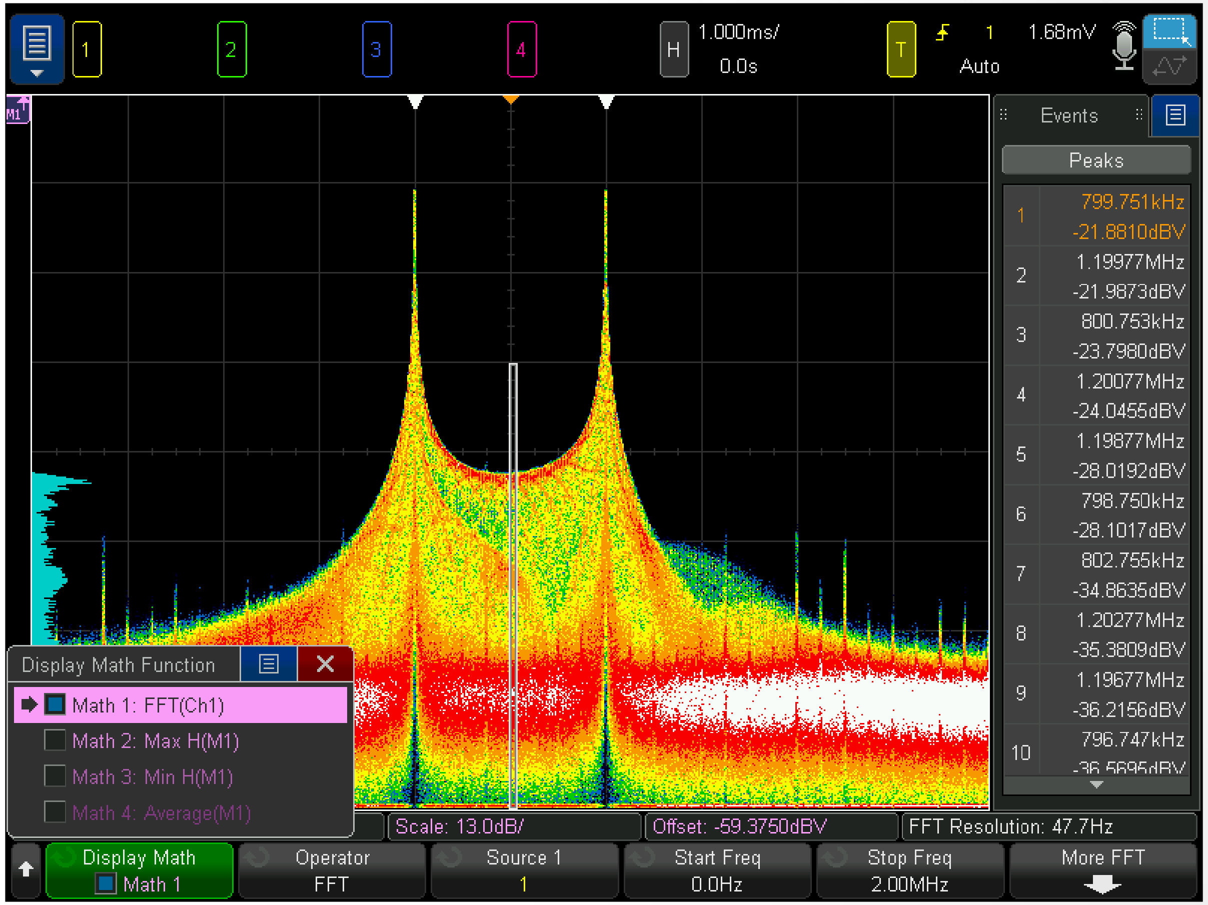
Signal Analyzer

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



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Sampling Basics

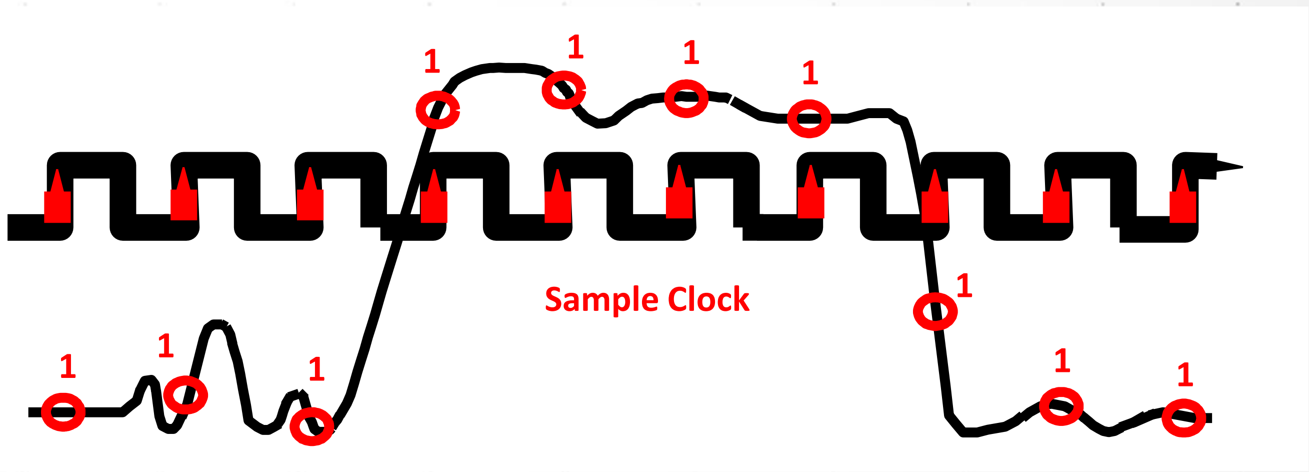
HOW OFTEN THE OSCILLOSCOPE MEASURES VOLTAGE – SAMPLE RATE

- 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

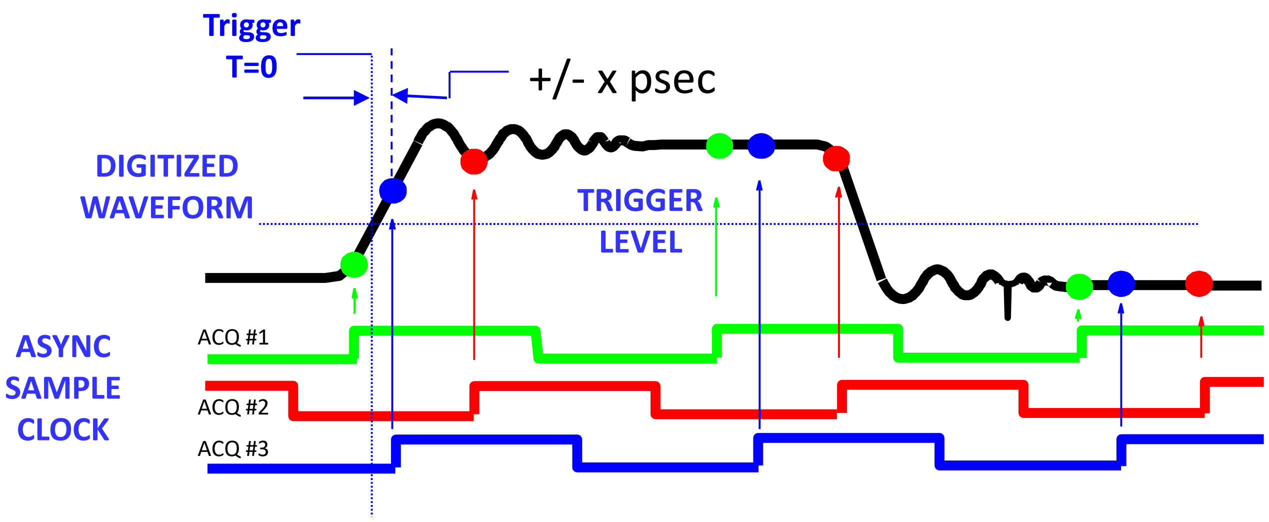


KEYSIGHT TECHNOLOGIES

Sampling Basics

EQUIVALENT TIME SAMPLING – "RANDOM REPETITIVE"

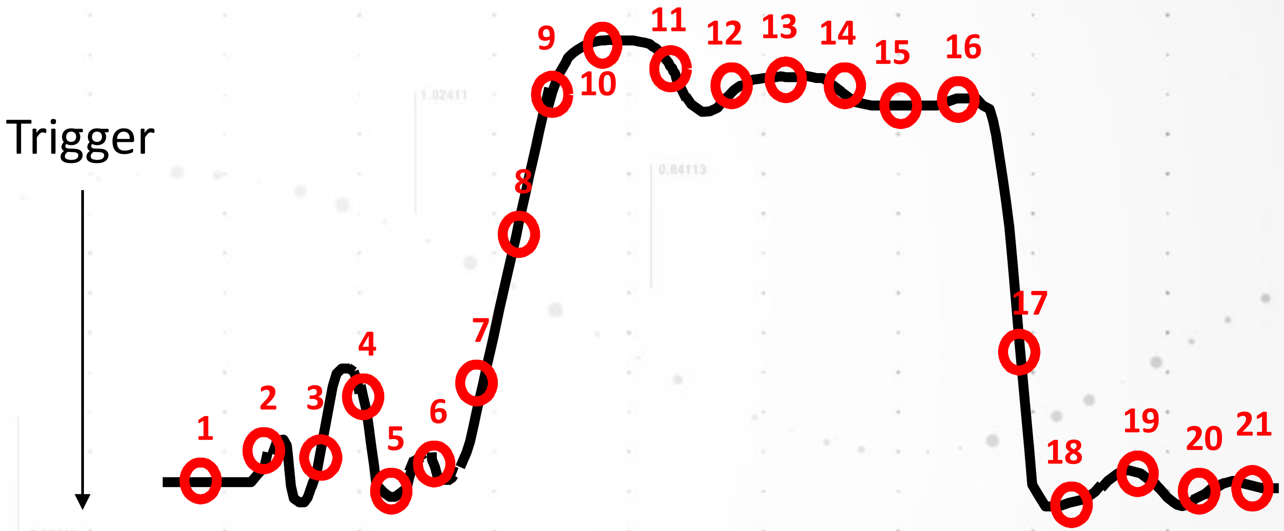
- Sample clock is asynchronous to input
- Pre-trigger acquisition is possible (data before trigger)
- Requires a repetitive waveform. Waveform "BUILDS-UP" with repetitive input.
- Bandwidth / sample density is not limited by sample rate
- Repetitive bandwidth is limited only by analog bandwidth
- **Not in common use today**



Sampling Basics

SEQUENTIAL SAMPLING

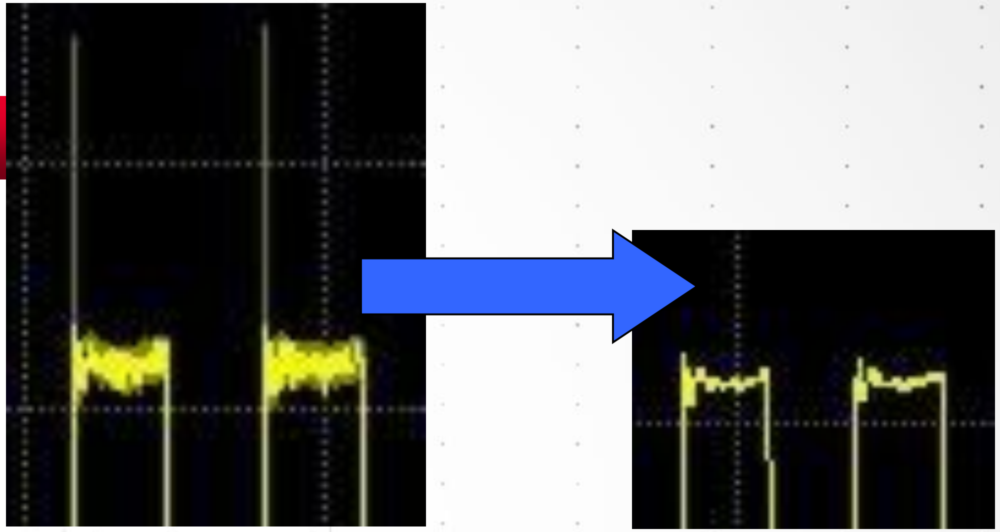
- One sample is taken on each trigger - the acquisition is slower
- Requires repetitive signal
- NO pre-trigger view (no data before the trigger point)
- Even increments of delay after each trigger
- Delay interval very small giving better timing resolution (higher BW)
- Provides very accurate waveform reconstruction - uses slower, higher resolution A/D Converters

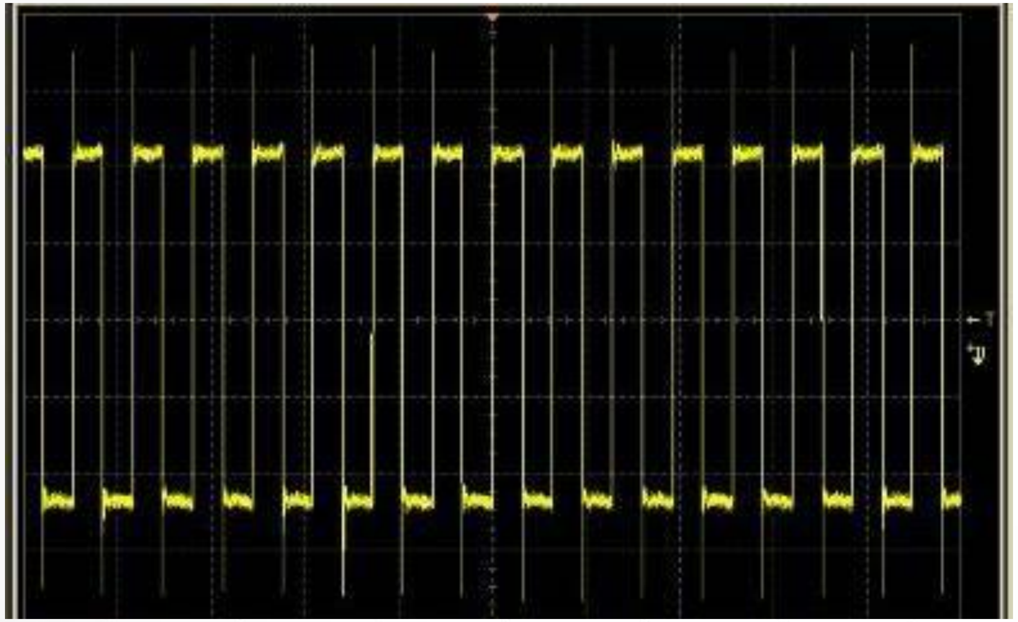


Sampling Basics

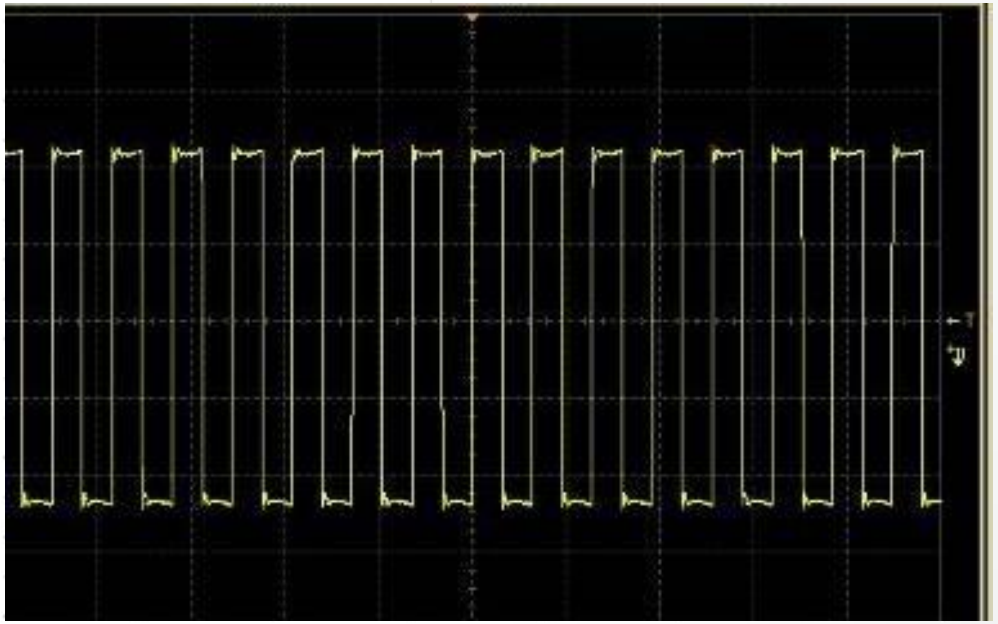
HIGH RESOLUTION MODE – REAL-TIME SCOPES

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





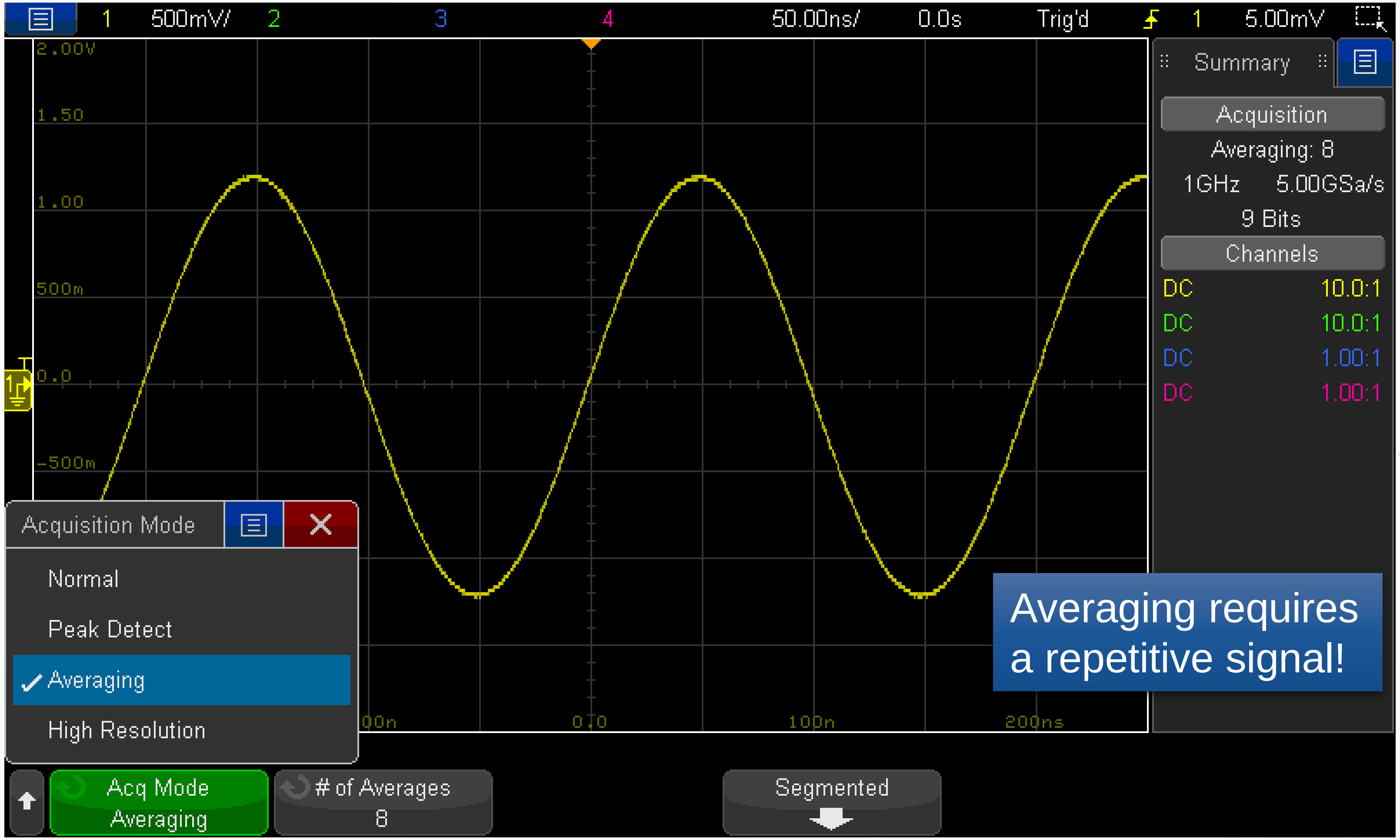
1.5MHz clock with Real-Time sampling



1.5MHz clock with High Resolution sampling

Sampling Mode

AVERAGING – REAL-TIME SCOPES



Averaging requires a repetitive signal!

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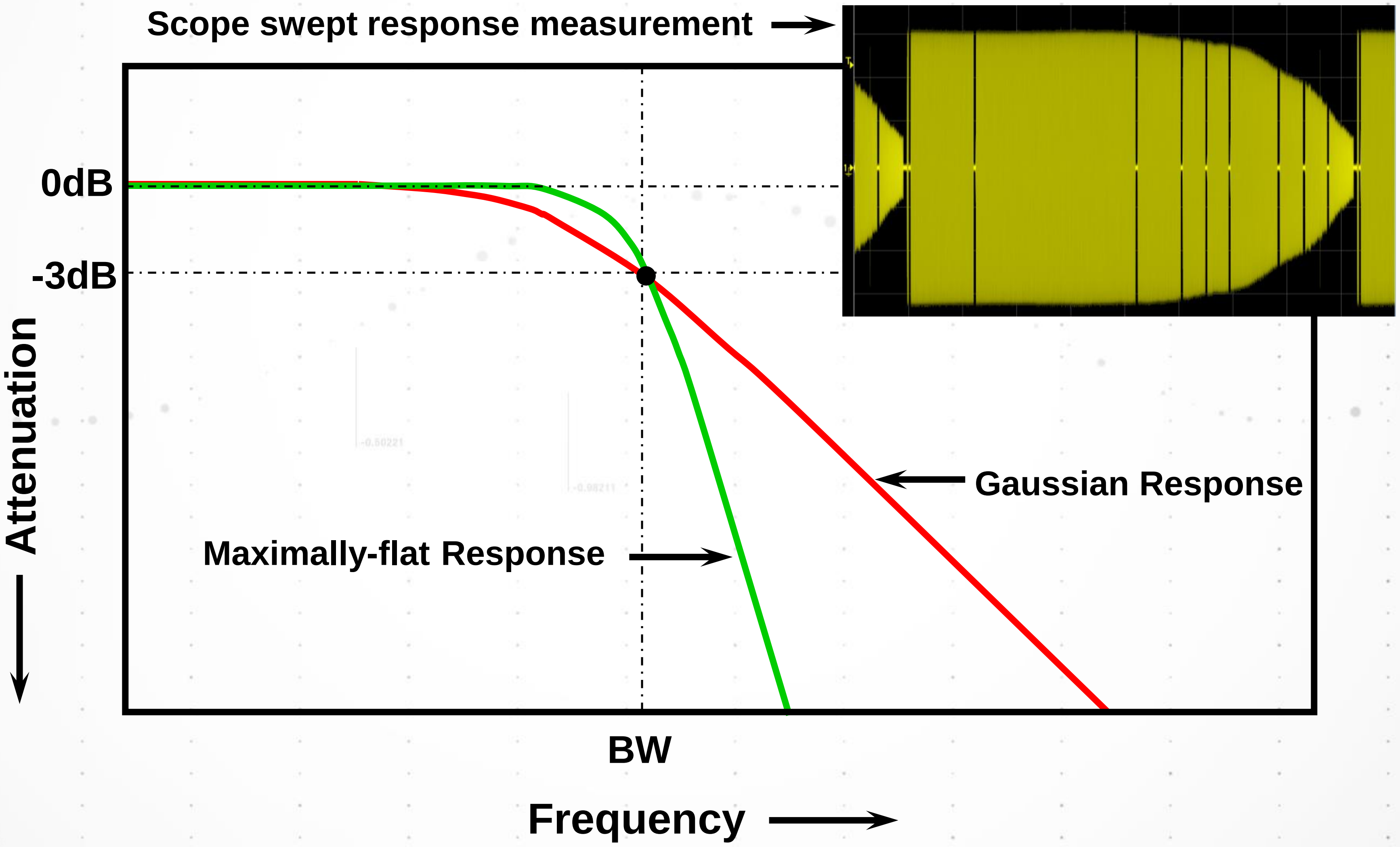
Bandwidth Basics

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”.

Bandwidth Basics

ALSO CALLED THE "3DB DOWN POINT"



Bandwidth Basics

HOW MUCH BANDWIDTH DO YOU NEED?

Step #1: Determine fastest rise/fall times of device-under-test.

Step #2: Determine 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.

Scope BW Calculation

Required Accuracy	Gaussian Response	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}

Step #4: Calculate required bandwidth.

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

Bandwidth Basics

HOW MUCH BANDWIDTH DO I REALLY NEED?

Determine the minimum bandwidth of an oscilloscope (assume Gaussian frequency response) to measure signals that have rise times as fast as 500 ps (10-90%):

f_{knee} (10-90%)= (0.5/RT) = (0.5/0.5 ns) = 1 GHz

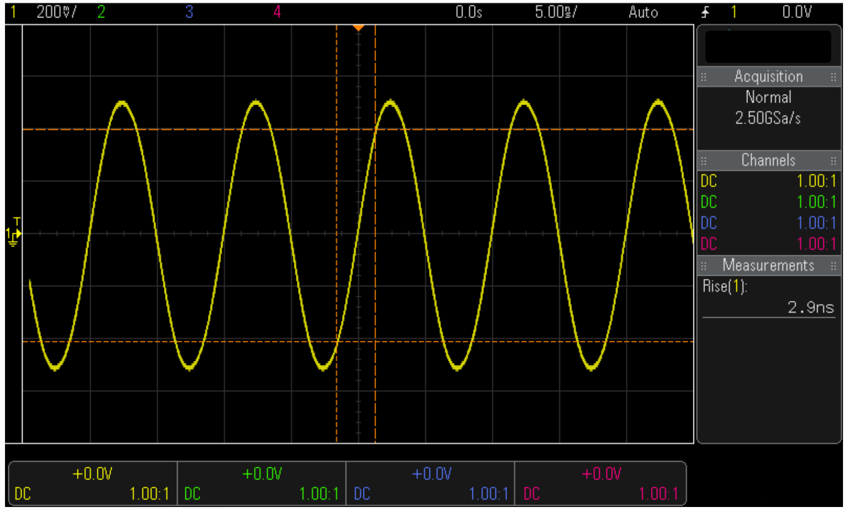
20% Accuracy: BW = 1.0 x f_{knee} = 1.0 x 1 GHz = 1.0 GHz

3% Accuracy: BW = 1.9 x f_{knee} = 1.9 x 1 GHz = 1.9 GHz

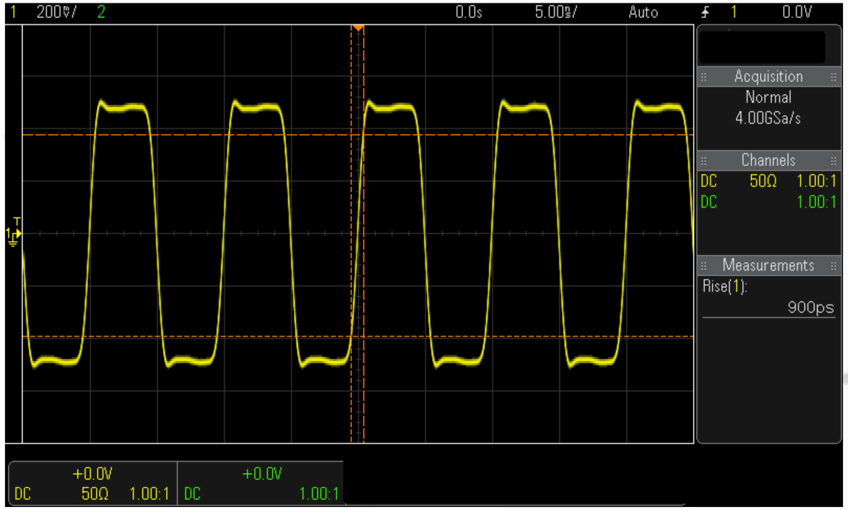
Bandwidth Basics

WHAT HAPPENS IF MY OSCILLOSCOPE IS TOO SLOW?

What does a 100-MHz clock signal really look like?



Response using a 100-MHz BW scope



Response using a 500-MHz BW scope

KEYSIGHT TECHNOLOGIES

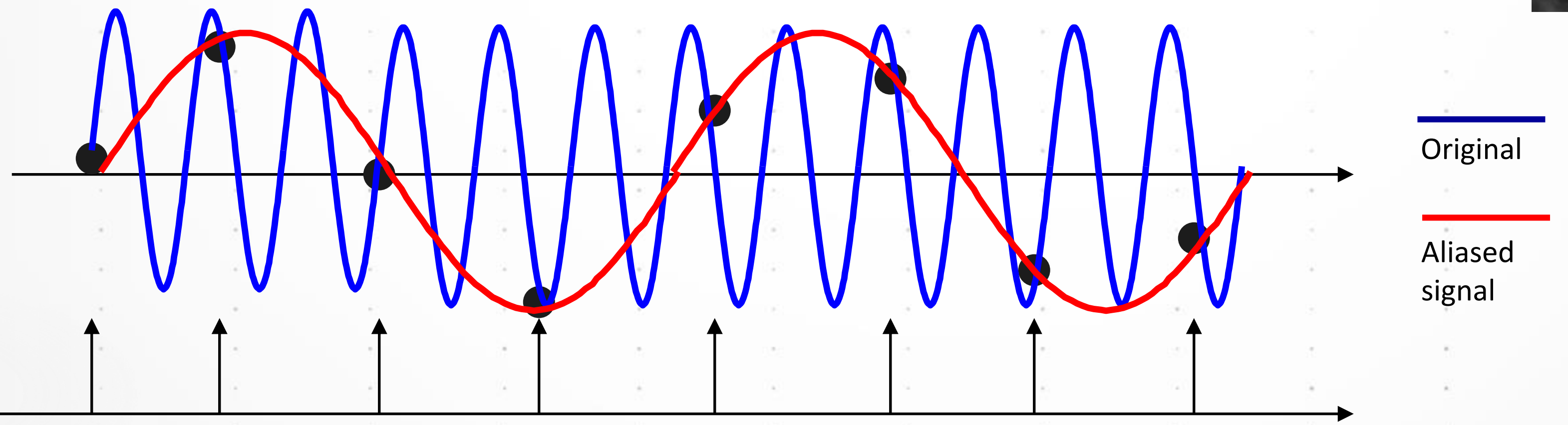
Sampling Basics

NYQUIST'S THEOREM: REMEMBERING THE COLLEGE DAYS

- **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.,

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

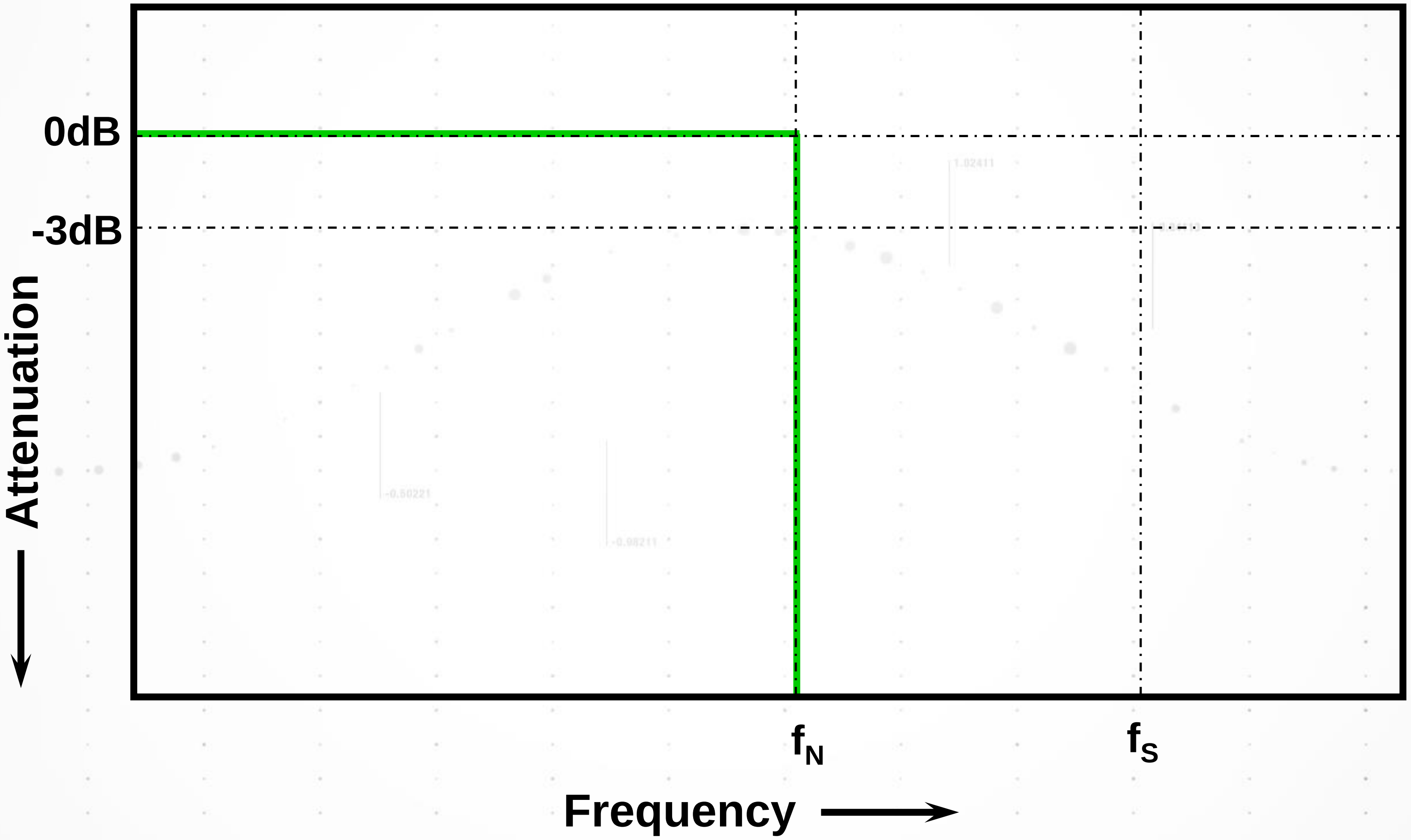
- in order to have the signal be uniquely reconstructed without aliasing.
- The frequency $\mathbf{2 \cdot f_{max}}$ is called the Nyquist sampling frequency (f_S). Half of this value, $\mathbf{f_{max}}$, is sometimes called the Nyquist frequency (f_N).



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

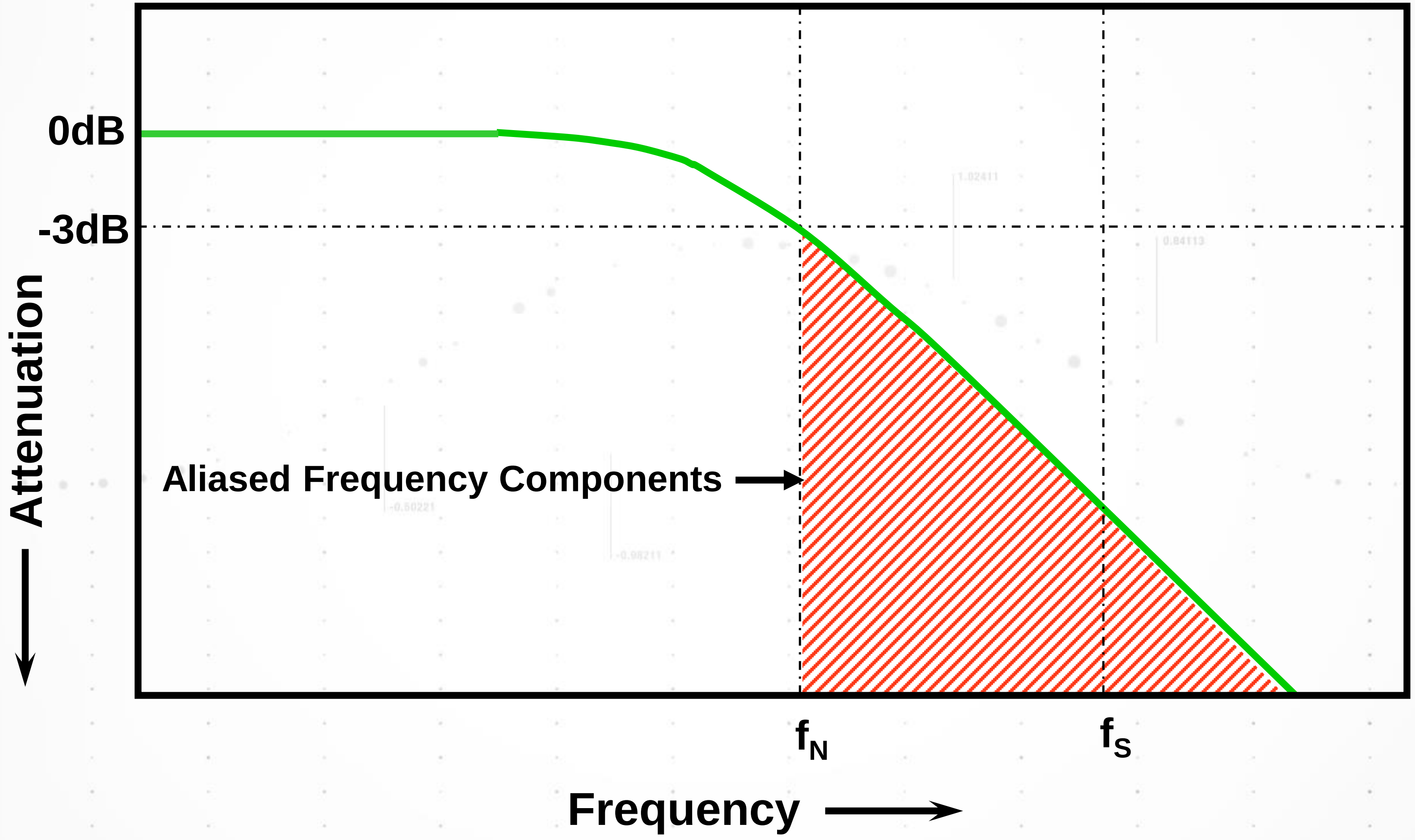
Ideal Brickwall Response w/ BW @ Nyquist (fN)

NOT FEASIBLE IN THE REAL WORLD



Gaussian Response w/ BW @ fs/2 (fN)

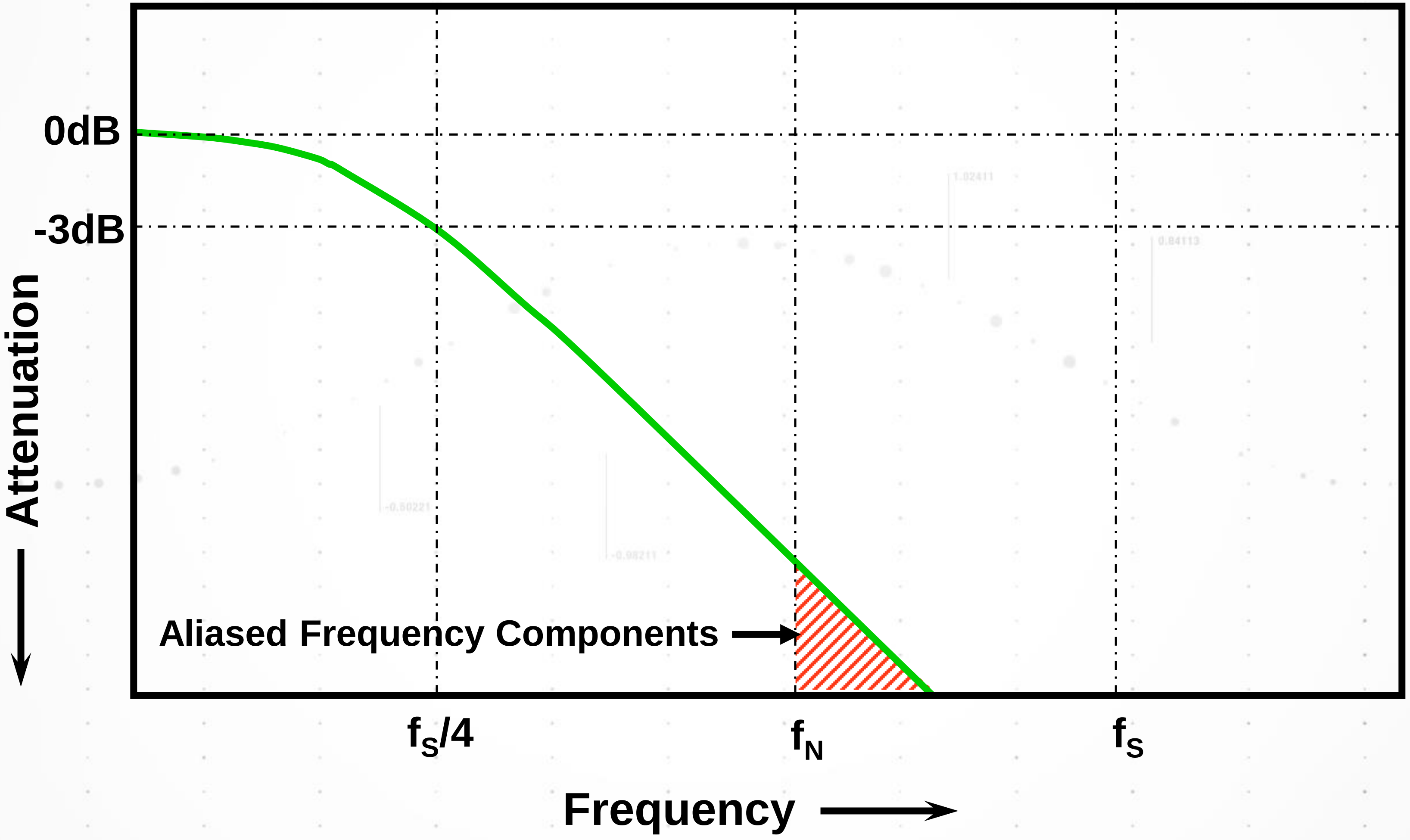
SAMPLE RATE IS TWICE BANDWIDTH



KEYSIGHT TECHNOLOGIES

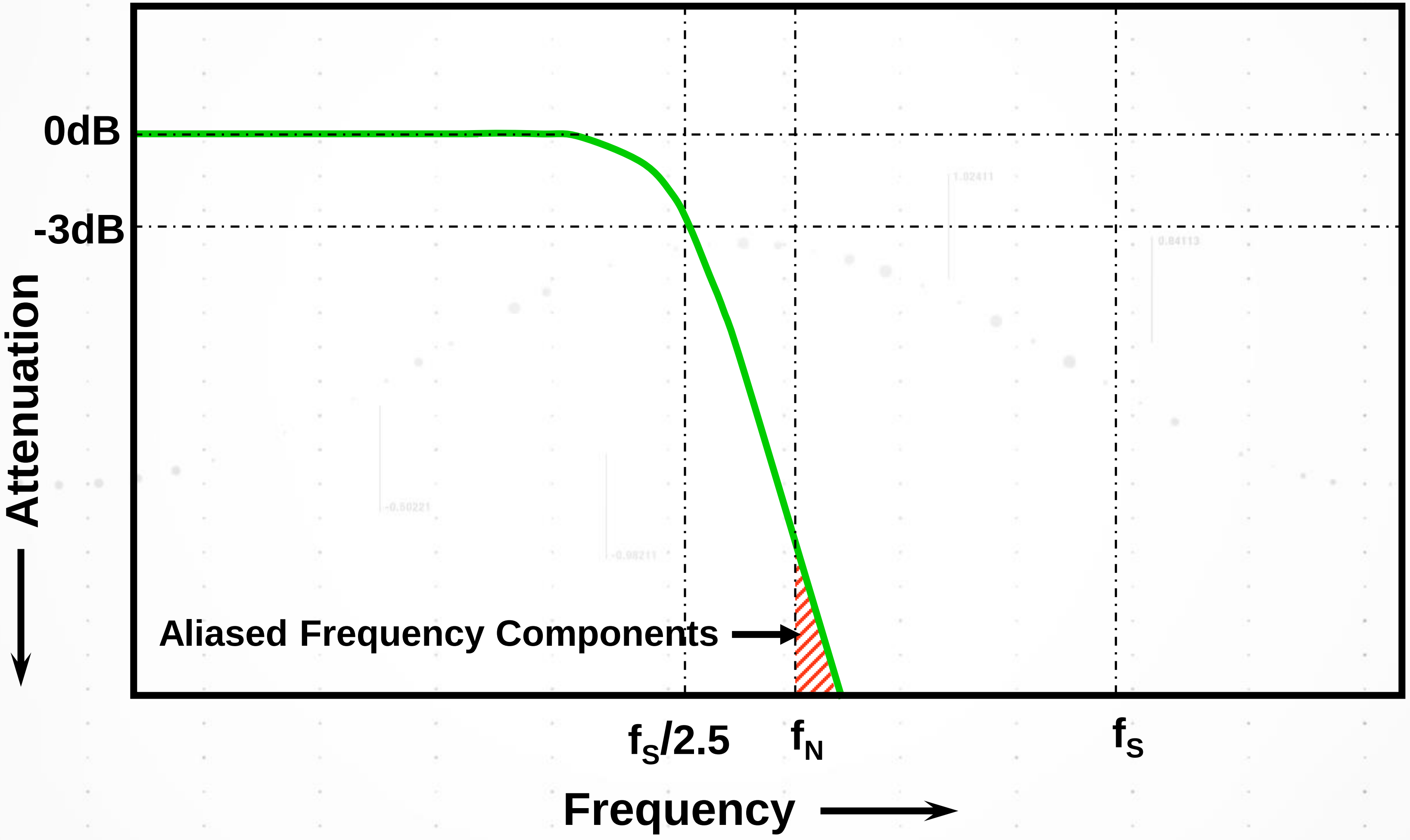
Gaussian Response w/ BW @ fs/4 (fN/2)

SAMPLE RATE IS FOUR TIMES BANDWIDTH



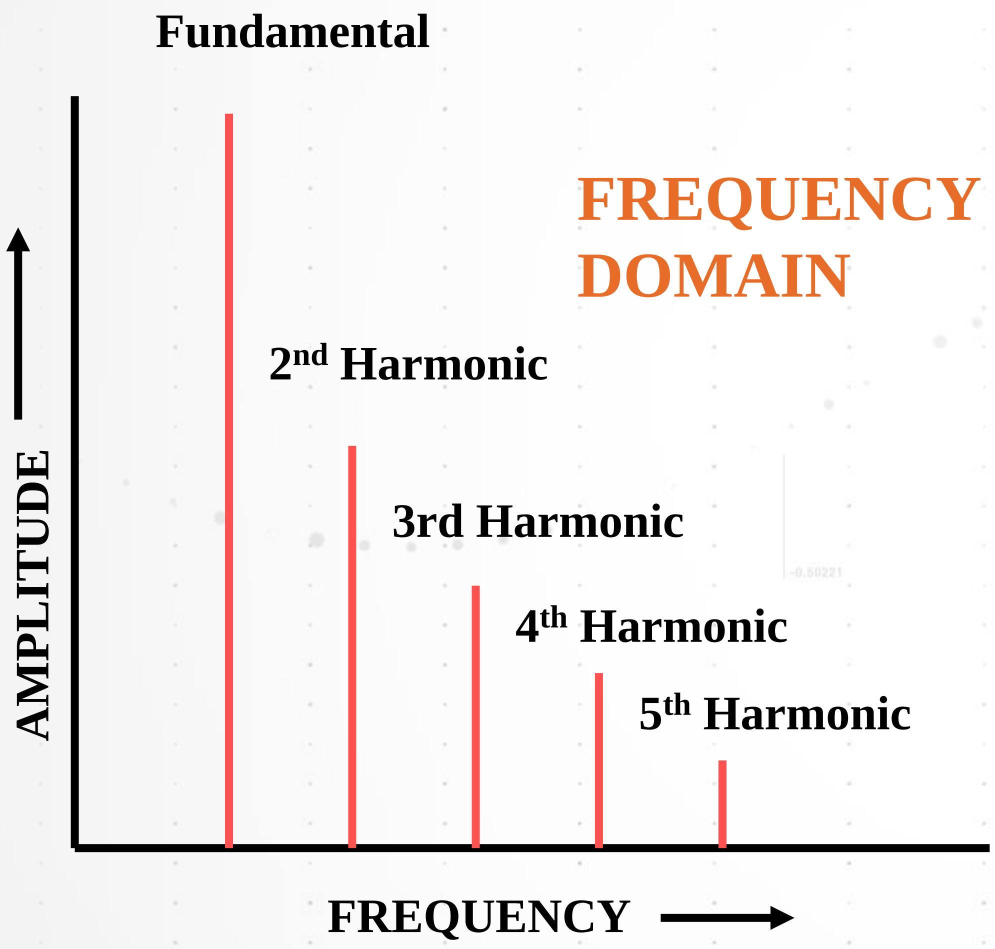
Maximally-Flat Response w/ BW @ fs/2.5 (fN/1.25)

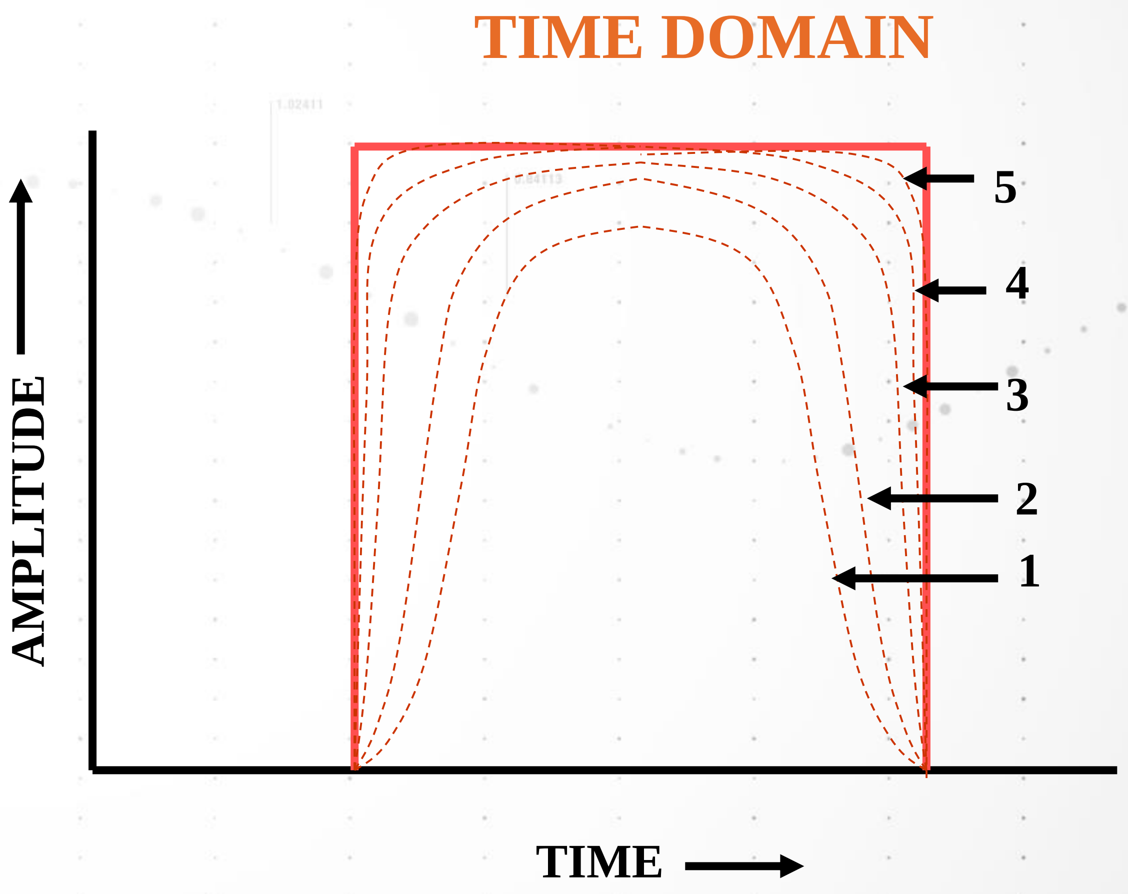
SAMPLE RATE IS 2.5X BANDWIDTH



Sampling Basics

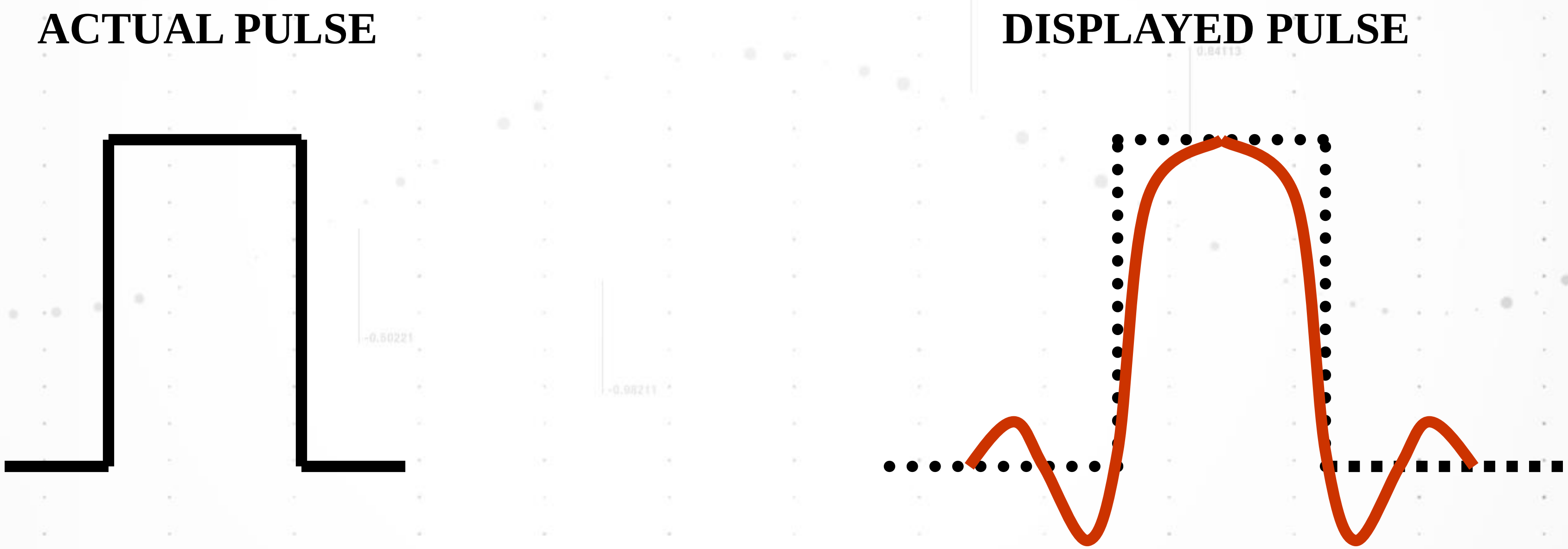
EVERY SIGNAL CONSISTS OF A FUNDAMENTAL AND ITS HARMONICS





Sampling Basics

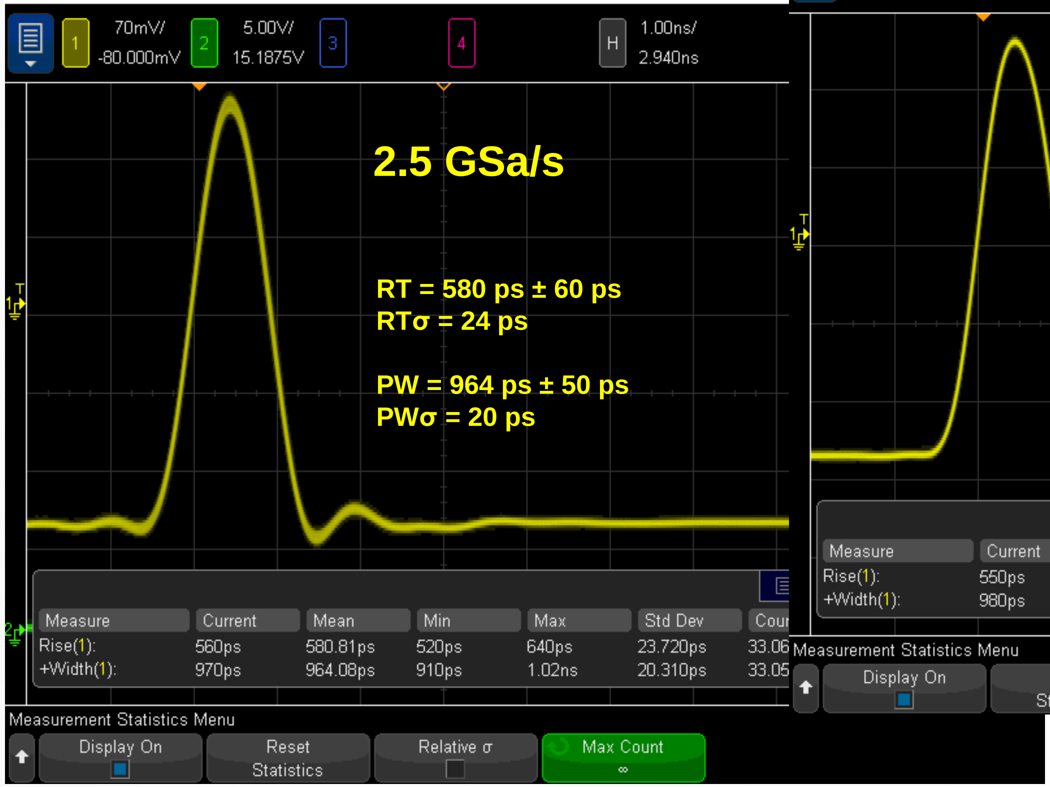
DISTORTION DUE TO ALIASING AND BANDWIDTH LIMITING



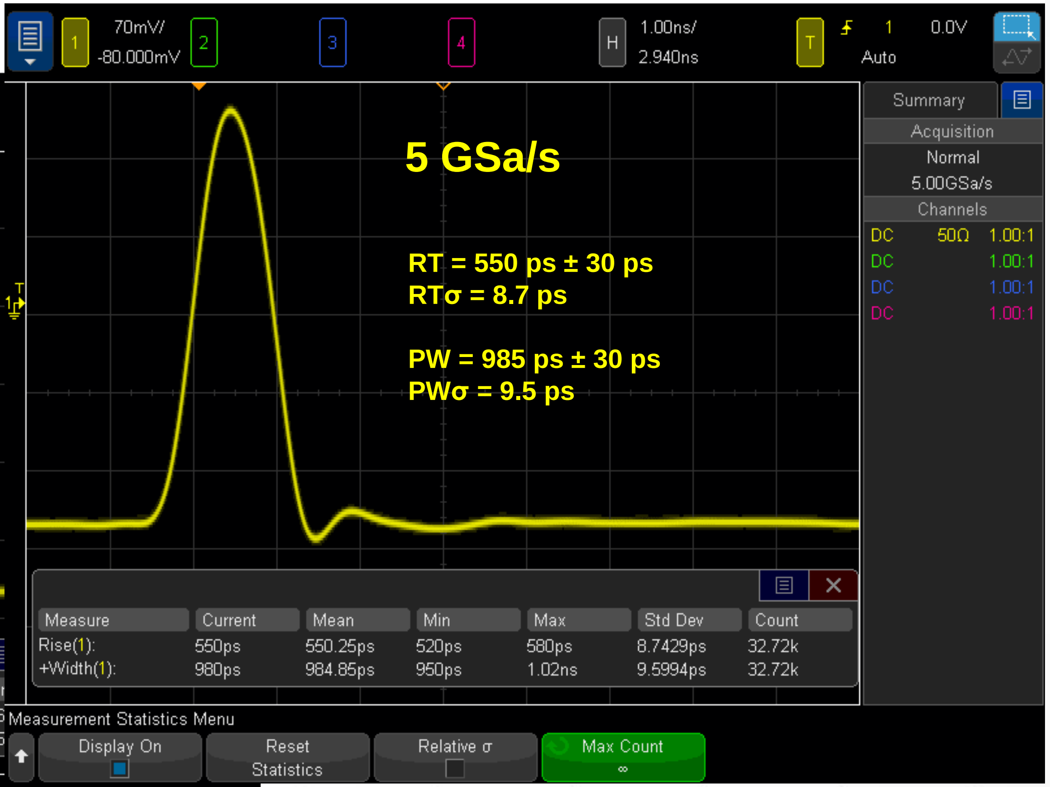
1-GHz Bandwidth Oscilloscope

INPUT TEST SIGNAL: 1 NS WIDE PULSE WITH 500 PS RISE TIME

SR = BW x 2.5



SR = BW x 5



KEYSIGHT TECHNOLOGIES

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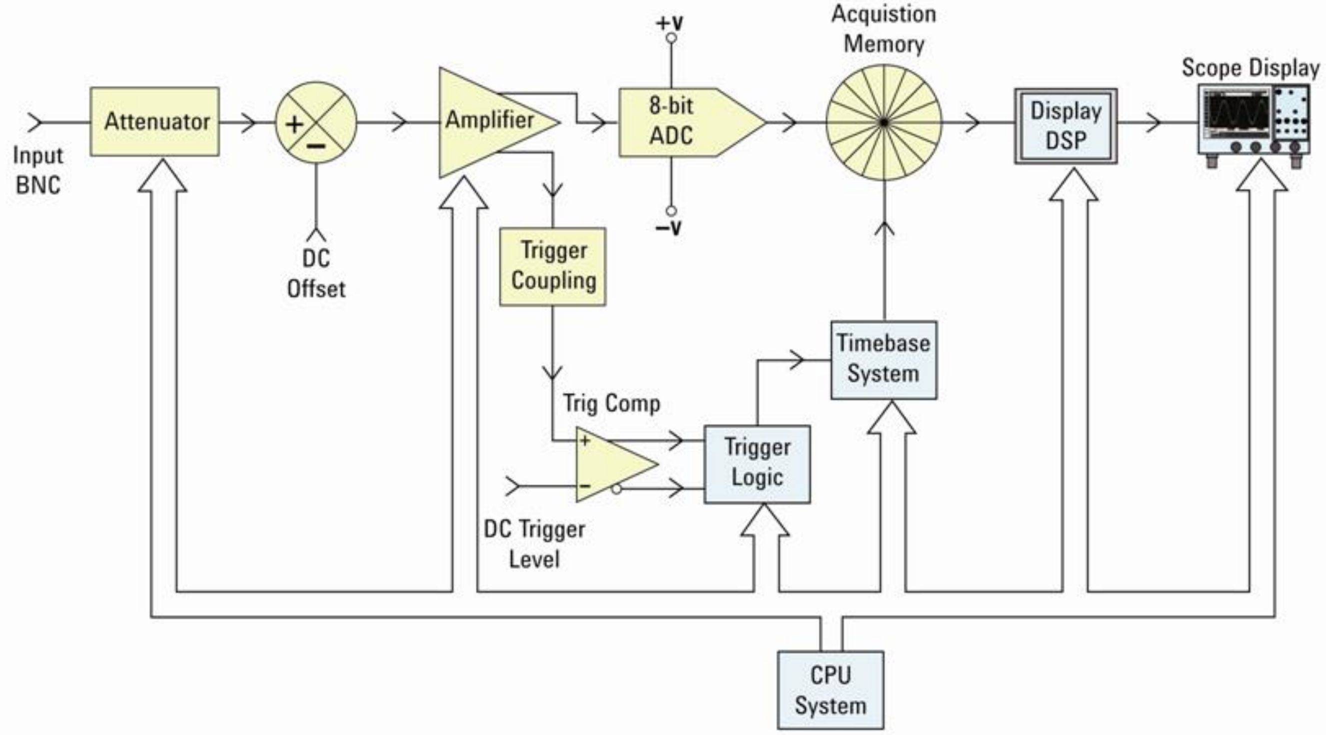
Oscilloscope Architecture

BASIC OSCILLOSCOPE BLOCK DIAGRAM



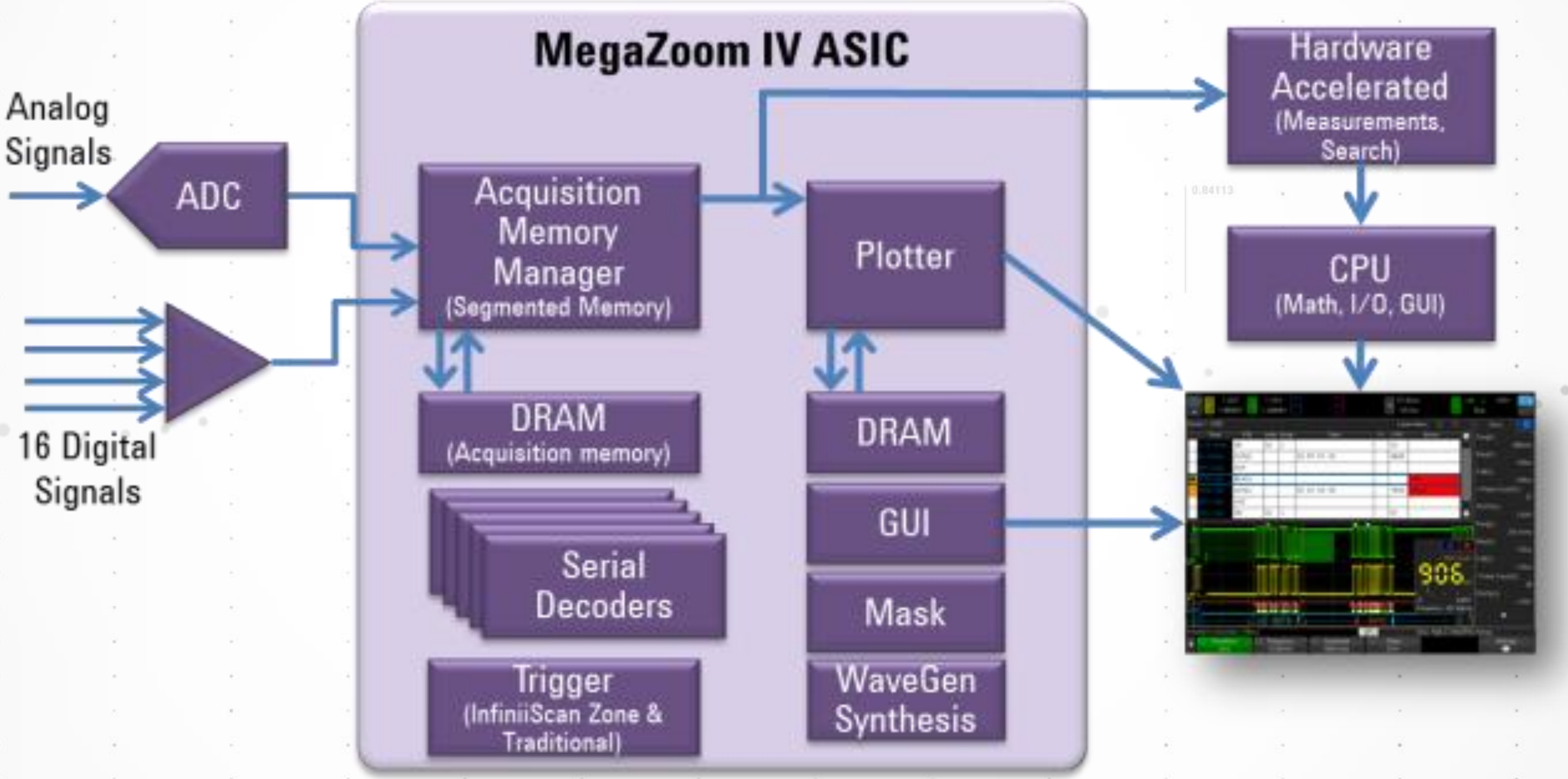
Yellow = Channel-specific blocks
Blue = System blocks (supports all channels)

DSO Block Diagram

KEYSIGHT TECHNOLOGIES

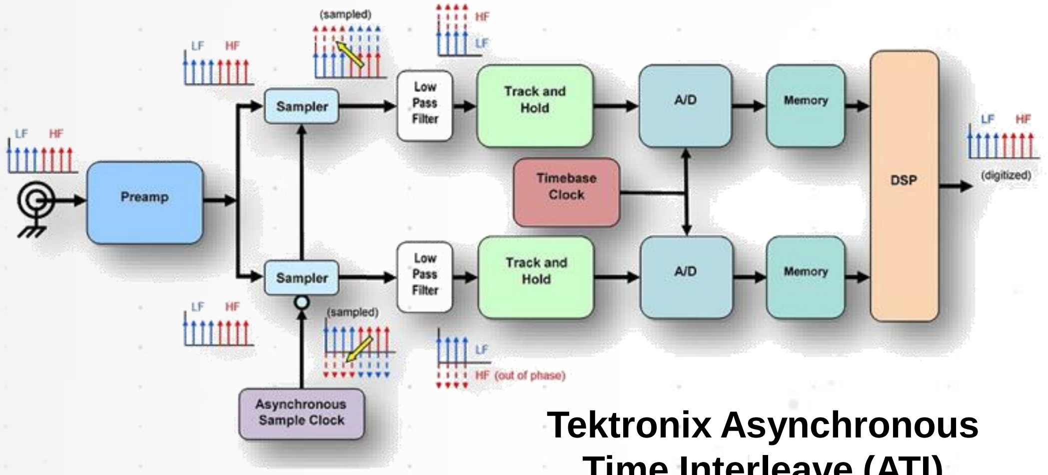
Oscilloscope Architecture

INFINIIVISION X-SERIES: SCOPE ON A CHIP FOR MAX PERFORMANCE



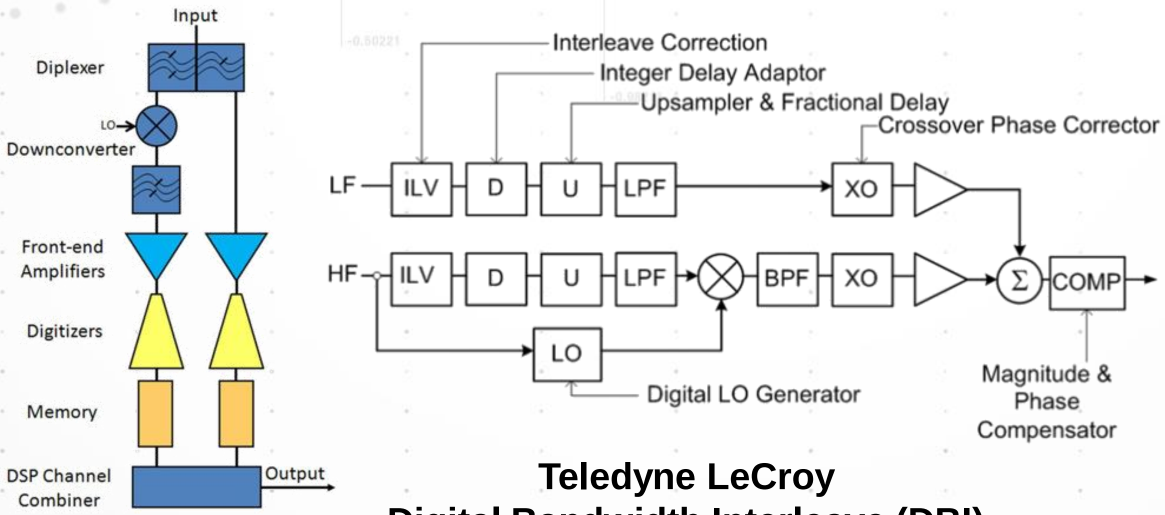
Frequency Based Interleaving – The Old Best Way

HOW TO ACQUIRE HIGHER BANDWIDTH SIGNALS THAN YOUR SCOPE'S SAMPLER



Tektronix Asynchronous Time Interleave (ATI)

- Time-Interleaved Sampling (TIS) used in traditional oscilloscopes was unable to keep pace with industry bandwidth demands
  - The fastest TIS technologies maxed out at ≤ 40 GHz
- Frequency based interleaving bridged the bandwidth gap
  - Splits an incoming signal into a low and high frequency path
  - Enabled multiple slower samplers to acquire higher BW inputs
- Splitting, amplifying and recombining frequency bands is complicated and inherently degrades signal integrity
  - Downside is creating superfluous noise, spurs and aliasing

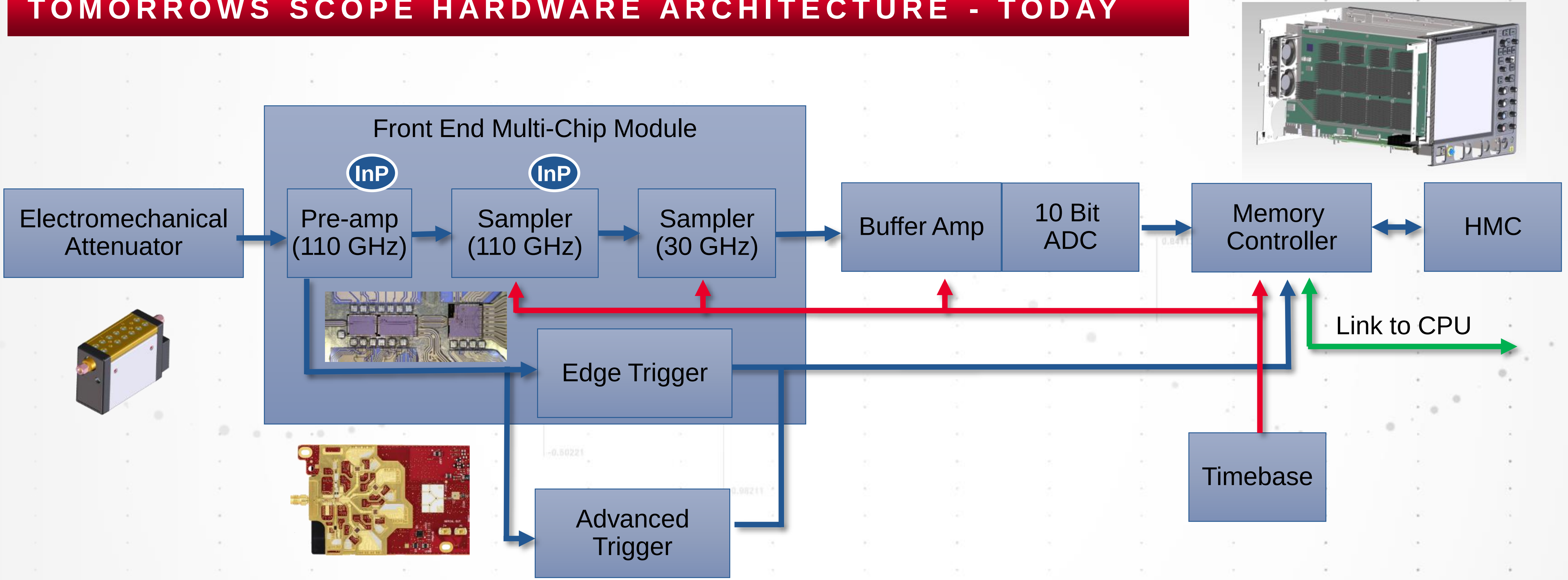


Teledyne LeCroy Digital Bandwidth Interleave (DBI)

KEYSIGHT TECHNOLOGIES

Infiniium UXR-Series – Returns to Time-Interleave Sampling

TOMORROWS SCOPE HARDWARE ARCHITECTURE - TODAY



Some Highlights

- **<u>No Frequency based Interleaving</u>** – provides a full bandwidth InP enabled sampling system
- Much higher frequency and more efficient data flow w/ less noise
- Adapts the latest technologies, including HMC and faraday cage Front End Multi-chip modules

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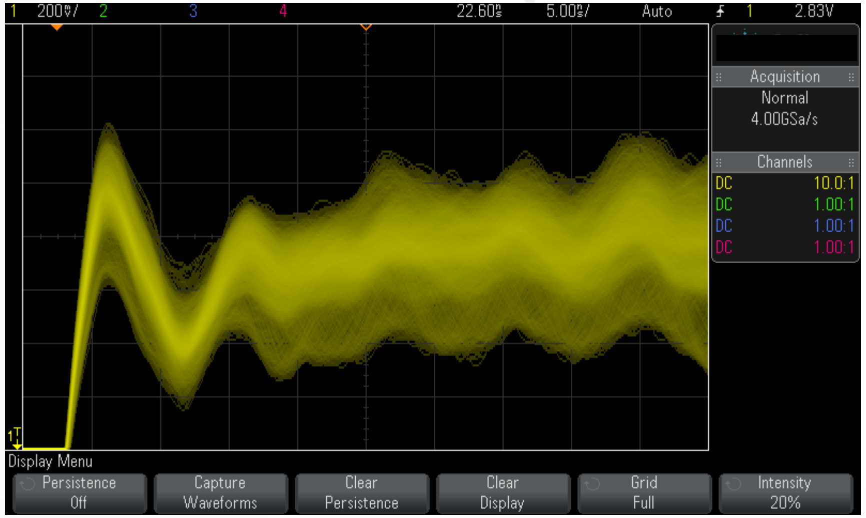
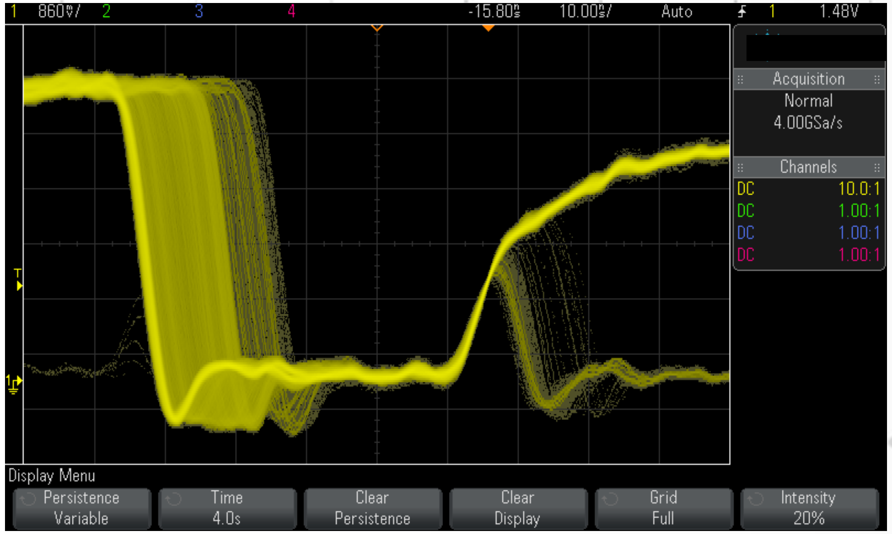
Waveform Update Rate

HOW OFTEN CAN THE OSCILLOSCOPE SHOW ME WAVEFORMS?

Improves scope usability



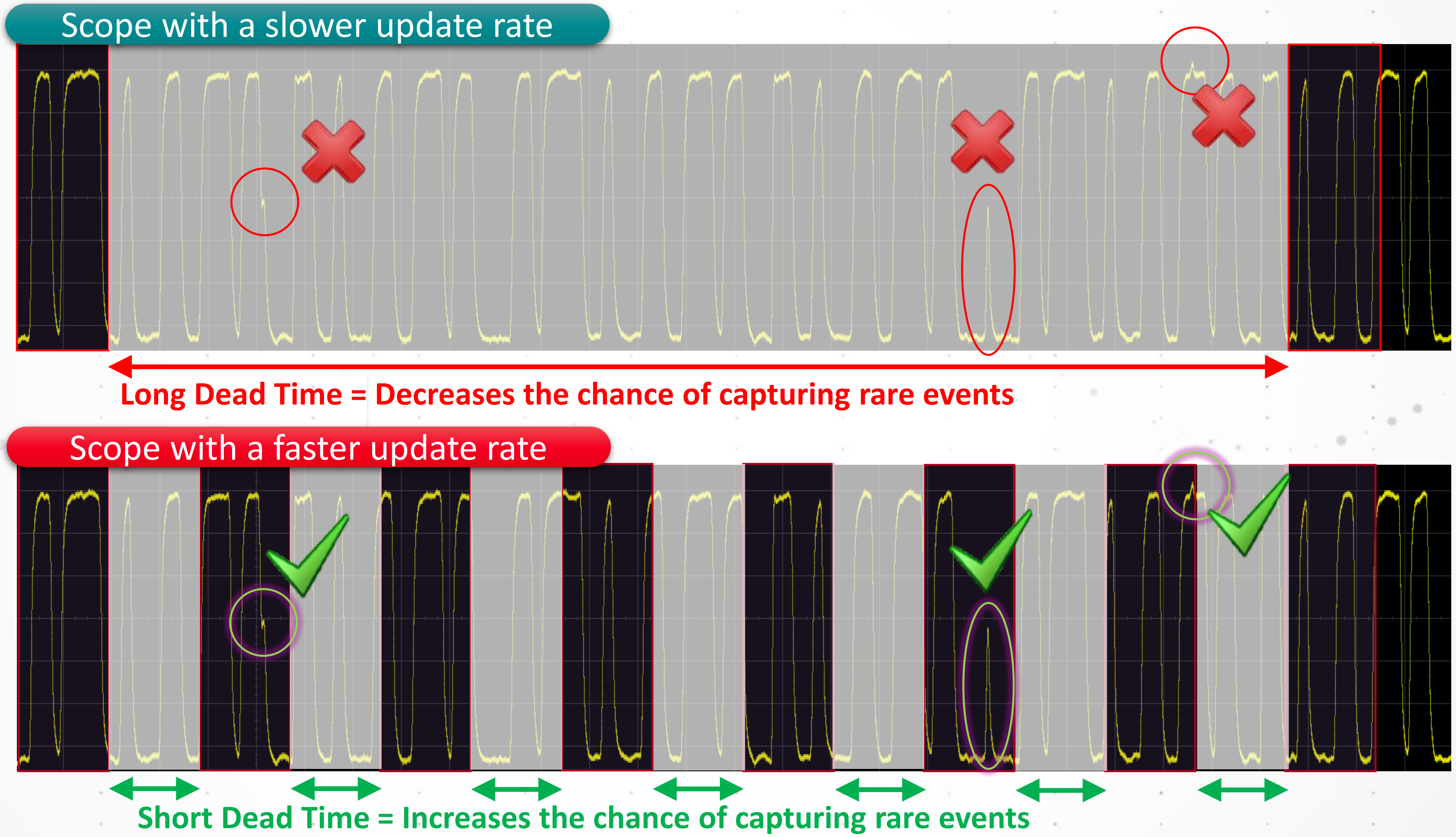
Improves scope display quality



Improves scope probability of capturing infrequent events

Waveform Update Rate

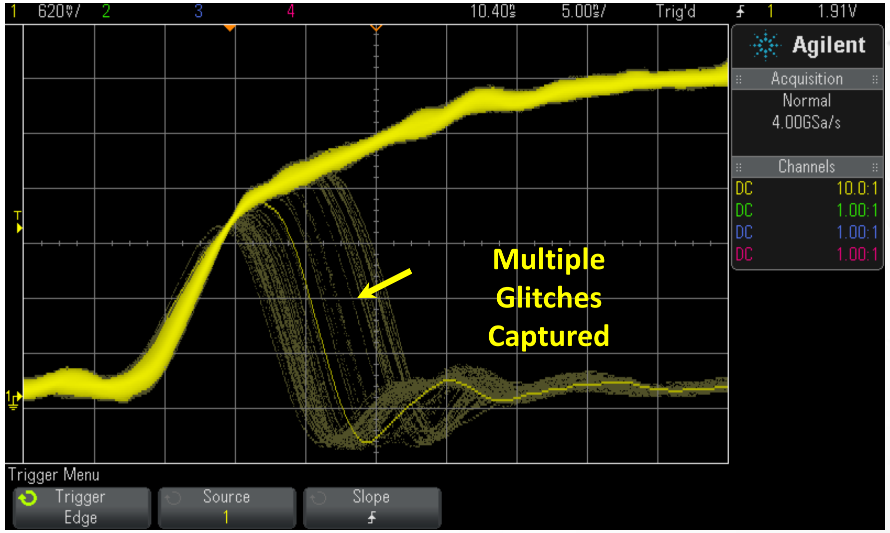
VISUALIZING THE DIFFERENCE



Waveform Update Rate

WHAT HAPPENS IF MY UPDATE RATE IS TOO SLOW?

- A slower update rate means you may miss important, fast moving, and rare events on a signal that are very important to see.
- Each acquisition is like a roll of the dice – the more often you roll the dice, the better chance you can get all possible outcomes!



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Memory Depth

HOW MANY SAMPLES CAN THE OSCILLOSCOPE TAKE AT ONCE?

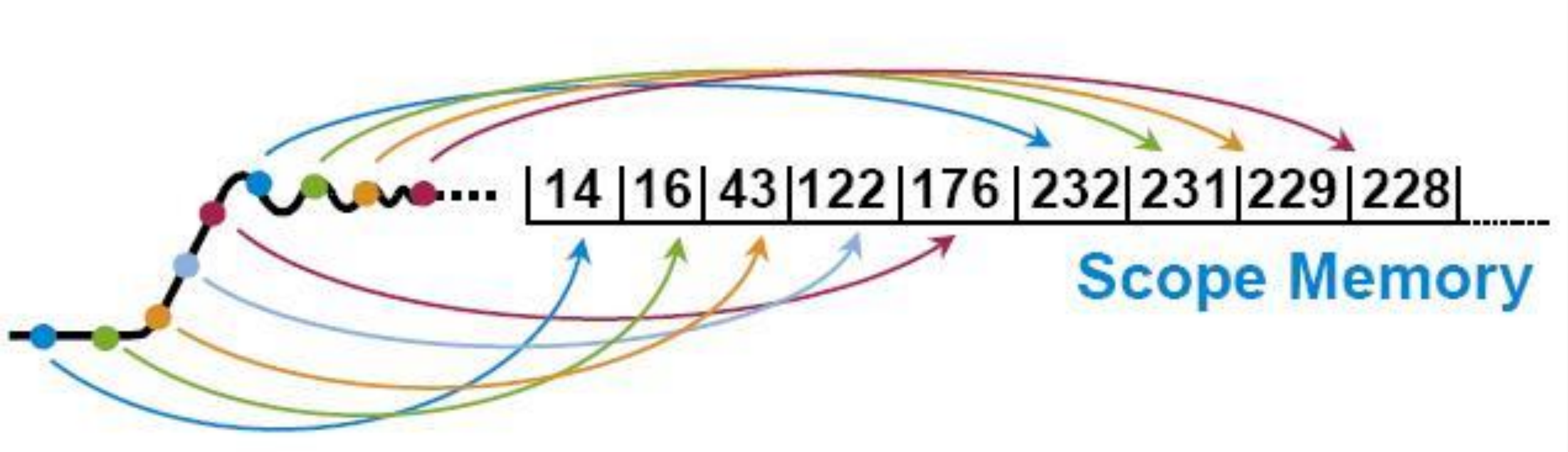
- Measured in samples or points. Modern scopes have millions or billions of samples in memory.
- More memory means more time can be shown on screen using maximum sample rate. But, more memory adds cost, slows down the responsiveness of the scope, and adds complexity.
- Keysight InfiniiVision X-Series are the only scopes in the market that automatically adjust memory depth to maximize performance. Others will give the user a setting to adjust manually.

$$Memory\ Depth\ (Sa) = Sample\ Rate\ \left(\frac{Sa}{s}\right) * Time\ (s)$$

Memory Depth

PURPOSE OF MEMORY IN DIGITIZING SCOPES

- Every sample must be stored in memory
- Deeper memory stores more samples
- Longer periods of time means more samples to store in order to maintain sample rate



Memory Depth

THE PURPOSE OF DEEP MEMORY

Maintain High Sample Rate While Capturing Longer Periods of Time

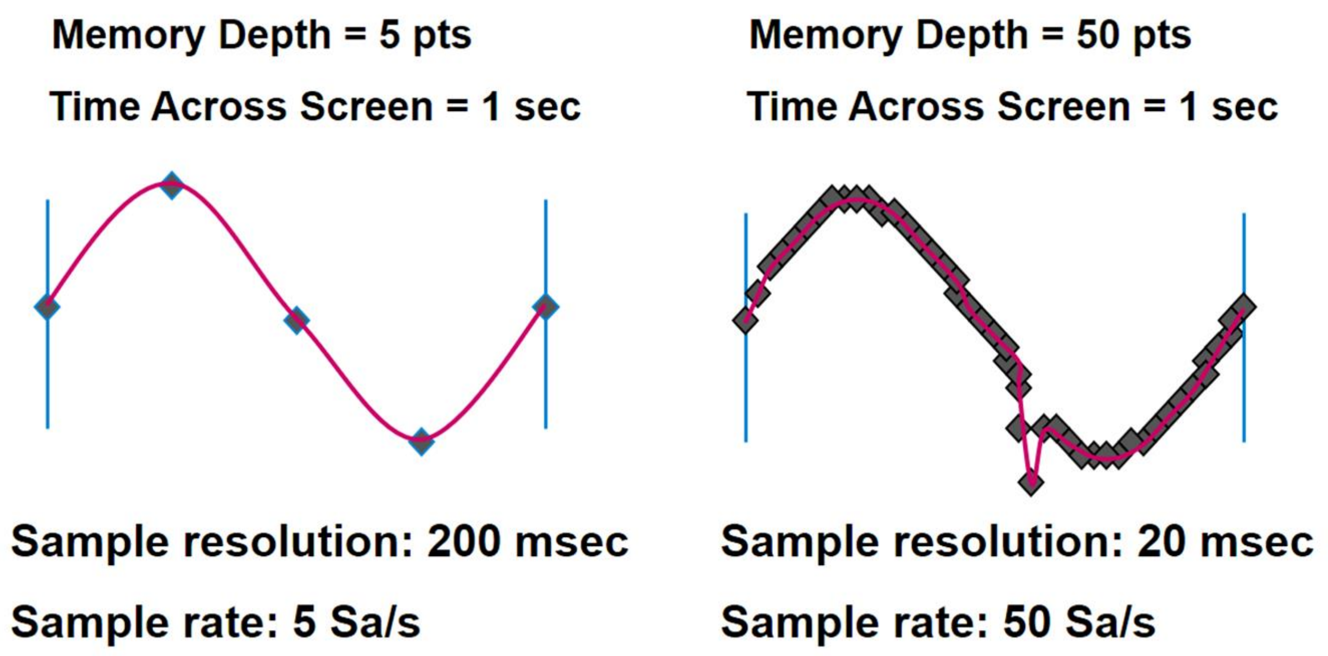
Ability to zoom-in and see all the details

Higher Sample Rate =

- *Capture higher BW signals (remember Nyquist?)*

Especially important in

- *Mixed analog and digital applications*
- *Serial communication applications*



Memory Depth

HOW MUCH MEMORY DO I NEED?

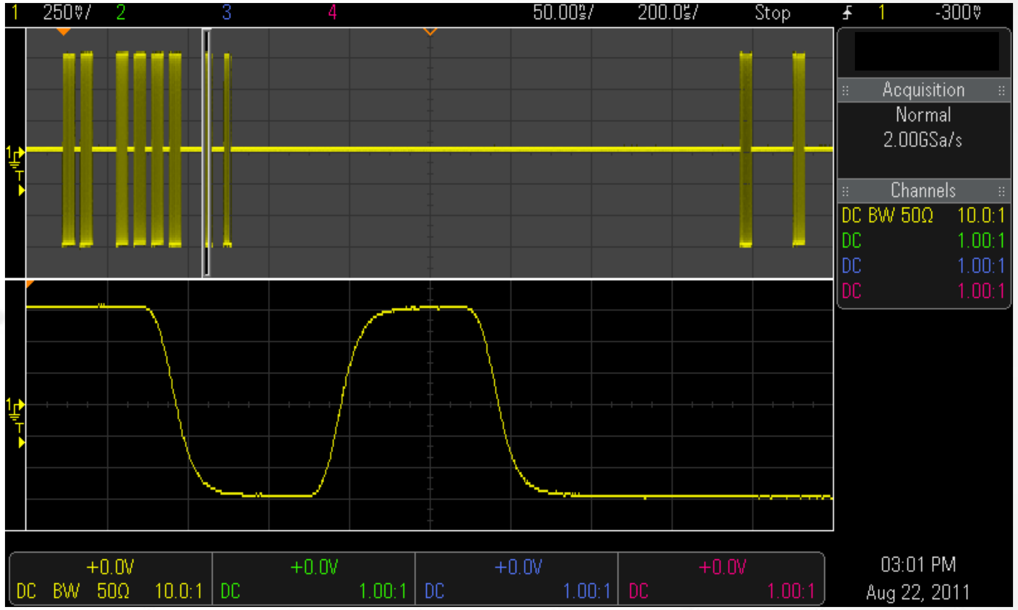
Determine required sample rate

- *Usually based on fastest clock rate or rise time*

Determine longest time-span to acquire

- *Usually based on slowest analog signal or digital packets*

$$Memory\ Depth\ (Sa) = Sample\ Rate\ \left(\frac{Sa}{s}\right) * Time\ (s)$$



<u>Example:</u>

Required Sample Rate = 2 GSa/s

Sample Interval = 1/SR = 500 ps/Sa

Longest Time Span = 2 ms (200 µs/div)

Required Memory Depth

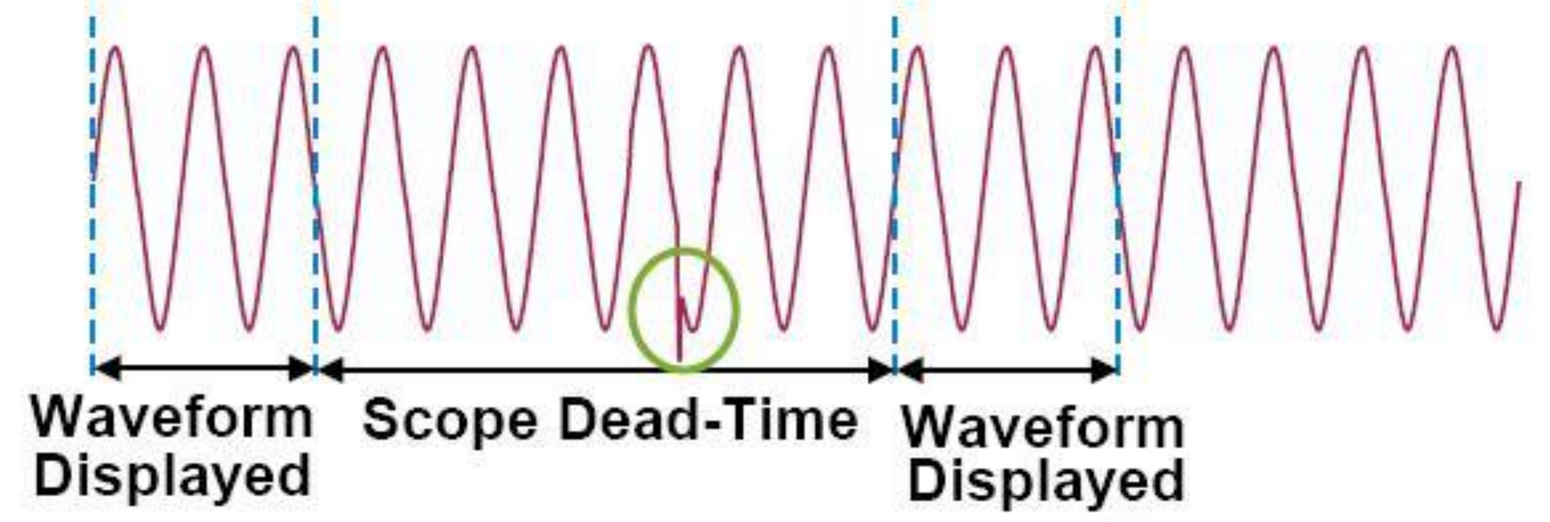
= 2 ms / 500 ps/Sa

= 4 MSa

Memory Depth

POSSIBLE NEGATIVE IMPLICATIONS OF DEEP MEMORY

- Slower Waveform Update Rate
- Slower User-Input Response Time
- Increased Dead-Time Between Acquisitions
- Missed Glitches and Anomalies during Dead-Time



Memory Depth

SOLVING THE DEAD-TIME PROBLEM IN DEBUG OSCILLOSCOPES

Custom ASIC hardware built into acquisition system

- *Keysight's MegaZoom Technology*

MegaZoom is a Memory Management Tool

- *Ping-Pong acquisition memory*
- *Preprocessing of data in hardware*
- *No special modes – always on and always fast*

Result is a fast waveform update rate with minimal dead-time between acquisitions and no processing bottlenecks.

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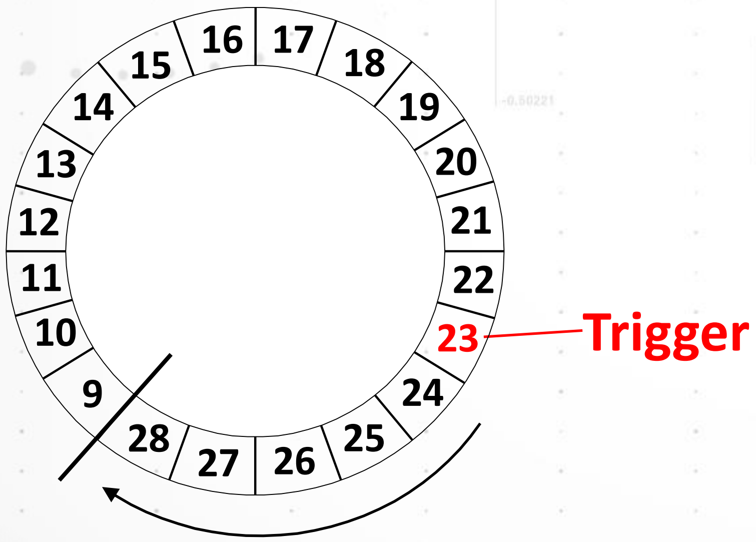
Triggering

RING ACQUISITION MEMORY

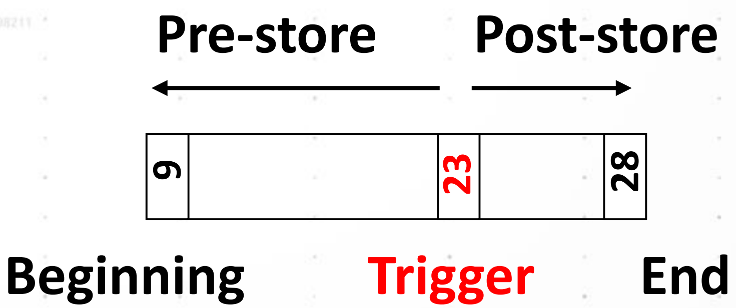
The oscilloscope is constantly acquiring data if no trigger event occurs. The acquisition memory is overwritten with new data.

When a trigger event occurs the memory content (waveform data) is transferred to the Display Memory and a new acquisition starts.

Ring Model

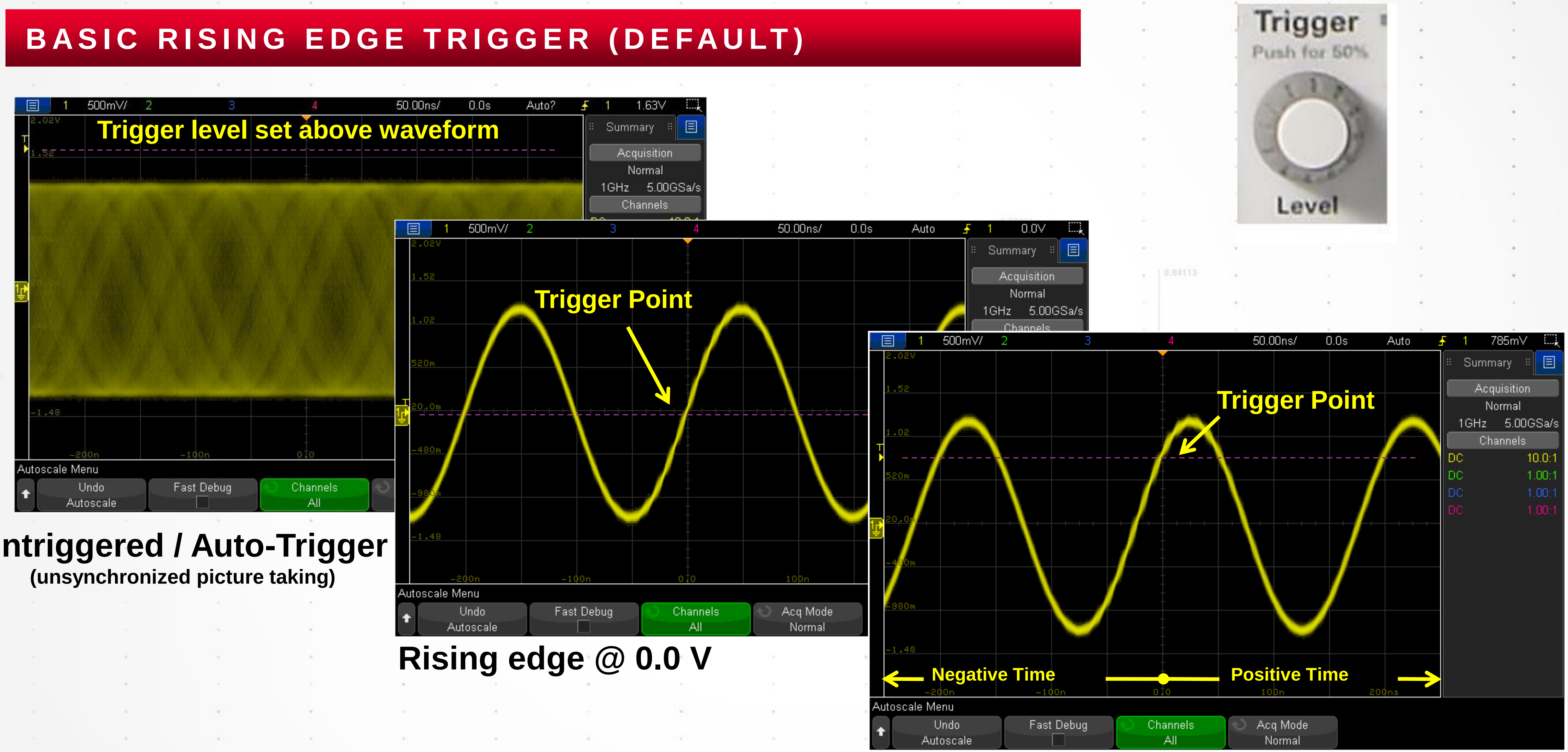


Linear Model



Triggering

BASIC RISING EDGE TRIGGER (DEFAULT)



Untriggered / Auto-Trigger
(unsynchronized picture taking)

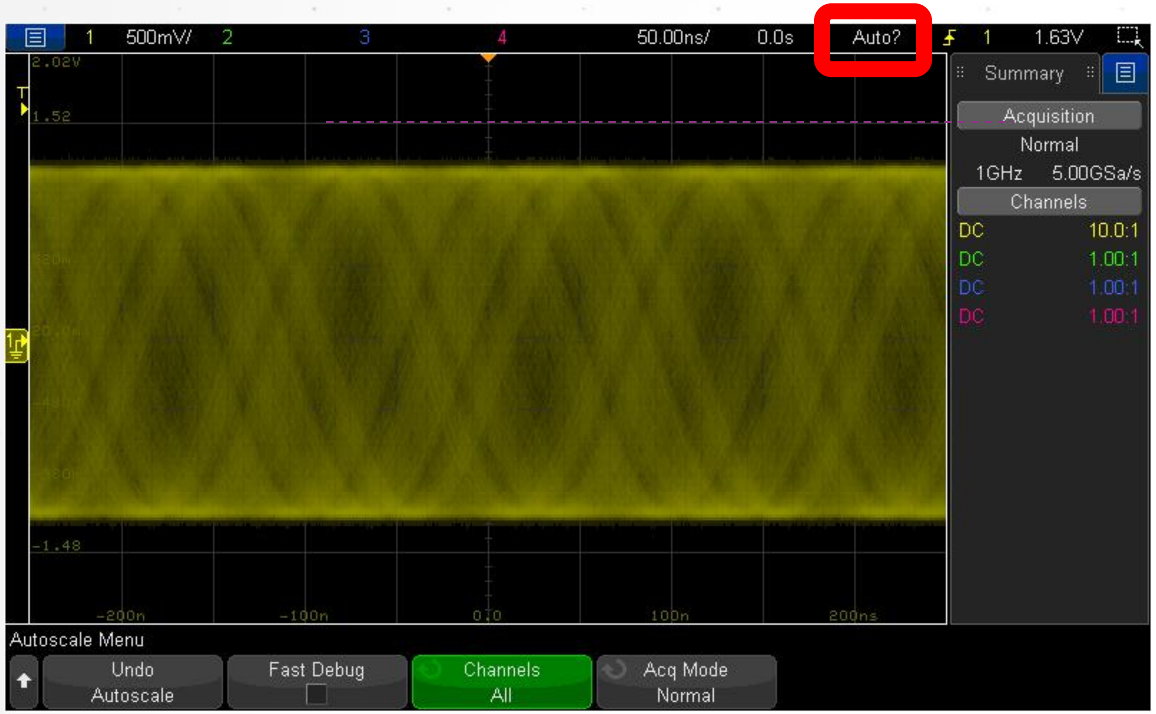
Rising edge @ 0.0 V

Rising edge @ +785 mV

KEYSIGHT TECHNOLOGIES

Triggering

AUTO VS. NORMAL: WHAT'S WITH THE SCOPE SPAGHETTI?



Auto trigger: "I don't see a trigger: I'll trigger on my own"

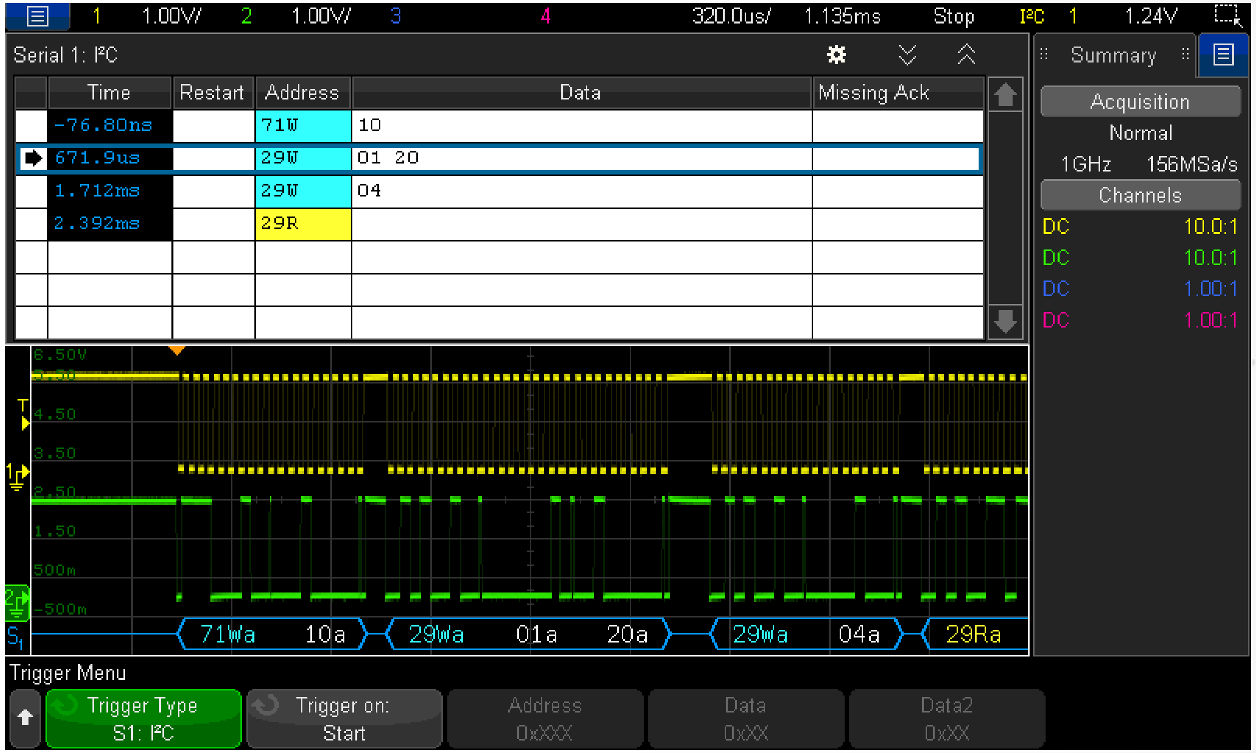
Normal trigger: "I don't see a trigger, I'll do nothing at all"

Triggering

ADVANCED OSCILLOSCOPE TRIGGERING

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

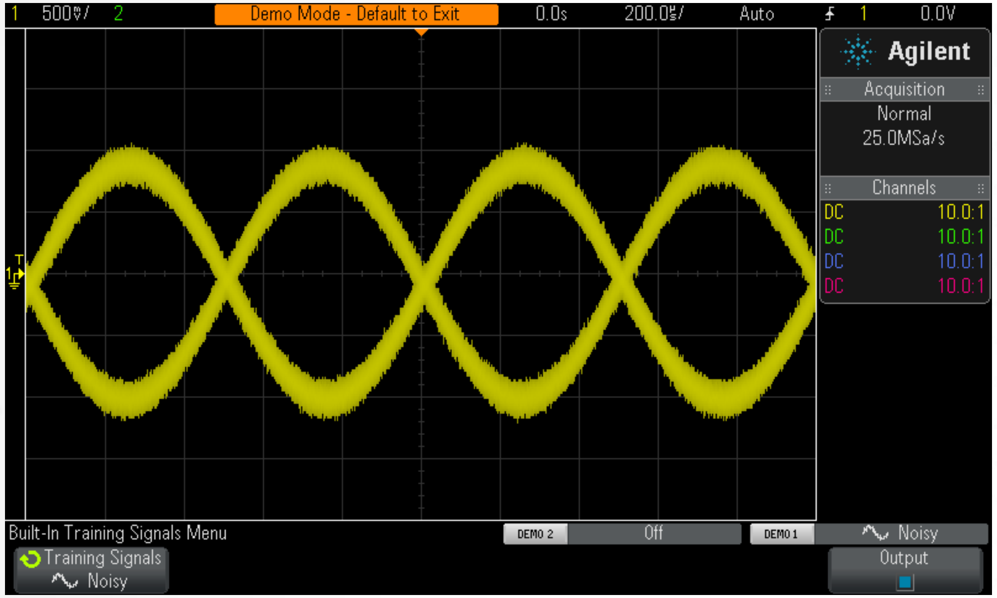
Triggering on more complex signals requires advanced triggering options.



Example: Triggering on an I^{2}C serial bus

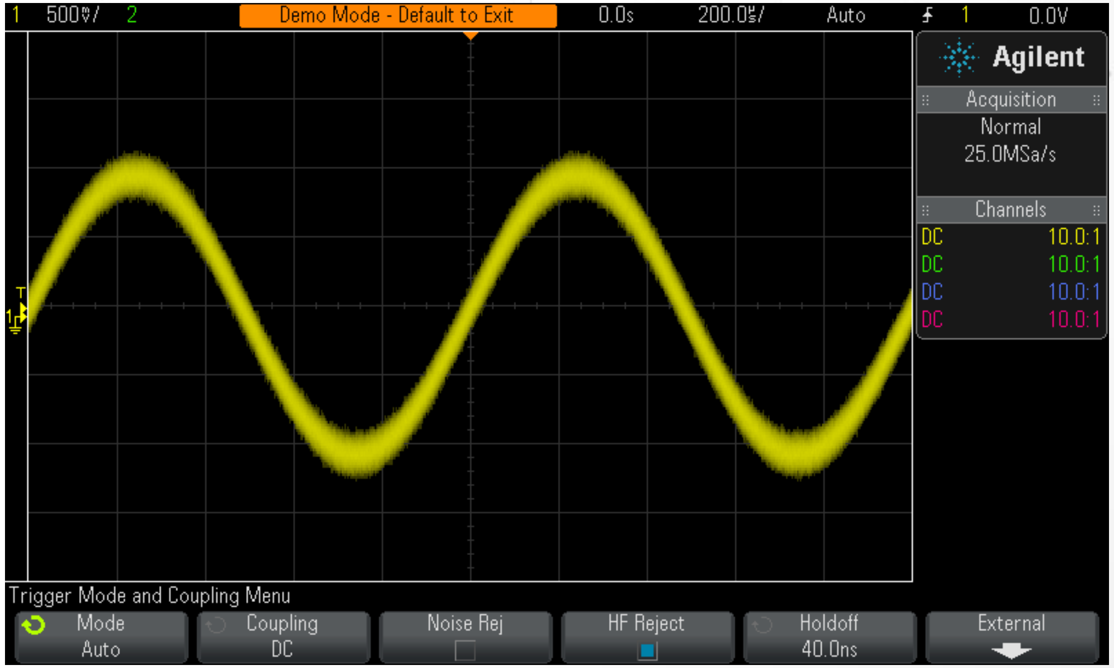
Triggering Basics

HOW TO DEAL WITH NOISY SIGNALS



Rising edge trigger – Scope triggers on high frequency noise during a falling edge of sine wave ☹

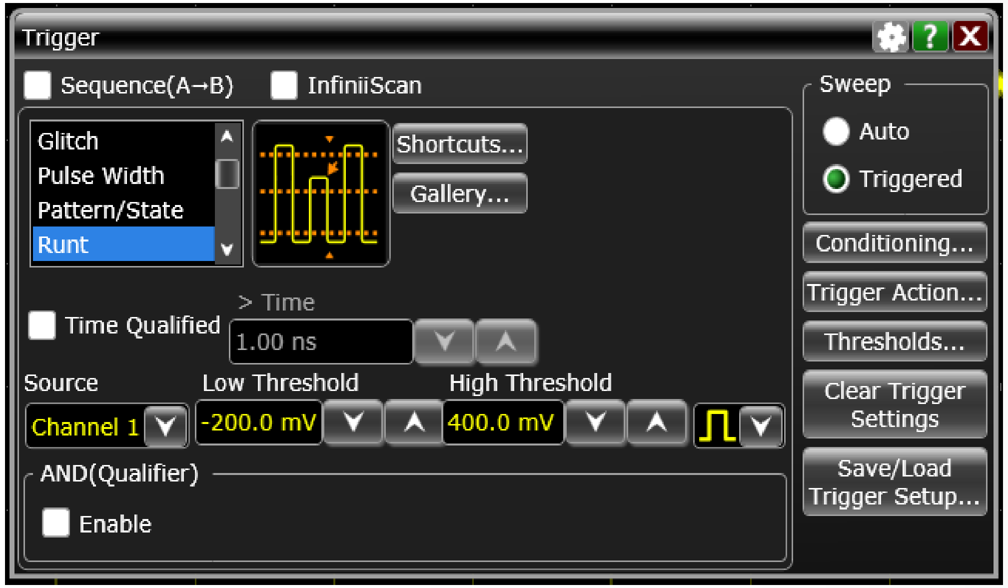
Rising edge trigger, HF Reject – Scope correctly triggers on high frequency noise



Advanced Triggering

HOW TO DEAL WITH NOISY SIGNALS

- **Standard Oscilloscope Triggering**
  - ✓Edge
  - ✓Pattern
  - ✓Video
- **Advanced Parametric Triggering**
  - ✓Pulse-width
  - ✓N^{th} Edge Burst
  - ✓Setup & Hold Time
  - ✓Runt
  - ✓Edge Speed
- **Serial Bus Triggering**
  - ✓I^2C, SPI, RS232/UART, I^2S, CAN, LIN, FlexRay, SENT, MIL-STD 1553



Oscilloscope Fundamentals

AGENDA SLIDE

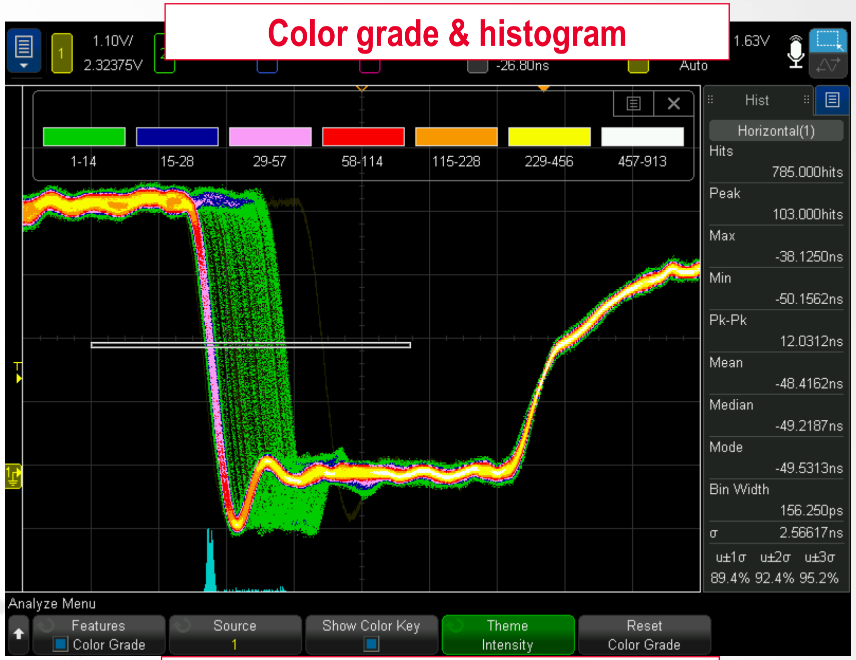
- Time Domain vs. Frequency Domain
- Sampling Rate and Modes
- Bandwidth and Aliasing
- Oscilloscope Architectures
- Waveform Update Rate
- Memory Depth and Methods
- Triggering: Basics and Advanced
- Waveform Visualization Tools
- Probing Architecture, Tips and Tricks

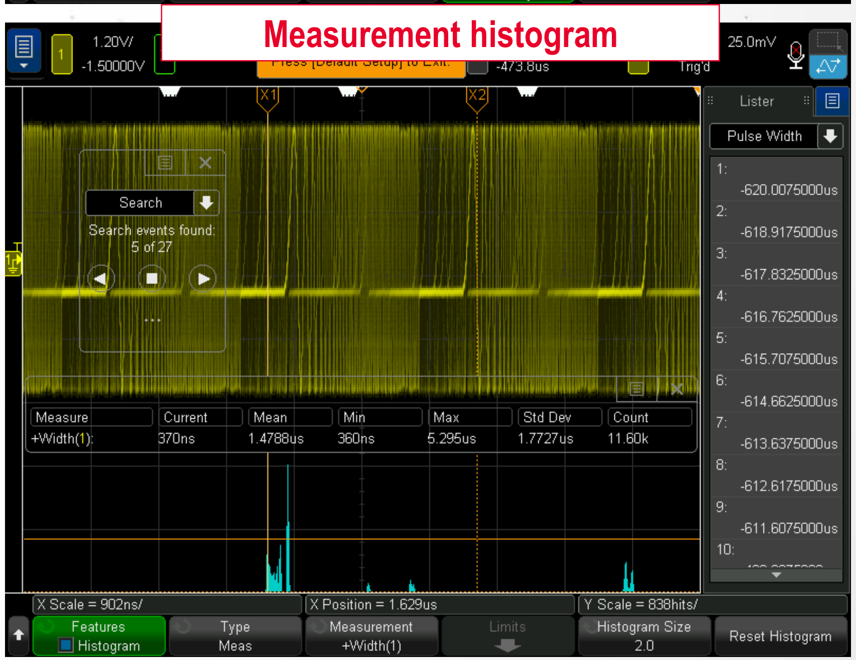
Waveform Visualization Tools

VISUALIZE THE SIGNAL DISTRIBUTION: COLOR GRADE + HISTOGRAM

Color gradation and histograms provide graphical representation of signal and measurement distributions.

- *Also see the distributions of some measurement results.*
- *An independent database for color gradation gives flexibility.*
- *Because color gradation/histograms operate like a function, they can be applied to analog waveforms, reference waveforms, and math functions, like FFT.*
- *Measurement histograms display a graphical distribution of the measurement results.*





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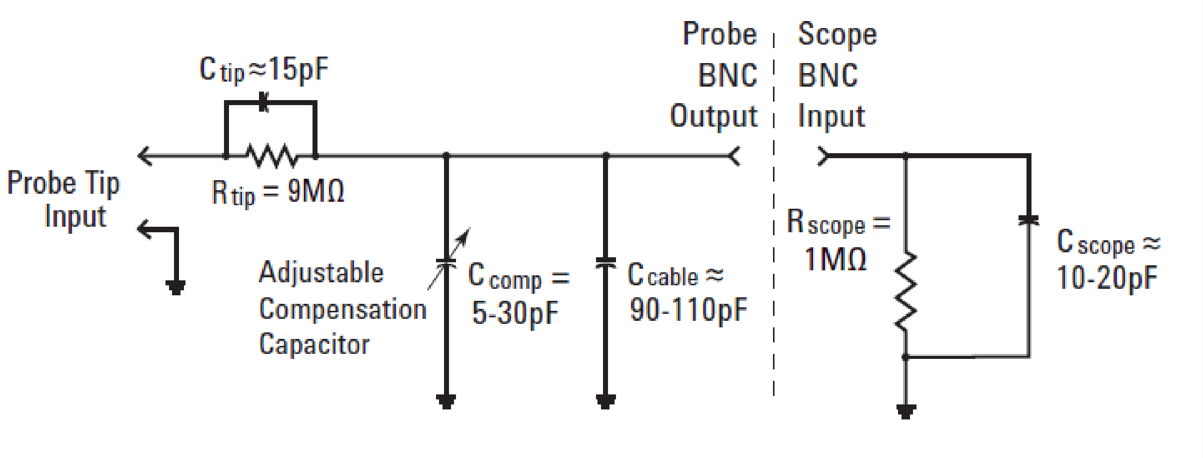
Probing Architecture, Tips, and Tricks

RESISTOR DIVIDER PROBES – BLOCK DIAGRAM

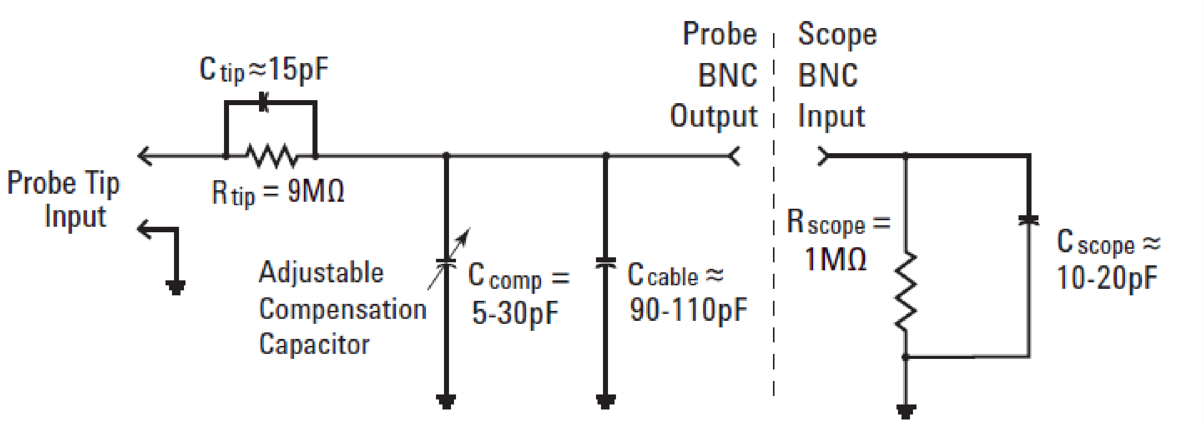


Passive 10:1 Probe Model

- 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 Architecture, Tips, and Tricks

RESISTOR DIVIDER PROBES – BLOCK DIAGRAM



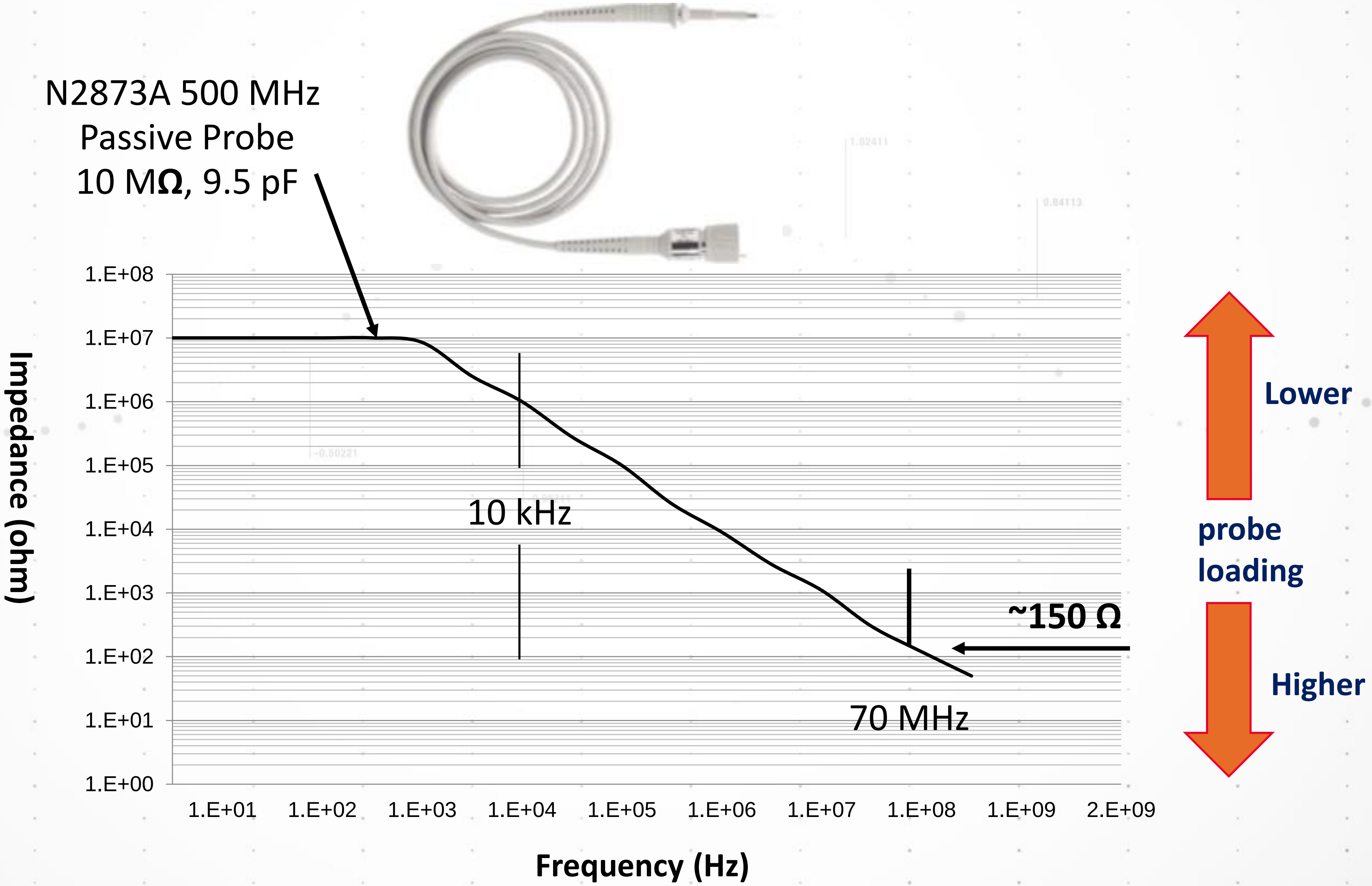
Where $C_{parallel} = C_{comp} + C_{cable} + C_{scope}$

- At high frequencies, we get an impedance divider, because capacitors will begin to express non-real resistances on our circuit.
- C_{comp} is adjusted by the user to create a 10:1 divider of capacitive elements using the following formula: $9\,C_{tip} = C_{parallel}$

KEYSIGHT TECHNOLOGIES

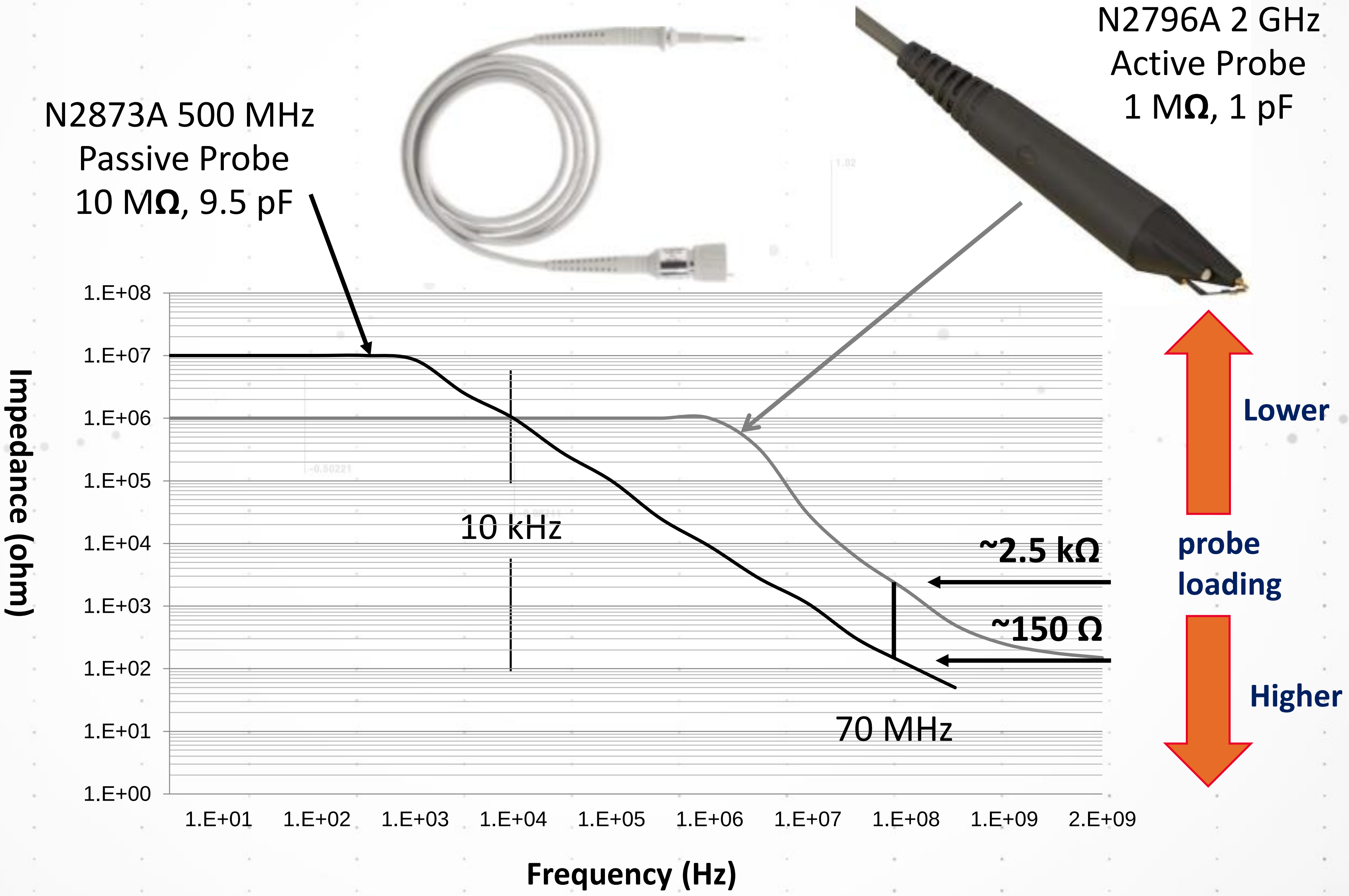
Probing Architecture, Tips, and Tricks

RESISTOR DIVIDER PROBES – LOADING CHARACTERISTICS



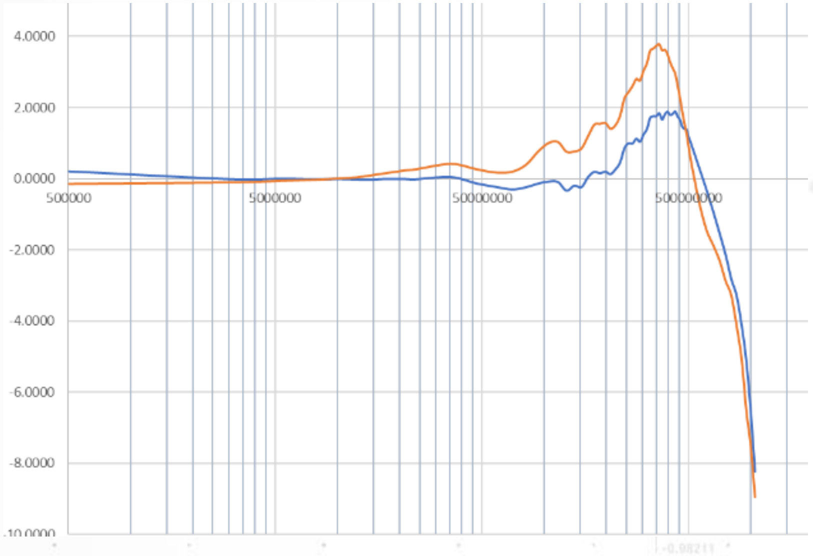
Probing Architecture, Tips, and Tricks

ACTIVE PROBE LOADING IS SUPERIOR TO PASSIVE

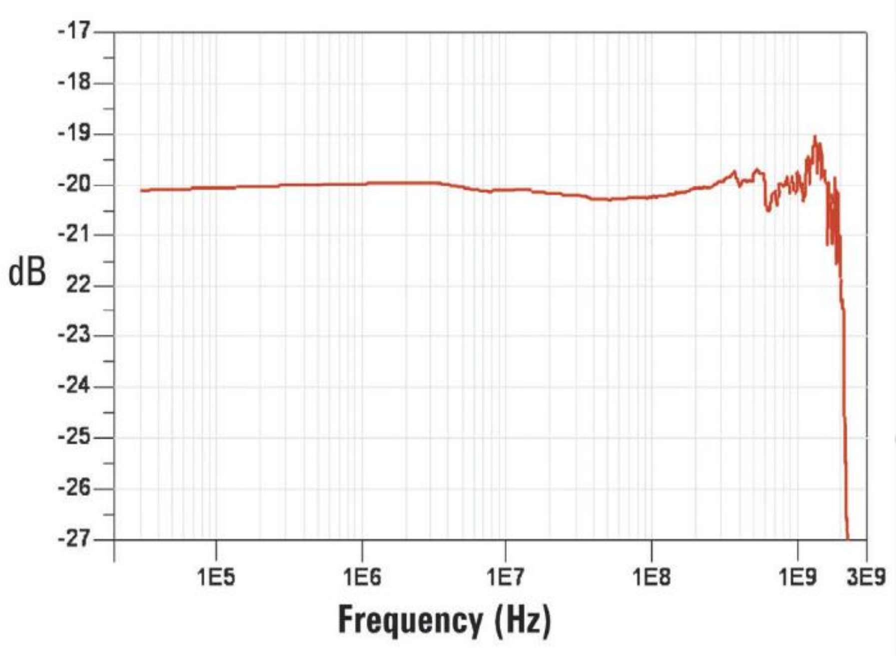


Probing Architecture, Tips, and Tricks

FREQUENCY RESPONSE OF PASSIVE, ACTIVE PROBES

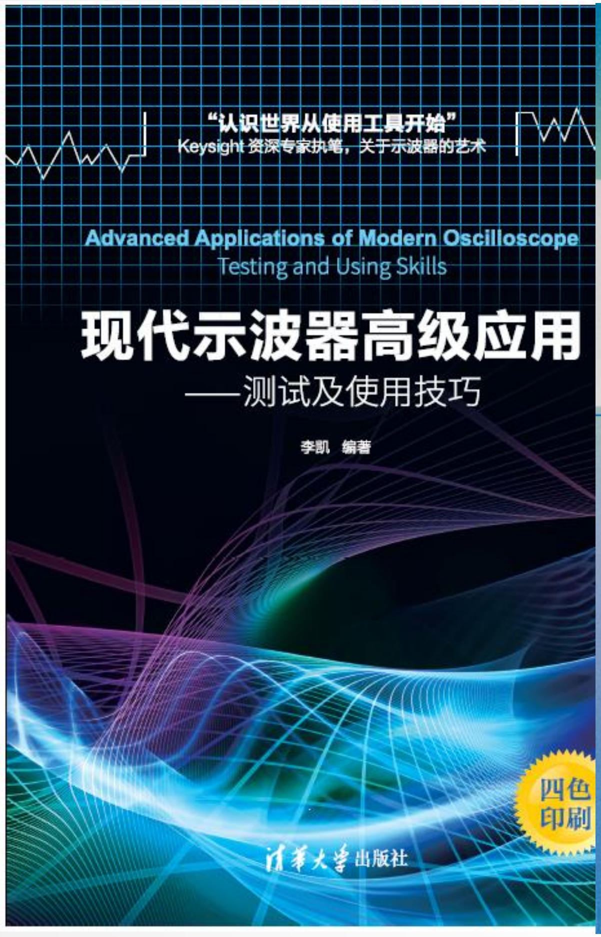


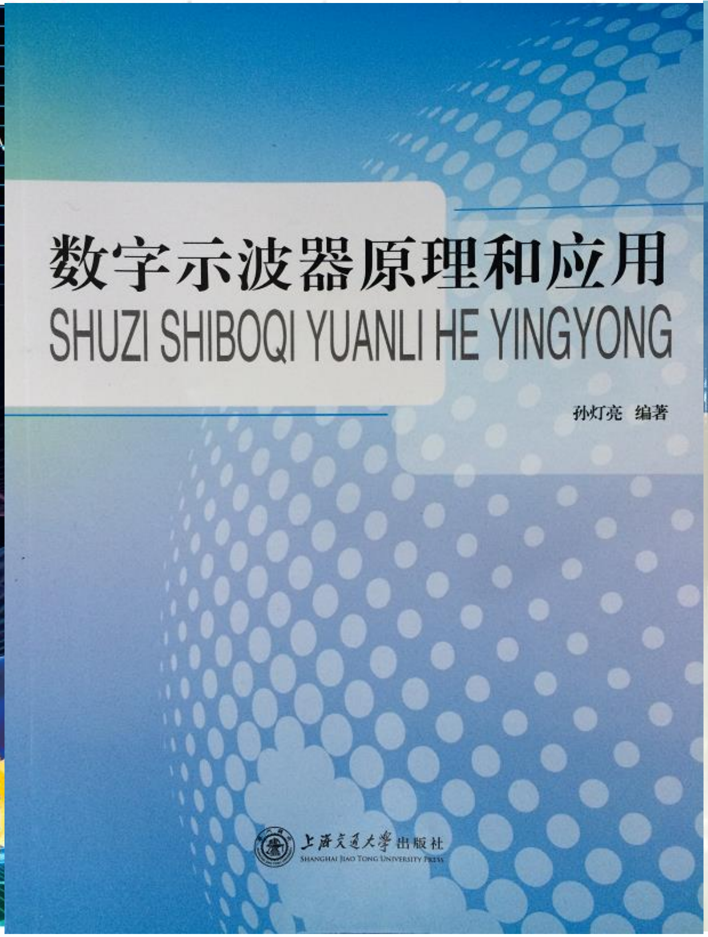
Example passive probe response plot

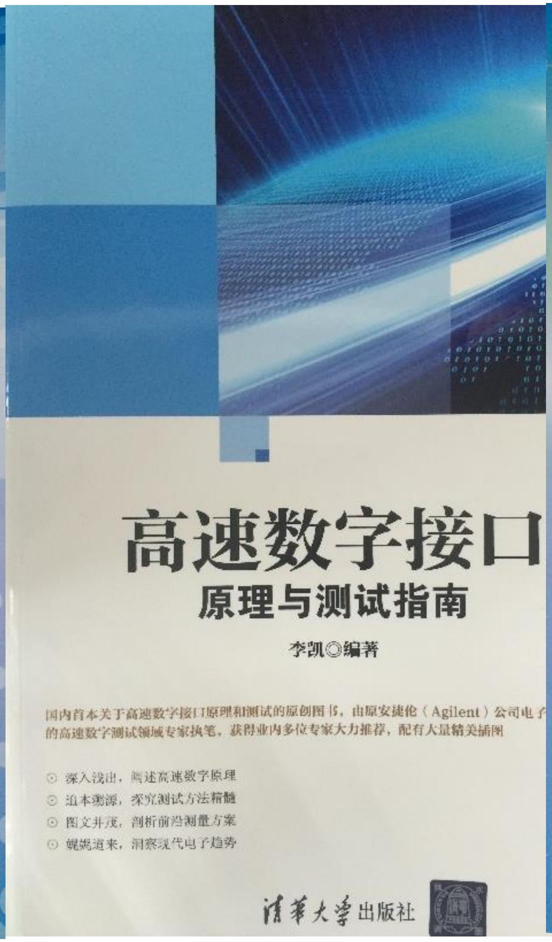


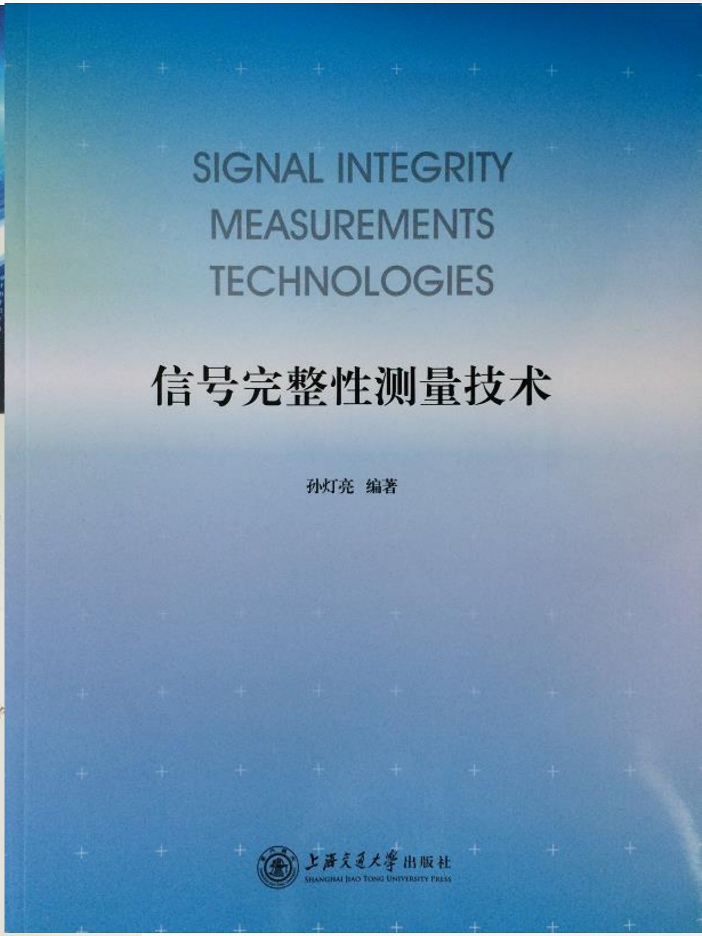
Example active probe response plot

For Reference Material on High Performance Scopes :









High Performance Oscilloscope Resources

- Keysight Digital Learning Center www.keysight.com/find/klcdigital
  - Webcast Recordings and Technical seminar videos , Application Notes
    - USB Type-C , PAM-4 , PCI-Express, DDR Memory
    - Signal Integrity , Power Integrity
    - Measurement Fundamentals for AWG, BERT, Scope etc.
- Keysight RF and Digital Monthly Webcast Series
  - Live and On Demand Viewing : www.keysight.com/find/webcastseries (U.S. Version)
  - Register for Future Webcasts : https://kee.smarket.net.cn/2019/index.html (中文平台)
- Keysight 大型活动
  - 感恩月历届技术干货汇总 ： 2017年感恩月示波器文章， 示波器 技术文章回顾
  - Keysight World 2019 技术演讲回看
- Oscilloscope Topics at Youtube :
  - Sampling: https://www.youtube.com/watch?v=yBC97UUljKo
  - Bandwidth: https://www.youtube.com/watch?v=VBJWkceO1OA
  - Update Rate: https://www.youtube.com/watch?v=CPDIrKSDrZk
  - Memory Depth: https://www.youtube.com/watch?v=GAM_CpxVYq8
  - Eye Diagrams: https://www.youtube.com/watch?v=mnugUjaMN70

KEYSIGHT
TECHNOLOGIES

示波器基础典型应用分享

Speaker Title / Company Name

Speaker Name

Engineers Never Stop Learning

示波器典型应用分享

- 是德科技抖示波器家族简介

Keysight示波器家族

多样化

- 手持式、USB无脸式、PXIe模块
- 便携式、台式
- 嵌入式操作系统、Windows操作系统
- 8-bit ADC，10-bit ADC

Infiniium 系列

- 实时带宽：超过100 GHz
- 存储：深达2G每通道
- 操作系统：Windows

InfiniiVision 系列

- 带宽: 50 MHz ～ 6 GHz
- 独特技术：直观显示信号
- 操作系统：嵌入式

U1600
20MHz
~40MHz

P924XA
USB示波器
200MHz~1GHz

U924XA
PXIe示波器
200MHz~1GHz

1000 X系列
50 MHz
~100MHz

2000 X系列
70 MHz
~200MHz

3000 X系列
100 MHz
~1GHz

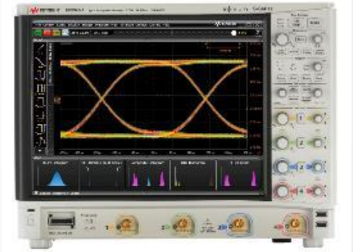
4000 X系列
200 MHz
~1.5GHz

6000 X系列
1GHz
~6GHz

UXR 系列 13-110GHz
10-bit ADC

Z 系列 20-63GHz

V 系列 8-33GHz



S 系列 500MHz-8GHz