Oscilloscopes and Accessories

Politecnico di Milano
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

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

\[
\text{Bandwidth} \times \text{Risetime} = 0.35^* \\
100 \text{ MHz Bandwidth} = 3.5 \text{ nsec Risetime}
\]

* 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

At the 3dB bandwidth frequency, the vertical amplitude error will be approximately 30%.

Vertical amplitude error 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 $\geq 5^{th}$ 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

\[ \text{Sample Rate} > 10 \times f_{\text{Highest}} \]

For linear interpolation

\[ \text{Sample Rate} > 2.5 \times f_{\text{Highest}} \]

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

Time = \frac{Record Length}{Sample Rate}
Oscilloscope Vertical System

Signal

- Attenuator
  - Coupling
  - Volts/div

Pre Amp

Delay Line

Amp

- ART Only
- ART CRT or DSO
- A/D Converter
- and Display

Position

Mode

Trigger System

Horizontal Time Base System
Oscilloscope Horizontal System

DSO

Acquisition

Variable Holdoff

ART

Ramp

Retrace

Time

Deflection Voltage

Variable Holdoff

Agilent Technologies
Triggering System Controls

Signal

Internal Triggers

External Trigger

Source (Channel, Line)

Coupling (AC/DC, HF/LF Rej)

Vertical System

Display System

Trigger System

Horizontal System

Level (P-P Auto, Norm)
Slope
Mode (Auto, TV, Single Sweep, Glitch, Width, Runt, Slew Rate, Setup/Hold, Logic)
Holdoff
System Bandwidth

System Bandwidth = Bandwidth of the Probes + Oscilloscope!
Measurements with Oscilloscopes

SCOPE

PROBES

UHH,! The wheel brakes must be on again.

DUT (Device Under Test)
Scope Disconnected from Ground - ‘Floating’
Basic Probe Types

- Voltage
  - Passive
  - Active
    - Z0
    - High Z
    - High Voltage
    - Differential
- Current
  - Passive
  - Active
- Logic
  - Passive
  - Active
- Temperature
  - Passive
  - Active
- Optical
  - AC
  - DC

Transducers

Optical Logic
Probes Affect the Measurement System As Well As the DUT

Without probe & Oscilloscope

Gain = \(- \frac{R_C}{R_E}\)

With probe & Oscilloscope

\[ f_0 = \frac{1}{2\pi R_C C_C} \]

Gain = \(- \frac{(R_C \parallel R_P)}{R_E}\)

\[ f_0 = \frac{1}{2\pi (R_C \parallel R_P)(C_C + C_P)} \]

NOTE: \(V_{CC}\) is an AC Ground
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

COMPENSATED

1 ms/div

1 µs/div

50 kHz

OVER COMPENSATED

1 ms/div

1 µs/div

50 kHz

UNDER COMPENSATED

1 ms/div

1 µs/div

50 kHz
Probe Tip Capacitance and Source Impedance Effects

\[ t_r \approx 2.2 \left( R_{\text{source}} \times C_{\text{in}} \right) \]

- \( R_{\text{source}} = 1 \, \text{k\Omega} \)
- \( C_{\text{in}} = 100\,\text{pF} \Rightarrow 220\,\text{nsec} \) for 1X Probe
- \( C_{\text{in}} = 10\,\text{pF} \Rightarrow 22\,\text{nsec} \) for 10X Probe

**Graphs:**
- Rise Time Waveform for the 1X Passive Probe
- Rise Time Waveform for the 10X Passive Probe

**Equations:**
- \( t_{\text{rise}} \) is the rise time due to capacitance loading.
- \( t_{\text{source}} = 3\,\text{ns} \) for 1X Probe
- \( t_{\text{source}} = 22\,\text{ns} \) for 10X Probe

Circuit Under Test Inductance Effects

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

Typical Ring Frequency From 6” Diameter Ground Loop:

$$\text{Frequency} = \frac{1}{2 \pi \sqrt{LC}} = 50 - 70 \, \text{MHz}$$

OR

$$t_r = 7 - 5 \, \text{ns}$$

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

Advantages:
- Low Input Capacitance
- Wide Bandwidth
- High Input R
- Compatible with 50 \( \Omega \) Systems and 1 M\( \Omega \) 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

Typical CMRR:
- 10,000 : 1 @ DC
- 2000 : 1 @ 20 MHz
Active Current Probe Model

Advantages:
- DC & AC Current Measurements
- Compatible With 50 Ω and 1 MΩ Single-ended Systems
- Lower DUT Loading 
  \( R_{\text{reflected}} \) typically << 1 Ω
  \( L_{\text{reflected}} \) 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

Simultaneous analog and digital channels
### Evolution of Oscilloscopes

<table>
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<th>Scope Technology</th>
<th>ART</th>
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<td>1950</td>
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</table>

#### Market Drivers
- Military
- Vacuum tube technology
- Emerging solid state technology
- Broadcast video

#### Customer Challenges
- Device characterization
- Signal edges and waveshapes
Analog Oscilloscope Definition

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

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Customer Challenges

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<td>• Device characterization</td>
<td>• Signal data</td>
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<td>• Signal edges and waveshapes</td>
<td>• High-frequency effects</td>
</tr>
<tr>
<td></td>
<td>• Documentation</td>
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Discrete Scope Block Diagram

Signal → A/D → Acquisition Memory Manager → Plotter (FPGA &/or CPU) → CPU processing

- 4 GByte/s
- 100-200 MByte/s
- Update rate = 100/s to 1000/s, some up to a few 10,000/s
A-D-C

Analog

-To-

Digital

Conversion
Sampling

TAKING SAMPLES OF AN INPUT SIGNAL AT SPECIFIC POINTS IN TIME

Samples

Sample Interval

Hold Time Needed for Digitizing

Samples Equally Spaced in Time

Sample Rate Measured in Sample/Second
(S/s, kS/s, MS/s, GS/s)
What Happens To The Samples?

Signal Sampling Digitizing Memory Storage

(Sample, Hold) (Convert to Number) (Sequence Store)

Screen Displays a Selected Portion of Memory

Scope Screen
# Types of Digital Resolution

<table>
<thead>
<tr>
<th>Vertical</th>
<th>1/# Levels</th>
<th>% of Full Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-Bits</td>
<td>1/64</td>
<td>1.56%</td>
</tr>
<tr>
<td>8-Bits</td>
<td>1/256</td>
<td>0.39%</td>
</tr>
<tr>
<td>10-Bits</td>
<td>1/1024</td>
<td>0.097%</td>
</tr>
<tr>
<td>12-Bits</td>
<td>1/4096</td>
<td>0.024%</td>
</tr>
</tbody>
</table>

Horizontal = Time/Sample

\[= \frac{1}{\text{Sample Rate}}\]
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.
Sequential Equivalent Time Digitizing

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Sequential Equivalent Time Digitizing

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

No Pre-trigger
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.
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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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.

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 too Slow

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

**Cause:** Sample Rate too 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

Glitch falls between sample points and would be missed in sample mode.

More samples taken for peak detect.

Additional samples taken, min/max displayed, glitch captured in peak detect mode.
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>
<thead>
<tr>
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<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>2</td>
<td>362:1</td>
</tr>
<tr>
<td>1</td>
<td>0.241</td>
<td>5</td>
<td>512:1</td>
</tr>
<tr>
<td>1.5</td>
<td>0.121</td>
<td>11</td>
<td>724:1</td>
</tr>
<tr>
<td>2</td>
<td>0.058</td>
<td>25</td>
<td>1024:1</td>
</tr>
<tr>
<td>2.5</td>
<td>0.029</td>
<td>52</td>
<td>1448:1</td>
</tr>
<tr>
<td>3</td>
<td>0.016</td>
<td>106</td>
<td>2048:1</td>
</tr>
</tbody>
</table>
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.
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

Market Drivers
- Military
- Vacuum tube technology
- Emerging solid state technology
- Broadcast video

ART
- 1950

DSO
- 1980
- Computers
- LSI
- Digital data
- Mixed signal environments
- Faster microprocessor clock rates
- System integration
- Quality assurance

DPO
- 1998
- 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

Digital Phosphor Oscilloscope
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

Acquire New Signal  Process Signal  Update Display

System Holdoff Time

Typical Capture Rate Range

1 - 100 Hz

ART Cycle

Displayed Sweep

Sweep Holdoff Time

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: 10 µsec
- Holdoff Time: 1 - 10 µsec
- Probability of Capture = 50% to 90%

Typical DSO Cycle

- Acquire Time: 10 µsec
- System Holdoff Time: .01 - 1 second (Typical)
- Probability of Capture = 0.1% to 0.001%

Time to see one fault will be about two seconds.

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

ART

Amp → Delay Line → Vert Amp → Display
Trigger → Horiz Sweep → Display

DSO

Amp → A/D → DeMUX → Acquisition Memory → uP → Display Memory → Display

DPO

Amp → A/D → Acquisition Memory → Display Memory → Display

Analog Display
Serial Processing
Parallel Processing

Digital Phosphor
DPX Waveform Imaging Processor

uP

Agilent Technologies
...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

MegaZoom IV SOC ASIC

- Meas Buffer (64K)
- Acquisition Memory Manager
- DRAM A/D Data
- Serial Decoders (simultaneous)
- Trigger
- Wave Gen synthesis
- Mask
- GUI
- DRAM

acceleration @ Meas, Search

CPU @ Math, Meas, Search

Update rate up to 1 Million/s, for very affordable price

CPU not needed for most operations
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