ADC Noise Hands-on Experiment

TIPL 4204-L
TI Precision Labs – SAR ADCs

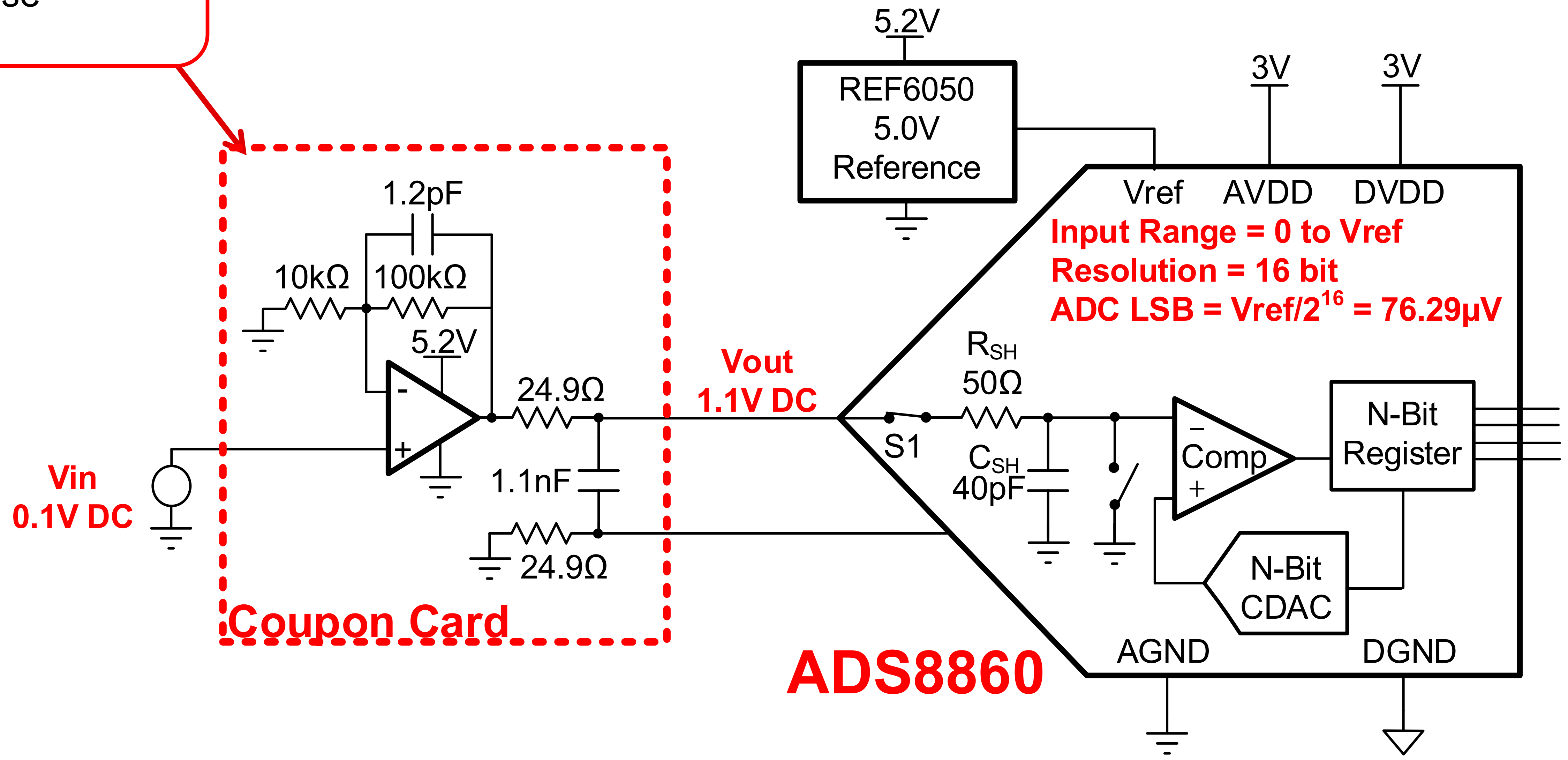
by Art Kay and Dale Li

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

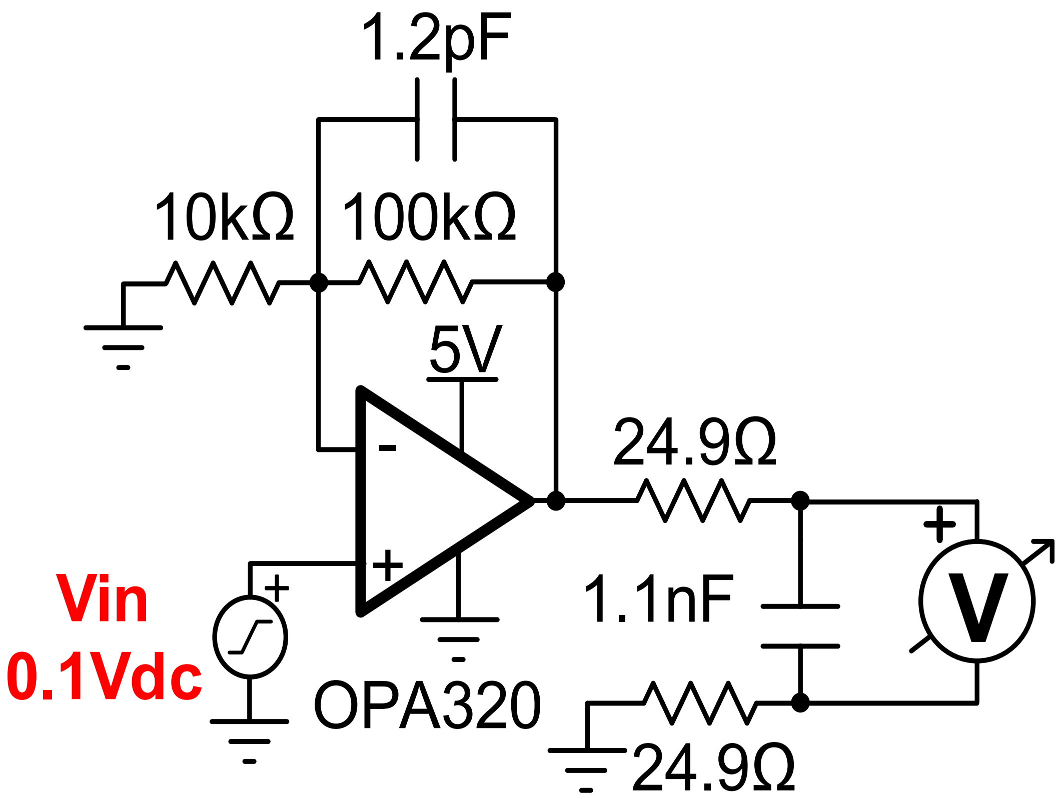
We will use two different "Coupon Cards". Each will have different noise characteristics..



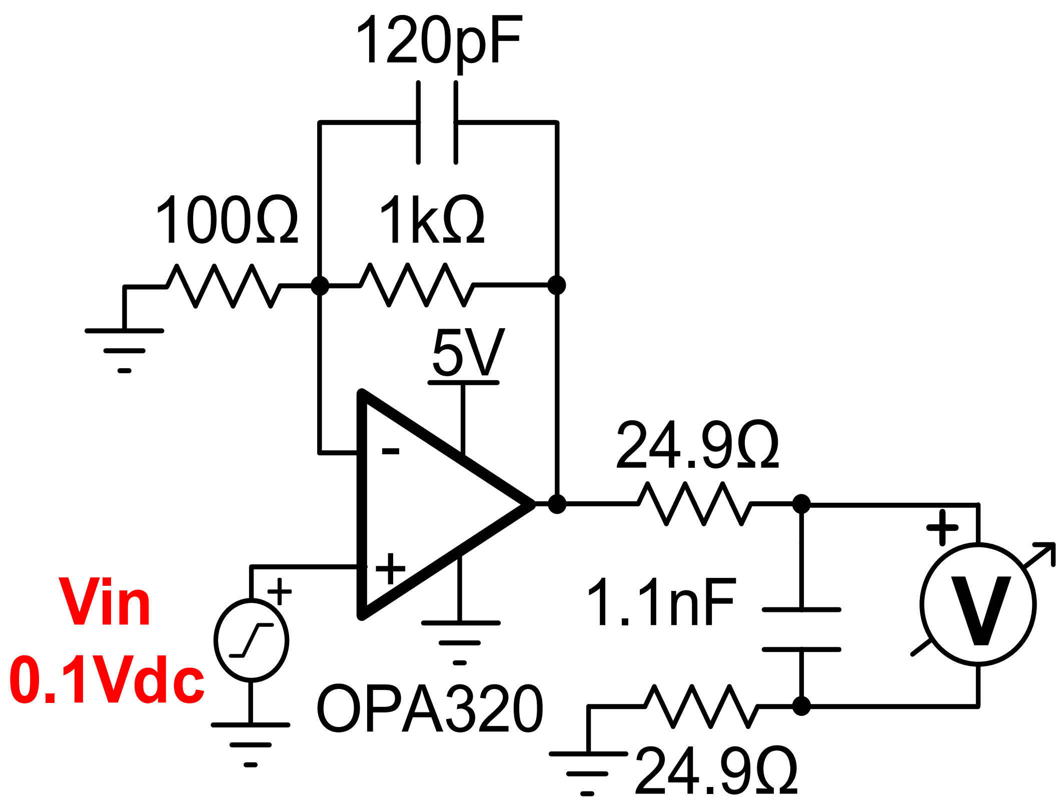
Noise Hand Calculation

- 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

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

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

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

$$f_{c\_system\_estimate} = 1.33MHz$$

$$\mathrm{BW}_n = K_n \cdot f_{c\_system\_estimate} = (1.22) \cdot (1.33MHz) = 1.62MHz$$

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.

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

$$\mathrm{e}_{n\,Req} = \sqrt{4 \cdot k \cdot R_{eq} \cdot T_k} = \sqrt{4 \cdot (1.38 \cdot 10^{-23} J/K) \cdot (9.09k\Omega) \cdot (298.15K)} = 12.23\, nV/\sqrt{Hz}$$

Noise from the feedback network.

$$\mathrm{e}_{nTotal} = \sqrt{\left(e_{n\,Req}\right)^2 + \left(e_{n\_Amp}\right)^2} = \sqrt{\left(12.23\,nV/\sqrt{Hz}\right)^2 + \left(7\,nV/\sqrt{Hz}\right)^2} = 14.09\,nV/\sqrt{Hz}$$

$$\mathrm{E}_{nTotal\_RTI} = \mathrm{e}_{nTotal} \cdot \sqrt{BW_n} = (14.09\,nV/\sqrt{Hz}) \cdot \sqrt{(1.62MHz)} = 17.88\mu V \text{ rms}$$

$$\mathrm{E}_{nTotal\_RTO} = \mathrm{Gain} \cdot \mathrm{E}_{nTotal\_RTI} = (11) \cdot (17.88\mu V) = 196.7\mu V \text{ rms}$$

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

Noise Calculation for Noise 2

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

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

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

$$f_{c\_system\_estimate} = 1.33MHz$$

$$\mathrm{BW}_n = K_n \cdot f_{c\_system\_estimate} = (1.22) \cdot (1.33MHz) = 1.62MHz$$

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.

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

$$\mathrm{e}_{n\,Req} = \sqrt{4 \cdot k \cdot R_{eq} \cdot T_k} = \sqrt{4 \cdot (1.38 \cdot 10^{-23} J/K) \cdot (90.9\Omega) \cdot (298.15K)} = 1.22\, nV/\sqrt{Hz}$$

Noise from the feedback network.

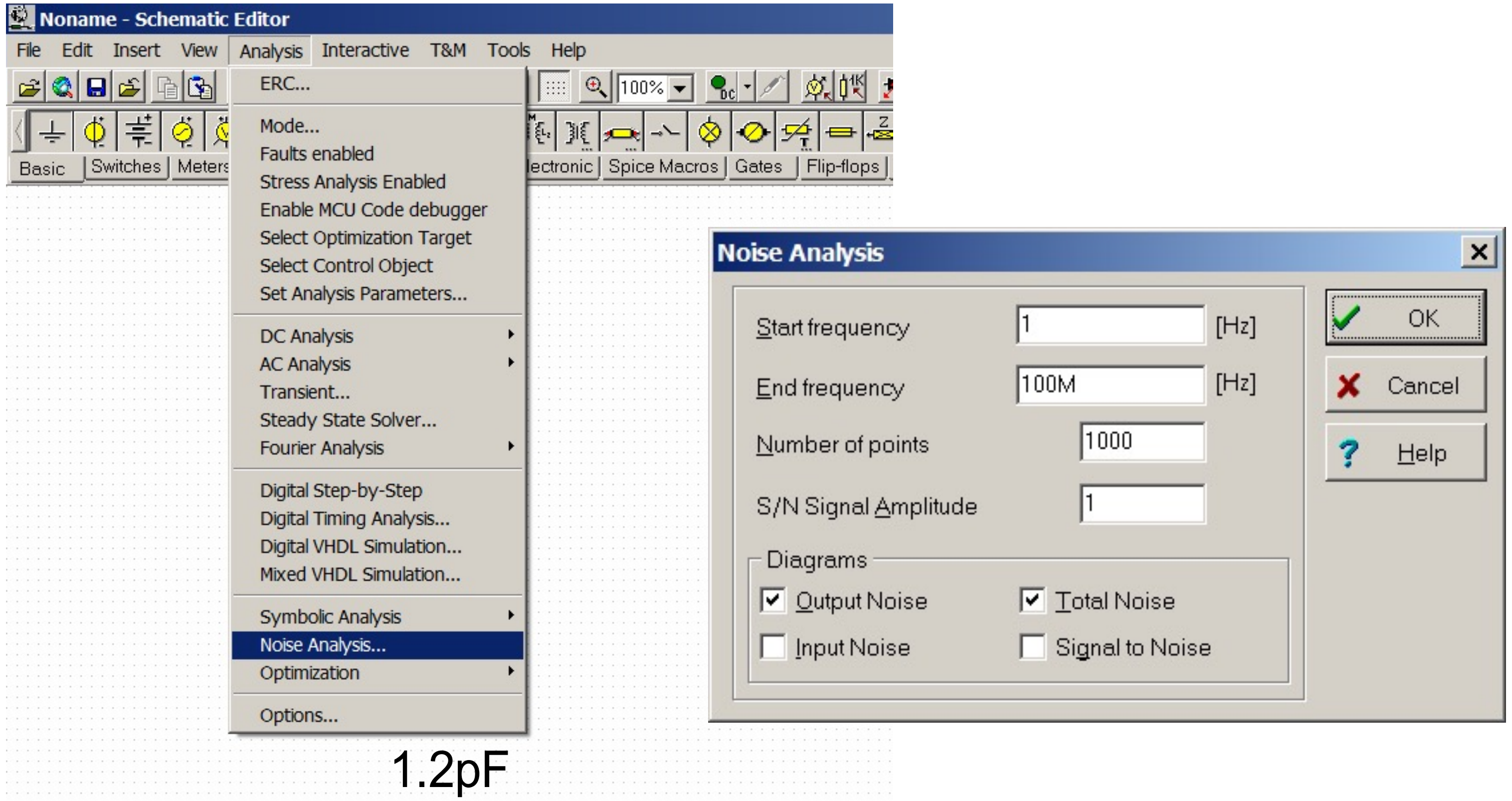
$$\mathrm{e}_{nTotal} = \sqrt{\left(e_{n\,Req}\right)^2 + \left(e_{n\_Amp}\right)^2} = \sqrt{\left(1.22\, nV/\sqrt{Hz}\right)^2 + \left(7\, nV/\sqrt{Hz}\right)^2} = 7.11\, nV/\sqrt{Hz}$$

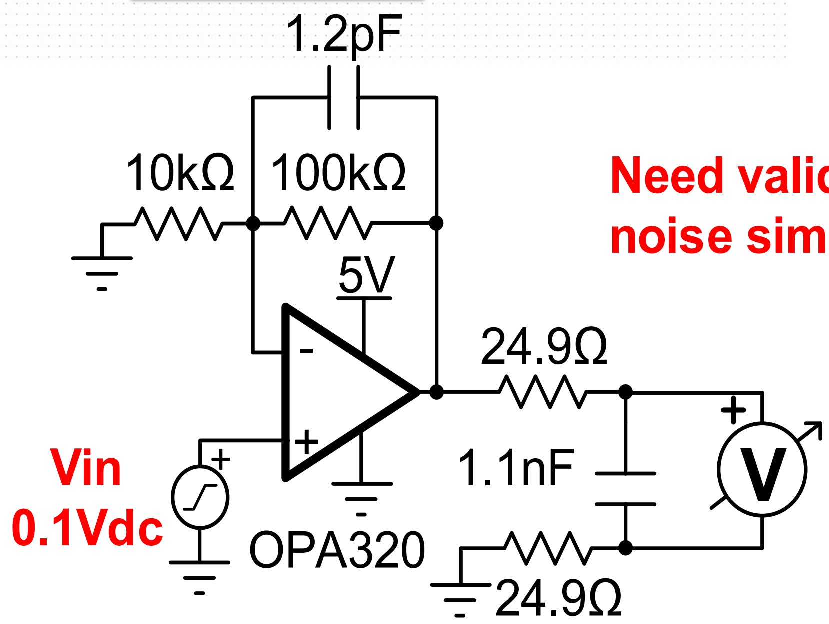
$$\mathrm{E}_{nTotal\_RTI} = \mathrm{e}_{nTotal} \cdot \sqrt{BW_n} = (7.11\, nV/\sqrt{Hz}) \cdot \sqrt{(1.62MHz)} = 9.02\mu V \text{ rms}$$

$$\mathrm{E}_{nTotal\_RTO} = \mathrm{Gain} \cdot \mathrm{E}_{nTotal\_RTI} = (11) \cdot (17.88\mu V) = 99.2\mu V \text{ rms}$$

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

Simulation of Noise1



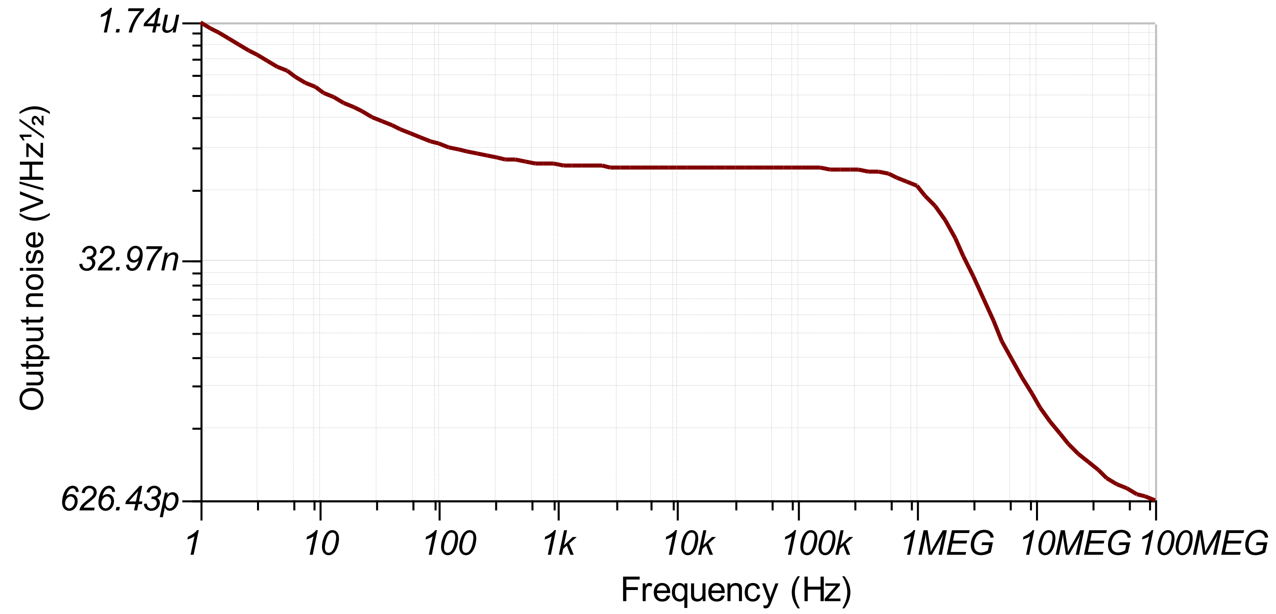


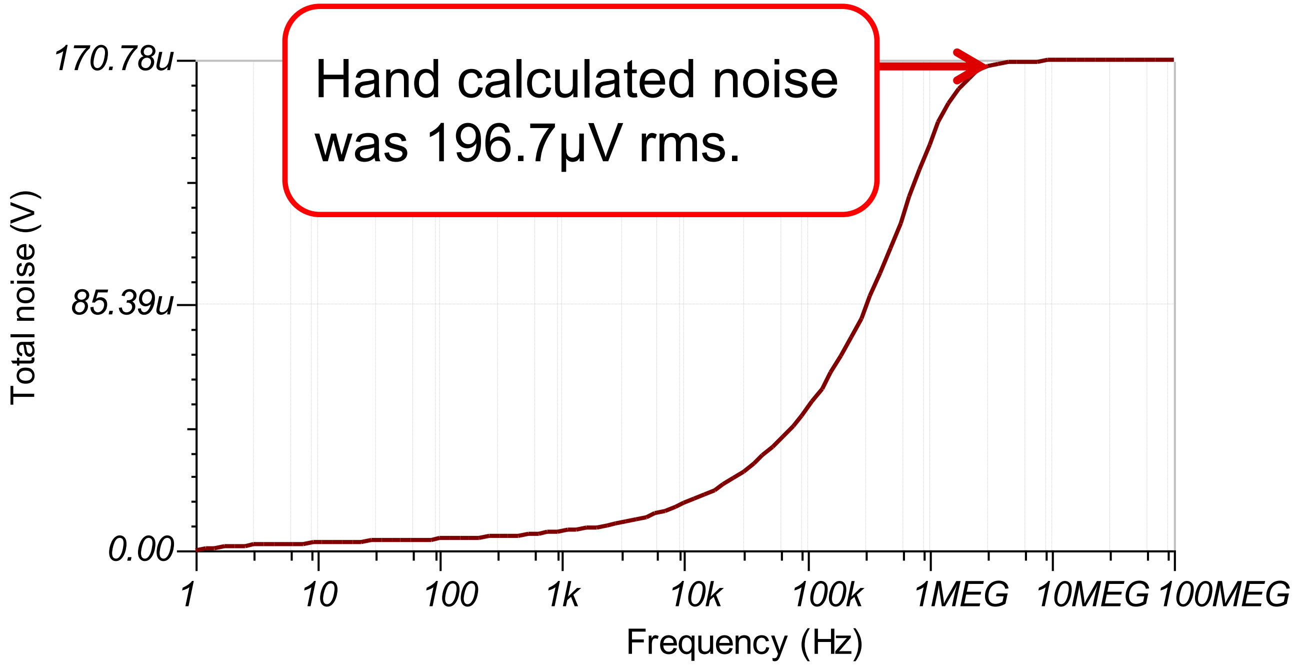
Need valid dc operating point for noise simulation!

V_{outDC} = 11 x 0.1V = 1.1V

E_{nrms} = 170.8μV rms

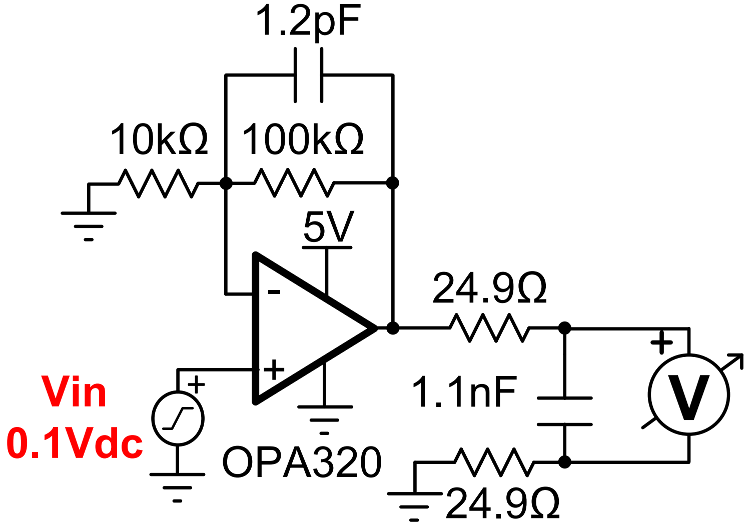
E_{npp} = 6·170.8μV rms = 1.03mVpp



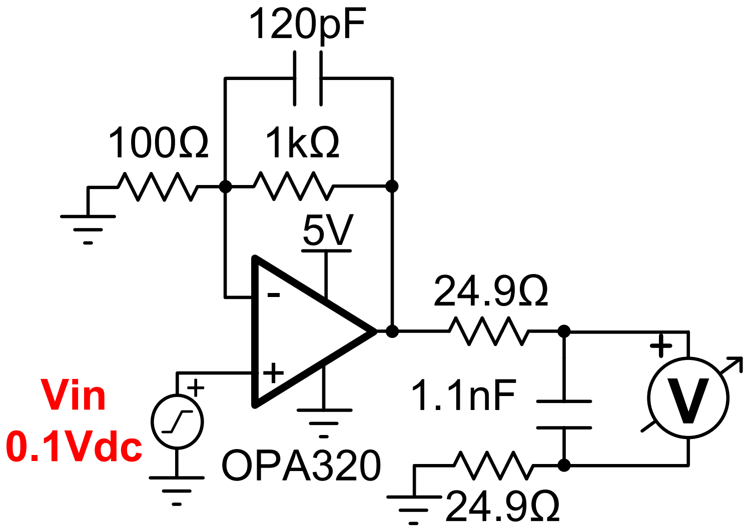


Noise 1 vs Noise 2

Noise 1



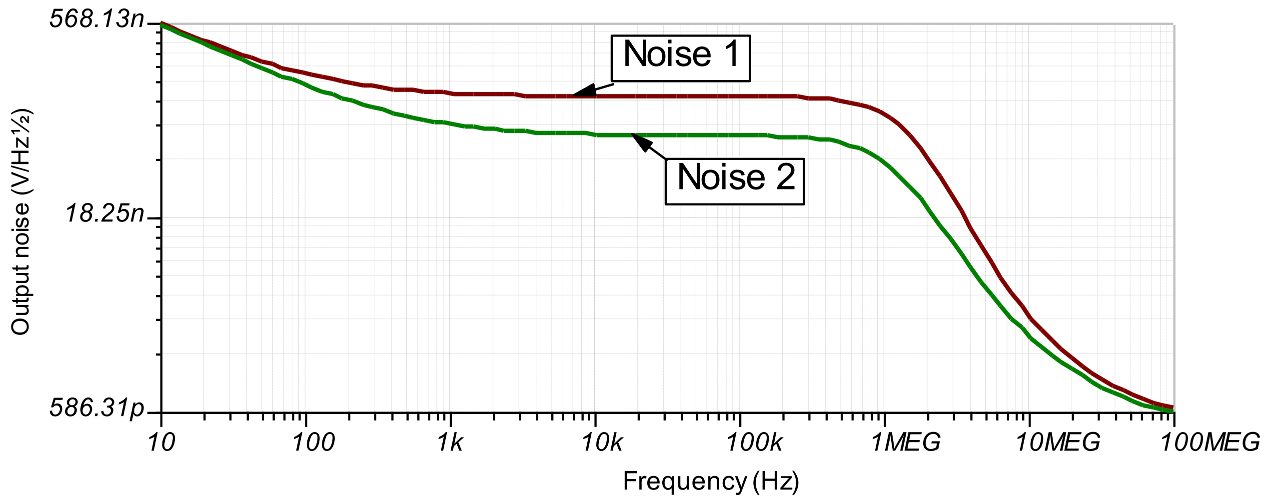
Noise 2

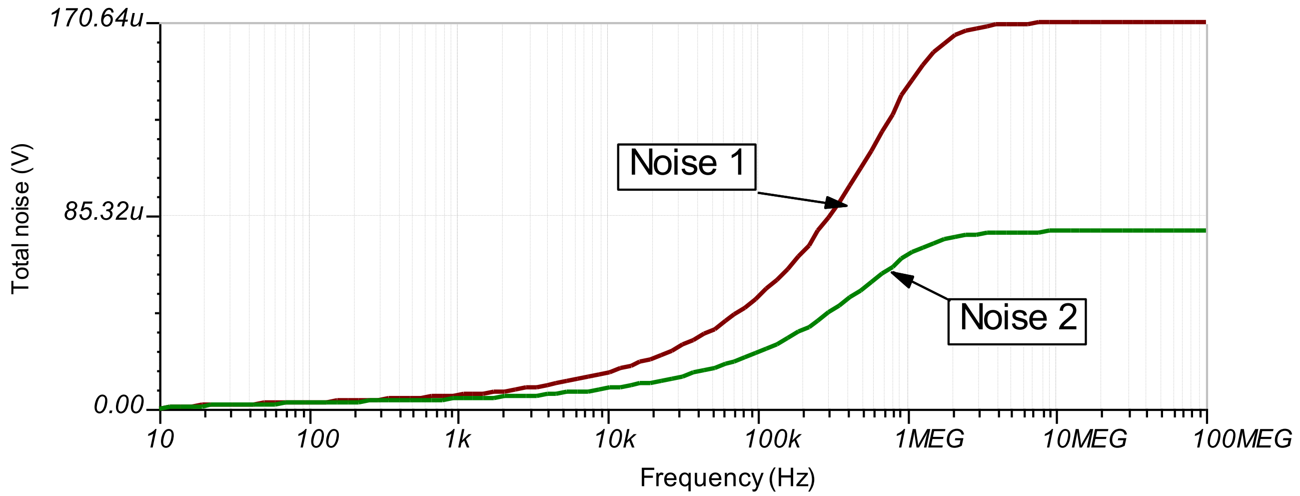


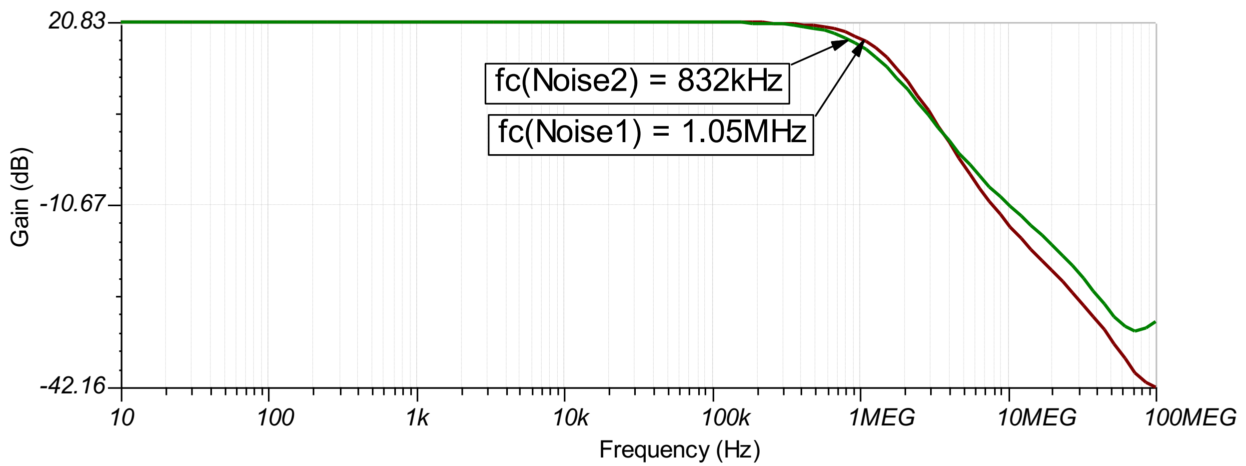
OPA320_Noise1.TSC

Click to access TINA simulation.

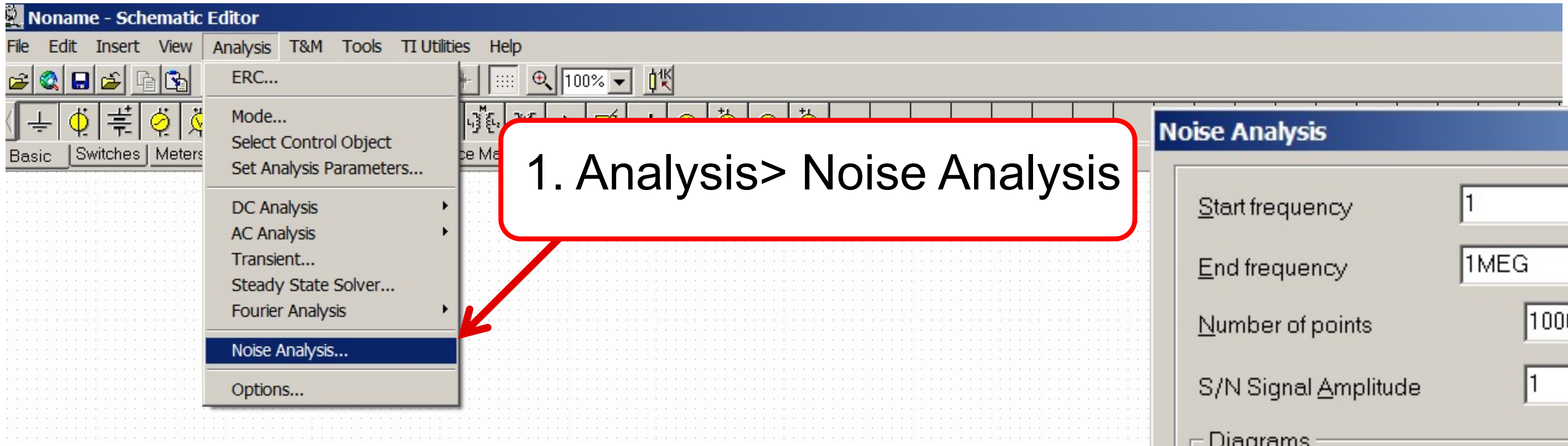
OPA320_Noise2.TSC



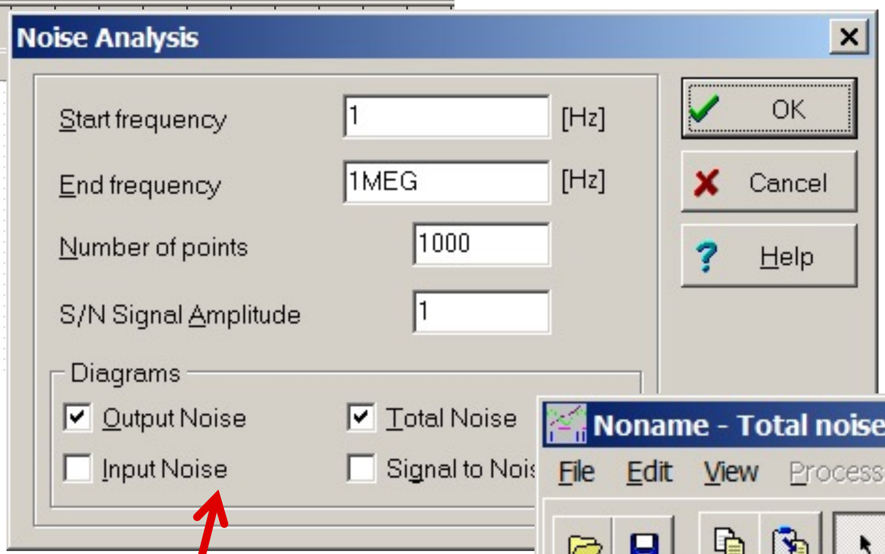


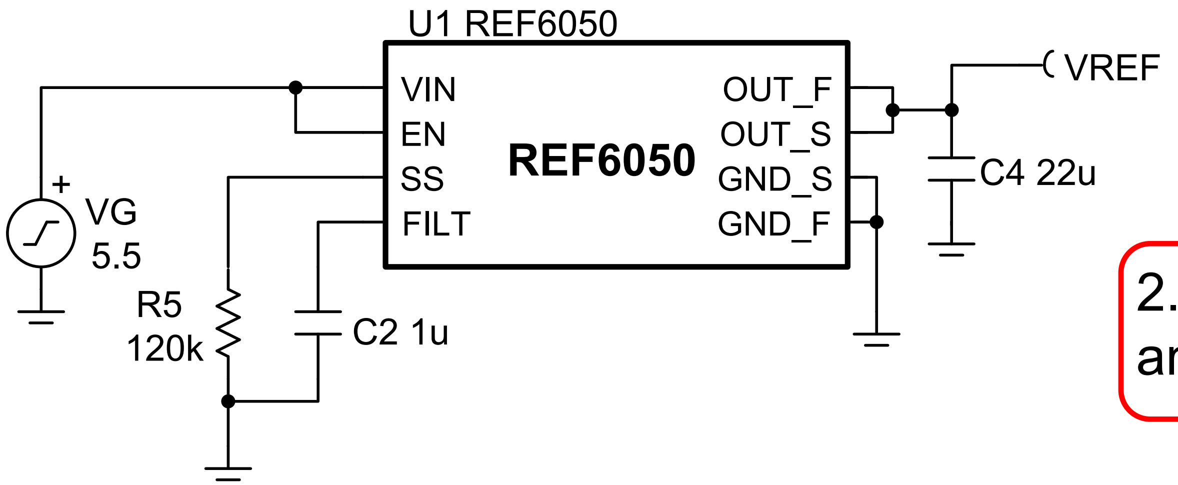


Find the REF6050 Noise

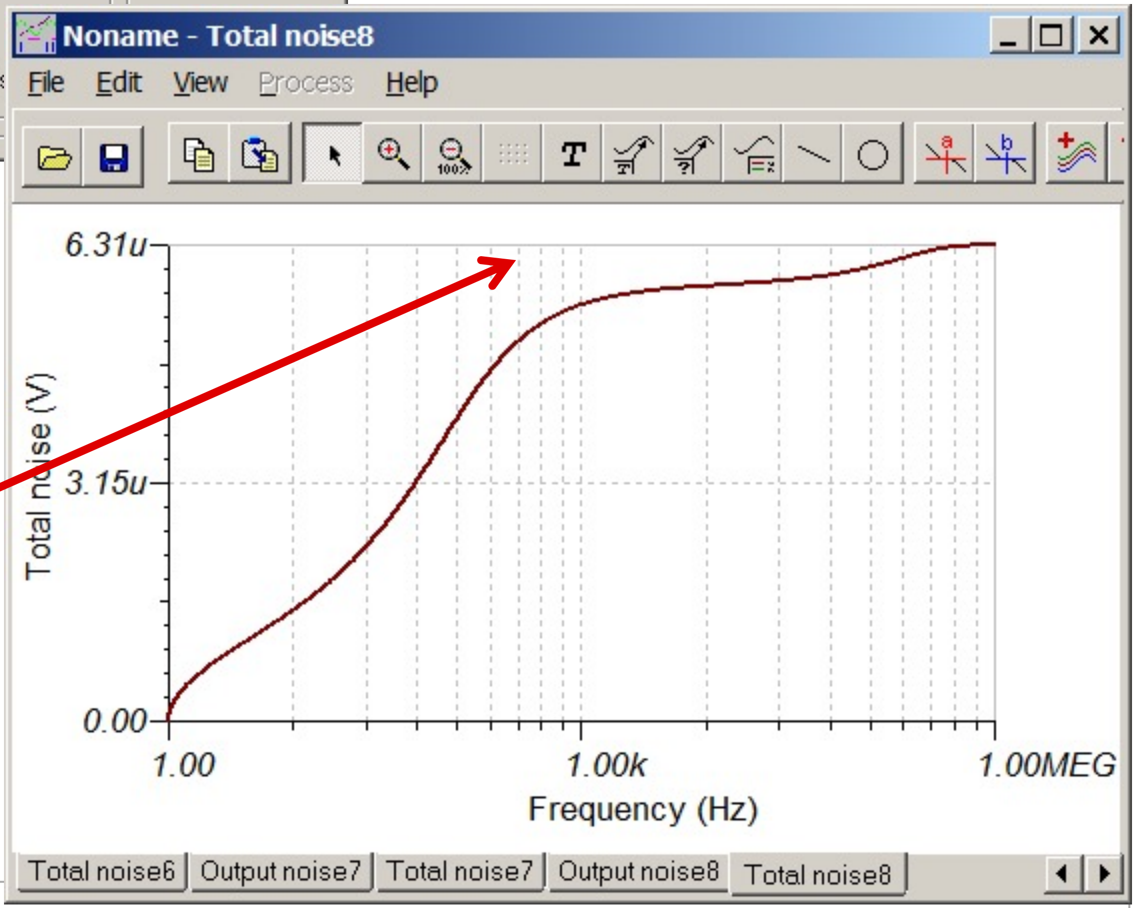


1. Analysis> Noise Analysis



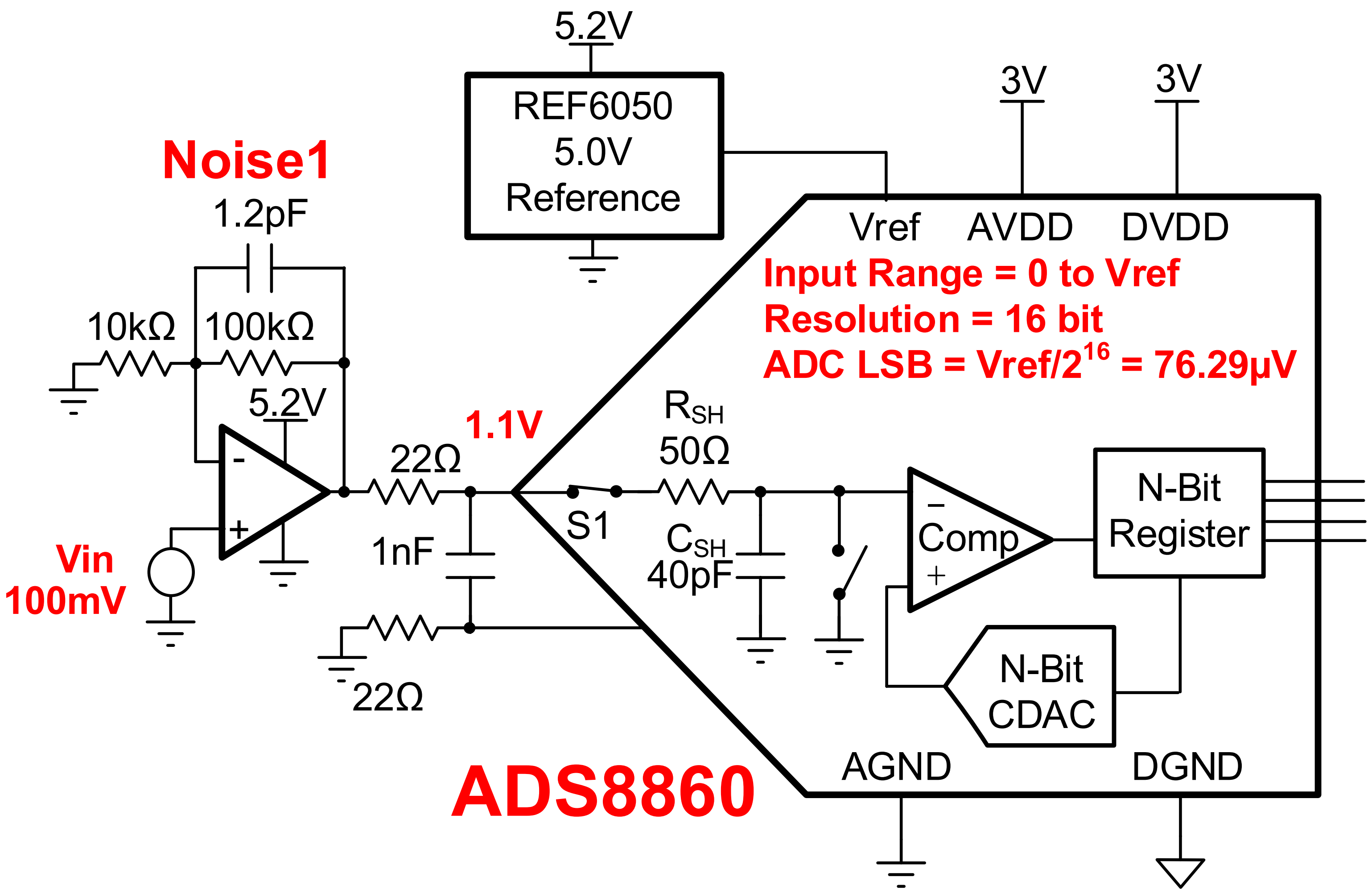


2. Enter the bandwidth and select the diagrams



3. The integrated noise is the "total noise". Look at the final value VnRef ≈ 6.31uV rms

Total System Noise for OPA320_Noise1



$$V_{FSR\_rms} = V_{FSRpk} \cdot 0.707$$

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

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

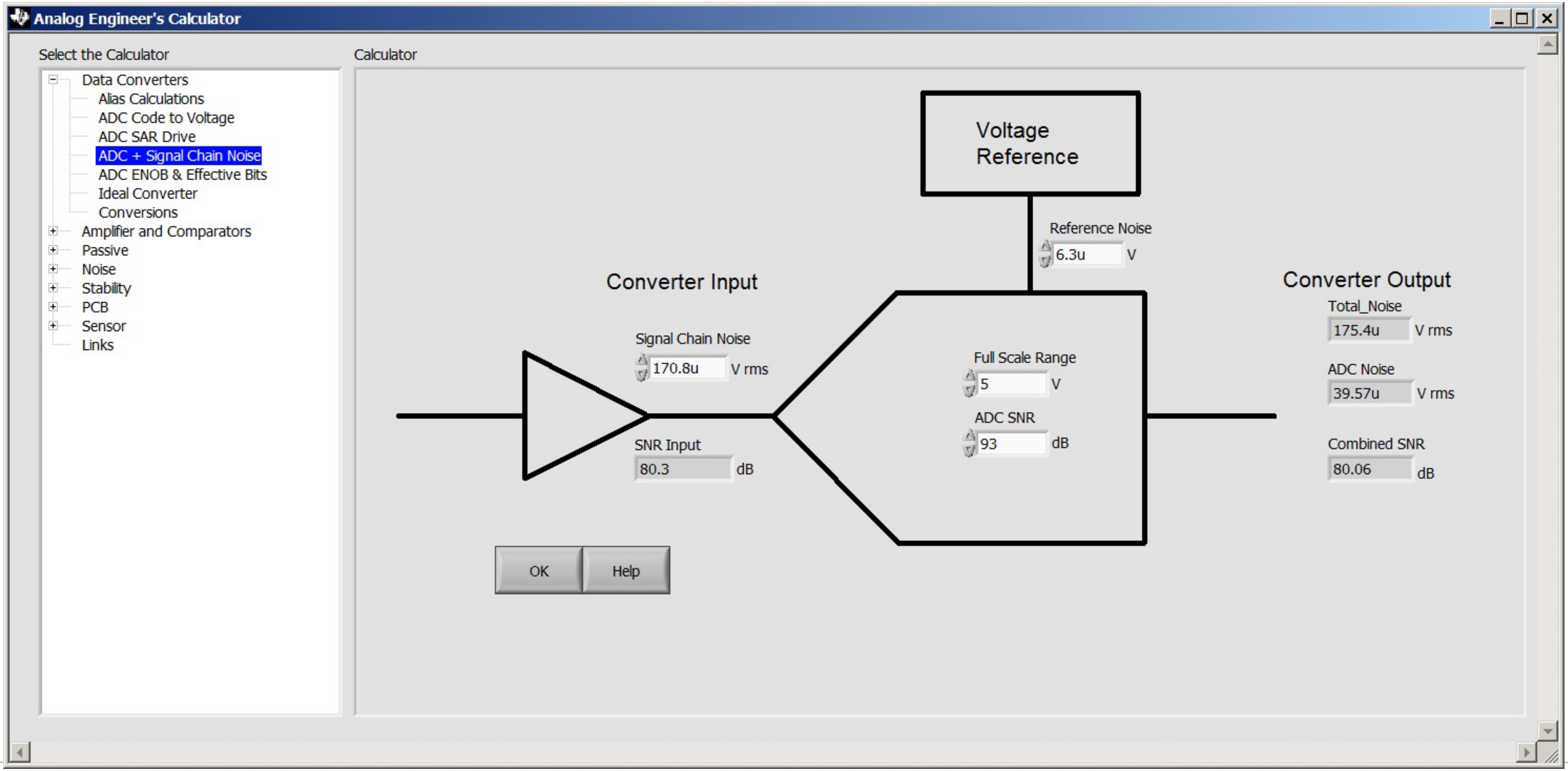
$$V_{nADC} = \frac{V_{FSR\_rms}}{10^{\left(\frac{SNR_{ADC}}{20}\right)}} = \frac{1.767V}{10^{\left(\frac{93dB}{20}\right)}} = 39.6\mu V\ rms$$

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

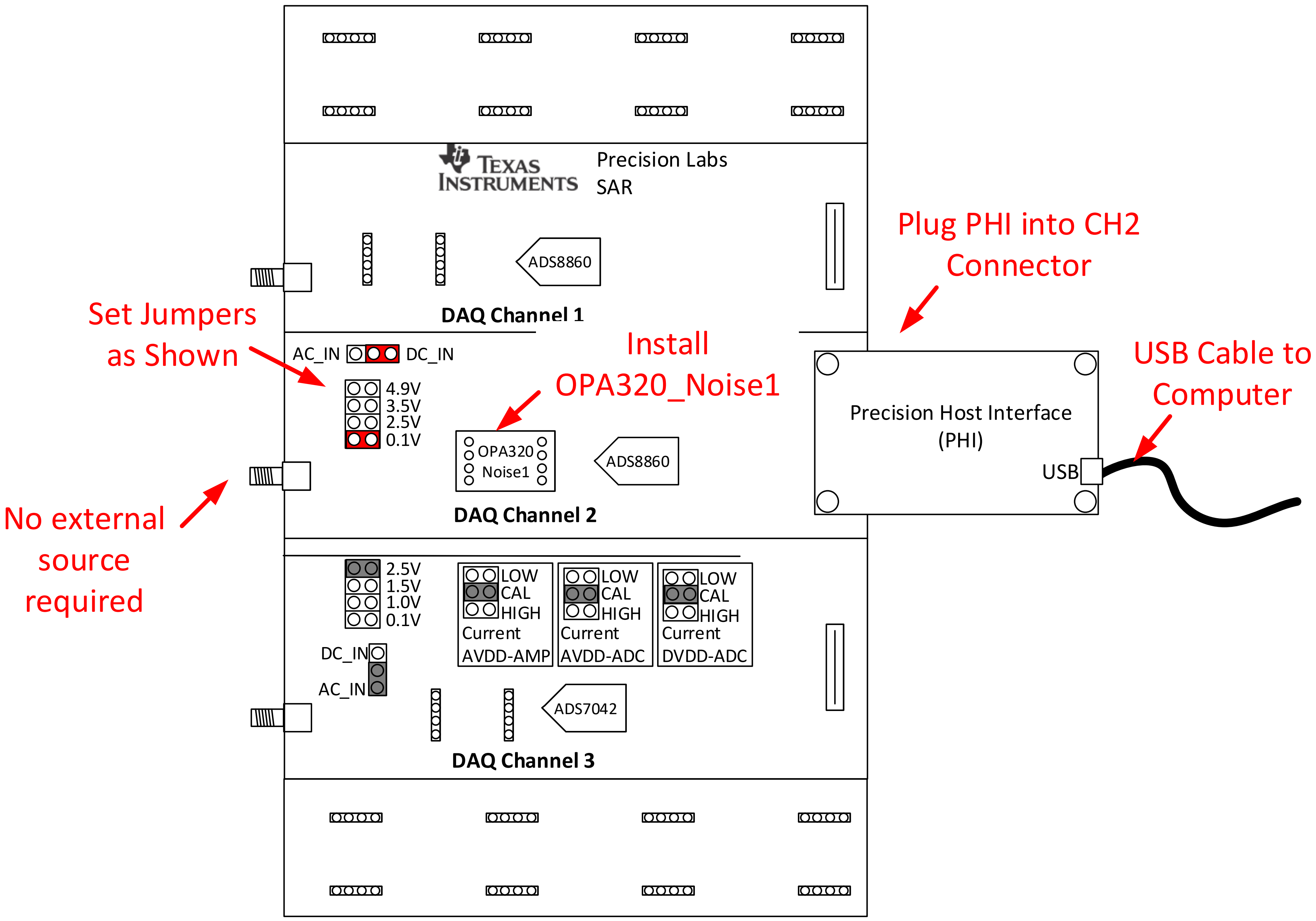
$$= \sqrt{(39.6\mu V)^2 + (170.8\mu V)^2 + (6.3\mu V)^2} = 175.4\mu V\ rms$$

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

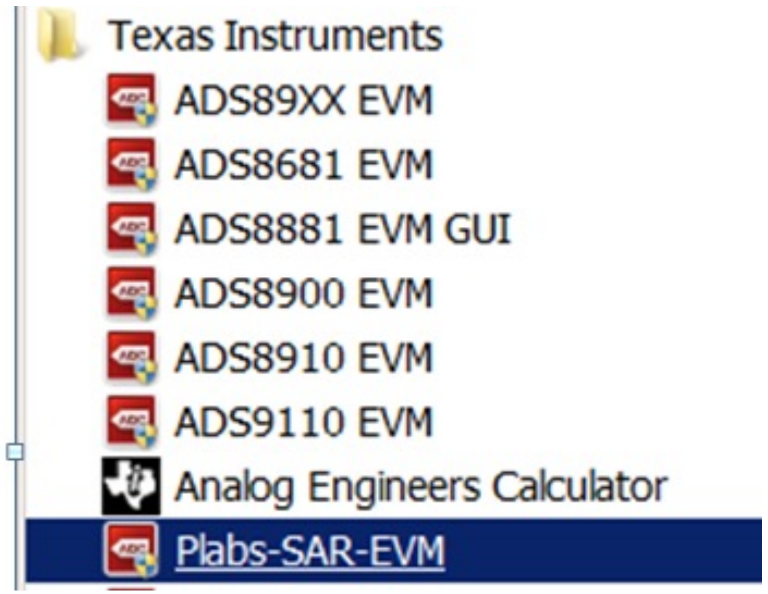
Solve Using the Analog Engineer's Calculator



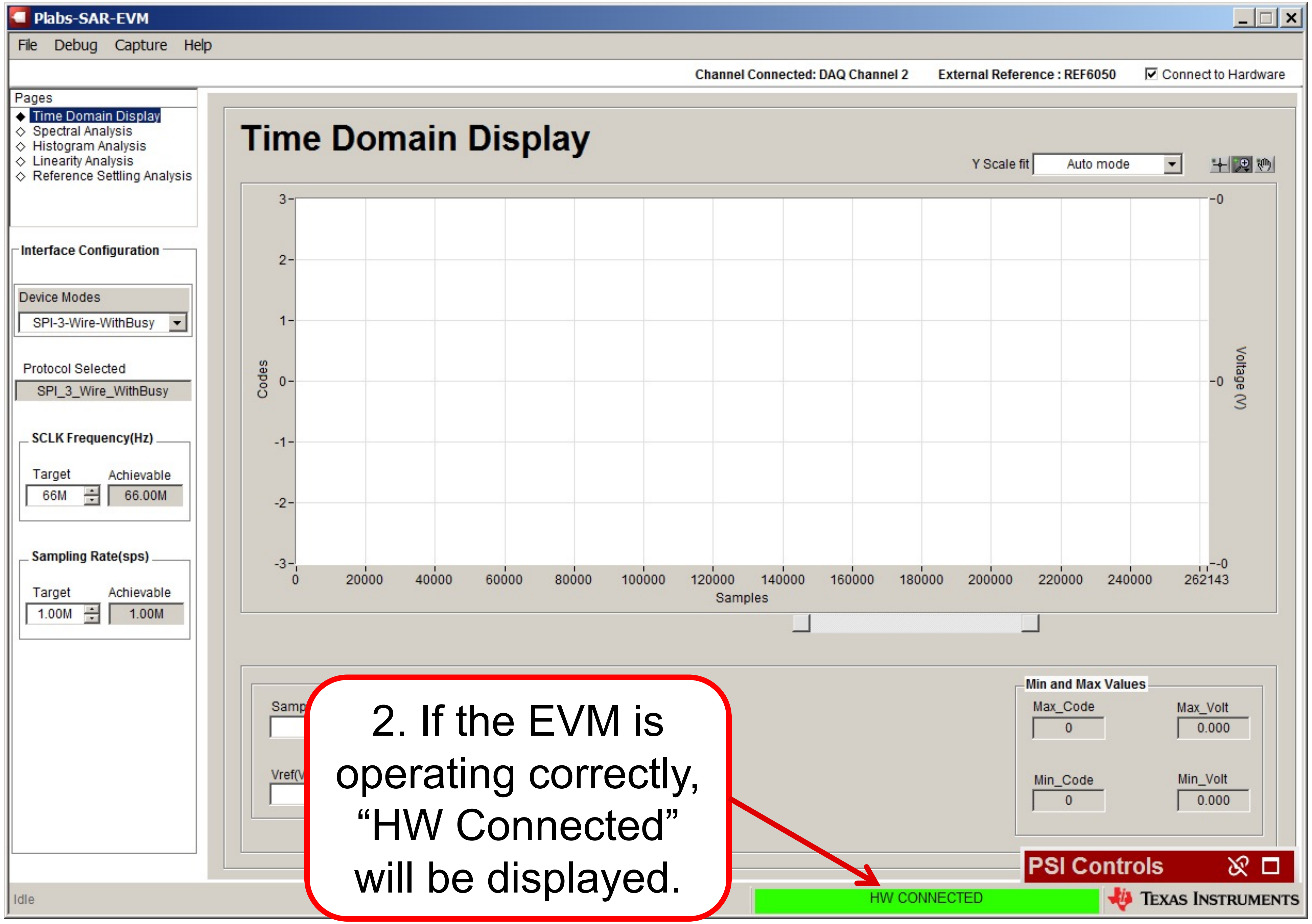
Connect the hardware



Start & Setup the PLABS-SAR EVM Software

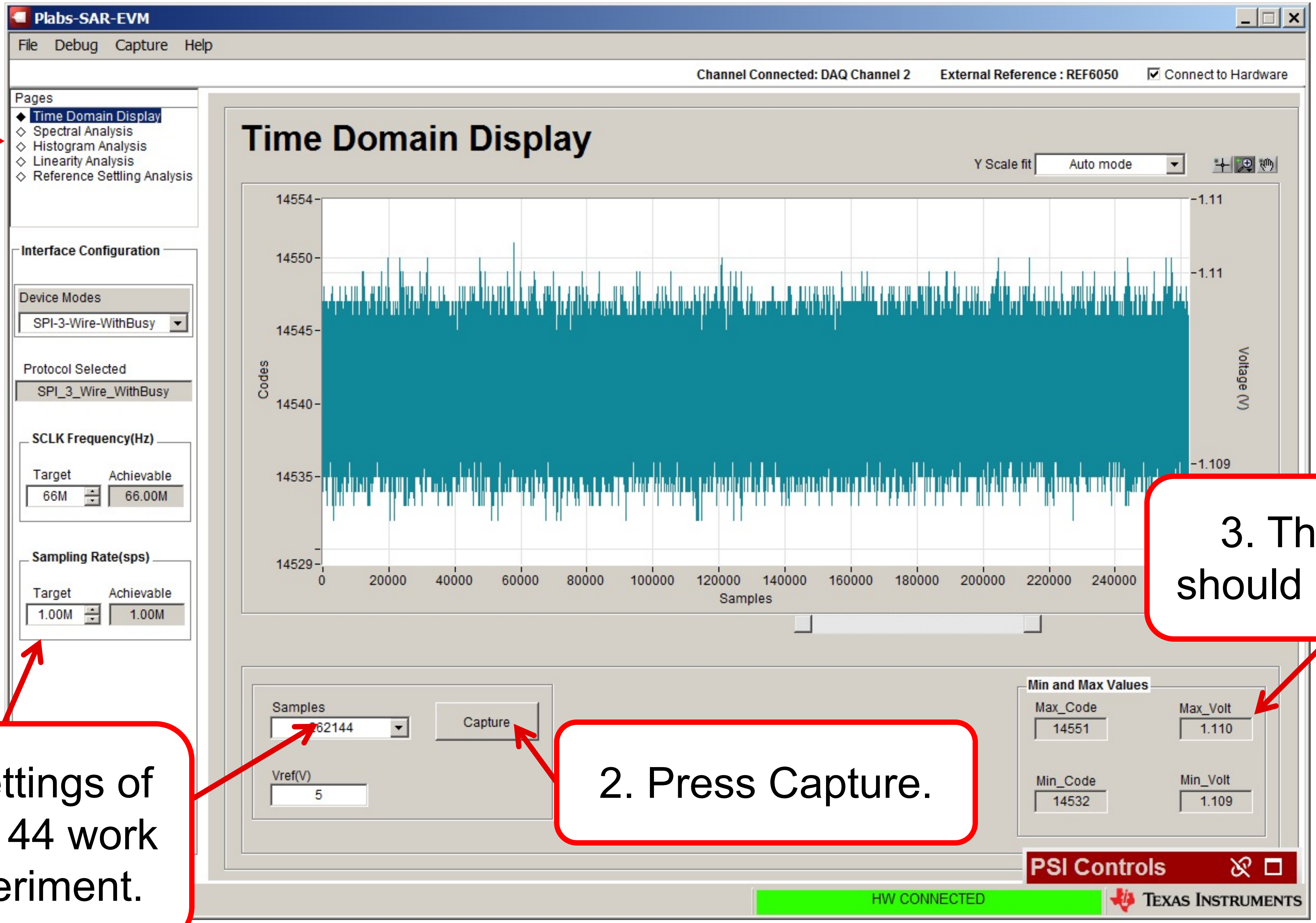


1. Select “Plabs-SAR-EVM” from “start>All Programs”



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

Measure the Noise and DC Level



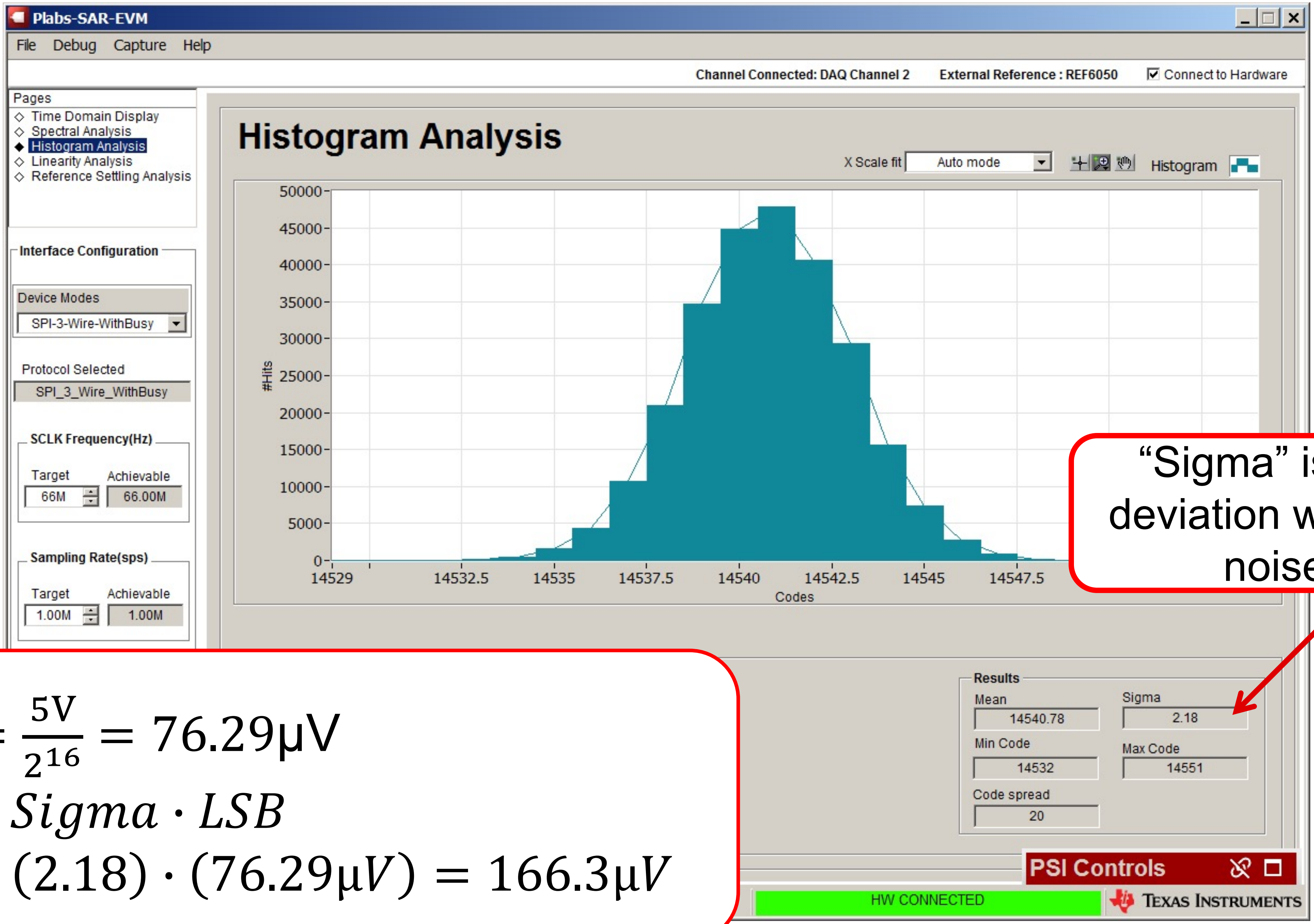
4. Change page to “Histogram Analysis”

3. The DC output should be about 1.1V.

2. Press Capture.

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

Look at the Statistics Under "Histogram Analysis"



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

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

$$V_{noise\_meas} = Sigma \cdot LSB$$

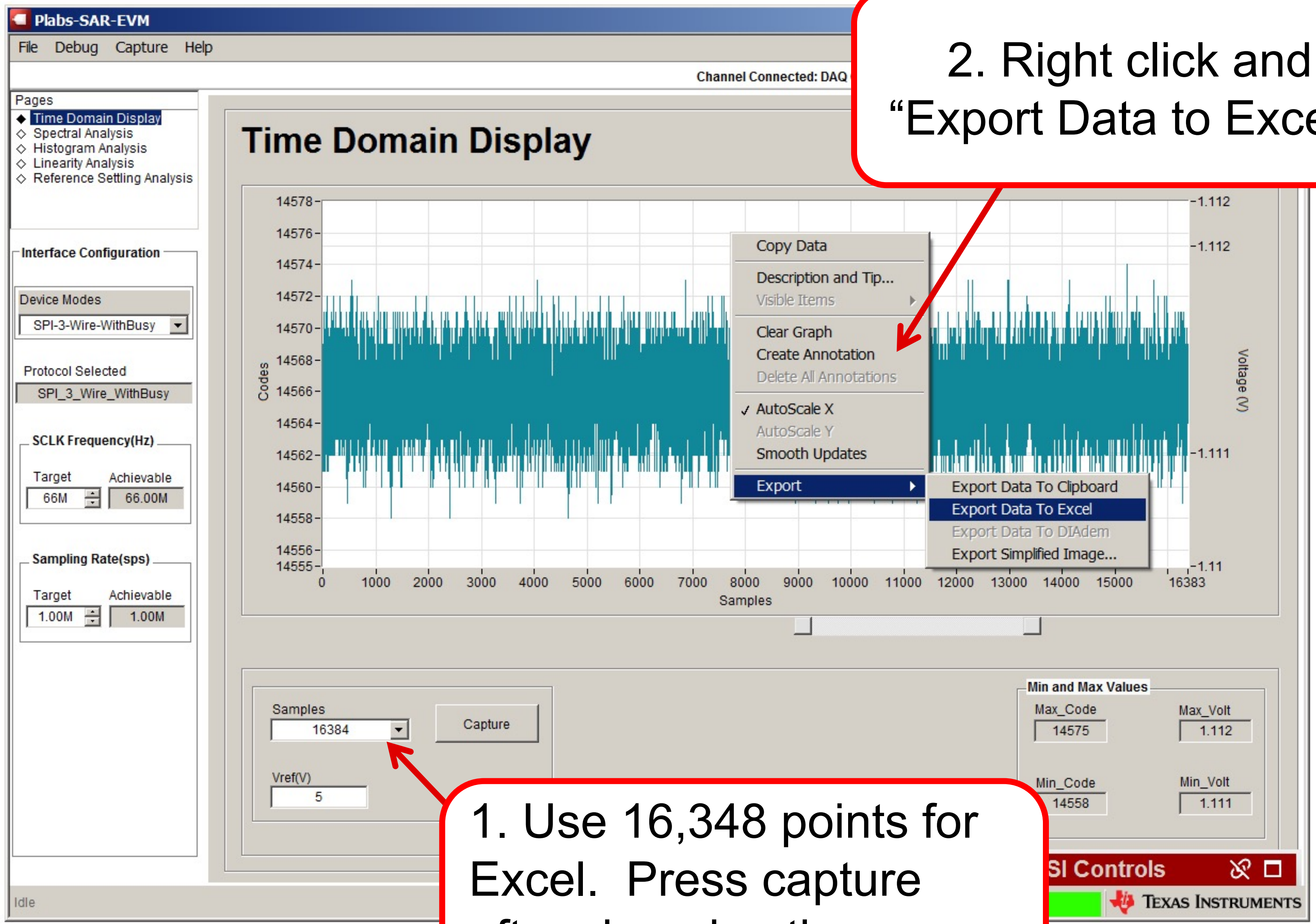
$$V_{noise\_meas} = (2.18) \cdot (76.29\mu V) = 166.3\mu V$$

Measured vs Expected Results

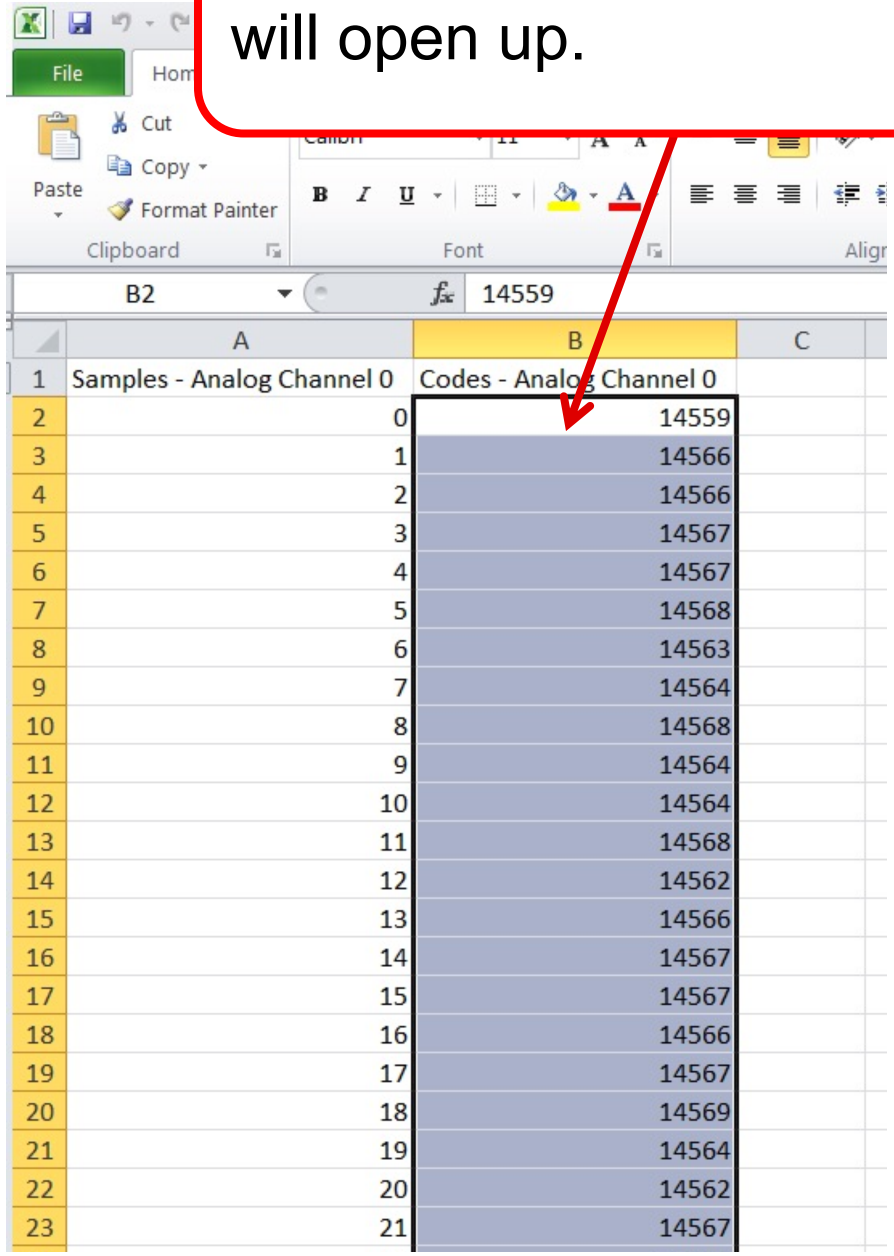
Your results should show the same trend as the expected result but the specific values will differ.

		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".



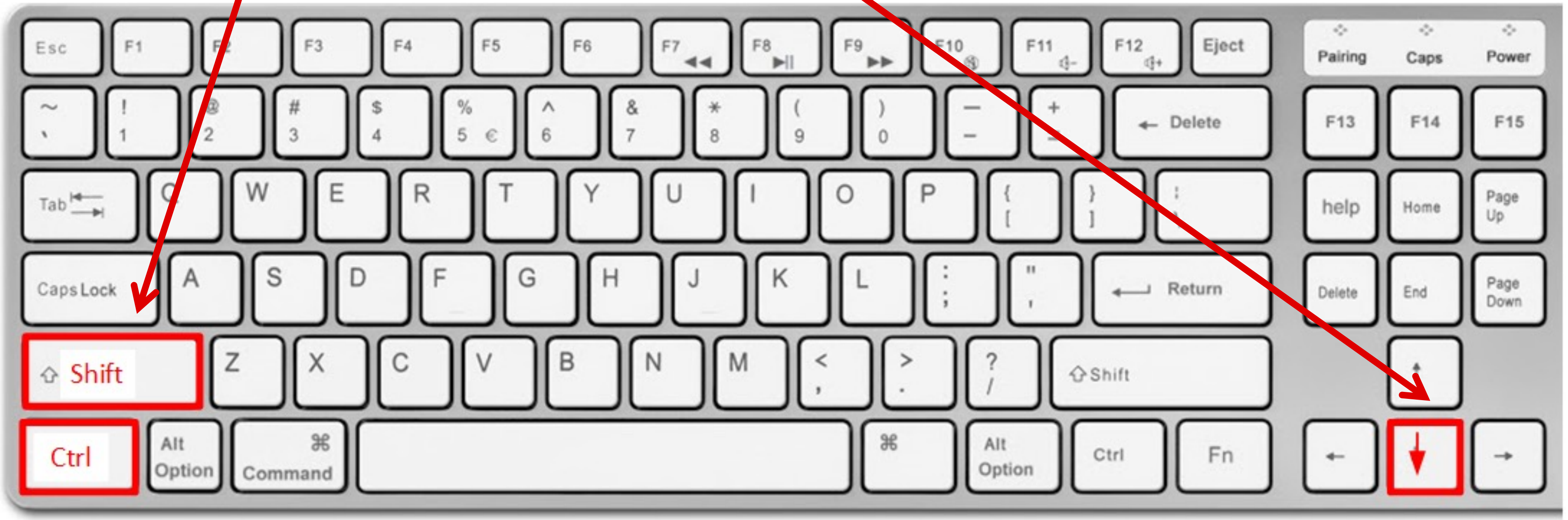
3. An Excel spreadsheet will open up.

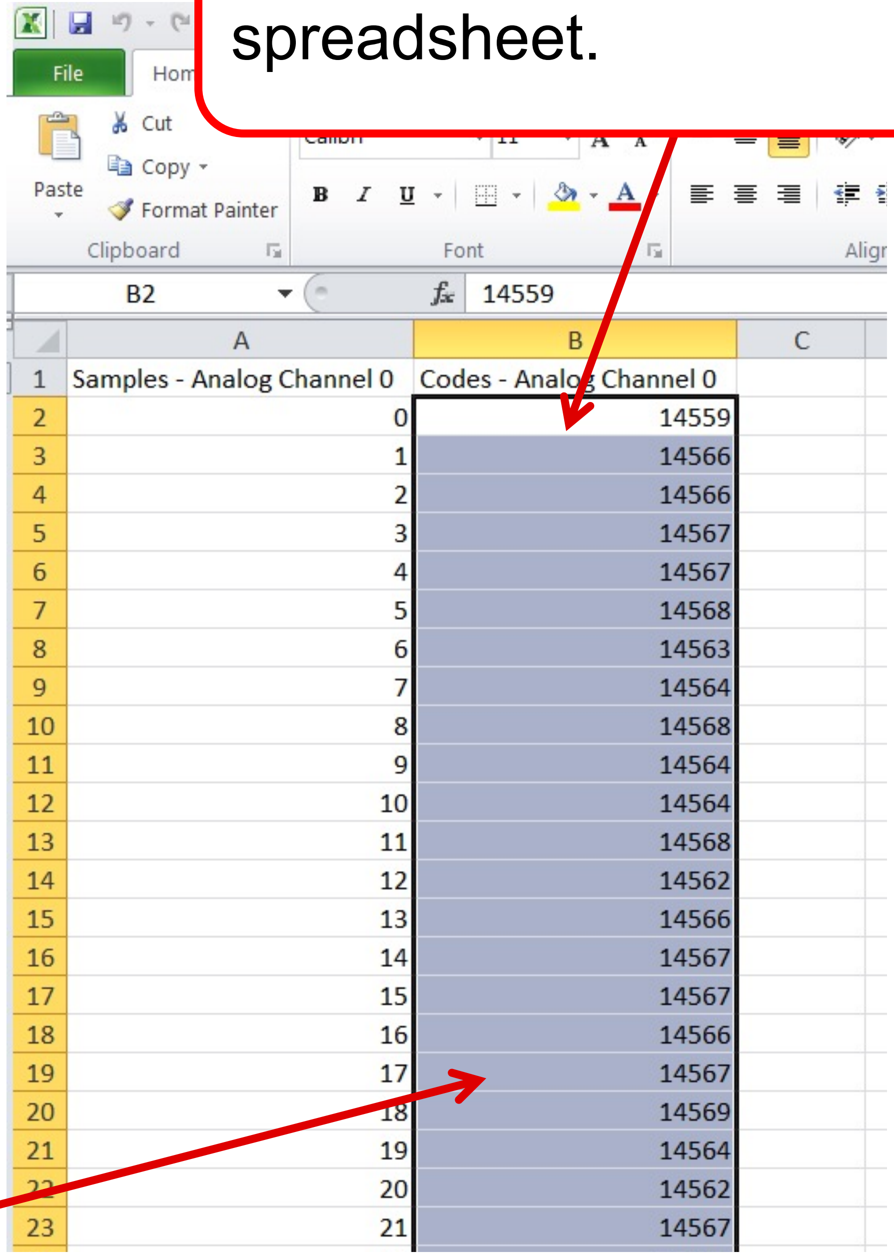
1. Use 16,348 points for Excel. Press capture after changing the number of samples.

Selecting a Column in Excel

1. Select cell “B2” in the spreadsheet.

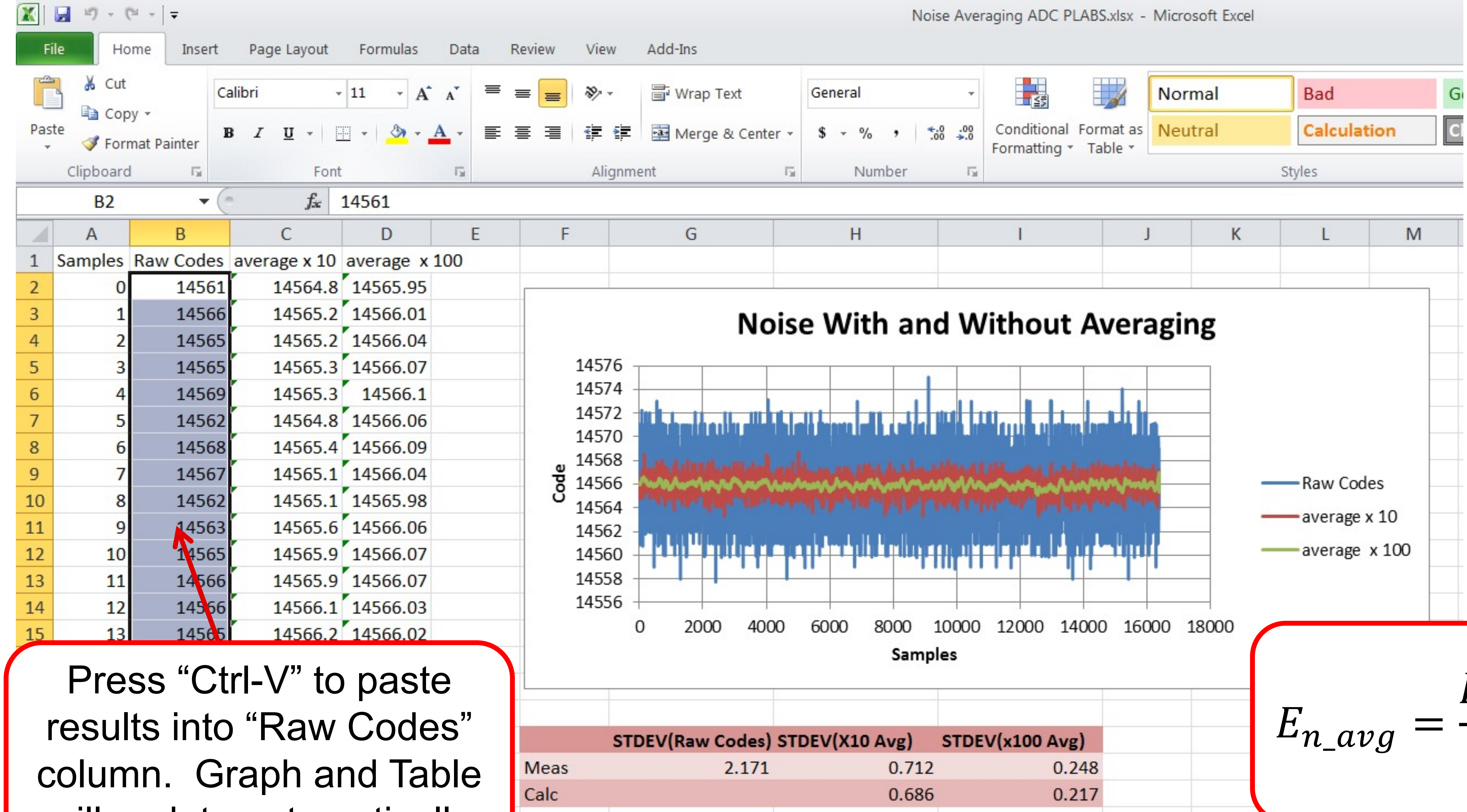
2. Press “Shift-Ctrl-Down Arrow” to select the entire row.





3. Press “Ctrl-C” to copy.

Paste Your Results Under “Raw Codes”



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

Click to access Excel Spreadsheet.

Microsoft Excel Worksheet

$$E_{n\_avg} = \frac{E_{n\_raw}}{\sqrt{N}}$$

Thanks for your time!