Oscilloscopes basics

Introduction

- modern oscilloscope is one of the most common and universal measuring instruments used in many applications
- oscilloscope displays a visual representation of the measured signal
  - usually the signal voltage (y axis) vs. time (x axis) – waveform
- gives a quick overview over the signal characteristics
  - signal shape (AC, DC parts), voltage values
  - time related parameters – frequency, period, impulse length, ...
  - amount of noise present in the signal
- can be used to measure various physical quantities using signal transducers
  - electrical current, pressure, strain, light intensity, ...

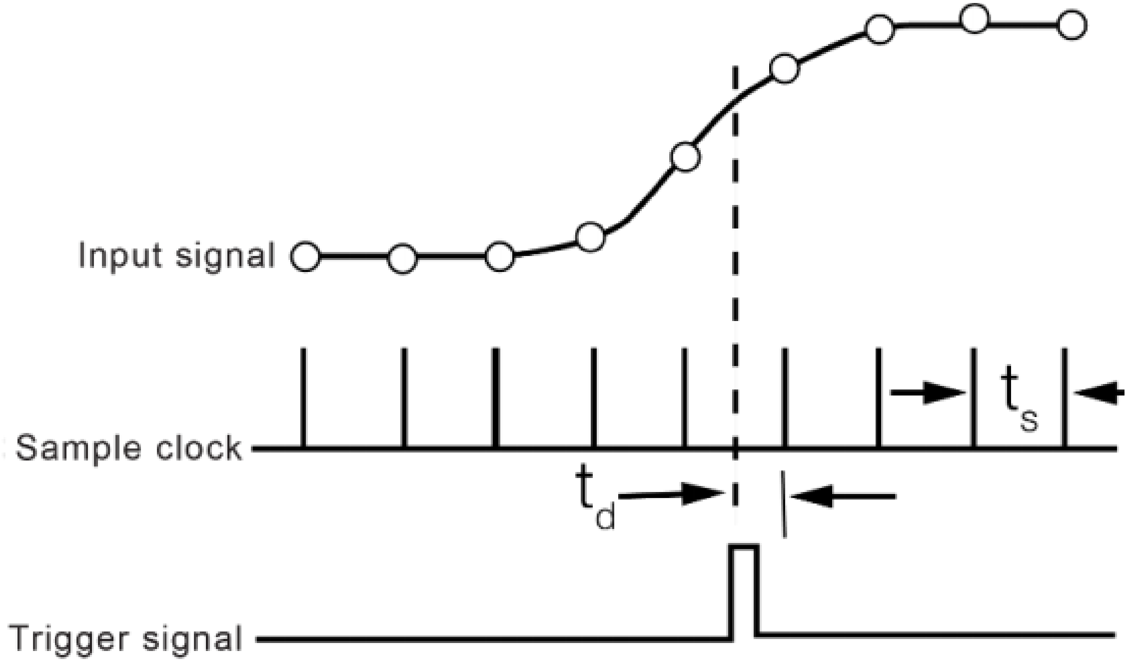
Introduction

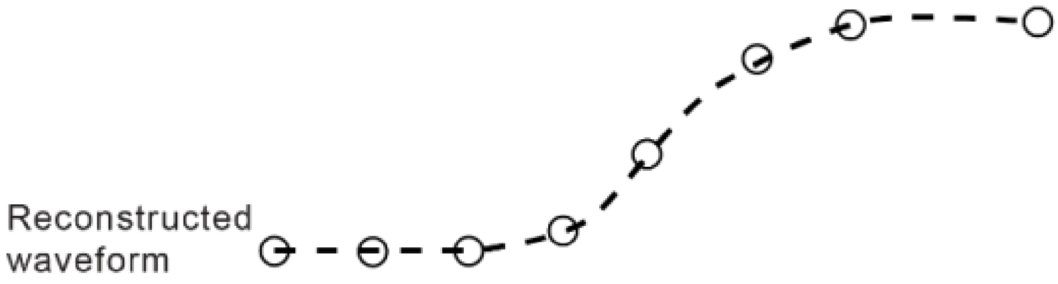
- basic types of oscilloscopes:
  1) legacy analog oscilloscopes
     - used a CRT to display the signal; require periodic signals; no signal postprocessing
  2) digital oscilloscopes
     - use ADCs to digitize the signal after passing through an analog frontend

real time sampling oscilloscopes or **equivalent time sampling** oscilloscopes

Real time oscilloscopes

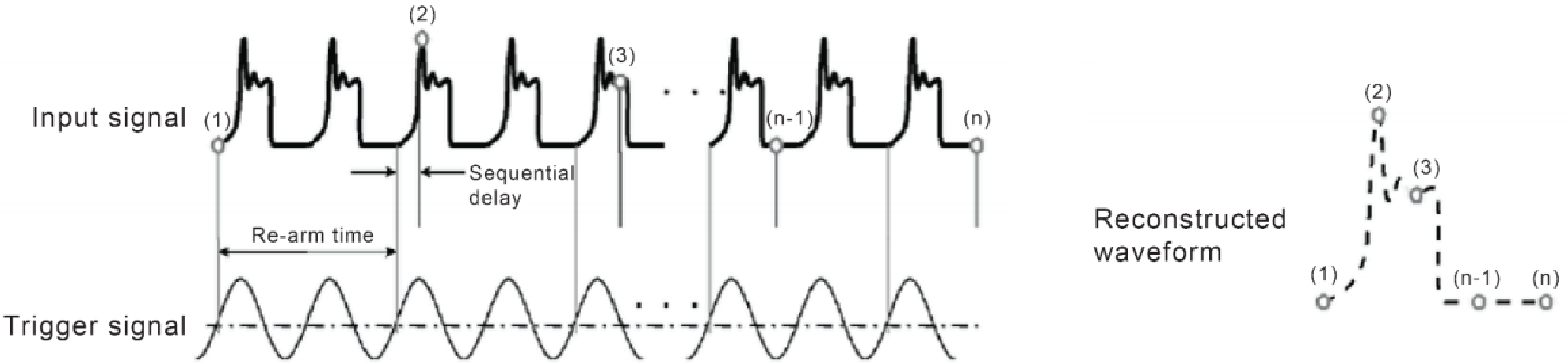
1) real time sampling oscilloscopes
   - use very fast ADCs (sample rate > 2,5 * bandwidth) and are capable of capturing an entire waveform on each trigger event (capable of “single shot” measurement)
   - doesn’t require an external trigger; can be triggered from the measured signal





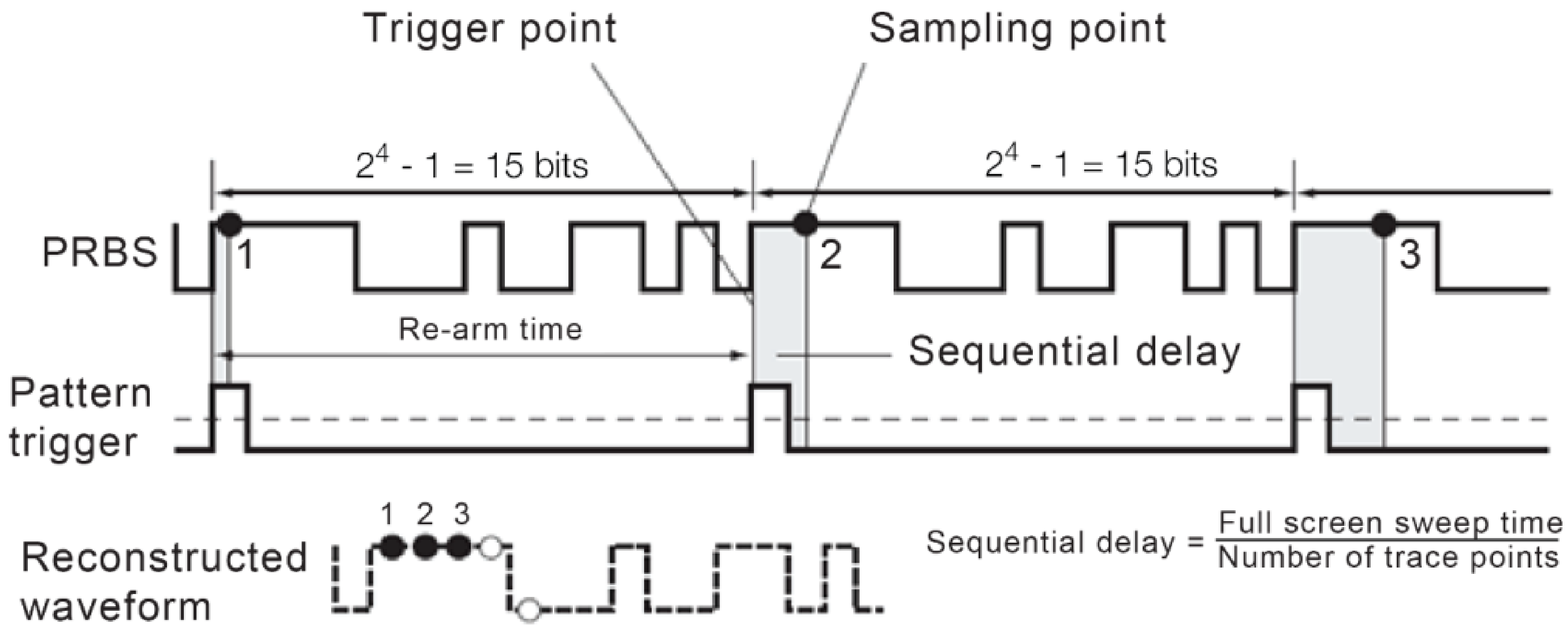
Equivalent time sampling oscilloscopes

2) equivalent time sampling oscilloscopes
   - use a slow ADC – “one sample per trigger” sampling
   - each new sampling occurs with slight (precisely known) incremental delay
   - only for repetitive signals – waveform is drawn over many measurement cycles
   - requires explicit trigger – either a trigger signal or a clock recovery module



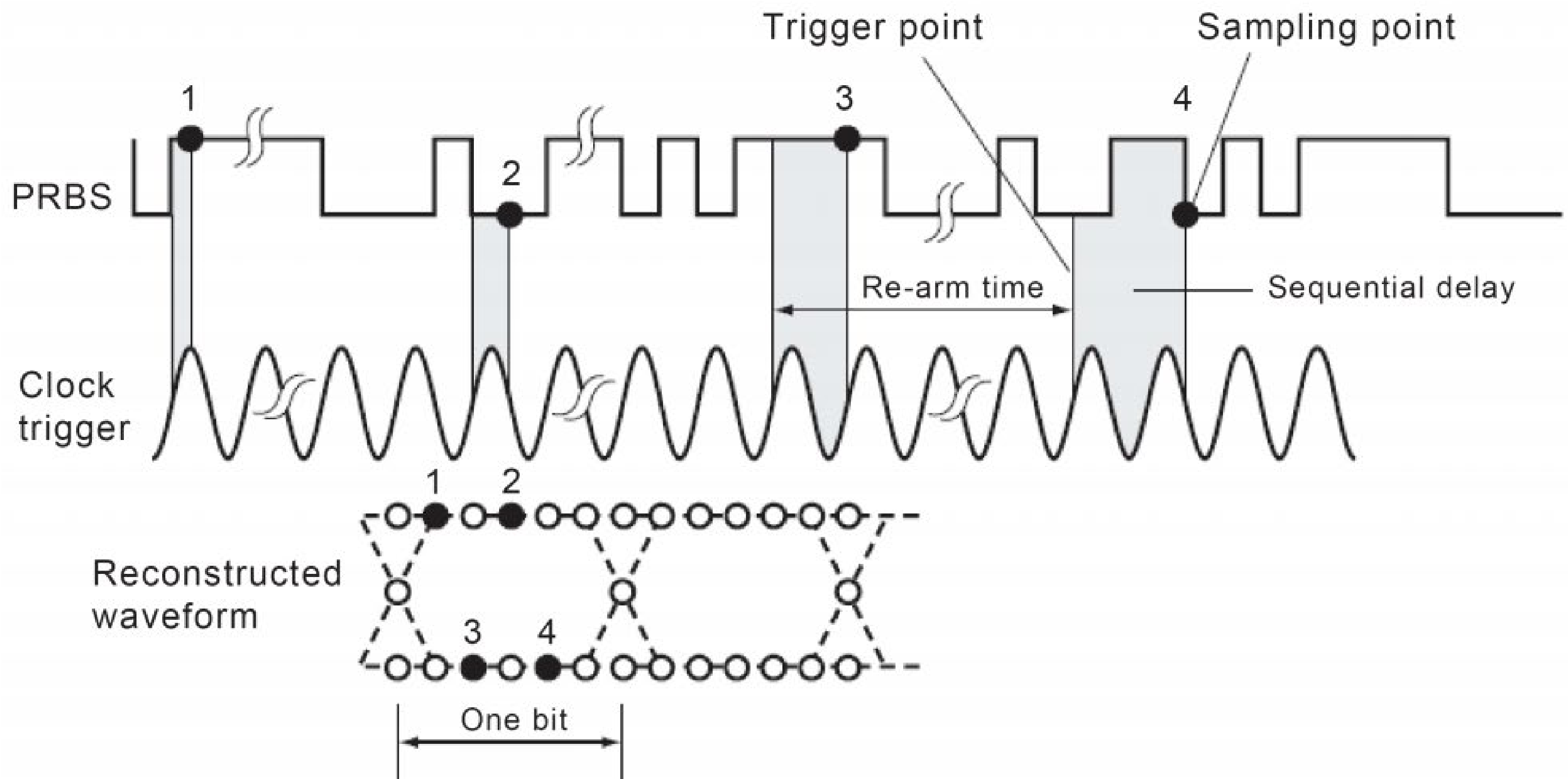
Equivalent time sampling oscilloscopes

- ETS oscilloscopes can be used for a bit stream measurement, but the trigger needs to be synchronized with the bit pattern period:



Equivalent time sampling oscilloscopes

- another (maybe more common) measurement type the ETS oscilloscopes are used for is a “eye diagram” measurement
  - shows all transitions present in measured digital signal
  - doesn’t require synchronisation to the bit pattern; often used with clock recovery



RT vs ET sampling oscilloscopes

real time vs. equivalent time oscilloscopes

real time

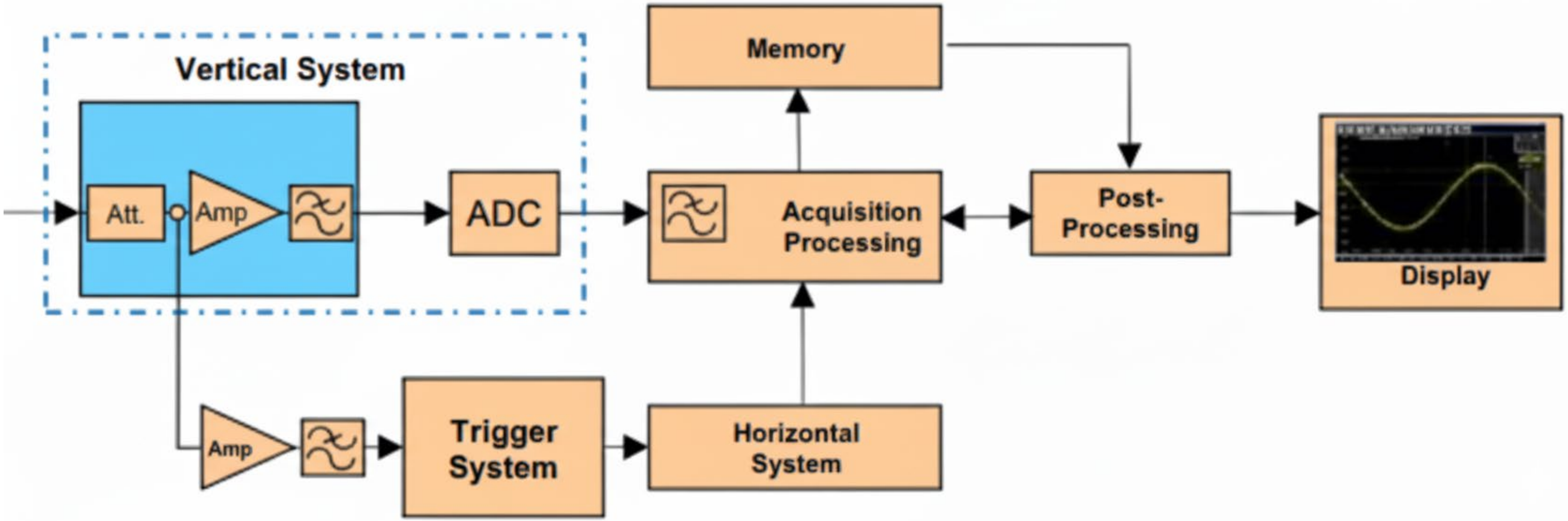
+ can capture “single shot” events
+ doesn’t require external trigger
+ longer memory; record length
+ many extra features (decoding, ...)
- worse bandwidth/price ratio (much more expensive than ET scope with given BW)
- high speed ADC design is tricky; signal integrity can be worse

equivalent time

- only for repetitive stable signals
- requires explicit external trigger
+ lower cost for the same bandwidth
+ slow ADCs with high resolution; some parameters can be better (noise floor, intrinsic jitter)

RT oscilloscopes - architecture

- basic real time digital oscilloscope block diagram:

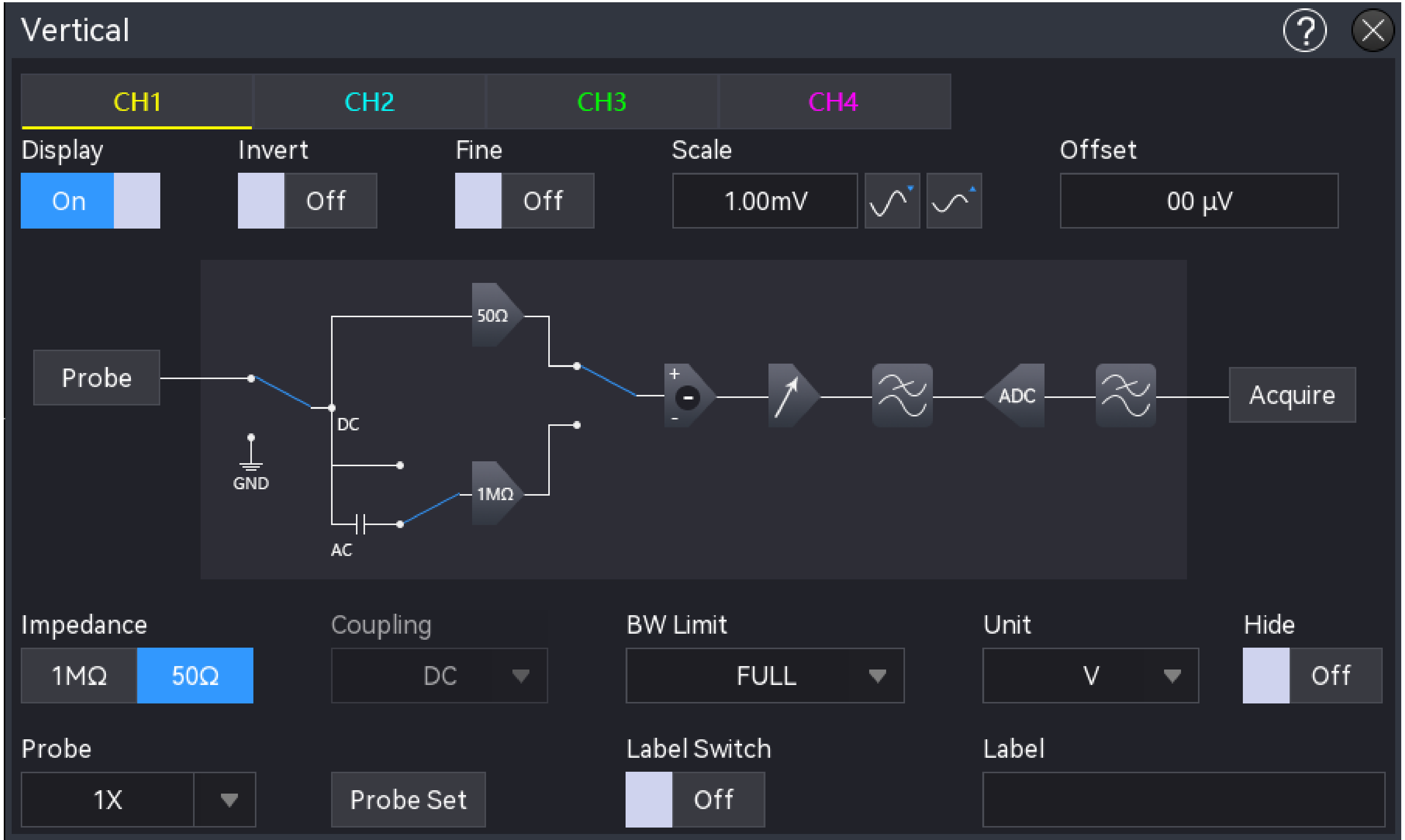


RT oscilloscopes – front end

- analog front end - input analog signal processing block present in every RT scope
  - provides attenuation and amplification of the input signal
    so it can be processed correctly by the ADC
  - input impedance – 1 MΩ (in parallel with certain capacitance) or 50 Ω
    - choice depends on the signal input type (direct coax / probe, probe type)
  - provides different signal path options:
    - input of the channel can be switched to internal ground
    - AC or DC coupling (AC can be used to remove the DC part of the signal)
  - provides hw low pass filtering of the signals
  - front end design quality is very important and directly affects the properties of the oscilloscope (noise, distortion, ...)

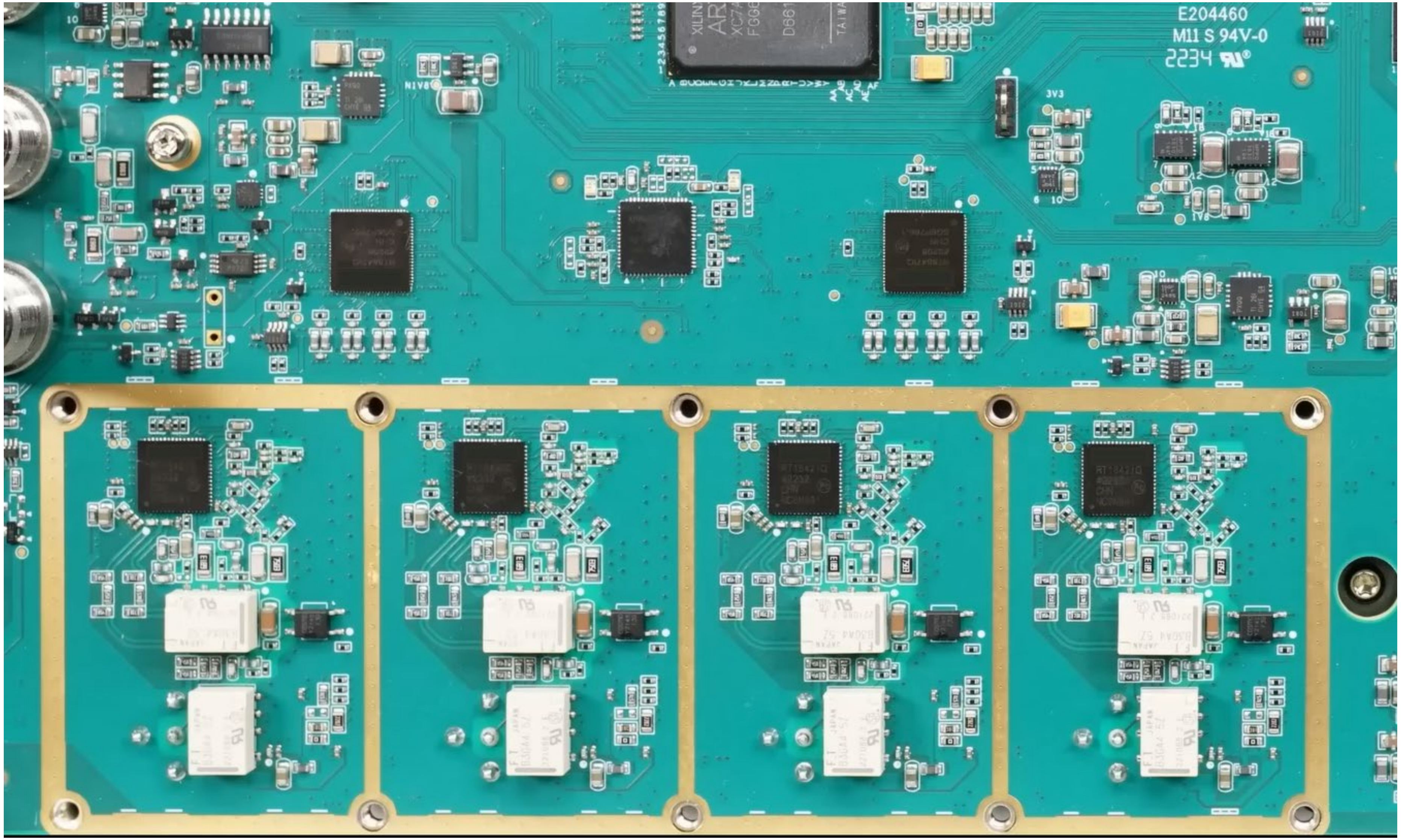
RT oscilloscopes – front end

- example of the signal input configuration dialogue:



RT oscilloscopes – front end

- analog front end (four channels):

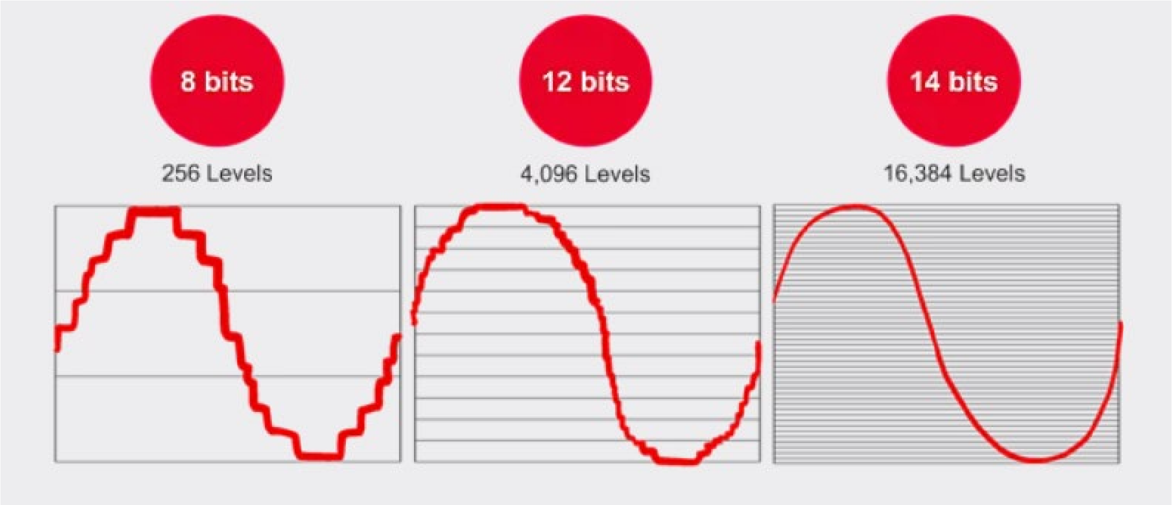


RT oscilloscopes – front end

- it is very important to keep in mind the voltage limits on the input connectors
  - typically > 100 V rms with 1 MΩ input impedance
  - typically 5 V rms into 50 Ω (thermal damage to the matching resistors)
- input connectors share common ground and are connected to the ground of the instrument (mains) – this can cause problems with passive probes
- the input capacitance is also specified here – can be important when choosing passive probes (so it falls within the probe compensation range)

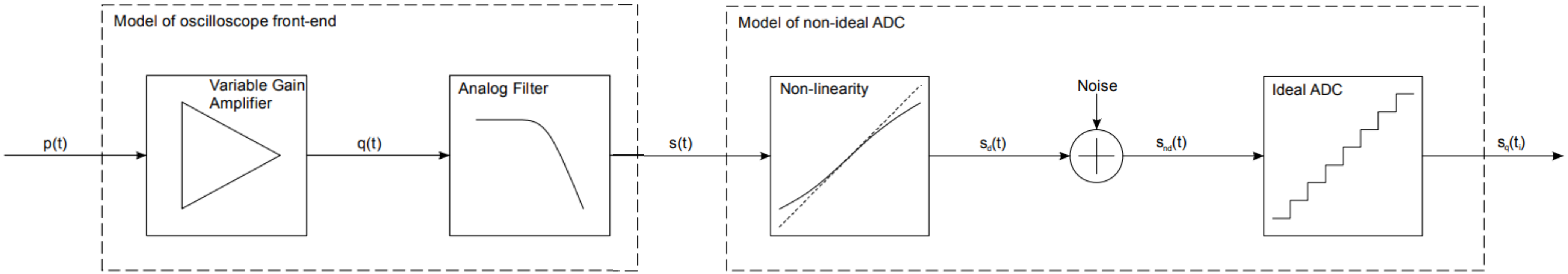
RT oscilloscopes – ADC

- ADC is another principal part of the oscilloscope
  - digitizes the input analog voltage signal; needs to be very fast
    - sample rate has to be theoretically at least 2x the BW
    - practically, at least 2.5x BW because of the low-pass filter rollout
  - one of the “popular” specifications of oscilloscopes is the resolution of ADC
    - 8 bits (256 levels) for lower end or older oscilloscope models
    - 10 (1024 levels), 12, 14 bits for modern oscilloscopes



RT oscilloscopes – ADC

- in practice, the physical resolution of the ADC is not that important and the better figure of merit is the “effective number of bits” (ENOB)
  - describes the overall noise and distortion performance of the oscilloscope (quantifies the quality of an analog to digital conversion)
    - including the performance of the analog front-end, which can be more important than the physical resolution of the ADC



- ENOB can be calculated from SINAD using this formula:

$$ENOB = (SINAD - 1.76) / 6.02$$

RT oscilloscopes – ADC

- RMS noise specification for the Keysight HD3 oscilloscope:

RMS noise floor ($V_{RMS\ AC}$) on 50 Ω inputs

Vertical setting	20 MHz	100 MHz	200 MHz	350 MHz	500 MHz	1 GHz
500 uV/div, 2 mV/div	13 u	20 u	26 u	30 u	35 u	48 u
5 mV/div	16 u	25 u	33 u	38 u	44 u	59 u
10 mV/div	24 u	35 u	49 u	56 u	67 u	87 u
20 mV/div	44u	63 u	89 u	104 u	124 u	159 u
50 mV/div	92 u	141 u	202 u	239 u	286 u	366 u
100 mV/div	189 u	278 u	399 u	474 u	568 u	723 u
200 mV/div	442 u	638 u	898 u	1.06 m	1.26 m	1.60 m
500 mV/div	942 u	1.41 m	2.03 m	2.41 m	2.88 m	3.66 m
1 V/div	1.78 m	2.82 m	4.04 m	4.79 m	5.74 m	7.26 m

- ENOB:

ENOB (normal sample mode 100 mV/div, 1M Ohm) on a 10 MHz 90% full-screen sine wave

Input	20 MHz	50 MHz	100 MHz	200 MHz	350 MHz	500 MHz	1 GHz
50 Ω	10.4	9.9	9.5	9.0	8.8	8.5	8.2
1M Ω	10.3	9.9	9.5	8.9	8.8	8.4	N/A

RT oscilloscopes – averaging

- most of the digital oscilloscopes offer two ways how to increase waveform resolution and decrease the amount of noise in the trace
  1) “Hi-Res” mode
     - in this mode, the oscilloscope takes certain number of subsequent samples from the ADC and calculates an average value which is displayed as a trace point
     - this mode **reduces the effective sample rate**, reduces noise, increases resolution and it can be used even for a single shot acquisition
  2) trace averaging
     - the oscilloscope shows an average of a defined number of previous traces
     - **doesn’t reduce the sample rate** but ....
     - .... requires a stable (low jitter) trigger to get a reasonable result
- Keysight HD3 oscilloscopes can use both of these methods at the same time

Basic specifications

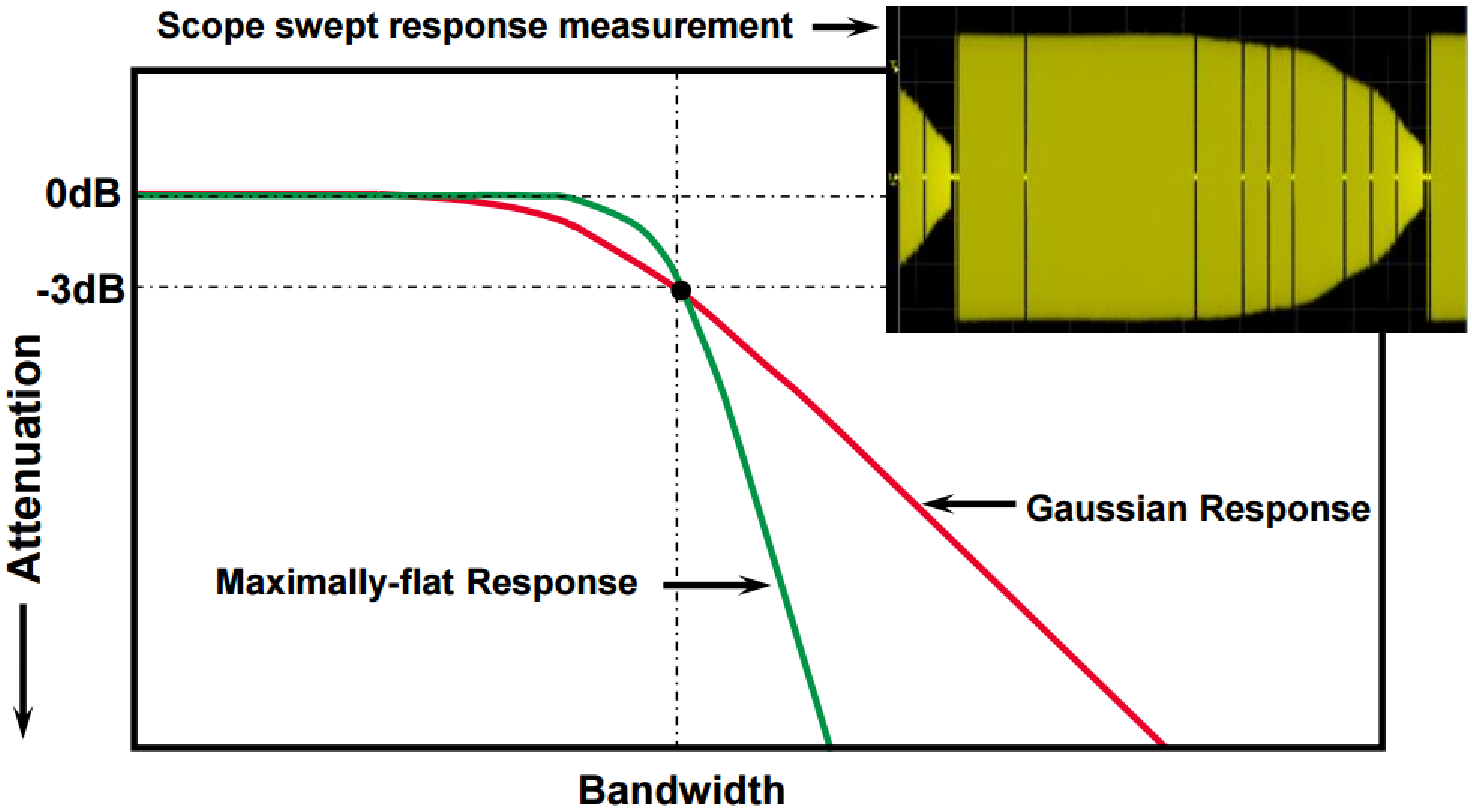
- number of channels
  - modern oscilloscopes can have 2, 4, 6 or 8 analog channels
    - more than 4 channels can be practical for example for power analysis (voltage+current)
  - most oscilloscopes can be equipped with 16 digital channels
- bandwidth – defines the fastest signal the oscilloscope can capture
- sample rate – often shared between channels
- memory depth – often shared between channels
- waveform update rate
- vertical resolution
- integrated AWG – maximum frequency, number of channels

Basic specifications

- other, not so obvious, but important specifications:
  - noise floor; ENOB – as mentioned, describes the overall performance
  - hw bandwidth filters – can be very useful for slower signals; noise reduction
  - sensitivity of the triggering system
  - offset range
  - amplitude accuracy
  - phase flatness
  - spurious free dynamic range (SFDR)
  - timebase accuracy
  - measurement speed with longer memory depths

Bandwidth

- defined as the -3 dB point on the oscilloscope's amplitude response



Bandwidth – Gaussian response

- older analog and digital oscilloscopes typically had Gaussian response
  - this is a result of a series of analog circuit elements with similar frequency response
  - Gaussian response offers good pulse response without overshoot (regardless of the input signal rise time)
  - larger signal attenuation before the -3 dB point and slower rolloff
  - -3 dB bandwidth is related to the rise time using this well known formula:

$$Bandwidth = 0.35 / RiseTime$$

  - overall system rise time (signal + oscilloscope + probes + ...):

$$SystemRT = \sqrt{RT_1^2 + RT_2^2 + \ldots}$$

Bandwidth – flat response

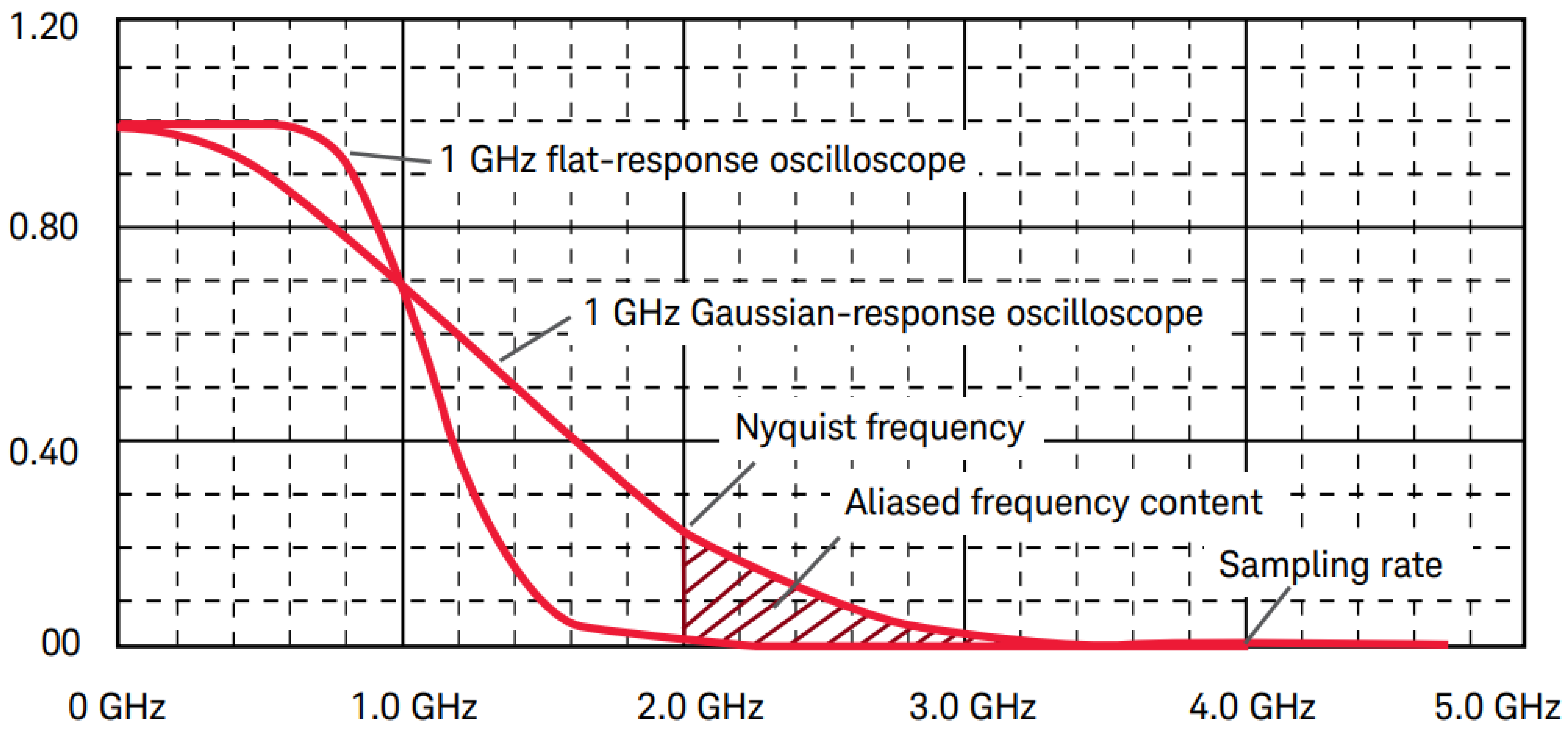
- modern high-bandwidth digital oscilloscopes typically exhibit a “maximally flat” (or so called “brick wall”) amplitude response
  - frequency content of the signal below the –3 dB point is less attenuated and thus measured more accurately
  - the steeper roll-off helps reduce sampling alias errors
  - in the time domain, a flat-response results in a pulse response with overshoot and ringing when the oscilloscope input is driven with a fast step input
  - the rise time is related to the bandwidth, as described in this formula:

$$Bandwidth = (0.4 - 0.5) / RiseTime$$

  - unlike Gaussian systems, the system bandwidth of a flat-response oscilloscope is not determined by the inverse RMS value of the subsystem parts

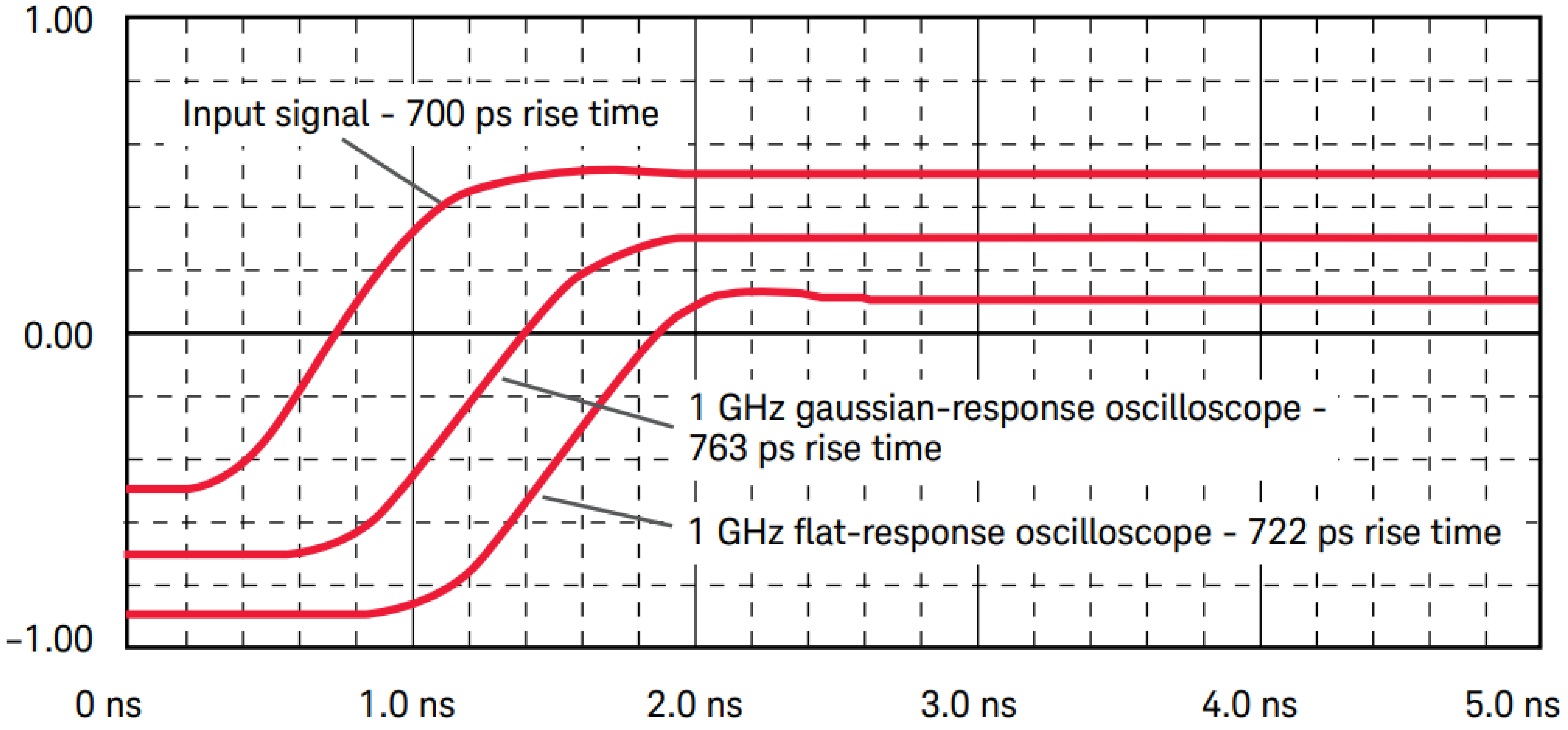
Bandwidth – flat response

- Gaussian vs. flat response comparison (frequency domain):



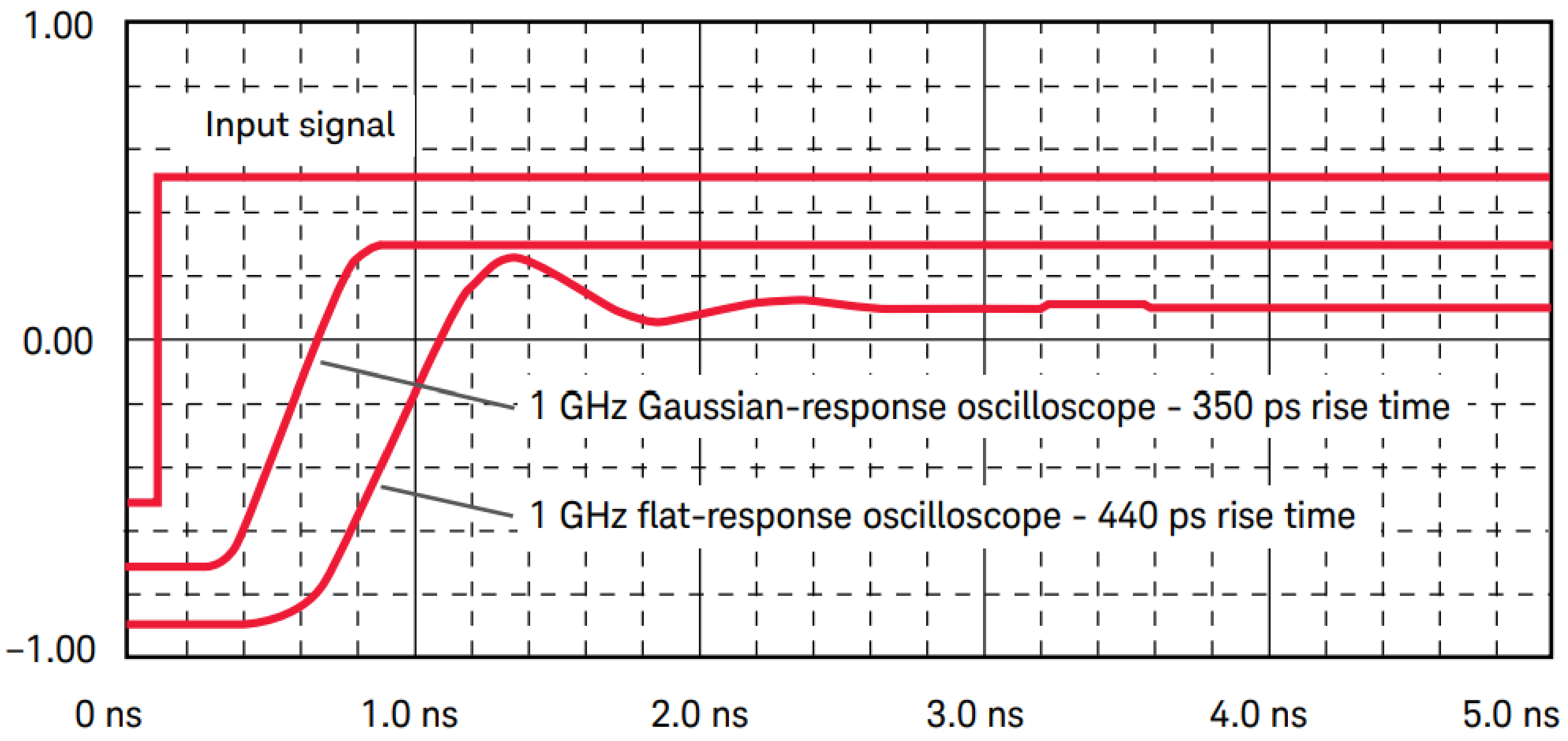
Bandwidth – flat response

- Gaussian vs. flat response comparison (time domain; 700 ps rise time):



Bandwidth – flat response

- Gaussian vs. flat response comparison (time domain; fast step):



Bandwidth filtering

- even older oscilloscope models typically offer some hw low-pass filters
  - in most cases 20 MHz, sometimes 200 MHz
- modern oscilloscopes have the ability to apply digital low-pass filtering with selectable cutoff frequencies
  - this can be implemented in hw (FPGA/ASIC) to speed up the processing
  - filtering brings significant noise level reduction and is recommended for measuring of slower signals which do not require the full hw bandwidth

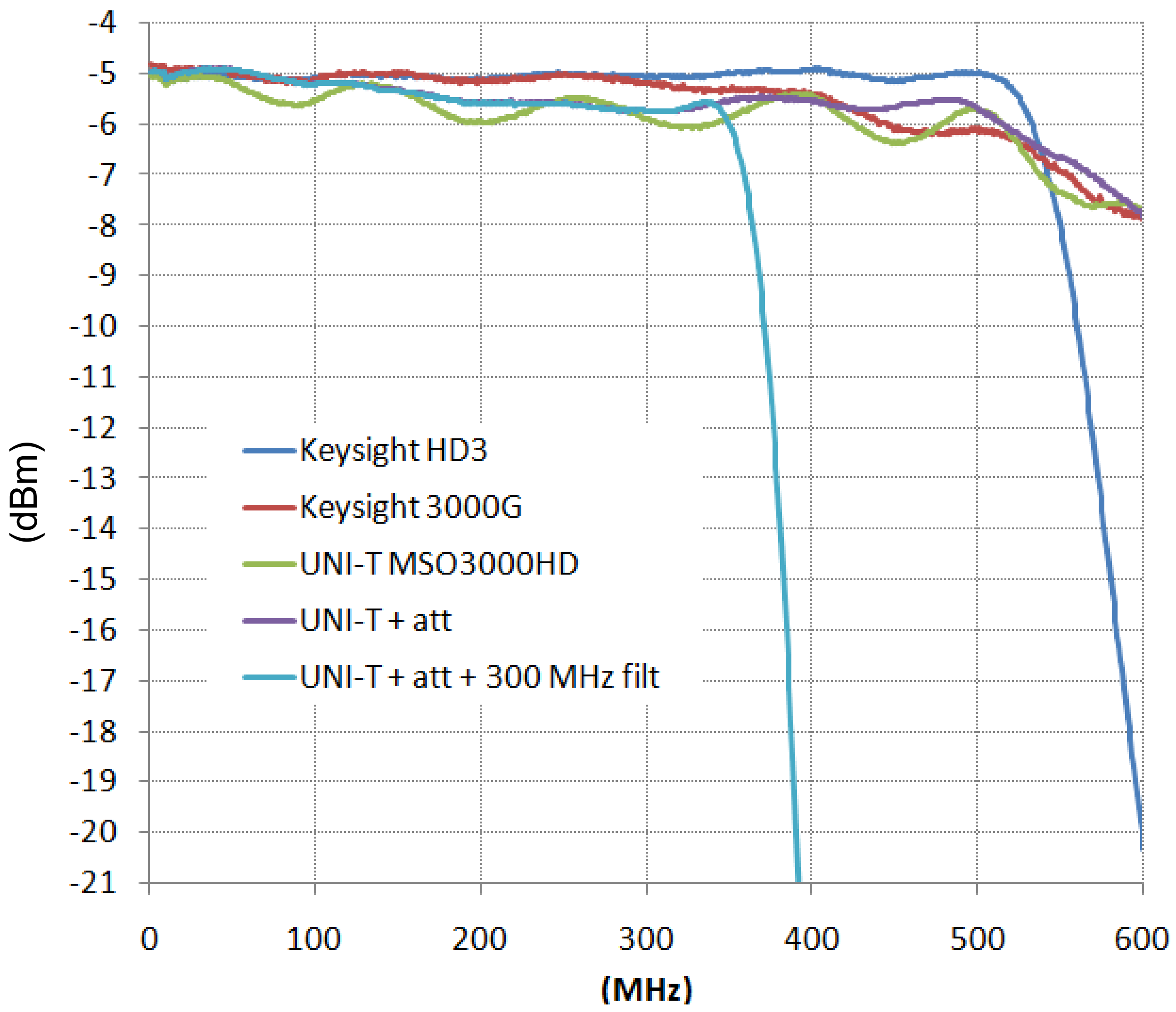
Vertical system analog channels	
Hardware bandwidth limits	20, 40, 50, 100, 200, 350 MHz (selectable), per-channel 5, 10, 20, 40, 50, 100, 200, 350 MHz (selectable), global

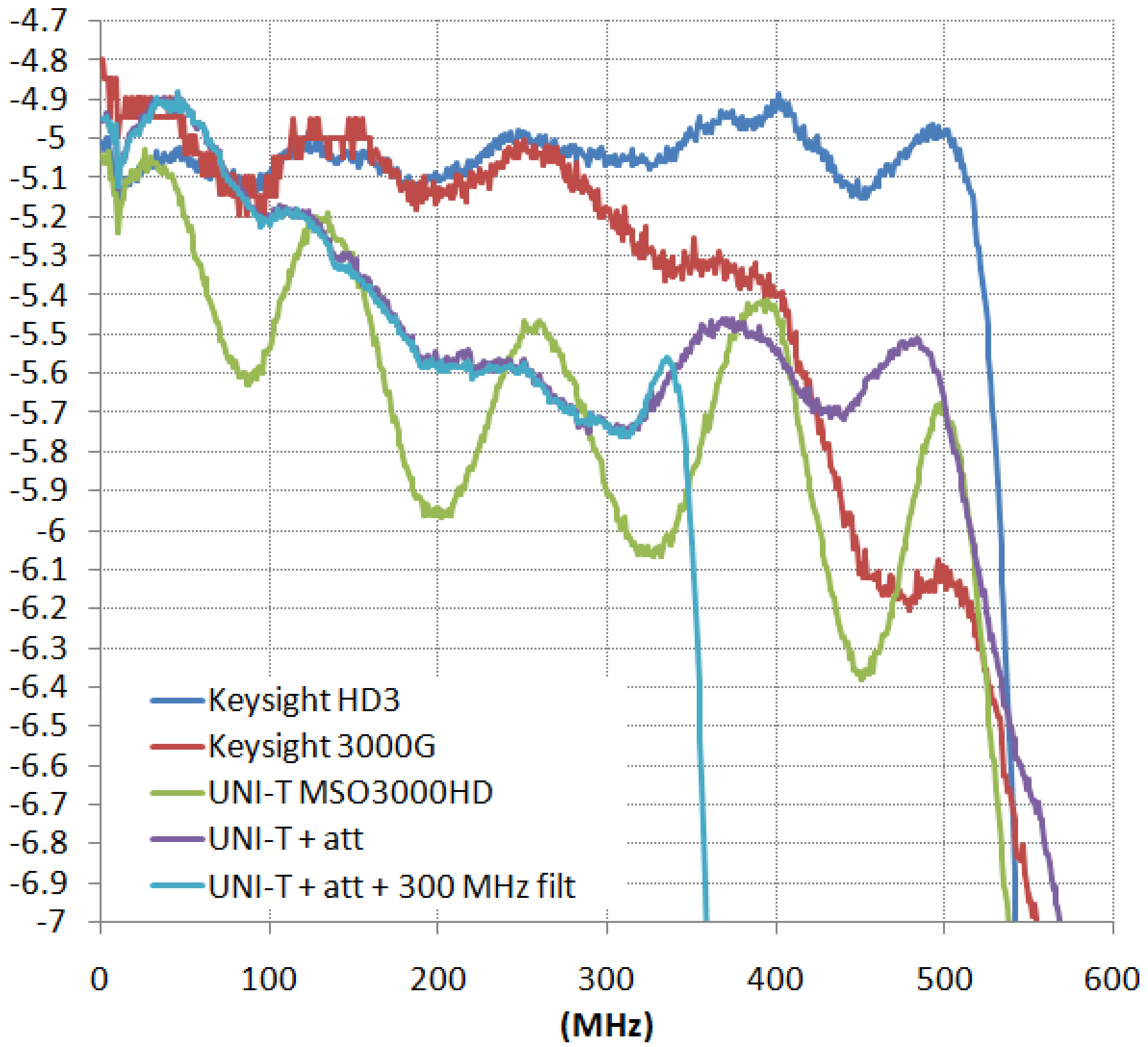
Frequency response / Correction filters

- each oscilloscope has a unique frequency response – the ability to accurately acquire signals up to the rated bandwidth
  - the oscilloscope should have a flat amplitude and phase frequency response
  - a non-flat response causes distortion of the measured signal (relative phase and amplitude shift for different frequency components building the signal)
- depending on the make and model, oscilloscopes can use analog filters (in the front-end) and DSP filters on the sampled data to achieve a uniform and flat frequency response

Frequency response / Correction filters

- example measurement of the amplitude frequency response (-5 dBm signal):



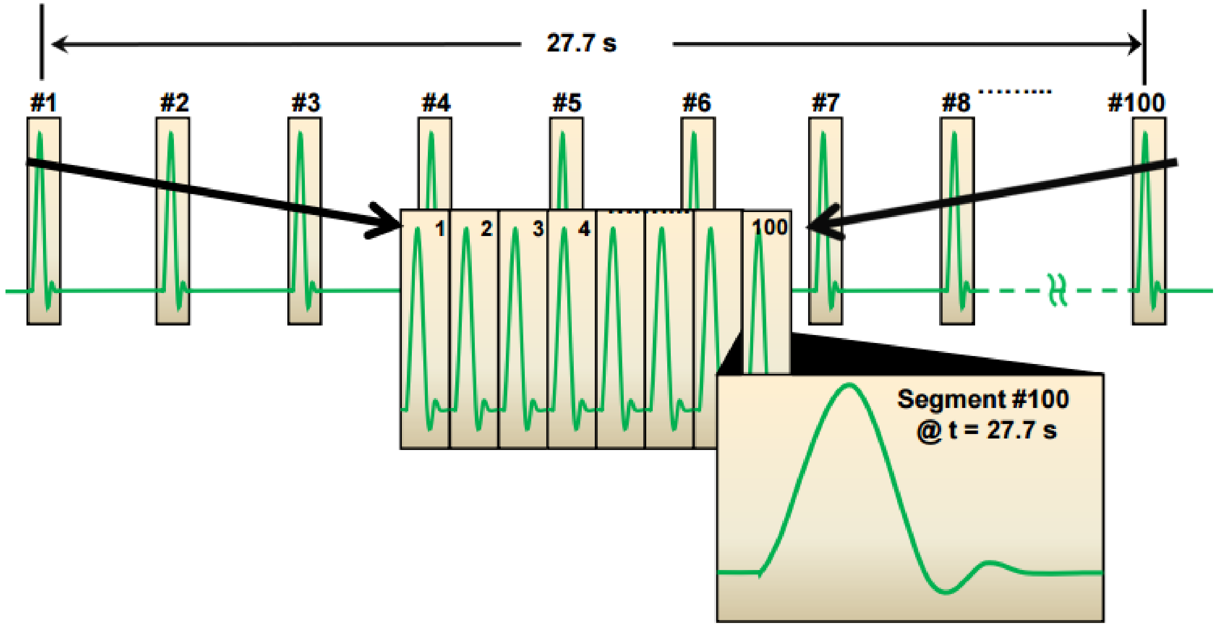


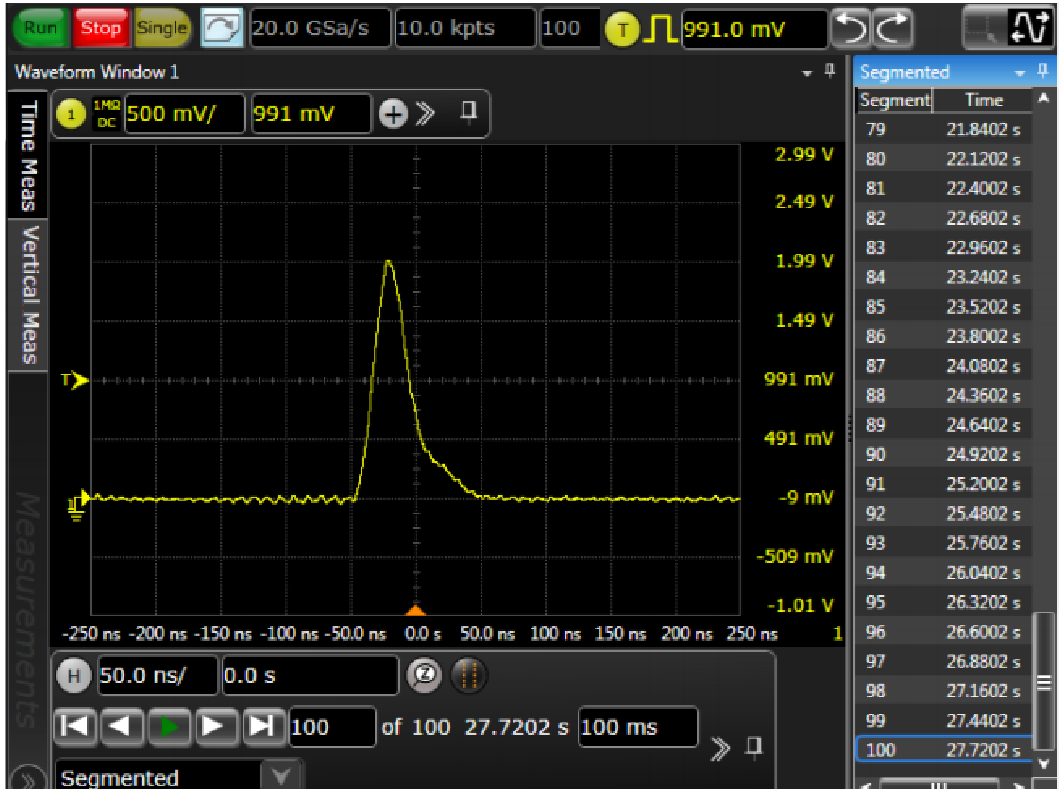
Memory depth

- "how many samples/points the oscilloscope can take at one time..."
- long memory can be important because the oscilloscope can keep the high sample rate (good time resolution) even with longer time captures
  - older oscilloscope models with shorter memory needed to reduce the sample rate early when setting slower time base (longer capture intervals)
  - latest scopes can have tens to hundreds of Mpoints per channel
  - for example, the HD3 can capture up to 30 ms with it's full sample rate of 3.2 GSa/s
  - long memory can be useful in combination with the "zoom" function – the user can capture long signal interval and still be able to look at the fine details later

Segmented memory

- “segmented memory” is a special mode of acquisition useful when capturing shorter signal intervals with large gaps between them
  - the memory is used only for the useful parts of the signal, not the “dead time”
  - especially useful for serial communication signals – the osciloscope can capture thousands of packets spanning minutes or hours



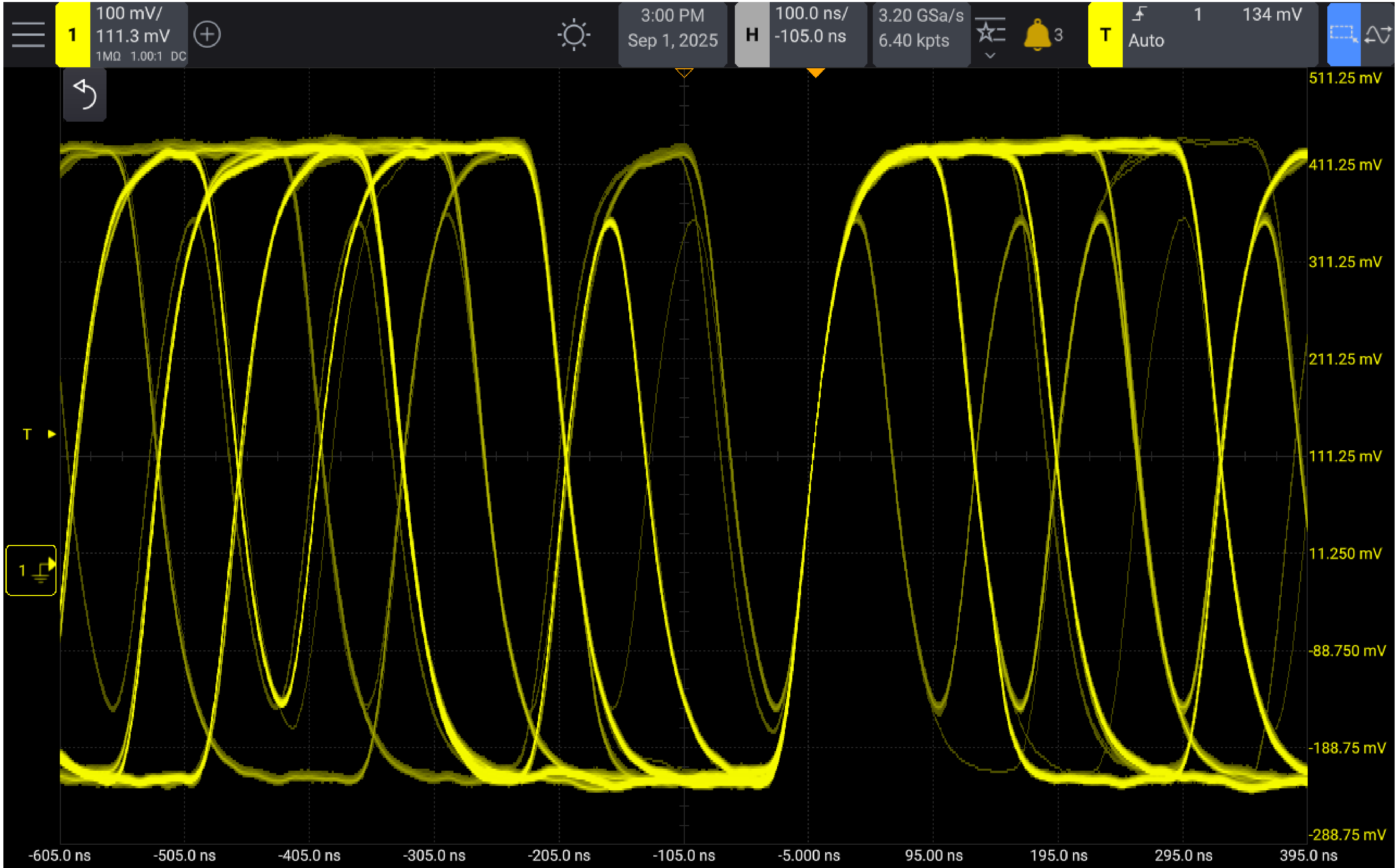


Waveform update rate

- waveform update rate (or trigger rate / capture rate) refers to the number of waveforms an oscilloscope can acquire, process, and display per second
- usually expressed in waveforms per second (wfms/s)
  - modern scopes can do hundreds of thousands to millions wfms/s
- depends on the “trigger re-arm time” (or so called “dead time”) between the individual acquisitions
- display update rate is much slower than the capture rate and the trace shown on the screen aggregates thousands of acquisitions
  - Keysight oscilloscopes use a very intuitive “intensity” display to show the probability of the signal being in a particular area

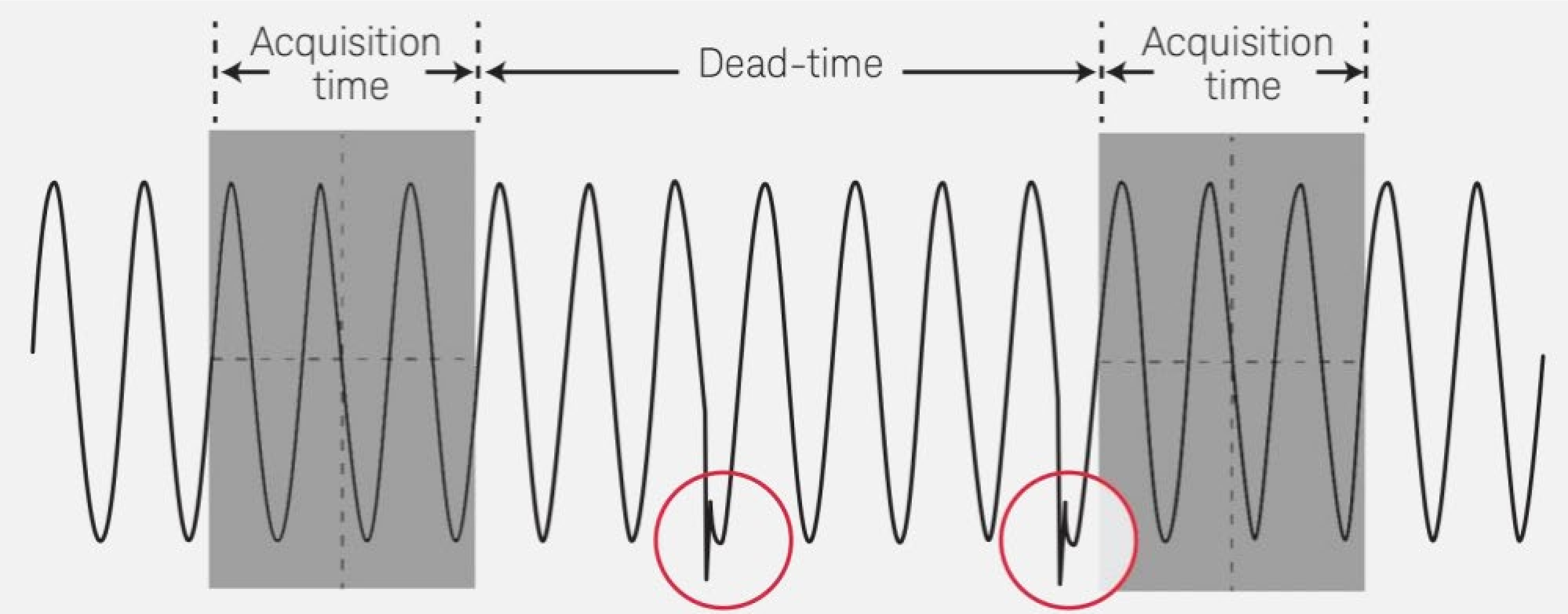
Waveform update rate

Waveform update rate



Dead time

- dead time is the time lost to the oscilloscope between individual acquisitions
  - shorter dead time means much higher probability of capturing intermittent glitches

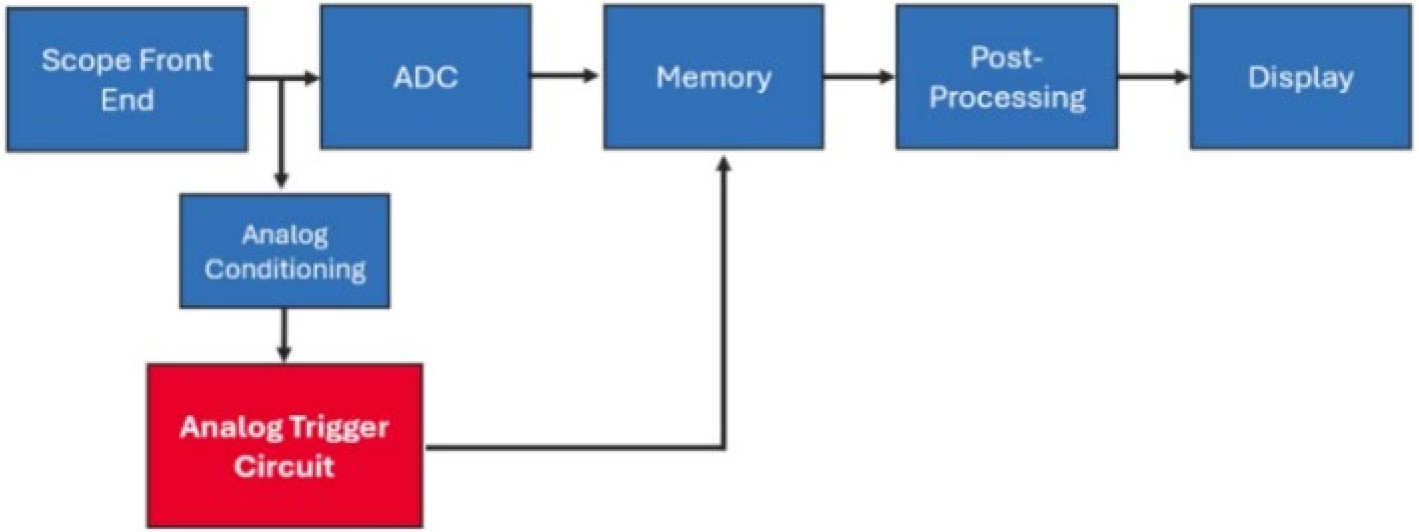


Triggering

- the trigger system is one of the fundamental elements of every oscilloscope
- trigger synchronizes the horizontal sweep with the input signal and is essential for clear signal characterization
  - stabilizes repetitive waveforms and allows a single-shot capture
- basic trigger modes:
  - “auto” – oscilloscope produces an automatic asynchronous trigger when a valid trigger condition is not present; displays an untriggered waveform
  - “triggered/normal” – produces a trigger only if a valid trigger condition occurs
  - “single” – waits for a valid trigger condition and produces a “single-shot” acquisition

Triggering

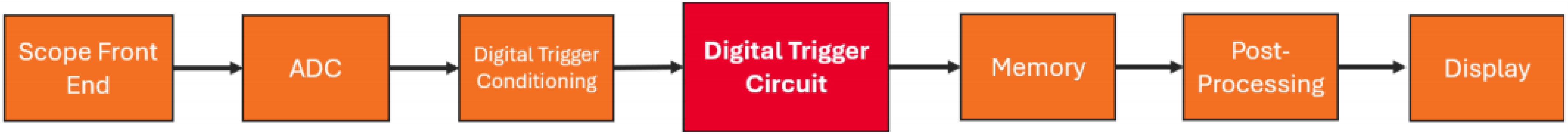
- older oscilloscopes used an analog trigger circuit (at least for edge trigger)
  - two separate signal paths – a measurement path and a trigger path



  - both paths contain different (non-)linear distortions which cause a systematic mismatch between the displayed signal and the determined trigger point
  - analog trigger is usually less accurate and sensitive

Triggering

- most of the modern oscilloscopes use a fully digital triggering
  - trigger system uses the main measurement path and operates directly on the samples of the ADC; looks for trigger conditions in the digitized data



  - some of the impairments that occur in analog trigger systems are inherently eliminated → digital triggers enable higher trigger accuracy and trigger sensitivity
  - faster re-arm times compared to analog triggers

Triggering

- modern digital oscilloscopes offer many different types of trigger conditions in addition to the most basic “edge” trigger:

- Edge-then-Edge – arming + trigger edge; defined delay between the edges

- Pulse width – trigger on a pulse (+ / -) with defined length (< / > / <>)

- Runt – triggers on pulses with defined amplitude between low and high levels

- Setup and hold – triggers on time violations on clock/data signals (the clock edge not within certain zone around the center of the data signal)

- Rise/fall time – trigger on specific rise or fall times (< / >)

- Pattern – user can define a combination of states (0/1) on analog and digital channels (+ one edge condition optionally)

- Or – trigger on any edge on selected analog and digital channels

Triggering

- current oscilloscopes can typically also trigger on serial bus communications
  - capabilities will depend on the oscilloscope model and bus type
  - for example, triggering on a CAN (FD, XL) bus on the Keysight HD3 oscilloscope:

CAN, CAN FD, CAN XL (optional)	Trigger on CAN (controller area network) version 2.0A, 2.0B, and CAN-FD (Flexible Data-rate) signals. Trigger on the Start of Frame (SOF), the end of frame (EOF), data frame ID, data frame ID and data (non-FD), data frame ID and data (FD), remote frame ID, remote or data frame ID, error frame, acknowledge error, from error, stuff error, CRC error, spec error (ack or form or stuff or CRC), all errors, BRS Bit (FD), CRC delimiter bit (FD), ESI bit active (FD), ESI bit passive (FD), overload frame., message, message and signal (non-FD), message and signal (FD, first 8 bytes only)

- large differences between oscilloscopes can be in the implementation of advanced triggering
  - lower-end instruments typically use software triggers; “better” instruments have triggering implemented in HW (FPGA/ASIC)
  - software triggering is much slower

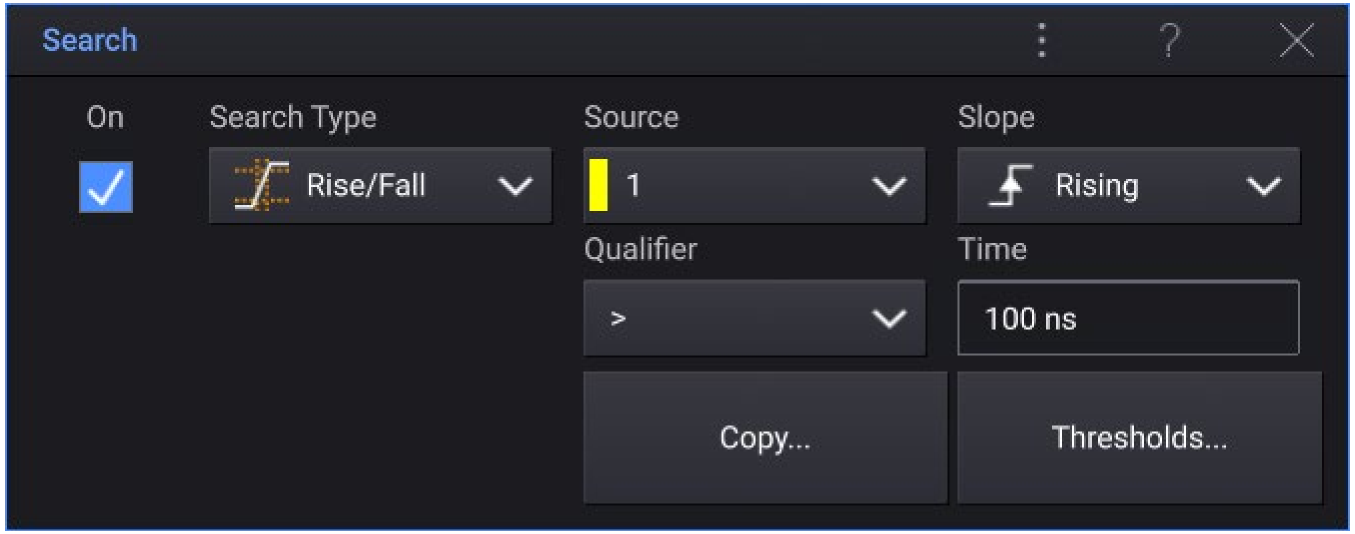
Triggering

- “Zone trigger” is another modern function implemented probably in most of the current digital oscilloscopes
  - zone trigger works as a complementary trigger condition to the primary trigger
  - zone(s) can be drawn on the display area to isolate certain waveforms within the measured signal; zone can be set as a “must intersect” or “must not intersect”
  - multiple zones can be used at the same time with logical “AND”/”OR” qualifiers
  - Keysight HD3 oscilloscopes can even define zones on different channels if needed
- advanced trigger settings
  - coupling – AC/DC; holdoff – useful for triggering on bursted signals
  - filtering – noise reject (LF, HF), hysteresis (disable for very low level signals)

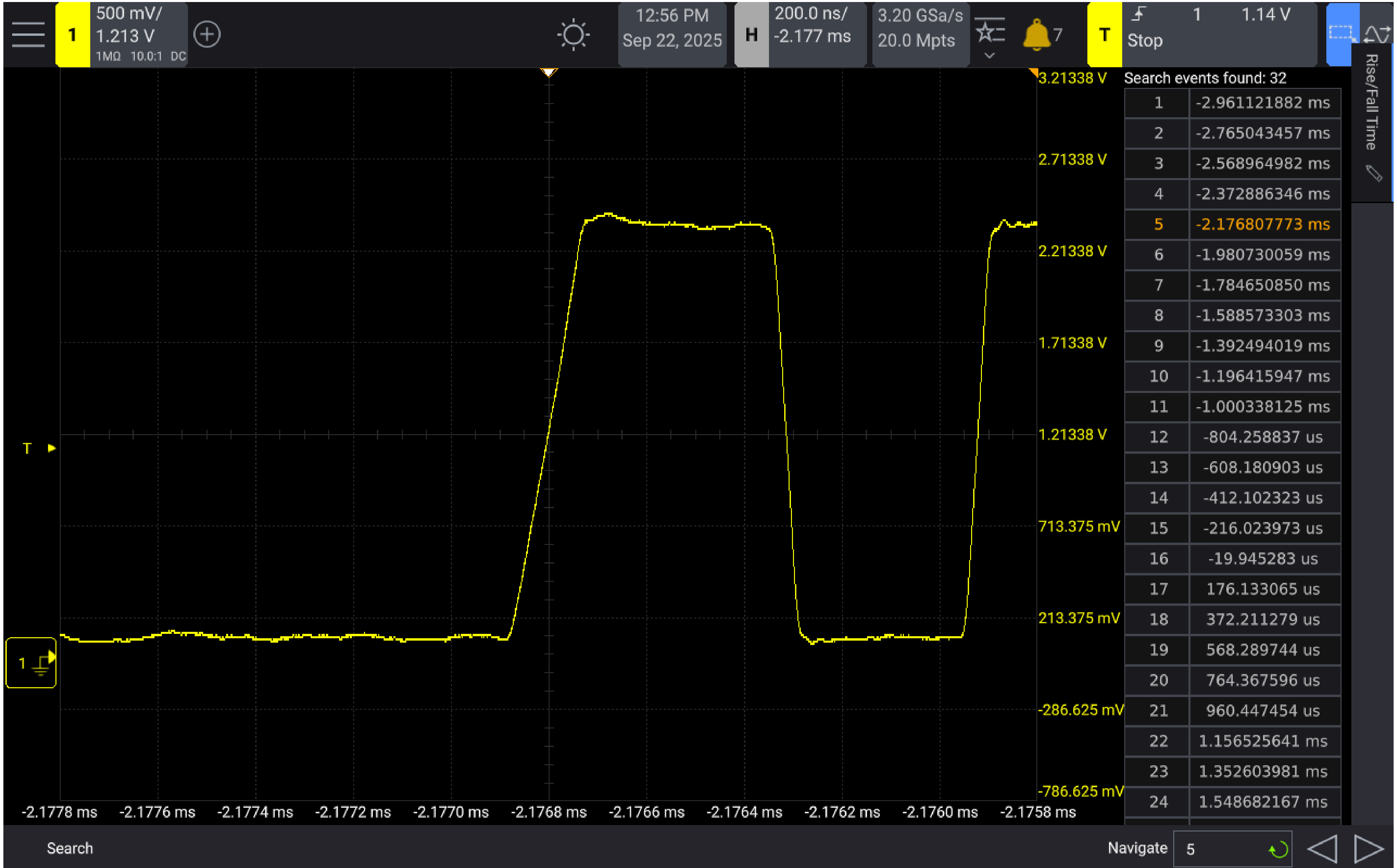
Zone trigger

Search

- search function can be used in combination with a “single” trigger
  - looks through the whole capture memory to find specified conditions on the signal
  - search conditions are similar to trigger conditions
    - edge, pulse width, rise/fall time, runt, protocol decoding
  - shows a table with time-stamped data listing all occurences of the defined condition



Search


500 mV/
1.213 V
1MΩ 10.0:1 DC
12:56 PM
Sep 22, 2025
H
200.0 ns/
-2.177 ms
3.20 GSa/s
20.0 Mpts
7
T
Stop
1
1.14 V
Rise/Fall Time
Search events found: 32
1 -2.961121882 ms
2 -2.765043457 ms
3 -2.568964982 ms
4 -2.372886346 ms
5 -2.176807773 ms
6 -1.980730059 ms
7 -1.784650850 ms
8 -1.588573303 ms
9 -1.392494019 ms
10 -1.196415947 ms
11 -1.000338125 ms
12 -804.258837 us
13 -608.180903 us
14 -412.102323 us
15 -216.023973 us
16 -19.945283 us
17 176.133065 us
18 372.211279 us
19 568.289744 us
20 764.367596 us
21 960.447454 us
22 1.156525641 ms
23 1.352603981 ms
24 1.548682167 ms
3.21338 V
2.71338 V
2.21338 V
1.71338 V
1.21338 V
713.375 mV
213.375 mV
-286.625 mV
-786.625 mV
-2.1778 ms
-2.1776 ms
-2.1774 ms
-2.1772 ms
-2.1770 ms
-2.1768 ms
-2.1766 ms
-2.1764 ms
-2.1762 ms
-2.1760 ms
-2.1758 ms
Search
Navigate
5

Measurements, math functions

- modern oscilloscopes can automatically perform many measurements on the displayed signal
  - vertical: P-P, max, min, amplitude, top, base, overshoot, pre-shoot, AC RMS, ...
  - horizontal (time): period, frequency, pulse width, duty cycle, rise/fall time, delay, ...
  - mixed: Area (N cycles or full screen), slew rate
- markers – can be used for manual measurements
- mathematical functions
  - add, subtract, multiply, divide, differentiate, integrate, FFT, Ax + B, squared, square root, absolute value, logarithm, exp, filters (low/high/band pass), average, smoothing, envelope, magnify, max hold, min hold, measurement trend
  - formula definion (some oscilloscopes)

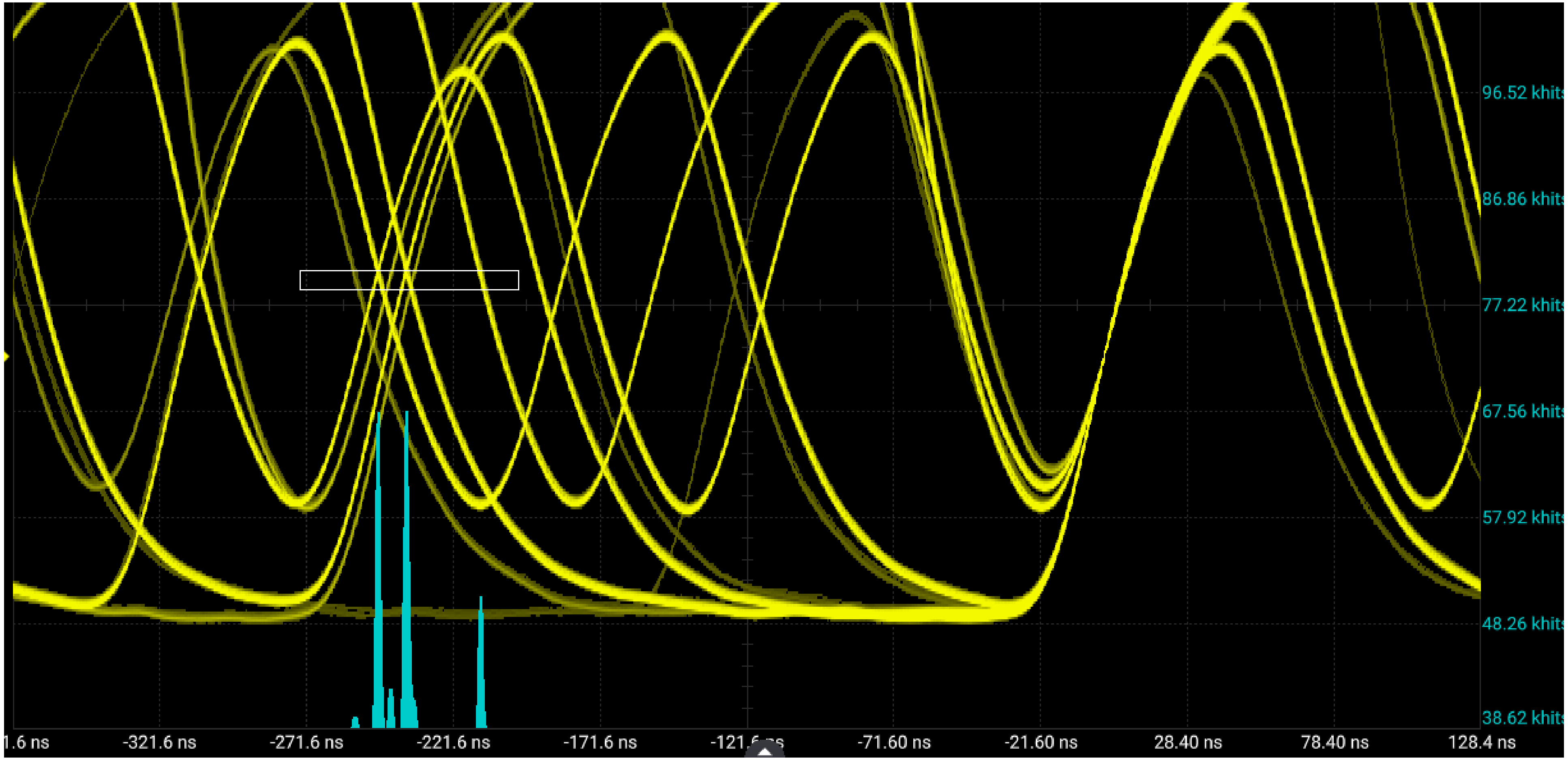
Fourier transform (FFT)

- current digital oscilloscopes can use the FFT function to calculate frequency domain representation (spectrum) of the captured time domain signal
  - can be used as a simple spectrum analyzer within the bandwidth of the scope
- some mid-range to higher-end oscilloscopes implement the FFT in hardware which brings much faster update of the spectrum display
- some oscilloscopes can calculate and display “gated FFT” spectrum
  - FFT is calculated from a selected time window (part of the whole signal capture)
  - very useful for analysis of swept or frequency modulated signals

gated FFT - example

Advanced functions

- latest oscilloscopes can have many additional measurement/analysis functions
    1) histogram – can be used to visualize a vertical (voltage) or horizontal (time) distribution of the signal within certain defined area (rectangle)



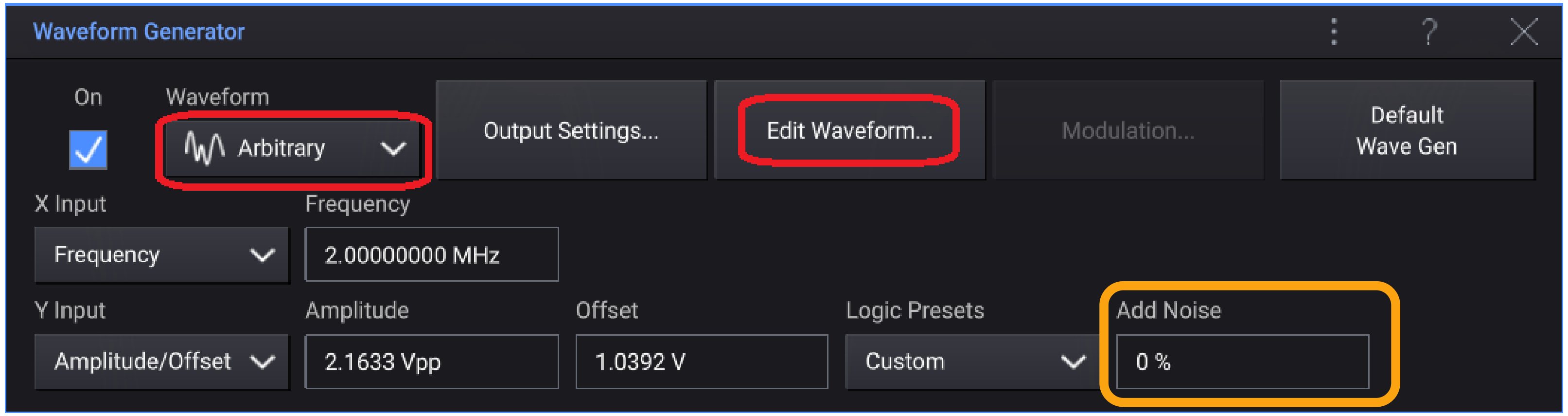
Advanced functions

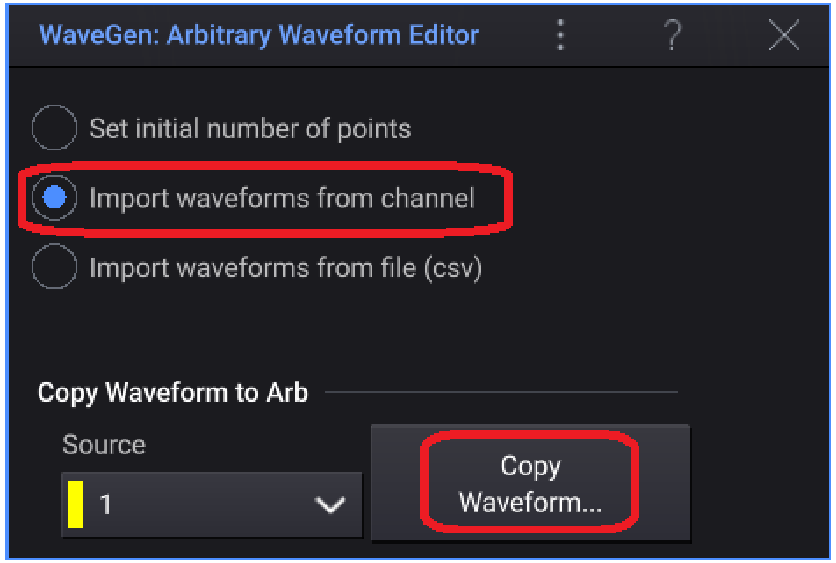
2) mask test – can be used to check that digital bus signals have the correct shape and comply to the standard defined voltage/time boundaries

Advanced functions

3) serial bus decoders – very useful feature of modern oscilloscopes
    - can be used to decode data from various types of serial communication busses
    - low speed – UART, I2C, SPI, CAN, LIN; high speed – USB, MIPI, Ethernet, ...
    - especially useful in combination with protocol triggering and segmented memory
4) frequency response analyzer (FRA, "Bode plot")
    - uses the integrated function generator and two analog channels to perform a amplitude/phase response analysis (typically measuring transmission of a DUT)
    - like a low frequency VNA
5) build in function/arbitrary generator (AWG)
    - integrated AWG can be used to stimulate a DUT with defined test signal
    - basic predefined waveforms (sine, square, ...) + arb capability
    - modulations on the carrier waveform (AM, FM, PM)

Advanced functions

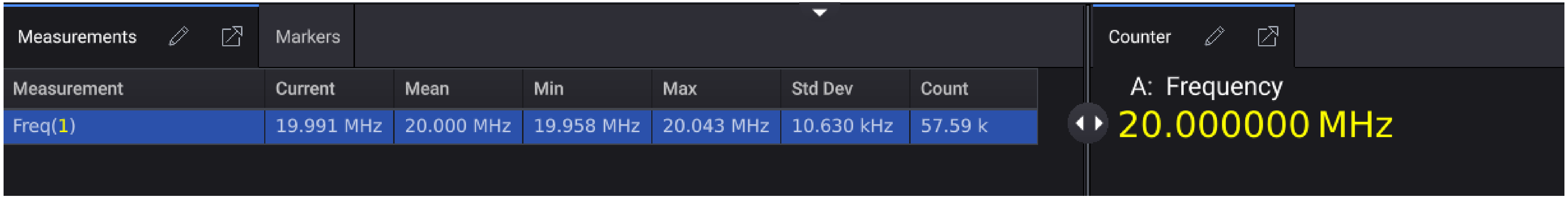




Advanced functions

6) frequency counter

- some oscilloscopes have a dedicated frequency counter function
- doesn't rely on the usual waveform frequency measurement; uses the trigger system to accurately count the edges during certain gate time
- Keysight EXR/MXR oscilloscopes also have very accurate OCXO frequency reference

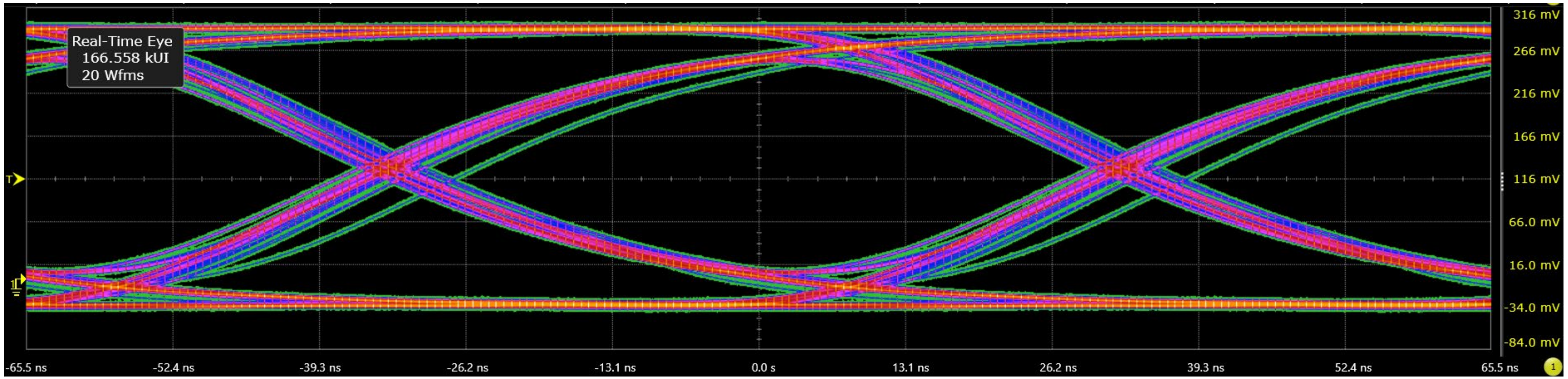


7) clock recovery, jitter analysis, eye diagram

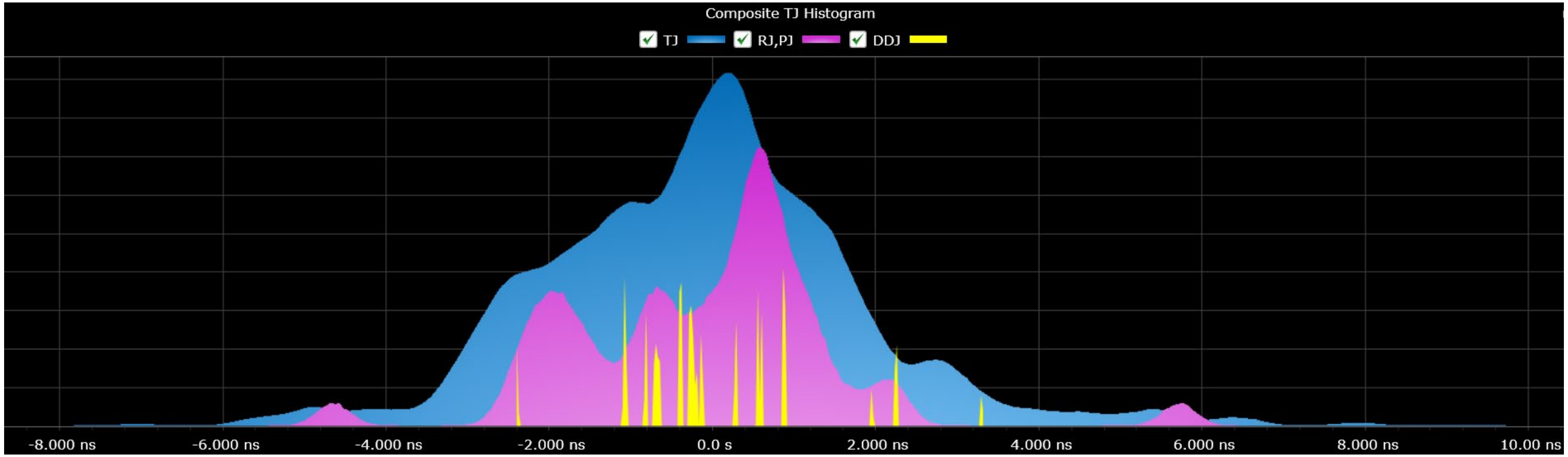
- advanced functions used to analyze the signal integrity on high speed serial buses

Advanced functions

- eye diagram example:



- jitter analysis example:



Using the oscilloscope

- default setup button – always a good starting point from a defined state
- input impedance – 1 MΩ or 50 Ω depending on the way the signal is measured
- “autoscale” button – usually a fast and easy way how to configure the scope
- vertical settings - place the signal on the screen correctly
  - using the two “vertical” knobs – sensitivity and offset
  - “sensitivity” knob can be set to “fine” mode if needed
  - offset can be set to 0 by pressing the knob
  - signal should occupy ~ 80 – 90 % of the display area vertically

Using the oscilloscope

- horizontal settings
  - change the timebase lenght (s/div) to display the signal correctly depending on the measurement needs (single or multiple periods, detail of rising/falling edge, ...)
  - if needed, adjust the horizontal position (trigger point) to balance the pre/post trigger time length

- trigger settings
  - adjust the trigger level if needed (the oscilloscope tries to find the optimal level after pressing the knob)
  - find the right trigger type if needed (+ potentially use the zone trigger)

Thank you for your attention !