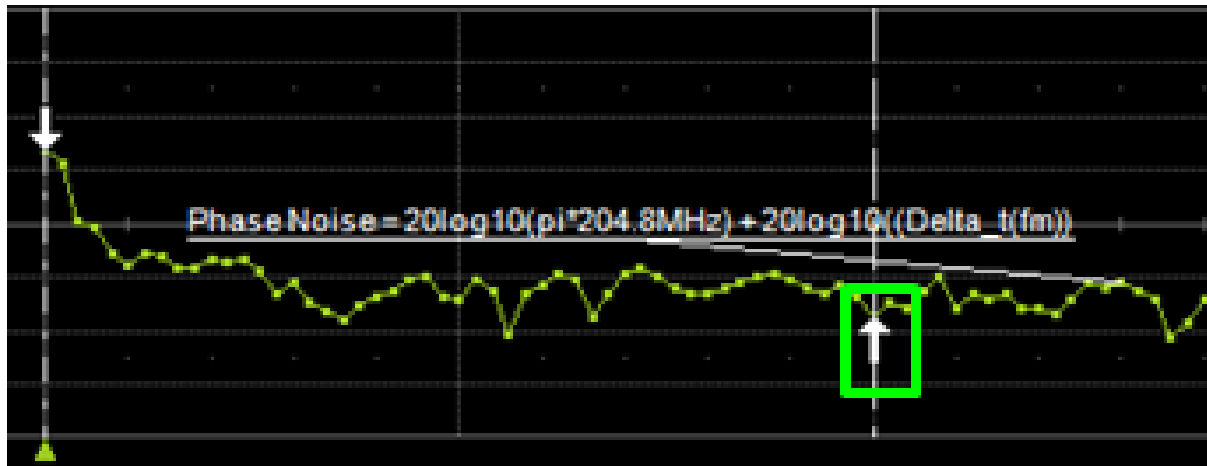


# How to Measure Phase Noise

Using a LeCroy Oscilloscope



# Purpose:

Phase noise is the power spectral density of a signal's random phase fluctuation, and is usually expressed as dBc/Hz in the frequency domain.

Signals with low phase noise are best measured using frequency domain equipment with a wide dynamic range, such as a spectrum analyzer and phase noise test set.

However, for signals with phase noise less than approximately -70 dBc (or -80 dBc with averaging), an oscilloscope may be used.

This document describes a test procedure for how to measure phase noise using an oscilloscope.

Select "Fixed Sample Rate" in the Timebase menu and choose a sample rate which provides adequate characterization of the edge shape (i.e., many points per rising edge).

File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help

M1

420 mV/div  
1.00 ns/div

Timebase 0.00 ns  
1.00 ns/div  
200 S 20 GS/s

Trigger C2 DC  
Stop 0.0 mV  
Edge Positive

Close

TimeBase Clock Source

RealTime Sampling Mode RIS

Roll

Timebase Mode

Time/Division 1.00 ns

200 S at 20 GS/s  
50 ps/pt for 10 ns

Delay 0.00 ns Set To Zero

Real Time Sampling Rate

Sampling Rate 20.0 GS/s

Set Maximum Memory Fixed Sample Rate

Digital Bandwidth Interleave

C1/C2 C3/C4

<=16GHz C1 C2 <=16GHz C3 C4

30 GHz C2 30 GHz C3

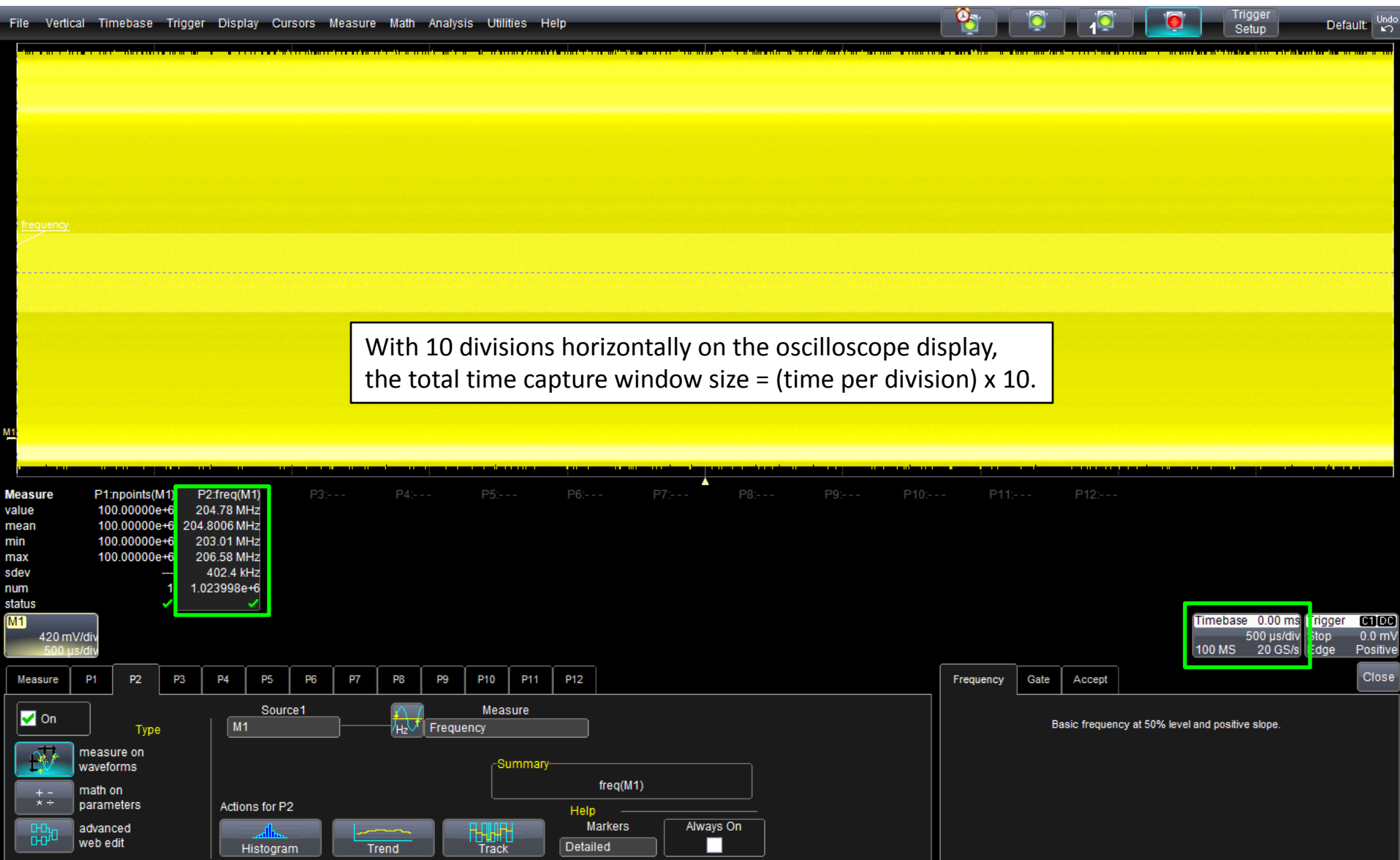
Acquire a minimum time capture window of 1 millisecond. This will provide 1 kHz frequency resolution in the FFT. A longer time capture window will provide greater frequency resolution (for example, the 5 millisecond time capture window shown below will provide 200 Hz resolution).

Frequency resolution =  $1 / (\text{time capture window size})$ . The frequency resolution of an oscilloscope FFT improves with increased time capture window size. If possible, set the oscilloscope to measure frequency resolution 10x better than the measurement point. For example, if phase noise is to be measured at 10 kHz, then set the time capture window to 1 ms which provides 1 kHz frequency resolution, or 10x better resolution than the measurement point.

The screenshot shows the oscilloscope's main interface. At the top, a menu bar includes File, Vertical, Timebase, Trigger, Display, Cursors, Measure, Math, Analysis, Utilities, and Help. On the right, there are icons for various functions and a 'Trigger Setup' button. The main display area is a large yellow rectangle representing the FFT plot. Below the plot, there are several control panels:

- M1 Panel:** Shows 420 mV/div and 500  $\mu$ s/div.
- Timebase Panel:** Shows Time/Division set to 500  $\mu$ s, with a note '100 MS at 20 GS/s' and '50 ps/pt for 5 ms'. It also has a Delay set to 0.00 ms and a 'Set To Zero' button.
- Real Time Sampling Rate Panel:** Shows a Sampling Rate of 20.0 GS/s and a 'Fixed Sample Rate' button highlighted with a green box.
- Digital Bandwidth Interleave Panel:** Shows settings for C1/C2 and C3/C4, with options for <math>\leq 16\text{GHz}</math> and 30 GHz.
- Trigger Panel:** Shows Timebase 0.00 ms, 500  $\mu$ s/div, 100 MS, and 20 GS/s. It also has buttons for Stop, Edge, and Positive.

Shown below, 100 million sample points of this 204.8 MHz clock were acquired with a 5 millisecond time capture window, in order to obtain a large time capture window.



Measure TIE of the clock waveform. Set the input source to be Clock.

The screenshot shows a digital oscilloscope interface with a yellow background. A clock waveform is visible at the bottom. A text box in the center reads: "Choose Measure -> Measure Setup -> My Measure, and select the measurement to be TIE@lv and the source to be the input waveform (for example Channel 1)."

**Measure Table:**

Measure	P1.npoints(M1)	P2.freq(M1)	P3.TIE@lv(M1)	P4---	P5---	P6---	P7---	P8---	P9---	P10---	P11---	P12---
value	100.00000e+6	204.78 MHz	18 ps									
mean	100.00000e+6	204.8006 MHz	8.73 ps									
min	100.00000e+6	203.01 MHz	-28 ps									
max	100.00000e+6	206.58 MHz	43 ps									
sdev	---	402.4 kHz	8.07 ps									
num	1	1.023998e+6	1.023999e+6									
status	✓	✓	✓									

**Measure Setup Panel (P3):**

- Source 1: M1
- Measure: TIE@lv
- Summary: TIE@lv(M1)
- Actions for P3: Histogram, Trend, Track
- Help: Markers, Always On

**Measurement Configuration Panel:**

- TIE: VClock, Gate, Accept
- Time Interval Error (Jitter) on either clock or data
- Input is: Clock
- Data is: NRZ
- Interval is: Edge-Ref
- Output in: Time
- Crossing Detection: Level is 50%, Percent level 50%, Slope Pos, Hysteresis 500 mdiv
- Virtual Edges:
- Annotate: 1 #

**Other UI Elements:**

- Timebase: 0.00 ms
- Trigger: C1 DC
- Stop: 0.0 mV
- Edge: Positive
- 420 mV/div, 500  $\mu$ s/div
- 100 MS, 20 GS/s

# "Find Frequency" of the signal using the VClock of TIE parameter tab.

The screenshot displays the oscilloscope's interface. At the top, a menu bar includes File, Vertical, Timebase, Trigger, Display, Cursors, Measure, Math, Analysis, Utilities, and Help. A toolbar on the right contains icons for various functions and a 'Trigger Setup' button. The main display area shows a signal trace with a yellow background. A text box in the center of the trace reads: "In the TIE parameter tab, select the VClock subtab and press the 'Find Frequency' button to have the scope automatically find the frequency of the input signal."

Below the trace, a 'Measure' table is visible:

Measure	P1.npoints(M1)	P2.freq(M1)	P3.TIE@lv(M1)	P4---	P5---	P6---	P7---	P8---	P9---	P10---	P11---	P12---
value	100.00000e+6	204.78 MHz	16 ps									
mean	100.00000e+6	204.8006 MHz	7.62 ps									
min	100.00000e+6	203.01 MHz	-28 ps									
max	100.00000e+6	206.58 MHz	41 ps									
sdev	---	402.4 kHz	7.68 ps									
num	1	1.023998e+6	1.023999e+6									
status	✓		✓									

At the bottom, the 'TIE' parameter tab is active, showing the 'VClock' subtab. The 'Reference' is set to 'Custom' with a value of '204.799819 Mbit/sec'. The 'Find frequency' button is highlighted with a green box. Other settings include 'PLL type' set to 'FC Golden' and 'Permit > 1/2UI' checked. The 'BW indep of data' checkbox is also checked.

Apply the Track math operator to TIE.

The screenshot shows the LeCroy oscilloscope interface. The main display area shows a signal trace with a yellow background. The top menu bar includes File, Vertical, Timebase, Trigger, Display, Cursors, Measure, Math, Analysis, Utilities, and Help. The bottom left shows the Measure table with columns for P1.npoints(M1), P2.freq(M1), and P3.TIE@lv(M1). The bottom right shows the Math Setup window with a table for Source1 and Operator1. A text box in the center provides instructions on how to apply the Track math operator to the TIE@lv measurement.

Measure	P1.npoints(M1)	P2.freq(M1)	P3.TIE@lv(M1)	P4---	P5---
value	100.00000e+6	204.78 MHz	18 ps		
mean	100.00000e+6	204.8006 MHz	8.73 ps		
min	100.00000e+6	203.01 MHz	-28 ps		
max	100.00000e+6	206.58 MHz	43 ps		
sdev	---	402.4 kHz	8.07 ps		
num	1	1.023998e+6	1.023999e+6		
status	✓	✓	✓		

Choose the Math operator Track to be applied to the measurement of TIE@lv. Track can be accessed from Math -> Math Setup -> F1 (for example), or alternatively by selecting the TIE@lv parameter (P3 for example) then pressing the "Track" button in the measurement subtab.

Source1	Operator1
P3	Track

Timebase	0.00 ms	Trigger	C1 DC
	500 $\mu$ s/div	Stop	0.0 mV
100 MS	20 GS/s	Edge	Positive

Zoom	Track	Close
Segments	Horizontal Center	Vertical Center
First	0 $\mu$ s	7.69 ps
Num	Scale / div	Scale / div
	500 $\mu$ s	10.0 ps
	x 1.00	Var.
	in	out
Reset Zoom		

Disable the software PLL and fine-adjust the TIE custom frequency for maximum flatness of the Track.

Required: Disable the software PLL by unchecking the "Enable PLL" checkbox. This allows jitter frequency content to be measured (and not filtered) inside of the range in which a software PLL would normally track (and therefore lowpass filter) low frequency jitter

Optional: If desired, fine-adjust the custom frequency in the VClock menu by clicking on "Custom Freq" value and adjusting it with the pop-up keypad. The goal of this is to make the level of the Track as horizontal (flat) as possible to minimize long-term drift

Measure	P1:npoints(M1)	P2:freq(M1)	P3:TIE@lv(M1)	P4:---	P5:---
value	100.00000e+6	204.78 MHz	-6 ps		
mean	100.00000e+6	204.8006 MHz	-3.48 ps		
min	100.00000e+6	203.01 MHz	-33 ps		
max	100.00000e+6	206.58 MHz	27 ps		
sdev	---	402.4 kHz	6.45 ps		
num	1	1.023998e+6	1.023999e+6		
status	✓	✓	✓		

Measure	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
On												
Type												
measure on waveforms												
math on parameters												
advanced web edit												
Source1	M1											
Measure			TIE@level									
Summary			TIE@lv(M1)									
Help												
Markers												
Always On												
Histogram												
Trend												
Track												
Detailed												

TIE	VClock	Gate	Accept	Close
Reference	Custom		Custom freq. 204.799818 Mbit/sec	Find frequency
Enable PLL	FC Golden		Permit > 1/2UI	
BW indep of data				

# Apply an FFT to the Track.

File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help

Trigger Setup Flashba... Undo

F1

F2

Frequency Spectrum of TIETrack

Select another math operator (for example F2) to be the FFT of the Track (for example F1). This provides a frequency spectrum (jitter spectrum) of the time-domain jitter (TIE vs. time).

Measure	P1.npoints(M1)	P2.freq(M1)	P3:TIE@lv(M1)	P4:---	P5:---	P6:---
value	100.00000e+6	204.78 MHz	-6 ps			
mean	100.00000e+6	204.8006 MHz	-3.48 ps			
min	100.00000e+6	203.01 MHz	-33 ps			
max	100.00000e+6	206.58 MHz	27 ps			
sdev	---	402.4 kHz	6.45 ps			
num	1	1.023998e+6	1.023999e+6			
status	✓	✓	✓			

F1 track(P3) 10.0 ps/div 500 μs/div

F2 FFT(F1) 2.00 ps/div 5.00 kHz/div

Timebase 0.00 ms Trigger C1 DC

500 μs/div Stop 0.0 mV

100 MS 20 GS/s Edge Positive

Math F1 F2 F3 F4 F5 F6 F7 F8

Trace On

single dual

f(x) g(f(x))

graph web edit

Source1 Operator1

F1 FFT

Summary

FFT(F1)

Actions for trace F2

Measure Store Label Next

Help Markers

Simple

Zoom FFT

Segments First

Horizontal Center

Vertical Center

0.00 kHz

3.10 ps

Scale / div

5.00 kHz

2.00 ps

x 200k

Var.

x10.00

Var.

Reset Zoom

in out

in out

Choose the FFT settings of "Magnitude", "VonHann", "LeastPrime", and uncheck "Suppress DC".

The combination of "Magnitude" output, "VonHann" window, and "LeastPrime" algorithm (which uses the full FFT record set) are used to calculate the frequency spectrum. Make sure that "Suppress DC" is unchecked.

Optional: If acquiring data on a live signal, use FFT averaging to improve dynamic range. To enable FFT averaging, select "Dual Function" in the measurement subtab and set Operator2 to be "Average".

File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help

Trigger Setup Flashba... Undo

Frequency Spectrum of TIETrack

Timebase 0.00 ms Trigger C1 DC  
500  $\mu$ s/div Stop 0.0 mV  
100 MS 20 GS/s Edge Positive

Math F1 F2 F3 F4 F5 F6 F7 F8

Trace On  
single dual  
 $f(x)$   $g(f(x))$   
graph web edit

Source1 Operator1  
F1 FFT

Summary  
FFT(F1)

Actions for trace F2  
Measure Store Label Next

Help Markers  
Simple

Zoom FFT

Output type  
Magnitude  
Window  
VonHann  
Algorithm  
LeastPrime

trunc zero fill Suppress DC

Transform 10000000 pts to 50000001 bins  
 $\Delta f = 200$  Hz  
DC - 10.000000 GHz  
ENBW = 1.500

# Apply Log10 to the FFT.

File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help

Trigger Setup Flashba... Undo

F1

F2

F3

Frequency Spectrum of TIE Track

Log10 of FFT

Measure

Measure	P1.npoints(M1)	P2.freq(M1)	P3.TIE@lv(M1)	P4---	P5---
value	100.00000e+6	204.78 MHz	-6 ps		
mean	100.00000e+6	204.8006 MHz	-3.48 ps		
min	100.00000e+6	203.01 MHz	-33 ps		
max	100.00000e+6	206.58 MHz	27 ps		
sdev	--	402.4 kHz	6.45 ps		
num	1	1.023998e+6	1.023999e+6		
status	✓	✓	✓		

F1 track(P3) 10.0 ps/div 500 μs/div

F2 FFT(F1) 2.00 ps/div 5.00 kHz/div

F3 log10(F2) 1.00/div 5.00 kHz/div

Math F1 F2 F3 F4 F5 F6 F7 F8

Trace On

single dual

f(x) g(f(x))

graph web edit

Source1 Operator1

F2 log<sub>10</sub> Log10

Summary

log10(F2)

Actions for trace F3

Measure Store Label Next Help Markers Simple

Timebase 0.00 ms 500 μs/div 100 MS 20 GS/s

Trigger C1 DC Stop 0.0 mV Edge Positive

Zoom Log10

Segments First

Horizontal Center 0.00 kHz Scale / div 5.00 kHz x 1.00 Var. in out

Vertical Center -12.544 Scale / div 1.00 x 0.76 Var. in out

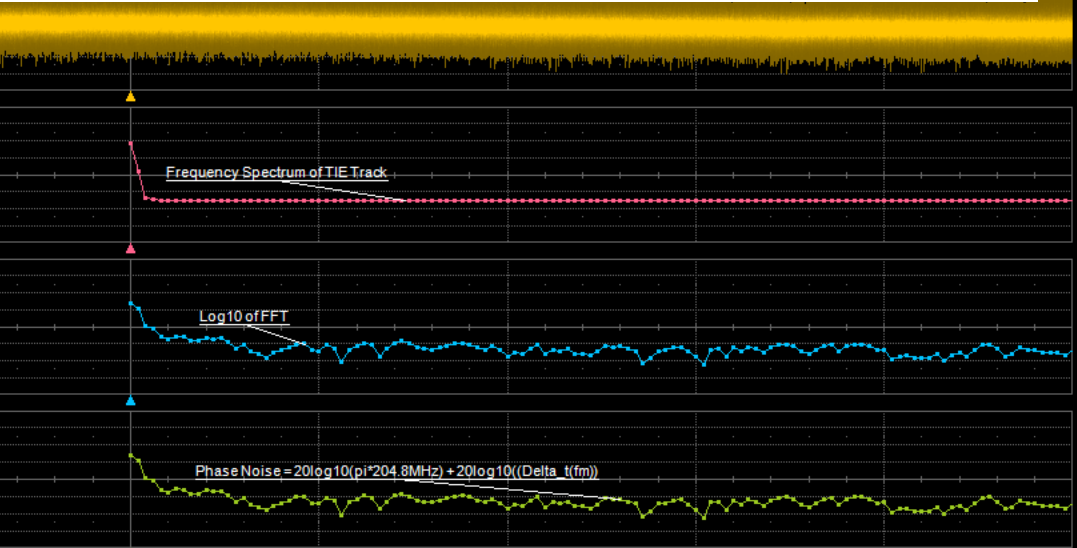
Reset Zoom

Select another math operator (for example F3) to be the Log10 of the FFT (for example F2). This provides the log value of the spectral magnitude.

In the Rescale operator, multiply by 20, then determine the constant to add as follows: Calculate  $20\log_{10}(\pi \cdot \text{carrier frequency})$ . In this example,  $20\log_{10}(643398175) = 176$ . Enter this value as the constant in the Rescale operator.

Select another math operator (for example F4) to be the Rescale of the Log10 operator (for example F3). The Rescale operator converts the result into Phase Noise.

Multiply the carrier frequency of the signal by Pi, then take the Log10 of this result and multiply by 20. The result is entered into the "then add" field of the Rescale operator.



Measure	P1:npoints(M1)	P2:freq(M1)	P3:TIE@lv(M1)	P4:---	P5:---	P6:---	P7:---	P8:---	P9:---	P10:---	P11:---	P12:---
value	100.00000e+6	204.78 MHz	-6 ps									
mean	100.00000e+6	204.8006 MHz	-3.48 ps									
min	100.00000e+6	203.01 MHz	-33 ps									
max	100.00000e+6	206.58 MHz	27 ps									
sdev	---	402.4 kHz	6.45 ps									
num	1	1.023998e+6	1.023999e+6									
status	✓	✓	✓									

F1 track(P3) 10.0 ps/div 500 μs/div  
F2 FFT(F1) 2.00 ps/div 5.00 kHz/div  
F3 log10(F2) 1.00/div 5.00 kHz/div  
F4 rescale(F3) 20.0 dB/div 5.00 kHz/div

Timebase 0.00 ms 100 MS  
 Trigger C1 DC 500 μs/div 20 GS/s  
 Stop 0.0 mV Edge Positive

Math F1 F2 F3 F4 F5 F6 F7 F8

Trace On   
 single dual   
 f(x) g(f(x))  
 graph web edit

Source1 Operator1  
 F3 y=ax+b Rescale

Summary  
 rescale(F3)

Actions for trace F4  
 Measure Store Label Next Help Markers Simple

Zoom Rescale Close

Linearly transform the vertical values of a waveform.

First multiply by: 20.0000000

then add: 176.000000 DBC

Override units

Output units DBC

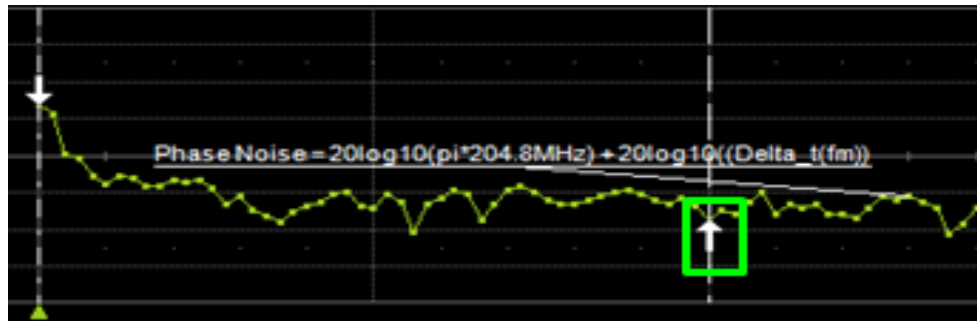
Place a cursor at the phase noise offset frequency (for example 10 kHz) and read out the cursor value in DBC from the F4 trace descriptor to determine phase noise.



# Note about Dynamic Range

An oscilloscope provides accurate phase noise measurements to -70 dBc with approximately +/- 1 dB accuracy without averaging. With averaging, an 8-bit oscilloscope dynamic range may be extended to approximately -80 dBc or greater.

Shown here, the left cursor is placed at DC, and the right cursor is placed at 10 kHz. The right cursor value at 10 kHz shows a **10 KHz offset phase noise value of -109.63 dBc**.



The left cursor placed at 0 Hz shows a carrier level of -47.401 dBc. However, since oscilloscope FFTs only display positive frequencies, the DC point needs to be adjusted by 6 dB. Therefore, the **dynamic range** of this measurement is  $(109.63 - 47.401 - 6.0) = 56.229$  dB, which is well within the dynamic range of an oscilloscope.

# Summary

By applying the TIE Track math operator to the input waveform, data is effectively sampled at the carrier frequency, translating the carrier down to zero frequency. By generating a scaled FFT of this result, phase noise can be determined at a fixed frequency displacement from the carrier frequency.

The absolute phase noise level measurement is not limited on an oscilloscope, but the dynamic range is. An oscilloscope with an 8 bit digitizer limits the maximum dynamic range of a phase noise measurement to approximately 80 dB, where the dynamic range is the ratio of the highest to lowest phase noise level. The scaling moves the phase noise graph up or down proportionally to the carrier frequency.

For low phase noise applications requiring wide dynamic range, a frequency domain instrument such as a spectrum analyzer or phase noise test set is recommended.