How to Improve Accuracy of Measurement When Using a Scope

TELEDYNE LECROY
Everywhereyoulook™

AE Tom Jiang

Agenda

- Teledyne LeCroy Overview
- Which Specs Can Influent Test Accuracy
- How to Improve Accuracy of Measurement

Teledyne LeCroy Overview

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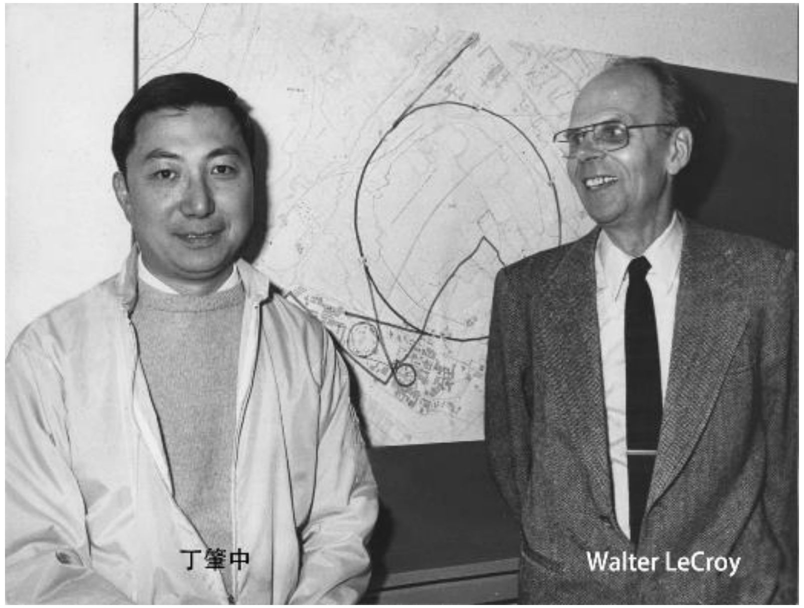
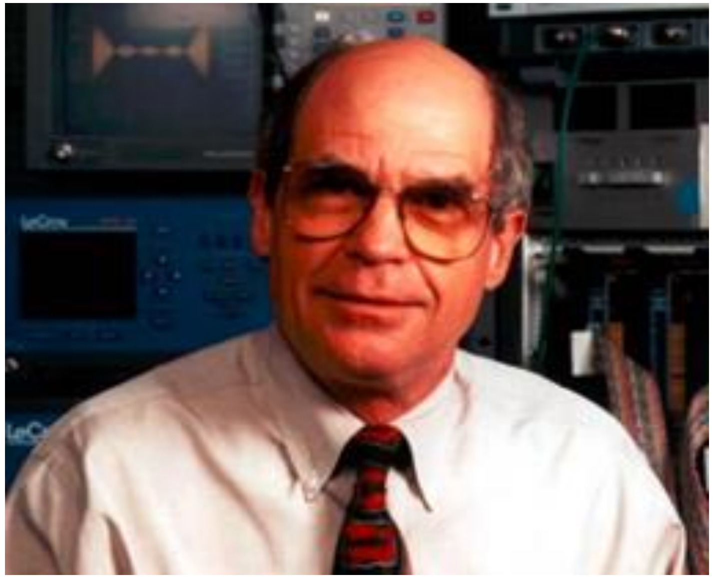
Teledyne LeCroy Overview

- LeCroy was founded by Walter LeCroy in 1964
    - Original products were high-speed digitizers for particle physics research
- Corporate headquarters is in Chestnut Ridge, NY (USA)
    - Regional sales/service offices in every major location around the world
- Long history of innovation in digital oscilloscopes
    - First digital storage oscilloscope
    - First 100 GHz real-time oscilloscope
    - First 12-bit high bandwidth oscilloscope
        - HD4096 technology – 12 bits all the time
- LeCroy is also the world leader in high-speed protocol analysis.
- In 2012, LeCroy was acquired by Teledyne Technologies and renamed Teledyne LeCroy

Founder- Mr. Walter LeCroy





Nobel Prize Owner Sam Ting

Walter LeCroy
(1935-2023)

Ting said on LeCroy's 30th anniversary, "The world High Energy Physics community owes a great deal to you through your brilliant instrumentation and innovation. None of our experiments could have been possible without the support and collaboration of your company."

First DSO in the world in 1971

- 3 inch CRT
- Record length: 20 samples
- ADC Resolution: 8 bits
- Sample Rate: 1 GS/s
- Sample Resolution: 1 ns
- 50 ohm inputs
- 1 V full scale

Continuing Innovation

	Bandwidth	Sample Rate	Channels	ADC
2008	30GHz	40GS/s	4CH	8 bit
2010	45GHz	80GHz		
2012	65GHz	120GS/s		**12 bit**
2013	**100GHz**	240GS/s	**80CH**	
2023		**320GS/s**		

Teledyne LeCroy Scope Product Line

12bit

8bit

Resolution

Bandwidth

350 MHz | 500 MHz | 1 GHz | 2 GHz | 2.5 GHz | 4 GHz | 8 GHz | 20 GHz | 30 GHz | 59 GHz | 100 GHz

HDO6000B
350 MHz – 1 GHz

WaveRunner/ MDA 8000HD
350 MHz – 2 GHz

WavePro HD
2.5 GHz – 8 GHz

WaveMaster8000HD
6 GHz – 65 GHz 320GS/s

LabMaster 10Z
20 GHz – 100 GHz

WaveMaster 8Z
4 GHz – 16 GHz

WaveRunner9000
500 MHz – 4 GHz

Other Instruments

Wave Generator

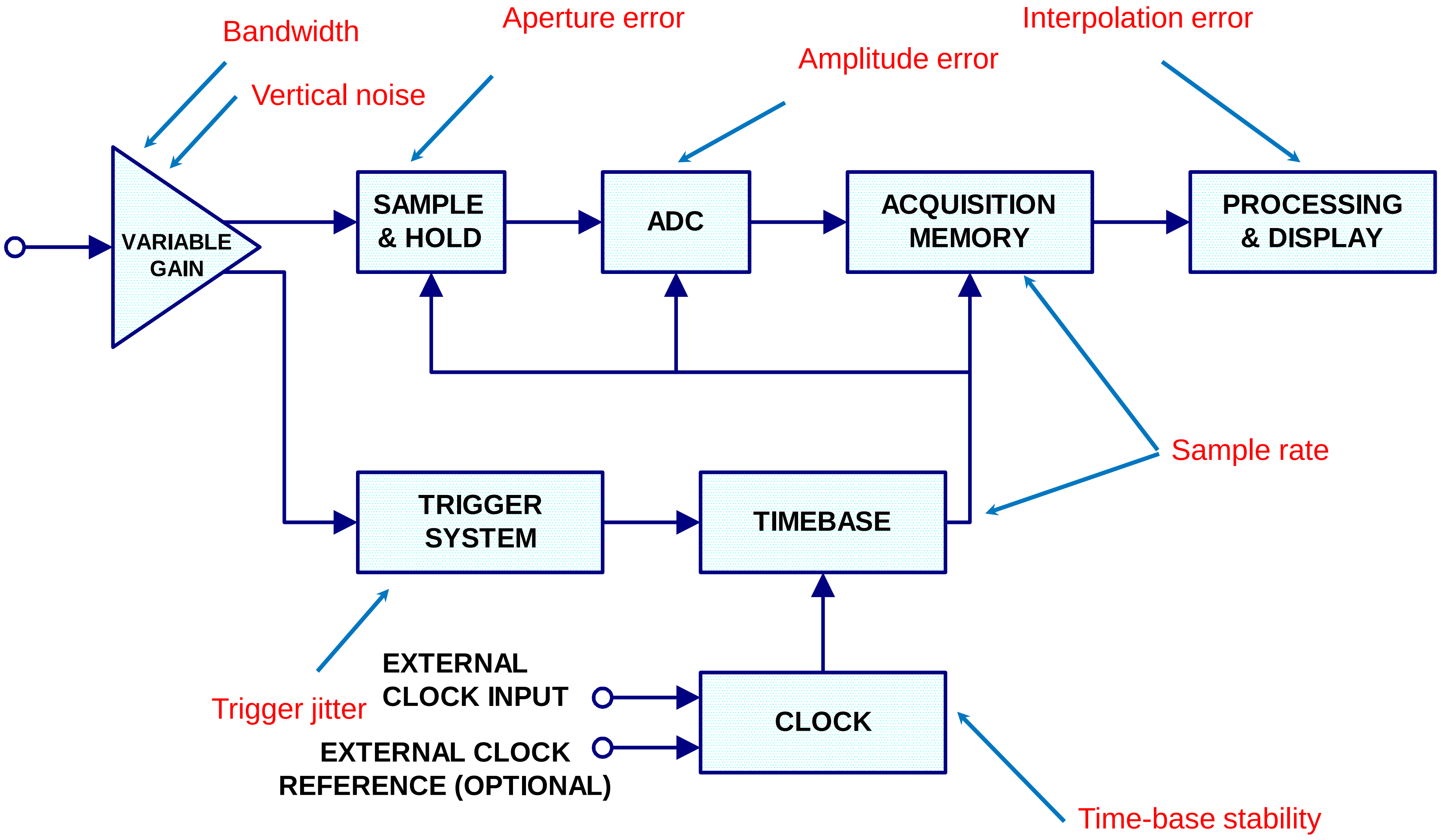
- **16 bits vertical resolution**
- Up to 12.32 GS/s
- Up to 5Vpp with HW offset ±2.5 V into 50Ω
- Up to 8Ch
- Multifunctional Platform:
    - Arbitrary Function Generator
    - Arbitrary Waveform Generator
    - Digital Pattern Generator

Time Domain Reflection

- Up to 40GHz @ 4ports
- Rise time up to 9.5ps
- Single-end, Differential
- Build in OSLT Calibration

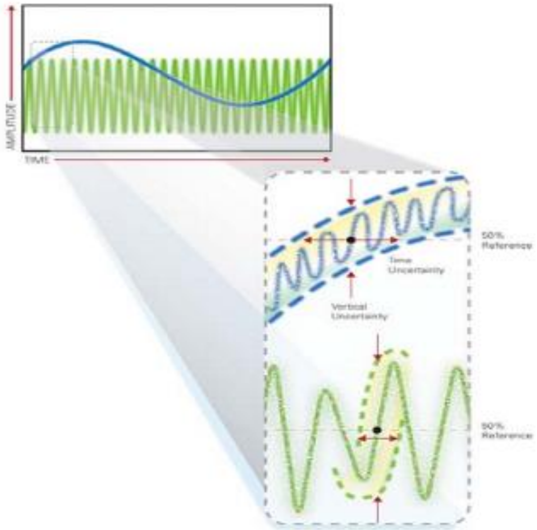
Which Factors Can Influent Accuracy

Workflow of Scope



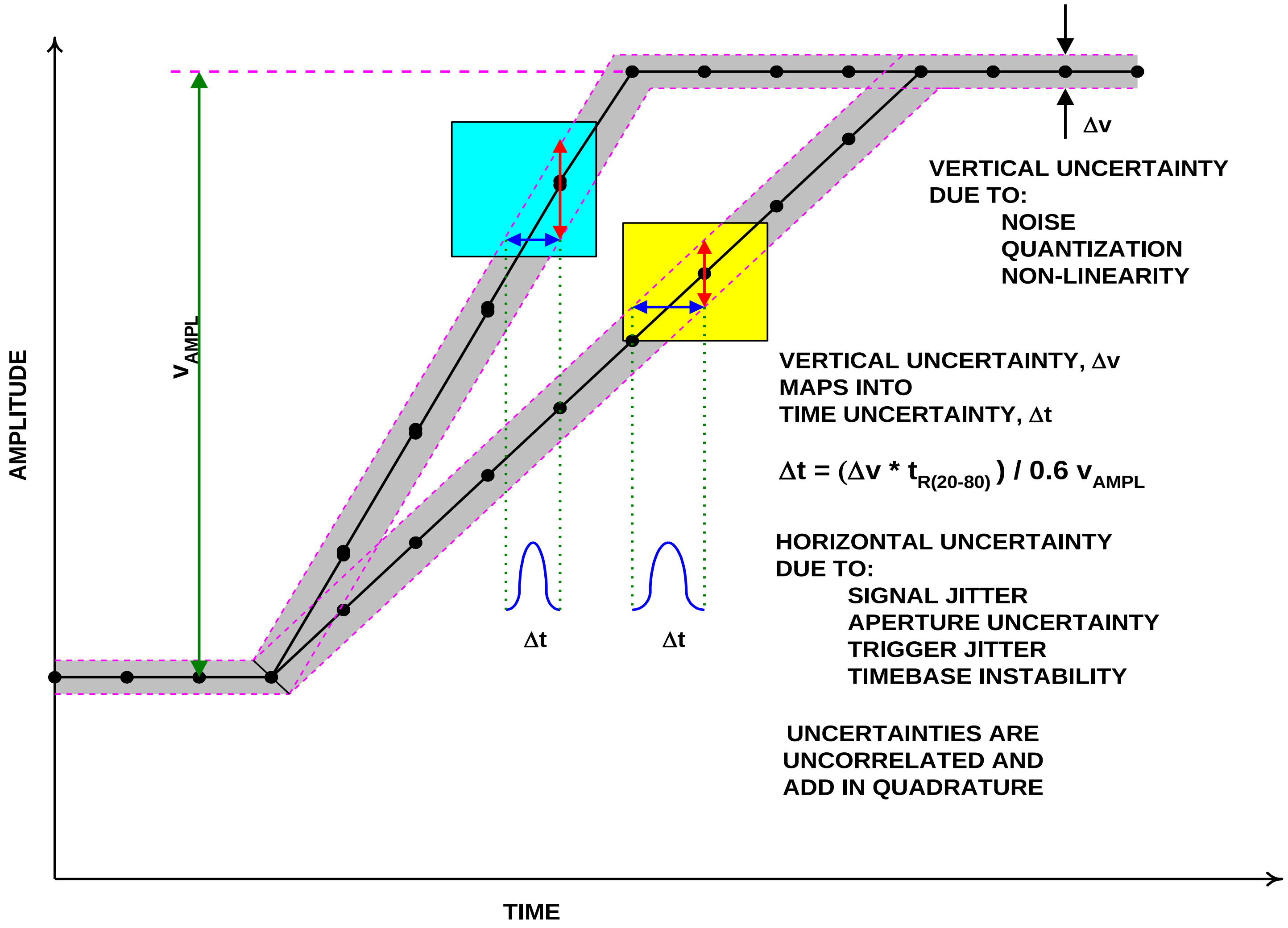
Factors influencing the accuracy of horizontal measurements

Clock Accuracy	< 1 ppm + (aging of 0.5ppm/yr from last calibration)
Sample Clock Jitter	Up to 10 µs Acquired Time Range: 100 fsrms (Internal Timebase Reference) Up to 6.4 ms Acquired Time Range: 150 fsrms (Internal Timebase Reference)
Delta Time Measurement Accuracy	$\sqrt{2} * \sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + (Sample\ Clock\ Jitter)^2}$ (RMS) + (clock accuracy * reading) (seconds)
Jitter Measurement Floor	$\sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + (Sample\ Clock\ Jitter)^2}$ (RMS, seconds, TIE)



The slope would convert vertical noise to horizontal jitter

How the measurement error of the vertical quantity affects the horizontal measurement quantity



VERTICAL UNCERTAINTY
DUE TO:
NOISE
QUANTIZATION
NON-LINEARITY

VERTICAL UNCERTAINTY, Δv
MAPS INTO
TIME UNCERTAINTY, Δt

$\Delta t = (\Delta v * t_{R(20-80)}) / 0.6\ v_{AMPL}$

HORIZONTAL UNCERTAINTY
DUE TO:
SIGNAL JITTER
APERTURE UNCERTAINTY
TRIGGER JITTER
TIMEBASE INSTABILITY

UNCERTAINTIES ARE
UNCORRELATED AND
ADD IN QUADRATURE

Errors in edge amplitude caused by ADC quantization errors, vertical noise and gain errors, channel stacking mismatches, etc., are converted into horizontal jitter.

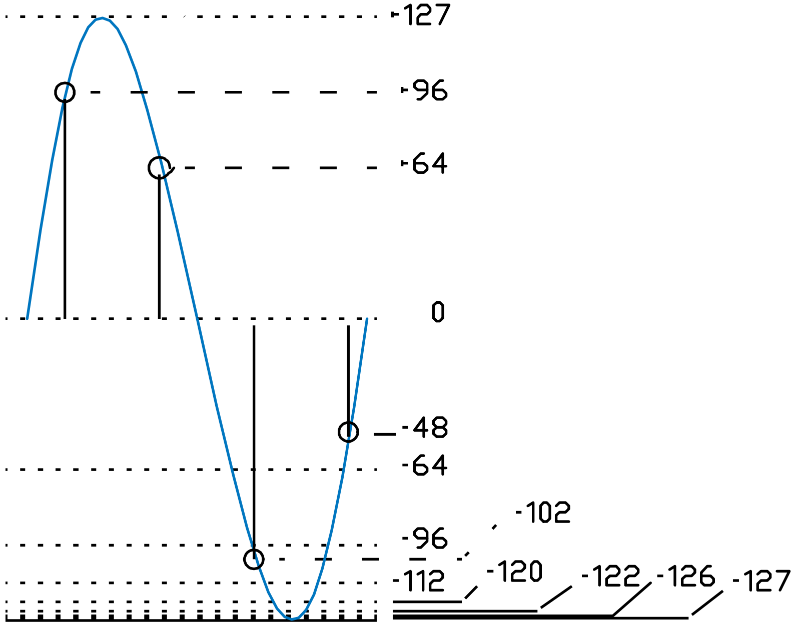
The intrinsic jitter associated with the amplitude error is calculated as follows:

$DT = e/(dV/dT) = DV * t_{R\ 20\text{-}80} / 0.6V_{AMPL}$

For example:
For example:
Assuming a quantization error of 0.28 LSB (1.7 mV @ 200 mV/div for an 8-bit ADC oscilloscope) and a 20%-80% rise time of 2ns for a 1 V signal:

$DT = 1.7\ mV*2ns/(0.6*1V) = 5.6\ ps$

The digital foundation of an oscilloscope



Decimal	Signed Binary
+127	11111111
+1	10000001
0	10000000
-1	01111111
-128	00000000

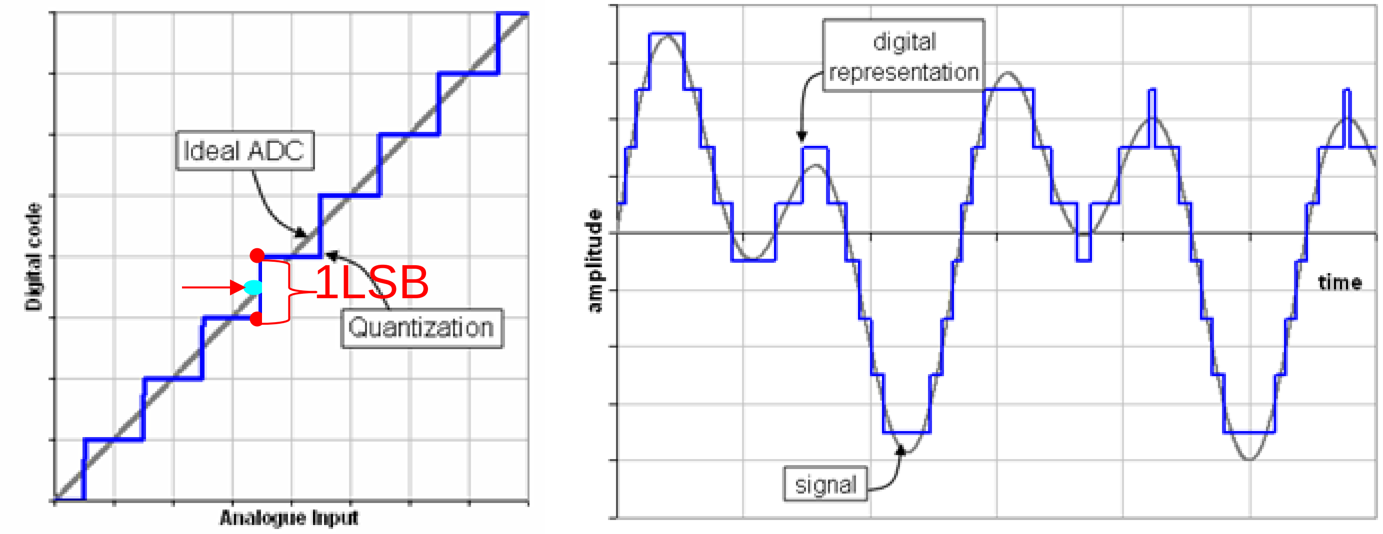
An N-bit precision ADC converts an analog voltage into a binary number of N bits

- # Bits resolution
- 8 256:1
- N 2^n :1

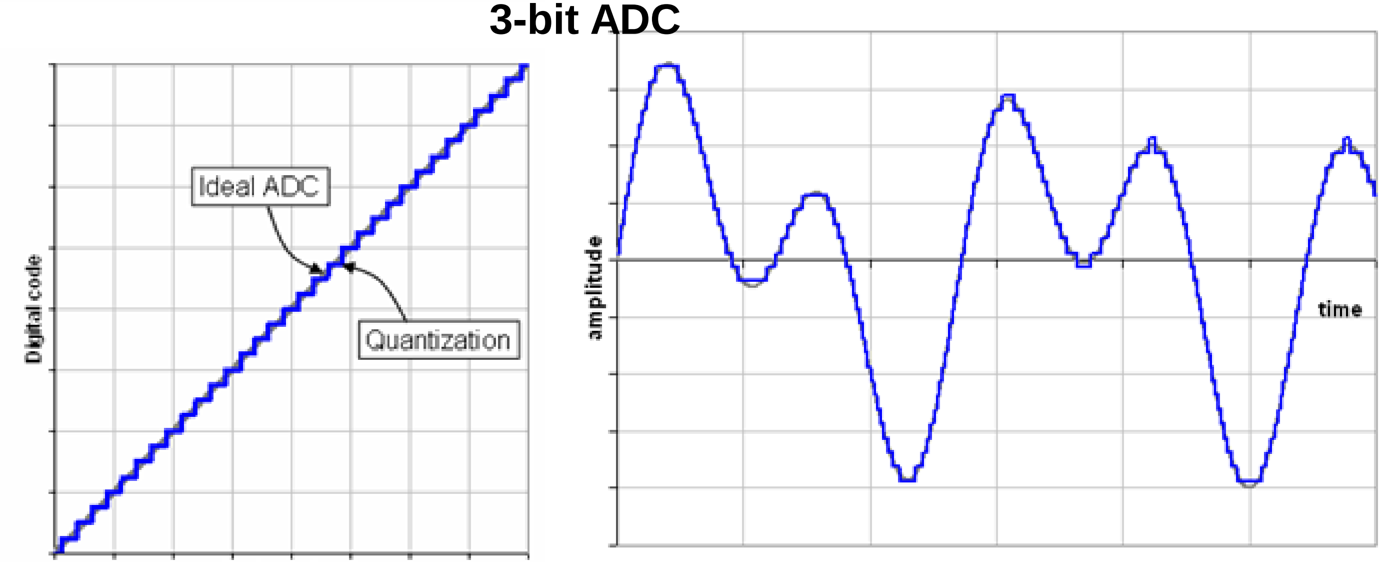
LeCroy uses the binary format of symbols as the digital output, so the binary code at the top of the screen is +127, 0 in the middle of the screen, and -128 at the bottom of the screen.

Binary codes correspond to different voltage values by vertical gain and offset.

Quantification error



3-bit ADC



5-bit ADC

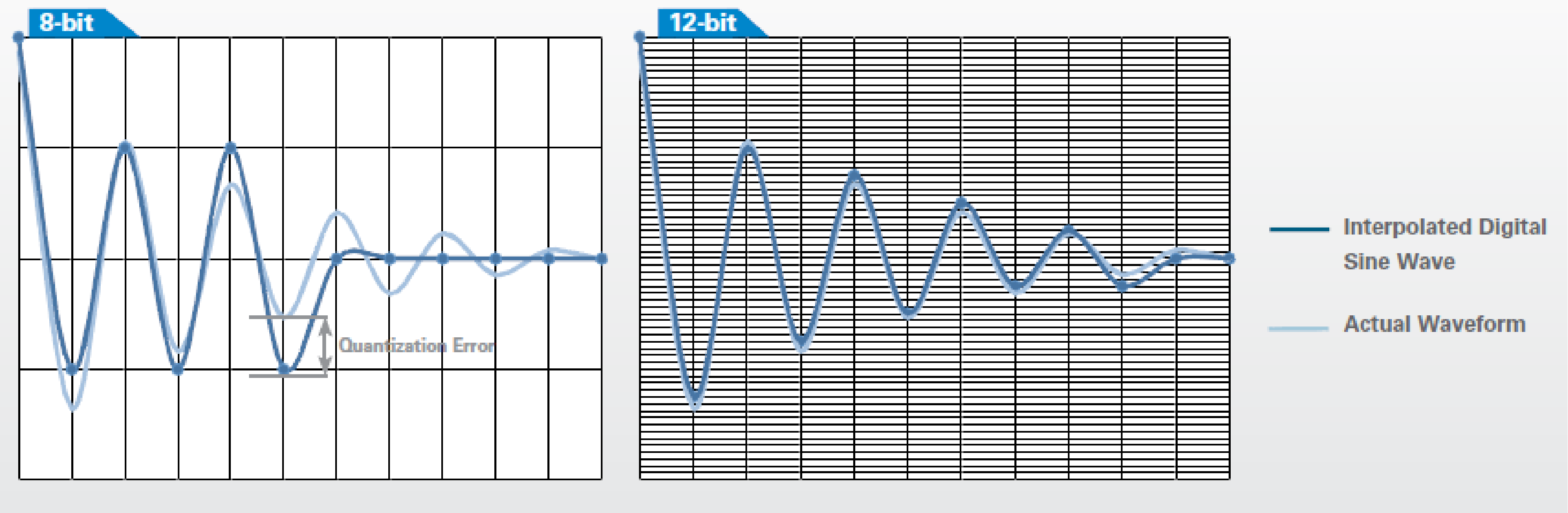
In the process of discretization of continuous analog signal into digital signal, because there is no infinite number of discretized digital levels to reassemble the continuous analog signal, there will always be a deviation between the actual analog voltage value and the corresponding digital level value, and this deviation value is called quantization error. The voltages within a certain range of values are represented by the same binary code, so the uncertainty of this quantization is ±1/2LSB. LSB can be understood as a step to digitization. The quantization error refers to the difference between the quantization result and the quantized simulation, and obviously the more quantization series, the smaller the relative error of quantization. Quantization series refers to the number of series in which the maximum value is equalized, and the size of each mean is called a quantization unit.

What is the resolution of an oscilloscope?

- The quantification level of the ADC = $2^{\text{N bits of Resolution}}$

ADC Resolution	Quantification level	Dynamic range
8	256	~48 dB
12	4096	~72 dB

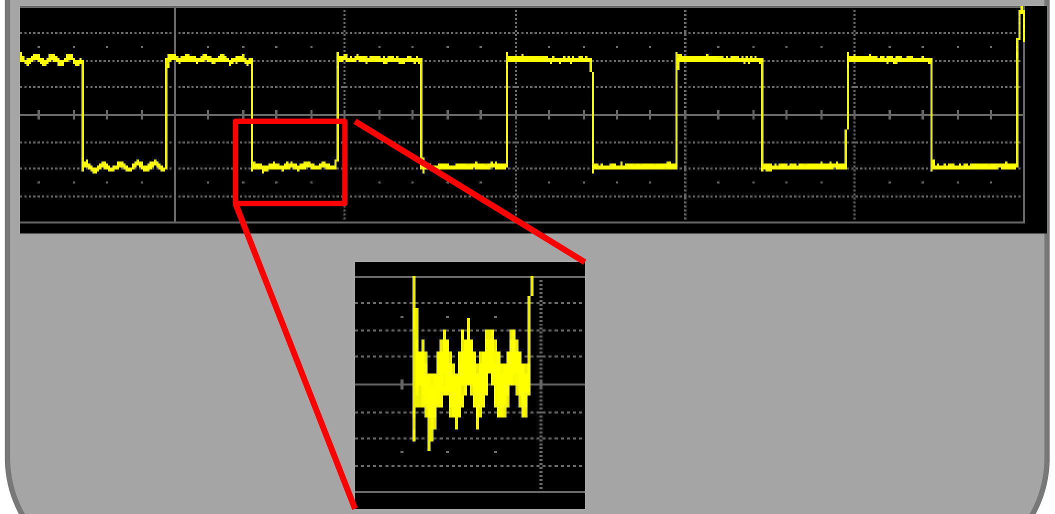
- quantification level–A 12-bit oscilloscope has 16 times more quantification levels than a traditional 8-bit oscilloscope



12-bit oscilloscope VS 8-bit oscilloscope

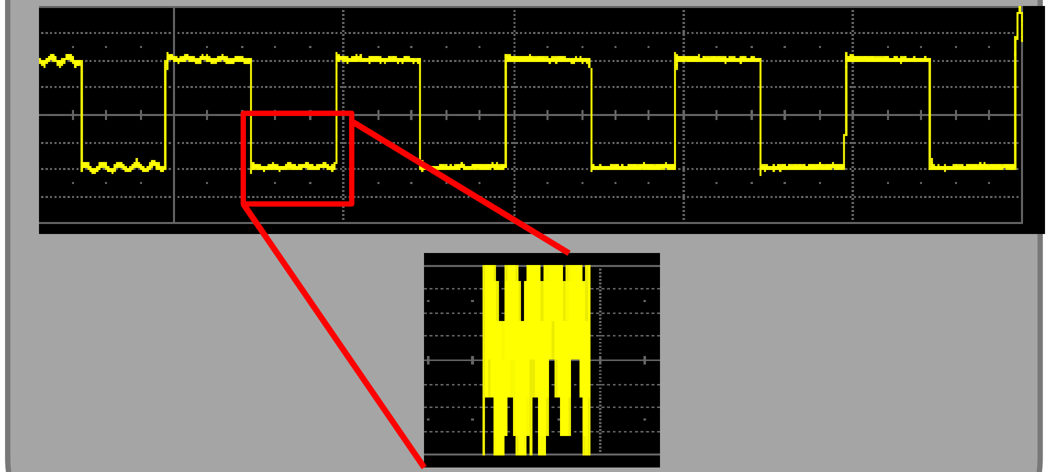
- The higher vertical resolution allows for unobstructed waveform detail, while the signal detail of the 8-bit oscilloscope is drowned out in quantization noise

The 12-bit Oscilloscope observes the ripple signals superimposed on the square wave



Ripple parameters (frequency, RMS, etc.) can be observed and measured

The 8-bit Oscilloscope observes the ripple signals superimposed on the square wave



Can you see ripples?

Materialize the effect of the number of bits of the ADC on the measurement

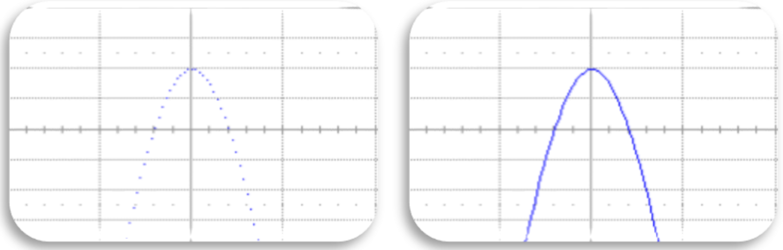
- **A higher number of digits means that smaller voltages can be measured**

	Smallest Voltage Step	
Full Scale	8 bits	12 bits
80 V	312.5 mV	19.5 mV
40 V	156.2 mV	9.76 mV
20 V	78.1 mV	4.88 mV
8 V	31.3 mV	1.95 mV
4 V	15.6 mV	976 µV
1.6 V	6.3 mV	390 µV
800 mV	3.1 mV	195 µV
400 mV	1.56 mV	97.6 µV
160 mV	625 µV	39 µV
80 mV	313 µV	19.5 µV
40 mV	156 µV	9.76 µV
16 mV	62.5 µV	3.9 µV
8 mV	31.2 µV	1.95 µV

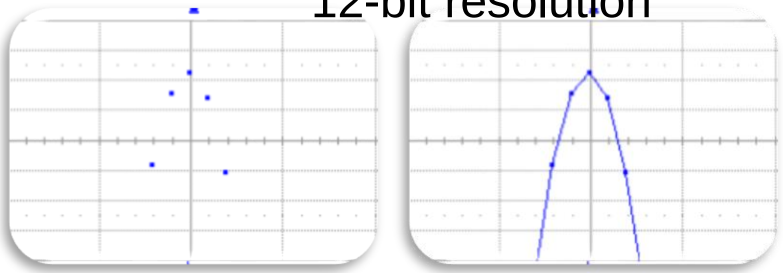
$1.95\text{ mV} = 8\text{V}/2^{12}$

$31.3\text{ mV} = 8\text{V}/2^{8}$

- The minimum detectable voltage value for an 8V signal measured with a 12-bit ADC is 1.95 mV, while the minimum detectable voltage value for an 8-bit ADC is 31.3 mV.



12-bit resolution



8-bit resolution

How to Improve Accuracy of Measurement

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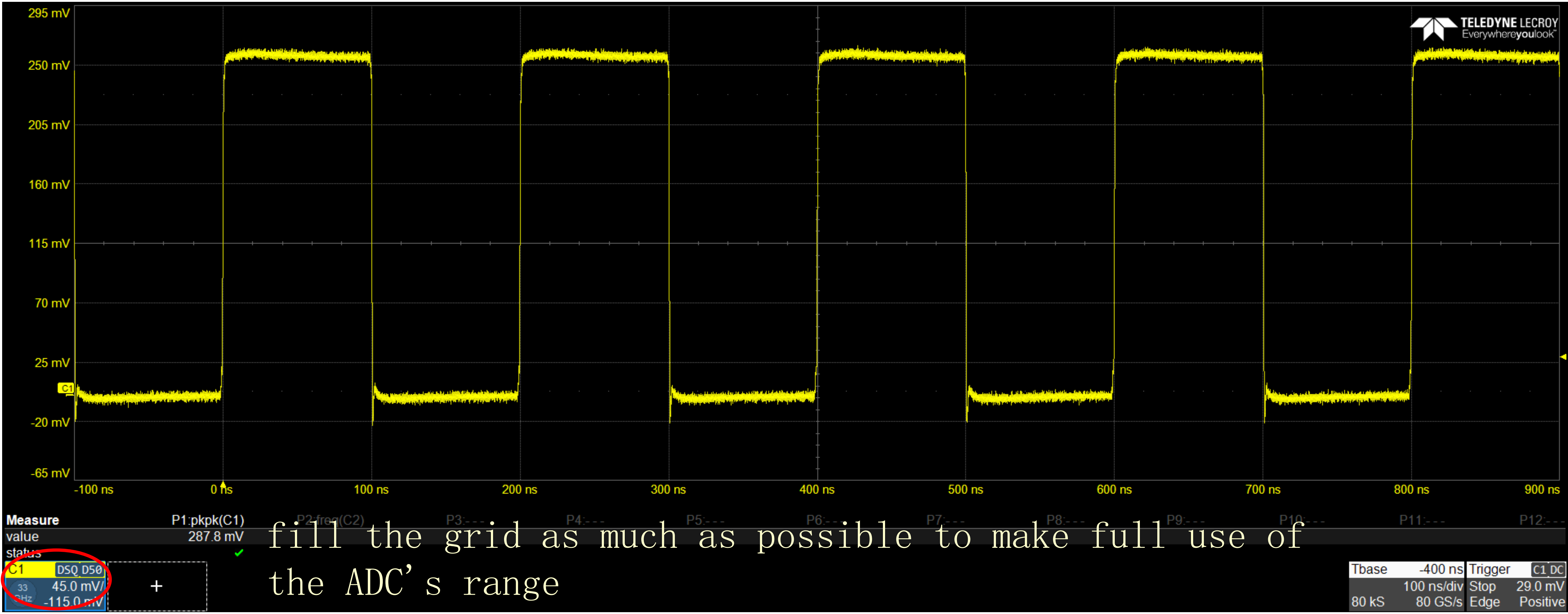
First rule of capturing signals: Minimize quantization errors

- Try to fill the grid with the waveform to make the most use of the ADC's range.
- Let’s see an example

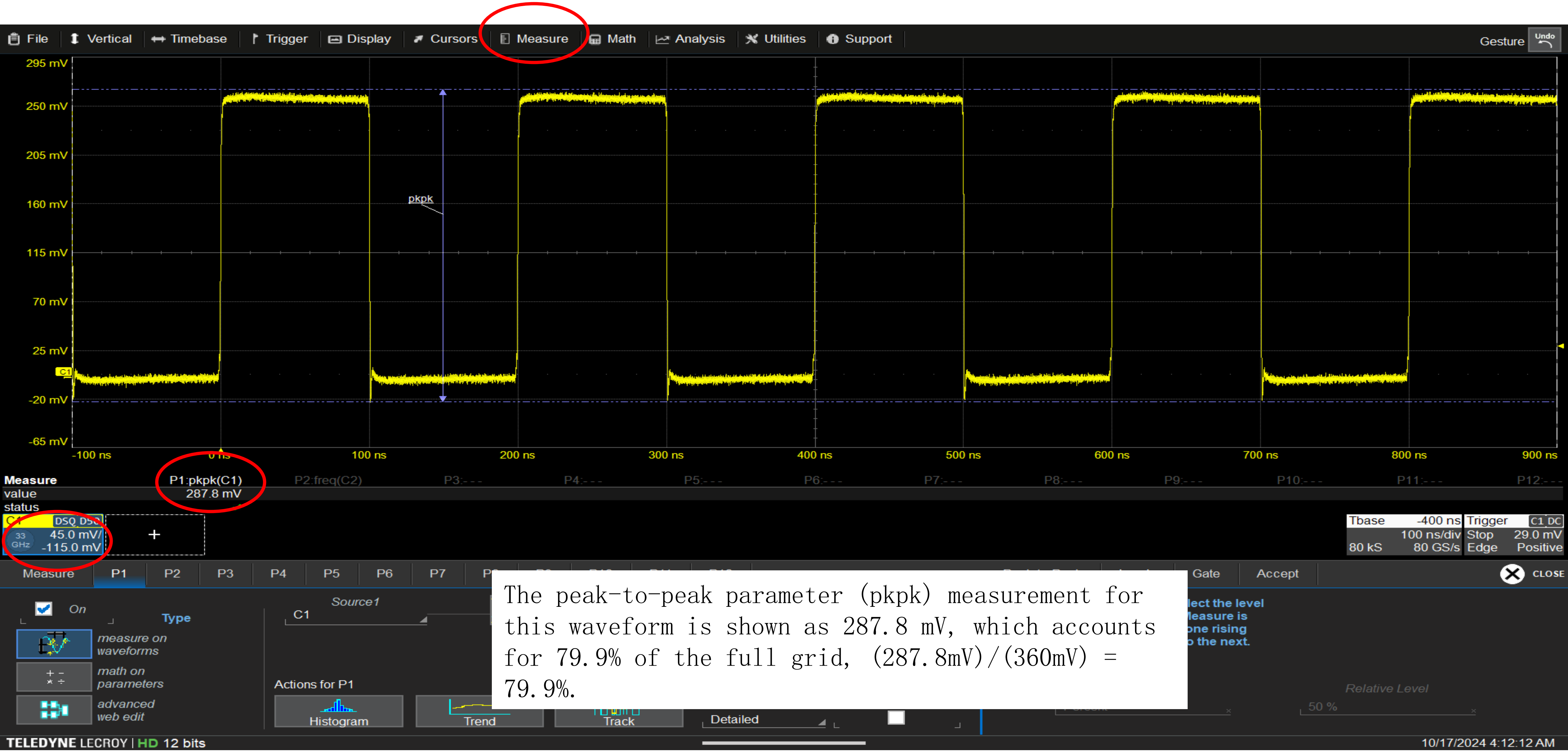


Measure	P1:pkpk(C1)
value	287.8 mV
status	✓

C1 DSQ D50
33 GHz 45.0 mV/
-115.0 mV

Tbase	-400 ns	Trigger	C1 DC
	100 ns/div	Stop	29.0 mV
80 kS	80 GS/s	Edge	Positive

fill the grid as much as possible to make full use of the ADC's range



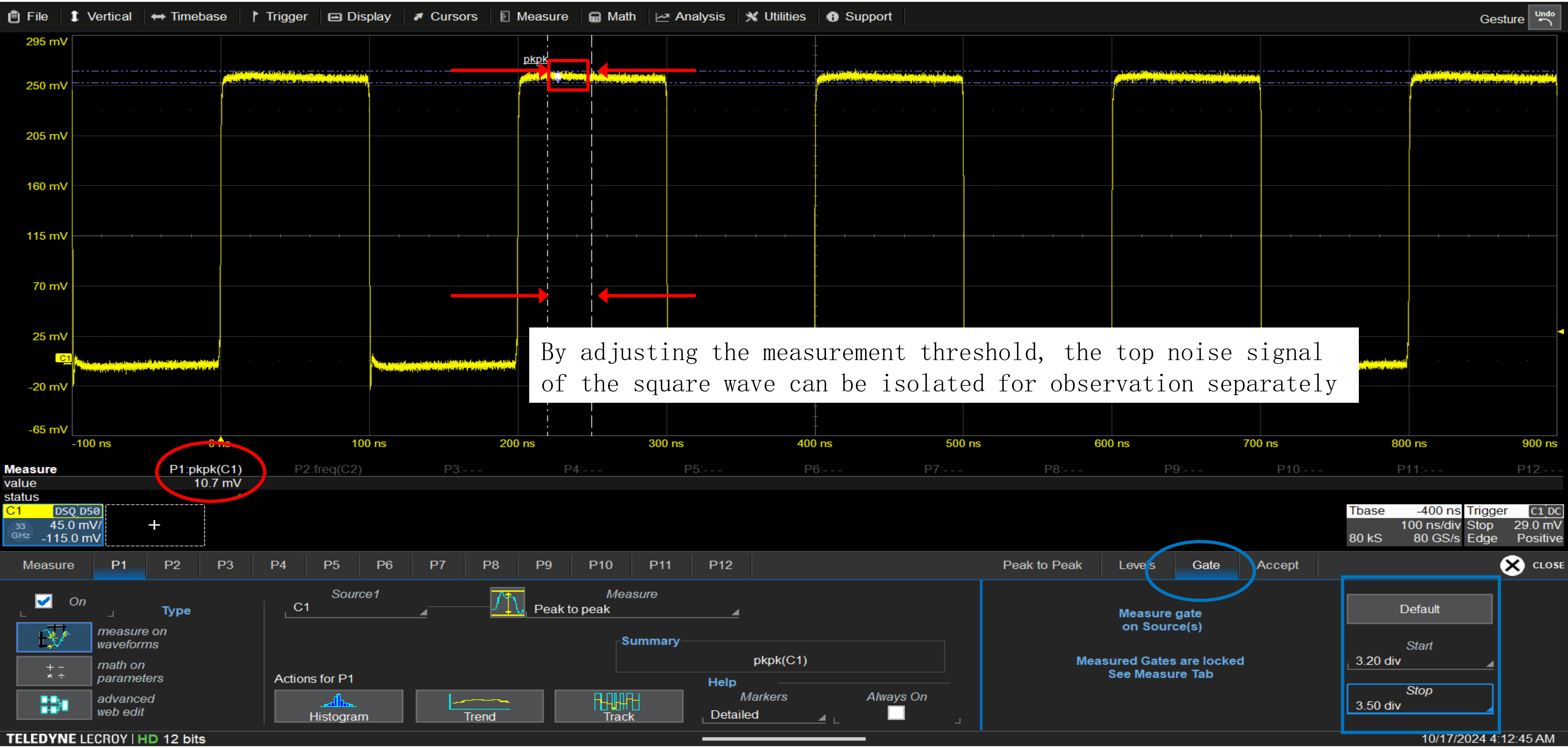
Measure P1:pkpk(C1)
value 287.8 mV
status

C1 DSQ DSQ 33 GHz 45.0 mV/ -115.0 mV

Tbase -400 ns 100 ns/div 80 kS 80 GS/s

Trigger C1 DC Stop 29.0 mV Edge Positive

The peak-to-peak parameter (pkpk) measurement for this waveform is shown as 287.8 mV, which accounts for 79.9% of the full grid, (287.8mV)/(360mV) = 79.9%.



By adjusting the measurement threshold, the top noise signal of the square wave can be isolated for observation separately

Measure: P1:pkpk(C1)

value: 10.7 mV

status

C1 DSQ D50 33 GHz 45.0 mV/ -115.0 mV

Tbase -400 ns, 100 ns/div, 80 kS, 80 GS/s

Trigger C1 DC, Stop 29.0 mV, Edge Positive

Source1: C1

Measure: Peak to peak

Summary: pkpk(C1)

Markers: Detailed

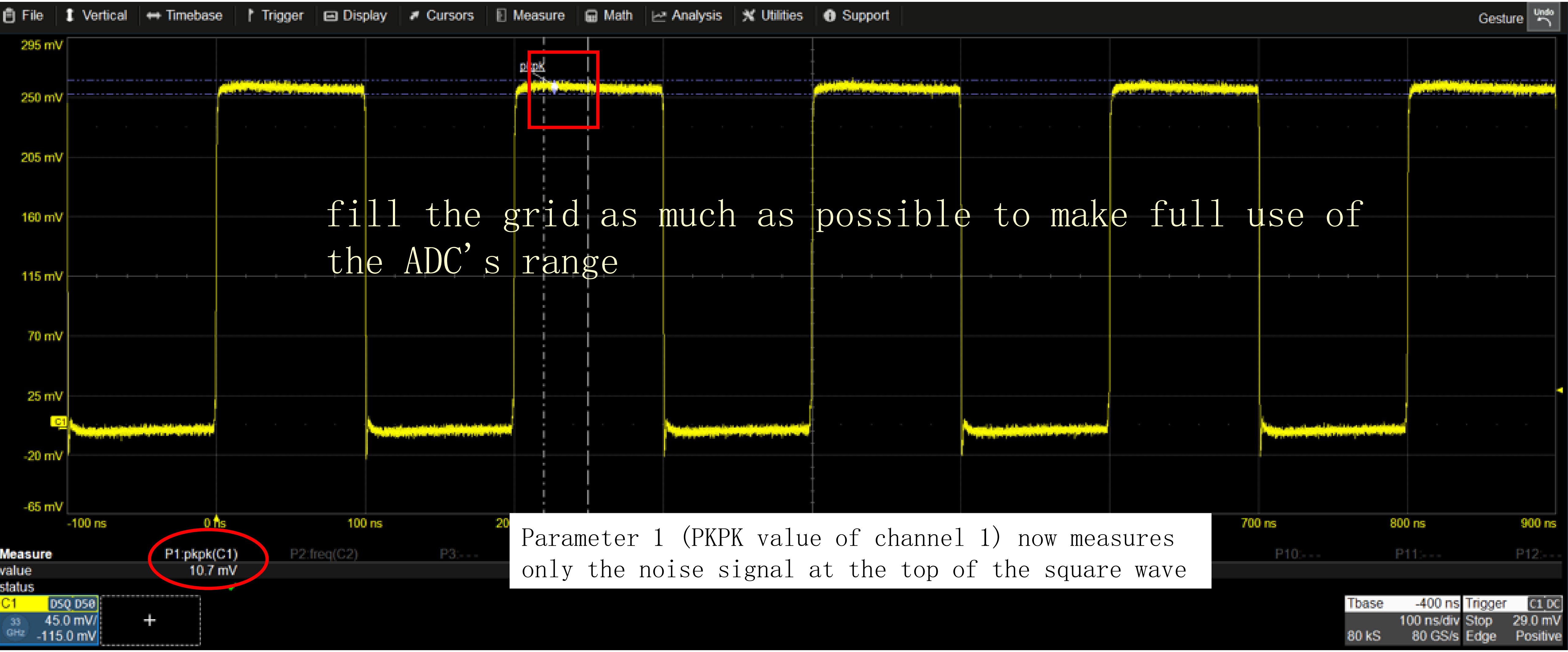
Measure gate on Source(s)

Measured Gates are locked See Measure Tab

Start: 3.20 div

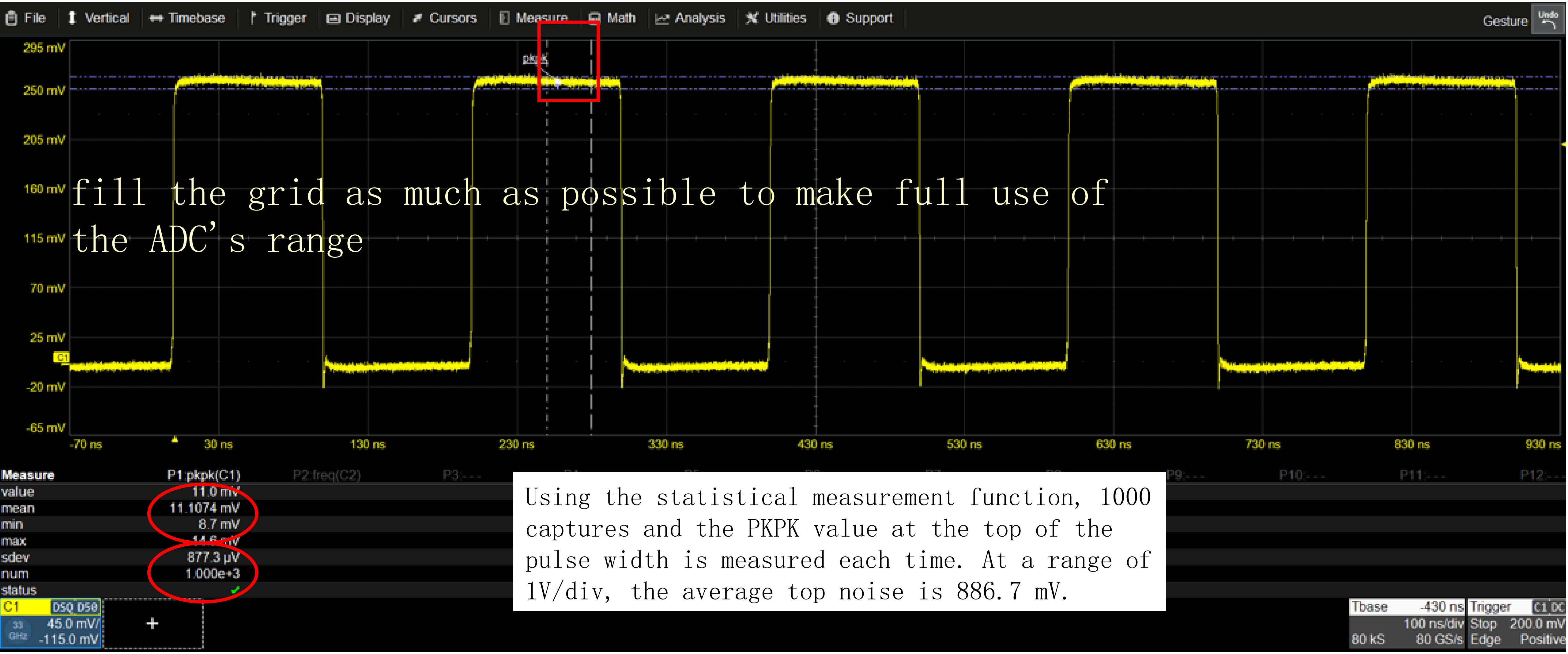
Stop: 3.50 div

10/17/2024 4:12:45 AM



fill the grid as much as possible to make full use of the ADC’s range

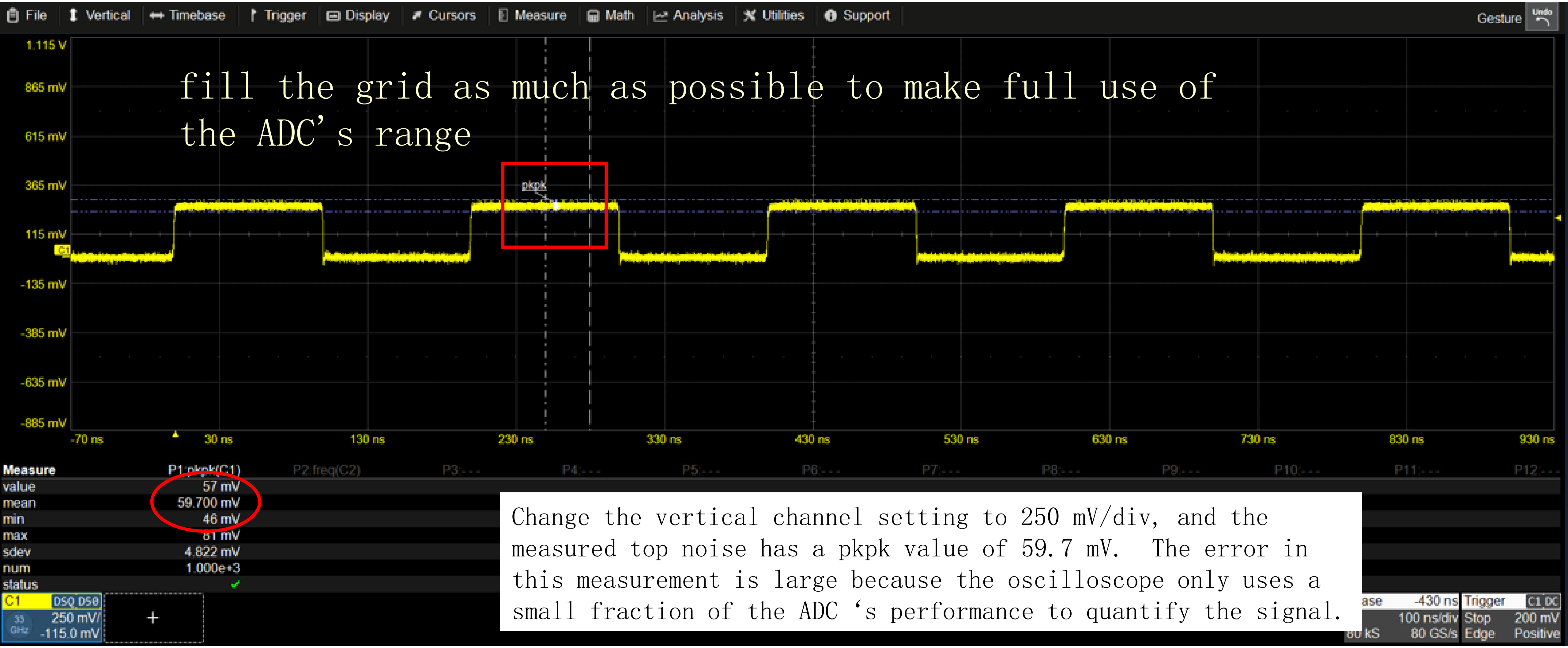
Parameter 1 (PKPK value of channel 1) now measures only the noise signal at the top of the square wave



fill the grid as much as possible to make full use of the ADC's range

Measure	P1:pkpk(C1)
value	11.0 mV
mean	11.1074 mV
min	8.7 mV
max	14.6 mV
sdev	877.3 µV
num	1.000e+3
status	✓

Using the statistical measurement function, 1000 captures and the PKPK value at the top of the pulse width is measured each time. At a range of 1V/div, the average top noise is 886.7 mV.

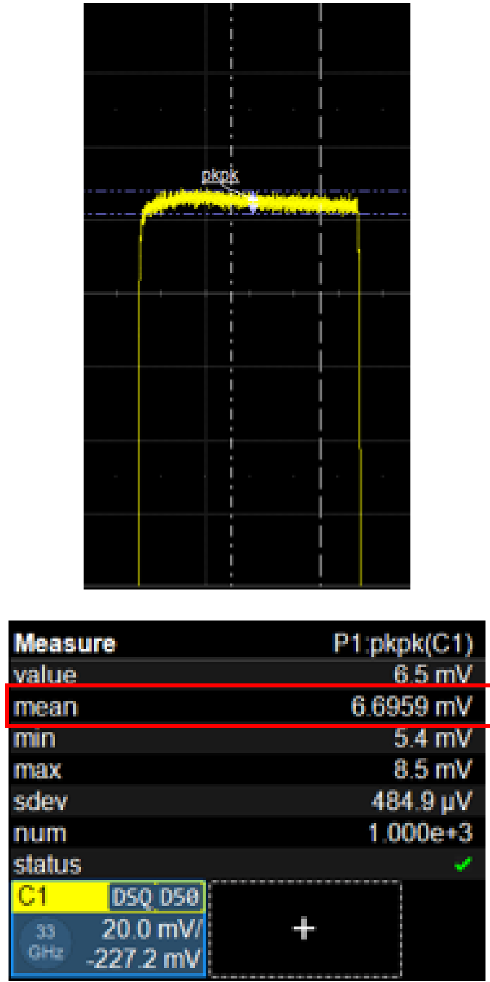


fill the grid as much as possible to make full use of the ADC's range

Measure	P1:pkpk(C1)	P2:freq(C2)	P3:---	P4:---	P5:---	P6:---	P7:---	P8:---	P9:---	P10:---	P11:---	P12:---
value	57 mV											
mean	59.700 mV											
min	46 mV											
max	81 mV											
sdev	4.822 mV											
num	1.000e+3											
status	✓											

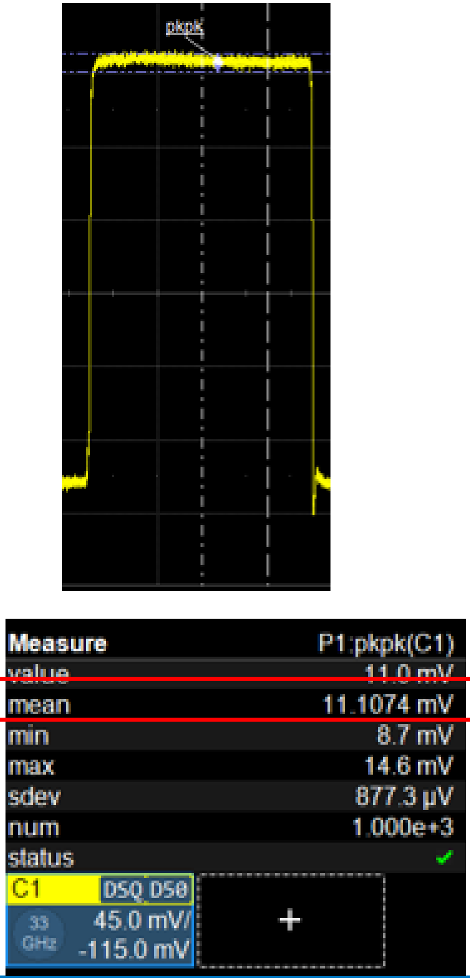
Change the vertical channel setting to 250 mV/div, and the measured top noise has a pkpk value of 59.7 mV. The error in this measurement is large because the oscilloscope only uses a small fraction of the ADC 's performance to quantify the signal.

The bigger vertical scale you use, the larger result you will get



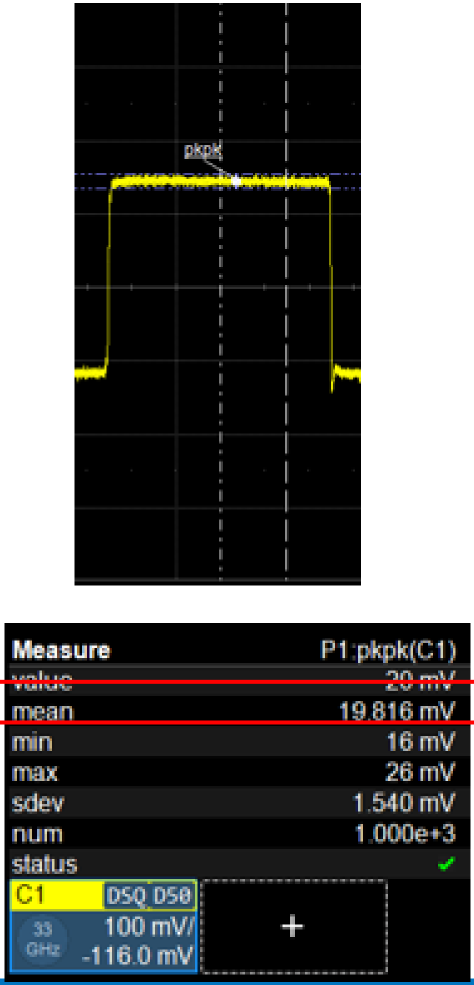
Measure	P1:pkpk(C1)
value	6.5 mV
mean	6.6959 mV
min	5.4 mV
max	8.5 mV
sdev	484.9 µV
num	1.000e+3
status	✓

C1 DSQ D50
33 GHz 20.0 mV/ -227.2 mV



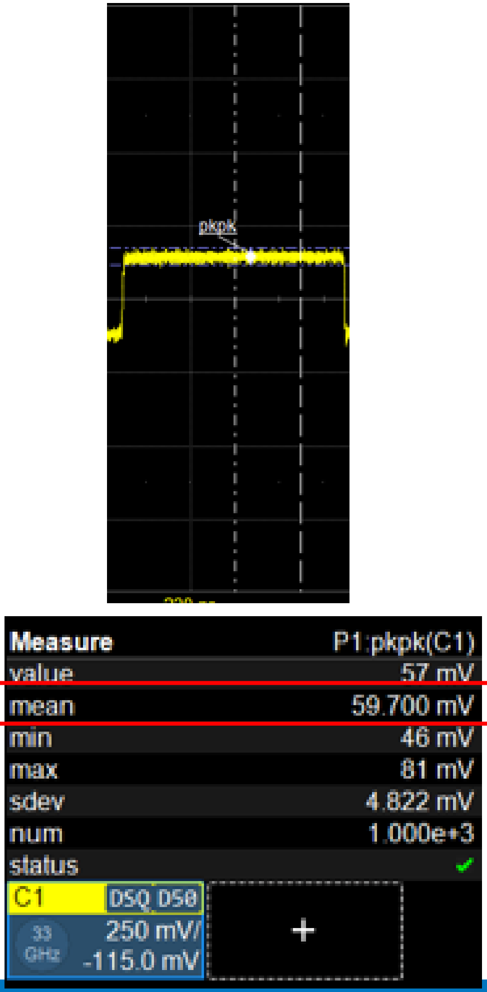
Measure	P1:pkpk(C1)
value	11.0 mV
mean	11.1074 mV
min	8.7 mV
max	14.6 mV
sdev	877.3 µV
num	1.000e+3
status	✓

C1 DSQ D50
33 GHz 45.0 mV/ -115.0 mV



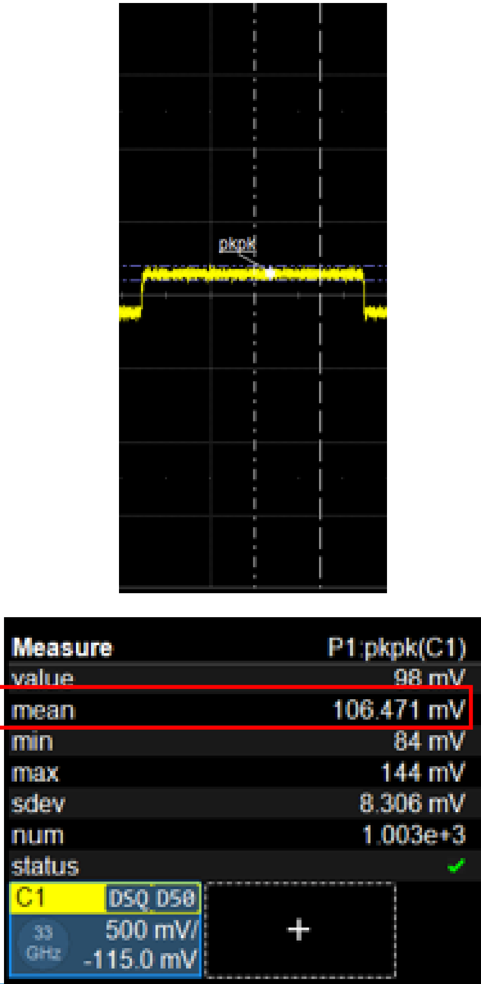
Measure	P1:pkpk(C1)
value	20 mV
mean	19.816 mV
min	16 mV
max	26 mV
sdev	1.540 mV
num	1.000e+3
status	✓

C1 DSQ D50
33 GHz 100 mV/ -116.0 mV



Measure	P1:pkpk(C1)
value	57 mV
mean	59.700 mV
min	46 mV
max	81 mV
sdev	4.822 mV
num	1.000e+3
status	✓

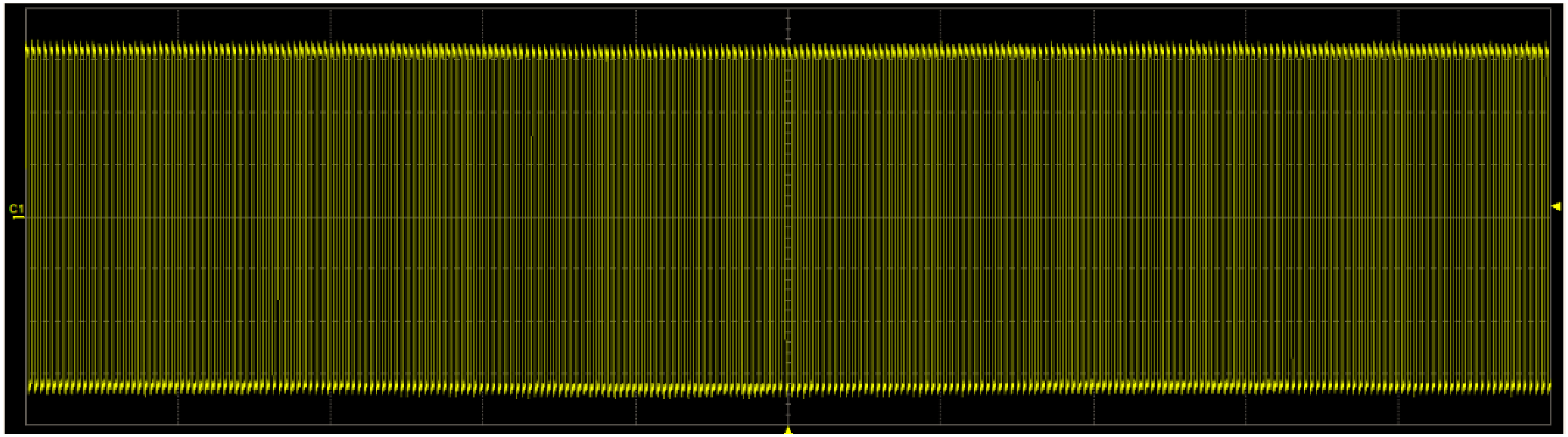
C1 DSQ D50
33 GHz 250 mV/ -115.0 mV

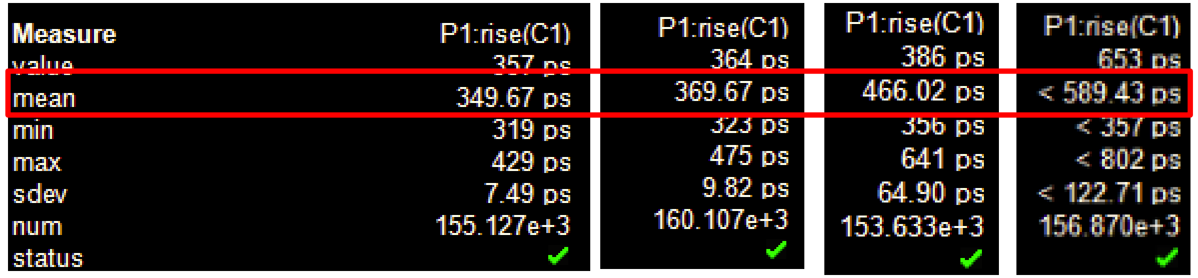


Measure	P1:pkpk(C1)
value	98 mV
mean	106.471 mV
min	84 mV
max	144 mV
sdev	8.306 mV
num	1.003e+3
status	✓

C1 DSQ D50
33 GHz 500 mV/ -115.0 mV

Second Rule: always be vigilant about the sampling rate



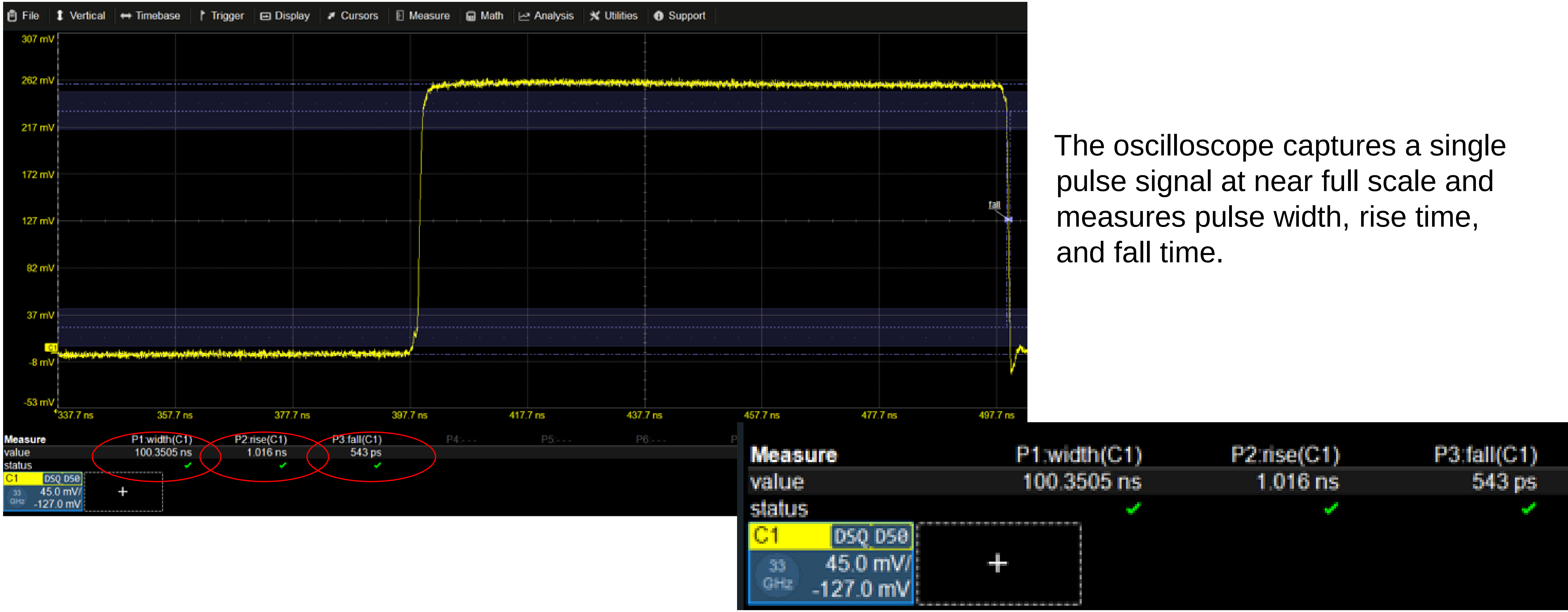


Measure	P1:rise(C1)	P1:rise(C1)	P1:rise(C1)	P1:rise(C1)
value	357 ps	364 ps	386 ps	653 ps
mean	349.67 ps	369.67 ps	466.02 ps	< 589.43 ps
min	319 ps	323 ps	356 ps	< 357 ps
max	429 ps	475 ps	641 ps	< 802 ps
sdev	7.49 ps	9.82 ps	64.90 ps	< 122.71 ps
num	155.127e+3	160.107e+3	153.633e+3	156.870e+3
status	✓	✓	✓	✓

20GS/s **10GS/s** **5GS/s** **2.5GS/s**

Measuring the rise time of the same signal at different sampling rates gets very different results. Therefore, we must always be vigilant about sampling rates.

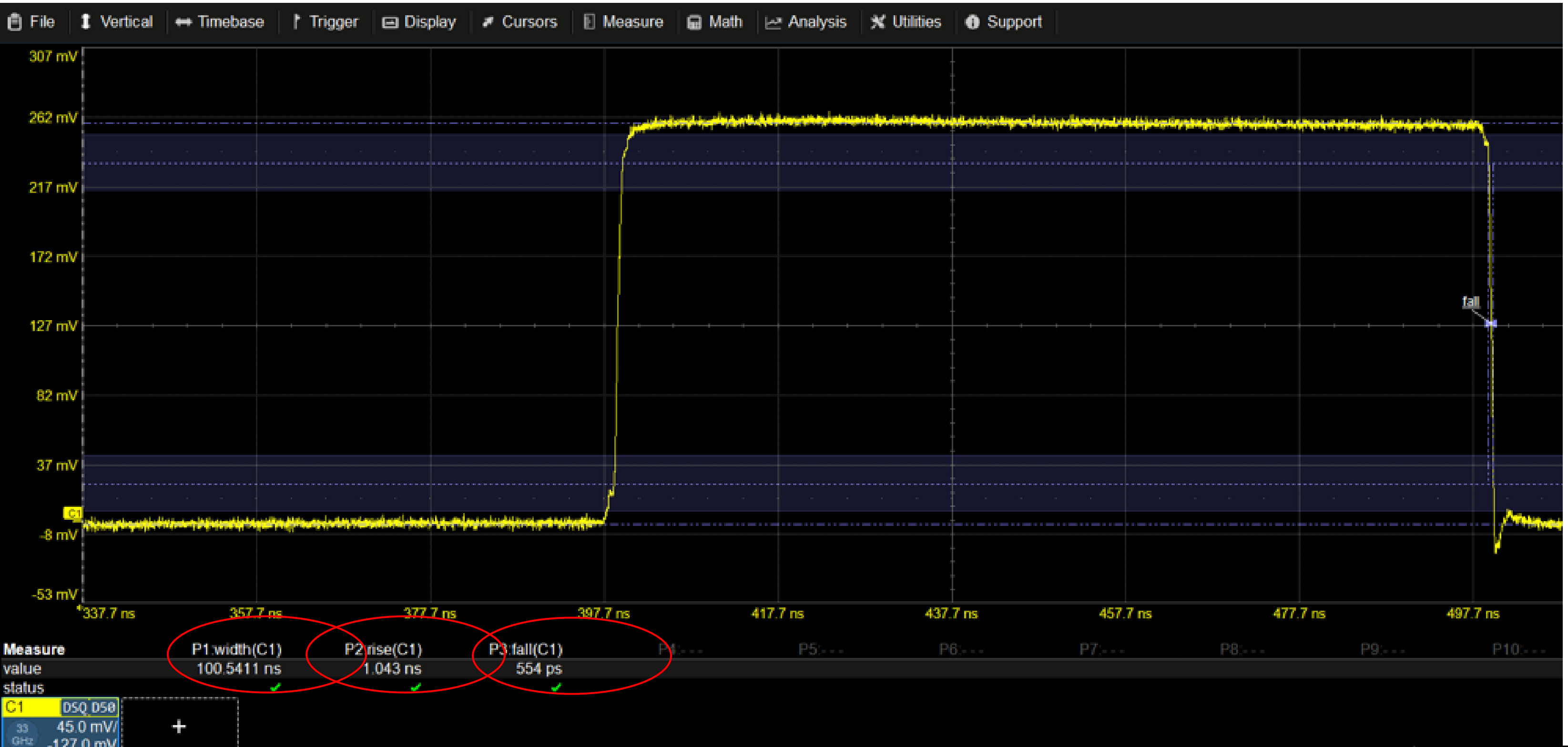
Third Rule: Using the Statistical Function



Measure	P1:width(C1)	P2:rise(C1)	P3:fall(C1)
value	100.3505 ns	1.016 ns	543 ps
status	✓	✓	✓

The oscilloscope captures a single pulse signal at near full scale and measures pulse width, rise time, and fall time.

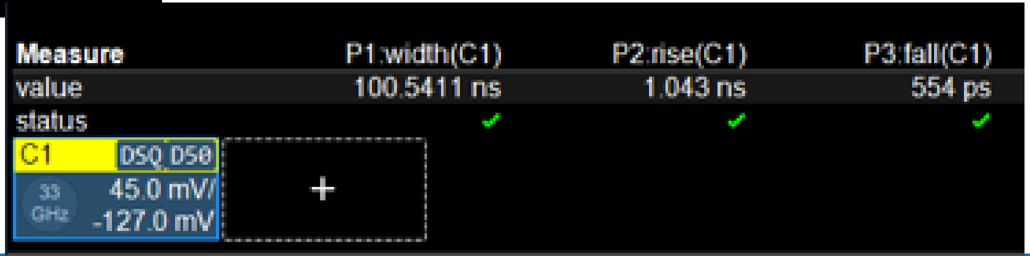
Use statistical functions to improve the accuracy of your measurements



Measure	P1:width(C1)	P2:rise(C1)	P3:fall(C1)	P4:---	P5:---	P6:---	P7:---	P8:---	P9:---	P10:---
value	100.5411 ns	1.043 ns	554 ps							
status	✓	✓	✓							

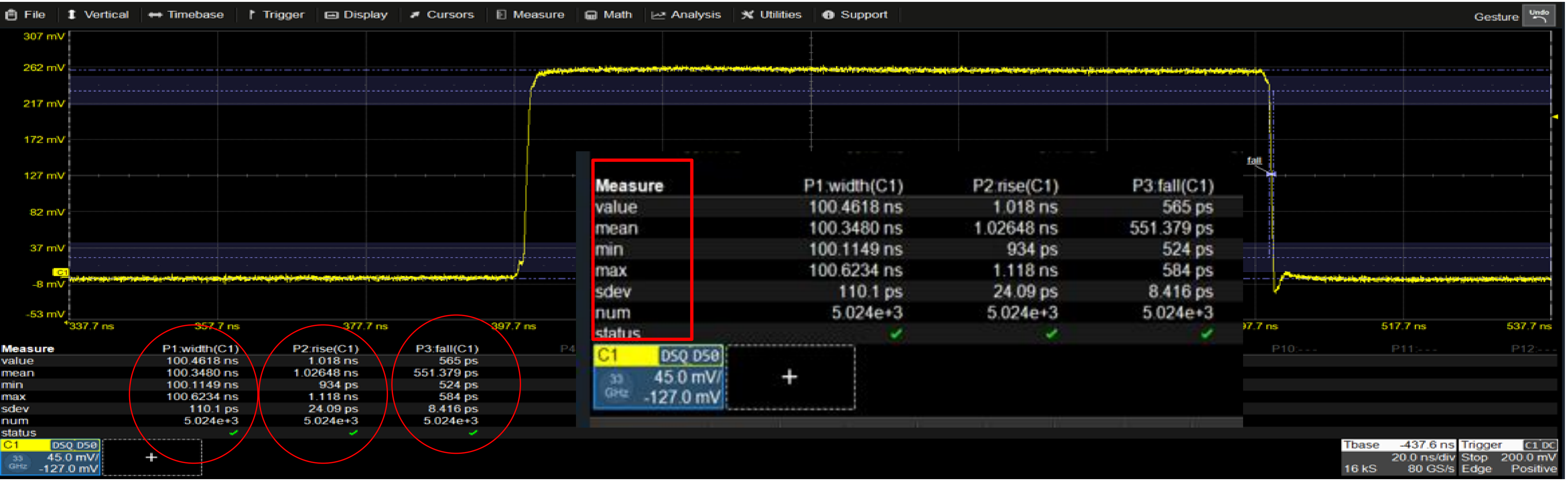
The measurements shown on this image are different from the last one, which one is ″correct″?

In fact, both are correct. The shape of the waveform is unstable, so the measurement results of the captured waveform are different each time.



Measure	P1:width(C1)	P2:rise(C1)	P3:fall(C1)
value	100.5411 ns	1.043 ns	554 ps
status	✓	✓	✓

Use statistical functions

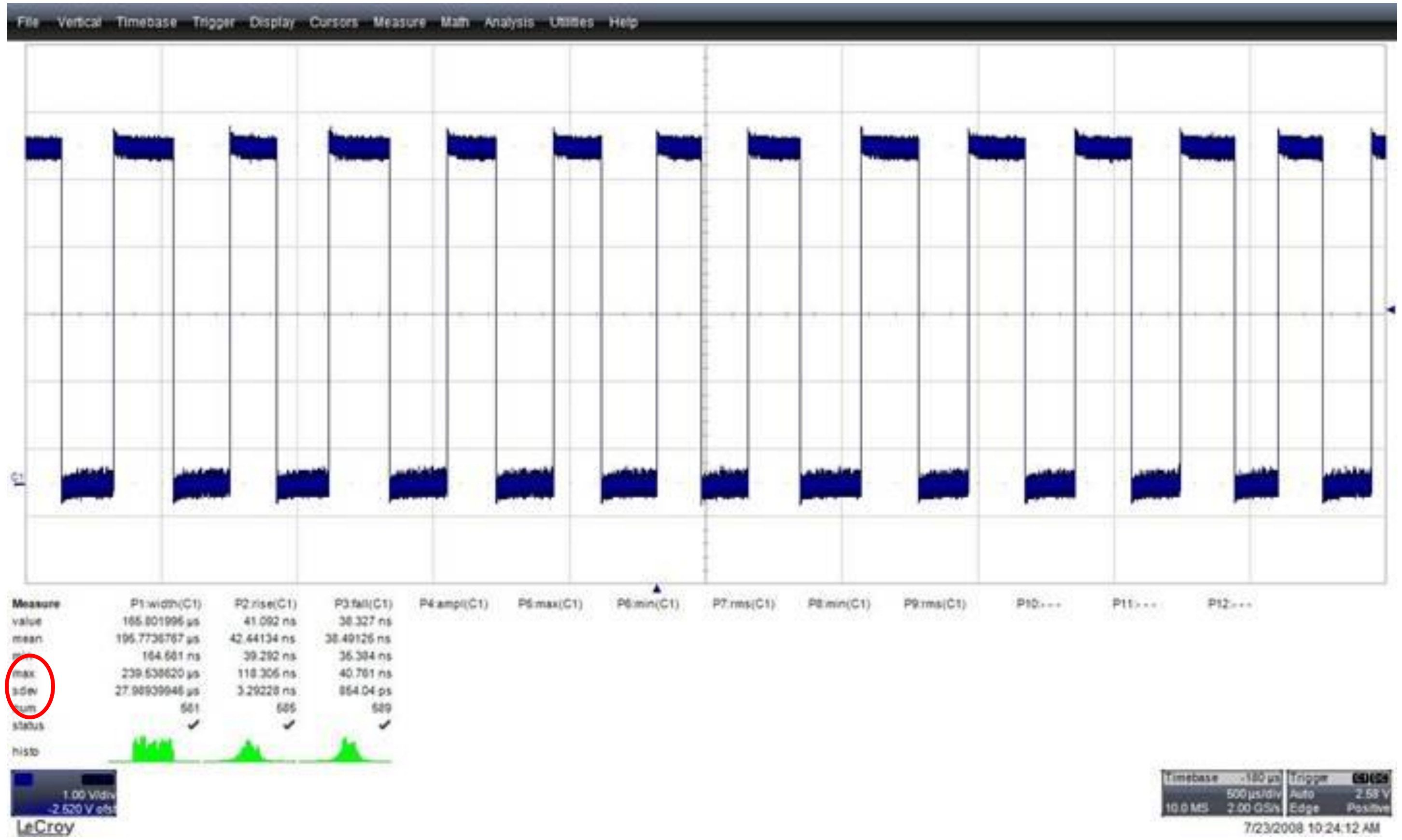


Measure	P1:width(C1)	P2:rise(C1)	P3:fall(C1)
value	100.4618 ns	1.018 ns	565 ps
mean	100.3480 ns	1.02648 ns	551.379 ps
min	100.1149 ns	934 ps	524 ps
max	100.6234 ns	1.118 ns	584 ps
sdev	110.1 ps	24.09 ps	8.416 ps
num	5.024e+3	5.024e+3	5.024e+3
status	✓	✓	✓

The oscilloscope now shows the parametric statistics. "Num" indicates the number of captures. (approx. 5,000)

With measurement statistics, you can discover the worst case of circuit performance and/or the parameter values of some intermittent signals. This is a good way to determine if a key signal feature is within specification.

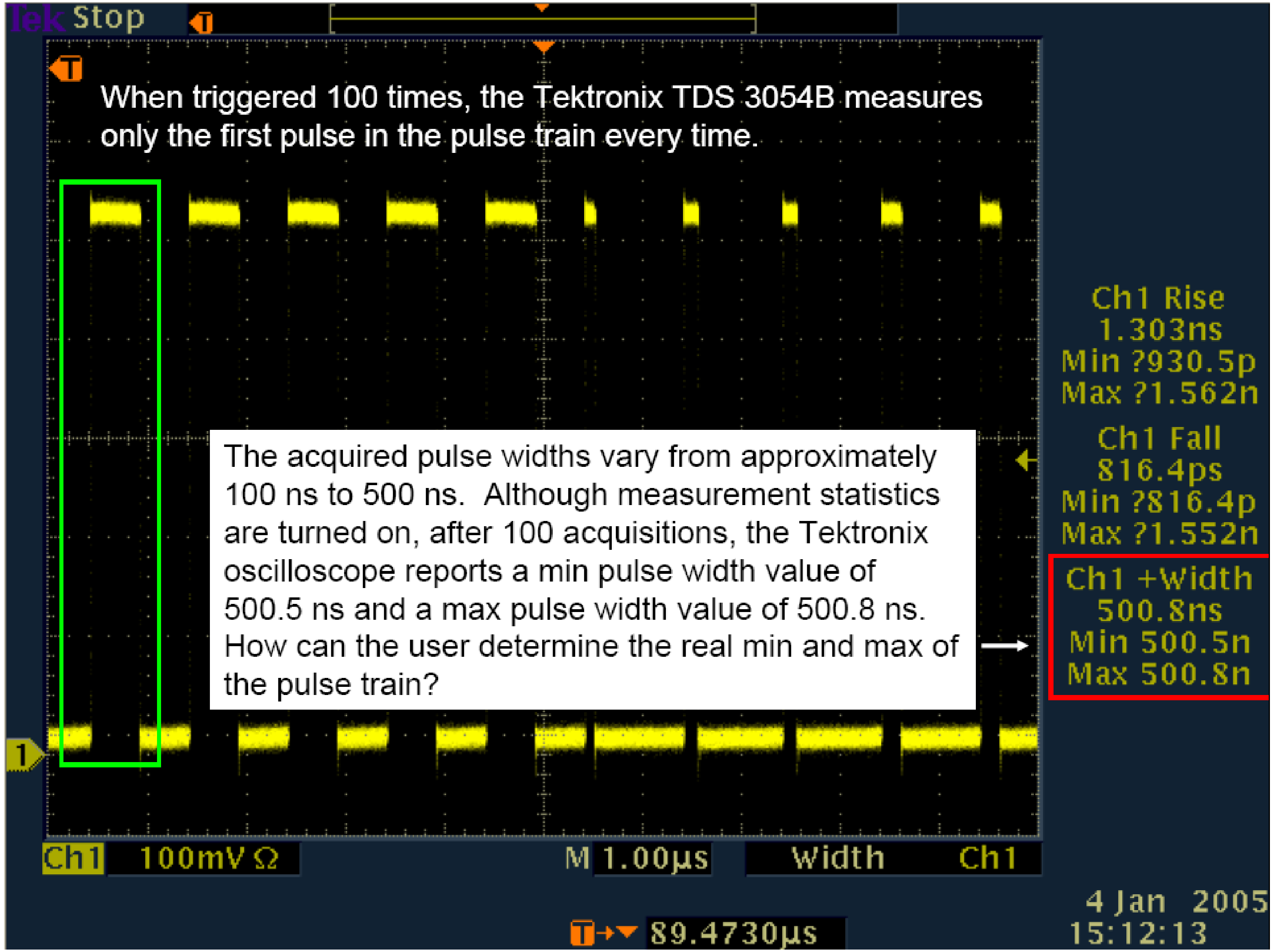
Use statistical functions to improve the accuracy of your measurements



Measure	P1:width(C1)	P2:rise(C1)	P3:fall(C1)	P4:ampl(C1)	P5:max(C1)	P6:min(C1)	P7:rms(C1)	P8:min(C1)	P9:rms(C1)	P10:---	P11:---	P12:---
value	165.801996 µs	41.092 ns	38.327 ns									
mean	195.7736767 µs	42.44134 ns	38.49126 ns									
min	164.681 ns	39.292 ns	36.384 ns									
max	239.538620 µs	118.306 ns	40.761 ns									
sdev	27.98939946 µs	3.29228 ns	854.04 ps									
num	581	585	589									
status	✓	✓	✓									
histo												

This is a typical signal on industrial control, and although it is slow, this example is applicable to signals at any speed. Comparing the ″max″ and ″min″ parameter values with the ″mean″ values, if there is a rare event, the parameter values will indicate this event. In this example, the pulse width is about 195 ns, but there is a rare pulse width of only 165 ns.

whether the oscilloscope you are using supports true measurement statistics



When triggered 100 times, the Tektronix TDS 3054B measures only the first pulse in the pulse train every time.

The acquired pulse widths vary from approximately 100 ns to 500 ns. Although measurement statistics are turned on, after 100 acquisitions, the Tektronix oscilloscope reports a min pulse width value of 500.5 ns and a max pulse width value of 500.8 ns. How can the user determine the real min and max of the pulse train?

Ch1 Rise
1.303ns
Min ?930.5p
Max ?1.562n

Ch1 Fall
816.4ps
Min ?816.4p
Max ?1.552n

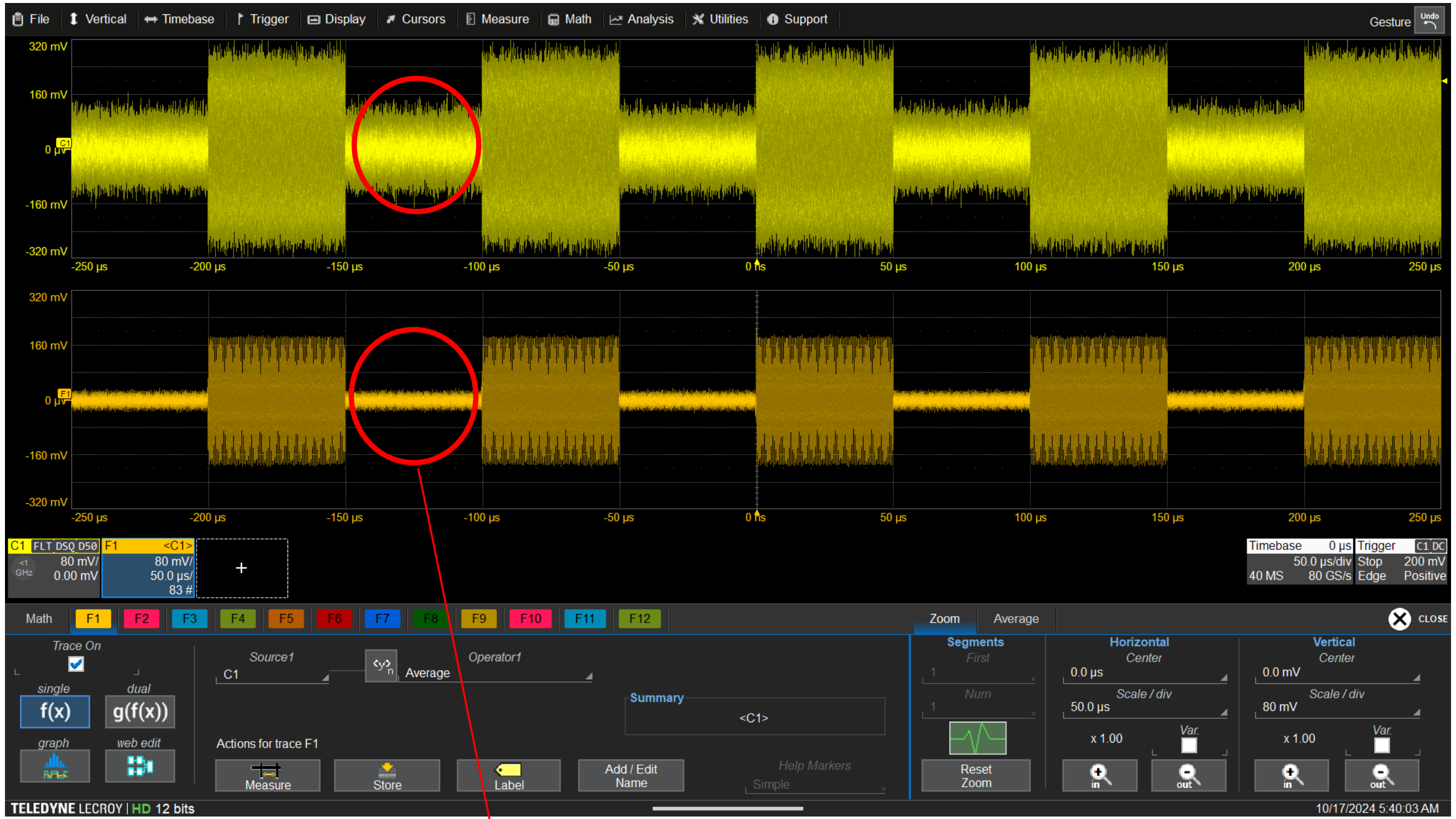
Ch1 +Width
500.8ns
Min 500.5n
Max 500.8n

4 Jan 2005
15:12:13

In this image, you can see that the pulse width is noticeably different, but the maximum and minimum values are almost the same. This is a pseudo-statistic, which simply measures the leftmost pulse duration parameter on the screen. Be wary of this feature when using such an oscilloscope for statistics.

Improve measurement accuracy with averaging and filtering

Observe small signals with noise



C1 FLT DSQ DSΘ 80 mV/ 0.00 mV

F1 <C1> 80 mV/ 50.0 µs/ 83 #

Timebase 0 µs 50.0 µs/div 40 MS 80 GS/s

Trigger C1 DC Stop 200 mV Edge Positive

Source1: C1

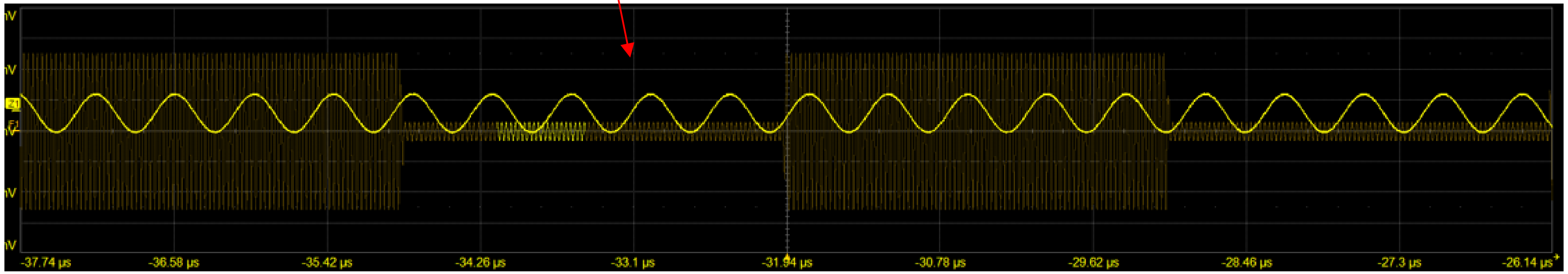
Operator1: Average

Summary: <C1>

Segments: First 1, Num 1

Horizontal: Center 0.0 µs, Scale / div 50.0 µs, x 1.00, Var. ☐

Vertical: Center 0.0 mV, Scale / div 80 mV, x 1.00, Var. ☐



The image above is a single captured signal. The image below shows the signal observed using the signal averaging function, which clearly reveals the true characteristics of the signal under the noise.

When making such measurements, the waveform should be triggered stably, and the storage depth and sampling rate should be sufficient.

Signal analysis:Improve signal-to-noise ratio

C1 DSQ D50 33 GHz 200 mV/ 0.0 mV

F1 <C1> 200 mV/ 100 ns/ 1.000 k#

Timebase 0 ns 100 ns/div 80 kS 80 GS/s

Trigger C1 DC Stop 200 mV Edge Positive

Trace On ☑

Source1 C1

Operator1 Average

Summary <C1>

Actions for trace F1

accumulation stops after the specified number of sweeps.

Sweeps 1000 sweeps

1000 processed

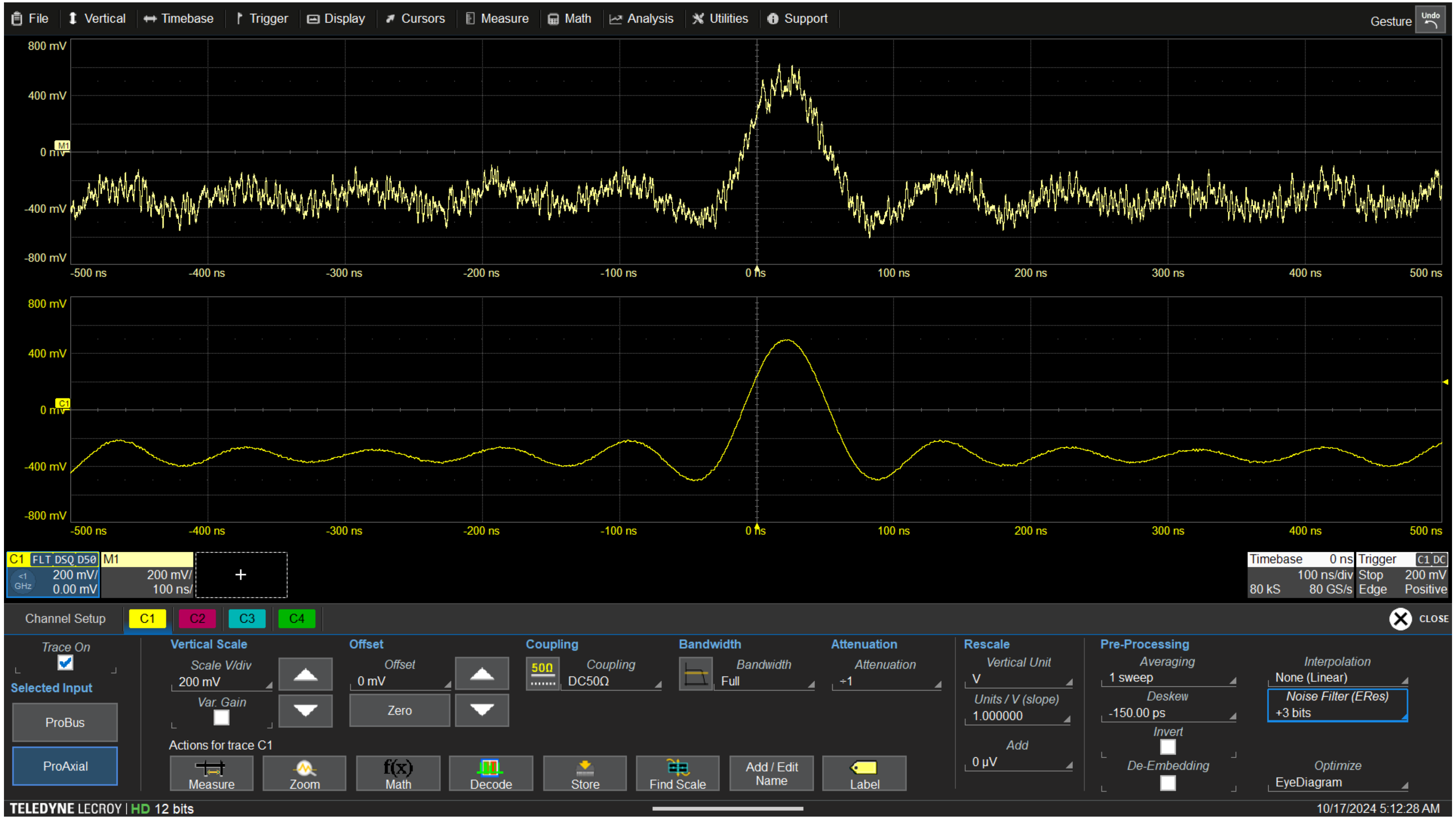
☐ Skip invalid input

10/17/2024 5:10:03 AM

For periodically repeatable signals, the noise of the signal can be reduced by using the method of multiple averaging after stable triggering. The averaging algorithm also reduces the noise introduced by the oscilloscope's analog front end and probes. You can see more detail and measure the signal characteristics more precisely.

1000 measurements averaged

Signal analysis:Improve signal-to-noise ratio



C1 FLT DSQ D50 <1 GHz 200 mV/ 0.00 mV

M1 200 mV/ 100 ns/

Timebase 0 ns 100 ns/div 80 kS 80 GS/s

Trigger C1 DC Stop 200 mV Edge Positive

Trace On ☑

Selected Input

Vertical Scale: Scale V/div 200 mV; Var. Gain ☐

Offset: Offset 0 mV; Zero

Coupling: 50Ω Coupling DC50Ω

Bandwidth: Bandwidth Full

Attenuation: Attenuation ÷1

Rescale: Vertical Unit V; Units / V (slope) 1.000000; Add 0 µV

Pre-Processing: Averaging 1 sweep; Deskew -150.00 ps; Invert ☐; De-Embedding ☐

Interpolation None (Linear); Noise Filter (ERes) +3 bits; Optimize EyeDiagram

10/17/2024 5:12:28 AM

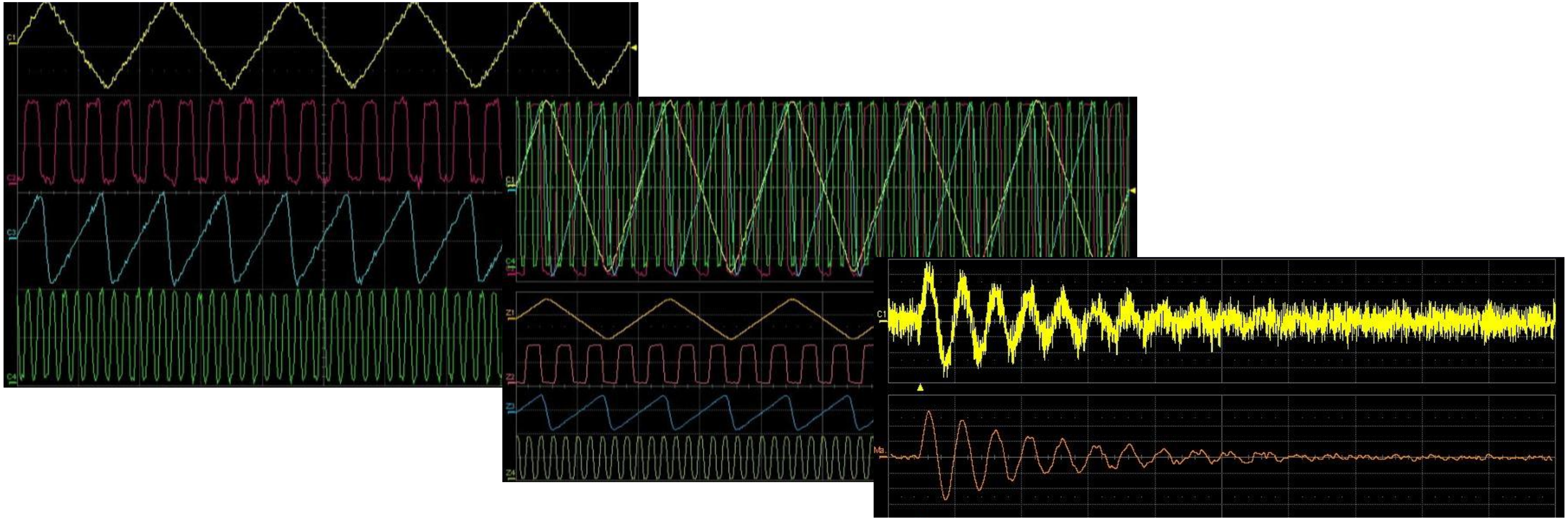
The FIR filter can also reduce noise, but it does not need to be averaged by multiple captures, so it can be used in cases where non-periodic repetitive waveforms cannot be stably triggered. LeCroy oscilloscopes offer a choice of high-precision modes that can simultaneously display a single captured waveform and a high-precision filtered waveform.

Single capture

Reduce noise with 3 bit ERES

Summary: How to Improve Accuracy of Measurement?

- Minimize quantization error: Maximize the waveform to fill the grid
- Always be vigilant about sampling rates: oversample, not under sample
- Take advantage of the measurement statistics function of the parameters
- Signal averaging (no need to measure the noise of the signal and the waveform is stable)
- Utilizes Els's Phil filter (no measurement noise required)
- Use High-precision oscilloscopes that use more digits of ADCs and lower noise analog front-ends



Q&A

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