From the Designers:
Optimize Scope Measurements and Features

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Common Oscilloscope Mistakes

- Probing ground lead too long
- Not compensating probes
- Terminating 50Ω probe into high impedance
- Incorrect time base setting
- Eliminating signal detail from bandwidth being too low
- DC coupling when AC coupling required
- Not maximizing vertical resolution for ADC gain
Agenda

• Overview
• Probing
• Bandwidth
• Small Signal Measurements
• Sampling Modes

Not Covered

• Triggering
• Streaming
• Synchronization
• DSP / Equalization
PXI Oscilloscope

NI 5162
5GSps, 1.5GHz

NI 5164
1GSps, 400MHz

NI 5172
250MSps, 100MHz
PXI Oscilloscope

- Front End
- ADC
- FPGA
- Memory
- Probe / Cable
- DUT
Probing
Probe Issues

Loss, roll-off, and dispersion in the response

Noise pick-up

Probe compensation

Loading

D.U.T.

SCOPE
Loading

**Capacitive Loading**

- **DUT**: 10:1 Passive Probe
- **10pF**: Capacitive Loading
- **$V_{FINAL}$**: True waveform
- **$V_{STEP}$**: Waveform slow to converge

**Resistive Loading**

- **DUT**: 10:1 Passive Probe
- **3MΩ**: Resistive Loading
- **$V_{STEP}$**: True waveform
- **$V_{FINAL}$**: Waveform never converges
Loading: Coax Cable vs. Passive Cable Divider Probe

1.2m Length RG58 Cable:
Heavy loading: \( C_{\text{LOADING}} = 112\text{pF} \)

1.2m Length Cable Divider Probe (NI CP500X):
Light Loading: \( C_{\text{LOADING}} = 10\text{pF} \)

BNC connector for DUT end.
Probing – Minimize Ground Lead Inductance

30cm clip lead

Reference lead with crocodile clip

Push-on reference grounding collar

25ns/div

ni.com
10:1 and 100:1 Passive Probes

- Up to 500 MHz bandwidth
- High voltage, up to 400V
- Tip impedance: 10 pF ||10 MΩ (typical)
- Some probes have 1:1 switch
  ... 1:1 setting: heavy loading & low BW e.g. 5MHz
- Scope is always set to 1Meg
- Probe compensation required!

**SP500X:**
10:1, 500MHz, 300V max, 11pF||10MΩ tip

**SP500C:**
100:1, 500MHz, 300V max, 4.6pF||100MΩ tip

**CP500X:**
1.2m length, 10:1, 500MHz, 10pF||10MΩ tip

**CP400X:**
2m length, 10:1, 400MHz, 13pF||10MΩ tip
Compensate Passive Probes – Always

Overcompensated

Undercompensated

Properly Compensated
How To Compensate a NI PXIe Oscilloscope

- NI Soft Front Panel

- NI LabVIEW

Calibration pulse once enabled is generated on PFI0
Looks good, right? But amplitude error is 25% above 100KHz.
CAUSE: probe not compensated!

This would only be noticeable when viewing a square edge on a long time base setting.
Passive Probe Connectivity

- Passive Probes with coax cables cannot be combined
# Active Probes vs Passive Probes

<table>
<thead>
<tr>
<th></th>
<th>Passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>~$150</td>
<td>~$1,000/GHz</td>
</tr>
<tr>
<td><strong>Typical Input Capacitance</strong></td>
<td>10pF</td>
<td>1pF</td>
</tr>
<tr>
<td><strong>Voltage Range</strong></td>
<td>&gt;300 V</td>
<td>1 to 10 V</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>200 to 500MHz</td>
<td>&gt;1GHz</td>
</tr>
<tr>
<td><strong>Scope Setting</strong></td>
<td>1MΩ</td>
<td>50Ω</td>
</tr>
<tr>
<td><strong>External Power Required?</strong></td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

*Active probes are generally preferred for high bandwidth applications and/or applications where minimal high frequency loading is important.*
Passive Probes Connectivity

- Ideal for signals referenced to each other as opposed to ground
- Reject common mode voltage, $V_{CM}$ (e.g. ground loops in single-ended measurements)

NI-5191:
- 10:1, 800MHz
- 2pF||100KΩ
- ±15V differential
- ±30V common mode

$V_O = A_v \cdot V_{DM}$
Mass Interconnects

- Benefits
  - Enhanced Electrical Performance
  - Eliminates Conventional Wiring Harnesses
  - Reduced System Integration Time and Costs

Images courtesy of Mac-Panel
Image courtesy of Virginia Panel
Specification Basics

- Bandwidth
- Rise Time
- Input Impedance
- Coupling
Bandwidth specification

100MHz Sinewave In

Analog Transmission Path with 100MHz -3dB Bandwidth

100MHz Sinewave Out

\[ \frac{1}{2\pi RC} = 100MHz \]

\[ \sim 0.7 \text{ V}_{pp} \]
Bandwidth of an Instrument

At NI, oscilloscope bandwidth is specified based on the -3dB point.

Continuous roll-off in passband! Here it is -1dB at 360MHz.

Very flat response to 350MHz

560MHz, margin: product spec’d at 500MHz.

415MHz, margin: product spec’d at 400MHz.
Bandwidth Impact on Time Domain Measurements

- Bandwidth should be 3-5 times the highest frequency component

<table>
<thead>
<tr>
<th>Gaussian step input -3dB point</th>
<th>Bandwidth Highest Freq</th>
<th>measured risetime input risetime</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>2GHz</td>
<td>.25</td>
<td>740ps/180ps</td>
<td>416%</td>
</tr>
<tr>
<td>500MHz</td>
<td>1</td>
<td>980ps/700ps</td>
<td>40%</td>
</tr>
<tr>
<td>167MHz</td>
<td>3</td>
<td>2.11ns/2.00ns</td>
<td>4.4%</td>
</tr>
</tbody>
</table>
Rise Time

rule of thumb: \( t_r = \frac{k}{BW} \)

- \( k \sim 0.35 \): \( BW \leq 1 \text{ GHz} \) (typically)
- \( k \sim 0.45 \): \( BW \geq 1 \text{ GHz} \) (typically)

\[
\begin{align*}
    t_r_{\text{system}} &= \sqrt{t_r^2_{\text{scope}} + t_r^2_{\text{probe}}} \\
    t_r_{\text{measurement}} &= \sqrt{t_r^2_{\text{system}} + t_r^2_{\text{signal}}} 
\end{align*}
\]
When To Use 1MΩ vs 50Ω Input Impedance

50 Ω
- 50 Ω systems (usually high bandwidth systems)
- Active probes

1MΩ
- Passive probes
- High voltage signals
When Examining Details on Large Offset

- AC Coupling – Uses a capacitor to filter out the DC signal component
  - Allows highest gain settings with a large DUT DC voltage offset e.g. Power supplies
  - Useful to remove DC (acts as voltage offset) component to gain resolution
When Examining Details on Large Offset

- DC Coupling – Allows both AC and DC signals to pass
  - When measurements require fast settling (discharge of AC capacitor)
  - High resolution can help to show more details
  - Allows for measurement of DC component and AC component with higher resolution

Using 2.5V input range to measure 100V input
Small Signal Measurements
Key Analog Metrics

Signal to Noise Ratio (SNR) = \(20 \log\left(\frac{\text{Full Scale Sine Input rms}}{\text{noise rms}}\right)\)  [dBFS]

Signal to Noise+Distortion (SINAD) = \(20 \log\left(\frac{\text{Full Scale Sine Input rms}}{\text{noise rms+harmonics rms}}\right)\)  [dBFS]

Spurious Free Dynamic Range (SFDR) = \(20 \log\left(\frac{\text{Full Scale Sine Input rms}}{\text{strongest spur spectral line}}\right)\)  [dBc]
Resolution of the ADC

- The number of discrete values represented within a range
- 3-bit resolution = $2^3 = 8$ voltage levels, 16-bit = $2^{16} = 65,536$ levels
Better Resolution Metric: ENOB – Effective Number of Bits

\[
ENOB = \frac{SINAD - 1.76 \, dB}{6.02 \, dB}
\]

- Expresses the scope’s true resolution.
- Derived directly from SINAD.
- ENOB tends to decrease with
  - Higher instrument bandwidth
  - Higher input frequency
  - Lower instrument resolution
  - High impedance vs 50 Ohm inputs
  - Smaller input range – this is OK!
High ENOB Allows Viewing Small Signals on Large Offsets.

10mVpp signal riding on a 3V step
Averaging to Reduce Noise

- Advantage: Does not lower bandwidth
- Disadvantage: Requires a repetitive signal and accurate triggering

4 averages $\rightarrow \frac{1}{2}$ Noise Voltage $\rightarrow$ 1 bit improvement
16 averages $\rightarrow \frac{1}{4}$ Noise Voltage $\rightarrow$ 2 bit improvement
64 averages $\rightarrow \frac{1}{8}$ Noise Voltage $\rightarrow$ 3 bit improvement
... 256 averages $\rightarrow$ 4 bit improvement

- Ultimately limited by ADC quantization effects and correlated noise
  - Additive dither signal can help
Lower Bandwidth to Reduce Noise

- Advantage: Eliminates noise above the frequency range of interest
- Disadvantage: Limits bandwidth

Triangle wave in noisy environment. Only 4 KHz.

Lowering BW substantially reduces noise.
Memory & Sampling Modes
Memory Depth

• A function of Sample rate
• The more memory, the longer a sample can be acquired at a given sample rate

• Time Interval = \( \frac{\text{Onboard Acquisition Memory}}{\text{Sample Rate (S/s)}} \)
Deep Memory and the Frequency Domain

• Deeper memory on digitizers allows for better FFTs because the FFT resolution increases with record length
• PXI digitizers have tremendous advantage over box scopes when taking large FFTs due to the very fast data transfer rate to the host PC

Frequency Resolution = Sampling Rate / Record Size

10 k point FFT

1 M point FFT
Sampling Modes

- **Real-Time Sampling**
  - Standard sampling mode for Scopes/Digitizers/DAQ Boards

- **Time-Interleaved Sampling (TIS)**
  - Two or more ADCs Interleaved to increase sample rate

- **Random Interleaved Sampling (RIS)**
  - Construct waveform by overlaying multiple acquisitions of a repetitive waveform
  - Increases apparent sample rate
What is Time Interleaved Sampling?

**Diagram:**
- **INPUT SIGNAL** connected to **ADC CH0**
- **ADC CH0** connected to **CH0 CLOCK**
- **ADC CH1** connected to **CH1 CLOCK**
- **CH0 CLOCK** and **CH1 CLOCK** linked through **DELAY 180deg**
- **CLOCK** connected to both **ADC CH0** and **ADC CH1**

**Graph:**
- X-axis: Time (0.0, 5.0, 10.0, 15.0, 20.0, 25.0, 30.0, 35.0, 40.0, 45.0, 50.0)
- Y-axis: ADC Data (0.0, 20.0, 40.0, 60.0, 80.0, 100.0, 120.0, 140.0)
- Data points for **CH0** and **CH1**

**Legend:**
- **CLOCK**
- **ADC**
- **CH0**
- **CH1**
- **DELAY 180deg**
What Can Go Wrong With TIS?

Perfect interleaved sampling

Gain error between ADCs

Offset error between ADCs

Phase error between ADCs
How It all Looks in the Frequency Domain

• Offset Error spurs
  • $f_{\text{offset}} = \frac{n \times f_s}{M}$
  • $M =$ number of interleaved ADCs
  • $n =$ integer number (0,1,2,3,...)
  • Spurs not related to signal frequency

• Gain & Phase Error spurs:
  • $F_{\text{gain,phase}} = \left(\frac{n \times f_{\text{sampling}}}{M}\right) \pm f_{\text{signal}}$

More info: [www.edn.com/design/analog/4407107/1/The-ABCs-of-interleaved-ADCs](www.edn.com/design/analog/4407107/1/The-ABCs-of-interleaved-ADCs)
Random Interleaved Sampling (RIS)

- Apparent sample rate increased by 10X or more
- Accomplished by overlaying triggered acquisitions
- *Repetitive signal required!* — not for one-time events
- Also called “Equivalent-Time Sampling” (ETS)

Real Time Sampling Example

Random Interleaved Sampling Example

four different acquisitions overlaid
Takeaways

- **Probing**
  - Always compensate passive probes or cable dividers
  - Reduce length of ground lead

- **Small Measurements**
  - Maximize sensitivity setting to lower noise
  - Average to reduce unwanted noise
  - Enable noise filters to reduce unwanted noise

- **Bandwidth**
  - 3-5x highest frequency component

- **Sampling modes**
  - RIS only usable for repetitive signals
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