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

**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

- 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
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
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
Sampling Basics

- 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
Averaging requires a repetitive signal!
Oscilloscope Fundamentals

- 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
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”.

![Image of an oscilloscope model showing 100 MHz and 5 Giga samples per second]
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 ($f_{knee}$).

\[
\begin{align*}
    f_{knee} &= 0.5/RT \ (10\% - 90\%) \\
    f_{knee} &= 0.4/RT \ (20\% - 80\%)
\end{align*}
\]

Step #3: Determine degree of required measurement accuracy.

Scope BW Calculation

<table>
<thead>
<tr>
<th>Required Accuracy</th>
<th>Gaussian Response</th>
<th>Maximally-flat Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>BW = 1.0 x $f_{knee}$</td>
<td>BW = 1.0 x $f_{knee}$</td>
</tr>
<tr>
<td>10%</td>
<td>BW = 1.3 x $f_{knee}$</td>
<td>BW = 1.2 x $f_{knee}$</td>
</tr>
<tr>
<td>3%</td>
<td>BW = 1.9 x $f_{knee}$</td>
<td>BW = 1.4 x $f_{knee}$</td>
</tr>
</tbody>
</table>

Step #4: Calculate required bandwidth.

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

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

20% Accuracy: \[ BW = 1.0 \times f_{\text{knee}} = 1.0 \times 1 \ \text{GHz} = 1.0 \ \text{GHz} \]

3% Accuracy: \[ BW = 1.9 \times f_{\text{knee}} = 1.9 \times 1 \ \text{GHz} = 1.9 \ \text{GHz} \]
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
Nyquist’s sampling theorem states that for a limited bandwidth (band-limited) signal with maximum frequency \( f_{\text{max}} \), the equally spaced sampling frequency \( f_s \) must be greater than twice of the maximum frequency \( f_{\text{max}} \), i.e.,

\[
f_s > 2 \cdot f_{\text{max}}
\]

in order to have the signal be uniquely reconstructed without aliasing.

The frequency \( 2 \cdot f_{\text{max}} \) is called the Nyquist sampling frequency \( (f_S) \). Half of this value, \( f_{\text{max}} \), 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**

- **Attenuation**
  - 0dB
  - -3dB

**Aliased Frequency Components**

Frequency

\( f_N \)

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

Sample rate is four times bandwidth

![Graph showing Gaussian response with bandwidth at fs/4 (fN/2).](image)

- Attenuation
  - 0dB
  - -3dB

- Frequency
  - $f_S/4$
  - $f_N$
  - $f_S$

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

SAMPLE RATE IS 2.5X BANDWIDTH

![Graph showing frequency response with aliased frequency components at frequencies f_s/2.5, f_N, and f_s.](image-url)
EVERY SIGNAL CONSISTS OF A FUNDAMENTAL AND ITS HARMONICS

- Fundamental
- 2nd Harmonic
- 3rd Harmonic
- 4th Harmonic
- 5th Harmonic

FREQUENCY DOMAIN

TIME DOMAIN

AMPLITUDE

FREQUENCY

TIME
Sampling Basics

DISTORTION DUE TO ALIASING AND BANDWIDTH LIMITING

ACTUAL PULSE

DISPLAYED PULSE
**1-GHz Bandwidth Oscilloscope**

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

---

**SR = BW x 2.5**

- **2.5 GSa/s**
  - RT = 580 ps ± 60 ps
  - RTσ = 24 ps
  - PW = 964 ps ± 50 ps
  - PWσ = 20 ps

**SR = BW x 5**

- **5 GSa/s**
  - RT = 550 ps ± 30 ps
  - RTσ = 8.7 ps
  - PW = 985 ps ± 30 ps
  - PWσ = 9.5 ps

---

[Image of oscilloscope screen displaying measurements for 2.5 GSa/s and 5 GSa/s.]
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
Oscilloscope Architecture

**Basic Oscilloscope Block Diagram**

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

DSO Block Diagram
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**

- 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

---

Tektronix Asynchronous Time Interleave (ATI)

Teledyne LeCroy Digital Bandwidth Interleave (DBI)
Infiniium UXR-Series – Returns to Time-Interleave Sampling

Some Highlights
- **No Frequency based Interleaving** – 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

Front End Multi-Chip Module

- Electromechanical Attenuator
- Pre-amp (110 GHz)
- InP
- InP
- Sampler (110 GHz)
- Sampler (30 GHz)
- Edge Trigger
- Advanced Trigger
- Buffer Amp
- 10 Bit ADC
- Memory Controller
- HMC
- Link to CPU

Timebase

Electromechanical Attenuator

Pre-amp (110 GHz)

Sampler (110 GHz)

InP

InP

Sampler (30 GHz)

Edge Trigger

Advanced Trigger

Buffer Amp

10 Bit ADC

Memory Controller

HMC

Link to CPU

Timebase
Oscilloscope Fundamentals

- 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
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

Scope with a slower update rate

Long Dead Time = Decreases the chance of capturing rare events

Scope with a faster update rate

Short Dead Time = Increases the chance of capturing rare events
• 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!
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
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.

\[
\text{Memory Depth (Sa)} = \text{Sample Rate} \left(\frac{\text{Sa}}{s}\right) \times \text{Time (s)}
\]
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
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 = 5 pts
Time Across Screen = 1 sec
Sample resolution: 200 msec
Sample rate: 5 Sa/s

Memory Depth = 50 pts
Time Across Screen = 1 sec
Sample resolution: 20 msec
Sample rate: 50 Sa/s
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)

Example:
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.
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
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.
Triggering

**BASIC RISING EDGE TRIGGER (DEFAULT)**

Untriggered / Auto-Trigger
(unsynchronized picture taking)

Rising edge @ 0.0 V

Rising edge @ +785 mV

Trigger Point

Trigger level set above waveform
Auto triggering: “I don’t see a trigger: I’ll trigger on my own”

Normal triggering: “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 I²C serial bus
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
  - ✔ Nth Edge Burst
  - ✔ Setup & Hold Time
  - ✔ Runt
  - ✔ Edge Speed

- Serial Bus Triggering
  - ✔ I²C, SPI, RS232/UART, I²S, CAN, LIN, FlexRay, SENT, MIL-STD 1553
Oscilloscope Fundamentals

• 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.

Images show visualizations of color grade and histogram, along with measurement histograms.
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
Probing Architecture, Tips, and Tricks

Resistor Divider Probes – Block Diagram

- 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.

Passive 10:1 Probe Model
At high frequencies, we get an impedance divider, because capacitors will begin to express non-real resistances on our circuit.

\[ C_{\text{parallel}} = C_{\text{comp}} + C_{\text{cable}} + C_{\text{scope}} \]

- \( C_{\text{comp}} \) is adjusted by the user to create a 10:1 divider of capacitive elements using the following formula: \( 9 C_{\text{tip}} = C_{\text{parallel}} \)
Probing Architecture, Tips, and Tricks

RESISTOR DIVIDER PROBES – LOADING CHARACTERISTICS

N2873A 500 MHz Passive Probe
10 MΩ, 9.5 pF

Impedance (ohm)

Frequency (Hz)

10 kHz

~150 Ω

Lower

Higher

probe loading
Probing Architecture, Tips, and Tricks

Active Probe Loading is Superior to Passive

N2873A 500 MHz
Passive Probe
10 MΩ, 9.5 pF

N2796A 2 GHz
Active Probe
1 MΩ, 1 pF

Impedance (ohm)

Frequency (Hz)

- Lower
- Higher

10 kHz
~2.5 kΩ
~150 Ω

70 MHz
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](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
  - Register for Future Webcasts: [https://kee.smarket.net.cn/2019/index.html](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=yBC97UUjlKo](https://www.youtube.com/watch?v=yBC97UUjlKo)
  - Bandwidth: [https://www.youtube.com/watch?v=VBJWkceO1OA](https://www.youtube.com/watch?v=VBJWkceO1OA)
  - Update Rate: [https://www.youtube.com/watch?v=CPDlrKSDrZk](https://www.youtube.com/watch?v=CPDlrKSDrZk)
  - Memory Depth: [https://www.youtube.com/watch?v=GAM_CpxVYq8](https://www.youtube.com/watch?v=GAM_CpxVYq8)
  - Eye Diagrams: [https://www.youtube.com/watch?v=mnugUjaMN70](https://www.youtube.com/watch?v=mnugUjaMN70)
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

Infinium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

- UXR系列 13~110GHz
  10-bit ADC
- Z系列 20~63GHz
- V系列 8~33GHz
- S系列 500MHz~8GHz