Oscilloscopes and Accessories

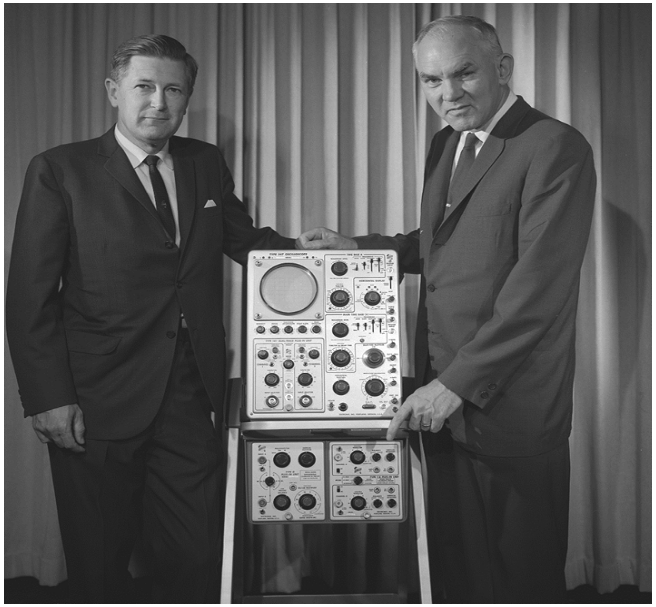
Politecnico di Milano

Agilent Technologies

The Role of Oscilloscopes

Oscilloscopes have played an important role in all major developments in electronics.

- The first computers
- Microprocessors and personal computers
- The space program
- Telecommunications
- Entertainment
- Radar and avionics
- Medical instrumentation

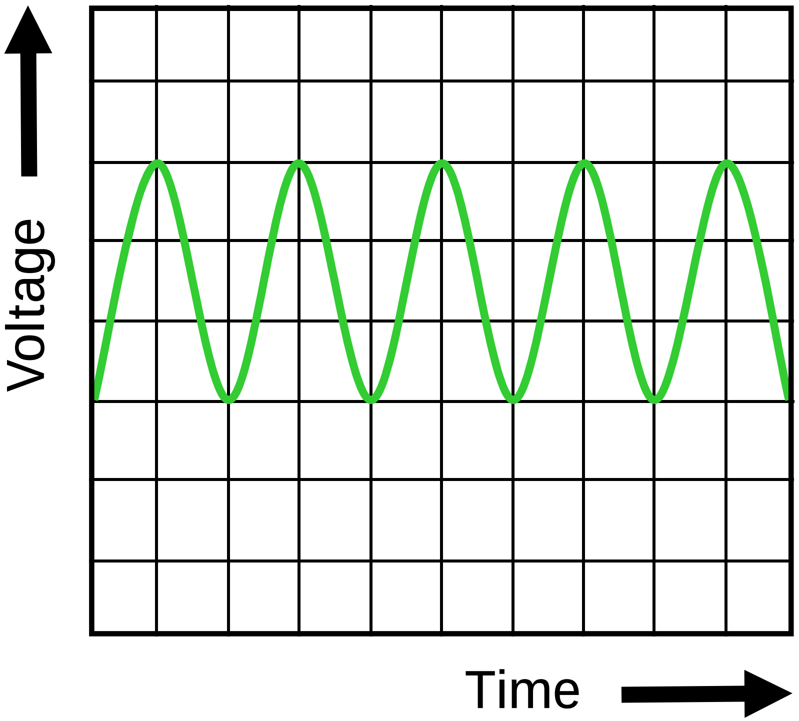


Tektronix founders, Jack Murdock and Howard Vollum, with an oscilloscope from the 1950s.

Oscilloscopes Show How Signals Change

Draws a graph of an electrical signal

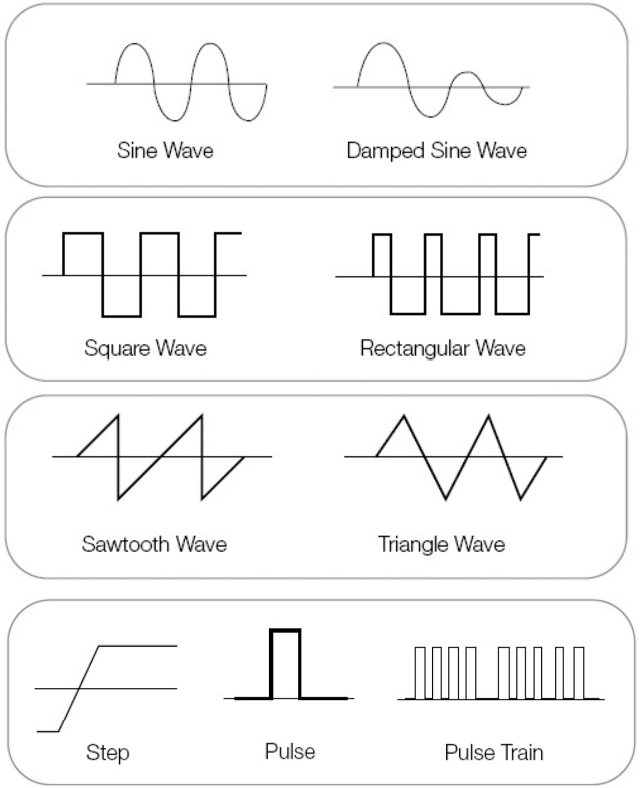
- Vertical (Y) axis is voltage
- Horizontal (X) axis is time



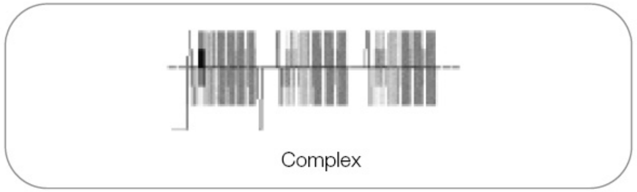
Types of Waves

You can classify most waves into these types:

- Sine waves
- Square and rectangular waves
- Triangle and saw-tooth waves
- Step and pulse shapes
- Periodic and non-periodic signals
- Synchronous and asynchronous signals
- Complex waves



Step, pulse and pulse train shapes.



An NTSC composite video signal is an example of a complex wave.

Choosing the Right Oscilloscope

Key parameters to evaluate:

Bandwidth

Rise Time

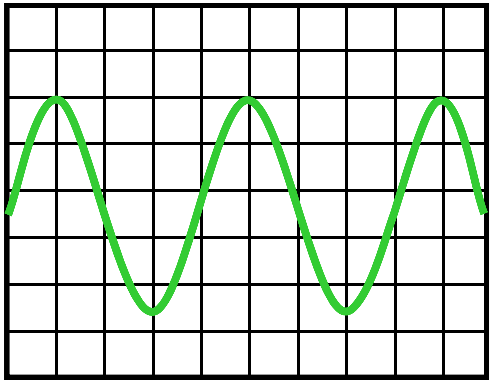
Sample Rate

Record Length

What Is Oscilloscope Bandwidth?

Bandwidth = Sine Wave -3 dB Point of a System

0 dB
6 div at 50 kHz



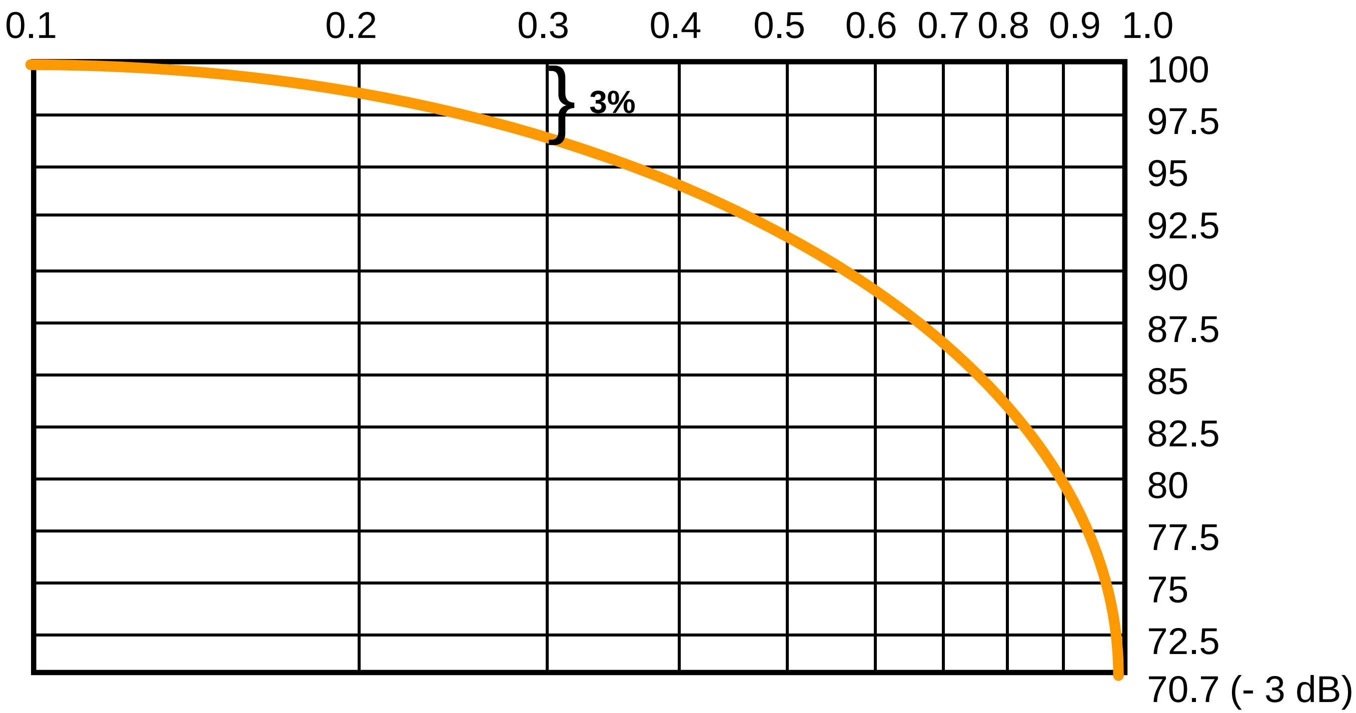
- 3 dB
4.2 div at bandwidth

Bandwidth x Risetime = 0.35*
100 MHz Bandwidth = 3.5 nsec Risetime

* This constant is based on a one pole model. For higher bandwidth instruments, this constant can range as high as 0.45.

Bandwidth vs. Amplitude Accuracy

$$BW = \frac{0.35^*}{t_{rise}}$$

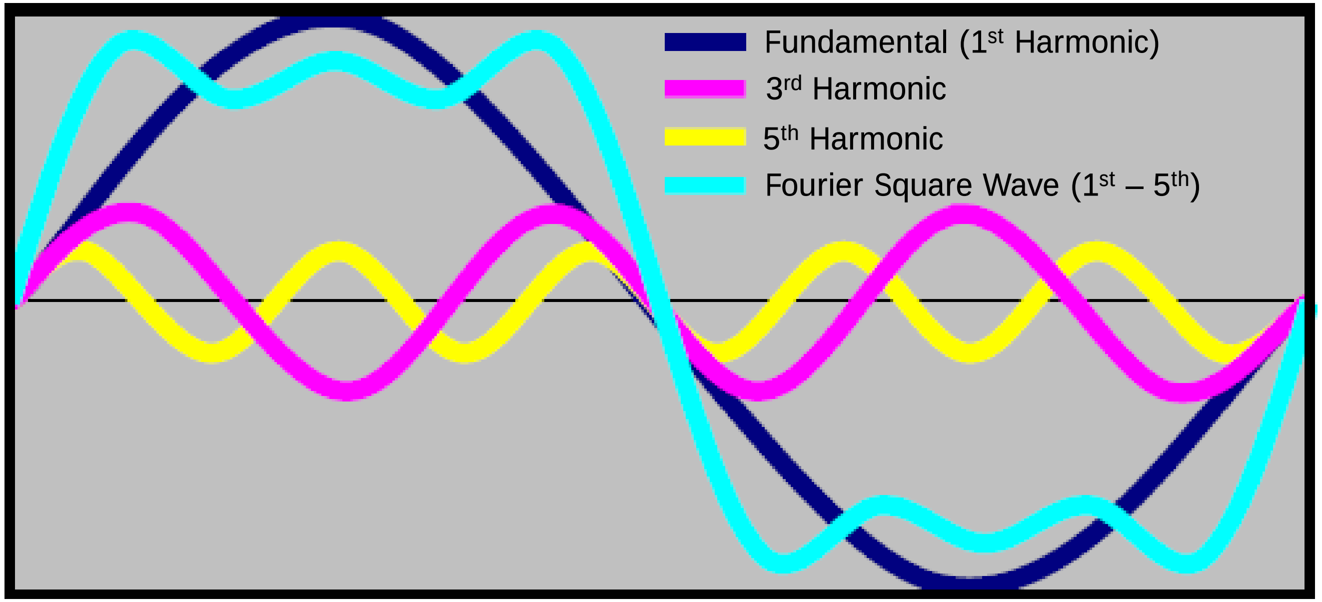


- **At the 3dB bandwidth frequency, the <u>vertical amplitude error</u> will be approximately 30%.**
- **<u>Vertical amplitude error</u> specification is typically 3% maximum for the oscilloscope.**

Use Caution with Complex Signals

Complex signals contain many spectral components that cumulatively form a signal over time.

- Spectral components are sine waves at varying frequencies and varying amplitudes which are added together to collectively form one signal.



Avoiding Bandwidth Measurement Errors

- Follow the **5 Times Rule** for Bandwidth
  - For less than +/- 2% measurement error

Bandwidth ≥ 5th Harmonic

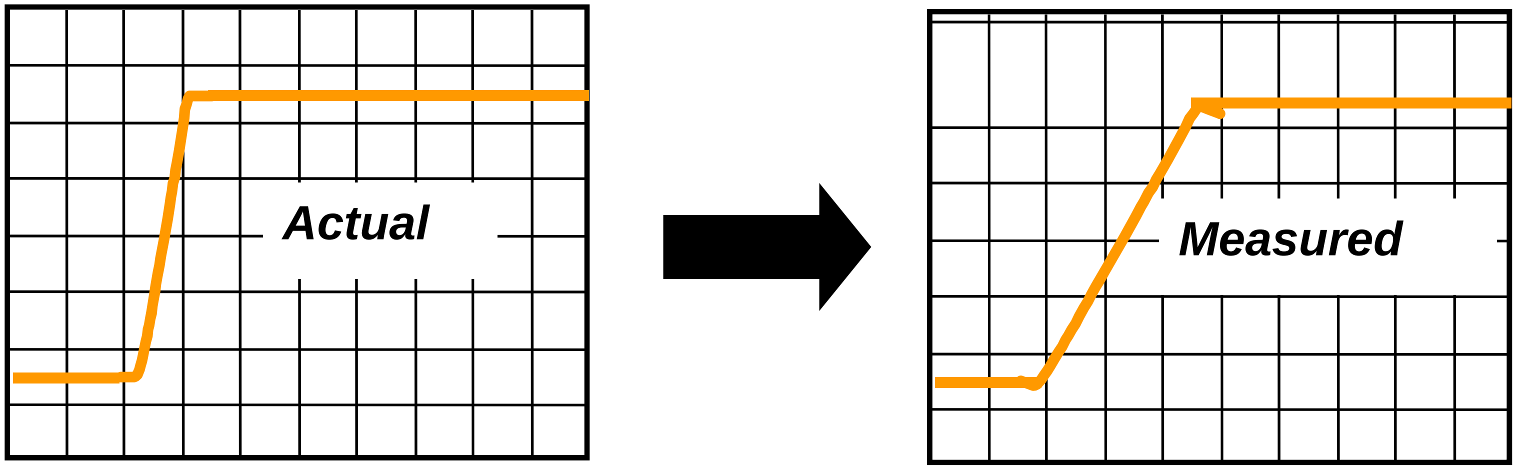
Key Performance Considerations: *Rise Time*

- Insufficient rise time will affect your signal
  - Many logic families have faster rise times than clock rates suggest

- Required Rise Time

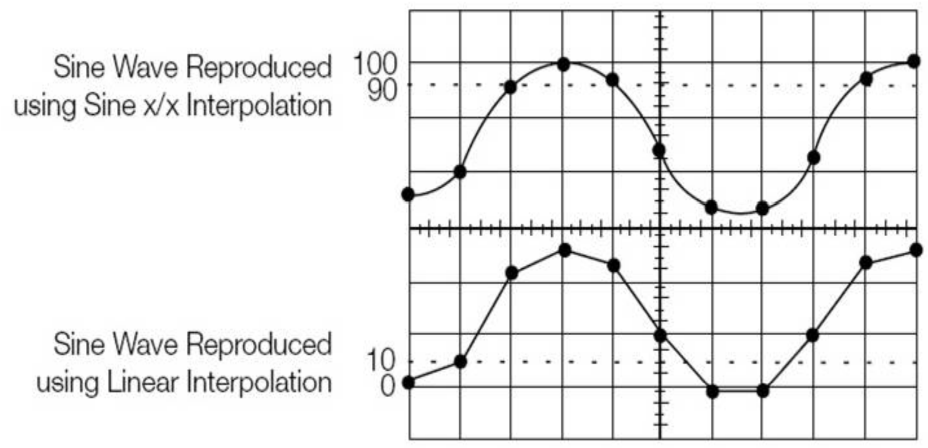
$$\text{Rise Time} = \frac{\text{Signal Rise Time}}{5}$$

$$\text{Measured Rise Time} = \sqrt{\left[\text{Oscilloscope Rise Time}\right]^2 + \left[\text{Signal Rise Time}\right]^2}$$



Key Performance Considerations: *Sample Rate*

- Determines how frequently an oscilloscope takes a sample
  - Faster sample rate, greater resolution and waveform detail



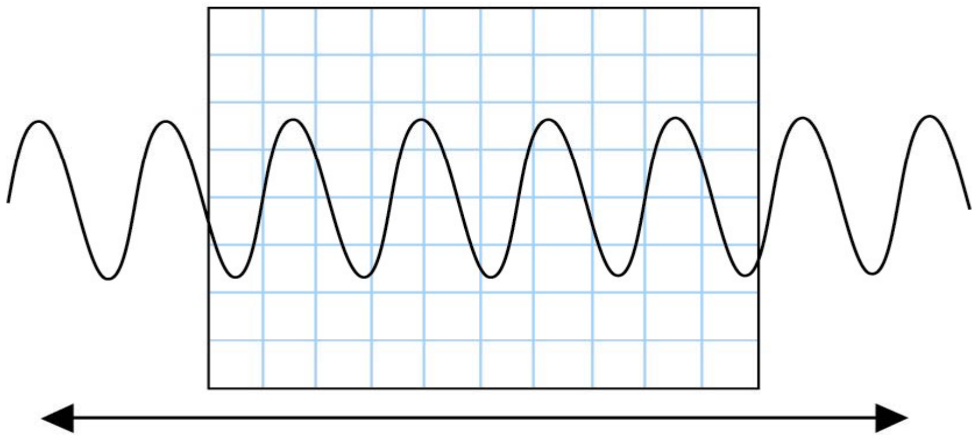
- Required Sample Rate

Sample Rate > 10 X $f_{Highest}$	Sample Rate > 2.5 X $f_{Highest}$
For linear interpolation	For sin(x)/x interpolation

5X oversampling is recommended to avoid aliasing and to capture signal details.

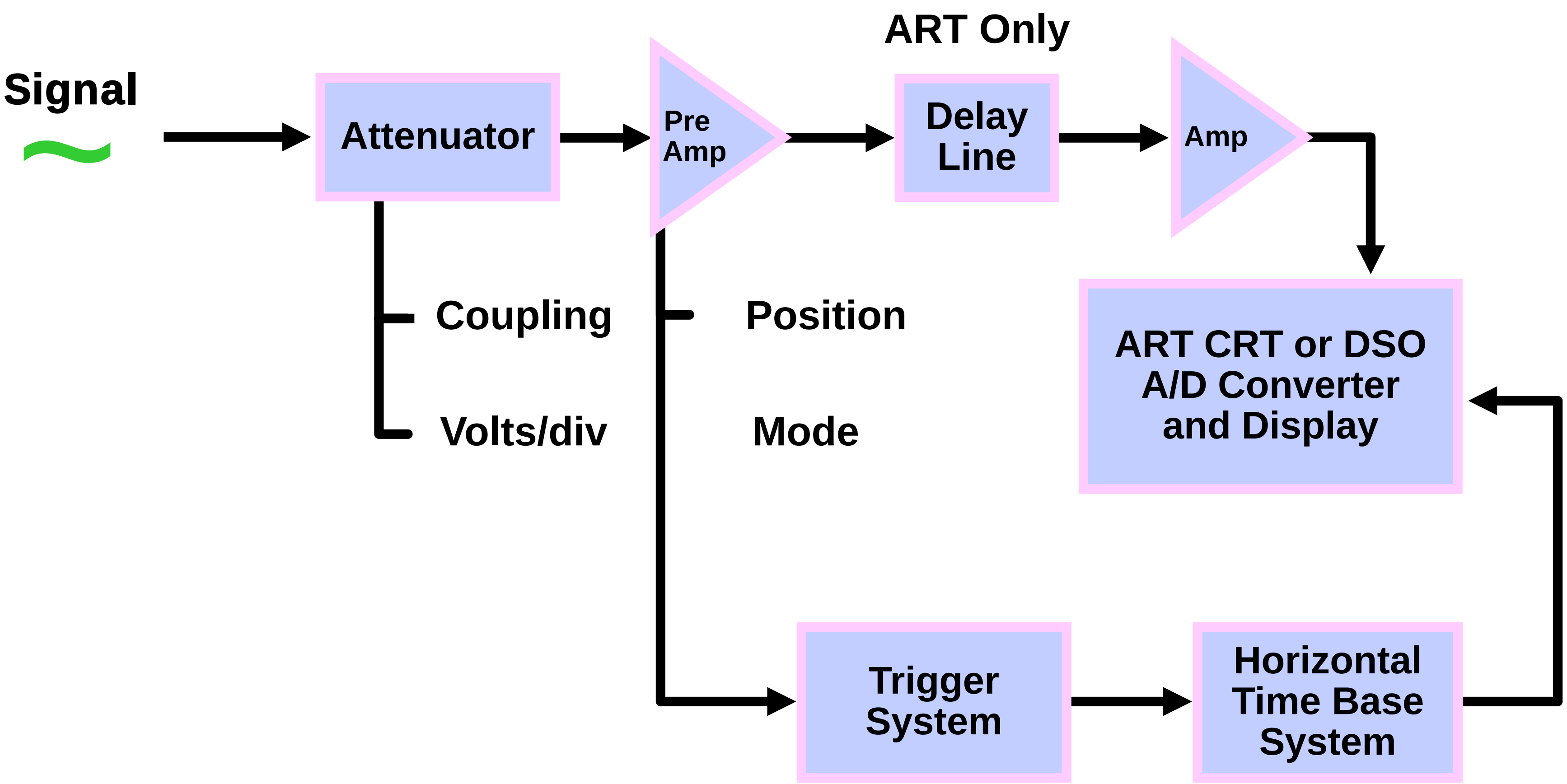
Key Performance Considerations: *Record Length*

- Determines how much "time" and detail can be captured in a single acquisition
  - Longer record length, longer time window with high resolution

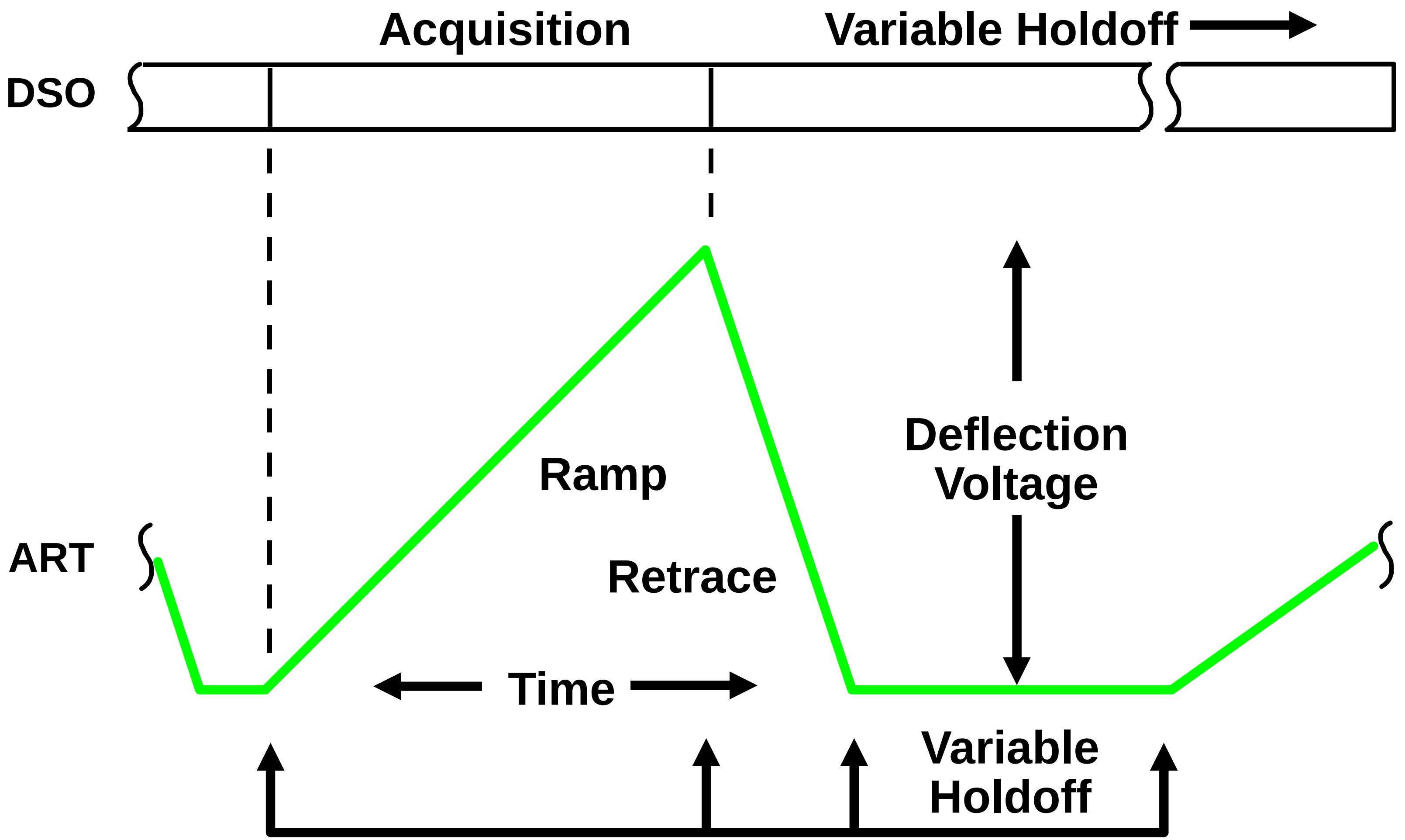


$$\text{Time} = \frac{\text{Record Length}}{\text{Sample Rate}}$$

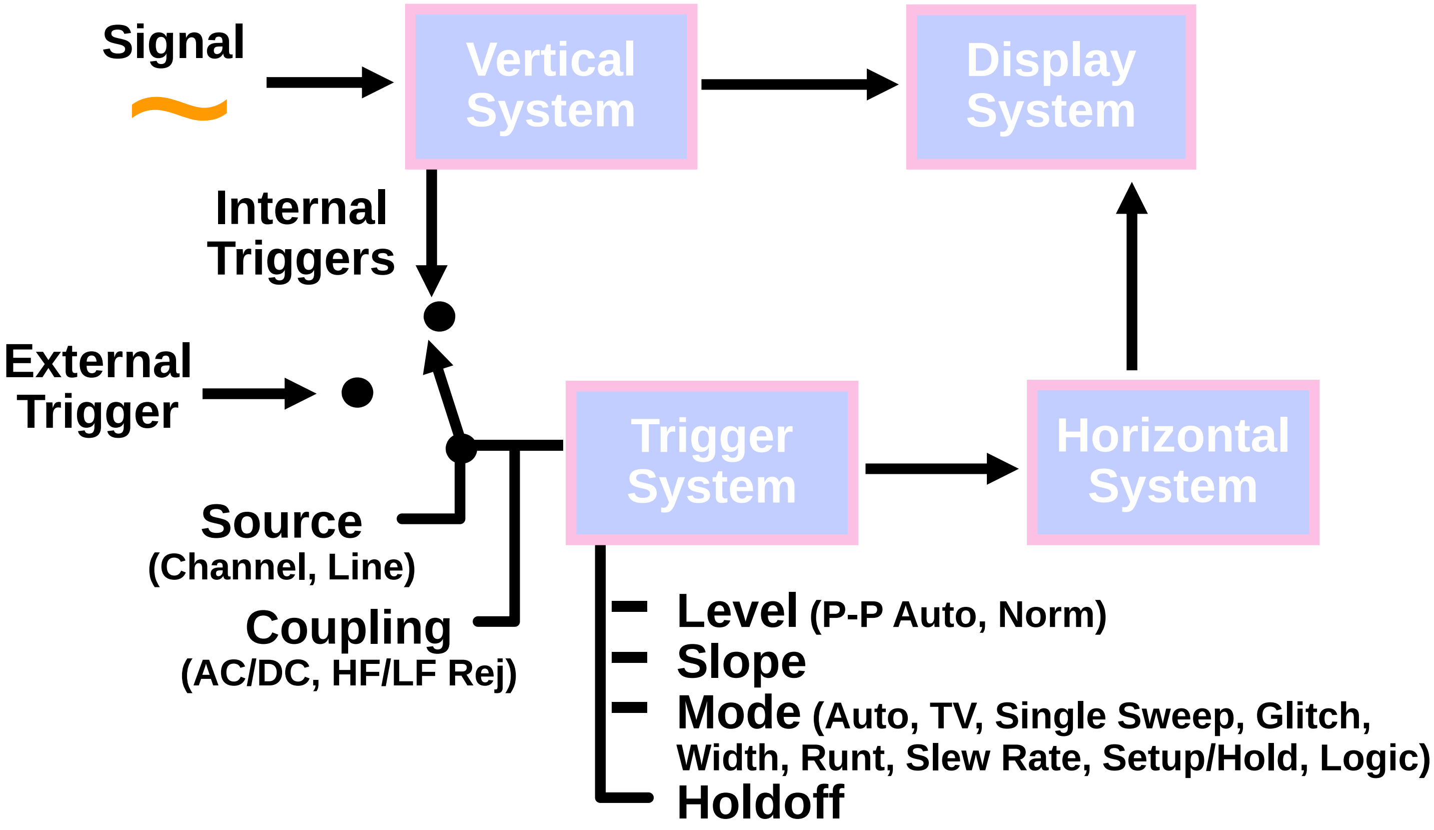
Oscilloscope Vertical System



Oscilloscope Horizontal System

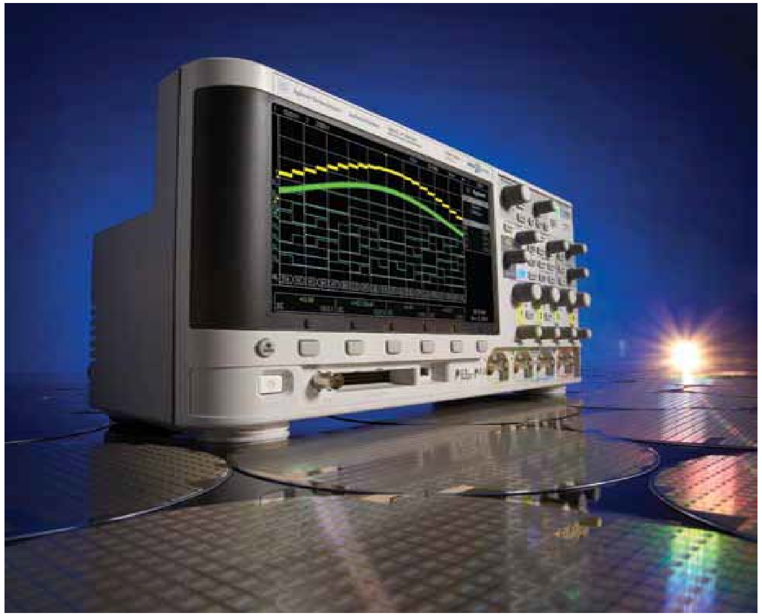


Triggering System Controls

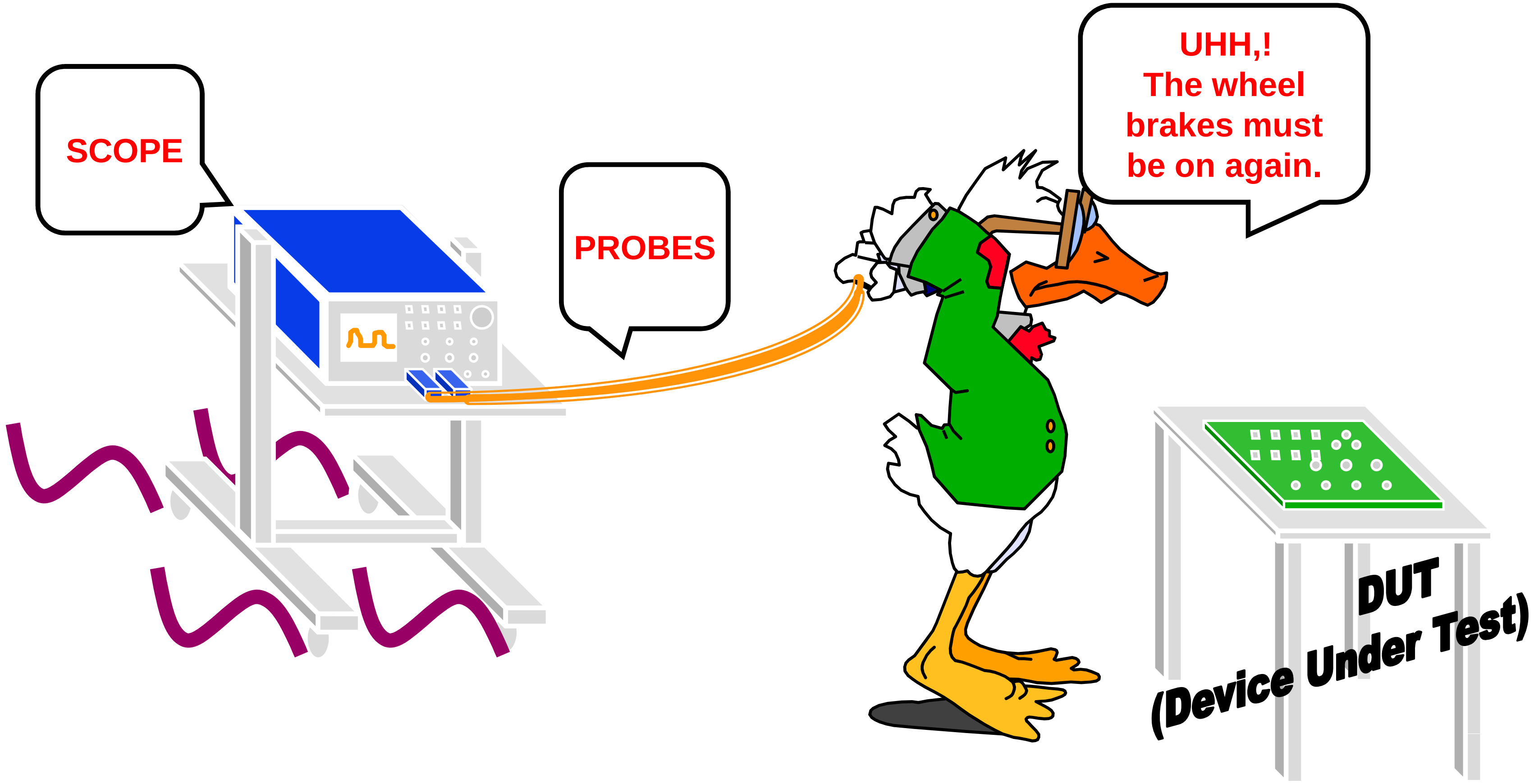


System Bandwidth

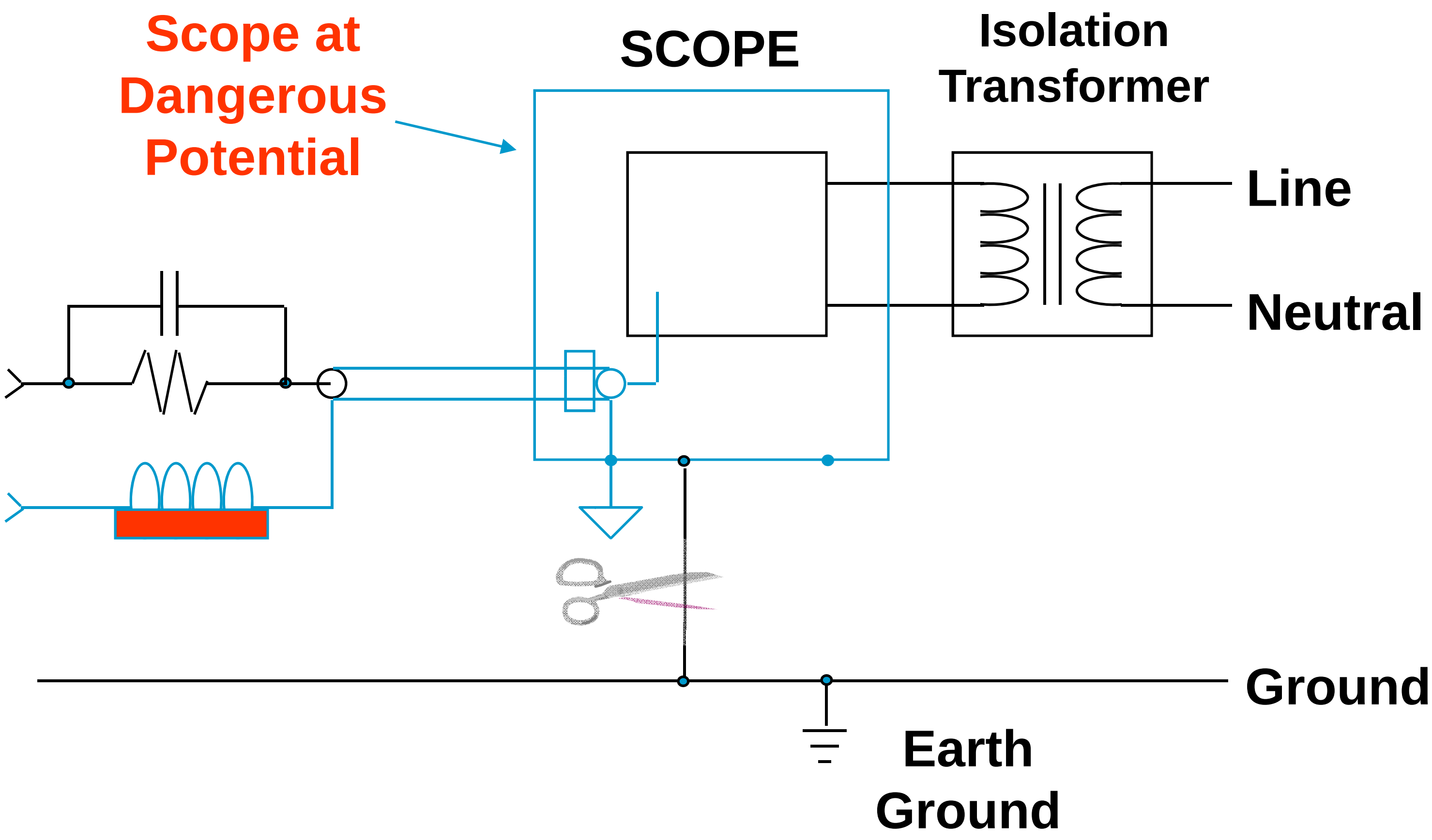
System Bandwidth = Bandwidth of the Probes + Oscilloscope !



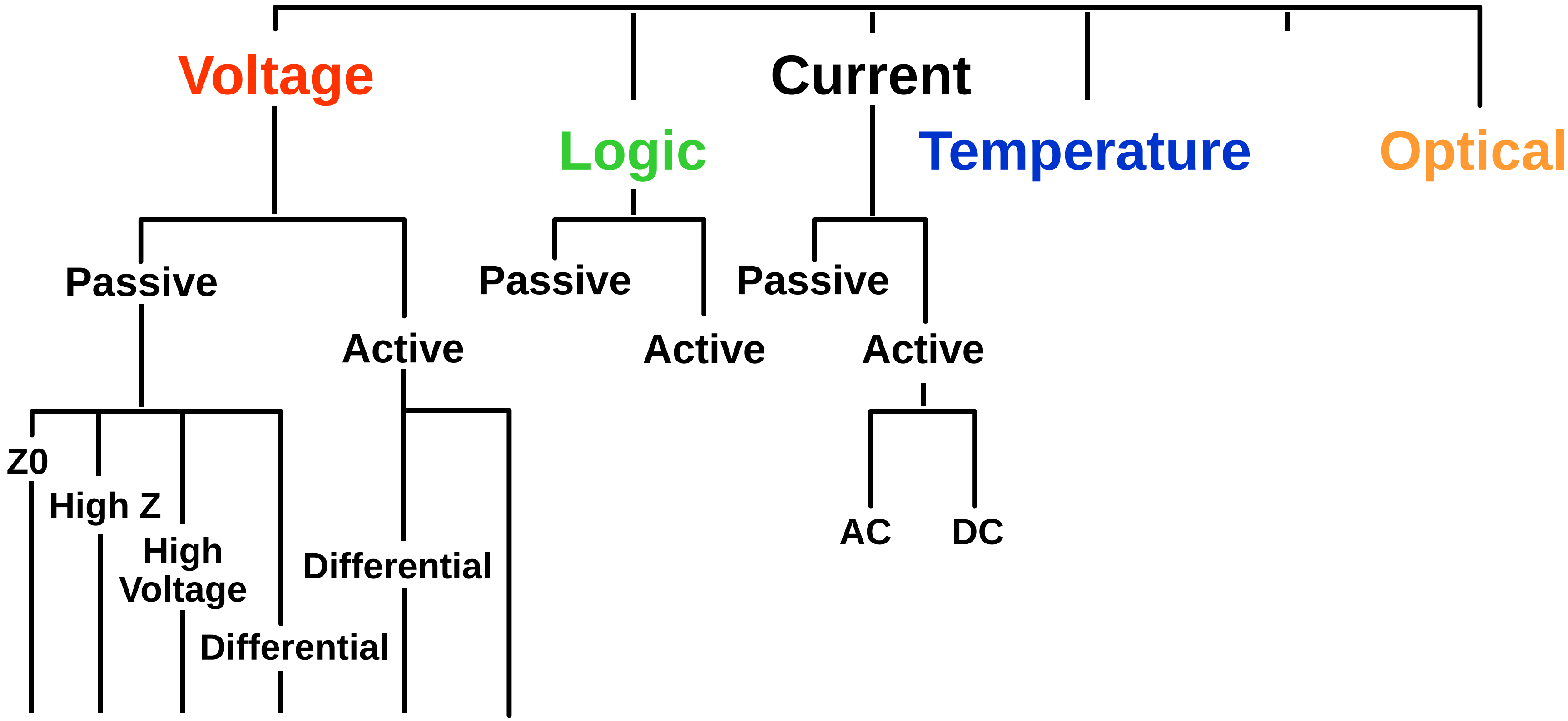
Measurements with Oscilloscopes



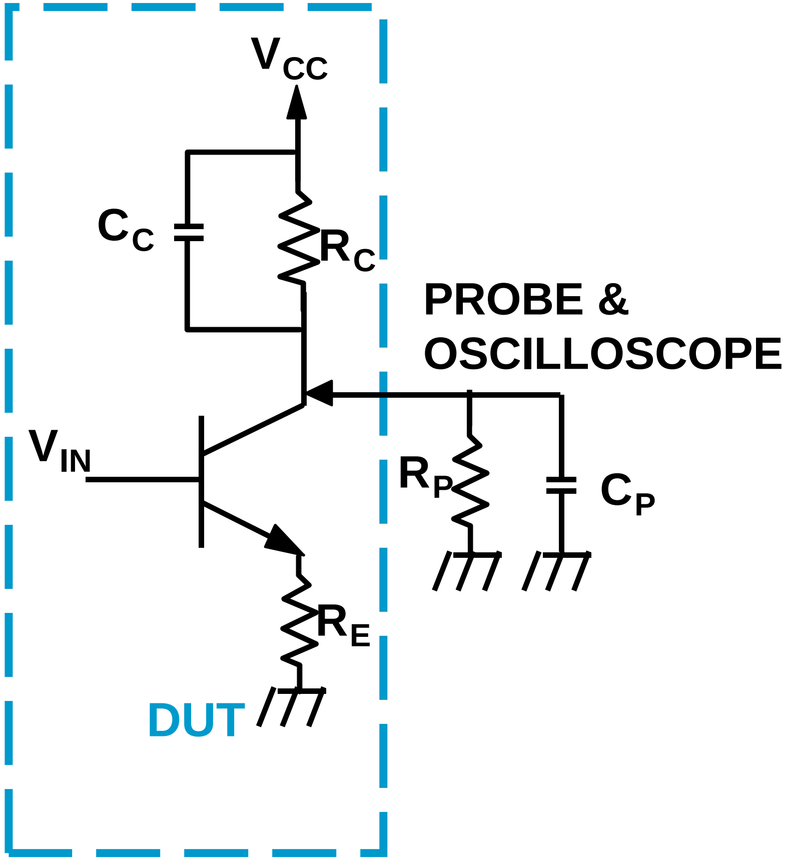
Scope Disconnected from Ground - 'Floating'



Basic Probe Types



Probes Affect the Measurement System As Well As the DUT



NOTE: V_{CC} is an AC Ground

Without probe & Oscilloscope

$$\text{Gain} = \frac{-R_C}{R_E}$$

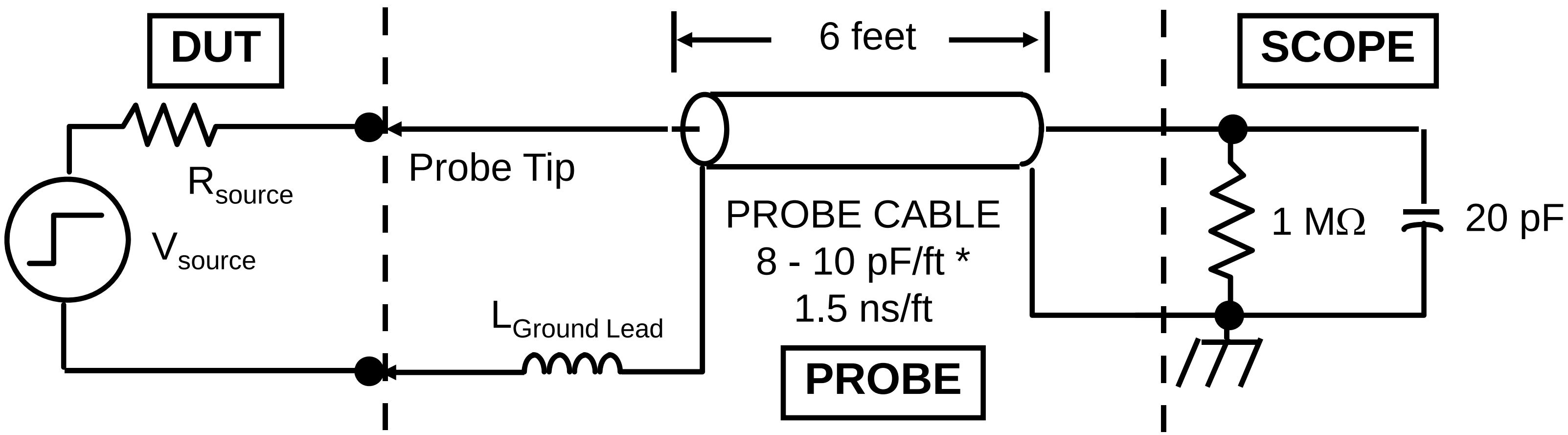
$$f_0 = \frac{1}{2\pi R_C C_C}$$

With probe & Oscilloscope

$$\text{Gain} = \frac{-(R_C \| R_P)}{R_E}$$

$$f_0 = \frac{1}{2\pi (R_C \| R_P)(C_C + C_P)}$$

1X Probe Model (Length of Cable)



Advantages:

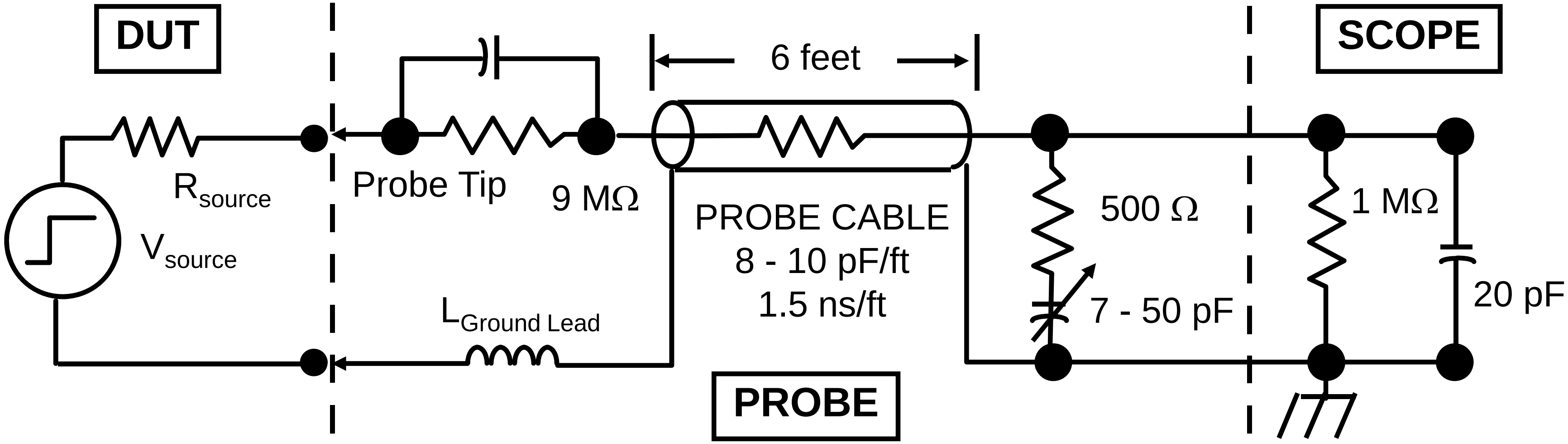
- **1X (No Attenuation)**
- **Inexpensive**

Disadvantages:

- **Very High Reflections**
- **Very High Input C**
- **Very Low Bandwidth**

*** Typical 50 Ω cable has about 30 pF/ft of capacitance**

Typical High Z 10X Passive Probe Model



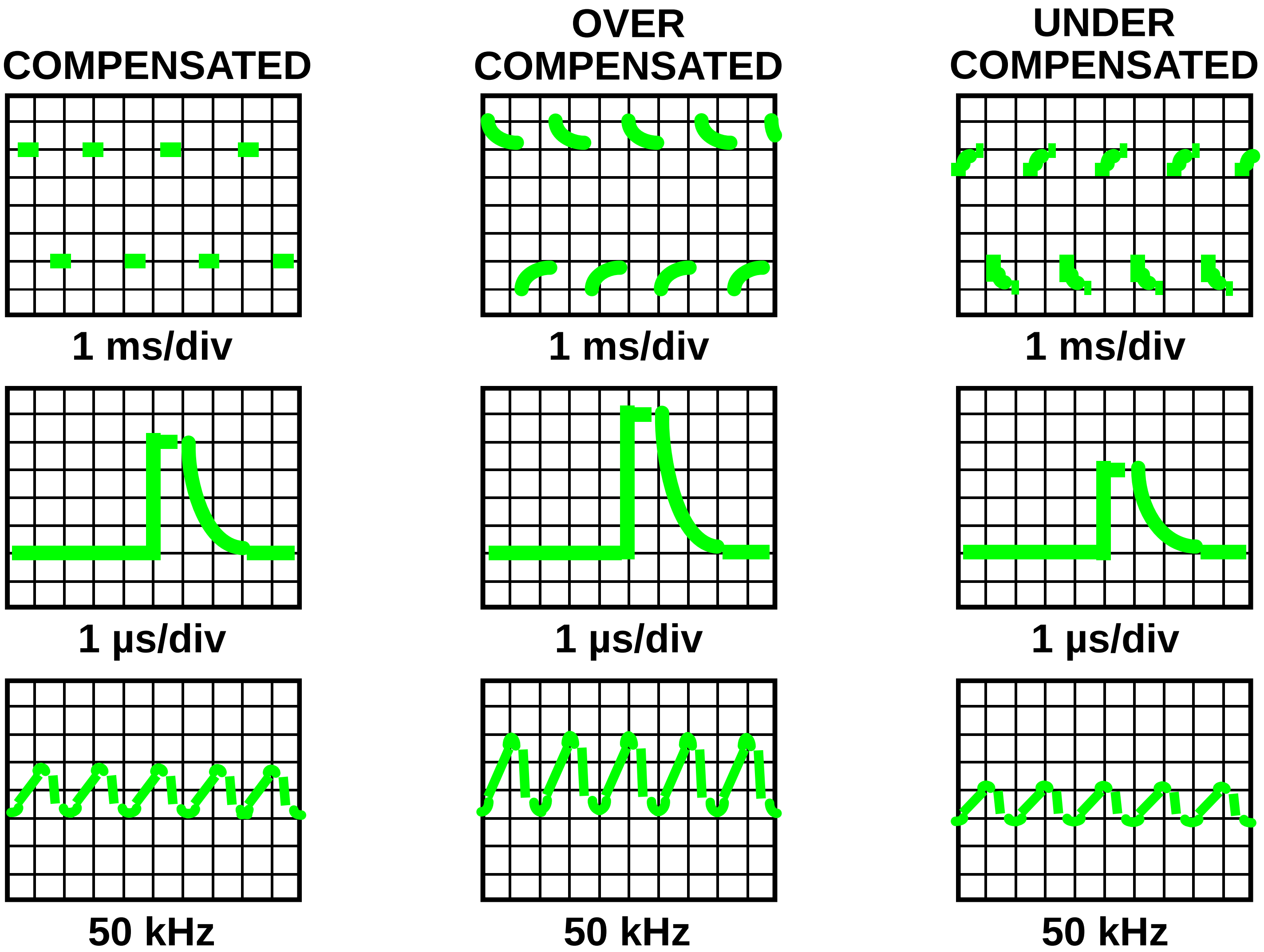
Advantages:

- **High Input R**
- **Wide Dynamic Range**
- **Inexpensive**
- **Mechanically Rugged**
- **Low Input C vs 1X Probe**

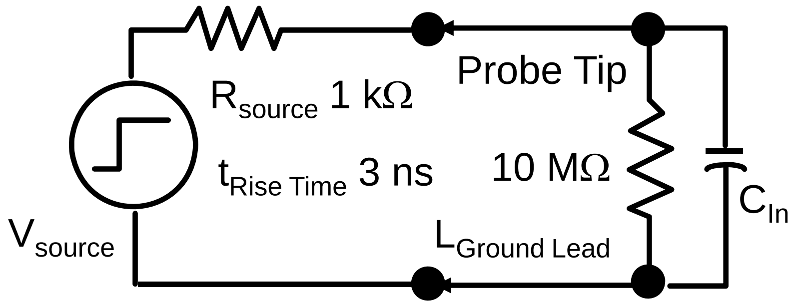
Disadvantages:

- **Input C Too High**
- **Not Compatible with 50 Ω Systems**
- **Must be Compensated**

Compensation Effects



Probe Tip Capacitance and Source Impedance Effects

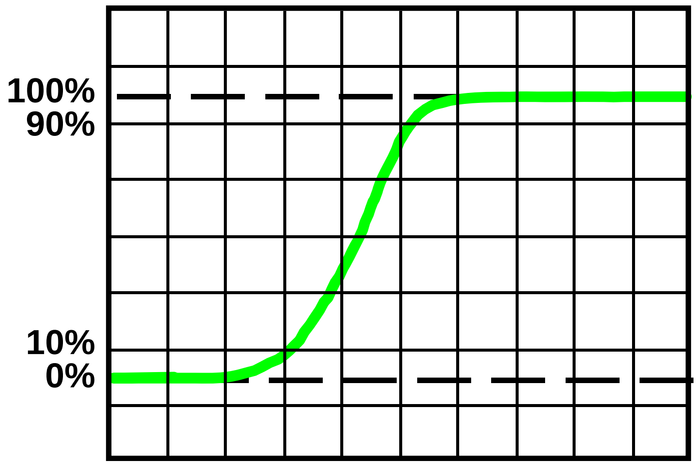


Rise Time Increase Due To Capacitance Loading

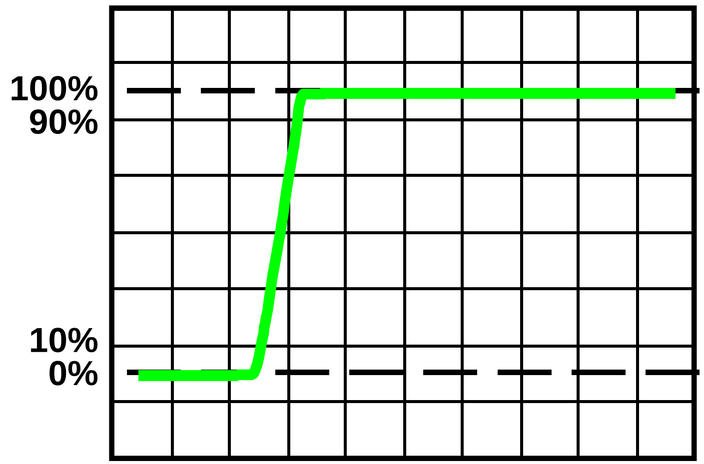
$t_r \approx 2.2 (R_{source} * C_{in})$

C_{in}= 100pF ≈ 220 nsec For 1X Probe

C_{in}= 10pF ≈ 22 nsec For 10X Probe

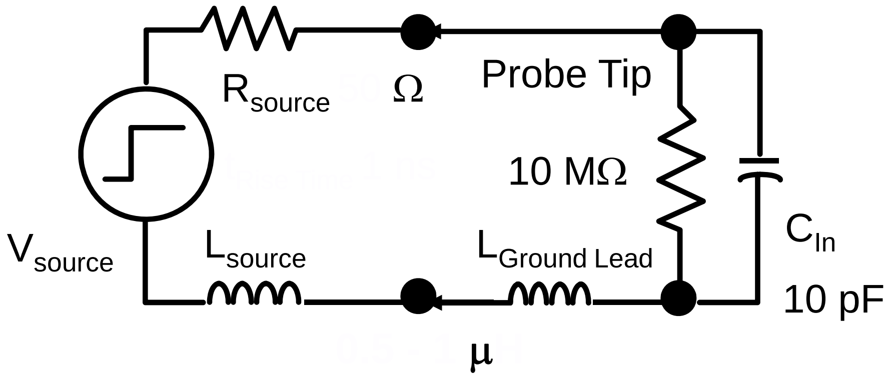


- Rise Time Waveform for the 1X Passive Probe

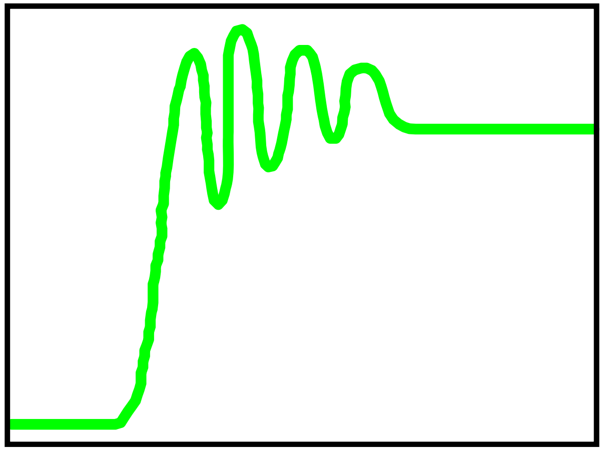


- Rise Time Waveform for the 10X Passive Probe

Circuit Under Test Inductance Effects



For a 10X Passive Probe with C_{in} = 10 pF and a 6” Diameter Ground Cable Loop



- **Ring Frequency Using a 10 pF Input Capacitance 10X High Z Passive Probe and 6” Ground Lead.**

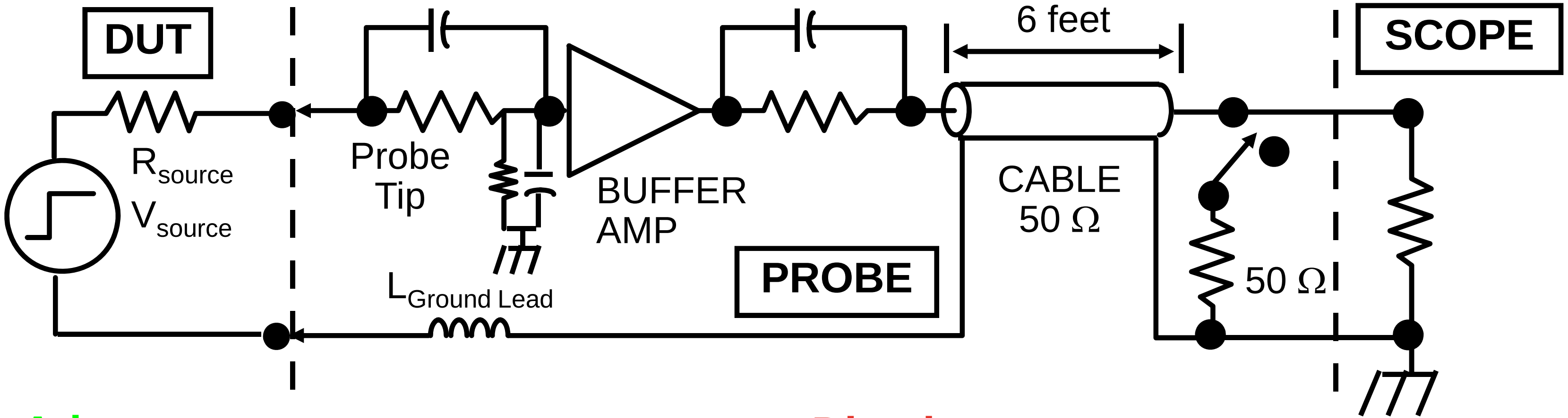
≈ **50% Error**

Typical Ring Frequency From 6” Diameter Ground Loop

$$= \frac{1}{2\pi\sqrt{LC}} =$$

50 - 70 MHz **OR** **t_r = 7 - 5 ns**

Active Probe Model



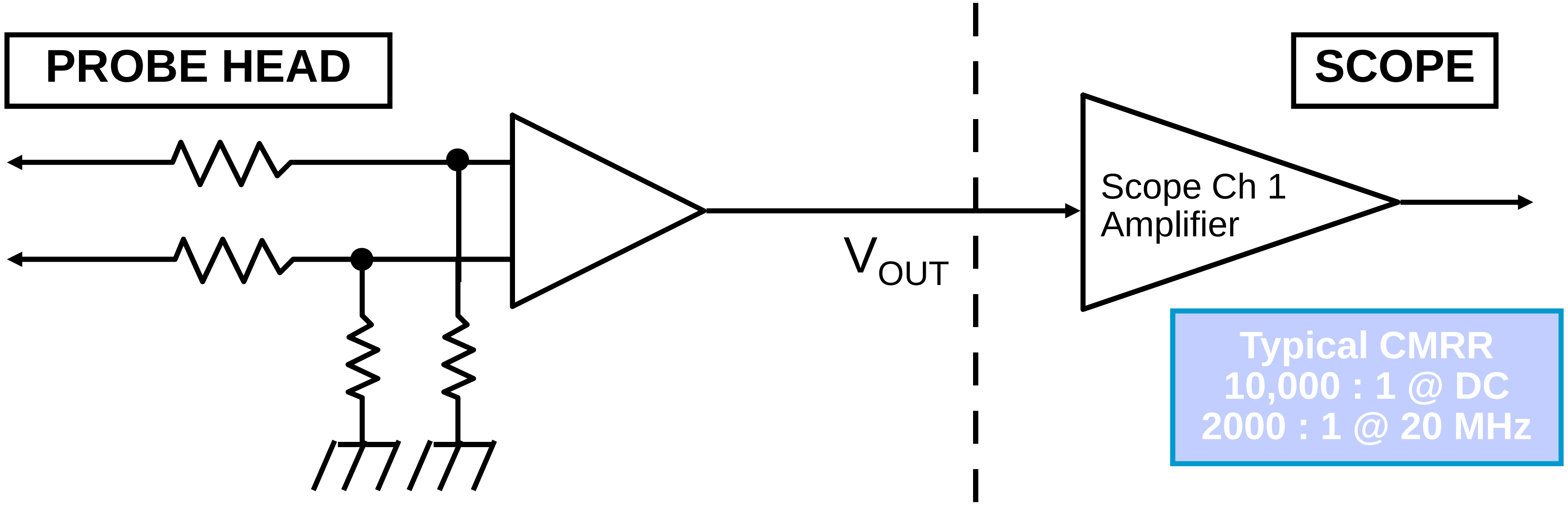
Advantages:

- **Low Input Capacitance**
- **Wide Bandwidth**
- **High Input R**
- **Compatible with 50 Ω Systems and 1 MΩ with Termination Resistor**
- **No Compensation Necessary**

Disadvantages:

- **Higher Cost**
- **Limited Dynamic Range**
- **Mechanically Less Rugged**
- **Requires Power**

Active Differential Probes



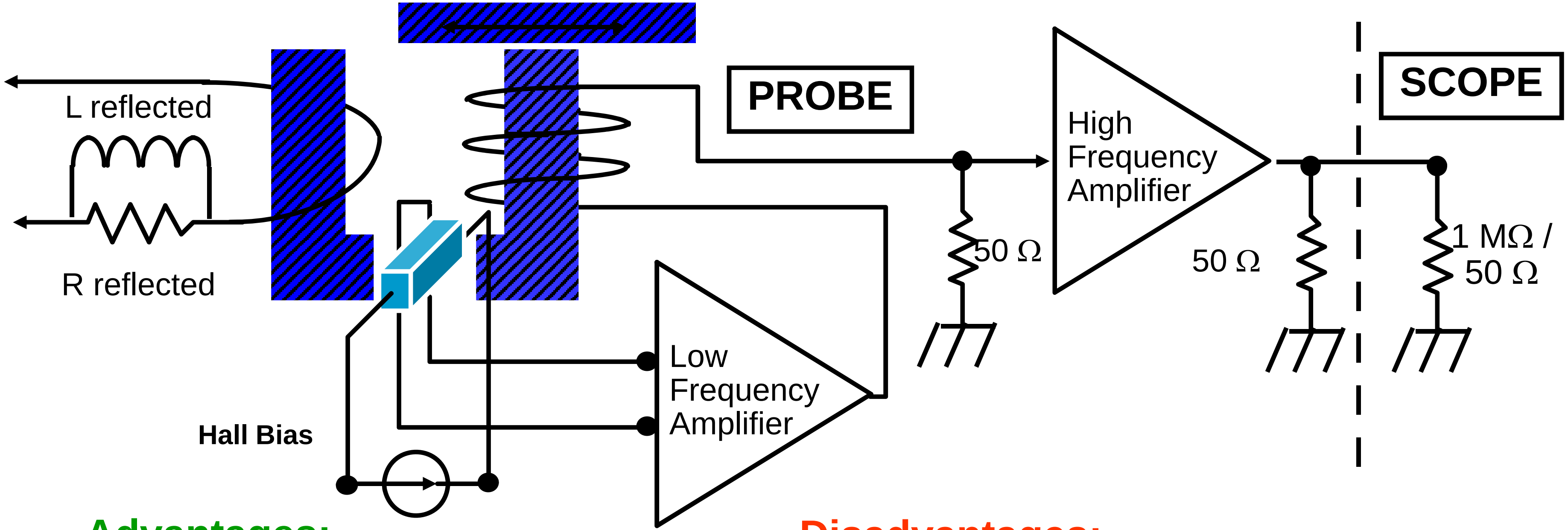
Advantages:

- Lower Input Capacitance
- Higher CMRR vs Frequency Than Passive Differential Pair
- Uses One Scope Channel

Disadvantages:

- Higher Cost
- Limited Dynamic Range
- Requires Power

Active Current Probe Model



Advantages:

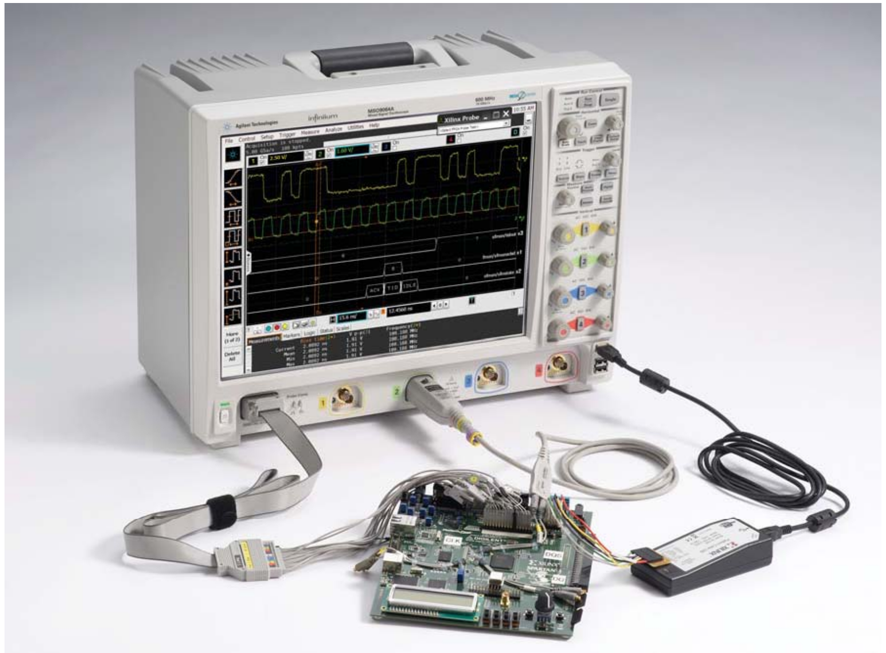
- DC & AC Current Measurements
- Compatible With 50 Ω and 1 MΩ Single-ended Systems
- Lower DUT Loading ($R_{reflected}$ typically <<1 Ω $L_{reflected}$ typically <5 μH)
- Direct Connection Types

Disadvantages:

- Higher Cost
- Mechanically Less Rugged and Larger Size
- Requires Power
- Non Direct Connection Require Additional Amplifier

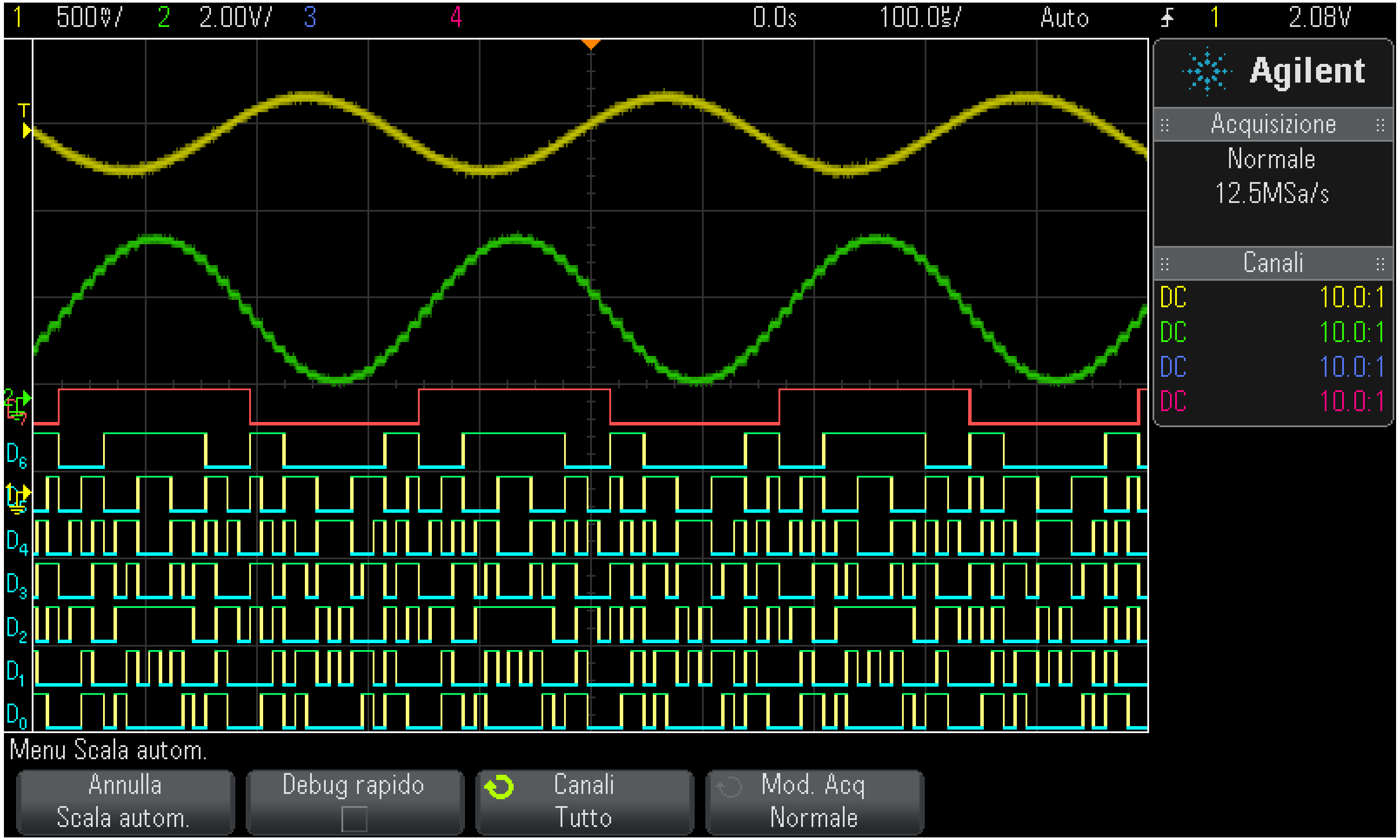
Digital Probe for Oscilloscope

- 18 or 36 Digital Channels
- 1.25 GS/s Sample Rate
  per Digital Channel
- 2 Mpts Memory per Digital
  Channel
- 12 Serial Decoder
  & Trigger Options



Digital Probe for Oscilloscope

Simoultaneous analog and digital channels

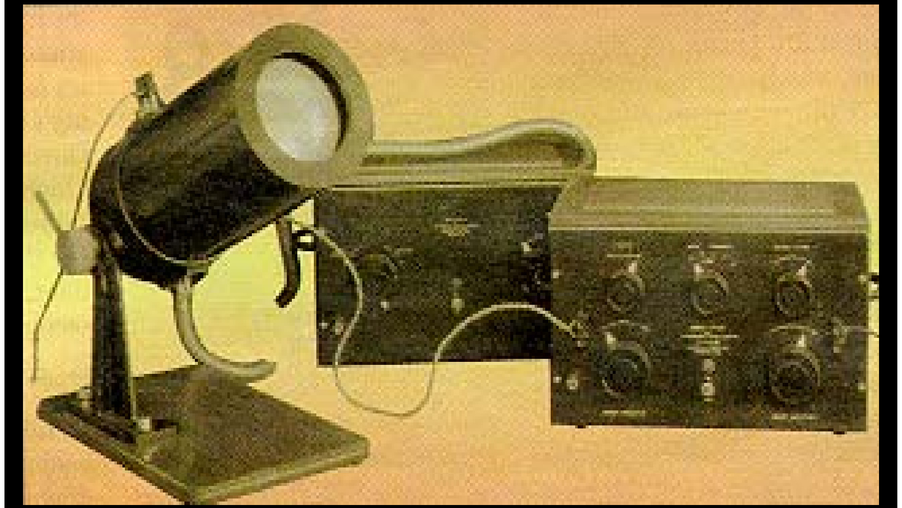


Oscilloscope Technology Overview

Evolution of Oscilloscopes

Scope Technology	ART
	1950
Market Drivers	• Military • Vacuum tube technology • Emerging solid state technology • Broadcast video
Customer Challenges	• Device characterization • Signal edges and waveshapes

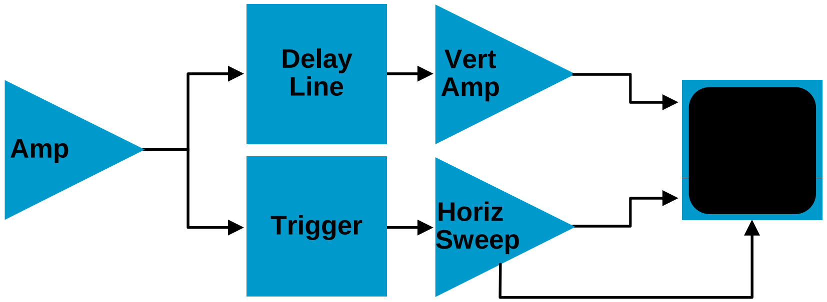
Analog Oscilloscope Definition



The General Radio Oscilloscope (1931), with sweep circuit (right).

Webster, 1906:
"An instrument in which variations in a fluctuating electrical quantity appears temporarily as a visible waveform on the fluorescent screen of a cathode-ray tube."

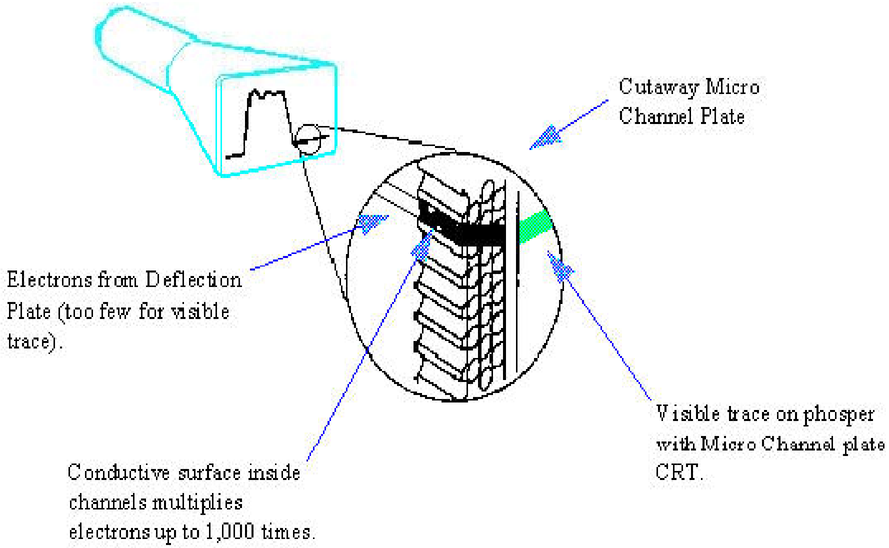
1998:
An instrument used for visually observing and measuring electronic signals.



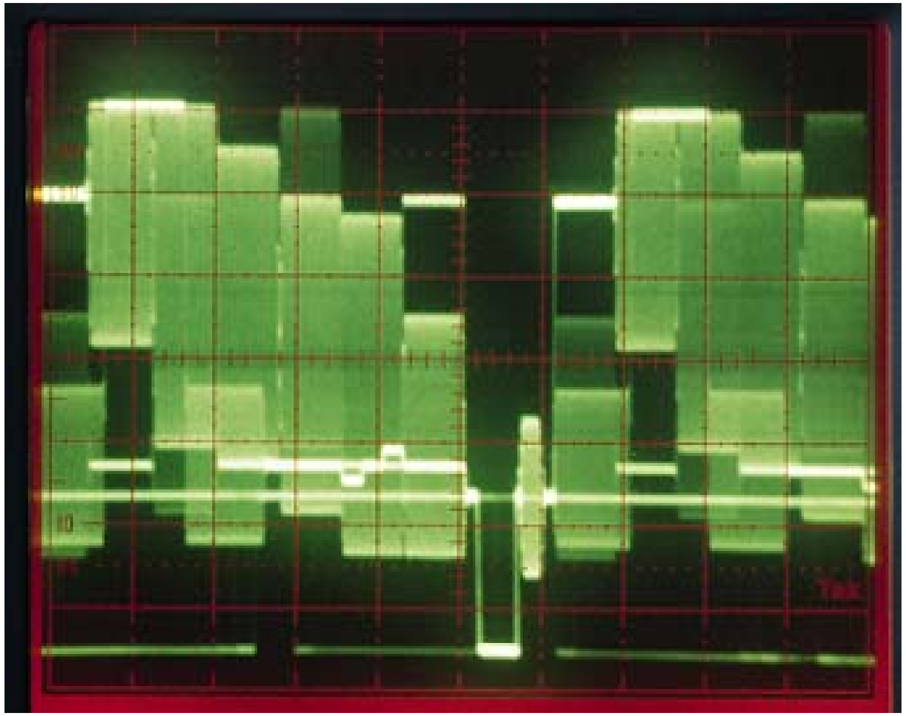
Micro Channel Plate (MCP)

Provides the Ability to See Single-Shot "Fast" Signals on an Analog Real Time Scope

The "Writing Speed" is 100 to 1000 Times Faster Than That of a Normal Analog Scope



Analog Oscilloscope Benefits



Direct visual impression of actual signal behavior

Intensity grading (frequency of occurrence information)

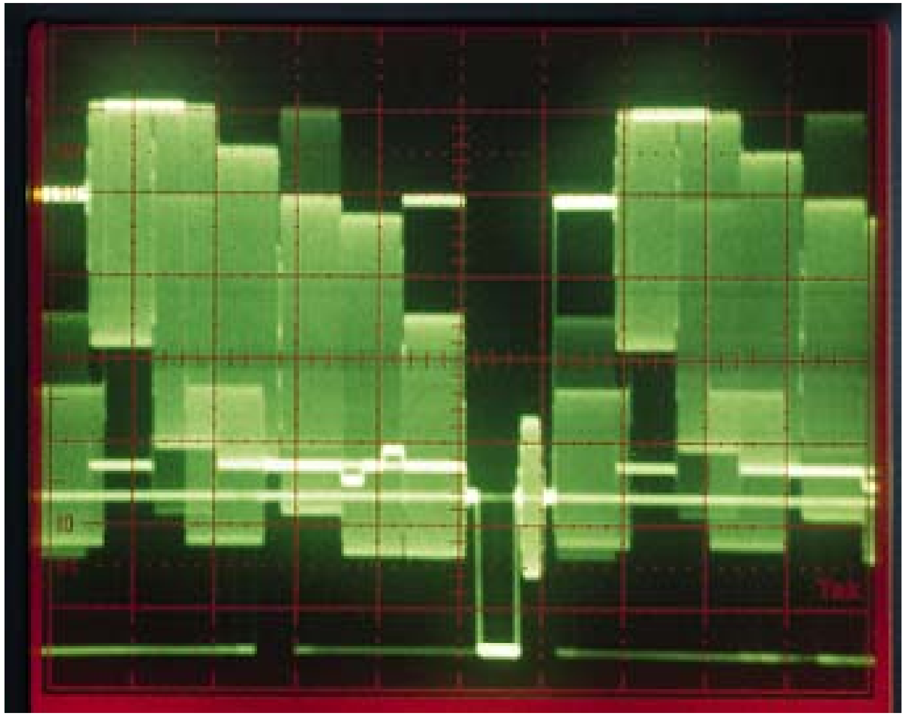
No quantizing error or aliasing

Very fast waveform capture rate

Single level user interface

Analog Oscilloscope Shortcomings

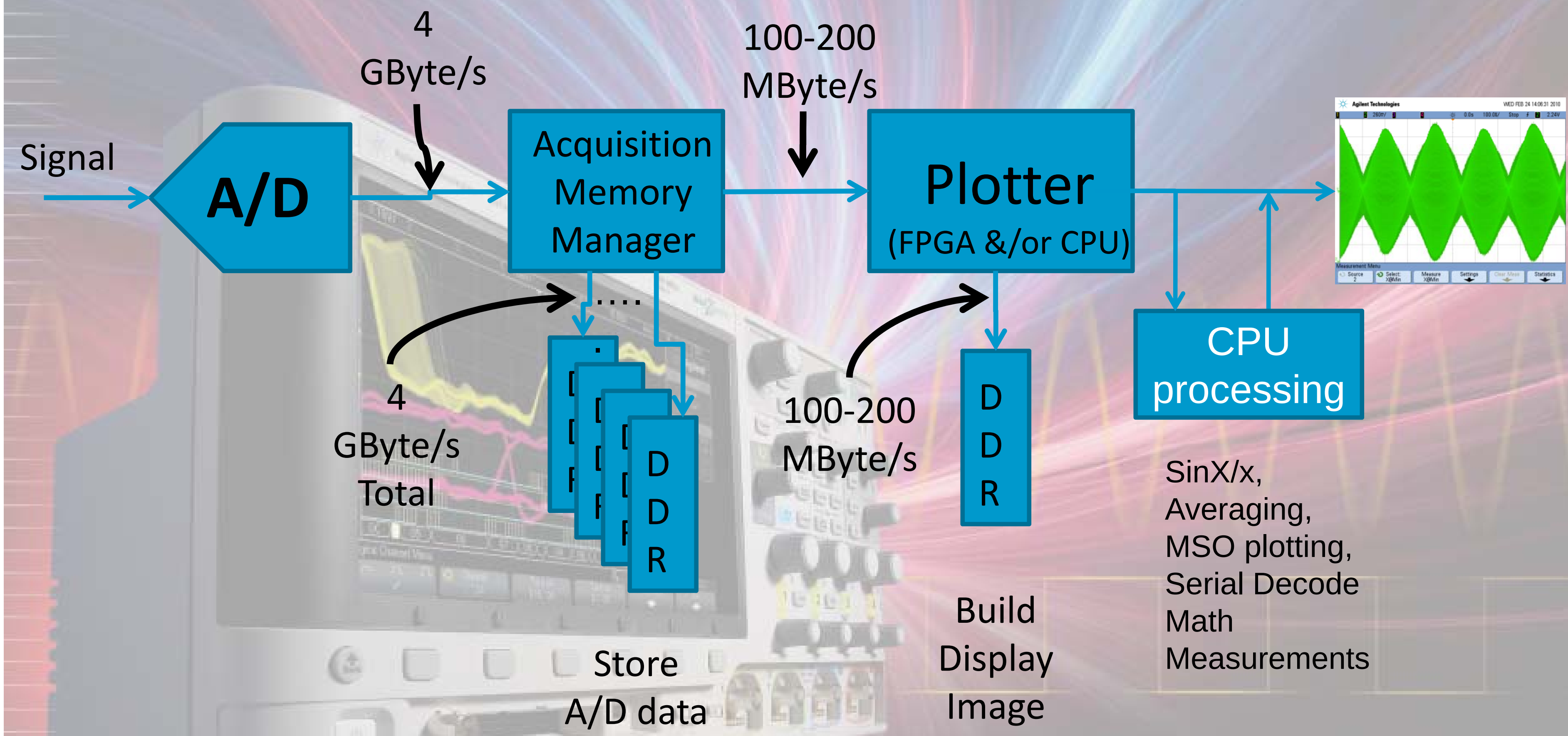
- Purely visual information
- Blink and miss
- Limited bandwidth performance
- Edge triggering
- No pre-trigger information
- Optimized for single channel operation
- Limited writing speed for low repetition rate signals



Evolution of Oscilloscopes

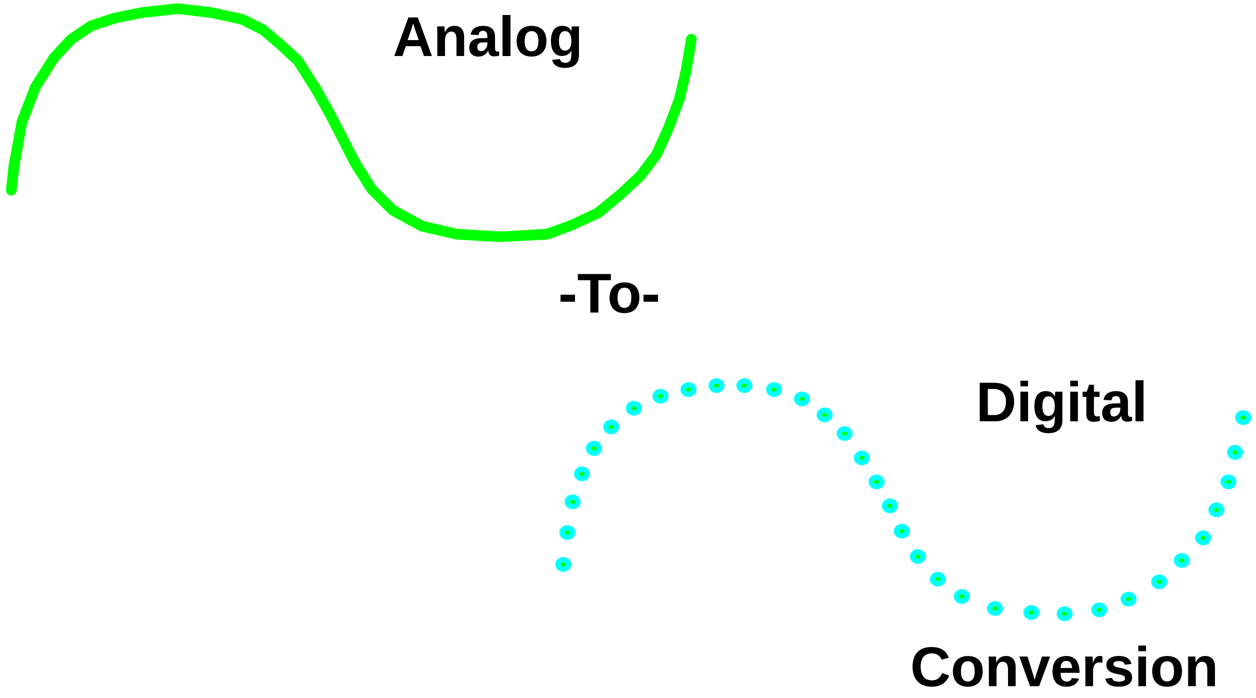
Scope Technology	ART	DSO
	1950	1980
Market Drivers	• Military • Vacuum tube technology • Emerging solid state technology • Broadcast video	• Computers • LSI • Digital data • Mixed signal environments • Faster microprocessor clock rates • System integration • Quality assurance
Customer Challenges	• Device characterization • Signal edges and waveshapes	• Signal data • High-frequency effects • Documentation

Discrete Scope Block Diagram



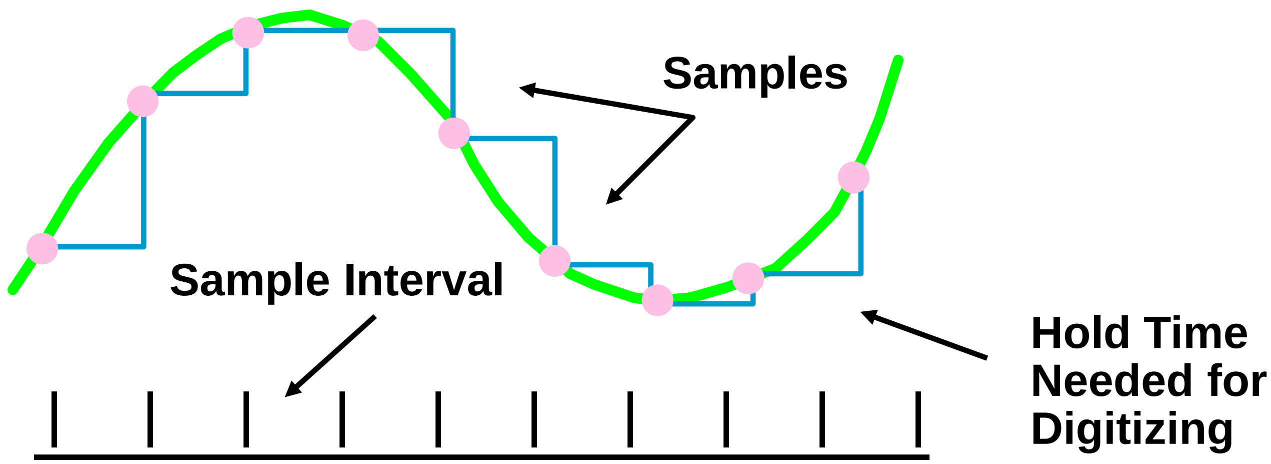
Update rate = 100/s to 1000/s, some up to a few 10,000/s

A-D-C



Sampling

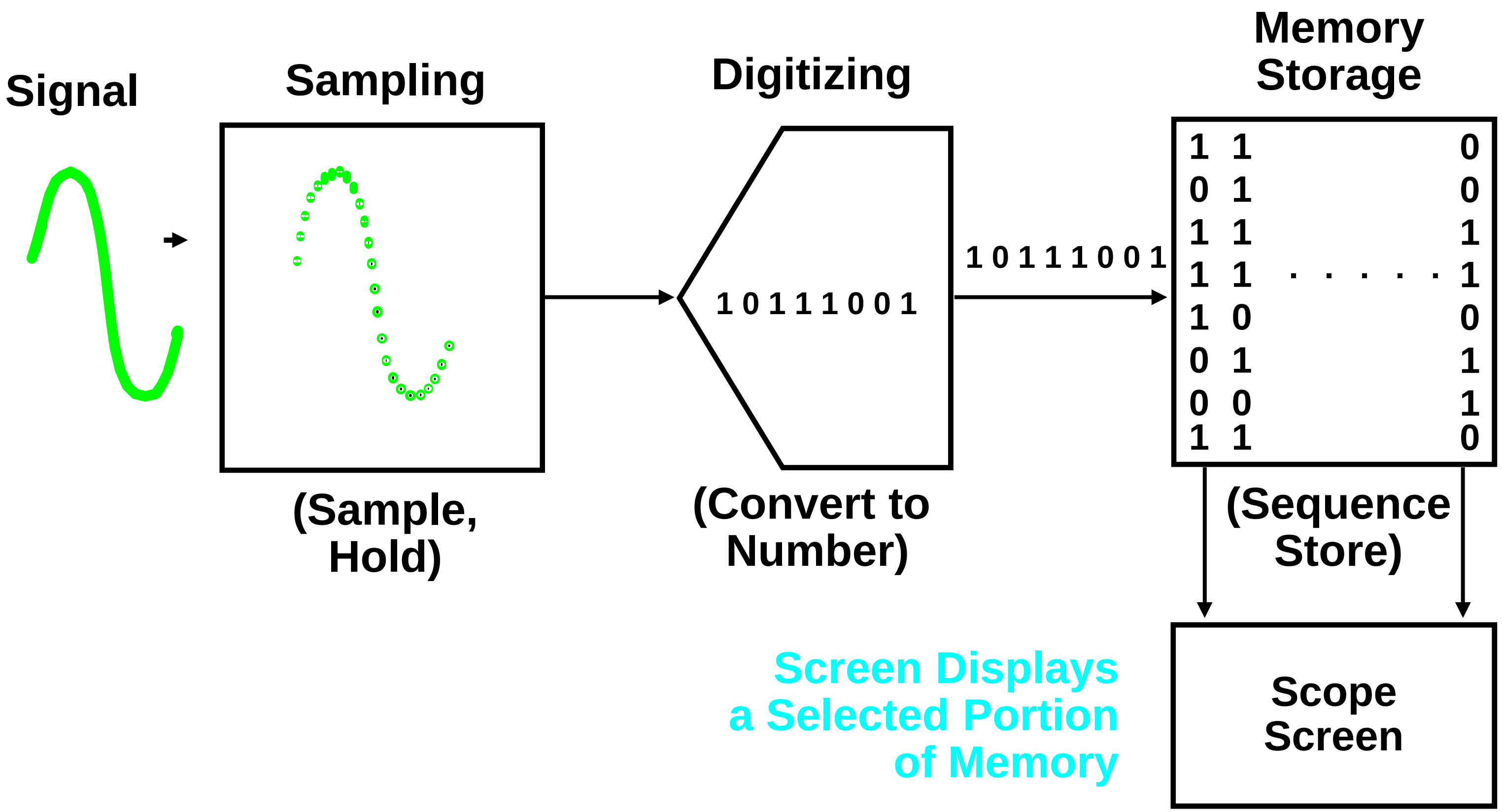
TAKING SAMPLES OF AN INPUT SIGNAL
AT SPECIFIC POINTS IN TIME



Samples Equally Spaced in Time

Sample Rate Measured in Sample/Second
(S/s, kS/s, MS/s, GS/s)

What Happens To The Samples?



Types of Digital Resolution

Vertical	→	1/# Levels	→	% of Full Scale
6-Bits	→	1/64	→	1.56%
8-Bits	→	1/256	→	0.39%
10-Bits	→	1/1024	→	0.097%
12-Bits	→	1/4096	→	0.024%

Horizontal = Time/Sample

= 1/Sample Rate

What About Horizontal Resolution?

Two criteria are affected when improving resolution (decreasing time) between samples for a given time window.

You need ...

More Sample Rate (or Speed)

More Record Length (or Memory)

Basic Types of Digital Storage Oscilloscope (DSO) Capabilities

Real Time Digitizing (RTD)

- samples single-shot events in real time.

Equivalent Time Digitizing (ETD)

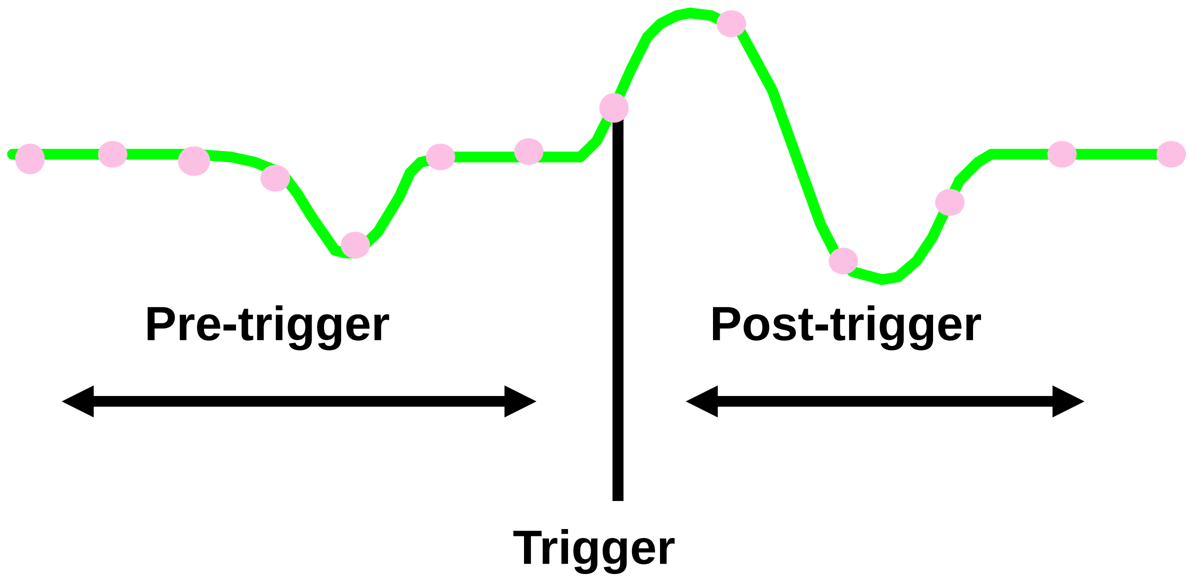
- uses repetitive sampling to reconstruct the shape of a high frequency repeating waveform over many triggered acquisition cycles.

Real Time Digitizing

Digitizes Samples:

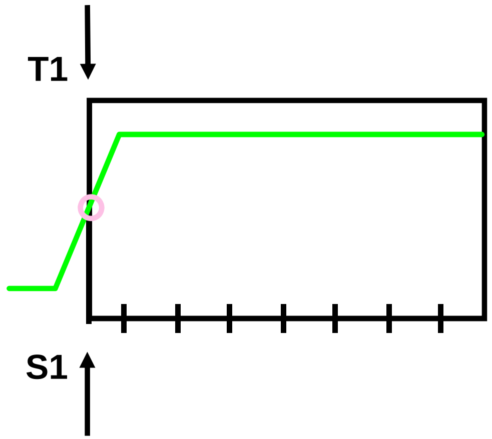
Equally Spaced in Time

With Selectable Pre/Post Trigger



Sequential Equivalent Time Digitizing

Digitized samples are accumulated in time sequence after each trigger point with one sample per trigger.



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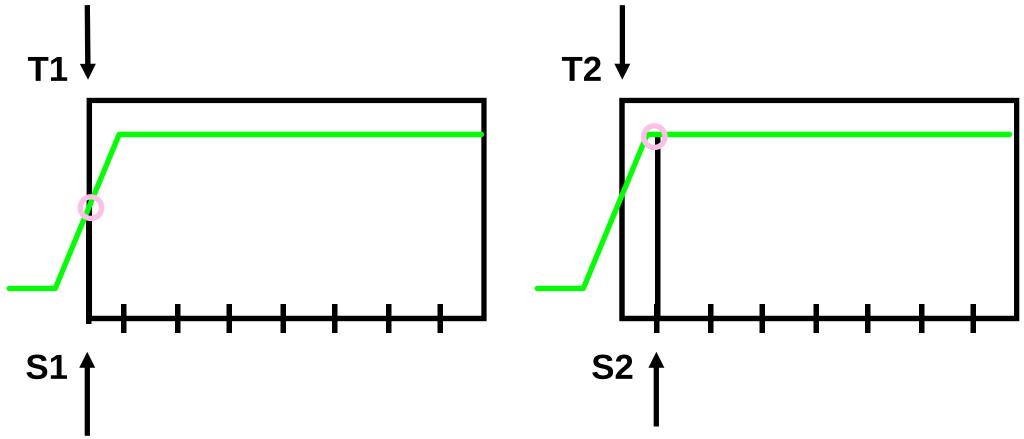

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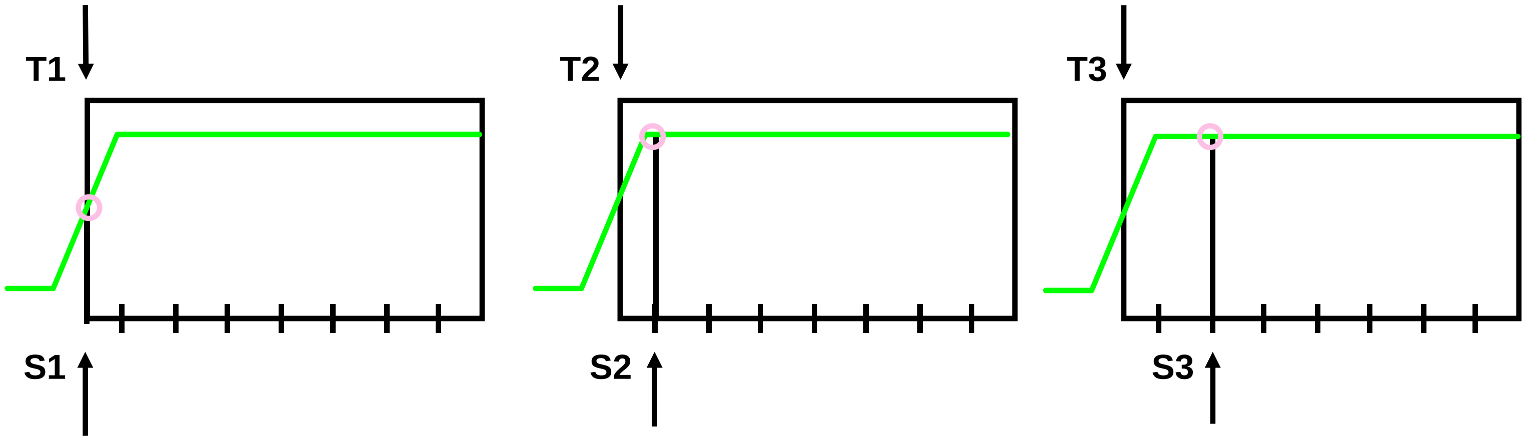

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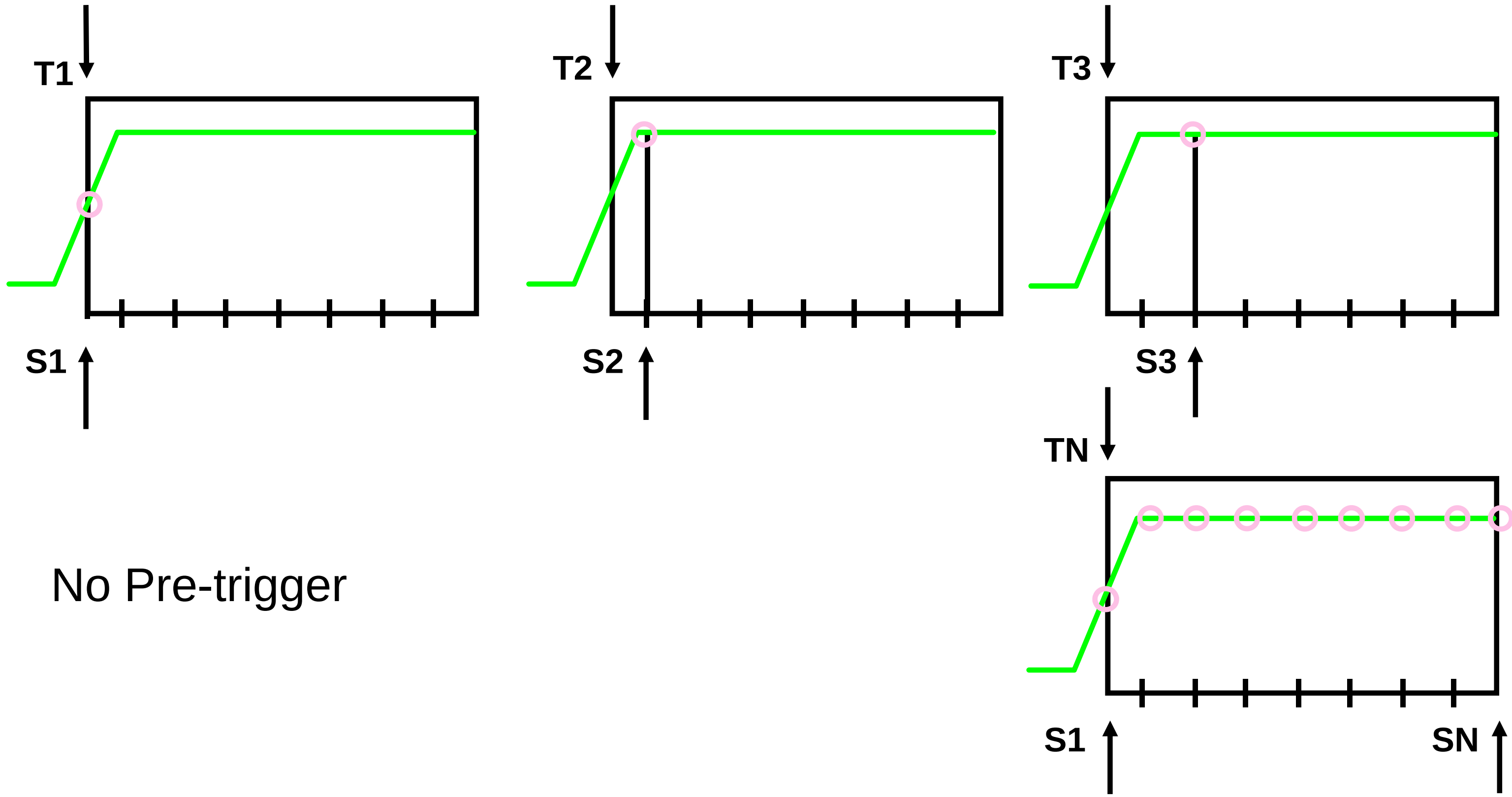
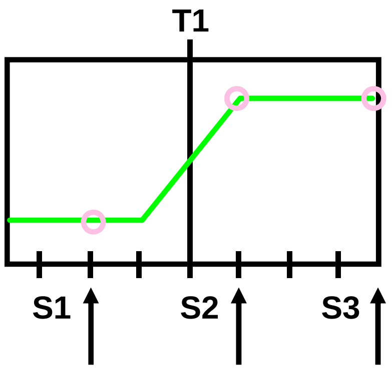


No Pre-trigger

Random Equivalent Time Digitizing

Digitized samples are accumulated randomly before and after each trigger point. Time must be measured from the trigger point to the next sample in order to correctly place the digitized samples in the display memory.



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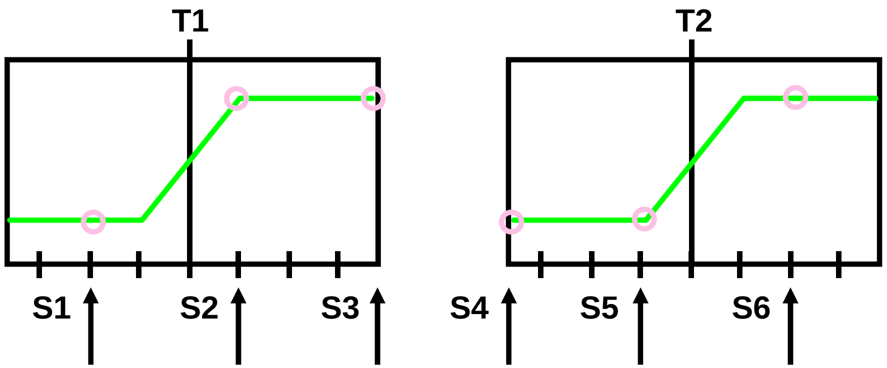

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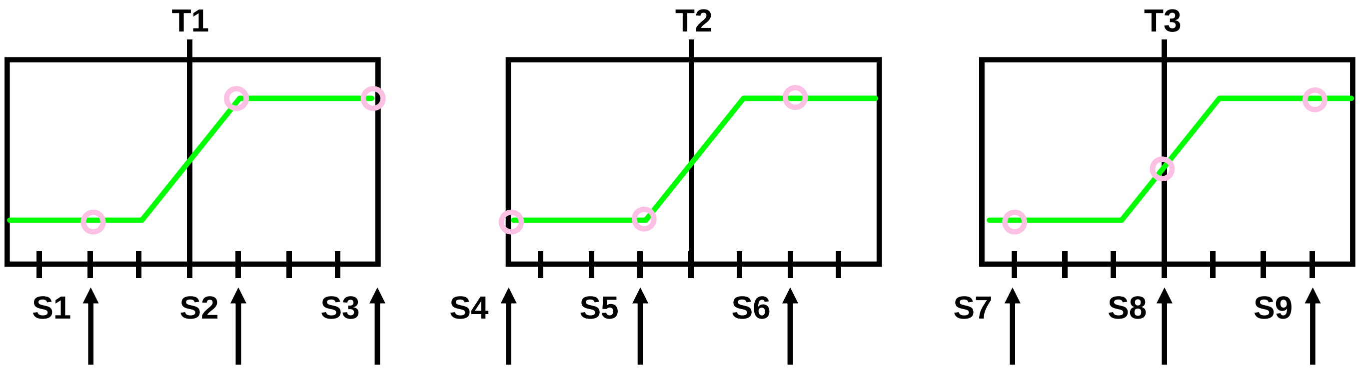

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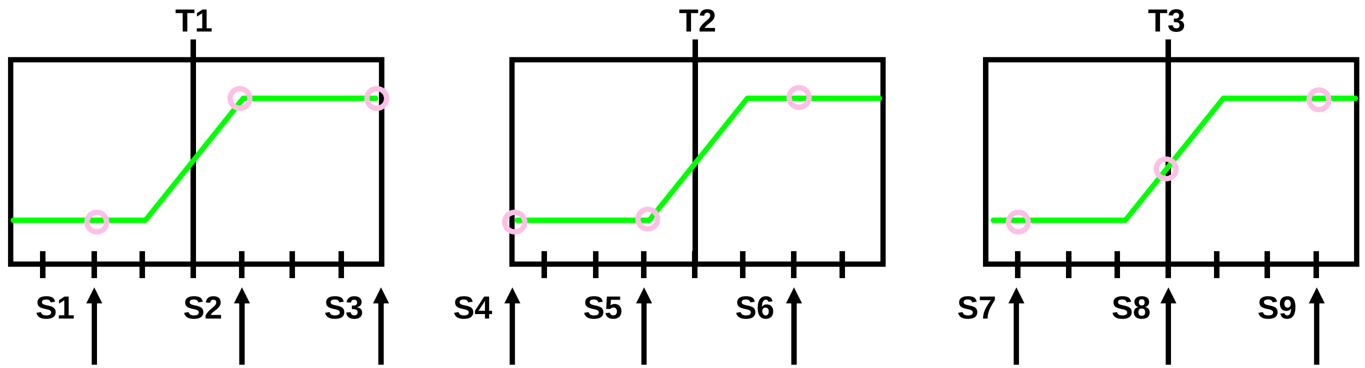
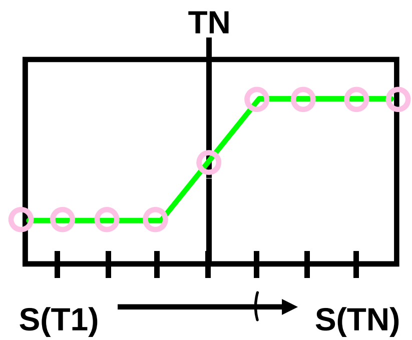


Multiple samples per trigger provide faster update rate.

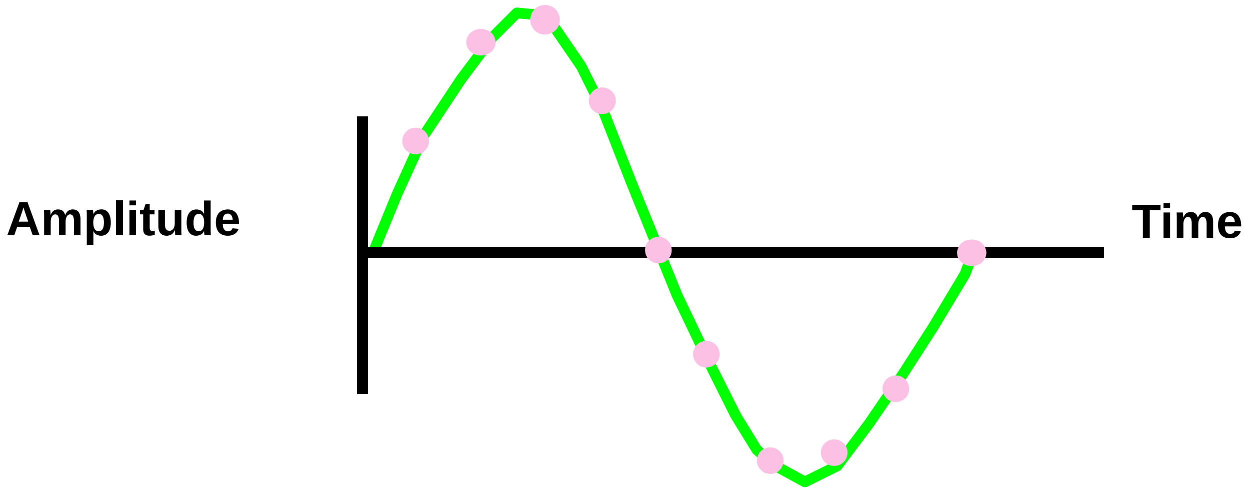
Pre/post trigger capability is preserved.



Single Event Bandwidth

Must Have Enough Sample Points to Reconstruct Waveform

Is Determined By the DSO's Analog Bandwidth, Maximum Sample Rate, and Method of Waveform Reconstruction



What Happens When Too Few Samples Are Acquired?

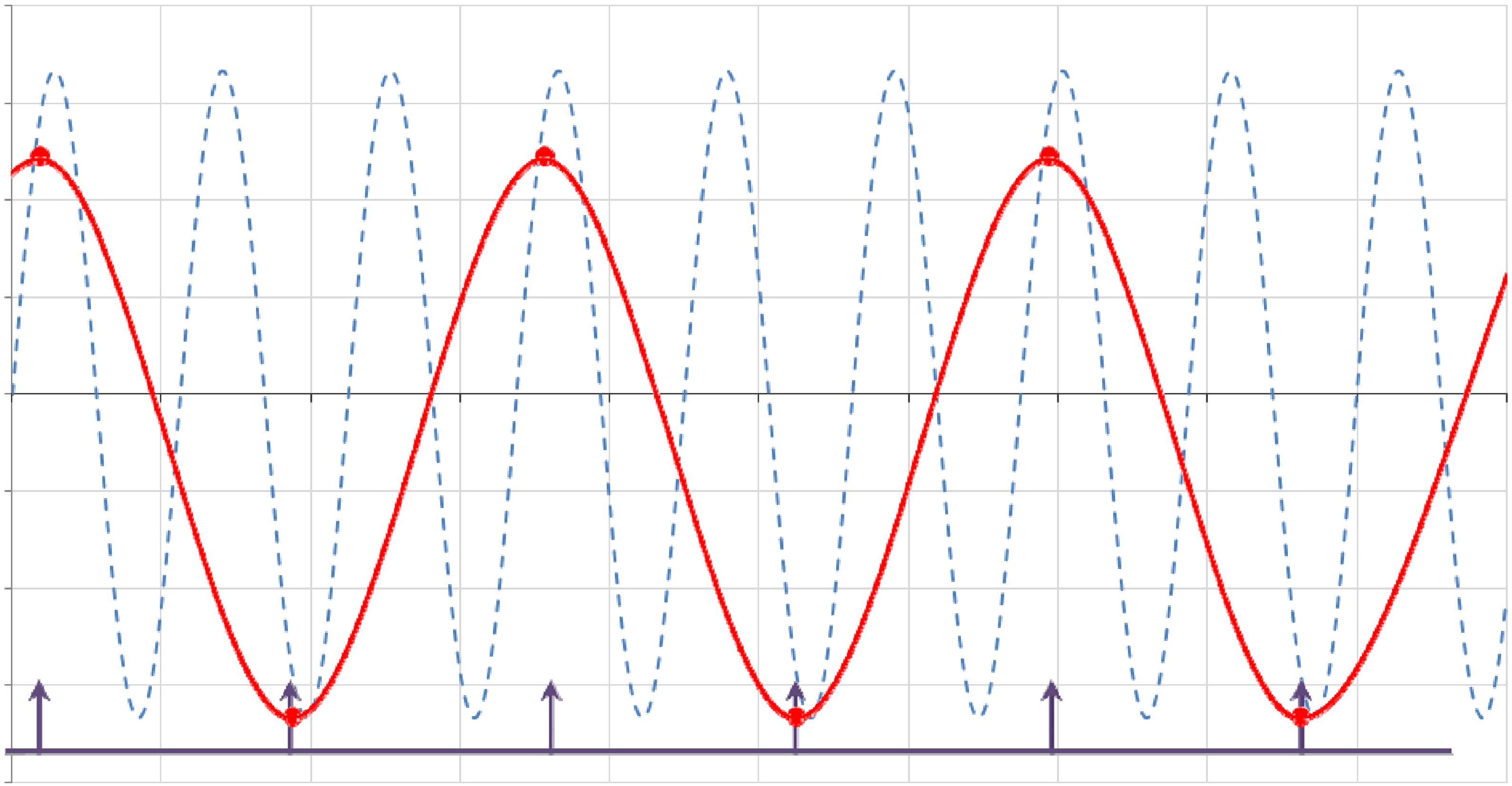
Aliasing
or
False Waveform
Reproduction

Real Time Sampling – Aliasing Example

Reason: Sample Rate to Slow

Result: too Low Frequency, Wrong Waveform, no Stable Trigger

Cause: Sample Rate to Slow or Insufficient Memory Selected



Perceptual Aliasing

Can Exist When Nyquist Theory is Satisfied

Cannot be Reliably Distinguished from Actual Aliasing Without

Interpolation

Linear Interpolation

Simply Means "Join the Acquired Samples" with Straight Lines

Can Reduce the Effects of Perceptual Aliasing

Sine (X)/X Interpolation (Based On Nyquist Theory)

Computes a Path Between the Acquired Samples Based on Digital Signal Processing Theory

Can Remove the Effects of Perceptual Aliasing Only When Nyquist Theory is Satisfied

DSO Acquisition Modes

Sample

- Takes samples at the displayed sample rate.

Peak Detect

- Detects peaks between displayed samples.

Envelope

- Accumulates peaks over multiple acquisitions.

ERES or High Resolution

- Box car averages between displayed samples.

Average

- Averages (normal or weighted) over multiple acquisitions.

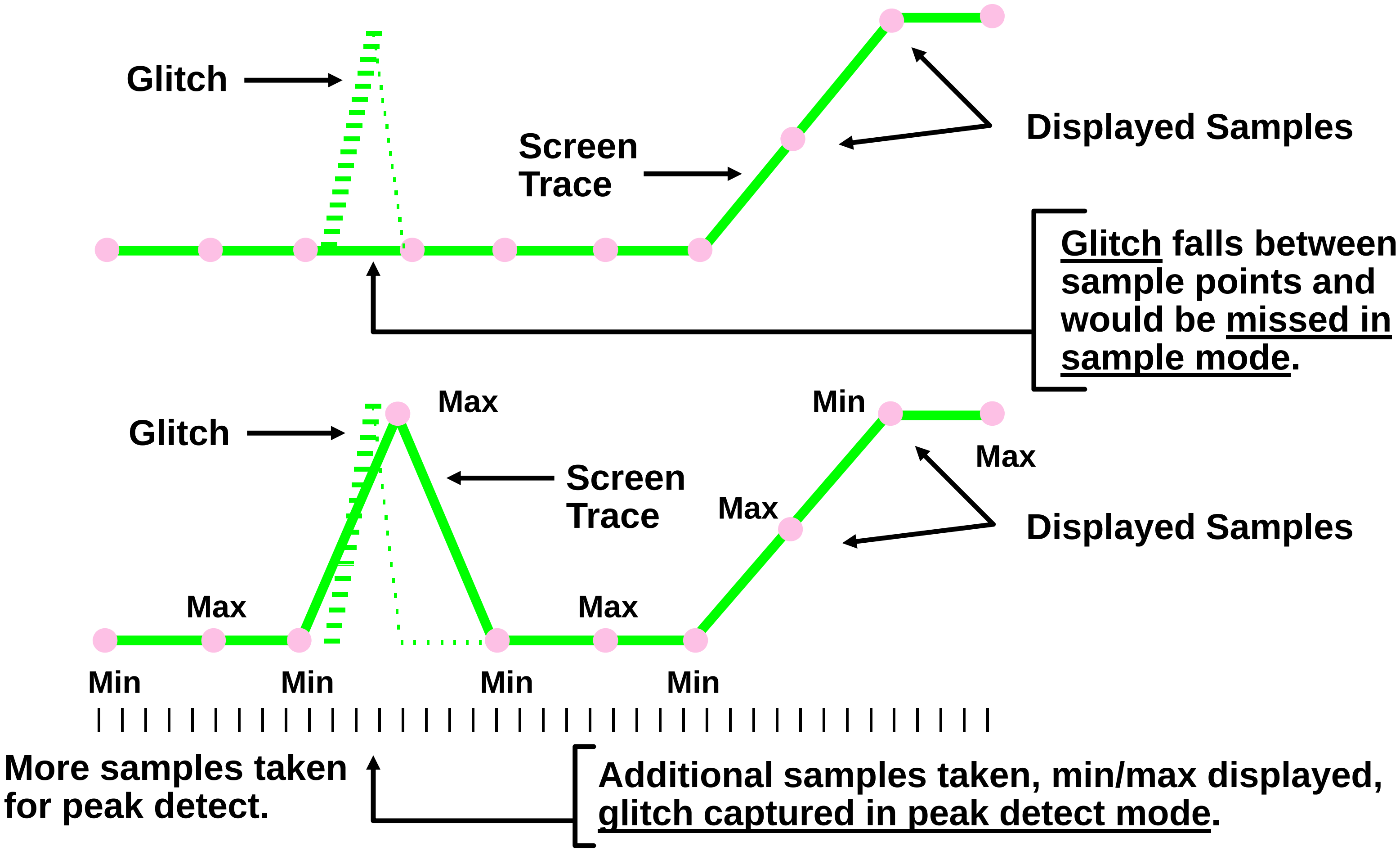
Digital Peak Detection Allows

Sampling at the Maximum Sample Rate At All Sweep Speeds

Retained Minimum and Maximum Values as Displayed Sample Pairs

Improved Writing Speed to Capture Glitches

Example of Digital Peak Detect



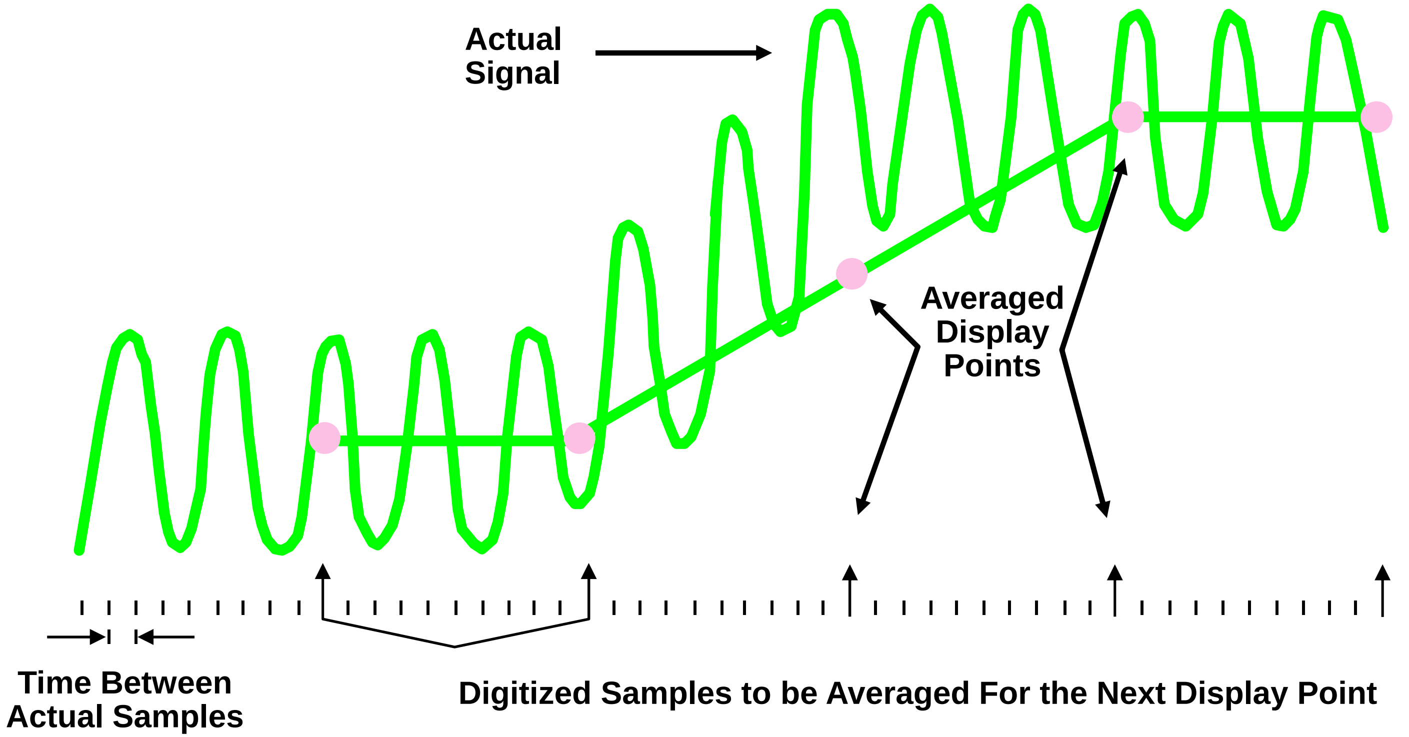
ERES Averaging

ERES processes N samples,but the sample values are weighted to produce a finite impulse response (FIR) filter with a more desirable low pass frequency response. The principal advantage of the ERES technique is that it produces a frequency response which is Gaussian; it has no side lobes in the frequency domain and it never causes overshoot or undershoot or ringing in the time domain.

Table 1 The Enhanced Resolution filter parameters			
Resolution Enhancement [Bits]	**-3 dB Bandwidth [x Nyquist]**	**Filter Length [samples]**	**Effective Dynamic Range**
0.5	0.5	2	362:1
1	0.241	5	512:1
1.5	0.121	11	724:1
2	0.058	25	1024:1
2.5	0.029	52	1448:1
3	0.016	106	2048:1

Box Car Averaging

As time/division is increased, better vertical amplitude resolution and noise removal can occur for a single triggered acquisition, at lower bandwidth. Used for High Resolution Acquisition Mode.



Comparison ERES and Box Car (HI Res)

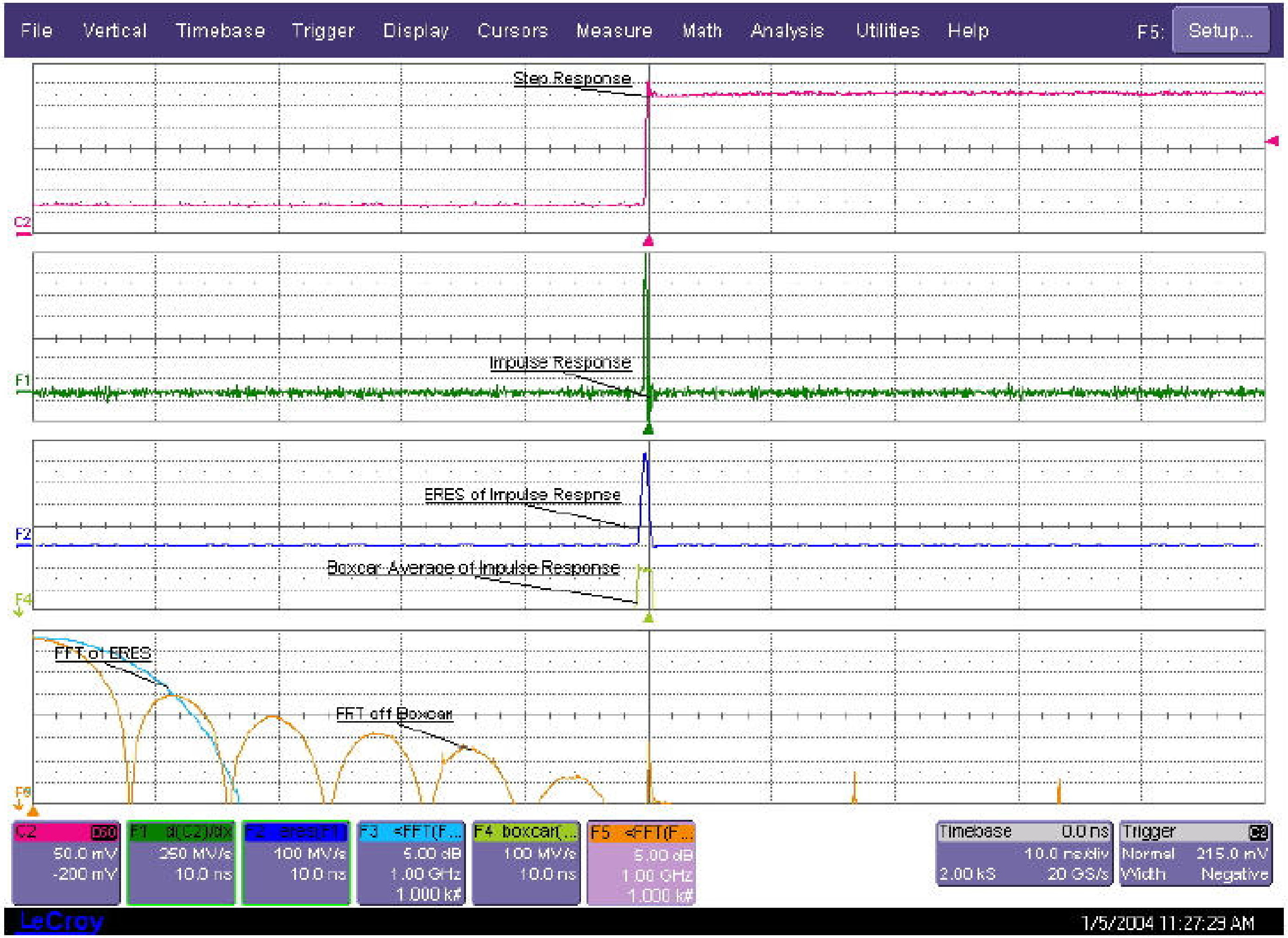


Figure 1 Comparing the impulse responses of ERES and Boxcar averaging

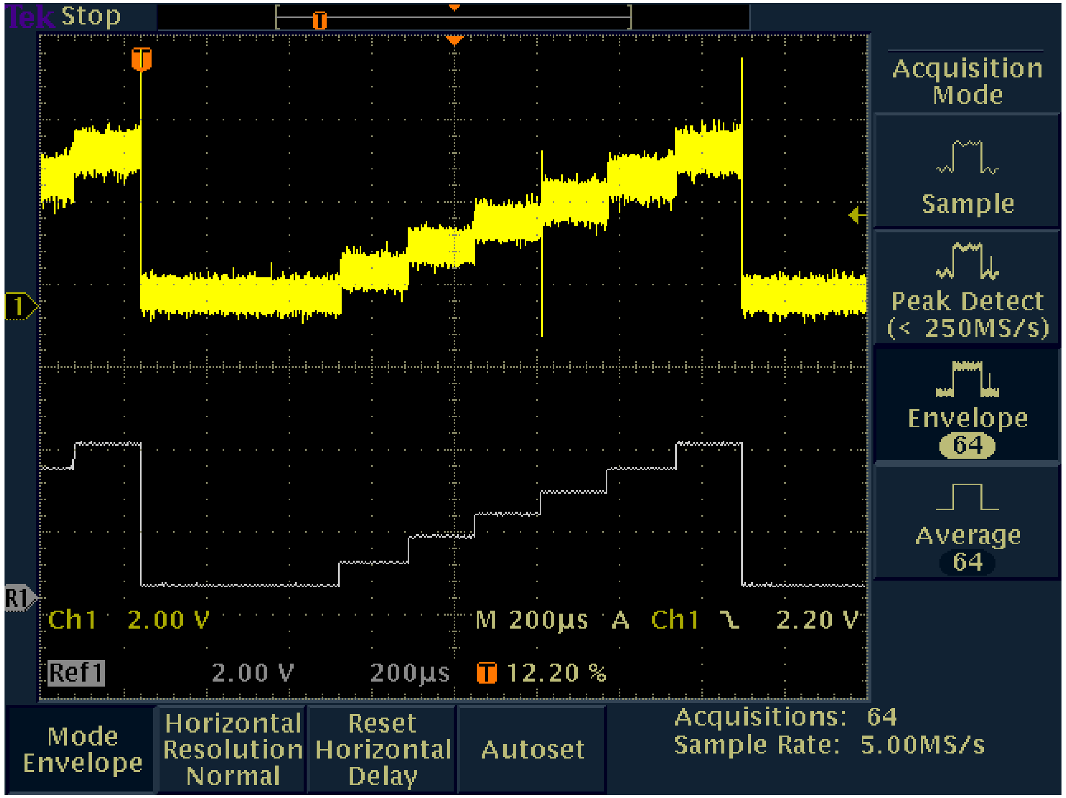
Envelope Mode Can Accumulate Noise
Average Mode Can Reduce Random Noise

First Trace

- Envelope Mode
- Shows Maximum Noise

Second Trace

- Average Mode
- Reduces Noise



Digital Storage Oscilloscope Benefits

Store waveforms

Capture infrequent anomalies

Use advanced triggering

Display pre-trigger waveshape

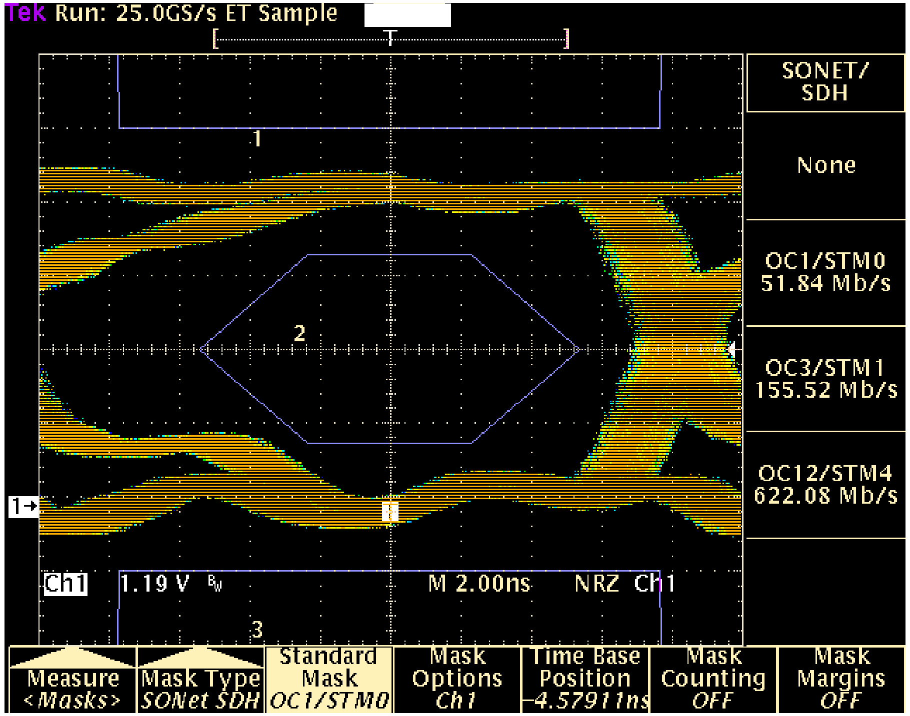
Remove noise

Provide more accurate time base

Allow color display

Process signals (averaging, FFT)

Transfer/copy stored waveforms

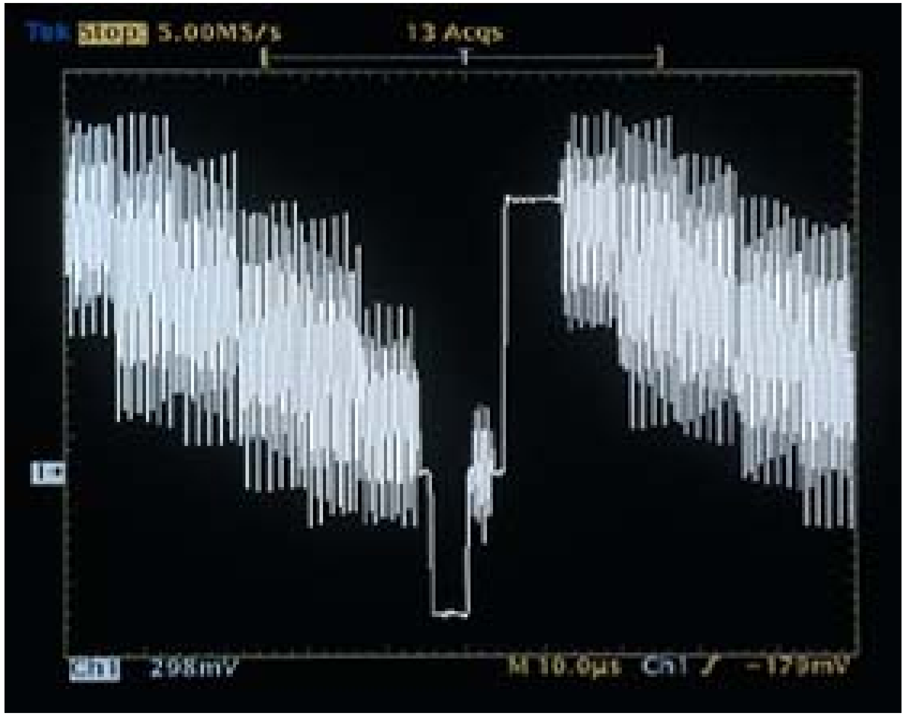


DSO Shortcomings

Limited waveform capture rates

Aliasing due to insufficient data

No intensity grading (distribution of occurrence information)



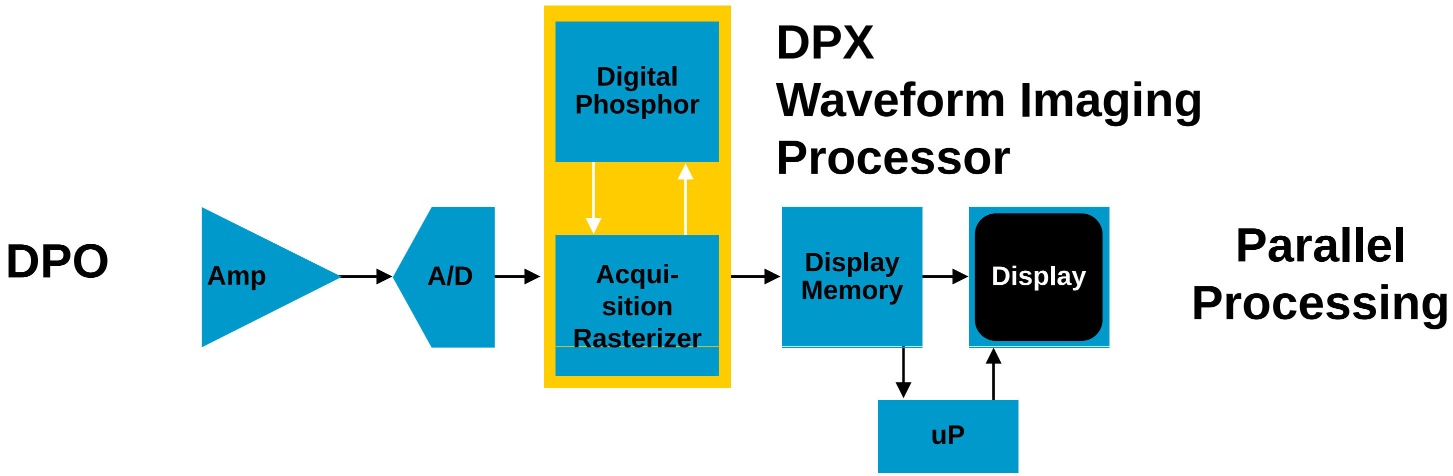
Evolution of Oscilloscopes

Scope Technology	ART	DSO	DPO
	1950	1980	1998
Market Drivers	• Military • Vacuum tube technology • Emerging solid state technology • Broadcast video	• Computers • LSI • Digital data • Mixed signal environments • Faster microprocessor clock rates • System integration • Quality assurance	• Convergence • Interoperability • Faster data rates and microprocessor clocks
Customer Challenges	• Device characterization • Signal edges and waveshapes	• Signal data • High-frequency effects • Documentation	• Complex signals • Standards compliance • Test equipment performance

A Breakthrough Solution
The Digital Phosphor Oscilloscope

<u>Digital Phosphor Oscilloscope</u>

An instrument that digitizes electrical signals and displays, stores, and analyzes three dimensions of signal information in real time.



You Cannot See What Occurs During Acquisition/Sweep Holdoff Time

For any scope, there is always holdoff time during a display update cycle when the signal cannot be acquired.

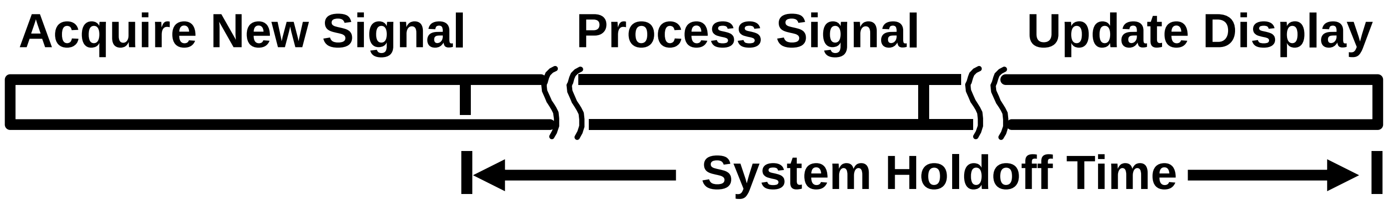
The probability of seeing the low rep-rate anomaly that occurs on the measured signal decreases as this holdoff time increases.

$$\text{Probability of Capture} = \frac{\text{Acquisition (Sweep) Time}}{\text{Acquisition (Sweep) Time} + \text{System (Sweep) Holdoff Time}}$$

You will not know this probability by simply looking at the display update.

Waveform Capture Rate Is Limited By Holdoff Time

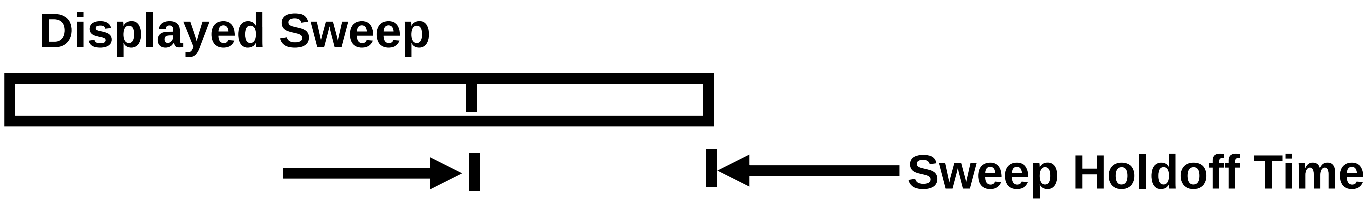
DSO Cycle



Typical Capture Rate Range

1 - 100 Hz

ART Cycle



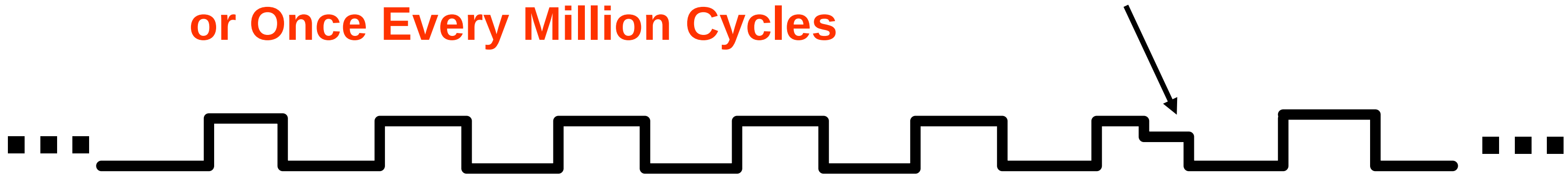
Maximum Capture Rate

1 MHz

How Likely Are You To See Your “Hard To Find” Problem?

Example: Assume

- 1 MHz Square Wave Signal
- 1 µsec/Division Time Base Setting
- Pulse Aberration Occurs About Once Per Second, or Once Every Million Cycles



Typical ART Cycle

Sweep Time | Holdoff Time

10 µsec | 1 - 10 µsec

Probability of Capture = 50% to 90%

Time to see one fault will be about two seconds.

Typical DSO Cycle

Acquire Time | System Holdoff Time

10 µsec | .01 - 1 second (Typical)

Probability of Capture = 0.1% to 0.001%

Time will be about 15 minutes for a 50% probability of seeing just one of the faults that are occurring every second.

DPO Acquisition Allows

Over 1,000,000 Acquisitions/Second

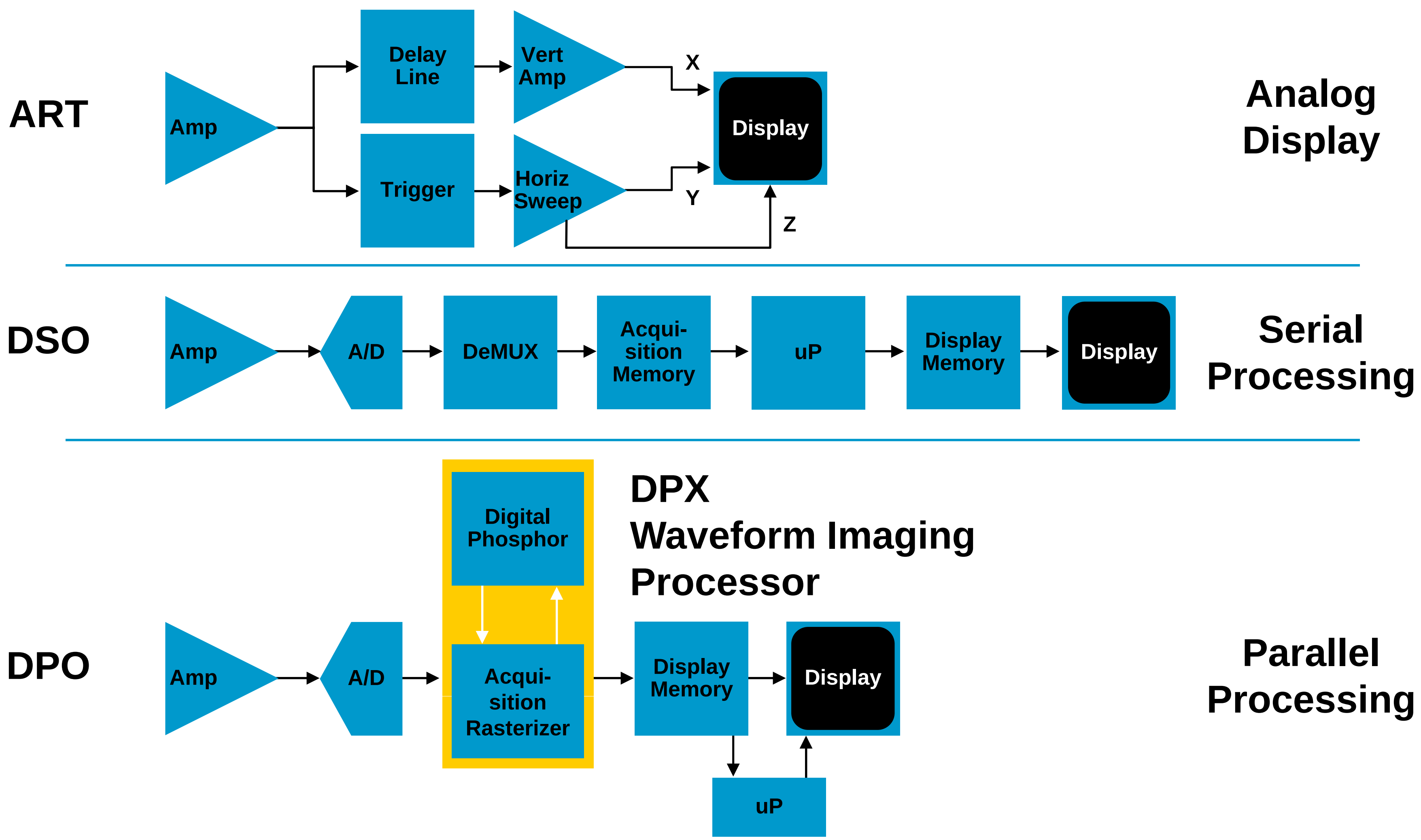
Color and Intensity Grading for Historical Information

Instantaneous Feedback on Signal Changes

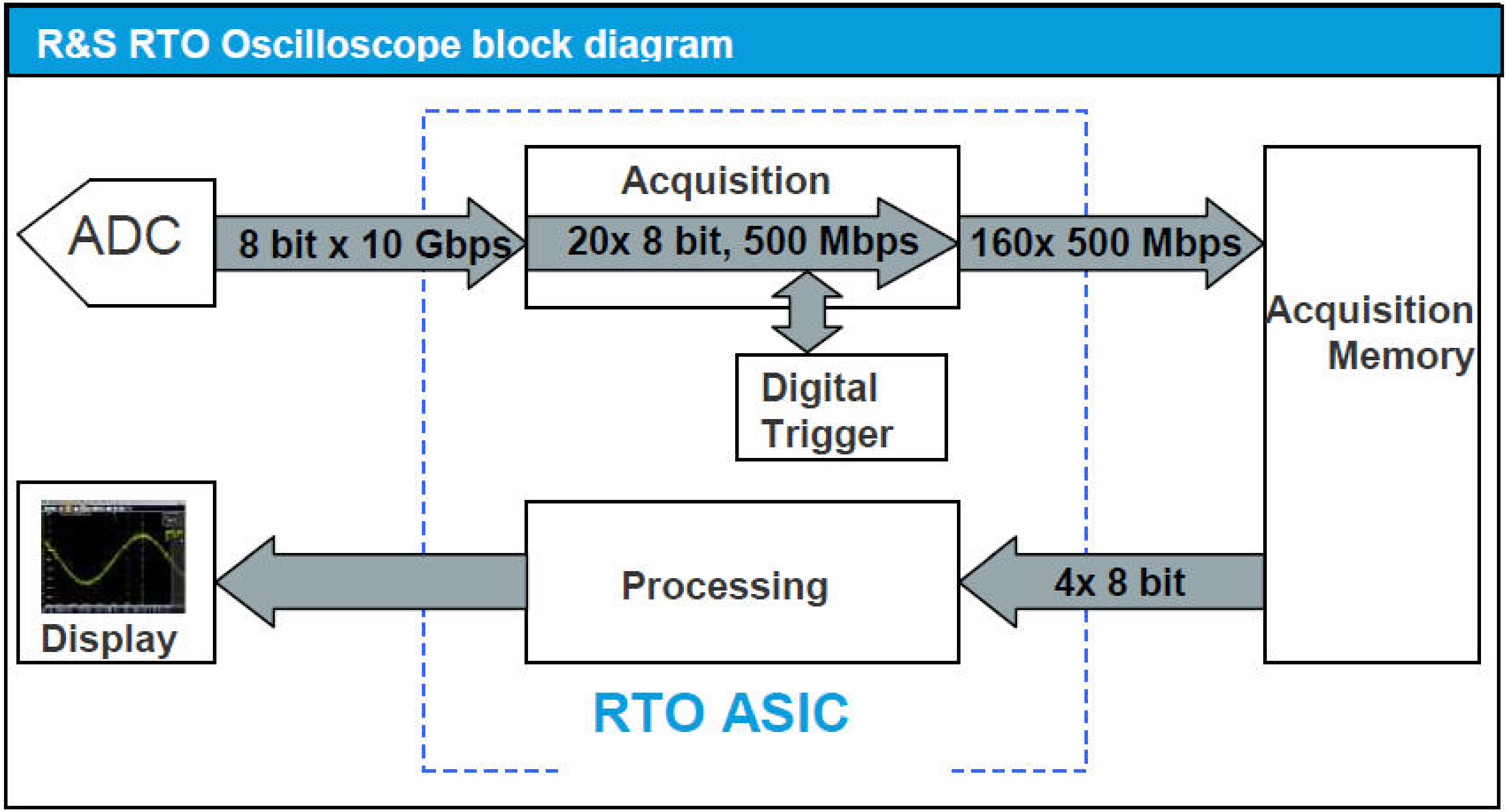
Simultaneous Viewing of All Channels (Analog Scopes Must Use Chop or Alternate)

Analog Scope Capture Confidence

Compare the Architectures

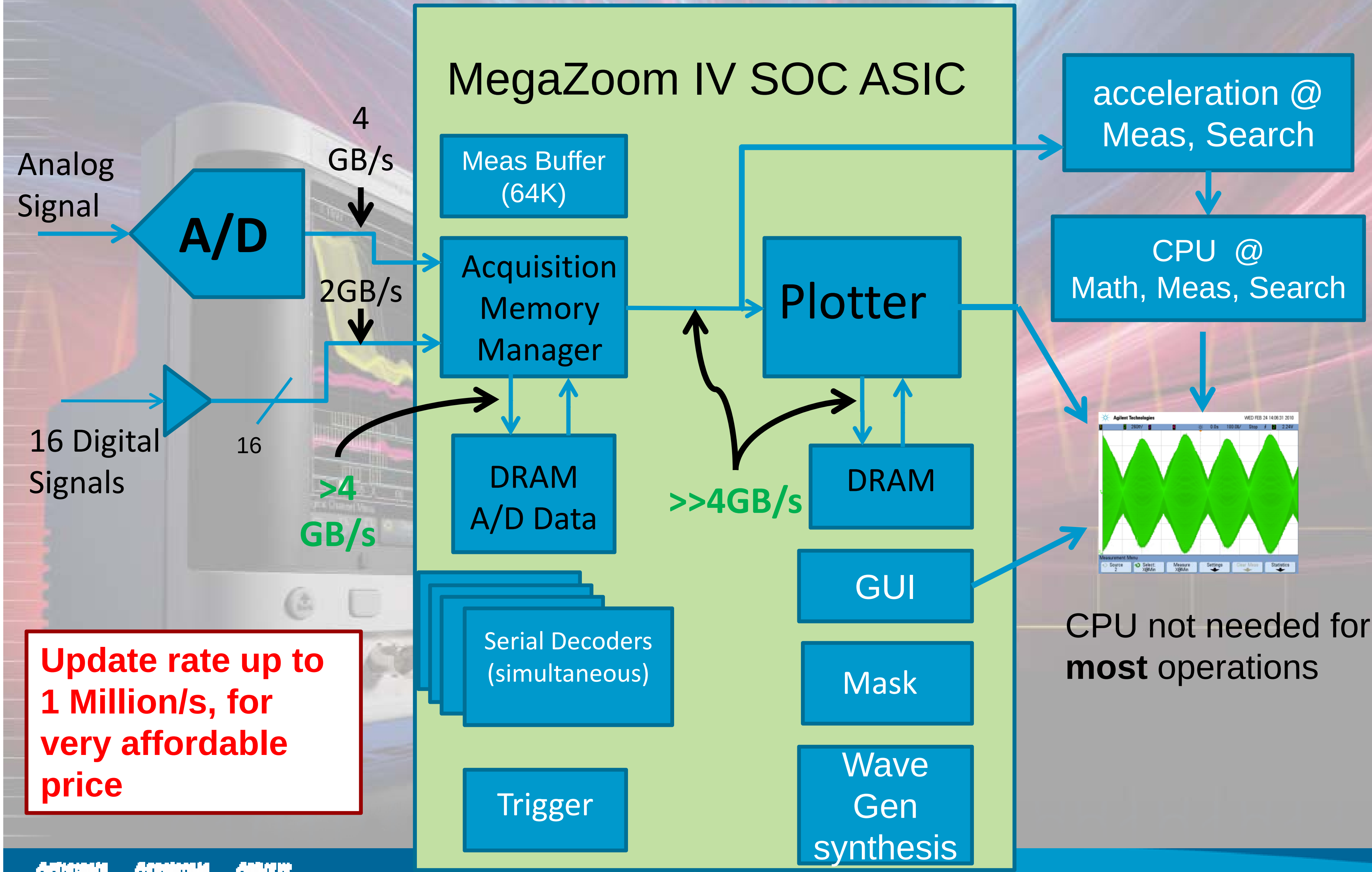


R&S ®RTO Digital Oscilloscopes



…With this architecture the processing path after the acquisition memory is able to achieve data throughput rates 1/5 that of the real time path in front of the acquisition memory. This translates into a theoretical active acquisition time of 20%....

MegaZoom IV Scope Block Diagram



Advantages of Analog Real Time

- Avoids Aliasing
- Displays Fast Waveform Update Rate
- Provides Micro Channel Plate Writing Speed
- Displays Gray Scale Information
- Provides Low Cost Repetitive Bandwidth
- Has Ease of Use Through Familiarity

Remember Writing Speed and Waveform Update Rate for finding low rep-rate faults.

Advantages of Digital Storage

Allows Up To 1 GHz Bandwidth Acquisitions For Single-Shot Events

Finds Glitches With Peak Detect/Envelope

Finds Anomalies With DPX™ Enhanced DPO Acquisition

Acquires Waveforms Before the Trigger

Makes More Accurate Timing Measurements

Provides Highest Bandwidth With Equivalent Time Digitizing

Enables Digital Signal Processing

Allows A Color Display

Advantages of Digital Phosphor Oscilloscope (DPO)

- Simulates the Characteristics of an Analog Real Time Oscilloscope's Fast Waveform Capture Rate and Intensity Graded Display
- Provides Intensity and/or Color Graded Display Showing Distribution of Amplitude Over Time, All In Real Time
- Integrates An Image Over Many Real Time Traces of the Signal

Remember Probing and Vertical Amplifier Issues

Such as:

Loading Effects

Differential Measurements

Current Sensing

High Voltage Breakdown

Transducer Characteristics

Vertical Range and Linearity

Vertical Sensitivity