

ADC Noise Hands-on Experiment

TIPL 4204-L

TI Precision Labs – SAR ADCs

by Art Kay and Dale Li

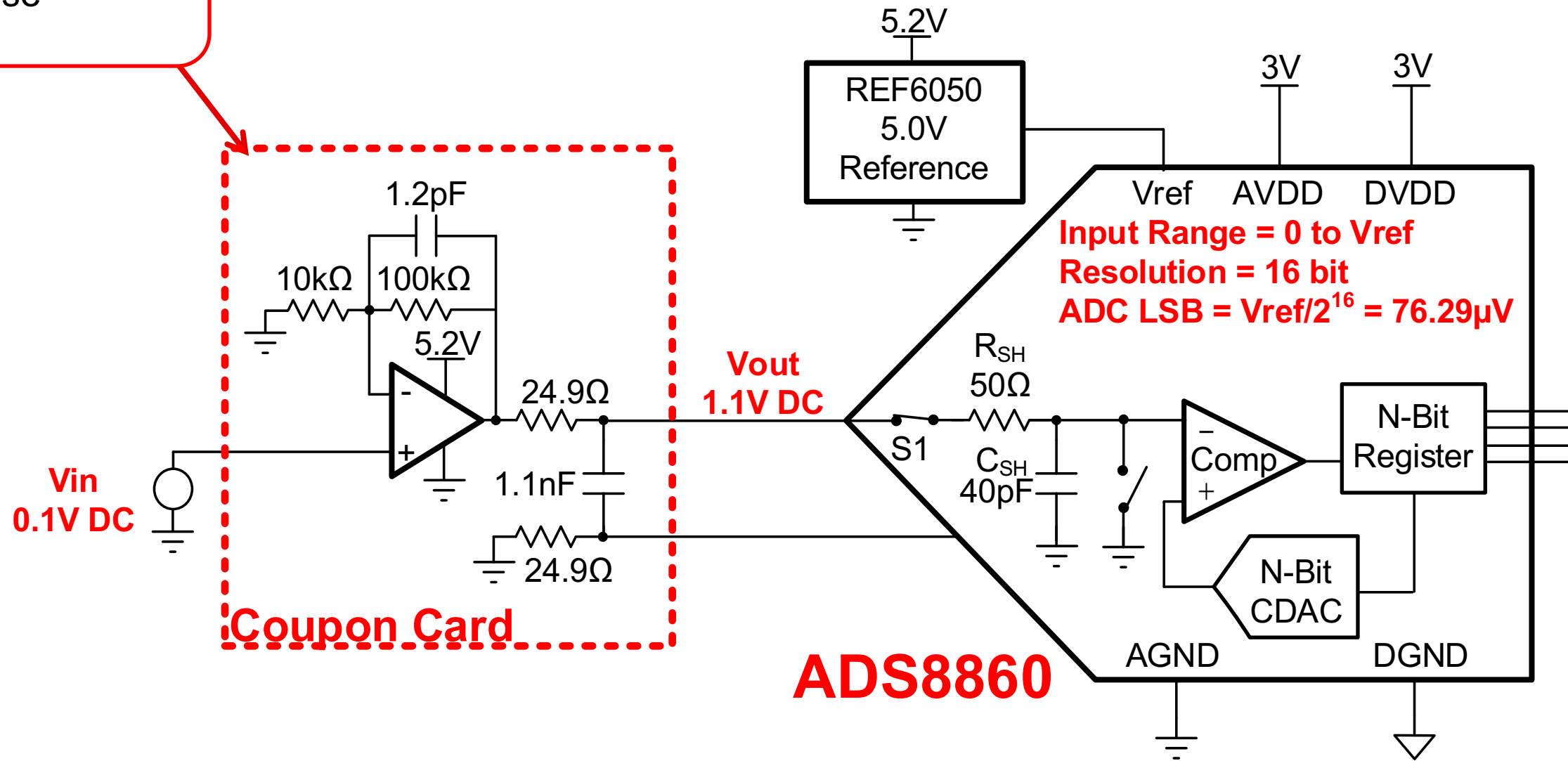


Required/Recommended Equipment

- Calculation
 - Simple calculation using OPA320
 - ADS8860 Data Sheet to find RMS noise voltage
 - Combine ADS8860, REF6050, and OPA320 noise for total noise
- Simulation
 - Simulation using OPA320 and REF6050 Models
- Measurement
 - PLABS-SAR-EVM-PDK
 - <http://www.ti.com/tool/plabs-sar-evm-pdk>
 - <http://www.ti.com/tool/ANALOG-ENGINEER-CALC>
 - Download EVM software and purchase EVM

System we are Analyzing and Measuring

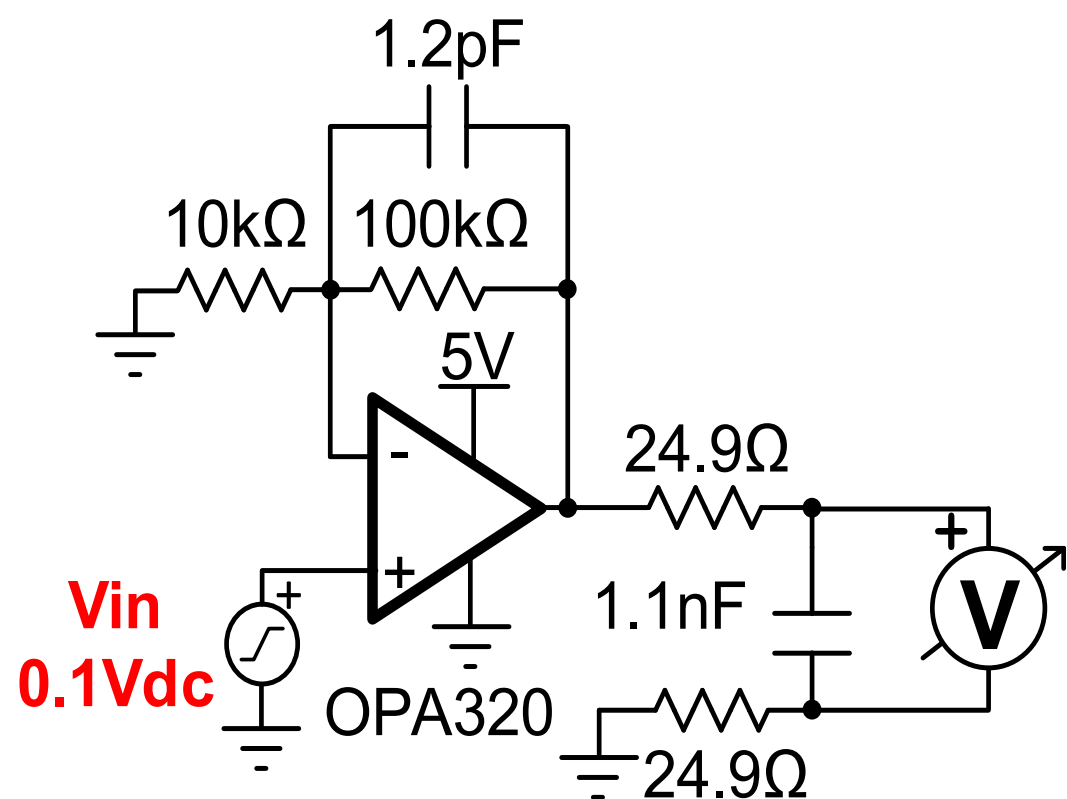
We will use two different "Coupon Cards". Each will have different noise characteristics..



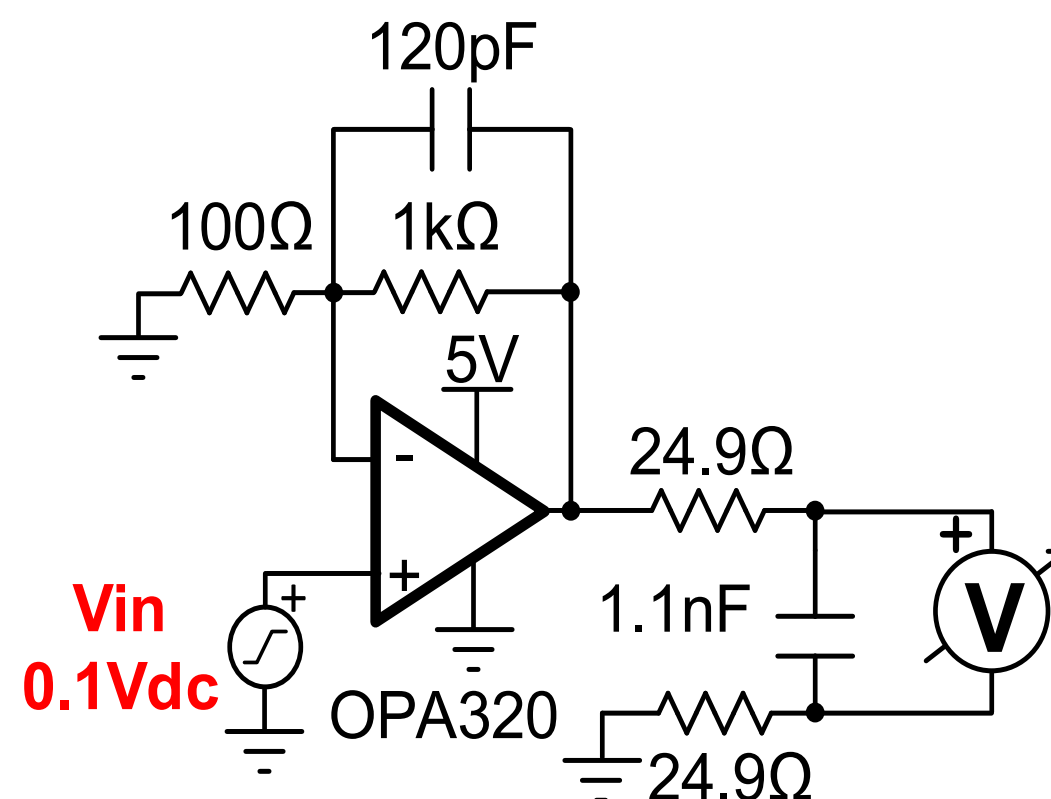
Noise Hand Calculation

- Both circuits have the same: gain, bandwidth, and output filter
- The difference is feedback network resistance is scaled by a factor of 100
- The objective is to see how thermal noise from feedback impacts overall noise

Noise 1



Noise 2



Noise Calculation for Noise 1

$$f_{c_feedback} = \frac{1}{2 \cdot \pi \cdot R_f \cdot C_f} = \frac{1}{2 \cdot \pi \cdot (100k\Omega) \cdot (1.2pF)} = 1.33MHz$$

$$f_{c_ChargeBucket} = \frac{1}{2 \cdot \pi \cdot R_{filt} \cdot C_{filt}} = \frac{1}{2 \cdot \pi \cdot (24.9\Omega) \cdot (1.1nF)} = 5.81MHz$$

$$f_{c_Amp} = \frac{GBW}{Gain} = \frac{20}{11} = 1.82MHz$$

$$f_{c_system_estimate} = 1.33MHz$$

$$BW_n = K_n \cdot f_{c_system_estimate} = (1.22) \cdot (1.33MHz) = 1.62MHz$$

$$R_{eq} = \frac{R_f \cdot R_g}{R_f + R_g} = \frac{(100k\Omega) \cdot (10k\Omega)}{100k\Omega + 10k\Omega} = 9.09k\Omega$$

$$e_{nReq} = \sqrt{4 \cdot k \cdot R_{eq} \cdot T_k} = \sqrt{4 \cdot (1.38 \cdot 10^{-23} J / K) \cdot (9.09k\Omega) \cdot (298.15K)} = 12.23nV / \sqrt{Hz}$$

$$e_{nTotal} = \sqrt{(e_{nReq})^2 + (e_{n_Amp})^2} = \sqrt{(12.23nV / \sqrt{Hz})^2 + (7nV / \sqrt{Hz})^2} = 14.09nV / \sqrt{Hz}$$

$$E_{nTotal_RTI} = e_{nTotal} \cdot \sqrt{BW_n} = (14.09nV / \sqrt{Hz}) \cdot \sqrt{(1.62MHz)} = 17.88\muV \text{ rms}$$

$$E_{nTotal_RTO} = Gain \cdot E_{nTotal_RTI} = (11) \cdot (17.88\muV) = 196.7\muV \text{ rms}$$

The system bandwidth is limited by three factors: feedback filter, charge bucket filter, and amplifier gain bandwidth. The overall bandwidth assumes that the feedback and amplifier poles are close, so the system is approximately second order.

Noise from the feedback network.

Combined noise from op amp and feedback network. Integrated and referred to the output.

Noise Calculation for Noise 2

$$f_{c_feedback} = \frac{1}{2 \cdot \pi \cdot R_f \cdot C_f} = \frac{1}{2 \cdot \pi \cdot (1k\Omega) \cdot (120pF)} = 1.33MHz$$

$$f_{c_ChargeBucket} = \frac{1}{2 \cdot \pi \cdot R_{filt} \cdot C_{filt}} = \frac{1}{2 \cdot \pi \cdot (24.9\Omega) \cdot (1.1nF)} = 5.81MHz$$

$$f_{c_Amp} = \frac{GBW}{Gain} = \frac{20}{11} = 1.82MHz$$

$$f_{c_system_estimate} = 1.33MHz$$

$$BW_n = K_n \cdot f_{c_system_estimate} = (1.22) \cdot (1.33MHz) = 1.62MHz$$

$$R_{eq} = \frac{R_f \cdot R_g}{R_f + R_g} = \frac{(1k\Omega) \cdot (100\Omega)}{1k\Omega + 100\Omega} = 90.9\Omega$$

$$e_{nReq} = \sqrt{4 \cdot k \cdot R_{eq} \cdot T_k} = \sqrt{4 \cdot (1.38 \cdot 10^{-23} J / K) \cdot (90.9\Omega) \cdot (298.15K)} = 1.22 nV / \sqrt{Hz}$$

$$e_{nTotal} = \sqrt{(e_{nReq})^2 + (e_{n_Amp})^2} = \sqrt{(1.22 nV / \sqrt{Hz})^2 + (7 nV / \sqrt{Hz})^2} = 7.11 nV / \sqrt{Hz}$$

$$E_{nTotal_RTI} = e_{nTotal} \cdot \sqrt{BW_n} = (7.11 nV / \sqrt{Hz}) \cdot \sqrt{(1.62MHz)} = 9.02 \mu V \text{ rms}$$

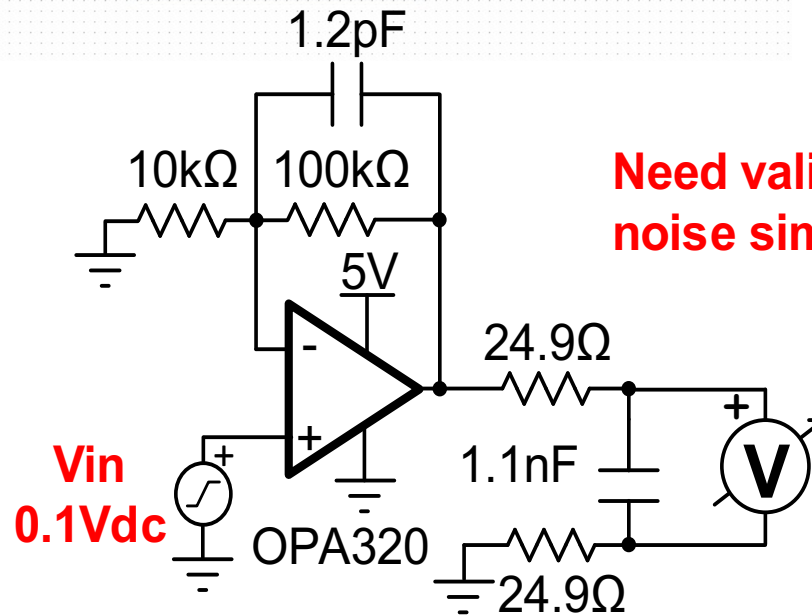
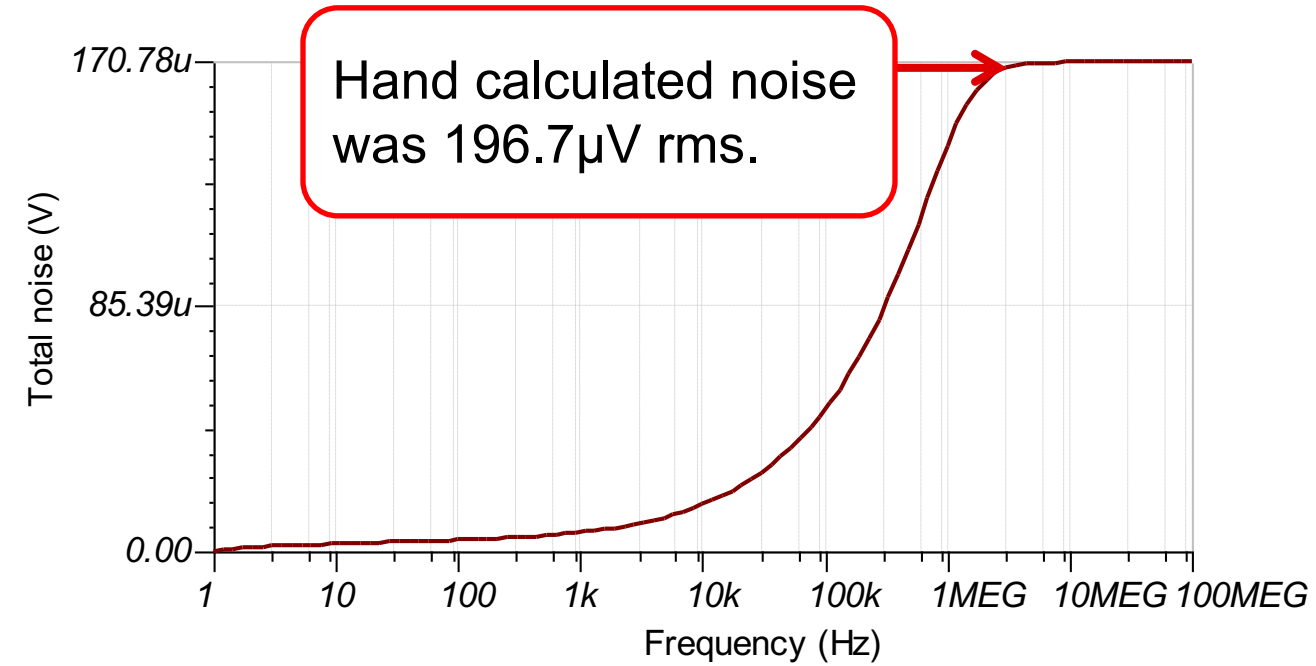
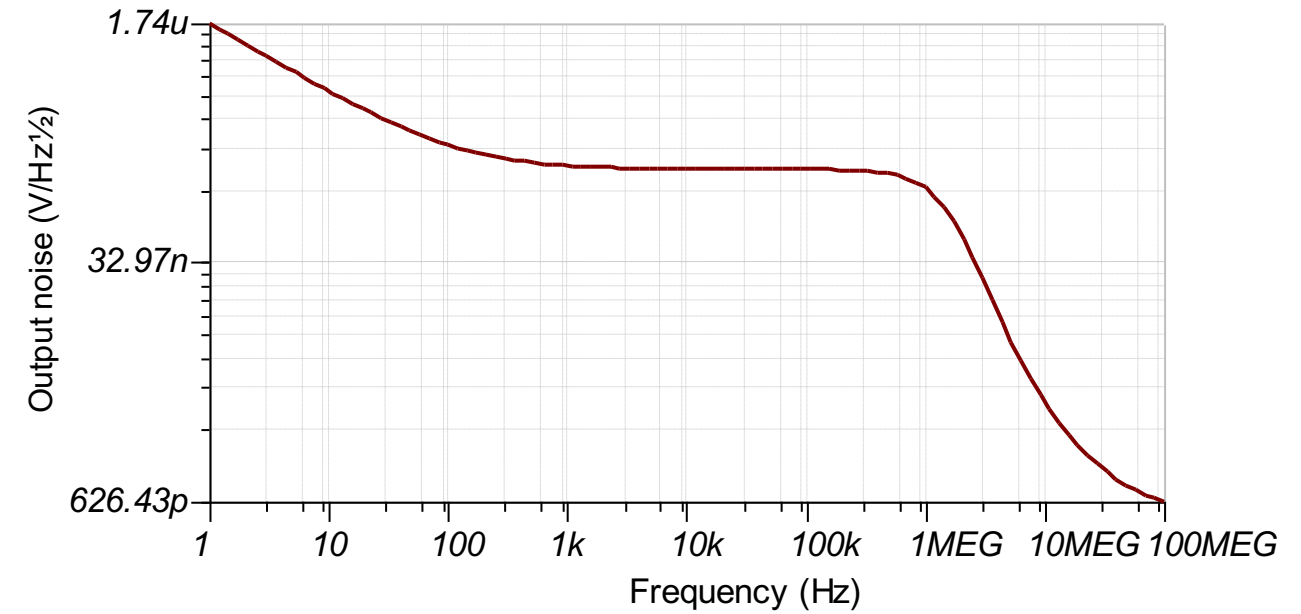
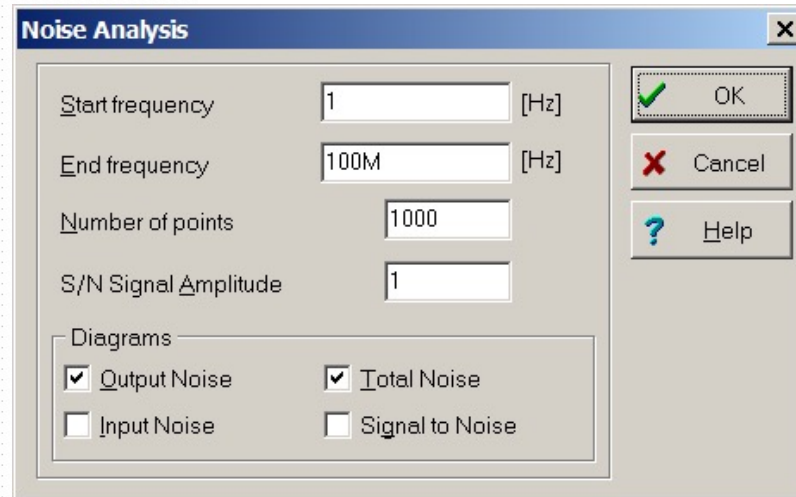
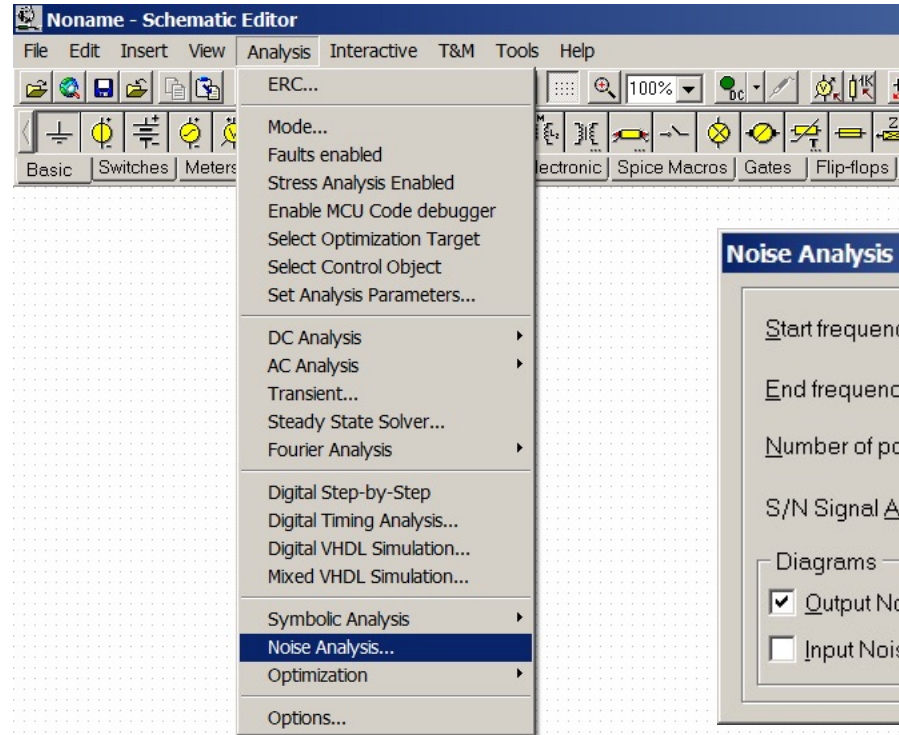
$$E_{nTotal_RTO} = Gain \cdot E_{nTotal_RTI} = (11) \cdot (9.02 \mu V) = 99.2 \mu V \text{ rms}$$

The system bandwidth is limited by three factors: feedback filter, charge bucket filter, and amplifier gain bandwidth. The overall bandwidth assumes that the feedback and amplifier poles are close, so the system is approximately second order.

Noise from the feedback network.

Combined noise from op amp and feedback network. Integrated and referred to the output.

Simulation of Noise1

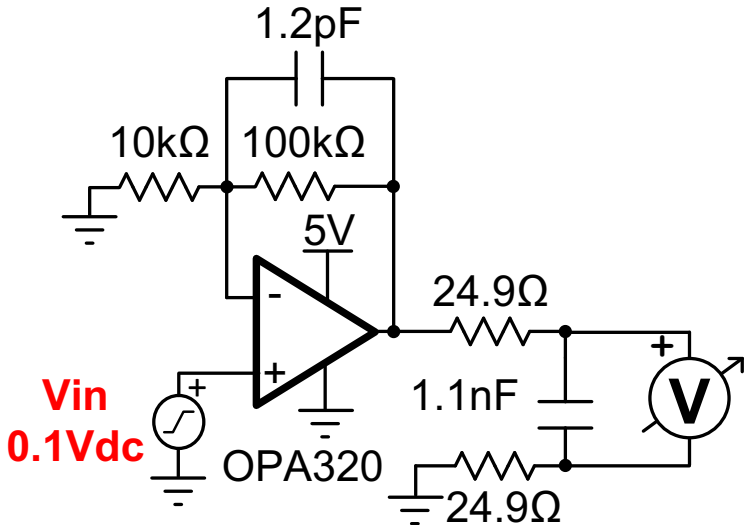


Need valid dc operating point for noise simulation!

$V_{outDC} = 11 \times 0.1V = 1.1V$
 $E_{nrms} = 170.8\mu V \text{ rms}$
 $E_{npp} = 6 \cdot 170.8\mu V \text{ rms} = 1.03mV_{pp}$

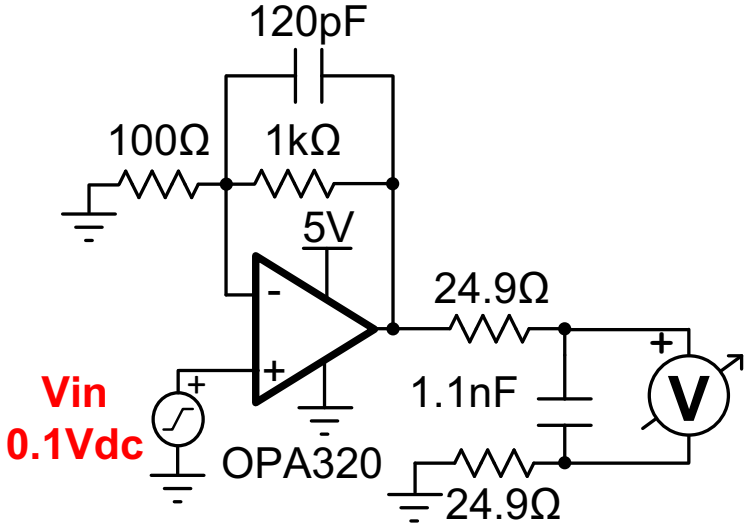
Noise 1 vs Noise 2

Noise 1



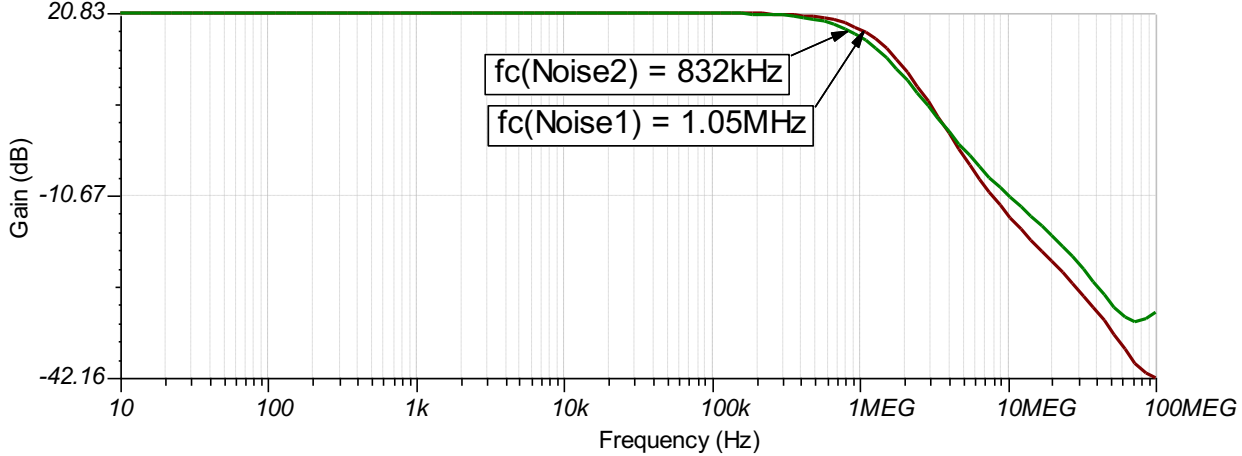
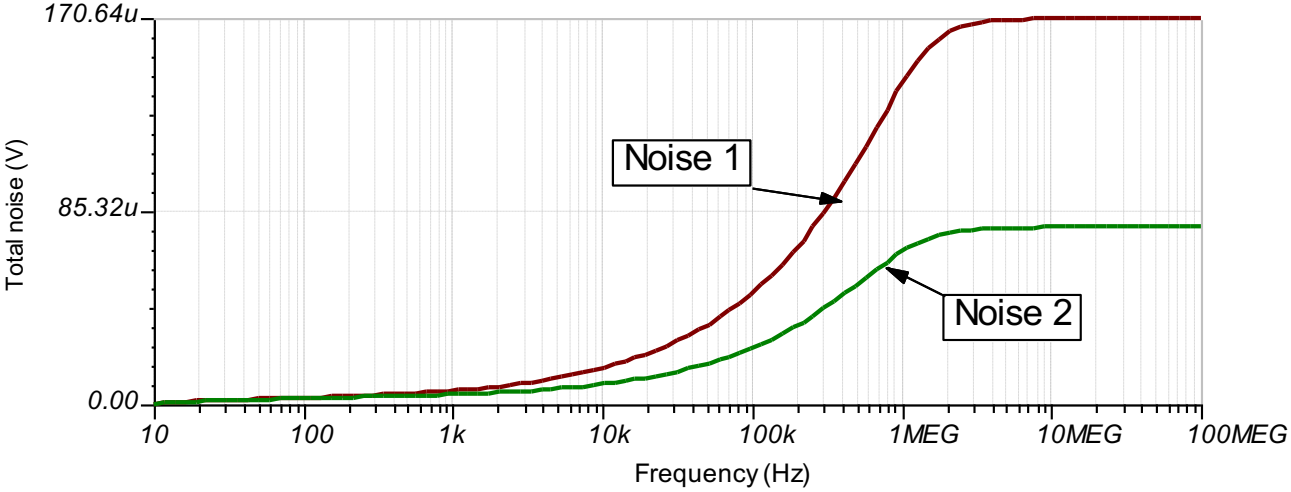
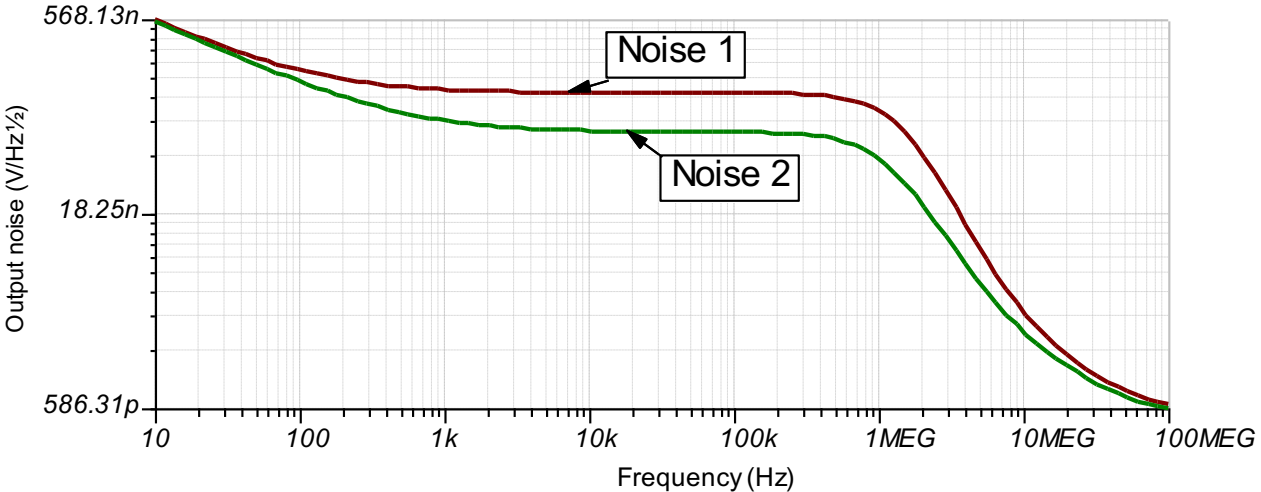

OPA320_Noise1.TSC

Noise 2

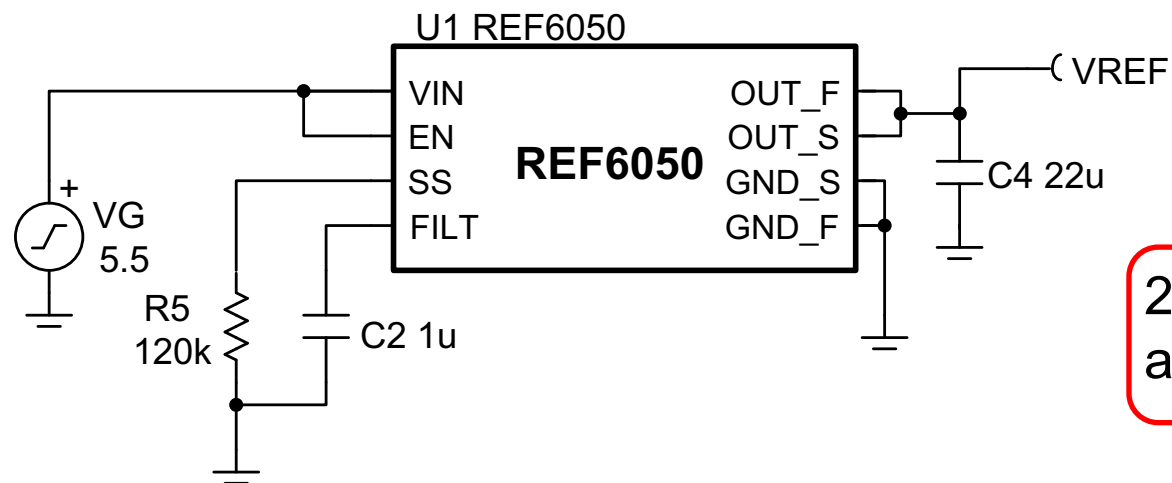
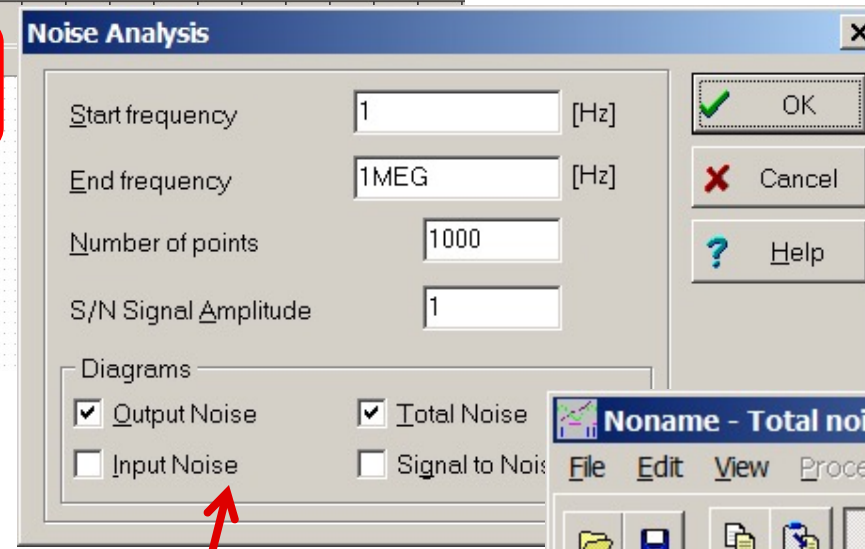
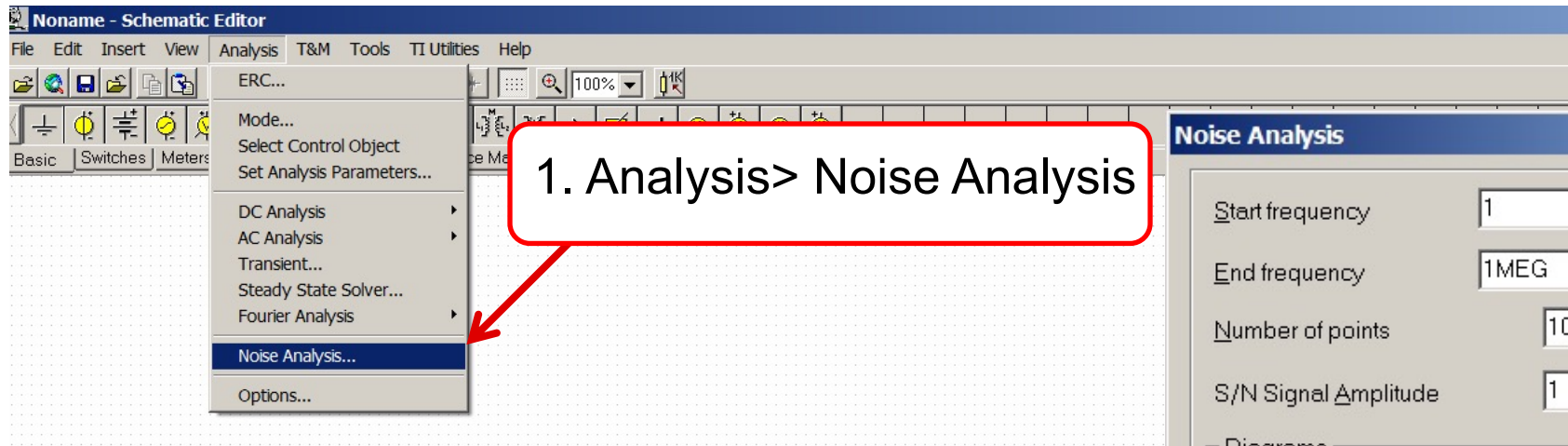



OPA320_Noise2.TSC

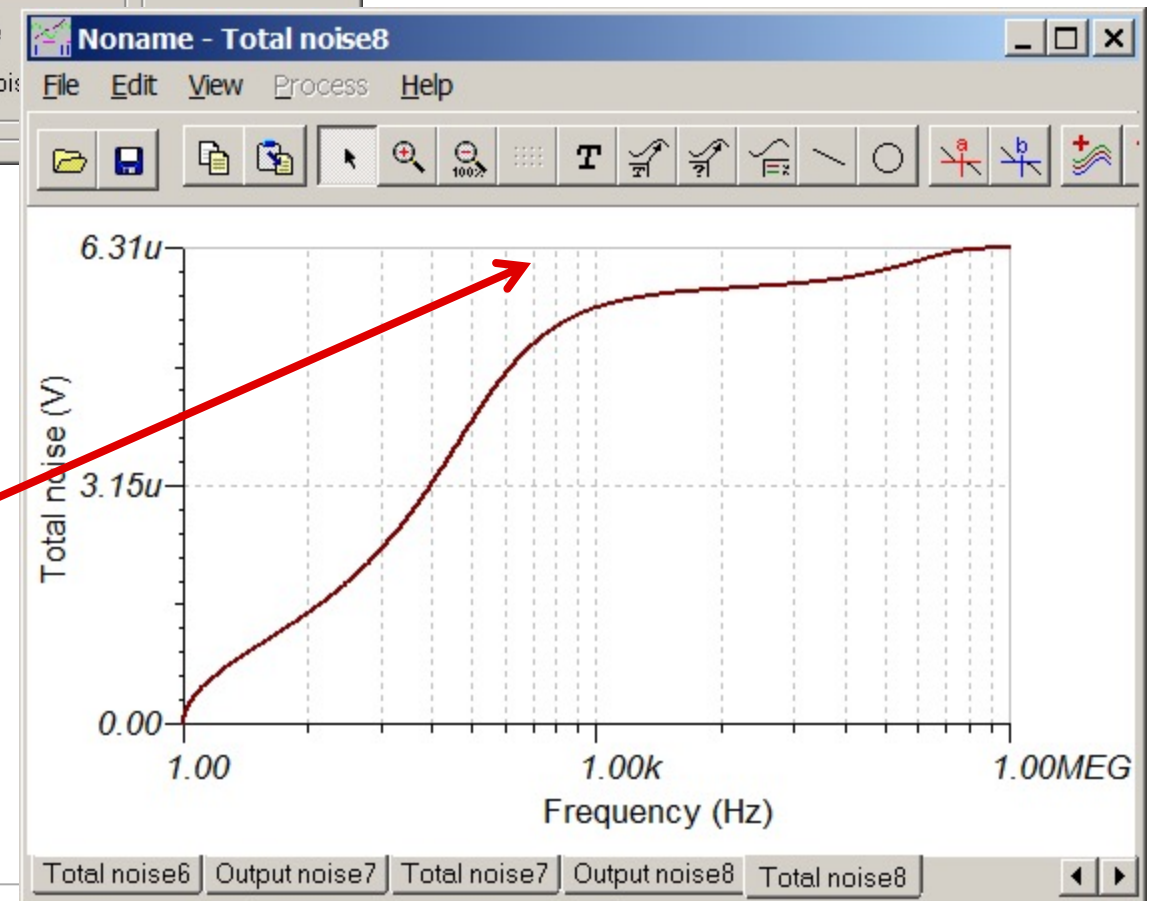
Click to access
TINA simulation.



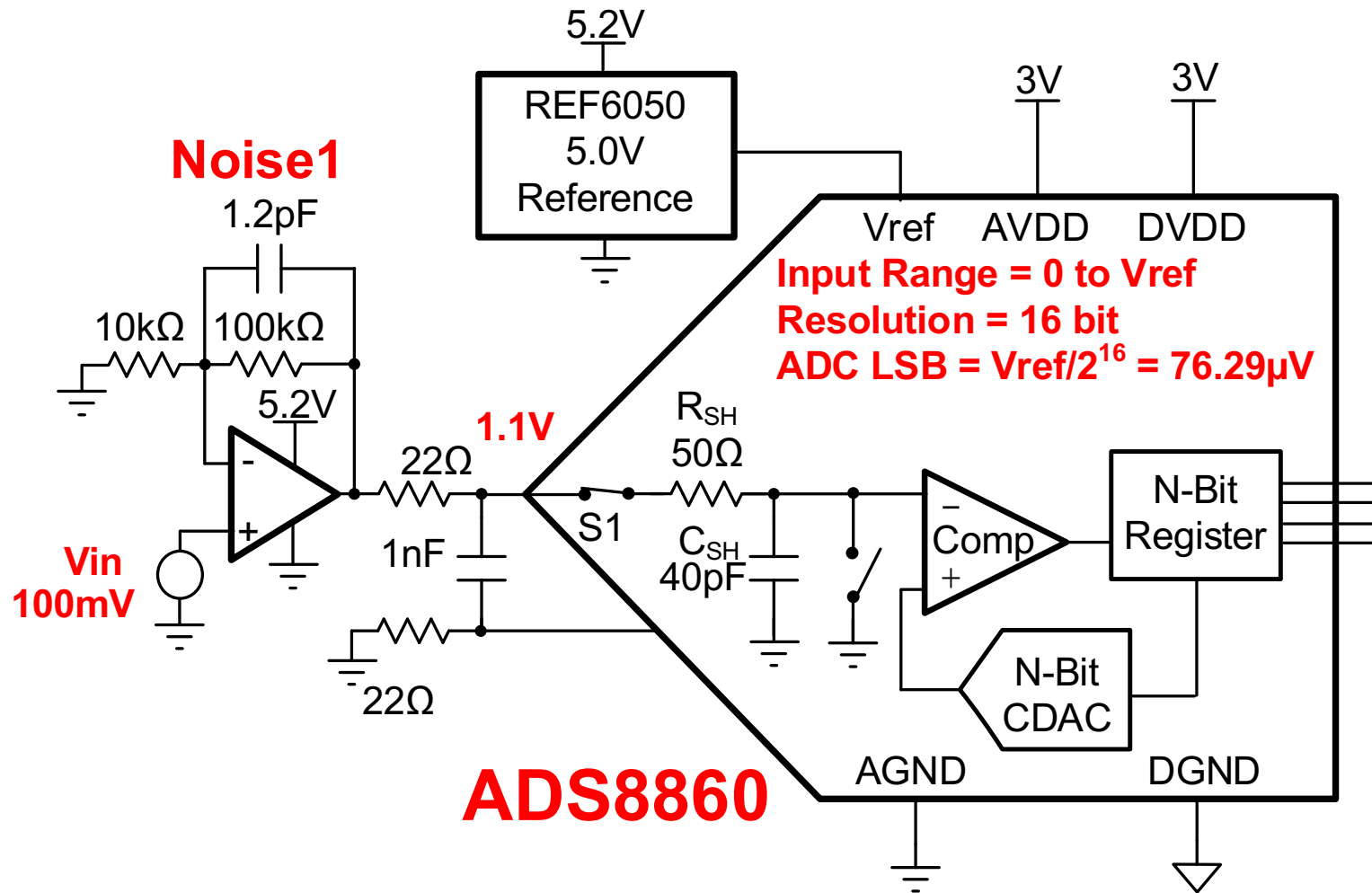
Find the REF6050 Noise



3. The integrated noise is the "total noise". Look at the final value $V_{nRef} \approx 6.31\mu\text{V rms}$



Total System Noise for OPA320_Noise1



$$V_{FSR_rms} = V_{FSRpk} \cdot 0.707$$

$$V_{FSR_rms} = 0.5 \cdot FSR \cdot 0.707$$

$$= 0.5 \cdot 5V \cdot 0.707 = 1.767V$$

$$V_{nADC} = \frac{V_{FSR_rms}}{10^{\left(\frac{SNR_{ADC}}{20}\right)}} = \frac{1.767V}{10^{\left(\frac{93dB}{20}\right)}} = 39.6\mu V \text{ rms}$$

$$V_{nT} = \sqrt{(V_{nADC})^2 + (V_{nAmp})^2 + (V_{nRef})^2}$$

$$= \sqrt{(39.6\mu V)^2 + (170.8\mu V)^2 + (6.3\mu V)^2} = 175.4\mu V \text{ rms}$$

$$SNR_{total} = 20 \cdot \log\left(\frac{V_{FSR_rms}}{V_{nT}}\right) = 20 \cdot \log\left(\frac{1.767V}{175.4\mu V}\right) = 80.1 \text{ dB}$$

Solve Using the Analog Engineer's Calculator

The screenshot displays the 'Analog Engineer's Calculator' software window. On the left, a tree view under 'Select the Calculator' has 'ADC + Signal Chain Noise' selected. The main workspace shows a block diagram of a signal chain. An input signal enters an amplifier block, then a 'Converter Input' block, and finally a 'Converter' block. A 'Voltage Reference' block is connected to the converter. The 'Converter Output' block shows the results of the calculation.

Calculator Parameters:

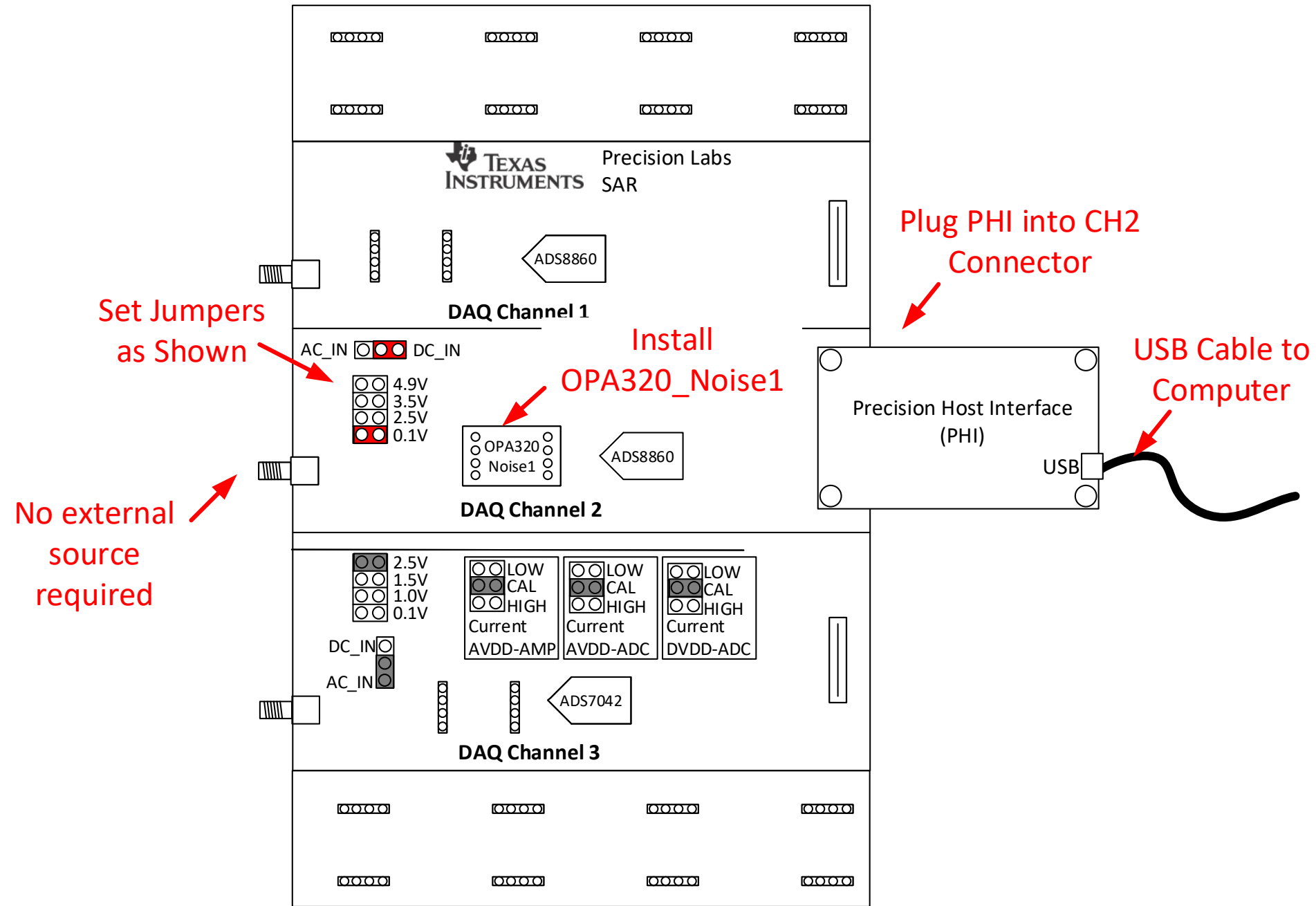
- Signal Chain Noise: 170.8u V rms
- SNR Input: 80.3 dB
- Reference Noise: 6.3u V
- Full Scale Range: 5 V
- ADC SNR: 93 dB

Converter Output Results:

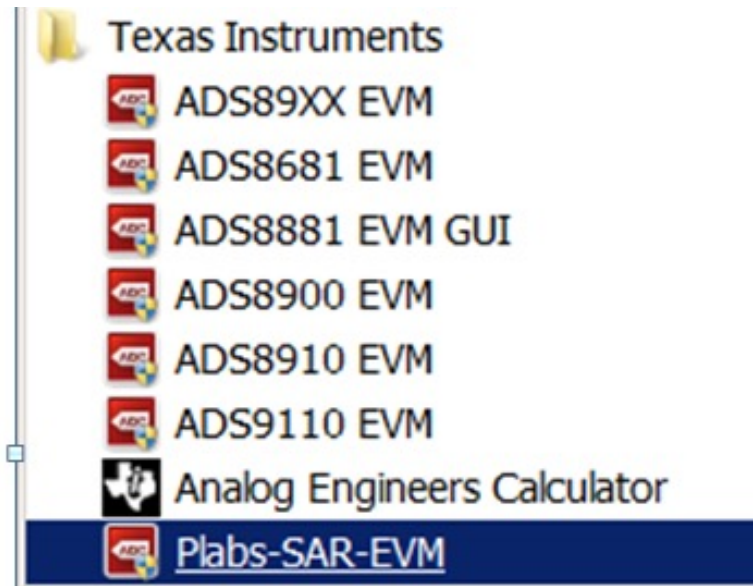
- Total_Noise: 175.4u V rms
- ADC Noise: 39.57u V rms
- Combined SNR: 80.06 dB

Buttons for 'OK' and 'Help' are located at the bottom of the calculator window.

Connect the hardware



Start & Setup the PLABS-SAR EVM Software



1. Select "Plabs-SAR-EVM" from "start>All Programs"

Plabs-SAR-EVM

File Debug Capture Help

Channel Connected: DAQ Channel 2 External Reference : REF6050 Connect to Hardware

Pages

- Time Domain Display
- Spectral Analysis
- Histogram Analysis
- Linearity Analysis
- Reference Settling Analysis

Interface Configuration

Device Modes

SPI-3-Wire-WithBusy

Protocol Selected

SPI_3_Wire_WithBusy

SCLK Frequency(Hz)

Target	Achievable
66M	66.00M

Sampling Rate(sps)

Target	Achievable
1.00M	1.00M

Time Domain Display

Y Scale fit Auto mode

Codes

Voltage (V)

Samples

Min and Max Values

Max_Code	Max_Volt	Min_Code	Min_Volt
0	0.000	0	0.000

PSI Controls

HW CONNECTED

TEXAS INSTRUMENTS

2. If the EVM is operating correctly, "HW Connected" will be displayed.

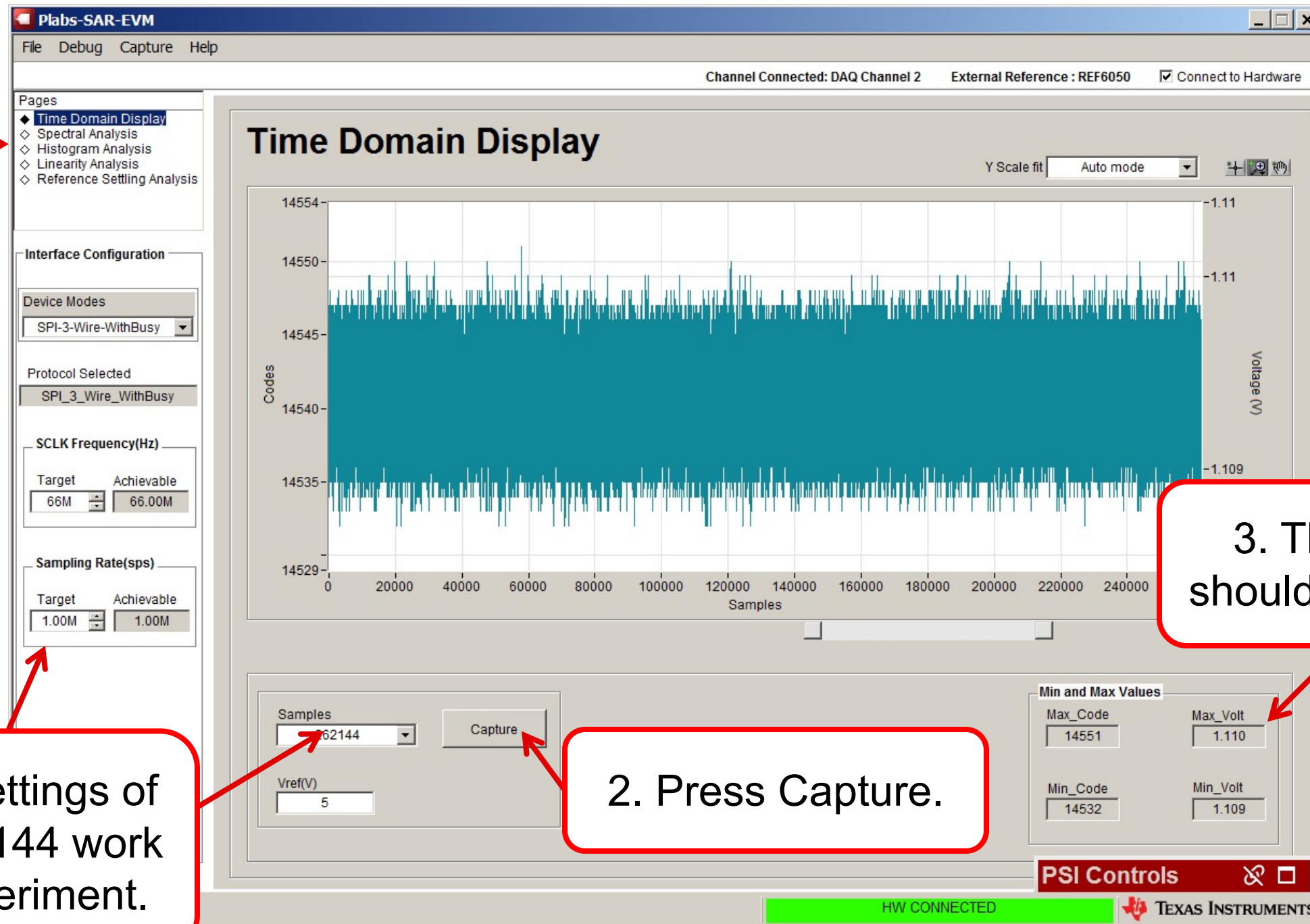
Measure the Noise and DC Level

4. Change page to "Histogram Analysis"

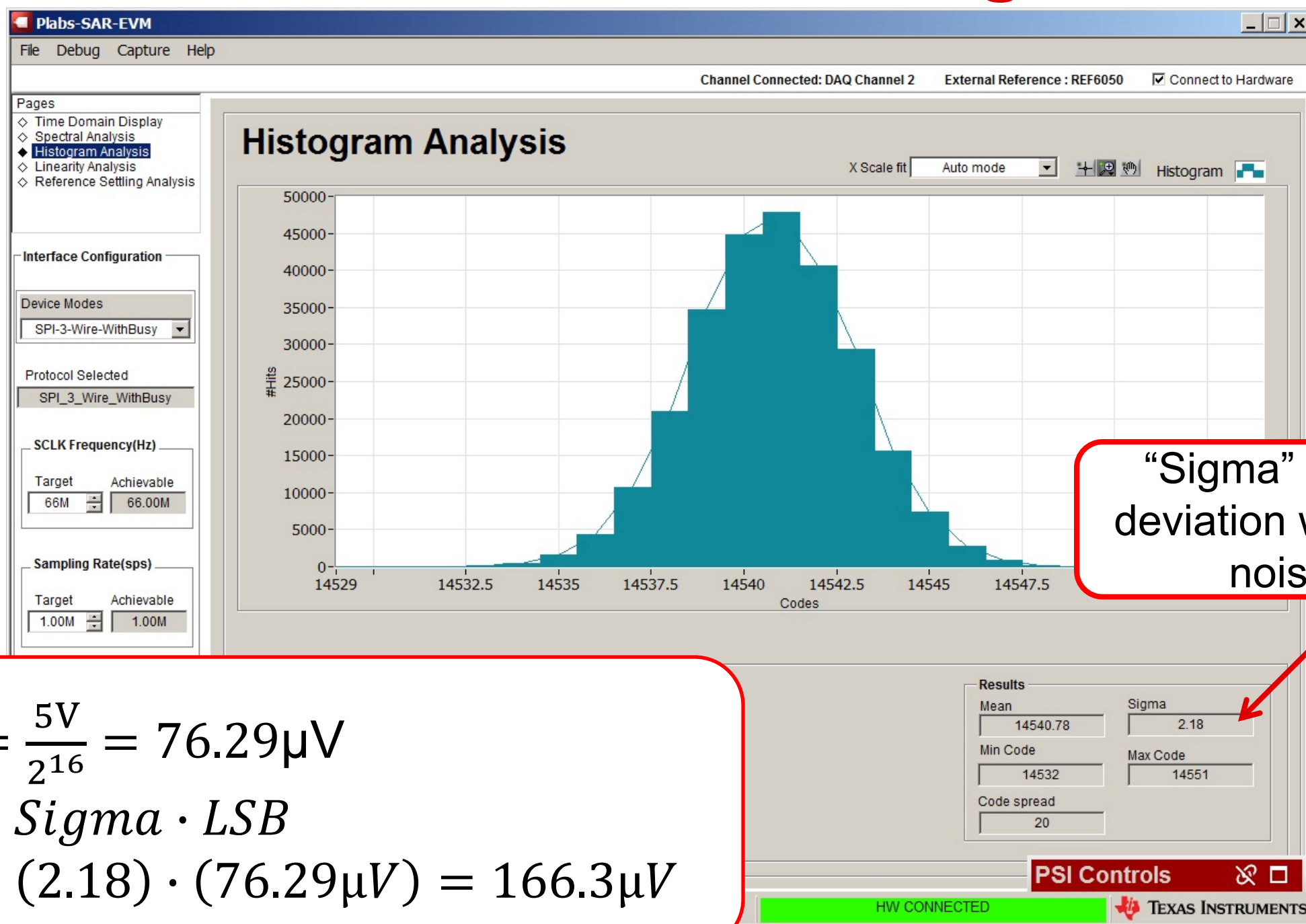
1. The default settings of 1Msps, and 262144 work well for this experiment.

2. Press Capture.

3. The DC output should be about 1.1V.



Look at the Statistics Under “Histogram Analysis”



“Sigma” is one standard deviation which is the RMS noise in codes.

$$LSB = \frac{V_{FSR}}{2^N} = \frac{5V}{2^{16}} = 76.29\mu V$$

$$V_{noise_meas} = Sigma \cdot LSB$$

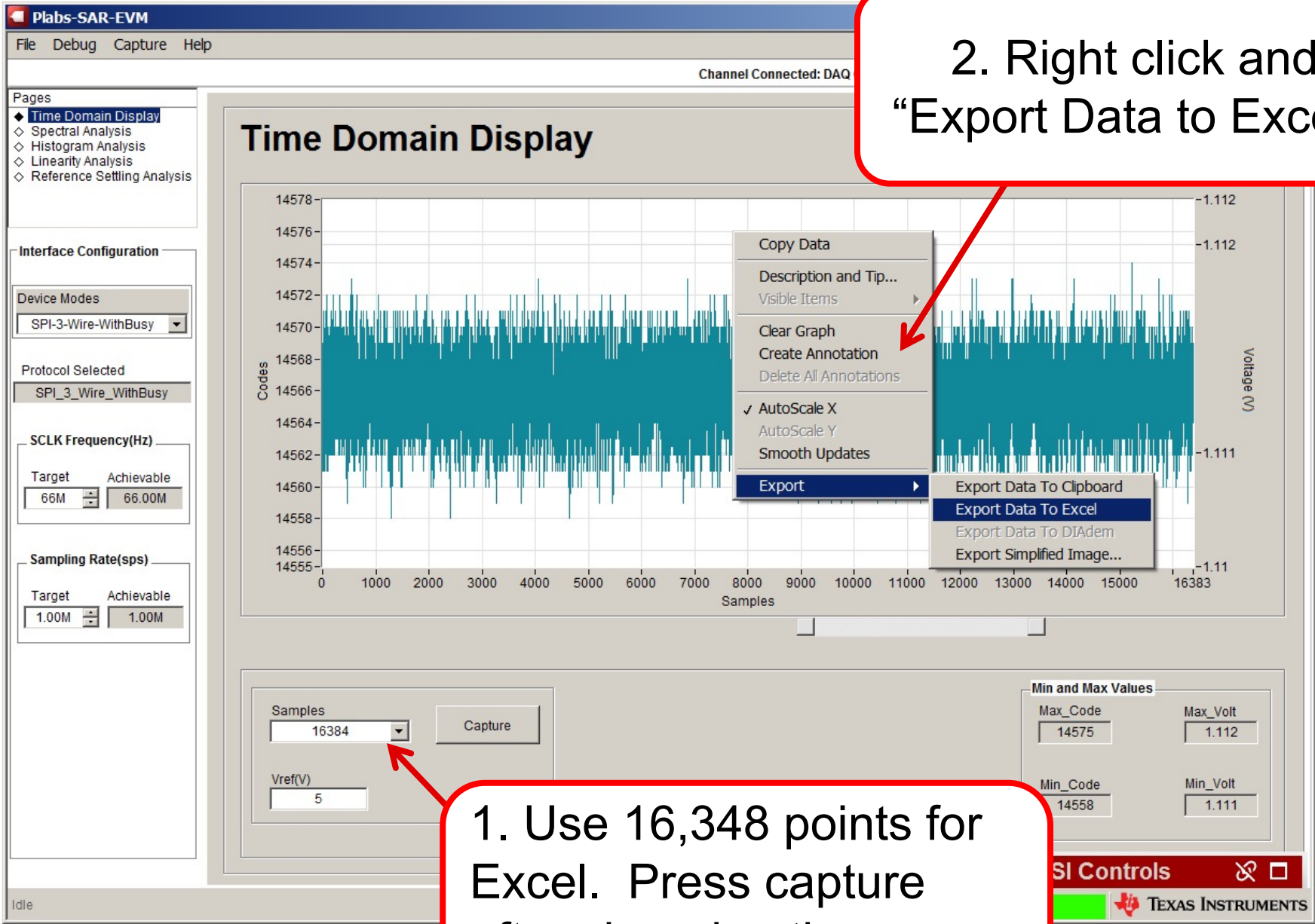
$$V_{noise_meas} = (2.18) \cdot (76.29\mu V) = 166.3\mu V$$

Measured vs Expected Results

Your results should show the same trend as the expected result but the specific values will differ.

		Vin = 0.1V DC, fsamp = 1MHz, Vref =5V, LSB = 76.29uV							
Device	Hand Calc	Simulated				Example Measurements		Your Measurements	
	Amp Noise (uV)	Amp Noise (uV)	ADC Noise (uV)	Ref Noise (uV)	Total Noise (uV)	Sigma	Noise (uV)	Sigma	Noise (uV)
Noise1	196.7	170.8	39.6	11.2	175.4	2.18	166.3		
Noise2	99.1	78.8	39.6	11.2	88.4	1.16	88.5		

Export Data to Excel



2. Right click and "Export Data to Excel".

1. Use 16,348 points for Excel. Press capture after changing the number of samples.

3. An Excel spreadsheet will open up.

The screenshot shows an Excel spreadsheet with the following data:

	A	B	C
1	Samples - Analog Channel 0	Codes - Analog Channel 0	
2		14559	
3		14566	
4		14566	
5		14567	
6		14567	
7		14568	
8		14563	
9		14564	
10		14568	
11		14564	
12		14564	
13		14568	
14		14562	
15		14566	
16		14567	
17		14567	
18		14566	
19		14567	
20		14569	
21		14564	
22		14562	
23		14567	

Selecting a Column in Excel

2. Press "Shift-Ctrl-Down Arrow" to select the entire row.



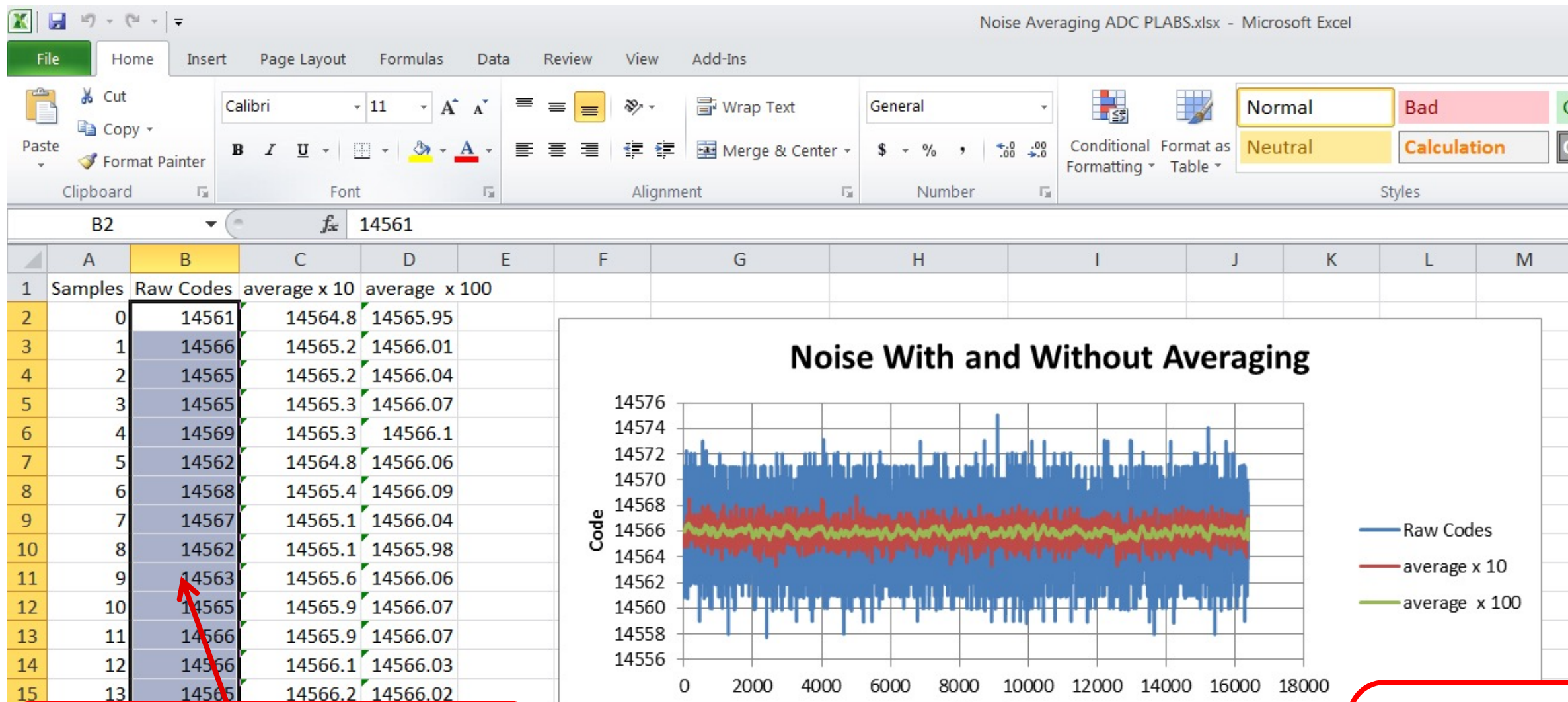
3. Press "Ctrl-C" to copy.

1. Select cell "B2" in the spreadsheet.

A screenshot of an Excel spreadsheet. The spreadsheet has two columns, A and B. Column A is titled "Samples - Analog Channel 0" and column B is titled "Codes - Analog Channel 0". The data in column B ranges from 0 to 21. Cell B2 is selected, and the entire column B is highlighted in blue. Red arrows point from the text boxes to cell B2 and the selected column.

	A	B	C
1	Samples - Analog Channel 0	Codes - Analog Channel 0	
2		0	14559
3		1	14566
4		2	14566
5		3	14567
6		4	14567
7		5	14568
8		6	14563
9		7	14564
10		8	14568
11		9	14564
12		10	14564
13		11	14568
14		12	14562
15		13	14566
16		14	14567
17		15	14567
18		16	14566
19		17	14567
20		18	14569
21		19	14564
22		20	14562
23		21	14567

Paste Your Results Under “Raw Codes”



Click to access Excel Spreadsheet.



Microsoft Excel Worksheet

Press “Ctrl-V” to paste results into “Raw Codes” column. Graph and Table will update automatically

$$E_{n_avg} = \frac{E_{n_raw}}{\sqrt{N}}$$

	STDEV(Raw Codes)	STDEV(X10 Avg)	STDEV(x100 Avg)
Meas	2.171	0.712	0.248
Calc		0.686	0.217

Thanks for your time!