ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Amplifier Training

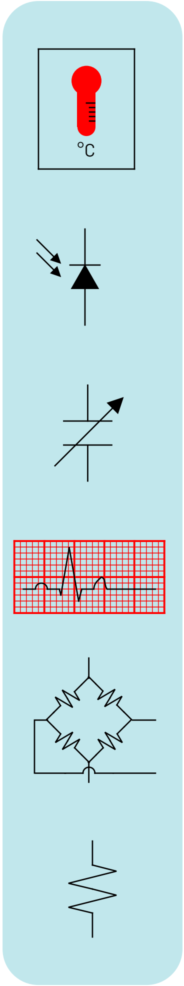
Demystifying Noise

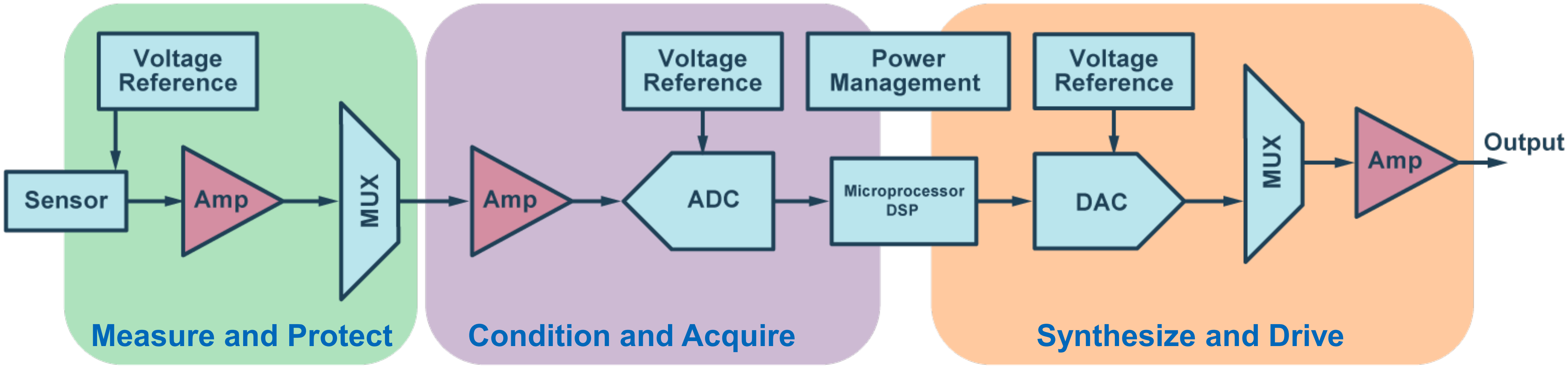
Why We Care About Noise

It can be difficult to carry on a conversation in a noisy environment such as a bar or a restaurant or near a waterfall

Similarly, it can be difficult to measure small signals in the presence of noise

Low Noise Enables Precision Signal Chains





- Low I_B Op-Amps
- PGTIAs
- Zero-Drift Op-Amps
- Current Sense
- TIA/High Speed Amps

- High Speed Amps
- High efficiency Amps
- Amps for ADC driving
- Active filters

- DAC Output buffering
- High Voltage
- High Output current
- High Capacitive Load drive

Why We Care About Noise

<u>Achieving low noise in analog circuits increases the information that is obtained from the sensor</u>

It is therefore important to understand:

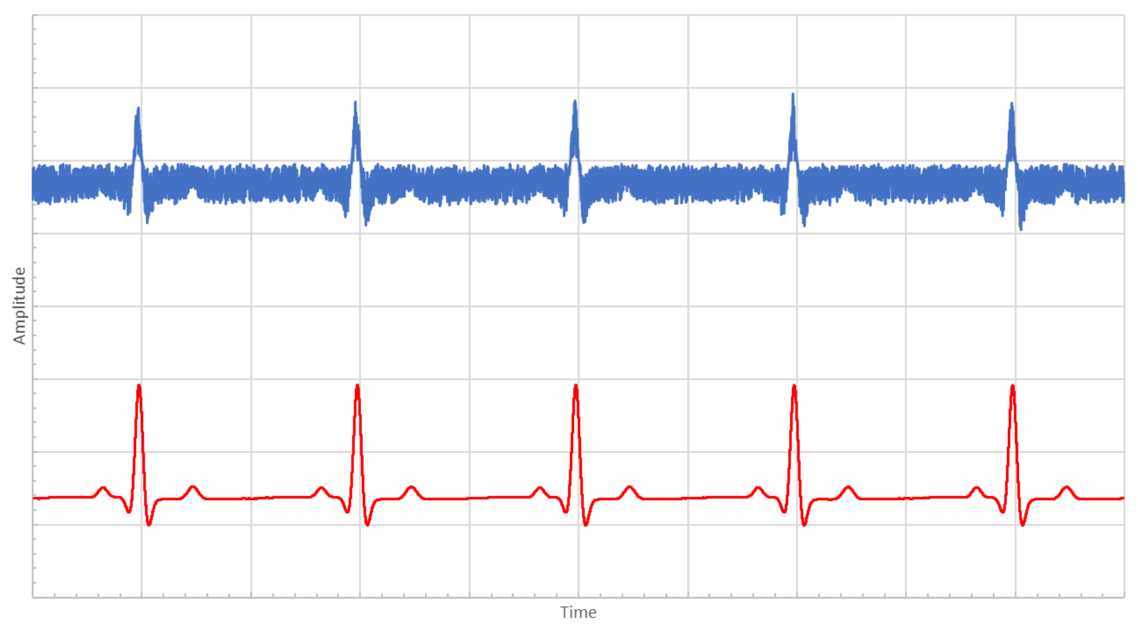
What are the different types of noise?

Where does noise come from?

How do we predict and analyze noise?

Noisy signal

Low noise signal



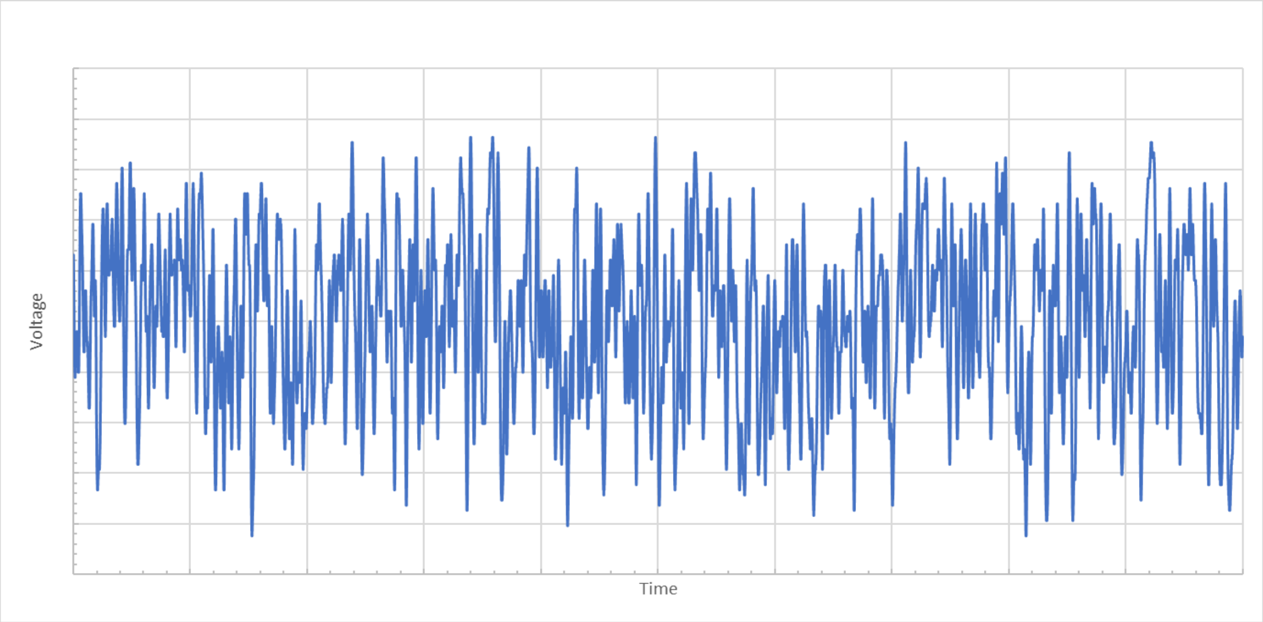
Terms and Definitions

- **RTO** – Acronym meaning Referred to Output
- **RTI** – Acronym meaning Referred to Input
- **Noise Power Spectral Density** – Expressed in (W/Hz) is the square of either voltage noise spectral density or current noise spectral density
- **Voltage Noise Spectral Density** - Voltage noise spectral density is a measurement of noise voltage per square-root hertz often expressed with units of nV_{RMS}/SQRT-Hz
- **Current Noise Spectral Density** - Current noise spectral density is a measurement of noise current per square-root hertz often expressed with units of fA_{RMS}/SQRT-Hz
- **Integrated Noise** – Also sometimes called total noise, can be thought of as the amount of "fuzz" you would see on a perfect, noiseless oscilloscope over a given measurement bandwidth. Integrated noise can be expressed in units RMS or peak-to-peak. It is called "integrated noise" as it is the area under the noise power spectral density curve when integrated over the frequency range of interest
- **Noise Bandwidth** – Is different than the signal bandwidth and is a concept used to relate the area under the noise power spectral density curve as a function of the steepness of the roll-off at high frequency

Terms and Definitions

- **Noise Gain** – Can be different than the signal gain. Noise Gain throughout this presentation refers to the gain from the opamps equivalent input noise voltage source. The gain will be the same gain as for the non-inverting opamp configuration, i.e. $1+Z_F/Z_G$
- **Equivalent Input Noise Voltage** – a voltage source with units of V/SQRT-Hz placed in series with IN+ terminal. This equivalent voltage source represents all of the noise sources internal to the opamp reflected to the input
- **Equivalent Input Noise Current** – a current source with units of A/SQRT-Hz placed at each input terminal of an opamp and ground. This equivalent current source represents the noise associated with the input bias current and leakage current of an amplifiers input stage
- **NSD –** Acronym meaning Noise Spectral Density. Describes the noise parameter as a function of frequency

Noise in the Time Domain



Noise is often times viewed in the time domain, with time plotted on the X-axis and voltage plotted on the Y-axis

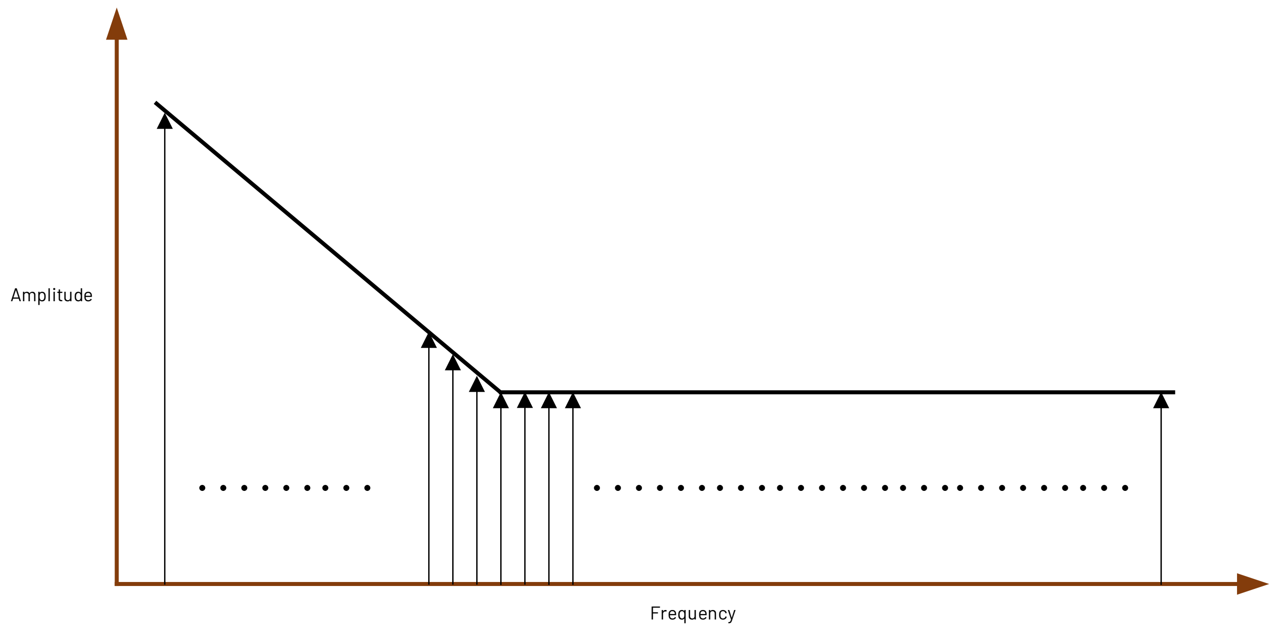
You can think of noise in the time domain as an infinite summation of sine waves at different frequencies

Specifically, for an opamp you can think of the equivalent voltage noise of an opamp as representing the input offset voltage changing in time

Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

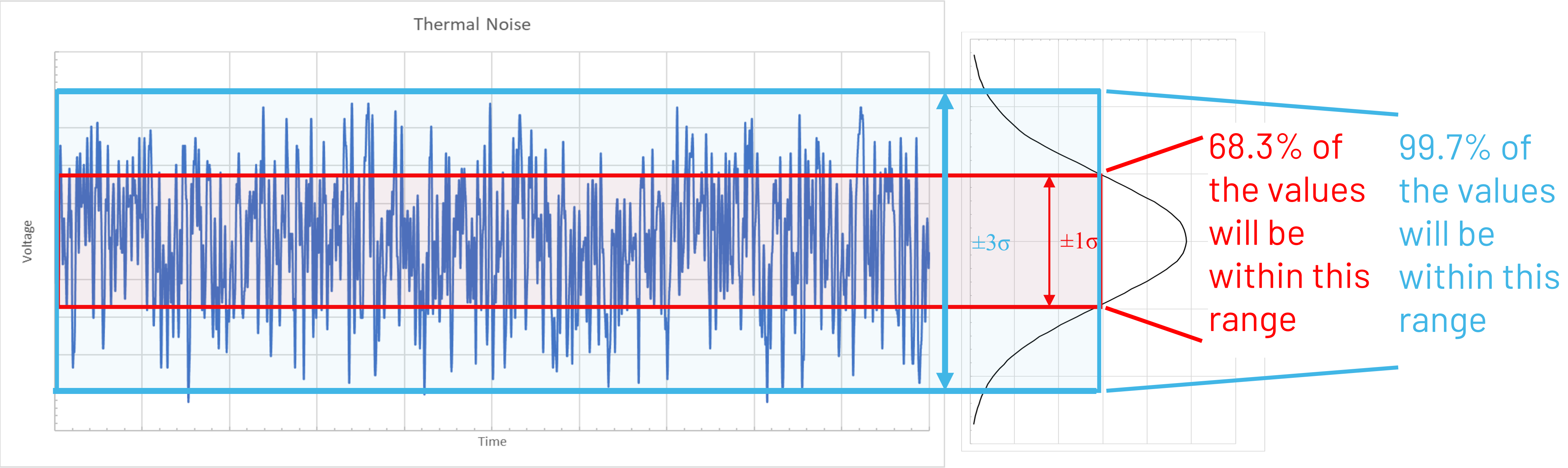
Noise in the Frequency Domain

Noise in the frequency domain can be thought of as an infinite number of impulses across the frequency spectrum



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Random Nature of Noise



Number of Standard Deviations	Chance of Measuring Voltage (%)
2 *sigma* (+/-1 sigma)	68.3
3 *sigma* (+/-1.5 sigma)	86.6
4 *sigma* (+/-2 sigma)	95.4
5 *sigma* (+/-2.5 sigma)	98.8
6 *sigma* (+/-3 sigma)	99.7
6.6 *sigma* (+/-3.31 sigma)	99.9

Noise is random in nature and generally has a Gaussian distribution. Statistical methods are used to analyze and combine noise signals

Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Rules of Thumb

Because noise has a Gaussian distribution you can estimate the relationship between RMS and Peak-to-Peak values as:

$$V_{PP} = 6 \times V_{RMS} \text{ for 99.7\% of the population (use 6.6 for 99.9\%)}$$

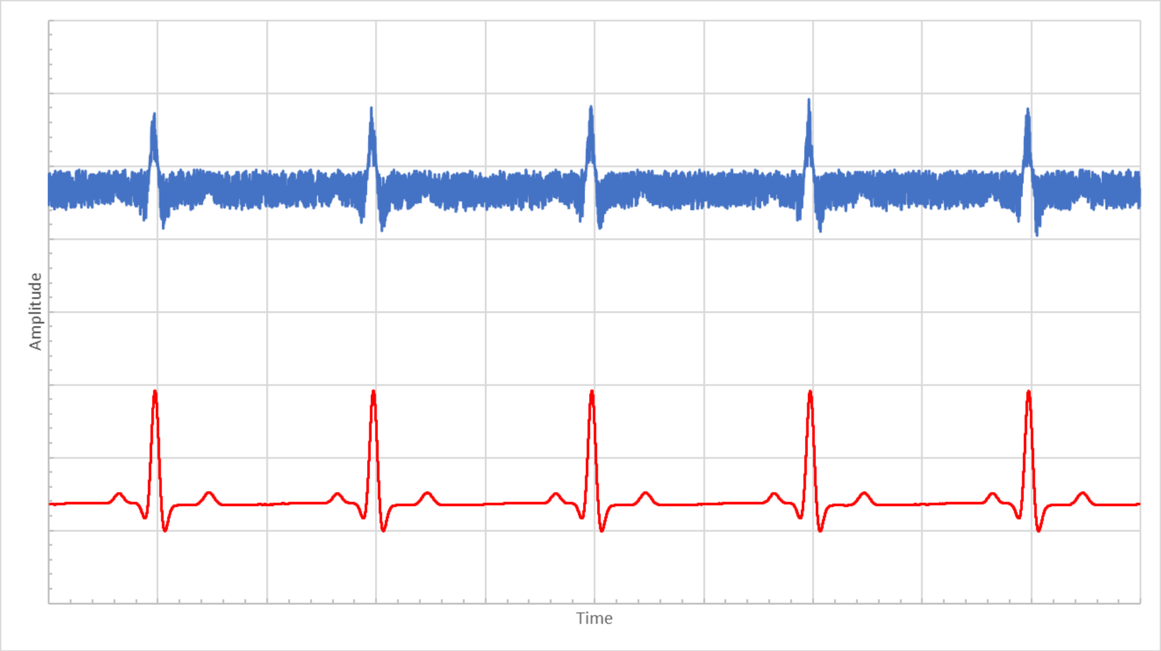
Because noise sources are uncorrelated, they are combined (added) as the square-root of the sum of the squares:

$$V_{n_{total}} = \sqrt{\left(V_{n_1}\right)^2 + \left(V_{n_2}\right)^2 \ldots + \left(V_{n_n}\right)^2}$$

Types of Noise

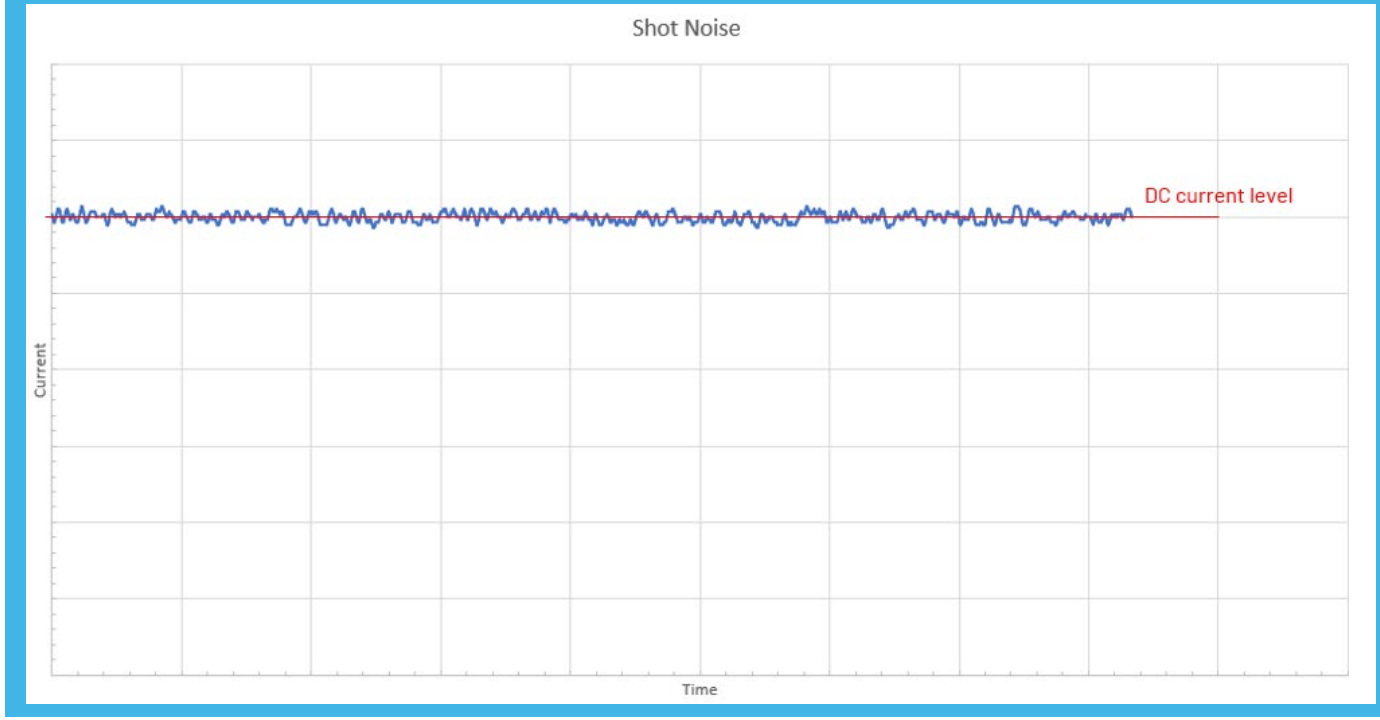
Types of Noise

- **Shot Noise** – Associated with DC current flow in PN junctions (Diodes, bipolar transistors)
- **Thermal Noise** – Associated with the random motion of thermally excited electrons in a conductor
- **1/f Noise** – Associated with DC current flow and related to traps and imperfections in silicon devices
- **Popcorn Noise** – A low-frequency noise, generally associated with ionic contamination, silicon defects, etc



Shot Noise

- DC Current flow through PN junctions will occur as individual carriers with charge *q*
- The electrons will transition across the PN junction randomly in time and in the aggregate will result in an average DC current
- If examined closely on a sensitive oscilloscope a DC current will look like a bunch of random current pulses and is modelled as a current source

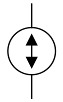


$$I_{SHOT} = \sqrt{2qI_{DC}\Delta f}$$

q = electronic charge, 1.602×10^{-19} Coulombs

I_{DC} = DC current in amps

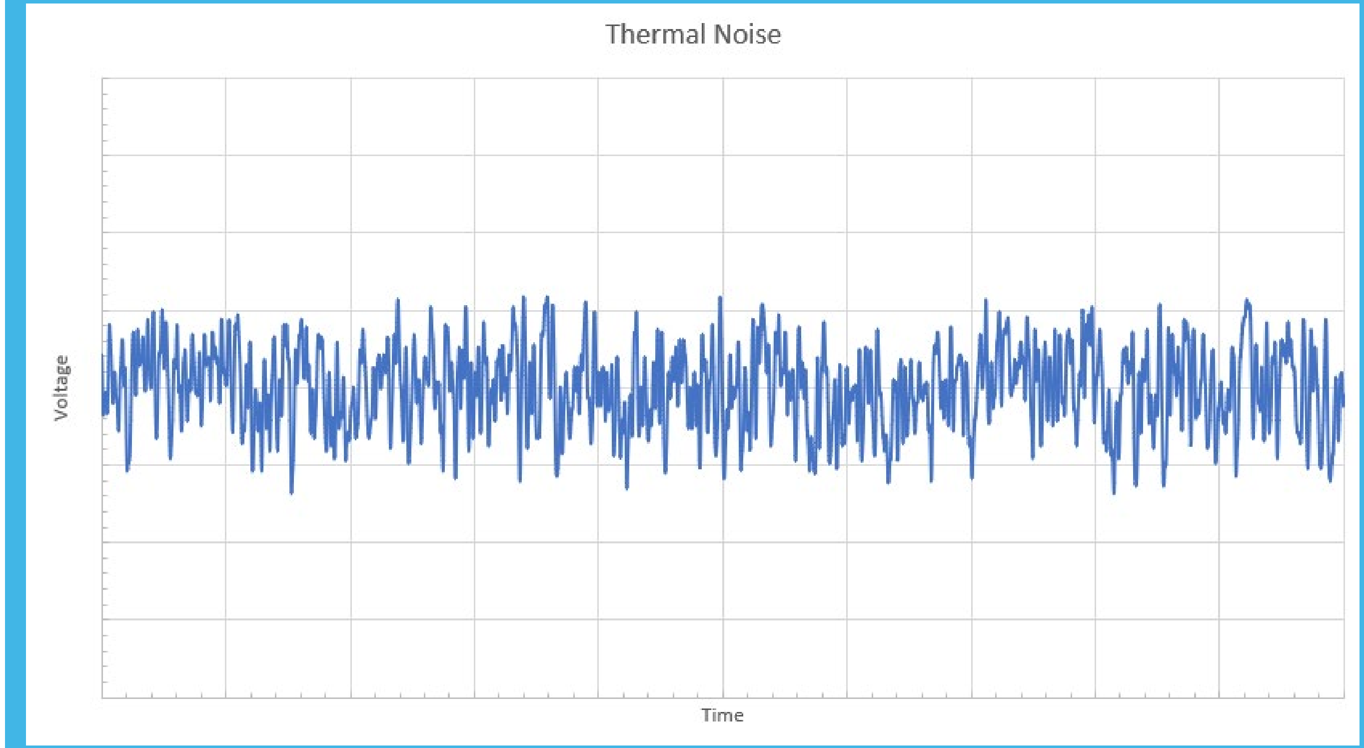
Δf = Noise bandwidth in Hertz



Source:
Paul R. Gray, Robert G. Meyer, Analysis and Design of Analog Integrated Circuits, Third Edition, New York, John Wiley & Sons, Inc., 1993

Thermal Noise

- Thermal noise in conductors is due to the random thermal motion of the electrons
- Thermal noise is directly proportional to temperature
- In a resistor, thermal noise can be represented by either a voltage source in series with the resistor or as a current source in parallel with the resistor



$$V_N = \sqrt{4kTR\Delta f}$$

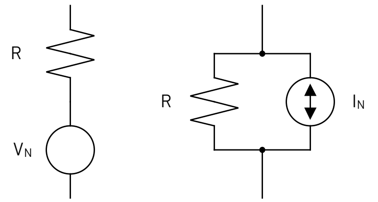
$$I_N = \sqrt{4kT\frac{1}{R}\Delta f} = \frac{V_N}{R}$$

k = Boltzmann's constant, 1.38 x 10^{-23} $\frac{\text{W-s}}{K}$

T = Temperature °K

R = Resistance Ω

Δf = Noise bandwidth in Hertz

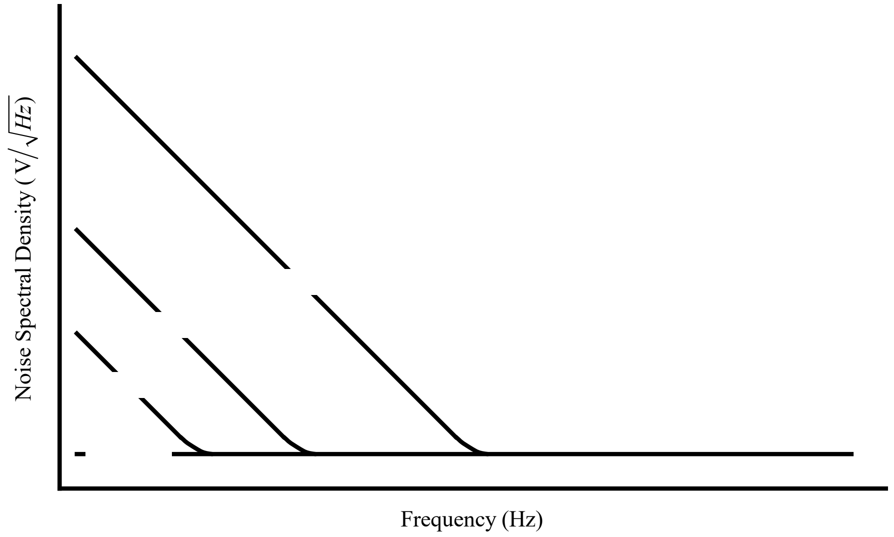


Source:

Paul R. Gray, Robert G. Meyer, Analysis and Design of Analog Integrated Circuits, Third Edition, New York, John Wiley & Sons, Inc., 1993

1/f Noise

- Also known as flicker noise, 1/f noise is associated with both active and passives devices and is associated with DC current flow
- In bipolar transistors, flicker noise is associated with traps caused by crystalline defects in the emitter-base depletion layer
- In CMOS devices, defects in the gate oxide or channel surface are the primary source of flicker noise
- Time constants associated with the traps and defects vary across the spectrum of process technologies giving rise to the typical NSD vs Frequency relationships shown below



$$I_{FN}^{\ 2} = K_1 \frac{I^a}{f^b} \Delta f$$

K_1 = a constant associated with the device technology

I = a DC current in amps

a = a constant between 0.5 and 2

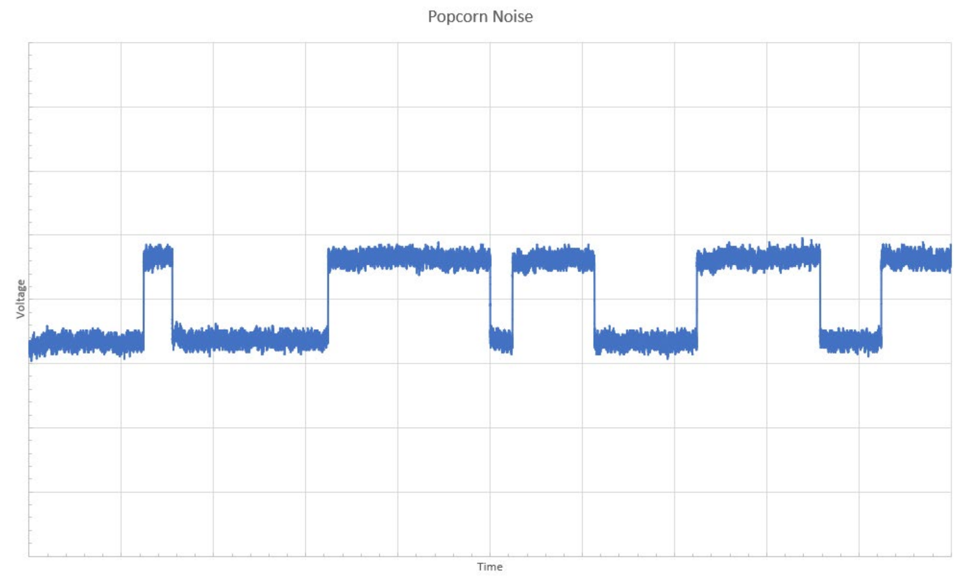
b = a constant ~1

Δf = Noise bandwidth in Hertz

Source:
Paul R. Gray, Robert G. Meyer, Analysis and Design of Analog Integrated Circuits, Third Edition, New York, John Wiley & Sons, Inc., 1993

Popcorn Noise

- Also known as burst noise or random telegraph noise
- Popcorn noise inherits its name from the fact that the frequency of the noise is often times in the audible spectrum and if listened through headphones can sound like corn popping
- The noise levels will take on two (or more) discrete levels
- In bipolar technologies, popcorn noise can be thought of as a sudden change in the h_{fe} (β) of a bipolar transistor



$$I_{BURST}^{\ 2} = K_2 \frac{I^C}{1+\left(\frac{f}{f_C}\right)^2}\Delta f$$

K_2 = a constant for a particular device technology

I = a DC current in amps

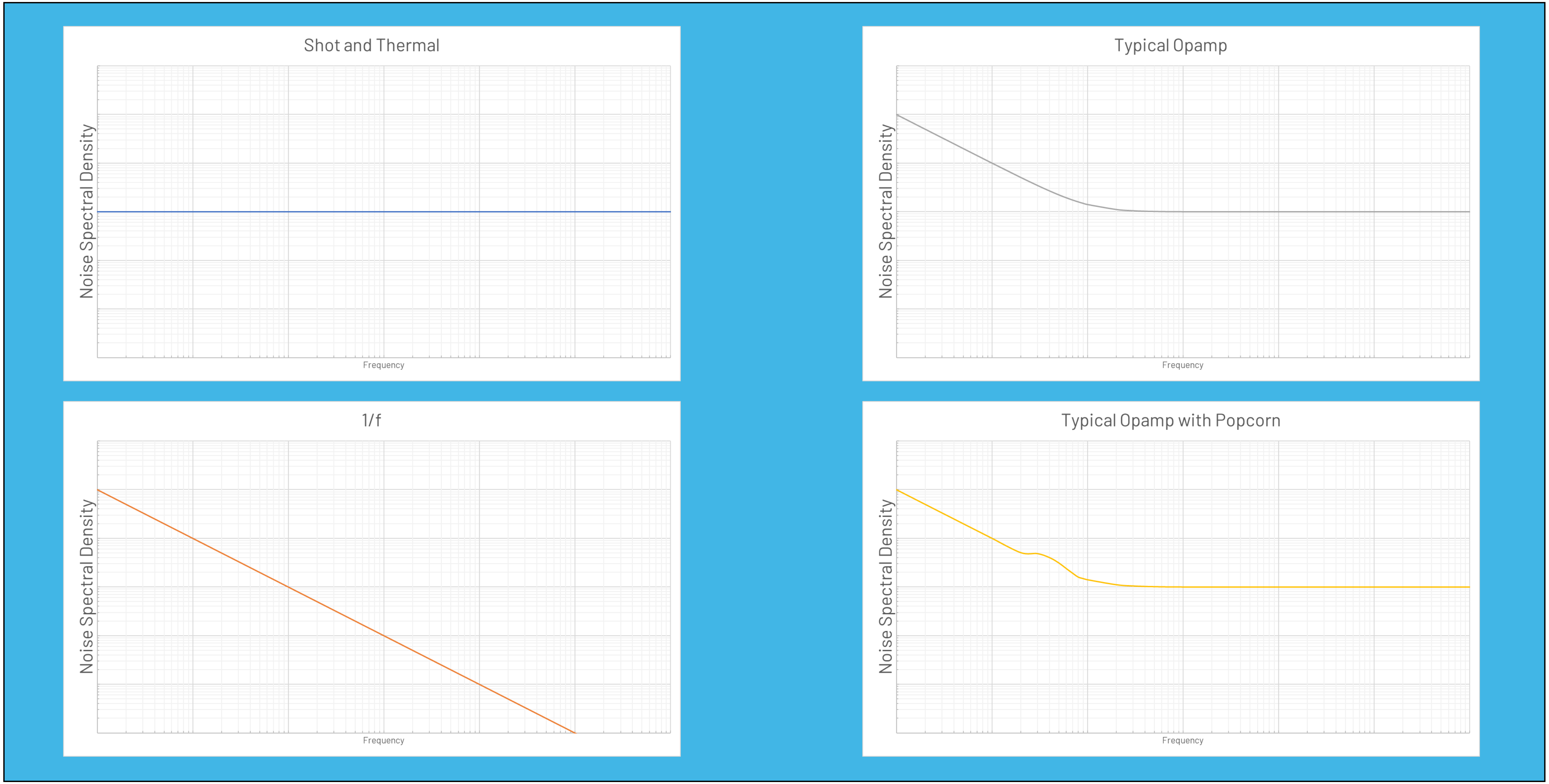
C = a constant in the range of 0.5 to 2

f_C = a particular frequency for a given noise process

Δf = noise bandwidth in Hertz

Source:
Paul R. Gray, Robert G. Meyer, Analysis and Design of Analog Integrated Circuits, Third Edition, New York, John Wiley & Sons, Inc., 1993

Spectral Content of Various Types of Noise



Noise in Resistors

Modeling Thermal Noise in Resistors

The noise power in a conductor is given by:

$$N_t = kT\Delta f$$

Where:

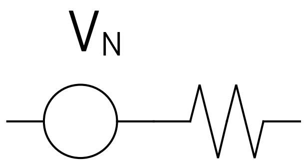
k = Boltzmann's constant, $1.38 \times 10^{-23}\ \frac{\text{W-s}}{K}$

T = Temperature °K

Δf = Noise bandwidth in Hertz

The noise voltage of a resistor is modelled as:

$$V_n = \sqrt{4kTR\Delta f}$$



Rule of Thumb

A 1kΩ resistor has a noise voltage of 4nV/SQRT-Hz, you can use this simple Rule of Thumb to determine the noise for any other resistor with the following equation:

$$V_{n_{R2}} = 4\,nV/\sqrt{Hz} \times \sqrt{\frac{R_2}{1k}}$$

Example: a 100k resistor has a noise density of $40\,nV/\sqrt{Hz}$

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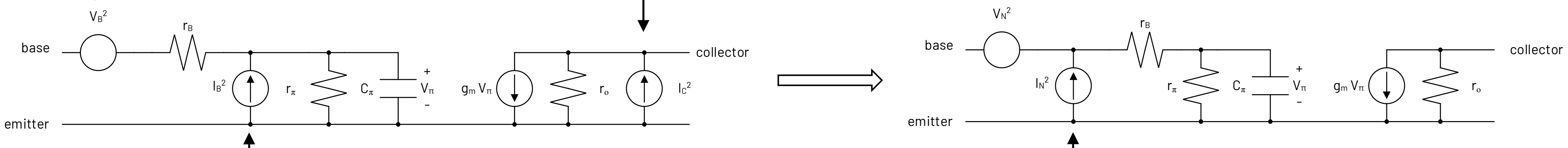
Noise in Transistors

Modeling Noise in Bipolar Transistors

Thermal noise in base resistance

Shot noise in collector current

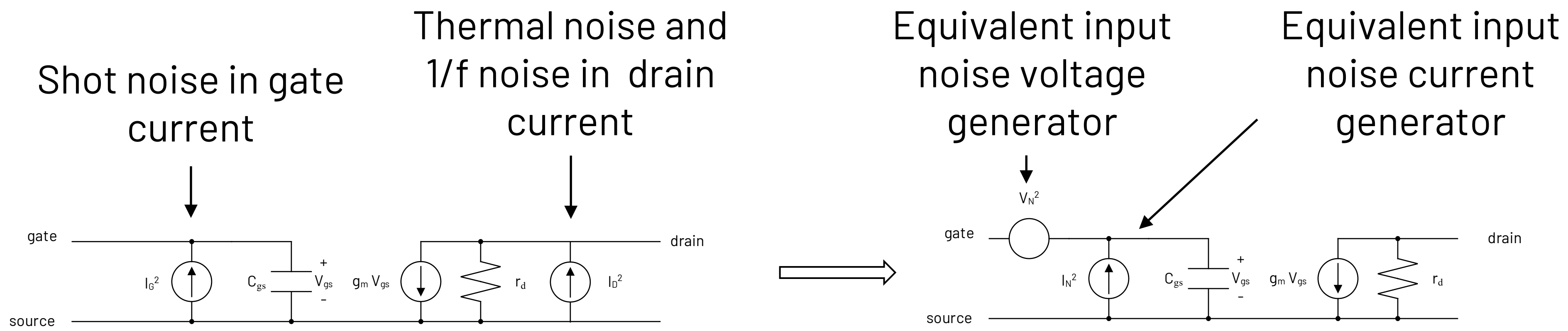
Equivalent input noise voltage generator



Shot noise +1/f noise in base current

Equivalent input noise current generator

Modeling Noise in JFET and CMOS Transistors



Summary (so far)

- Noise, if not mitigated can mask out small details in analog signals
- Noise is random in nature, having a Gaussian distribution
- You can think of noise as the input offset voltage of an opamp changing in time (similar for input bias current)
- There are common types of noise in every opamp circuit
  - Thermal noise from resistors, JFETS and CMOS devices
  - Shot noise from bipolar transistors and input leakage currents
  - Flicker noise from bipolar, JFET and CMOS transistors
  - Popcorn noise is generally eliminated for amplifiers and rarely needs to be considered
- The lowest noise amplifiers have historically been Bipolar, followed by JFET then CMOS This is particularly true for the low frequency region dominated by 1/f noise
- Zero-Drift amplifiers are built on CMOS technologies and eliminate 1/f noise and as such only the broadband noise spectral density needs to be considered in any noise analysis
- Ultimately overall system noise performance can be limited by the 1/f noise in very low frequency systems

Noise in Amplifiers

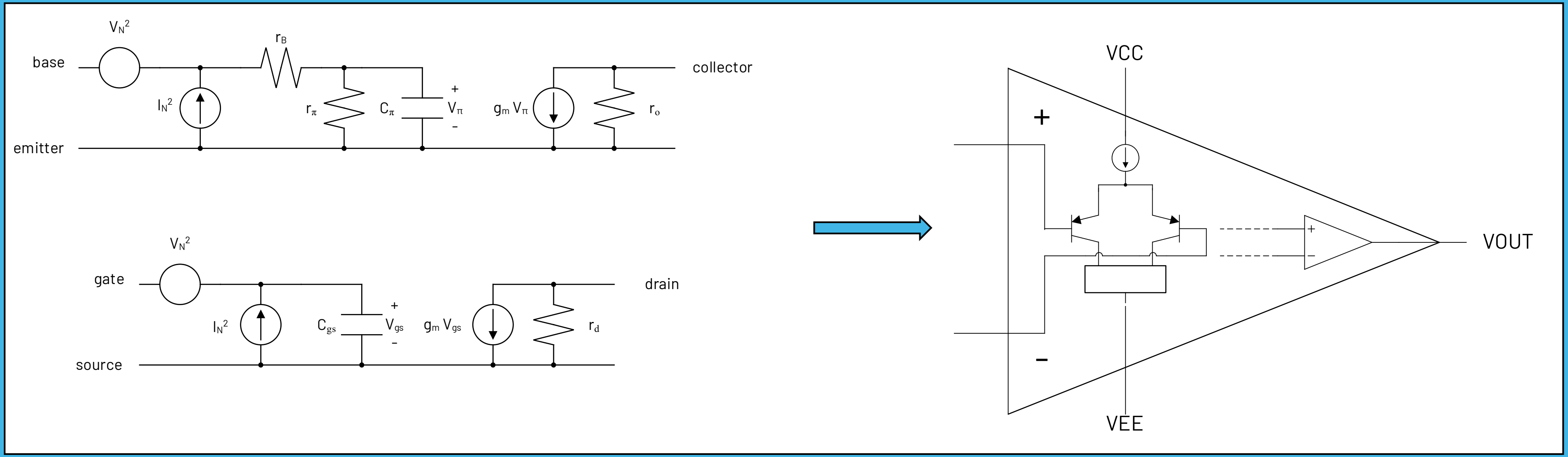
Sources of Noise in Operational Amplifiers

- Operational amplifiers are made from transistors, resistors and capacitors
- Transistors will be either bipolar, JFET or CMOS
- Each of these noise sources can be represented by a noiseless element with its corresponding noise sources (voltage and/or current) placed at the input
- It stands to reason then an amplifier will likewise consist of many internal noise sources than can be modelled as voltage and current sources at the amplifier inputs
- In an opamp the dominant sources of noise are found in the input stage

Bipolar

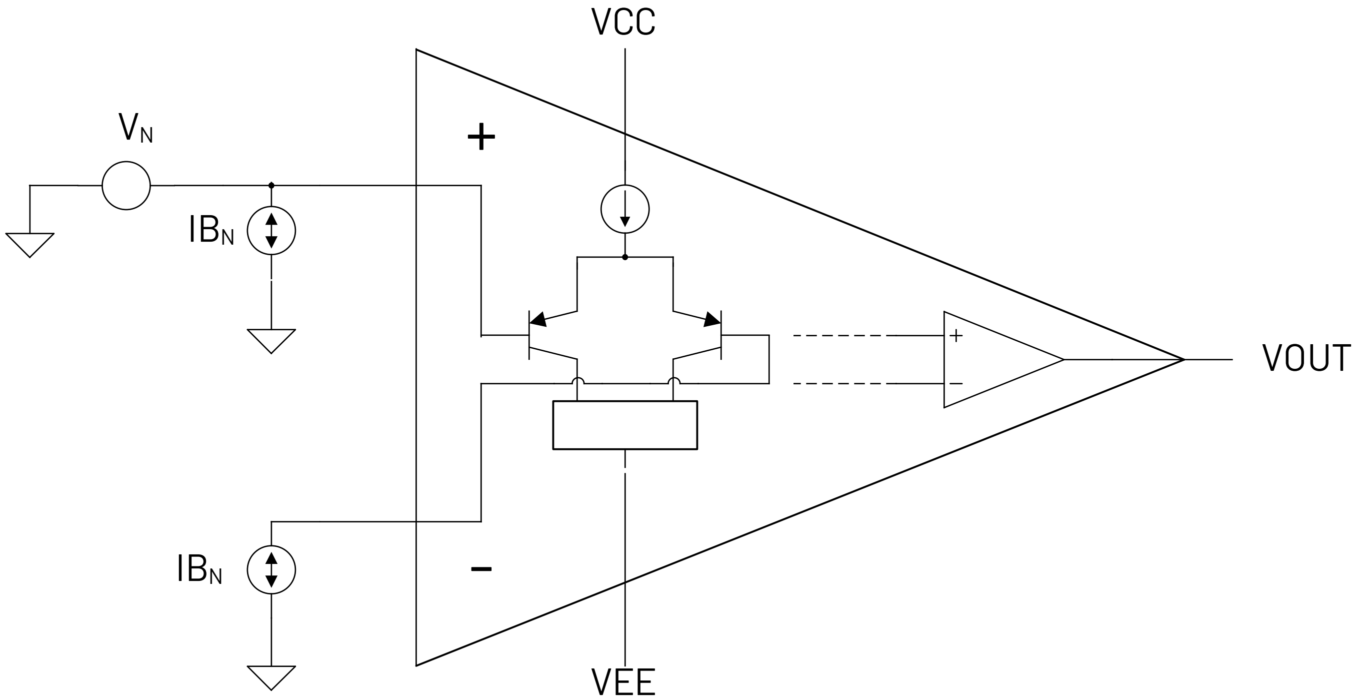
JFET

CMOS

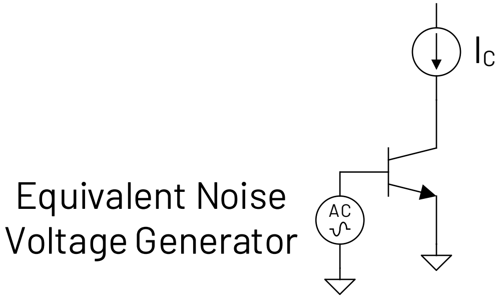


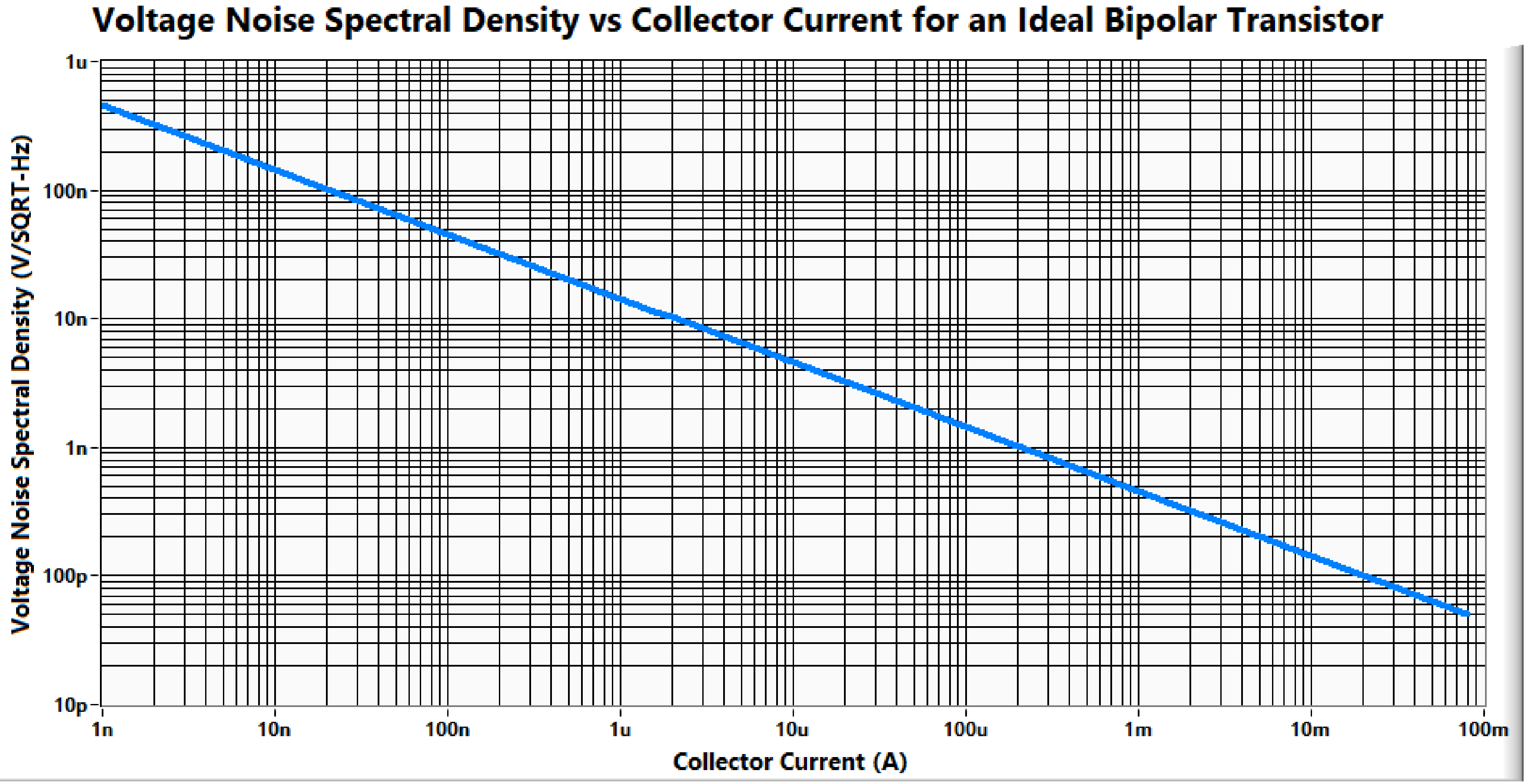
Opamp Noise Model

- The opamp is modelled with an equivalent noise voltage source connected in series with the non-inverting input and two equivalent current sources, one at each input



Noise Reduces with Increased Power Consumption

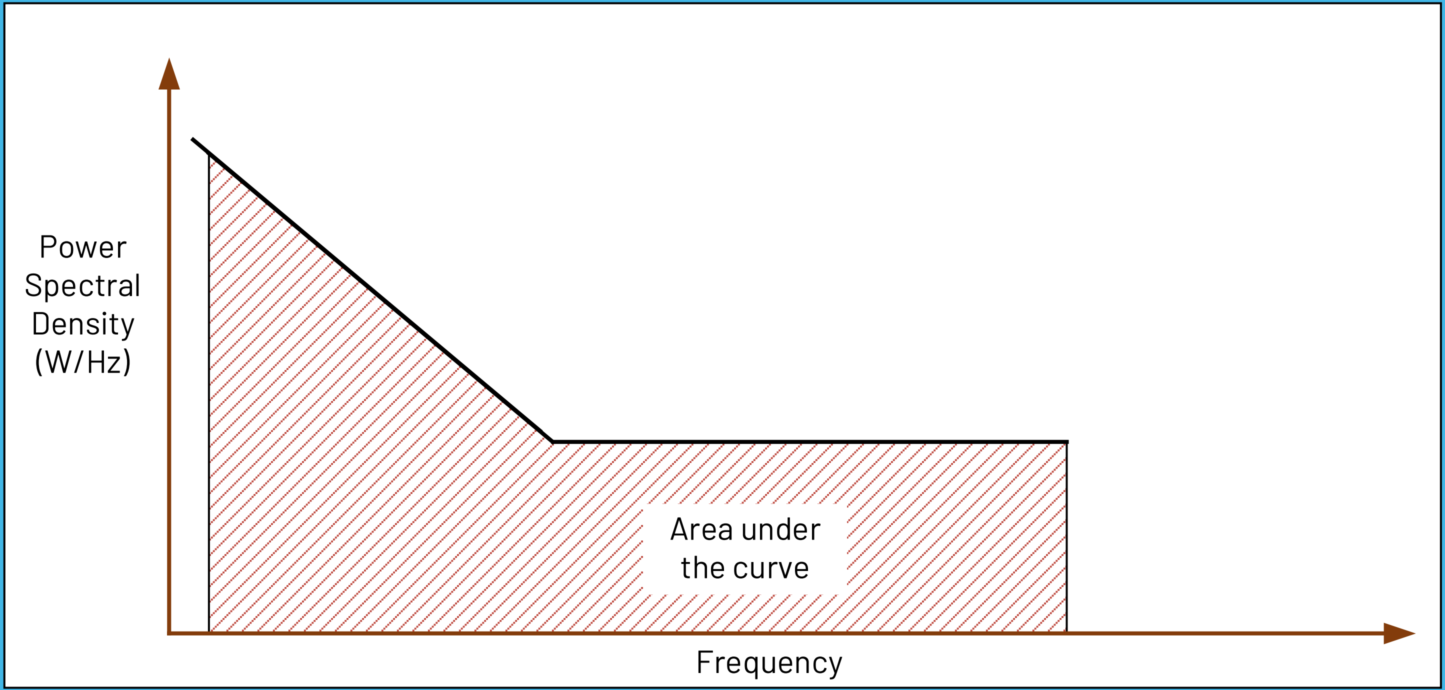




Integrated Noise

Integrated Noise

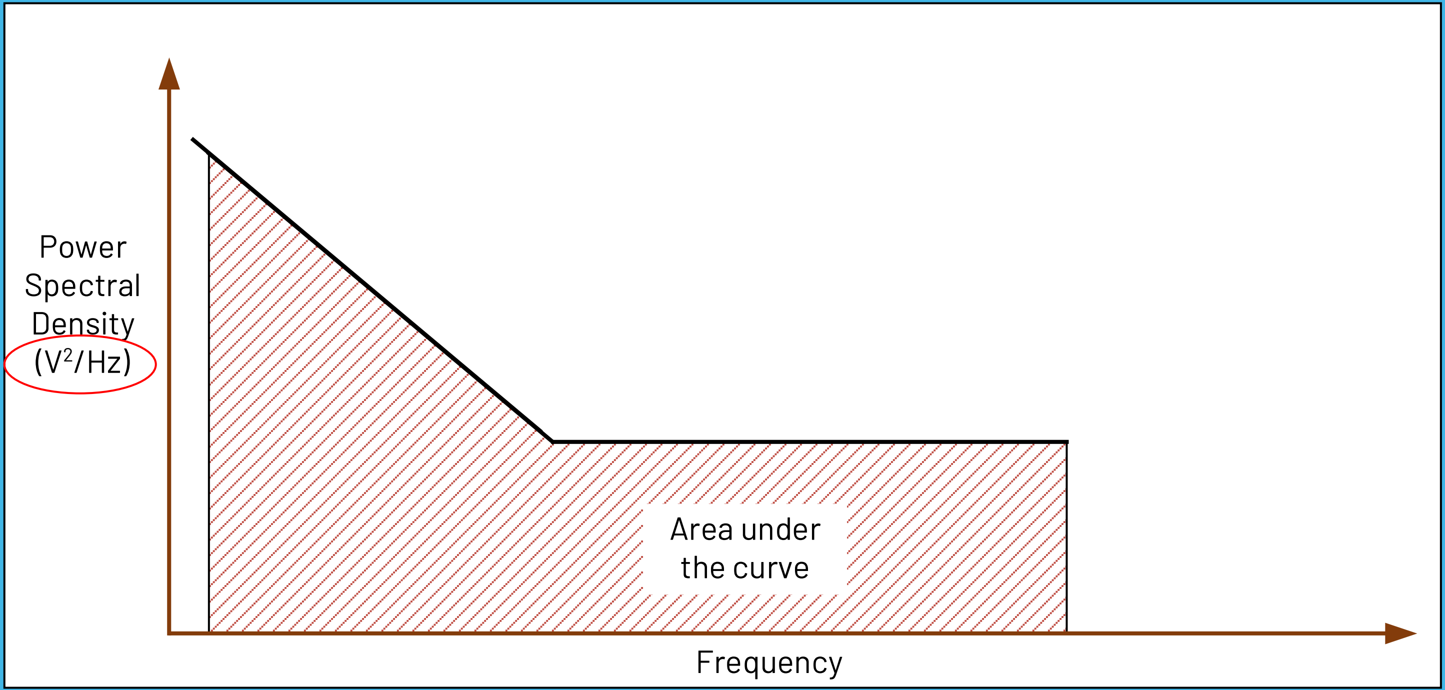
- Integrating the Noise Power Spectral Density curve over frequency will result in the total RMS noise power of a signal
- This is equivalent to the *area under the noise power spectral density* curve over the frequency range of interest…wider bandwidth results in more area under the curve which in turn results in more noise



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Integrated Noise

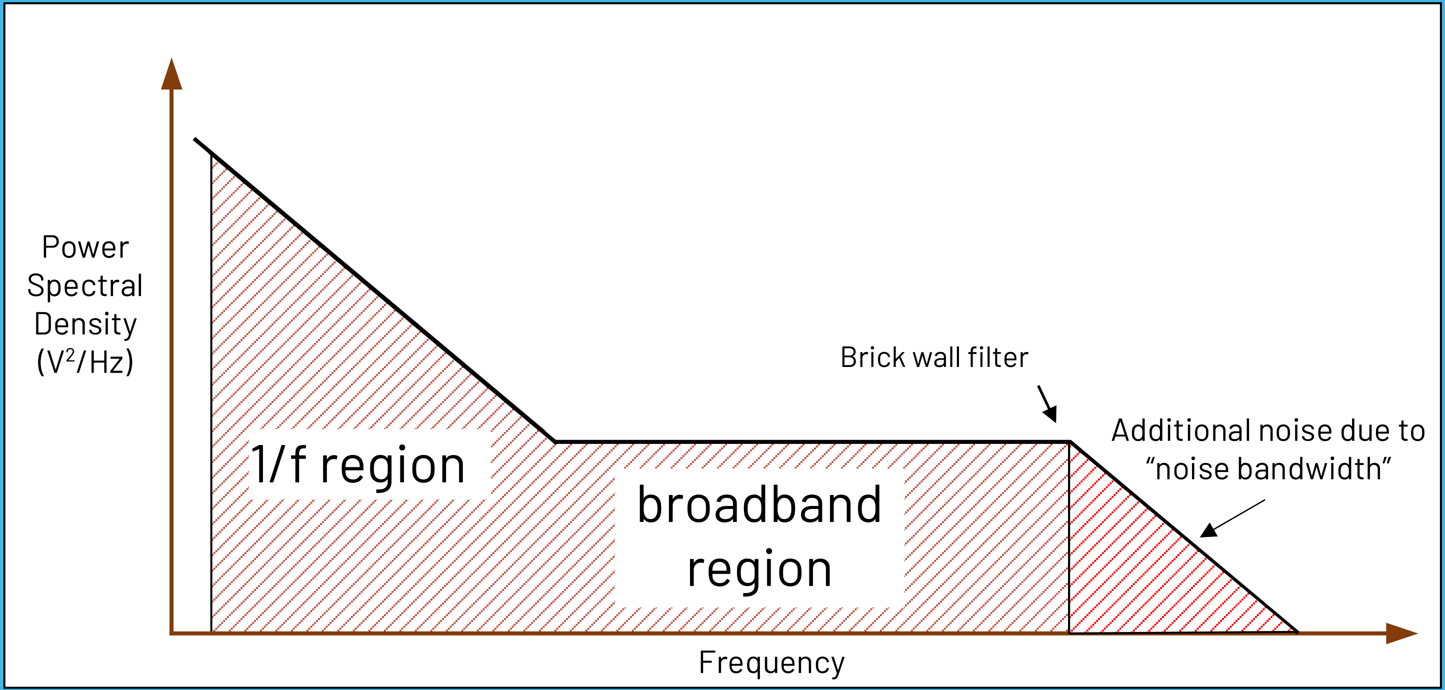
- Opamp manufacturers do not provide Noise Power Spectral Density curves, they provide Voltage Noise and Current Noise Spectral Density Curves…so now what?
- The correct way is to convert from voltage or current to power (V^2 or I^2) and perform the integration



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

All Systems Have Finite Bandwidth

- Circuit bandwidths in practice do not extend to infinity and we do not have “brick wall filters”
- Consider the most common band limiting filter, a first-order low-pass filter



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Noise Bandwidth

- The concept of "noise bandwidth" accounts for the additional area under the noise power spectral density curve
- The steeper the filter, the closer to an ideal "brick wall filter" a system will behave
- Conveniently if the order of the LPF is known, a scaling factor can be used to relate the small-signal bandwidth and noise bandwidth of the system

$$\text{noise bandwidth} = \text{small signal bandwidth} \times \text{noise bandwidth ratio}$$

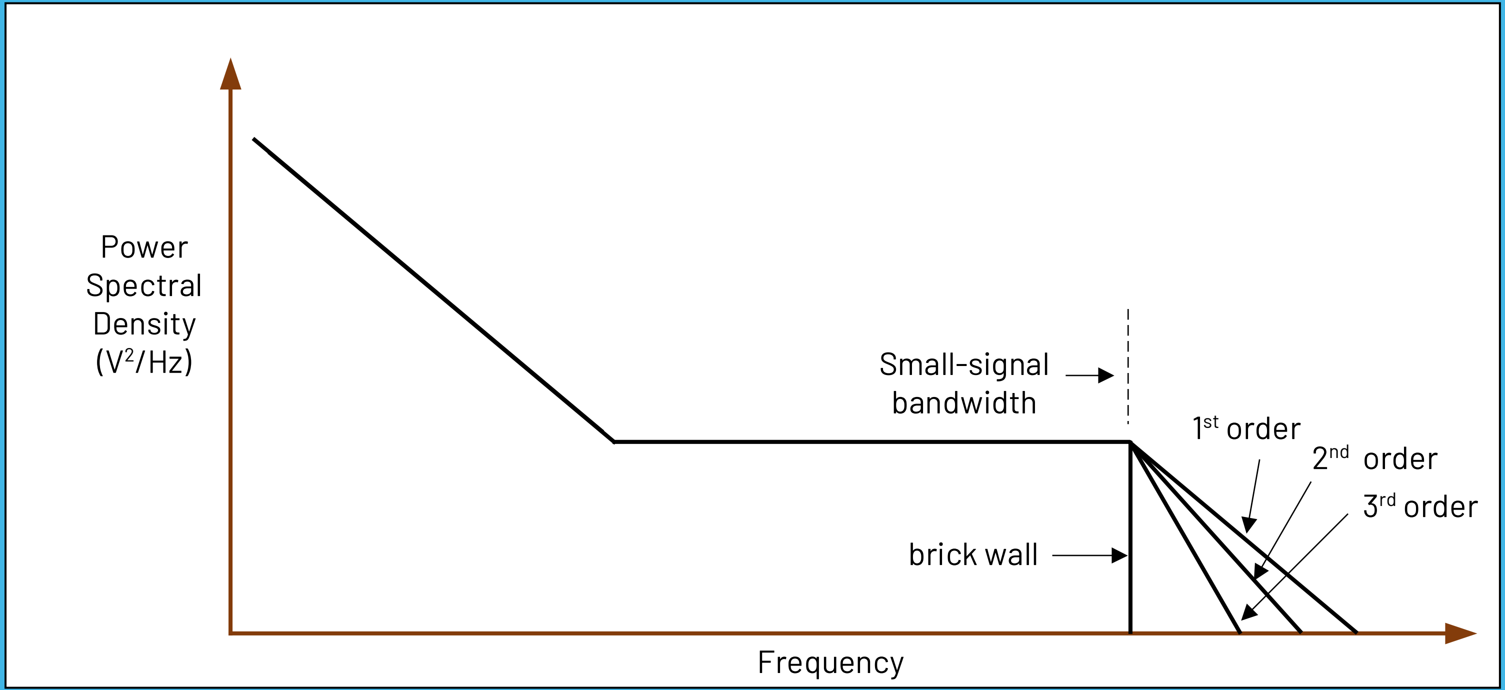
Number of Poles in Filter	Noise Bandwidth Ratio
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

Table 1

Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Noise Bandwidth and Filter Order

- The steeper the filter (higher filter order) the less area under the curve resulting in lower total noise



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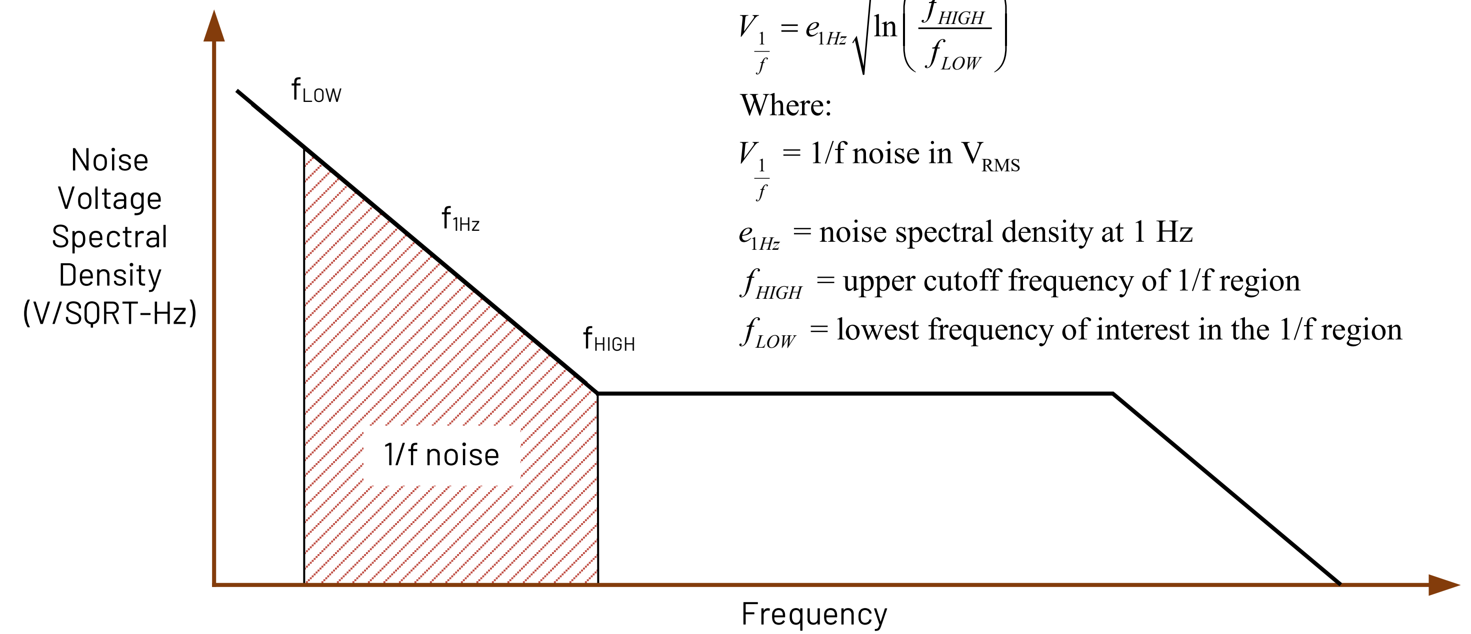
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Calculate the 1/f Noise Voltage in V_{RMS}

- The Voltage Noise Spectral Density is given in the opamp data sheet
- Calculate the total RMS noise in the 1/f region as:



$$V_{\frac{1}{f}} = e_{1Hz}\sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)}$$

Where:

$V_{\frac{1}{f}}$ = 1/f noise in V_{RMS}

e_{1Hz} = noise spectral density at 1 Hz

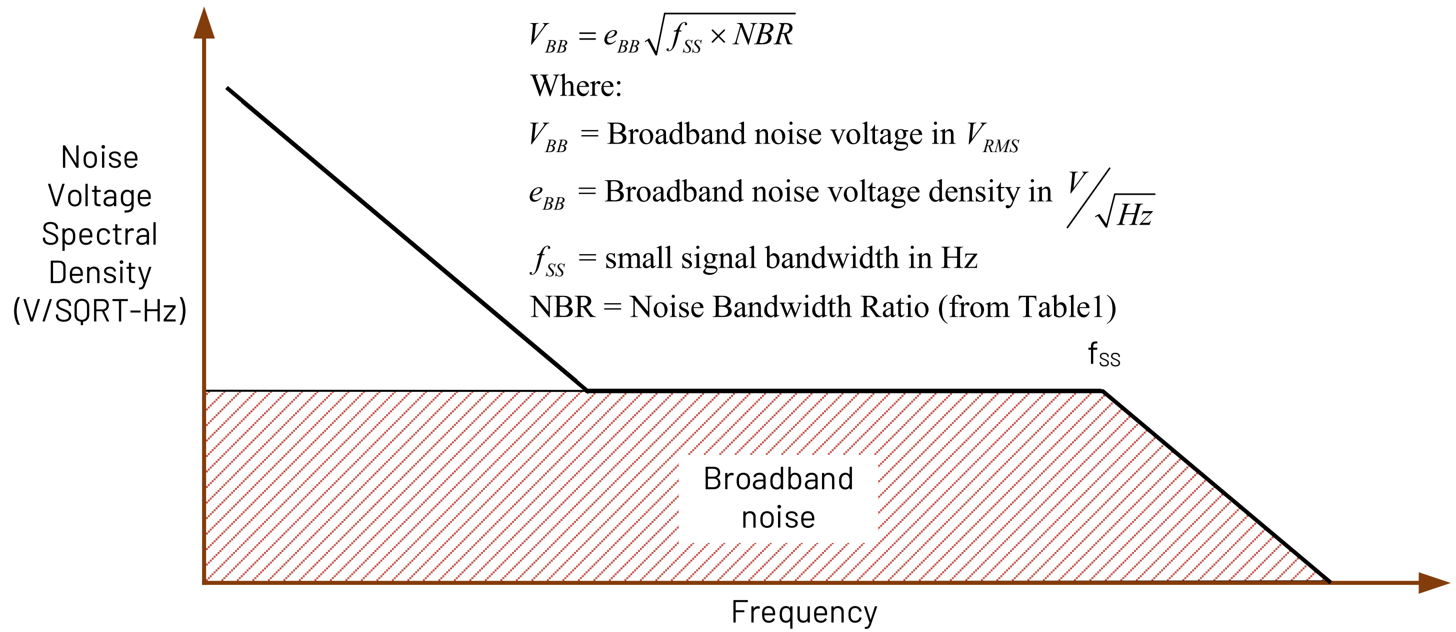
f_{HIGH} = upper cutoff frequency of 1/f region

f_{LOW} = lowest frequency of interest in the 1/f region

Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Calculate the Broadband Noise Voltage in V_{RMS}

- The Voltage Noise Spectral Density is given in the opamp data sheet
- Calculate the total RMS noise in the broadband region as:



$$V_{BB} = e_{BB}\sqrt{f_{SS} \times NBR}$$

Where:

V_{BB} = Broadband noise voltage in V_{RMS}

e_{BB} = Broadband noise voltage density in $V/\sqrt{Hz}$

f_{SS} = small signal bandwidth in Hz

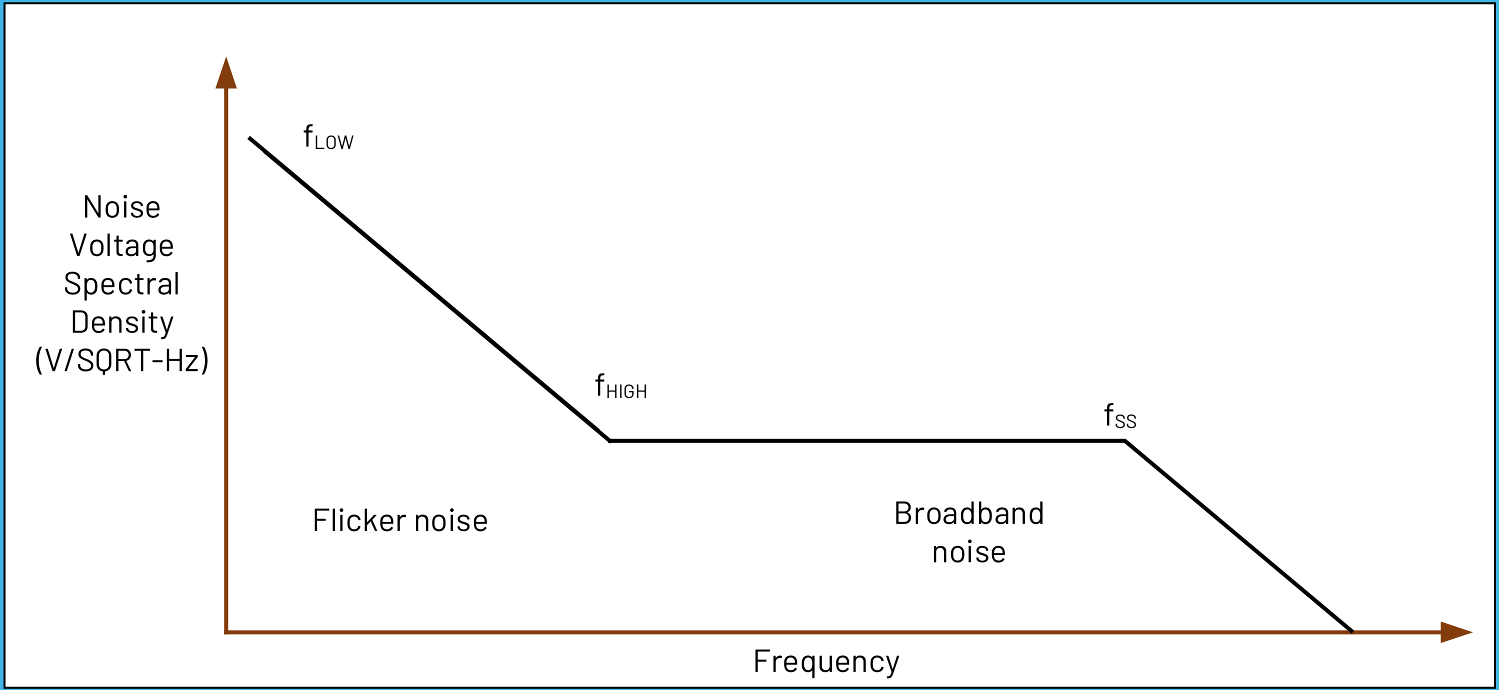
NBR = Noise Bandwidth Ratio (from Table1)

Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Computing the Total Noise

- To compute the total RMS noise in a system, add the 1/f noise to the broadband noise:

$$V_{n_{total}} = \sqrt{\left(V_{1/f}\right)^2 + \left(V_{BB}\right)^2}$$



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Summary (so far)

- Amplifiers are made from transistors, resistors and capacitors
- Amplifiers have their internal noise sources represented by equivalent voltage noise and current noise generators placed at their inputs to aid in noise analysis
- Amplifiers commonly have
  - 0.1 Hz to 10 Hz noise voltage expressed in $\mu V_{PP,}$
  - Voltage NSD specified in nV/SQRT-Hz at 1kHz (or sometimes 10kHz)
  - Current NSD specified in fA/SQRT-Hz (JFET/CMOS, bipolar opamps may have units of pA/SQRT-Hz)
- Total noise in a circuit is determined by integrating the noise power over the frequency range determined by the noise bandwidth.
- Methods to estimate noise use simplified algebraic terms to estimate total noise without having to perform actual integration of complex noise spectral density plots over frequency
- 1/f noise and broadband noise can be estimated separately and combined as the square root of the sum of the squares to estimate total noise

Estimating Noise in Amplifier Circuits

Estimating Noise in Amplifier Circuits

- Estimating noise in an amplifier circuit can be a daunting task…there is no doubt attention to detail is warranted…but breaking the process down into a several simple steps will ease the process

  1) Determine all the sources of noise in the circuit

  2) Refer each noise source to the output (RTO)

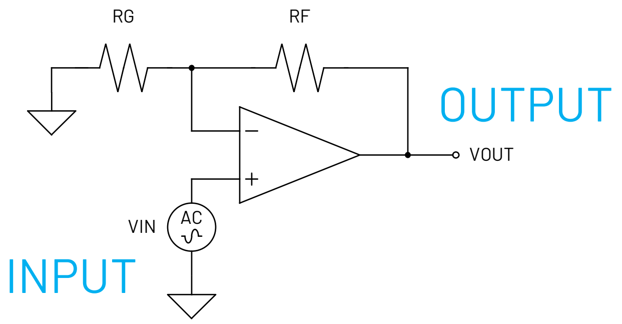
  3) Combine all output referred noise sources into a single noise value RTO (because noise sources are random and uncorrelated their noise terms add as square root of the sum of the squares)

$$V_{n_{total}} = \sqrt{\left(V_{n_1}\right)^2 + \left(V_{n_2}\right)^2 \ldots + \left(V_{n_n}\right)^2}$$

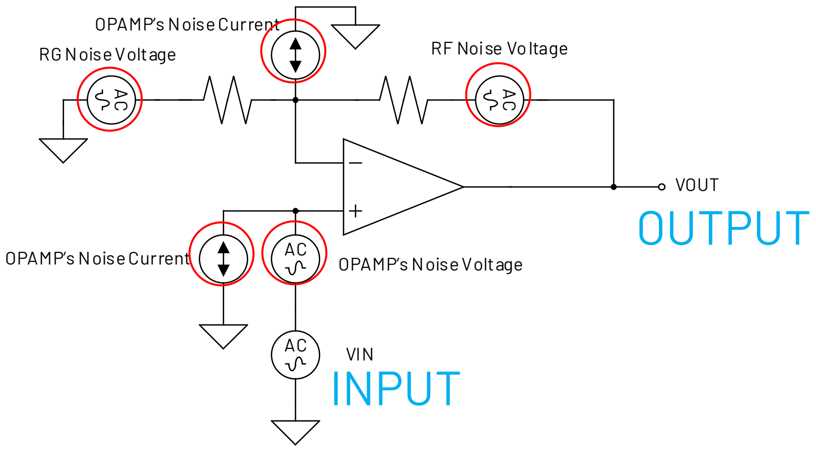
  4) Convert from units of V/SQRT-Hz to Vrms or Vpp by integrating over the noise bandwidth

  5) Refer the combined RTO noise value back to the input if interested to know RTI noise based upon the noise gain o the amplifier

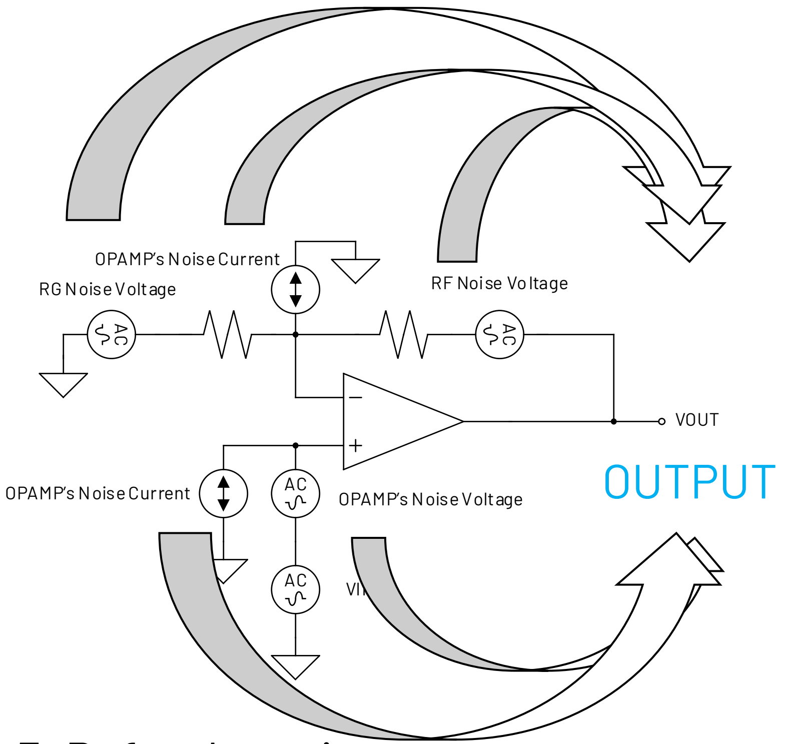
Example for a Simple Non-Inverting Amplifier



1. Start with your circuit



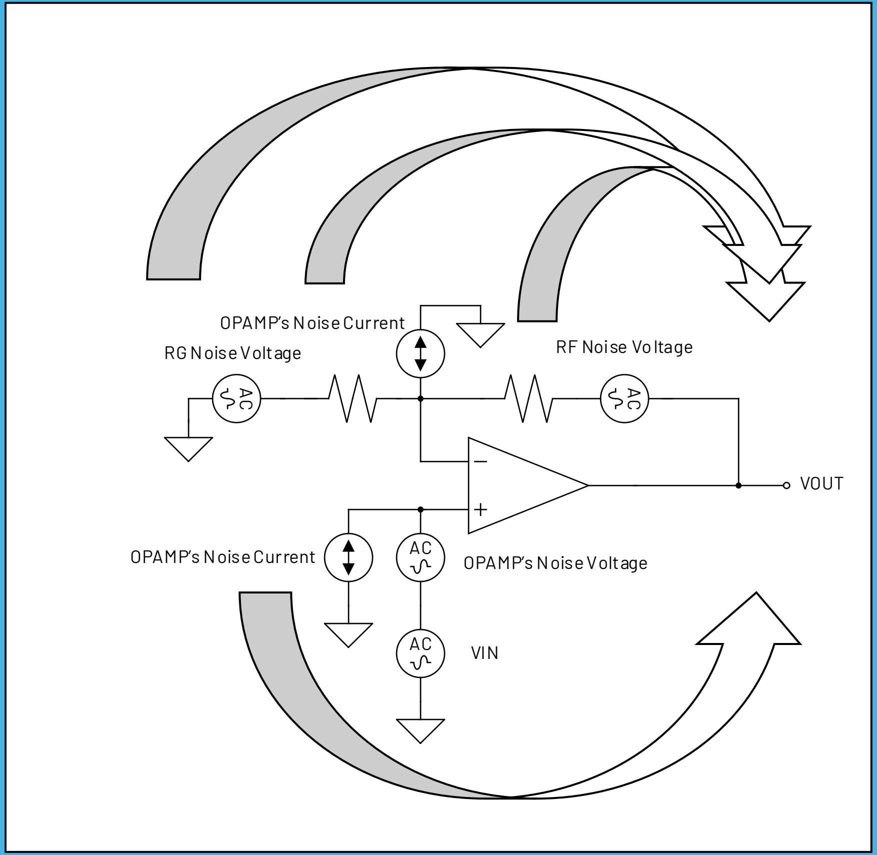
2. Add the noise sources



3. Refer the noise sources to the output

Referring Noise Sources to the Output

- To refer a noise source to the output, the gain from each noise to the output must be computed
- It may be different for each noise source



By inspection:

The gain from RG to the output is –RF/RG. (Since noise is random, uncorrelated and has no phase we can ignore the sign) ➔ RF/RG

The gain from RF to the output is 1

The gain from the opamps voltage noise source is 1+RF/RG

The gain from the opamp current noise source at the –IN pin is RF

Since in this analysis we will assume the source impedance of voltage source VIN is zero the current noise source at the +IN pin sees zero impedance and does not contribute noise in this circuit

Referring Noise Sources to the Output

The RTO noise from R_G is given by:

$$V_{n\ RG} \times gain = V_{n\ RG} \times \frac{R_F}{R_G}$$

The RTO noise from R_F is given by:

$$V_{n\ RF} \times gain = V_{n\ RF} \times 1$$

The RTO noise from the opamp voltage noise is given by:

$$V_{n\ OPAMP\_VOLTAGE} \times gain = V_{n\ OPAMP\_VOLTAGE} \times \left(1 + \frac{R_F}{R_G}\right)$$

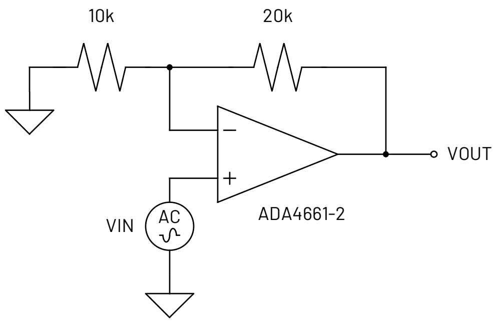
The RTO noise from the opamp current noise is given by:

$$I_{n\ OPAMP\_CURRENT} \times gain = I_{n\ OPAMP\_CURRENT} \times R_F$$

Summing all the individual RTO noise sources:

$$V_{n_{RTO}} = \sqrt{\left(V_{n\ RG} \times \frac{R_F}{R_G}\right)^2 + \left(V_{n\ RF}\right)^2 + \left(V_{n\ OPAMP\_VOLTAGE} \times \left(1 + \frac{R_F}{R_G}\right)\right)^2 + \left(V_{n\ OPAMP\_CURRENT} \times R_F\right)^2}$$

Let's Add Some Actual Values to Our Circuit



Let's determine the noise voltage from each resistor using a simple rule of thumb where:

$$1k = 4nV/\sqrt{Hz} \rightarrow \begin{array}{l} 10k = 4\times\sqrt{\frac{10k}{1k}} = 4\times\sqrt{10} = 12.65\,nV/\sqrt{Hz} \\ 20k = 4x\sqrt{\frac{20k}{1k}} = 4\times\sqrt{20} = 17.89\,nV/\sqrt{Hz} \end{array}$$

From the ADA4661-2 data sheet the noise is given as:

NOISE PERFORMANCE				
Total Harmonic Distortion Plus Noise	THD + N	$A_V = 1$, $V_{IN} = 0.44$ V rms at 1 kHz		
Bandwidth = 80 kHz			0.002	%
Bandwidth = 500 kHz			0.003	%
Peak-to-Peak Noise	e_n p-p	f = 0.1 Hz to 10 Hz	3	µV p-p
Voltage Noise Density	e_n	f = 1 kHz	18	nV/√Hz
		f = 10 kHz	14	nV/√Hz
Current Noise Density	i_n	f = 1 kHz	360	fA/√Hz

$\rightarrow$ ADA4661-2 Voltage Noise $= 14\,nV/\sqrt{Hz}$

ADA4661-2 Current Noise $= 360\,fA/\sqrt{Hz}$

Summing all the individual RTO noise sources:

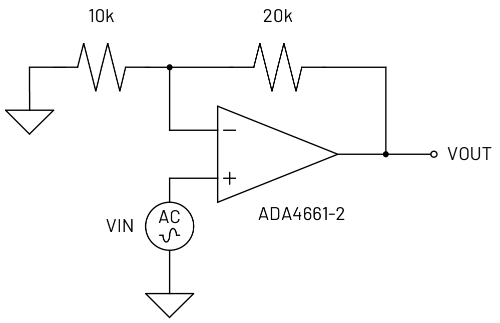
$$V_{n_{RTO}} = \sqrt{\left(12.65e^{-9}\times\frac{20k}{10k}\right)^2 + \left(17.89e^{-9}\right)^2 + \left(14e^{-9}\times\left(1+\frac{20k}{10k}\right)\right)^2 + \left(360e^{-15}\times 20k\right)^2}$$

$$V_{n_{RTO}} = \sqrt{\left(25.3e^{-9}\right)^2 + \left(17.89e^{-9}\right)^2 + \left(42e^{-9}\right)^2 + \left(7.2e^{-9}\right)^2} = 52.68\,nV/\sqrt{Hz}$$

To compute the RTI noise voltage divide by the signal gain:

$$V_{n_{RTI}} = \frac{52.68e^{-9}}{3} = 17.56\,nV/\sqrt{Hz}$$

Let's Estimate the Total Broadband Noise in the Circuit



The unity gain frequency of the ADA4661 is 4MHz

In the gain of 3 shown the small signal bandwidth is 1.33MHz (this is that "brick wall" filter value)

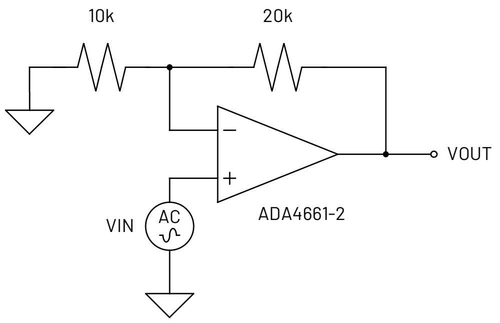
Since there are no additional filters in the circuit the roll off is only from the opamp and is first order

Compute the noise bandwidth as 1.33MHz*1.57 = 2.1MHz

Using the estimated RTI noise voltage of 17.56nV/SQRT-Hz, a noise gain = 3V/V and 2.1MHz noise bandwidth we estimate the broadband RMS noise to be: $V_{NOISE\_TOTAL} = e_{BB} \times noisegain \times \sqrt{noisebandwidth}$

$$V_{NOISE\_TOTAL} = 17.56e^{-9} \times 3 \times \sqrt{2.1e^{6}} = 76\mu V_{RMS}$$

Let's Estimate the Total 1/f Noise in the Circuit



From the data sheet curve we can estimate the 1Hz 1/f noise at 300nV/SQRT-Hz

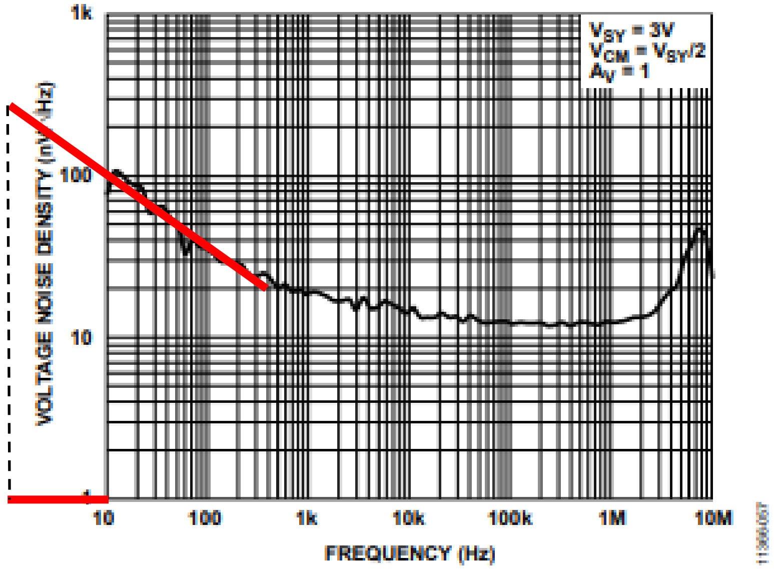


Figure 56. Voltage Noise Density vs. Frequency

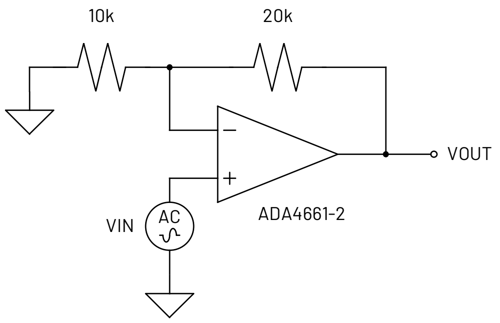
We can also estimate the 1/f corner frequency of 10kHz

Using:

$$V_{\frac{1}{f}} = e_{1Hz}\sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)} \times noisegain$$

We can estimate the 1/f noise as 300e-9*SQRT(LN(10e3/1))*3 = 2.7μV_{RMS}

Let's Estimate the Total Noise in the Circuit



Combining the 1/f noise and the broadband noise we estimate the total noise as:

$$V_{n_{total}} = \sqrt{\left(76e^{-6}\right)^2 + \left(2.7^{e-6}\right)^2} = 76\mu V_{RMS}$$

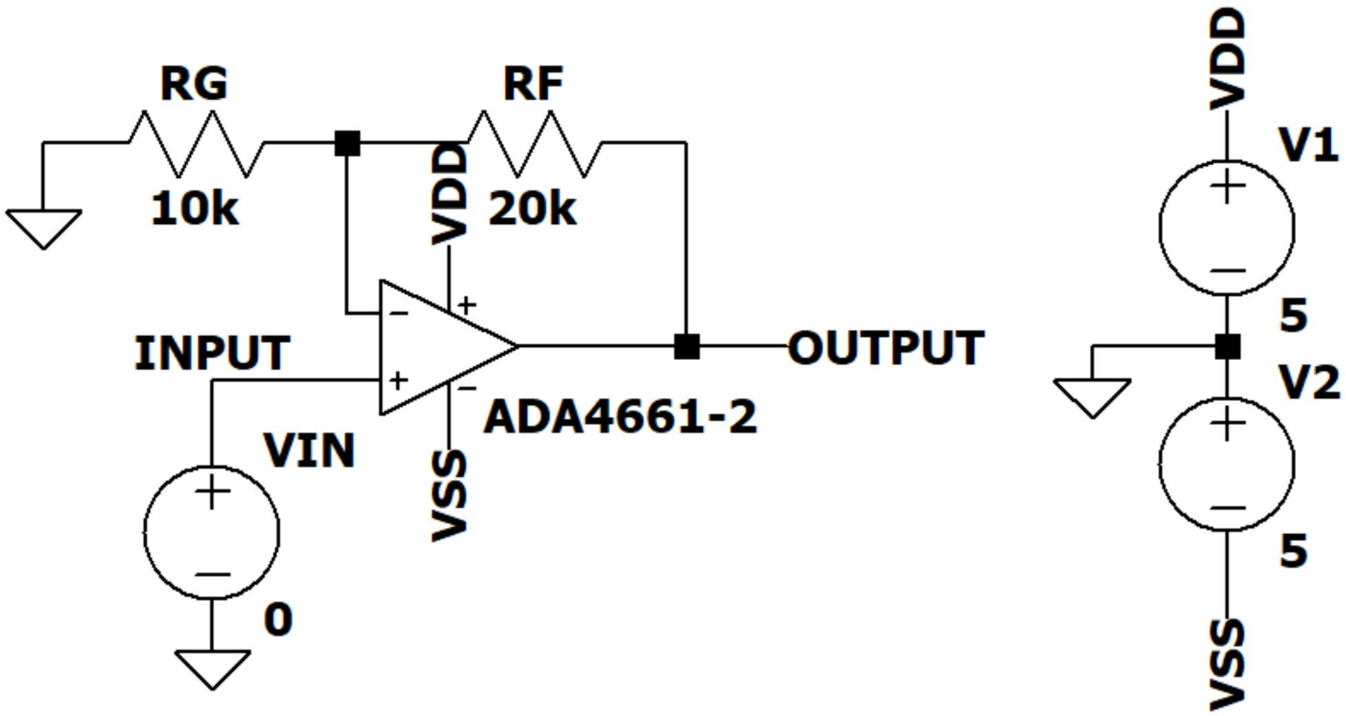
And converting to peak-to-peak we estimate $456\mu V_{PP}$

Summary (so far)

- To analyze noise, identify all the sources of noise, refer them to the output and combine them appropriately to estimate the RTO NSD
- Determine the RTI NSD by referring the RTO noise to the circuit input. This requires determination of the noise gain.
- The noise gain is generally indicating the gain from the non-inverting terminal of an amplifier to the output but could be whatever you determine you want to use as your input. You simply must be consistent within your analysis
- Determine the noise bandwidth of your circuit
- Multiply RTI NSD by Noise gain by the square root of the noise bandwidth to estimate rms noise at the output
- Multiply by 6 or 6.6 to estimate the peak-to-peak noise voltage
- Understanding the dominate noise sources and the nature of the noise gain and the nature of the noise bandwidth can help understand how to optimize the circuits noise performance

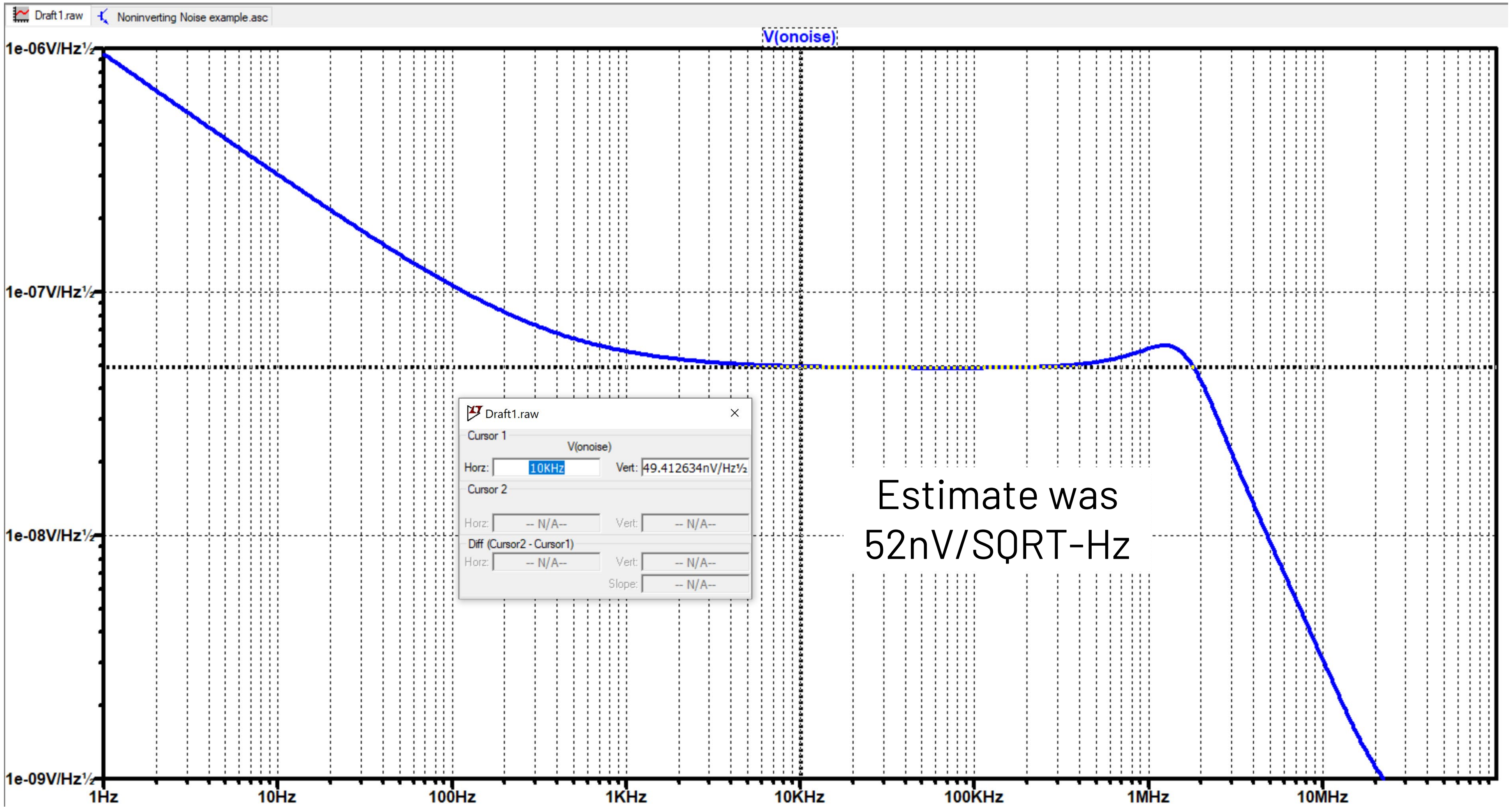
Simulating Noise in Amplifier Circuits

Simulation Circuit in LTSpice

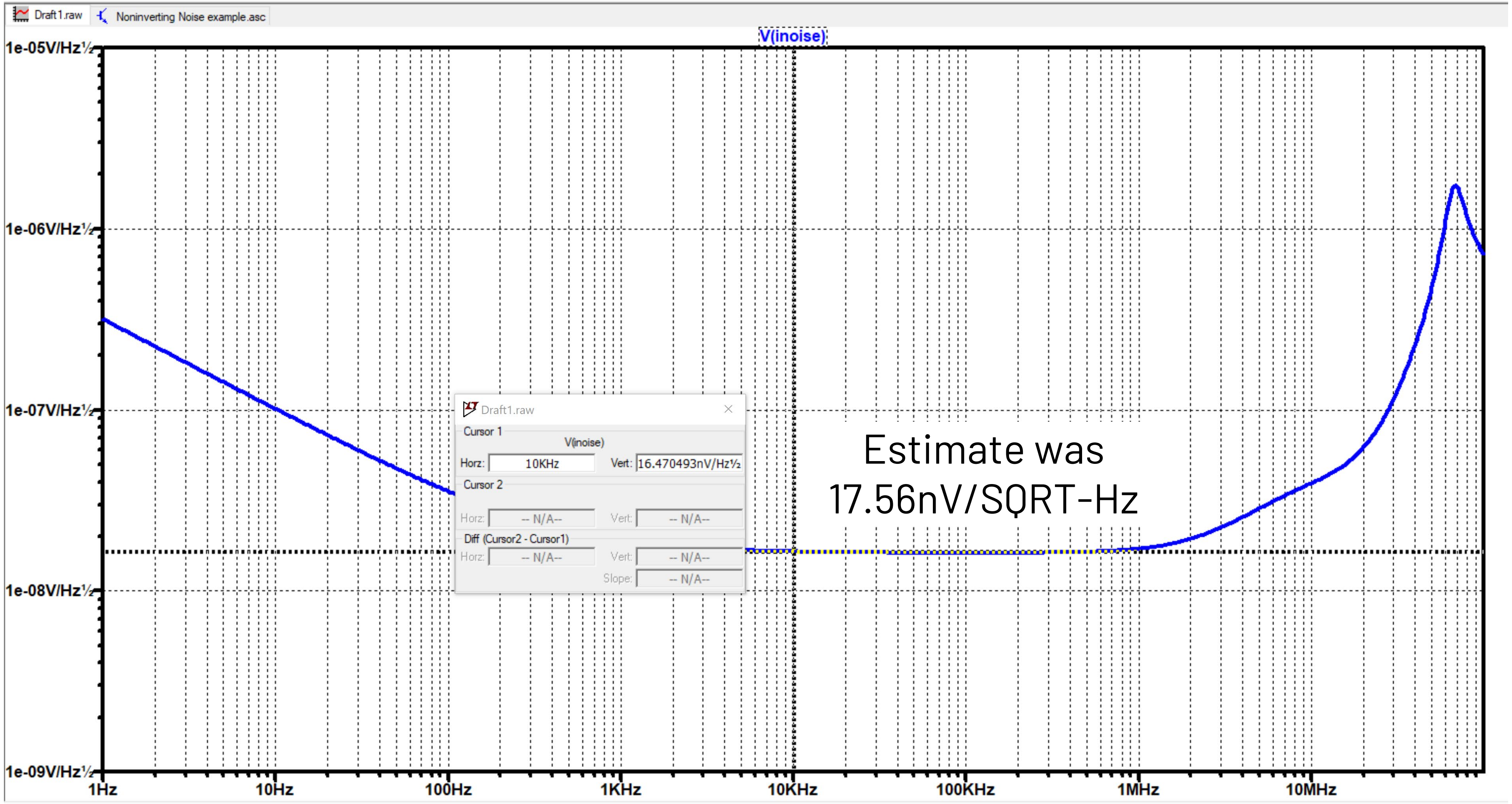


.noise V(OUTPUT) VIN dec 100 1 100e6

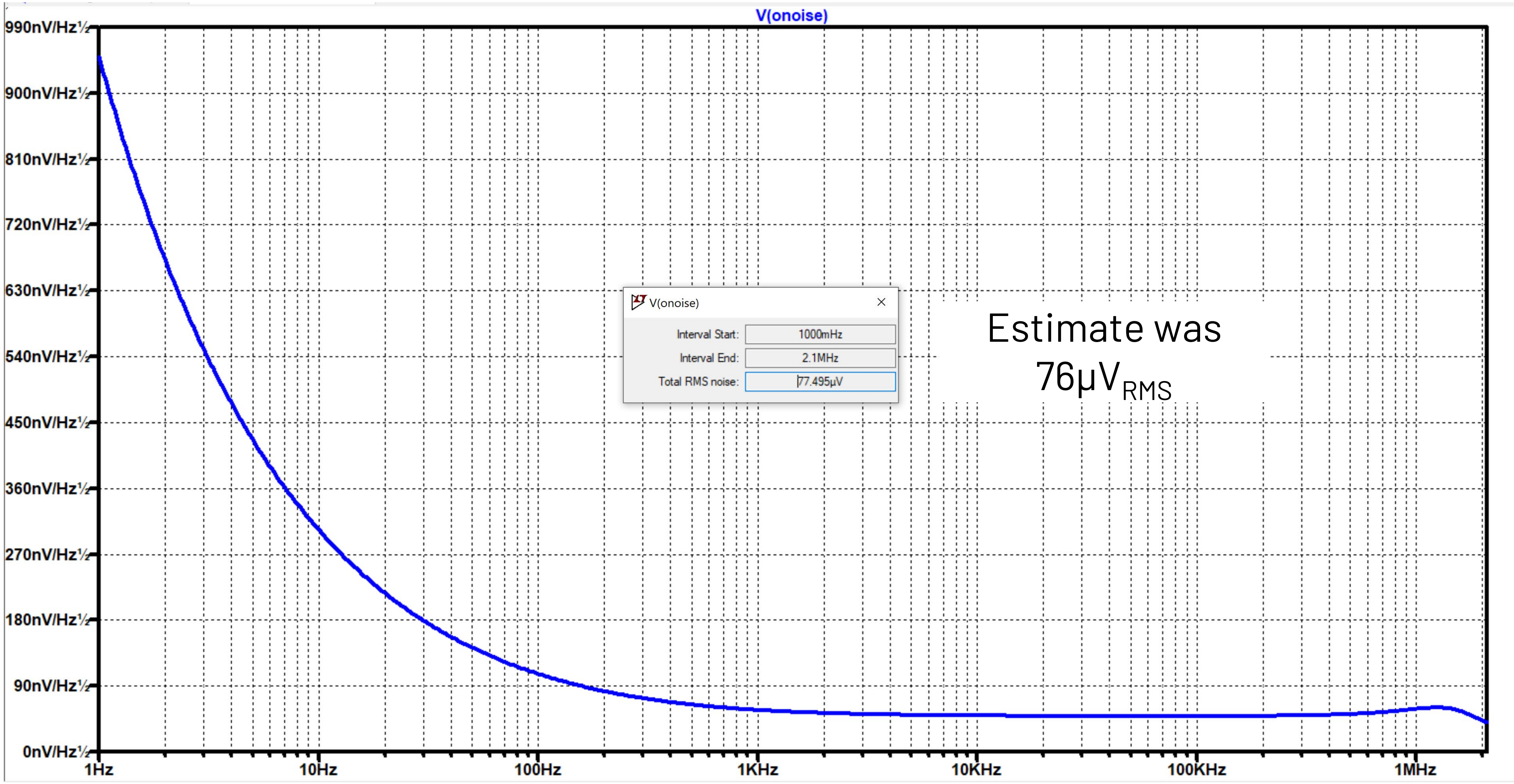
Simulation Results - RTO



Simulation Results - RTI



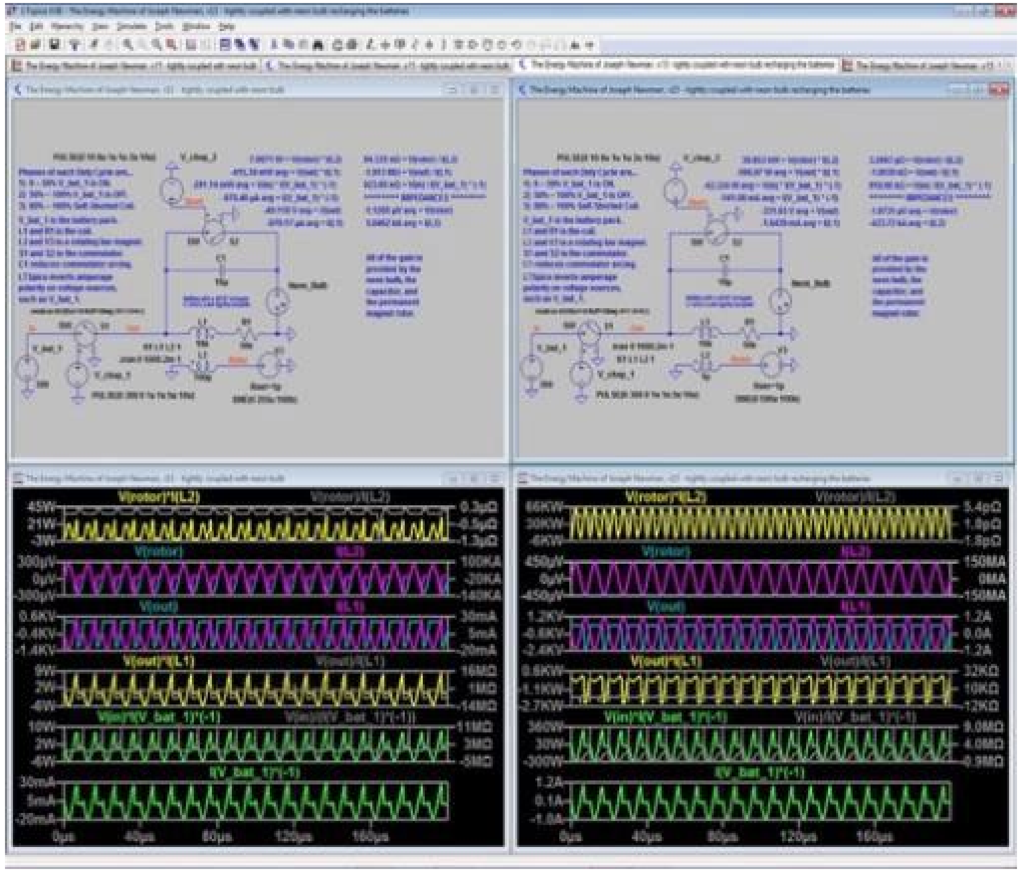
Simulation Results – Integrated Noise



Estimate was $76\mu V_{RMS}$

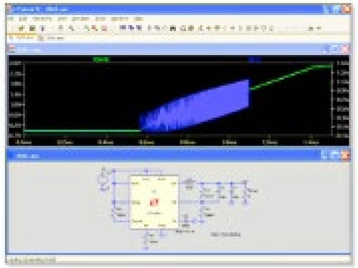
LTSpice Simulation Software

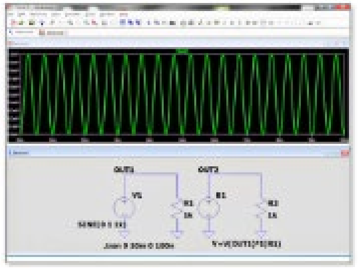
- LTSpice Simulation Software is a powerful, fast and free SPICE simulator software, schematic capture and waveform viewer with enhancements and models for improving the simulation of analog circuits.
- It contains hundreds of ADI models that are being tested and updated regularly

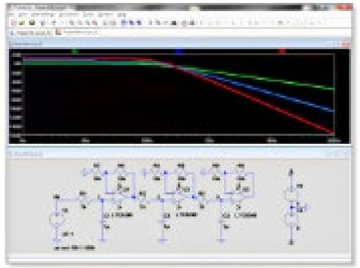


Learn How to Use LTspice

Instructional Videos







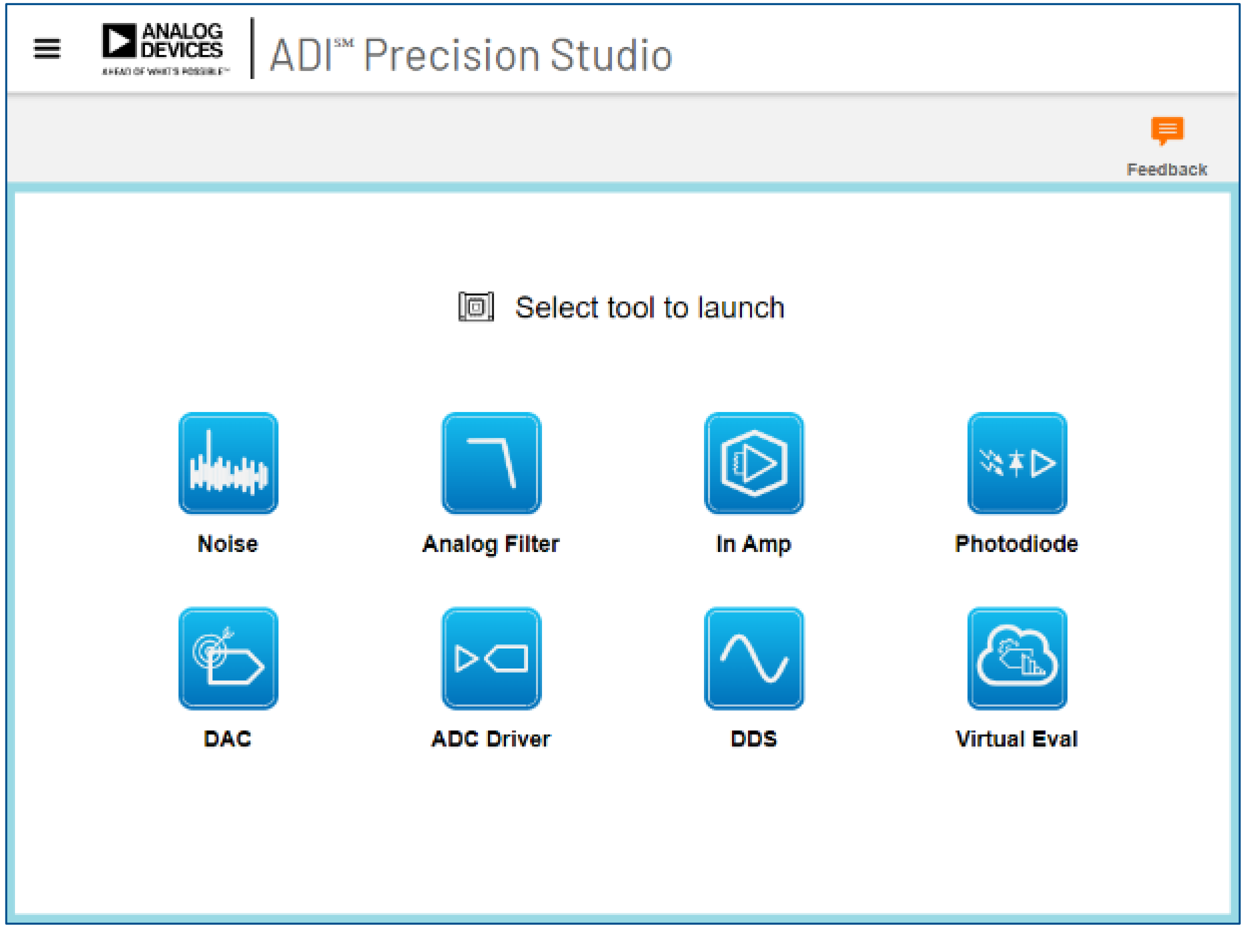
Download here!

LTspice Information Center | Analog Devices

ADI℠ Precision Studio

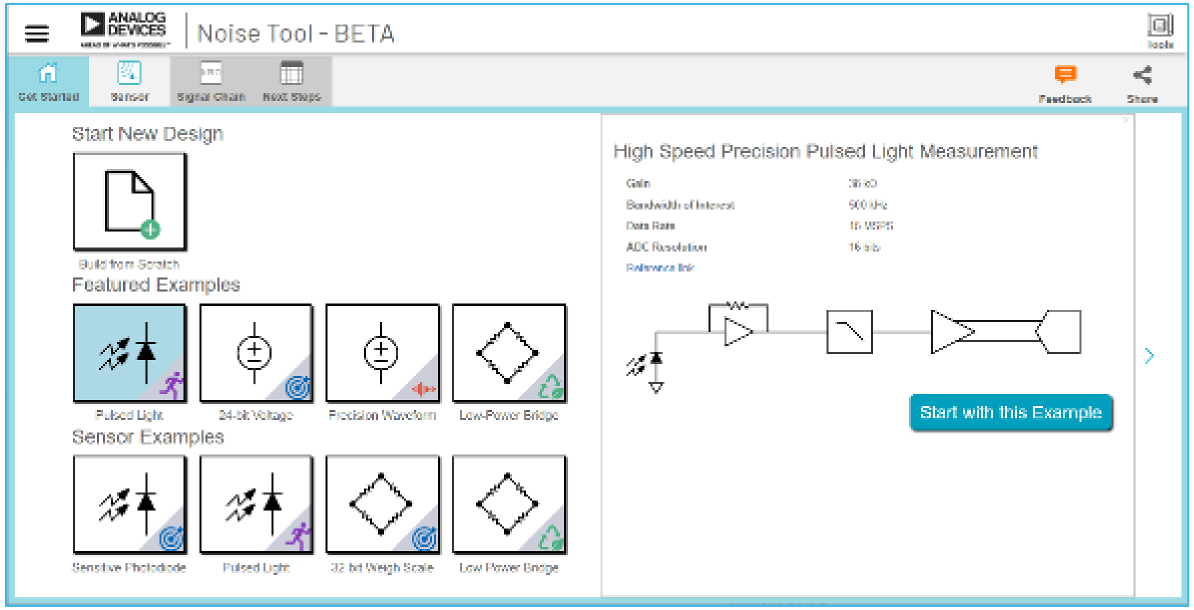
- ADI℠ Precision Studio is a collection of tools to help design signal conditioning circuits

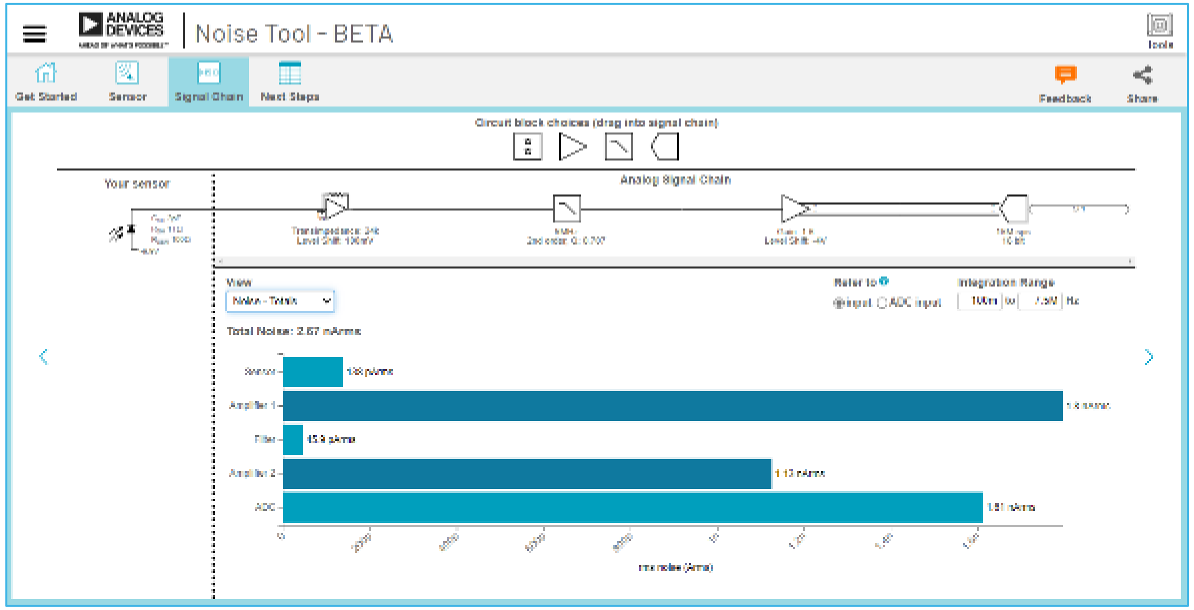
Access it here!
[ADI℠ Precision Studio | Analog Devices]



- **Noise Tool**
- **Analog Filter Wizard**
- **In-Amp Diamond Plot Tool**
- **Photodiode Circuit Design Wizard**
- **Precision DAC Error Budget Calculator**
- **Precision ADC Driver Tool**
- **Direct Digital Synthesis Simulator**
- **Virtual Evaluation Tool**

ADI℠ Precision Studio: Noise Tool



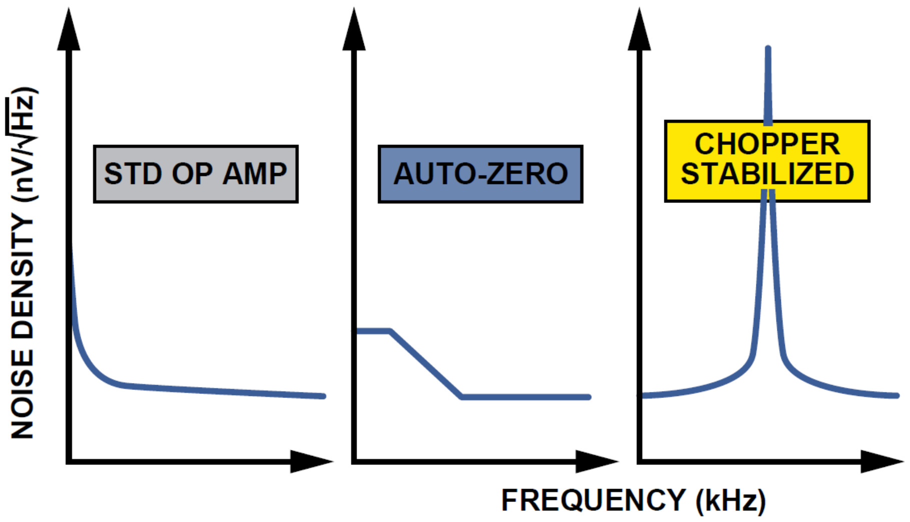


- ▸ Design sensor signal conditioning
- ▸ Generate schematic blocks
  - Example: 10kHz, Q=1.5 filter
- ▸ Simulate AC and noise performance
  - Entire signal chain
- ▸ Export to LTspice

Additional Reading and Resources

- 11 Myths About Analog Noise
- Noise Analysis of Precision Data Acquisition Signal Chain
- LTSpice Tutorial for AC & Noise Analysis (Video) | Analog Devices
- LTSpice: Noise Simulations
- LTSpice: Integrating Noise Over a Bandwidth | Analog Devices
- Step-by-Step Noise Analysis Guide for Your Signal Chain
- Low Frequency Noise Analysis for Sensor Signal Chains
- Noise Analysis in Precision Analog Designs
- Analysis of Input Current Noise with Even Harmonics Folding Effect in a Chopper Op Amp
- Practical Input-Referred Calculations in Precision Systems | Analog Devices
- Signal Chain Noise Calculator | Precision Studio | Analog Devices
- Low Noise Amplifier Selection Guide for Optimal Noise Performance | Analog Devices
- Understanding and Eliminating 1/f Noise | Analog Devices

Voltage Noise of Zero-drift amplifiers



Standard Amp

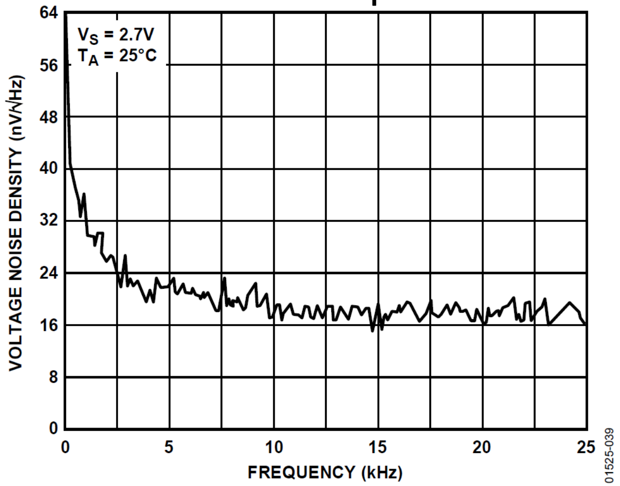


Figure 39. Voltage Noise Density vs. Frequency

Auto-zero

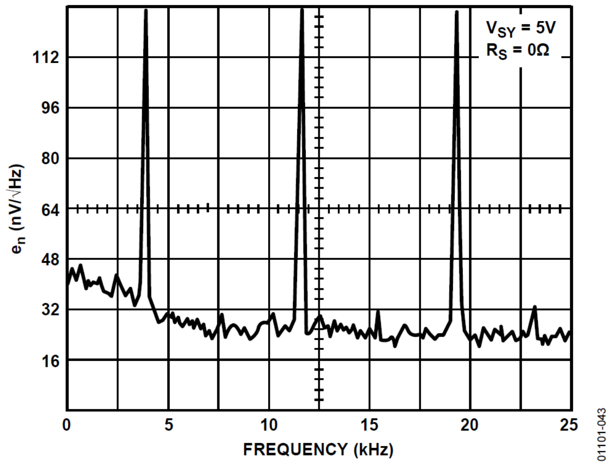


Figure 43. Voltage Noise Density at 5 V from 0 Hz to 25 kHz

Chopper

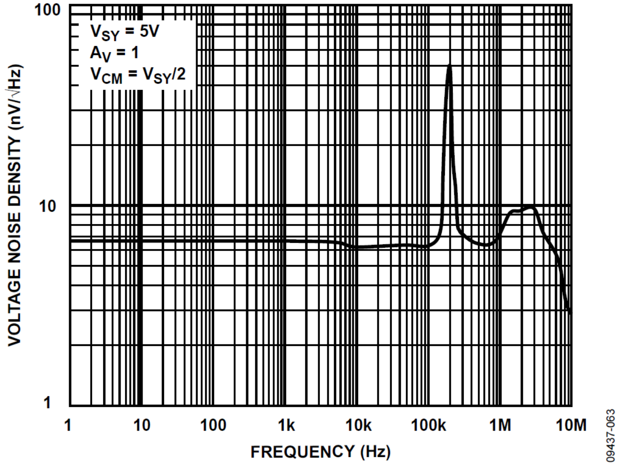


Figure 67. Voltage Noise Density vs. Frequency

Noise Comparison of Zero-Drift Amplifiers

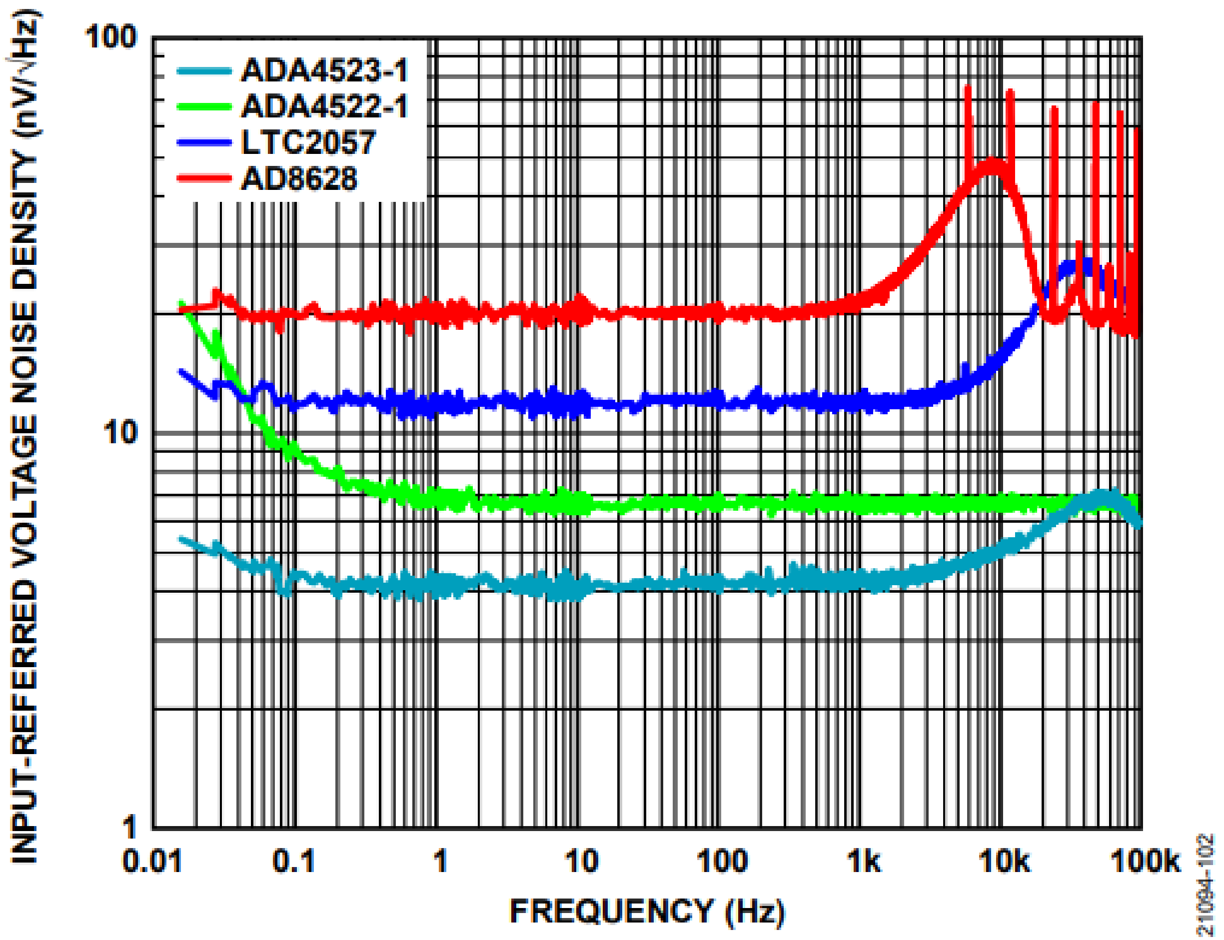


Figure 2. Input-Referred Voltage Noise Density vs. Frequency, Zero Drift Amplifier Family Comparison

Where Do I Find More Information About Zero-Drift Amplifiers?

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

- Zero-Drift Amp Landing Pages
  - http://www.analog.com/en/products/amplifiers/operational-amplifiers/zero-drift-amplifiers.html
  - http://www.linear.com/products/Zero-Drift_Amplifiers
- Zero-Drift Amplifiers: Now Easy to Use in High Precision Circuits
  - http://www.analog.com/library/analogdialogue/archives/49-07/Zero-Drift_Amplifiers.html
- AN-1114 Lowest Noise ZD Amplfiier Has 5.6 nV/√Hz Voltage Noise Density
  - http://www.analog.com/media/en/technical-documentation/application-notes/AN-1114.pdf
- MS-2062 To Chop or Auto-Zero: That Is the Question
  - http://www.analog.com/media/en/technical-documentation/technical-articles/MS-2062.pdf
- Ask the Apps Engineer 39—Zero-Drift Operational Amplifiers
  - http://www.analog.com/library/analogdialogue/archives/44-03/zero_drift.html
- Demystifying Auto-Zero Amplifiers—Part 1
  - http://www.analog.com/library/analogdialogue/archives/34-02/demystify/index.html
- Demystifying Auto-Zero Amplifiers—Part 2
  - http://www.analog.com/library/analogDialogue/archives/34-03/chopper/index.html
- MT-055 Chopper Stabilized (Auto-Zero) Precision Op Amps
  - http://www.analog.com/media/en/training-seminars/tutorials/MT-055.pdf

Low-Frequency Noise Demo

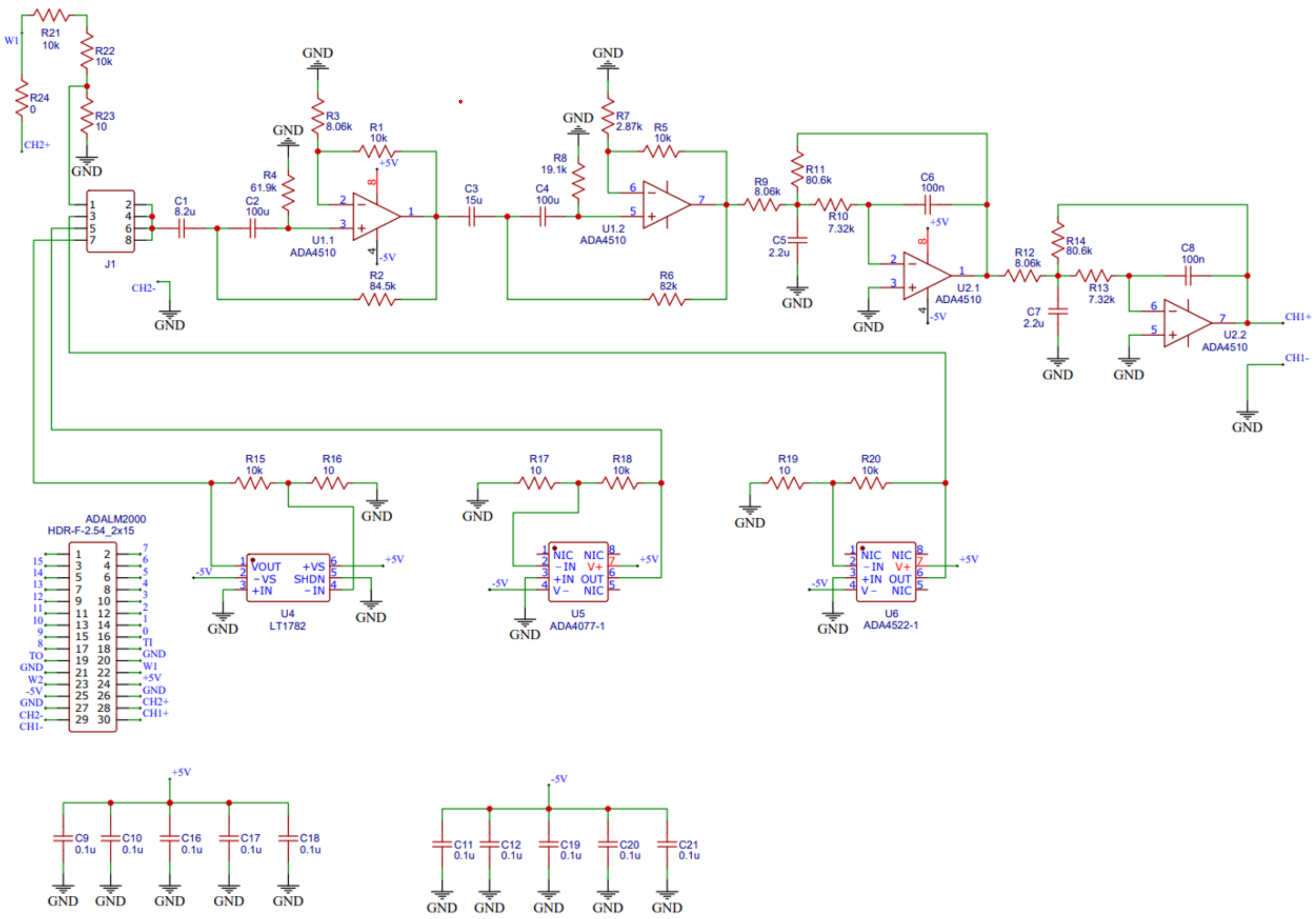
Needed for the Demo

- Laptop
- ADALM2000
- Noise Demo Board, one jumper
- USB cable that fits your laptop and the ADALM2000 (USBxxx to USB Micro B)
- Scopy software installed
- Scopy Configuration Files

The Setup


scopy
Print
Run
Single
Channel 1
OpenGl rendering
Instrument: 0.149394 fps / 6693.7 ms
ADALM2000
Active Learning Module
vPRO

0.1 Hz to 10 Hz Demo Board Schematic



ADA4510: Precision, 40 V, Low Input Bias, Low Noise, CMOS Op Amp

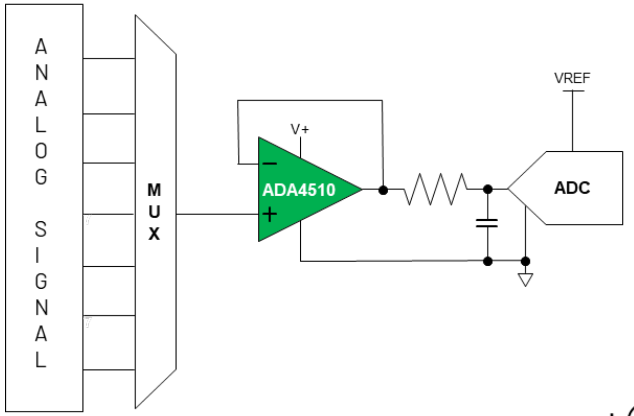
Key Features:

Sampling

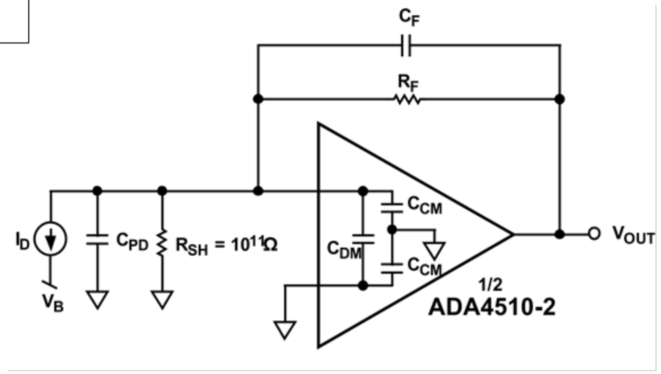
- Low Offset Voltage: **±5μV** typ., **±20μV** max
- Low Offset Voltage Drift: **0.5μV/°C** max
- Low Noise: **5nV/√Hz** @ 1kHz and **1.0μVp-p** typ. from 0.1 to 10Hz
- Wide GBW: **10.4MHz** typ.
- Fast Slew Rate: **19V/μs** typ.
- Low Input Bias Current: **10pA** max
- Heavy Capacitive Load Drive Capability: 1nF
- Integrated EMI Filter

Key Applications:

- Mux-Compatible
- Precision Instrumentation
- Data acquisition systems
- Multipole filters



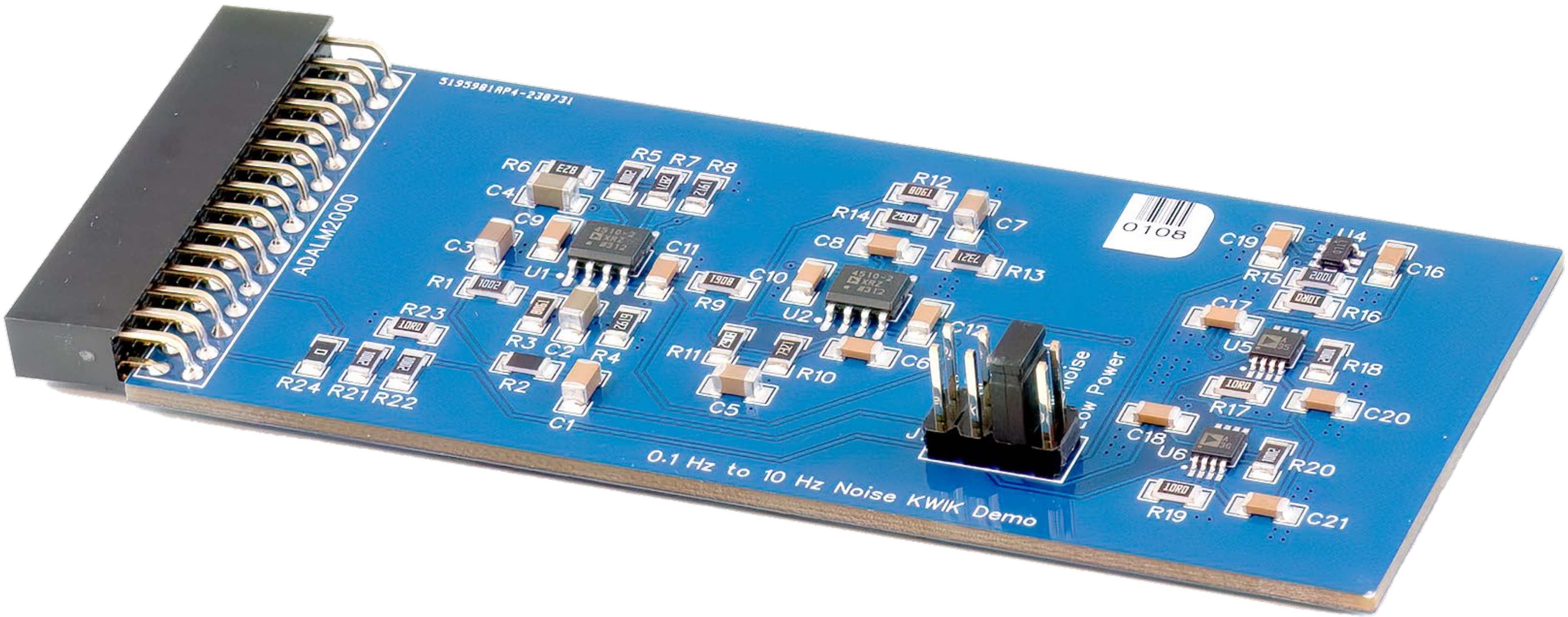
Multiplexed Data Acquisition System



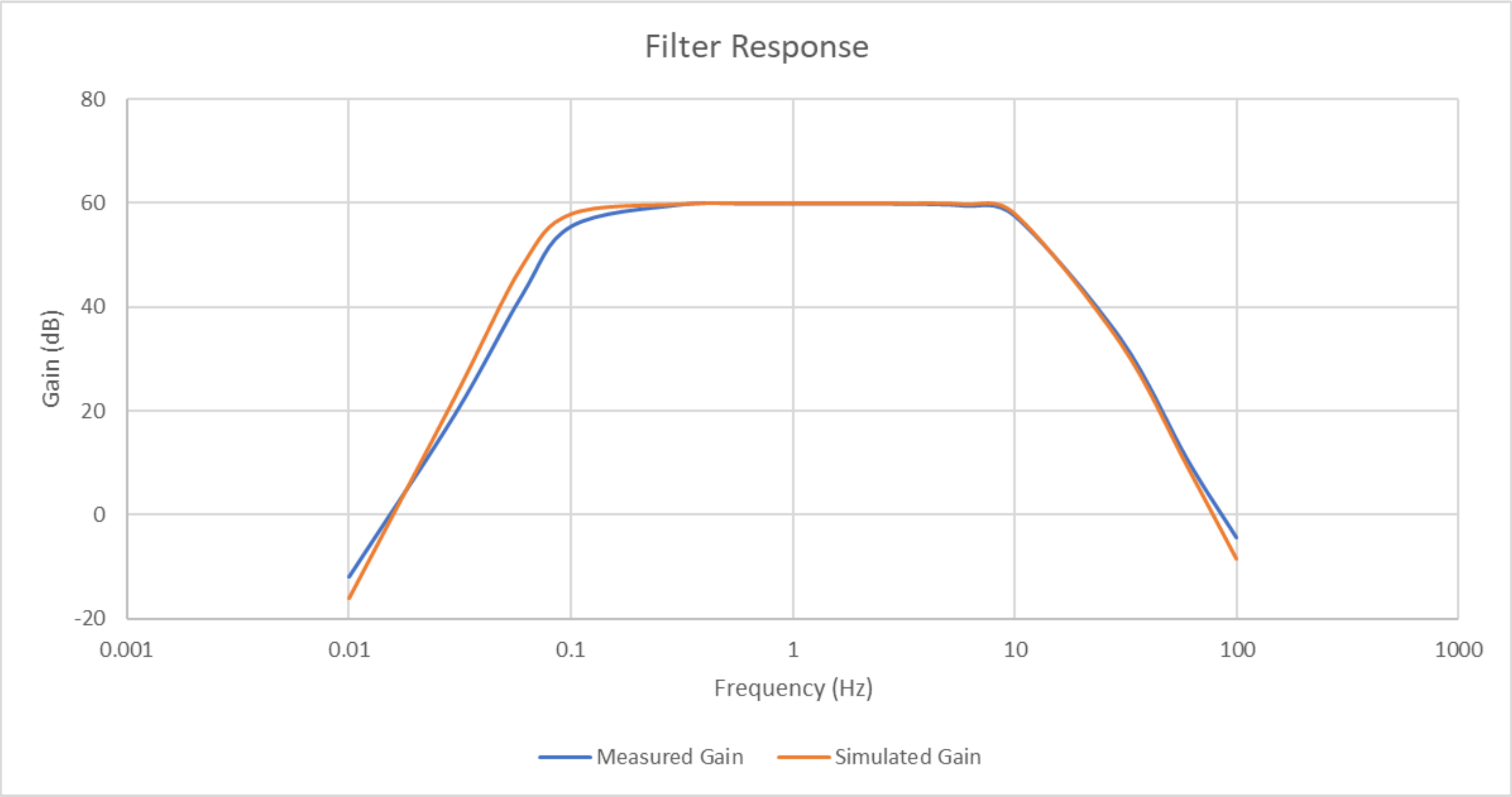
Photodiode TIA Circuit

	ADA4510	Competitor
Offset Voltage (Max)	**20 μV**	25 μV
1/f Noise	**1.0 μVp-p**	1.3 μVp-p
Voltage Noise Density	**5 nV/√Hz**	5.5 nV/√Hz

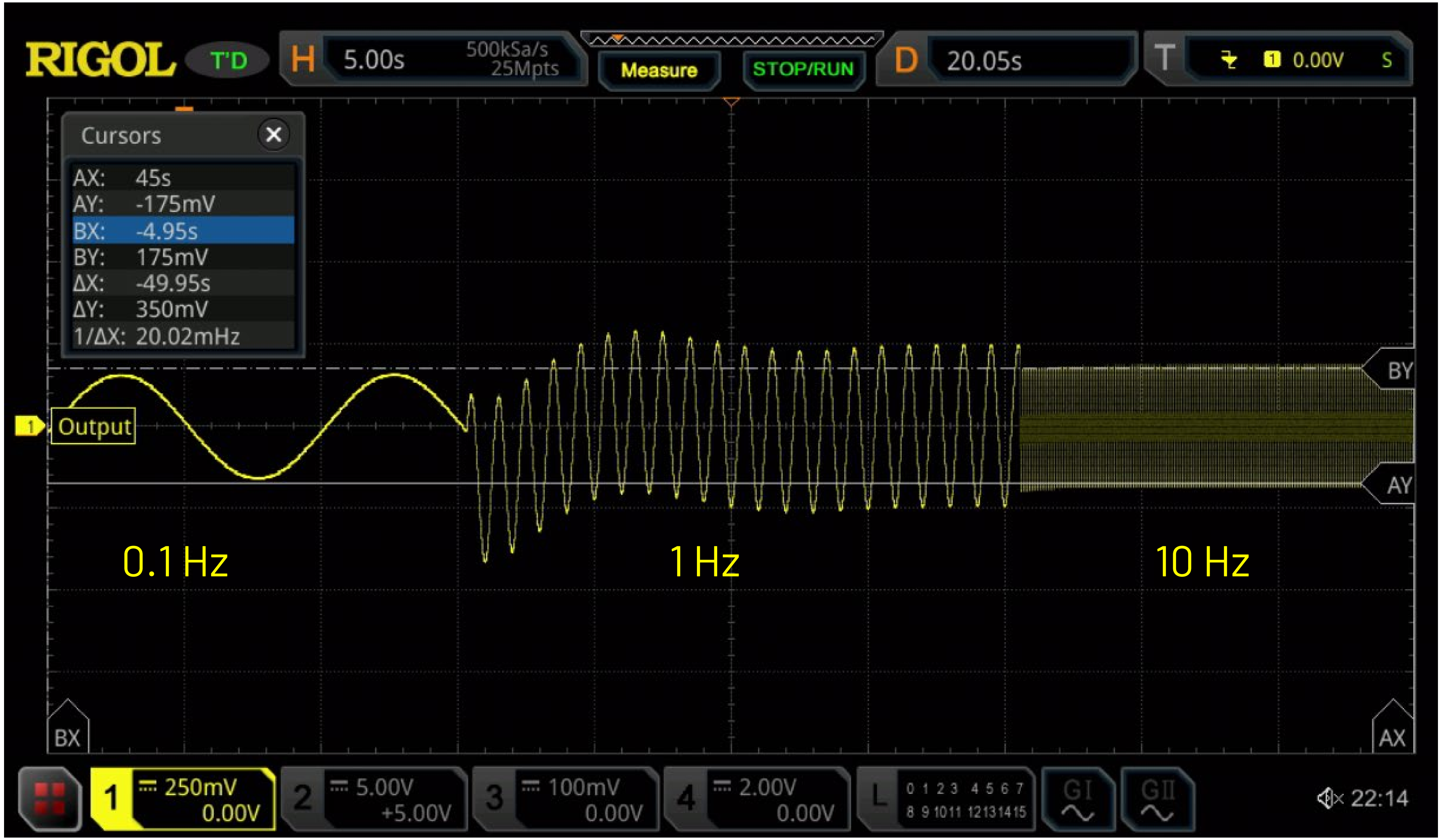
0.1 Hz to 10 Hz Demo Board



0.1 Hz to 10 Hz Demo Board Verification Results



0.1 Hz to 10 Hz Demo Board Verification Results



0.1 Hz to 10 Hz Demo

- In this demo we are going to estimate the 0.1 Hz to 10 Hz noise for three different amplifiers
  - LT1782 – a low power opamp
  - ADA4077 – a low noise, bipolar opamp
  - ADA4522 – a low noise, zero-drift opamp
- We will compare the estimate to the data sheet information
- We will use the ADALM2000 + demo board and measure the noise
- We will compare our measured results to our estimated results
- We will use the Network Analyzer feature of the ADALM2000 to measure the filter response from 1 Hz to 100 Hz

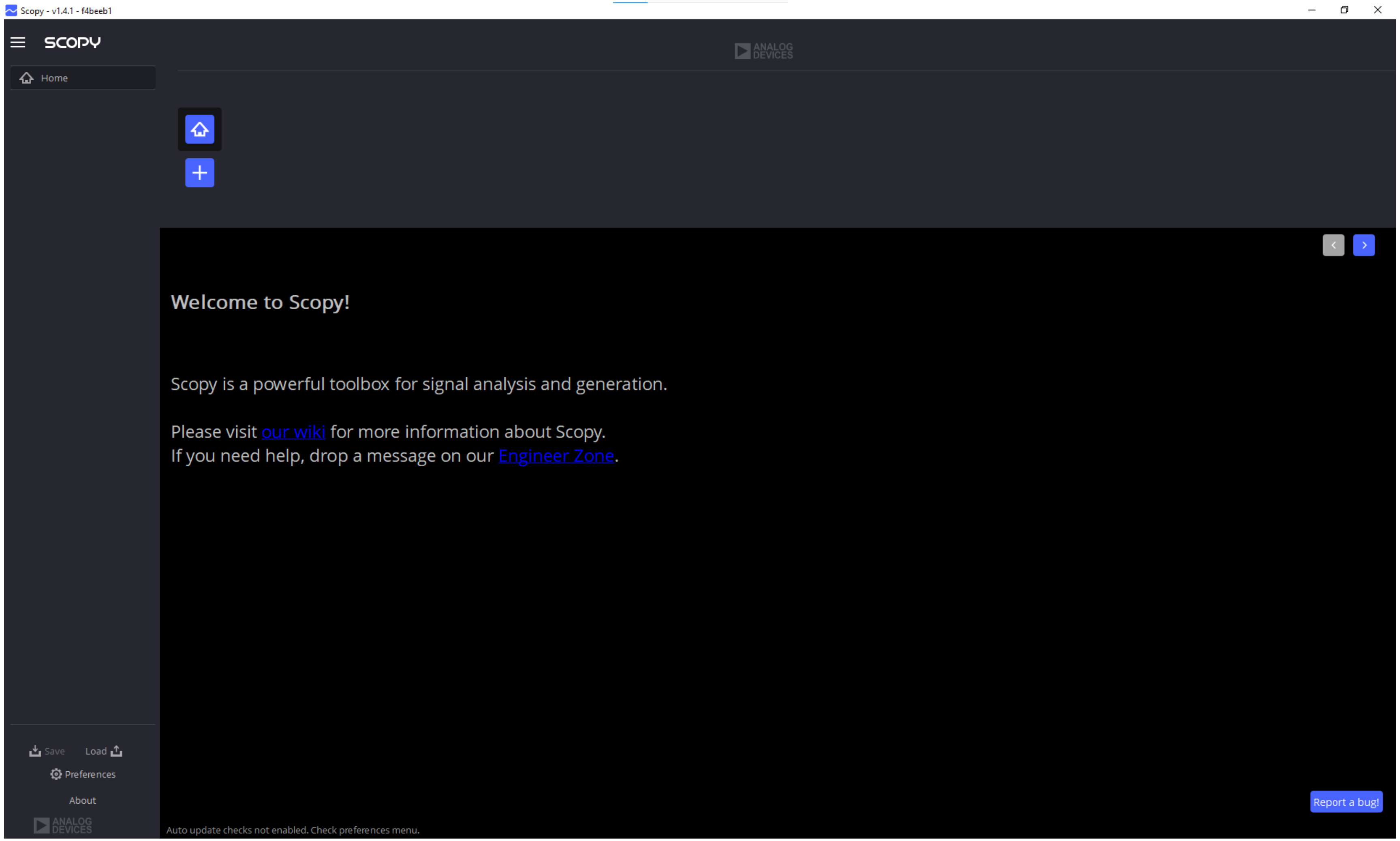
0.1 Hz to 10 Hz Noise Board Demo Step-by-Step Guide

Physically Connect PCB to ADALM2k

Carefully align pins and insert firmly

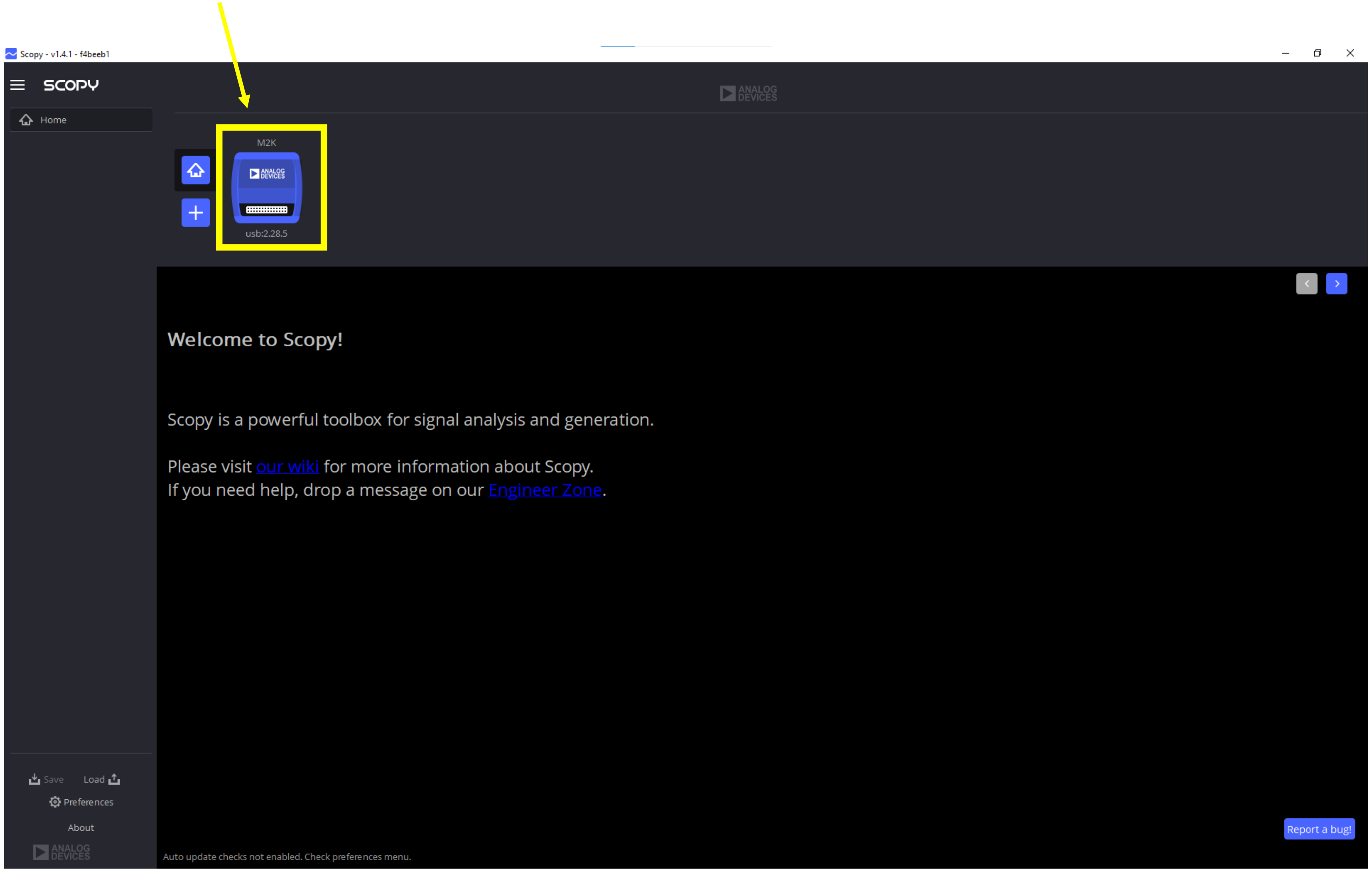
ADALM2000 should be powered off when connecting or disconnecting the PCB

Launch the Scopy Software

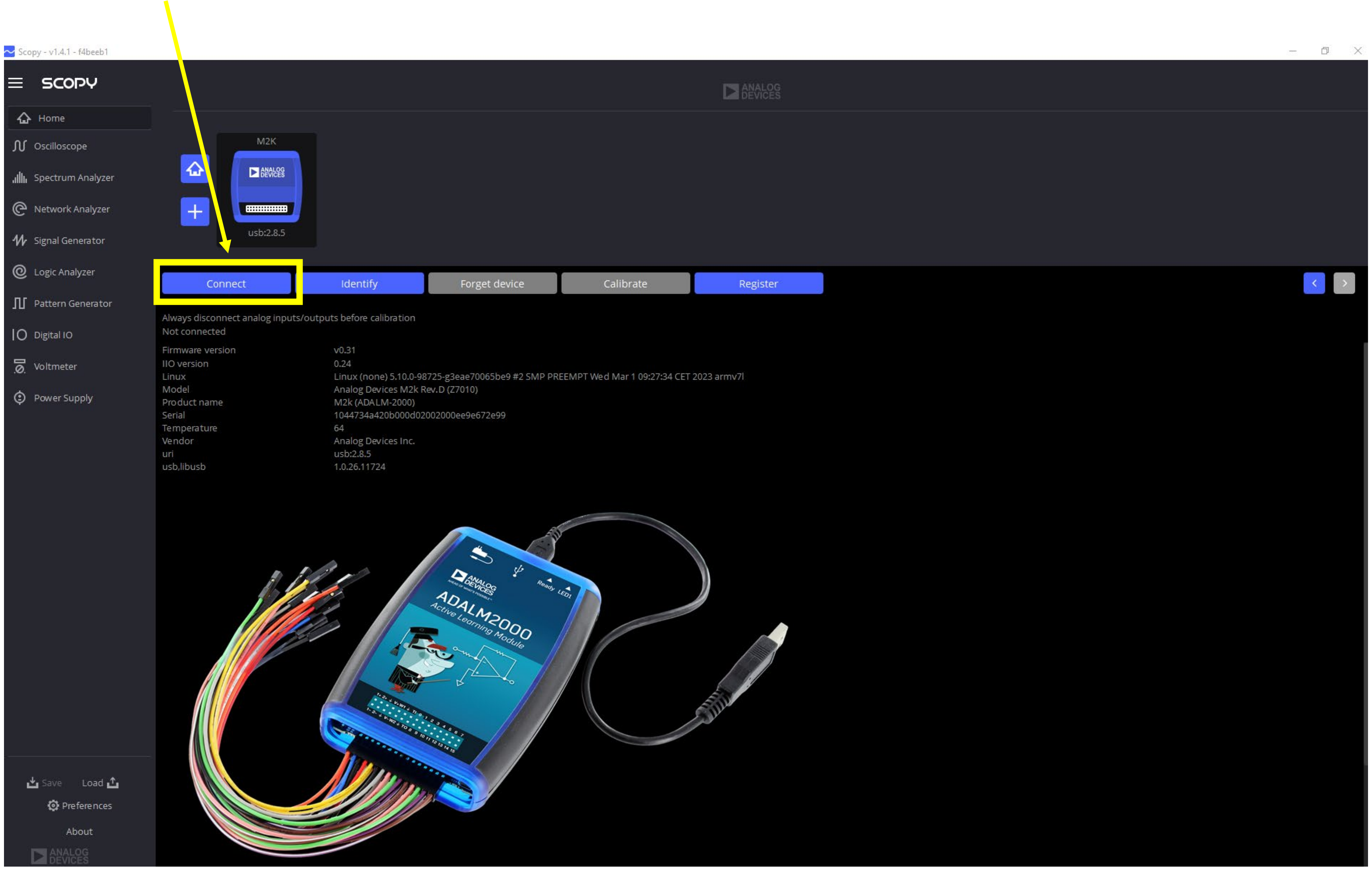


Physically Connect the ADALM2k to the Laptop

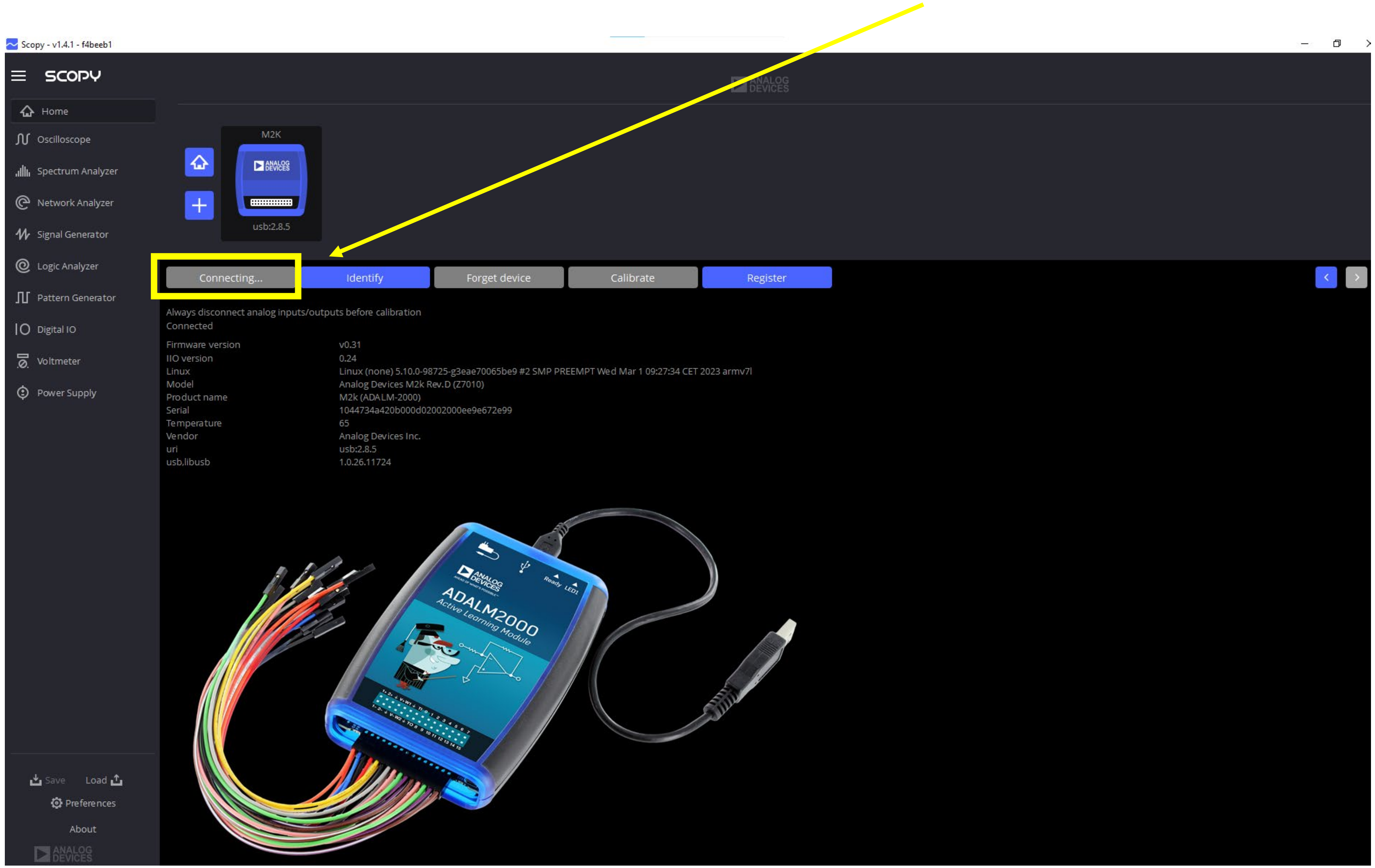
Click on the Icon



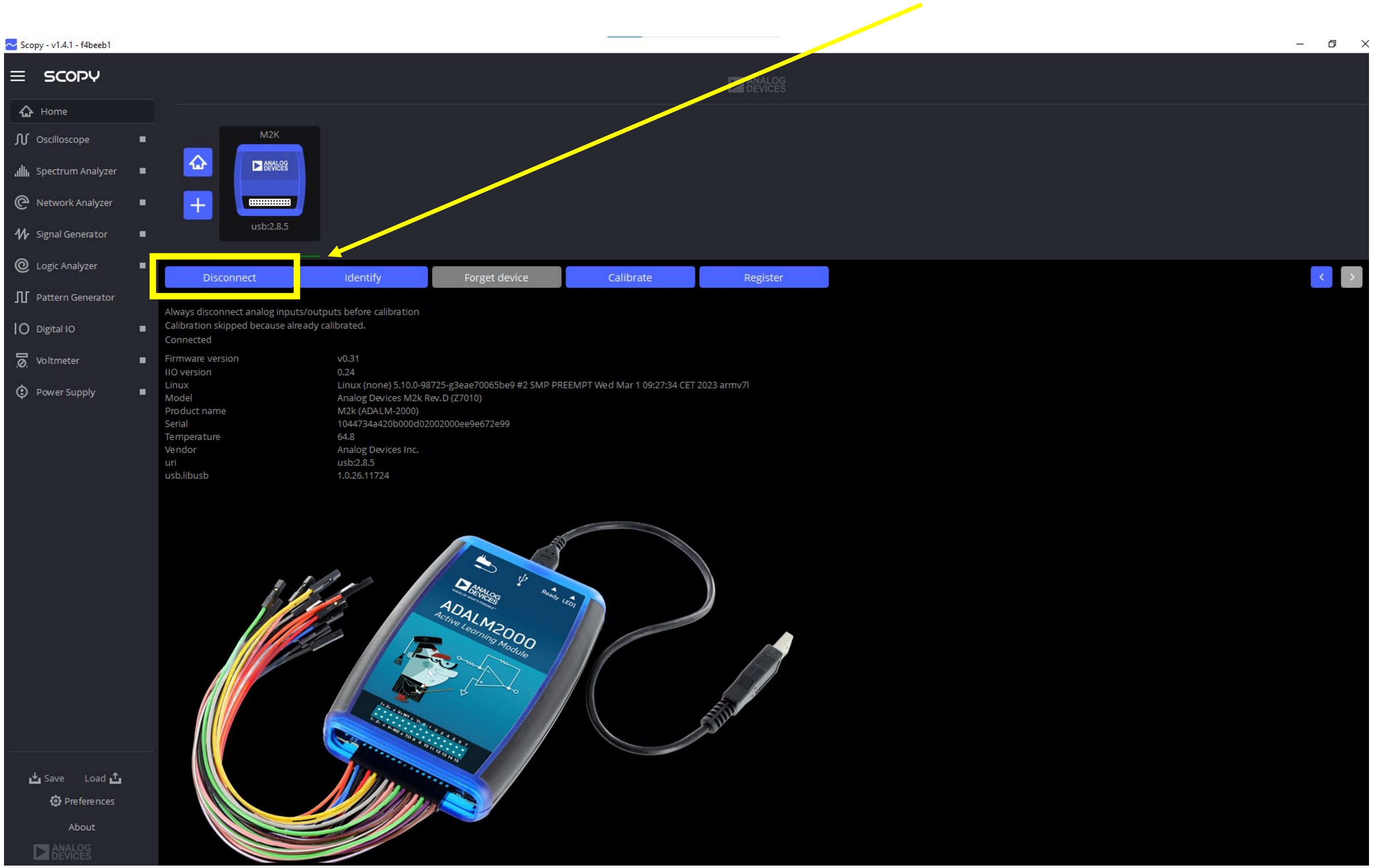
Click “Connect”



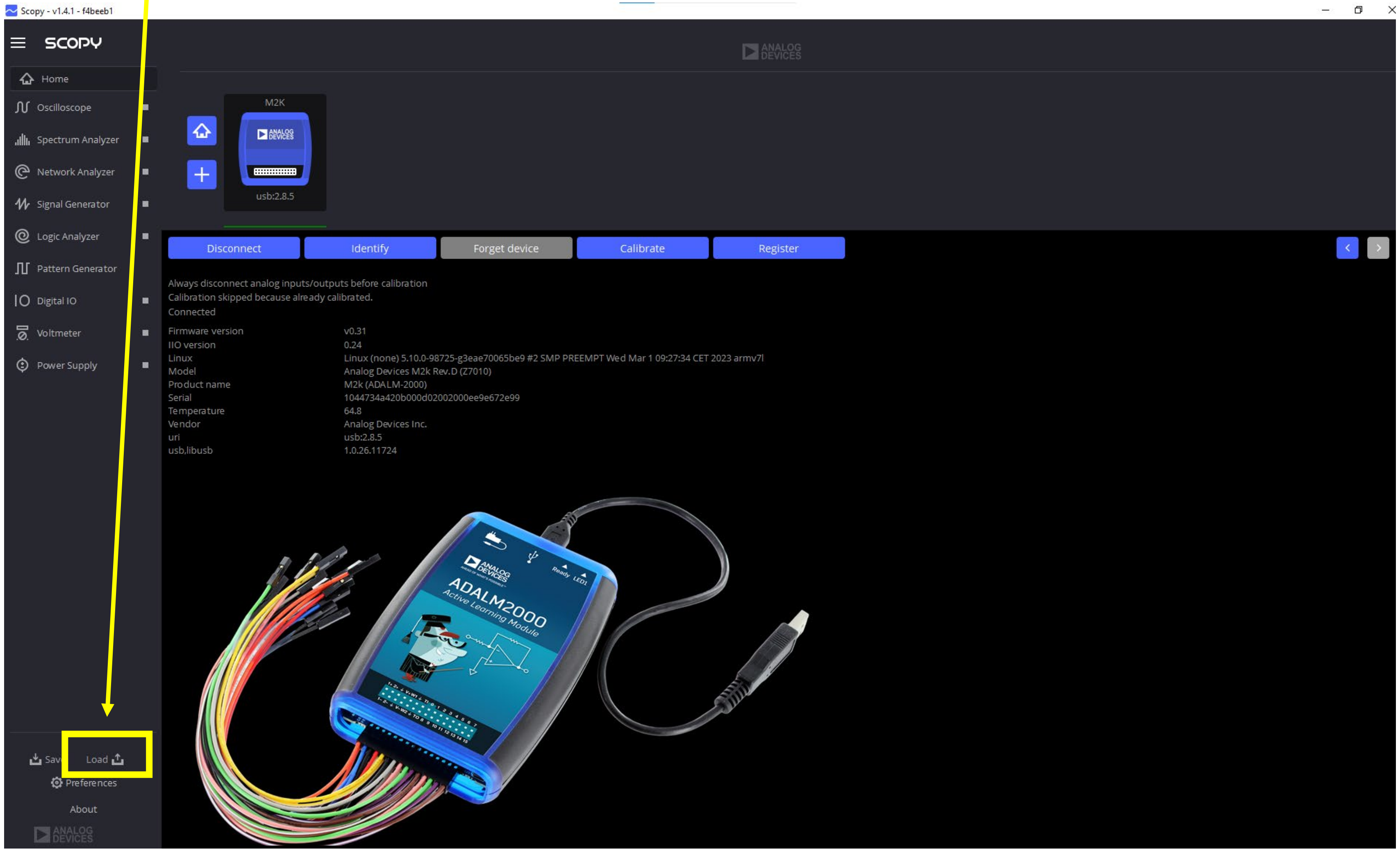
The ADALM2k will Begin the Connection Process



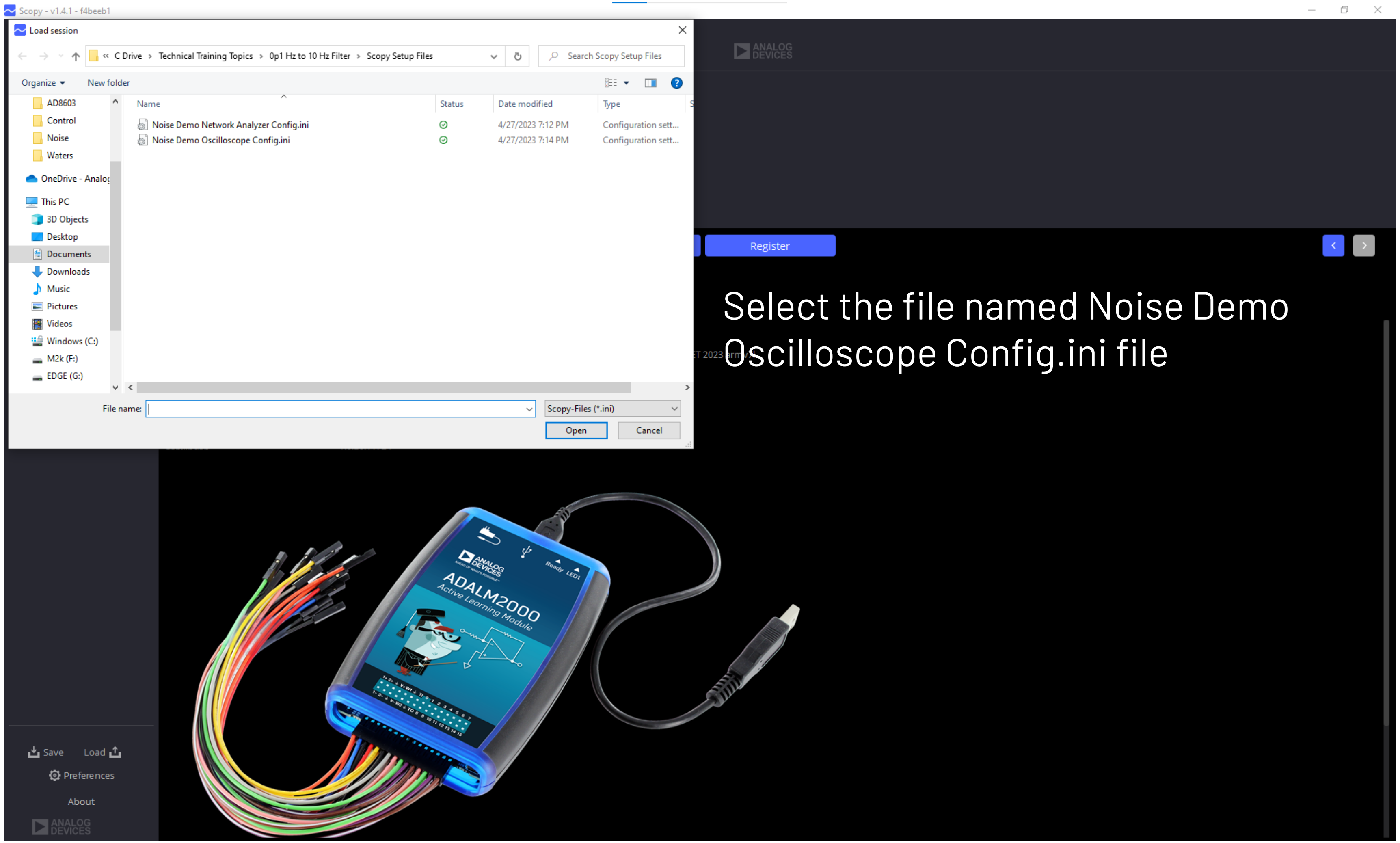
Successful Connection Looks Like This



Load the Config Files



Navigate to the Config File Location



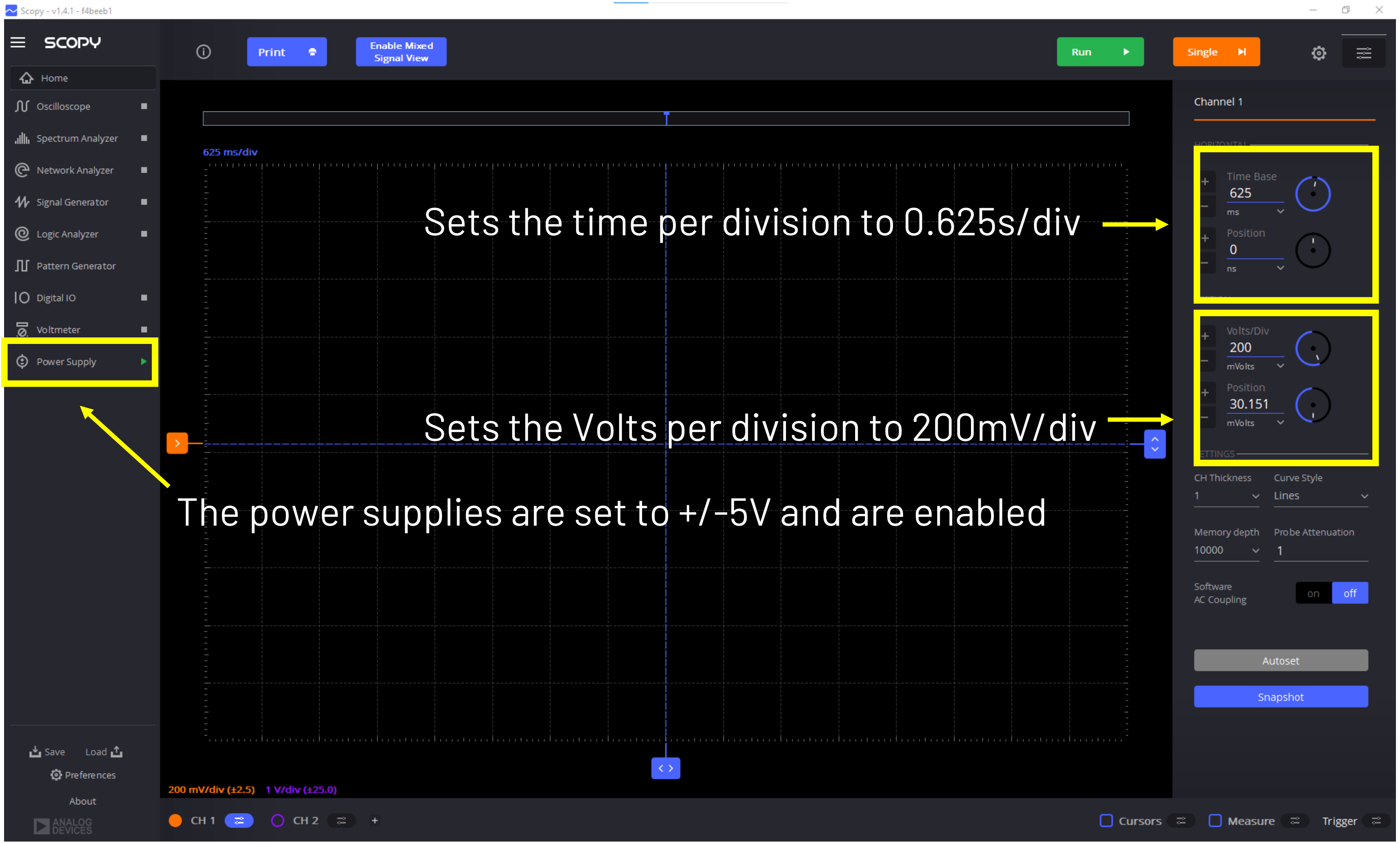
Select the file named Noise Demo Oscilloscope Config.ini file

Noise Demo Network Analyzer Config.ini

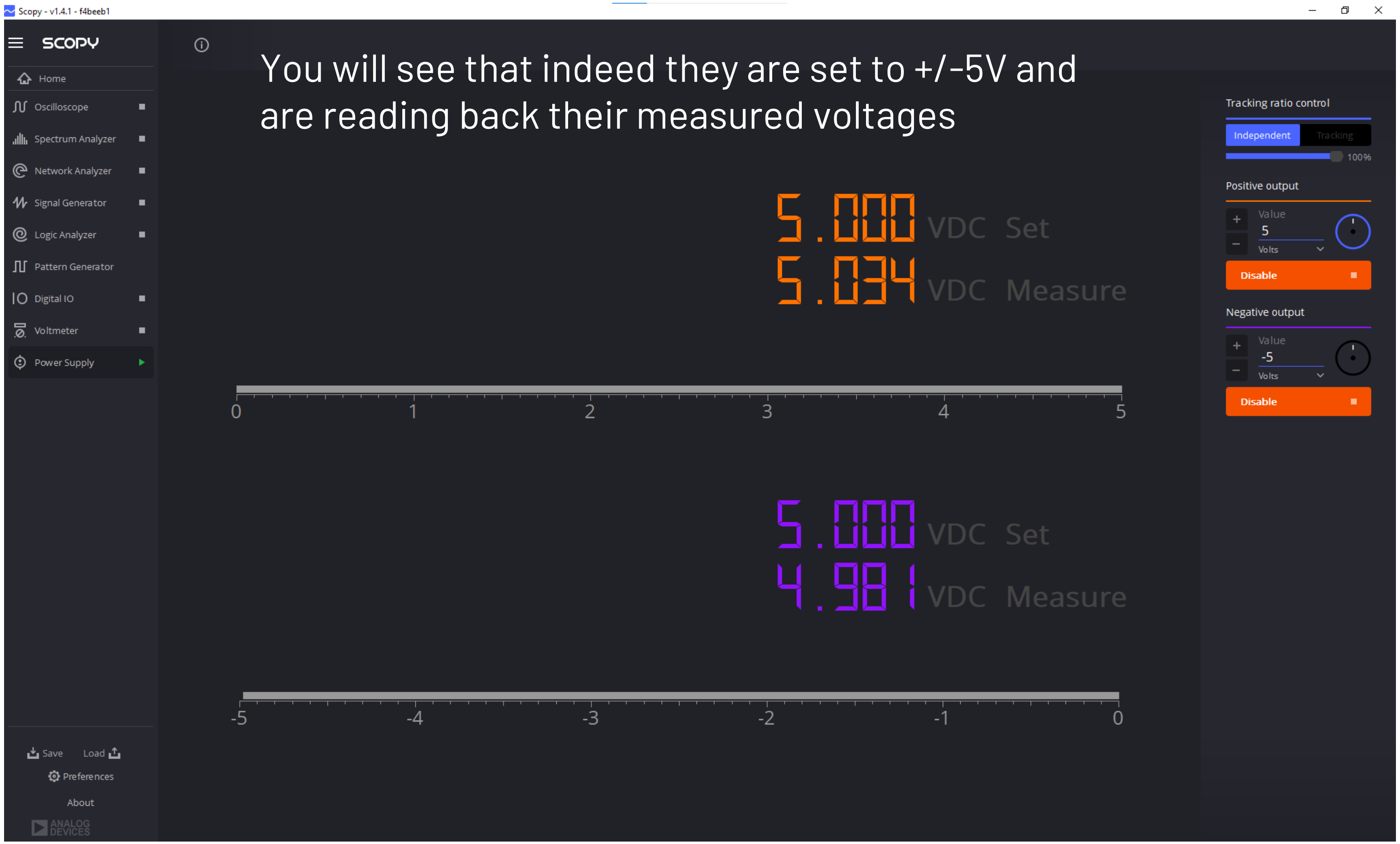
DO THIS FIRST

Double-click on the icon above and save to your preferred location on your laptop

The O-Scope Will be Configured as Shown



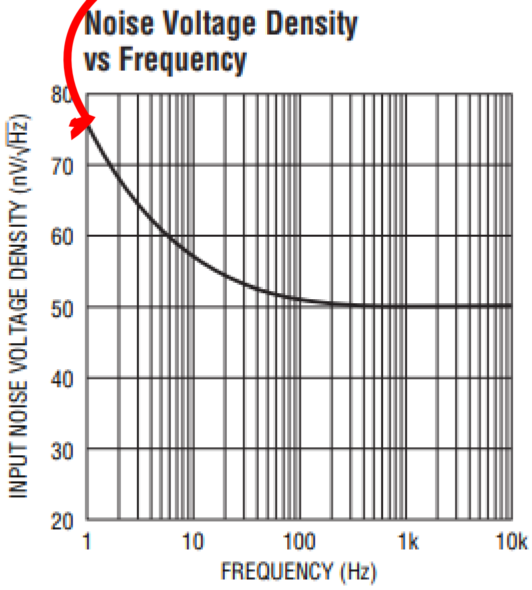
If You Click on the Power Supply Label



Set the Jumper to “Low Power”

Let's Estimate the 1/f Noise for the LT1782

While the filter is settling, let's take a minute to estimate the low frequency noise



From the data sheet curve, we can estimate the 1Hz 1/f noise at 75nV/SQRT-Hz

We will integrate from 0.1 Hz to 10 Hz

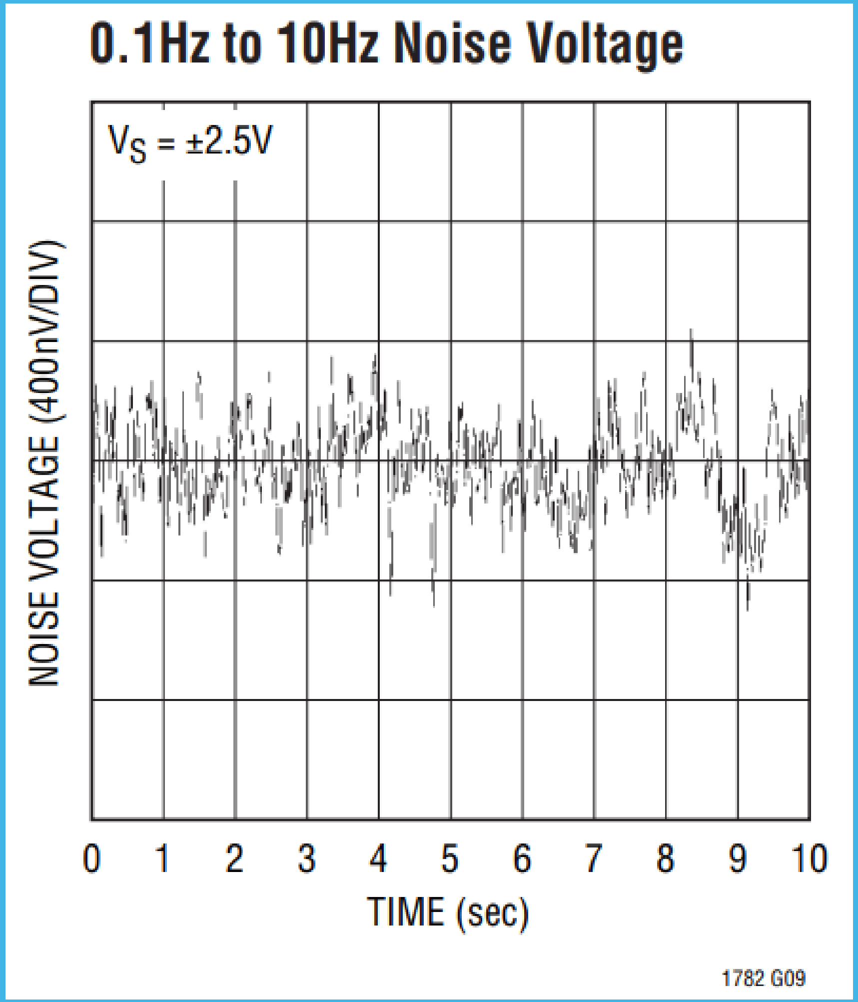
Calculation:

$$V_{\frac{1}{f}} = 6.6 \times e_{1Hz} \times \sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)} = 6.6 \times 75e^{-9} \times \sqrt{\ln\left(\frac{10}{0.1}\right)} = 1.06\mu V_{PP}$$

Let's Compare our Estimate to the LT1782 Datasheet

Data Sheet:

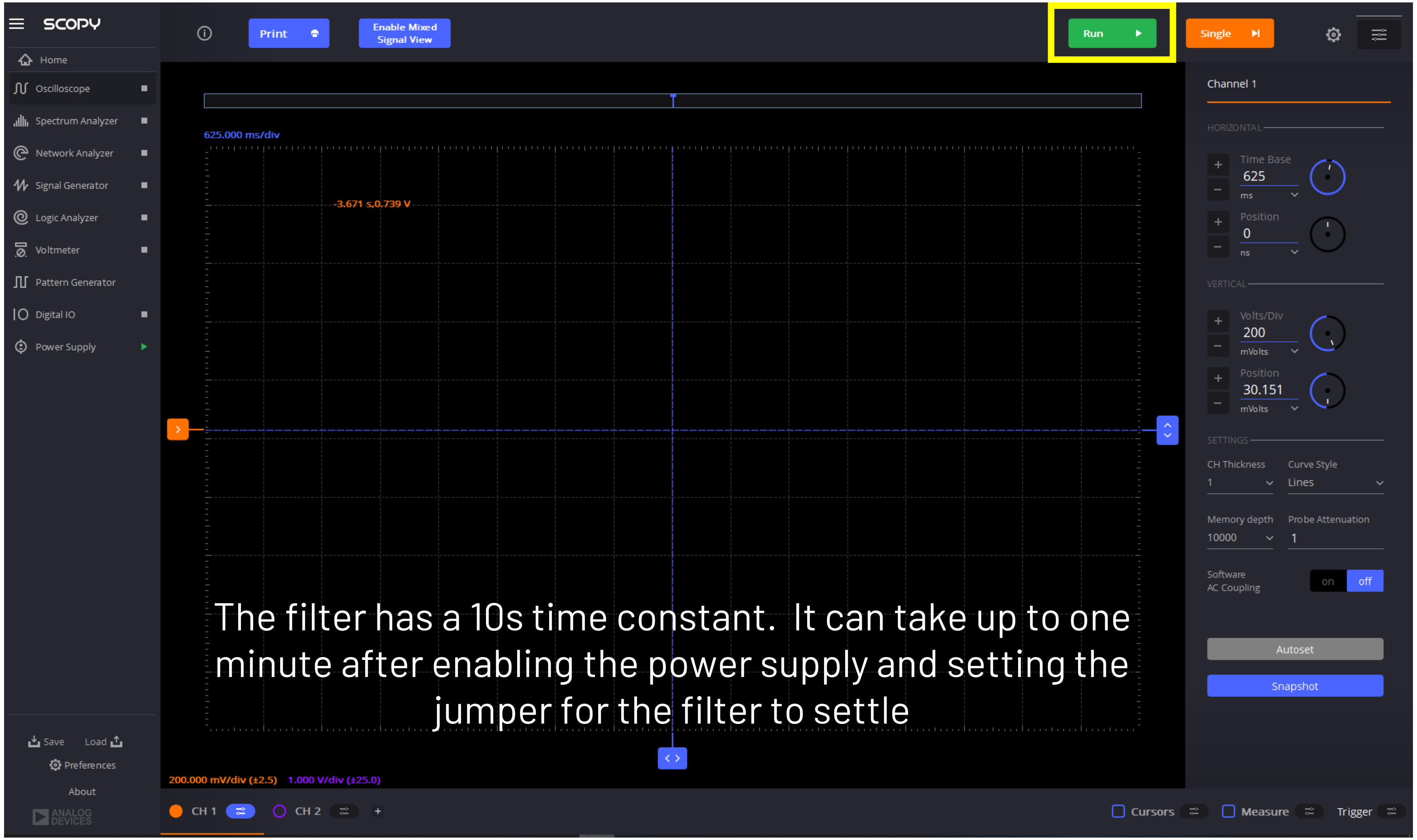
PARAMETER	CONDITIONS	LT1782C/LT1782I MIN	TYP	MAX	UNITS
Input Noise Voltage	0.1Hz to 10Hz		1		µVP-P



Estimate:

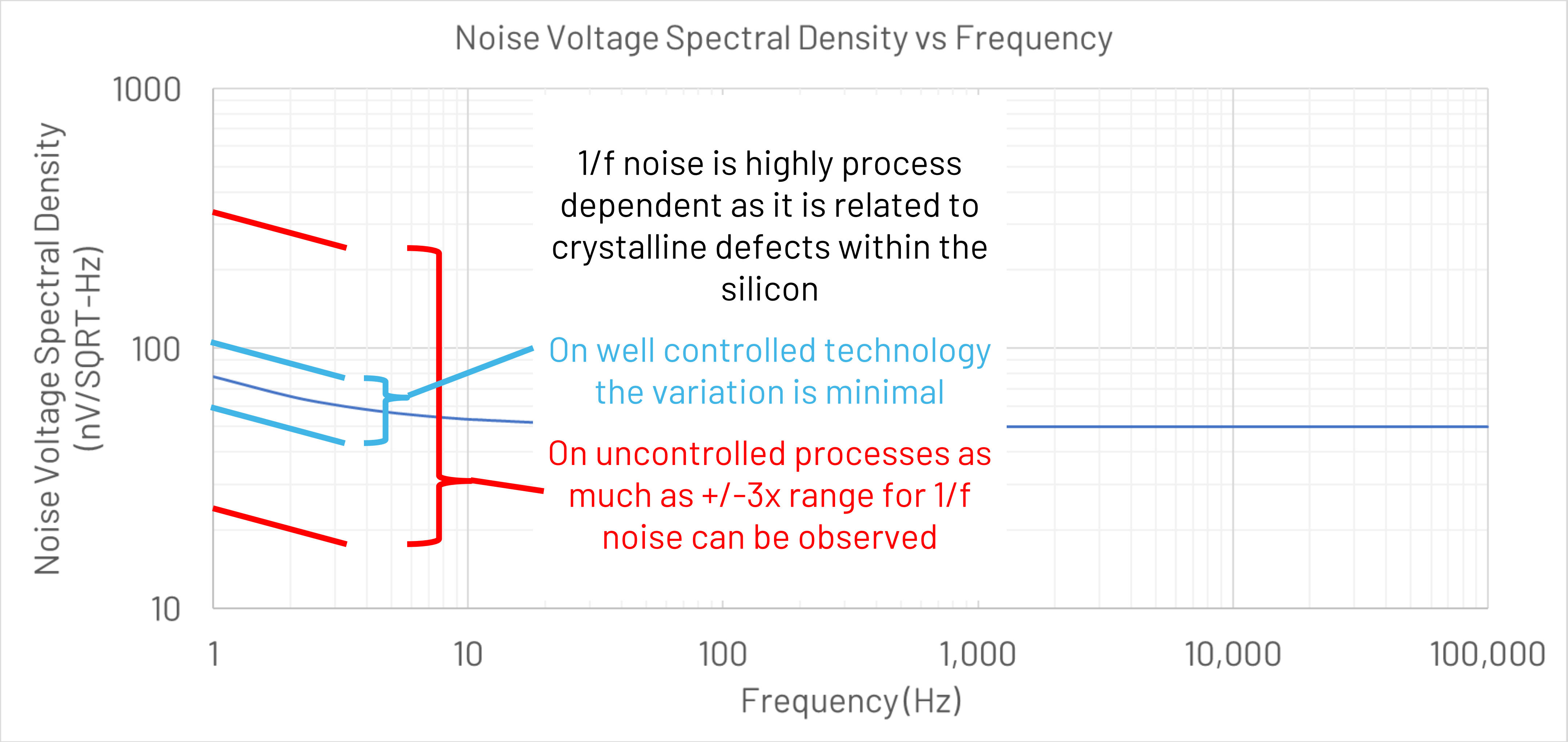
$$V_{\frac{1}{f}} = 6.6 \times e_{1Hz} \times \sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)} = 6.6 \times 75e^{-9} \times \sqrt{\ln\left(\frac{10}{0.1}\right)} = 1.06\mu V_{PP}$$

Click on the Green “Run” Button



The filter has a 10s time constant. It can take up to one minute after enabling the power supply and setting the jumper for the filter to settle

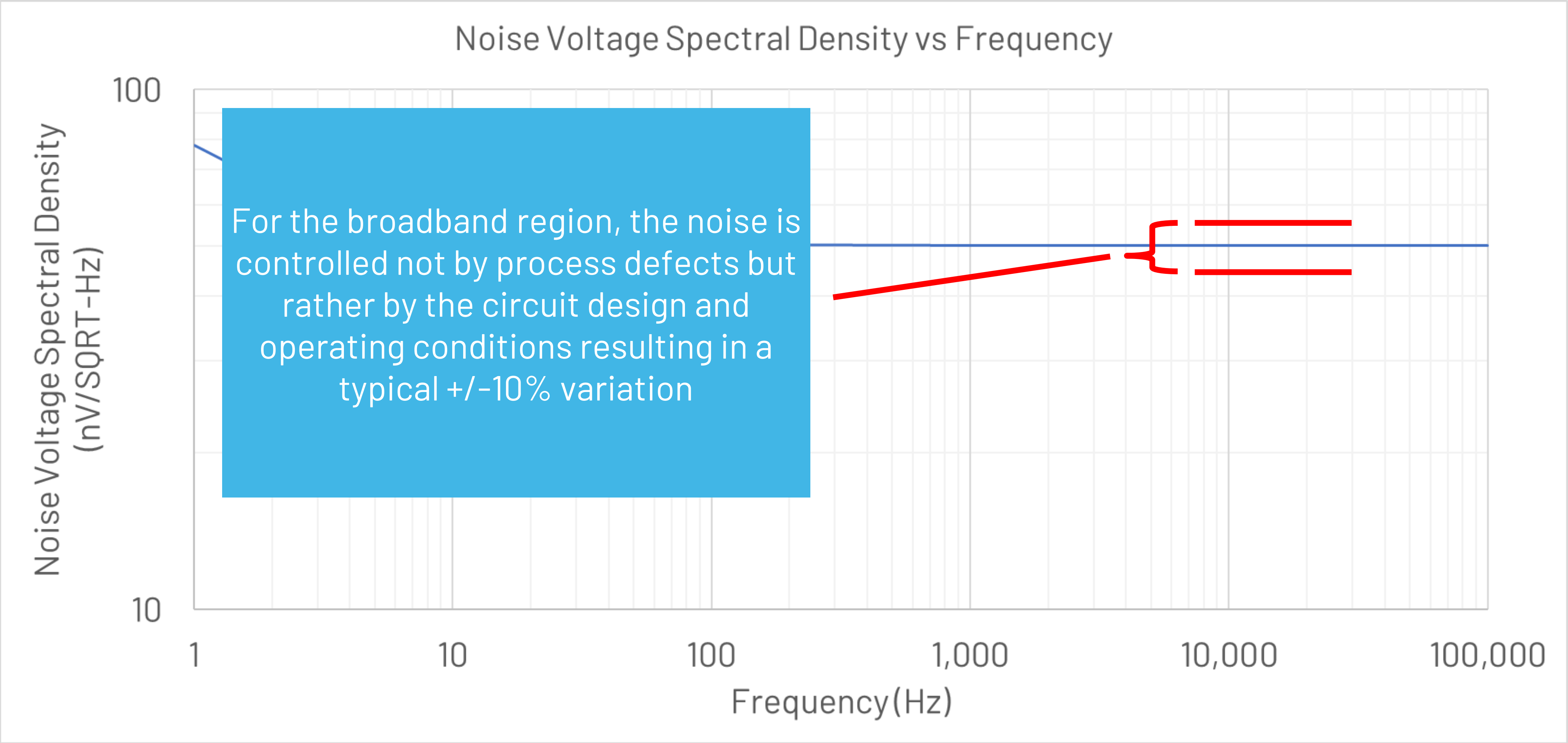
What to Expect if Only a Typical Value is Given?



Source:

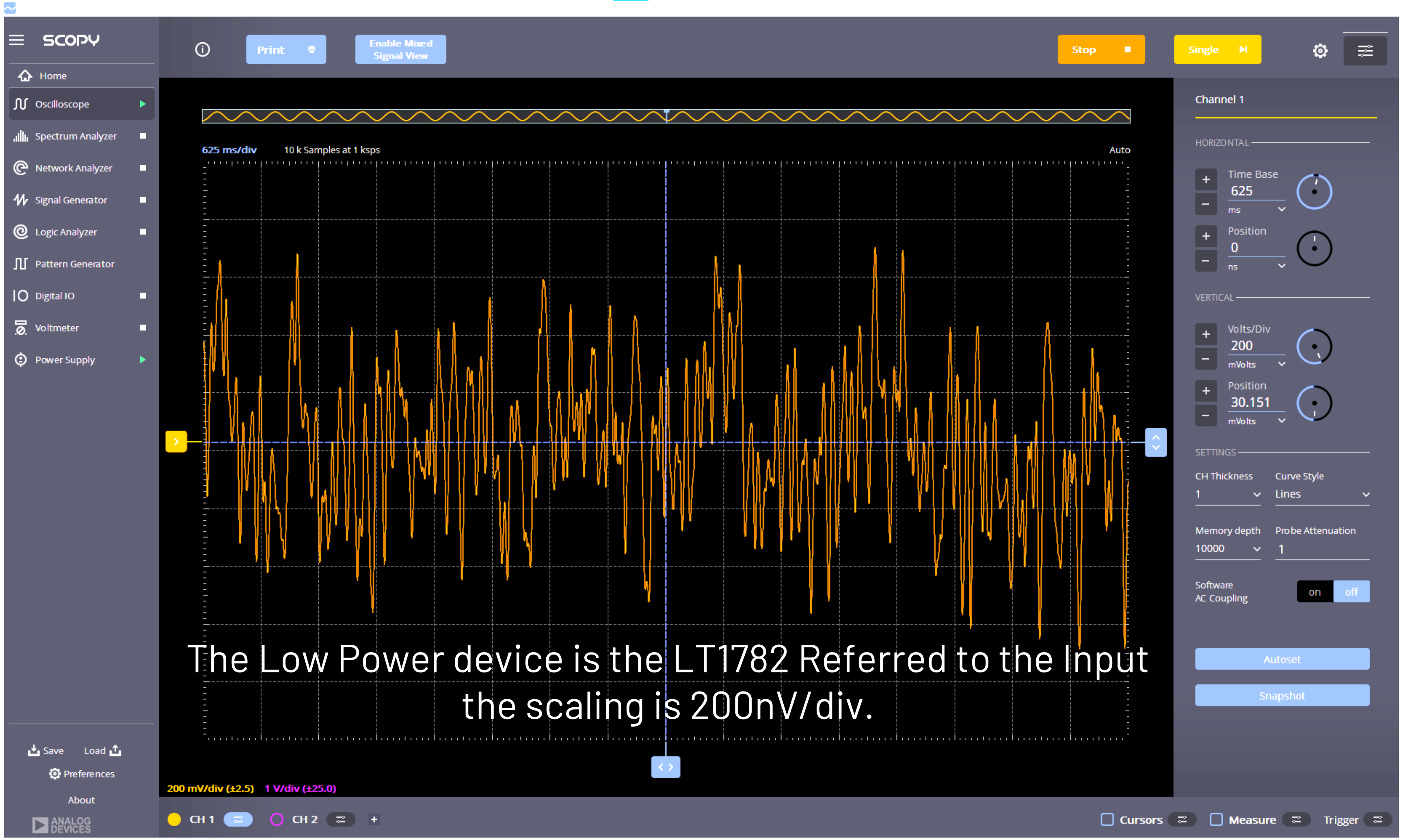
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

What to Expect if Only a Typical Value is Given?



Source:
Art Kay, Operational Amplifier Noise Techniques and Tips for Analyzing and Reducing Noise, Boston, Newnes/Elsevier, 2012

Typical Result for the Low Power Device



The Low Power device is the LT1782 Referred to the Input the scaling is 200nV/div.

Set the Jumper to “Low Noise”

Let’s Estimate the 1/f Noise for the ADA4077

While the filter is settling, let’s take a minute to estimate the low frequency noise

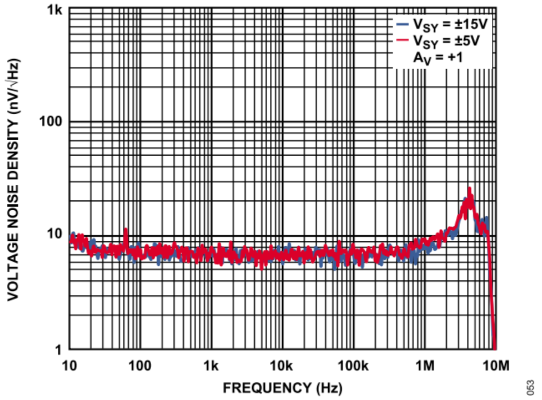


Figure 58. Voltage Noise Density vs. Frequency, V_{SY} = ±5 V and V_{SY} = ±15 V

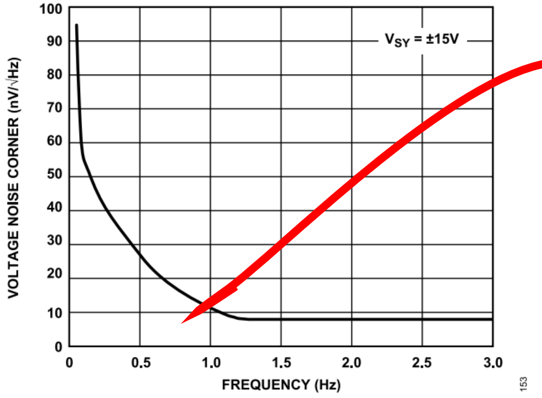


Figure 61. Voltage Noise Corner vs. Frequency, V_{SY} = ±15 V and V_{SY} = ±5 V

From the data sheet curve, we can estimate the 1Hz 1/f noise at 13nV/SQRT-Hz

We will integrate from 0.1 Hz to 10 Hz

Calculation:

$$V_{\frac{1}{f}} = 6.6 \times e_{1Hz} \times \sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)} = 6.6 \times 13e^{-9} \times \sqrt{\ln\left(\frac{10}{0.1}\right)} = 0.18\mu V_{PP}$$

Let's Compare our Estimate to the ADA4077 Datasheet

Data Sheet:

NOISE PERFORMANCE				
Voltage Noise	e_n p-p	0.1 Hz to 10 Hz	0.25	µV p-p
Voltage Noise Density	e_n	f = 1 Hz	13	nV/√Hz

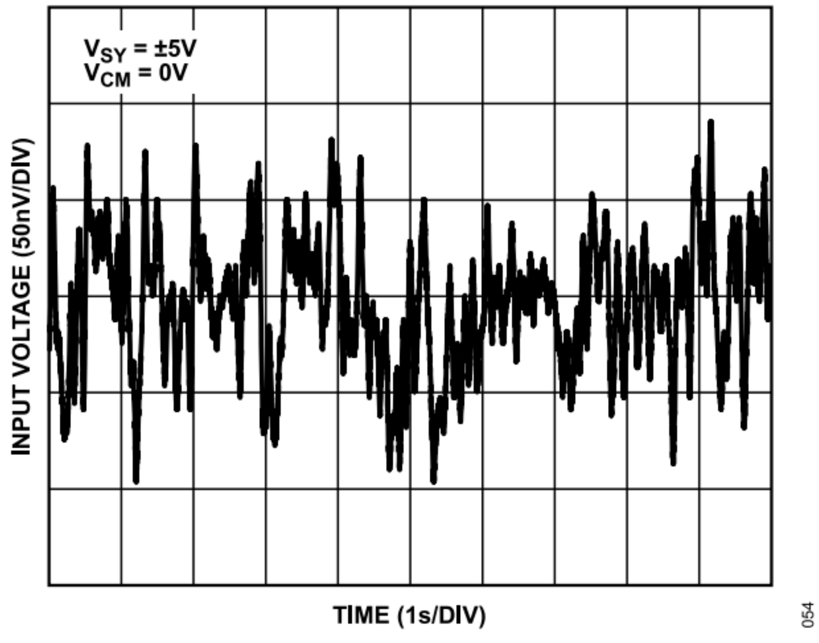
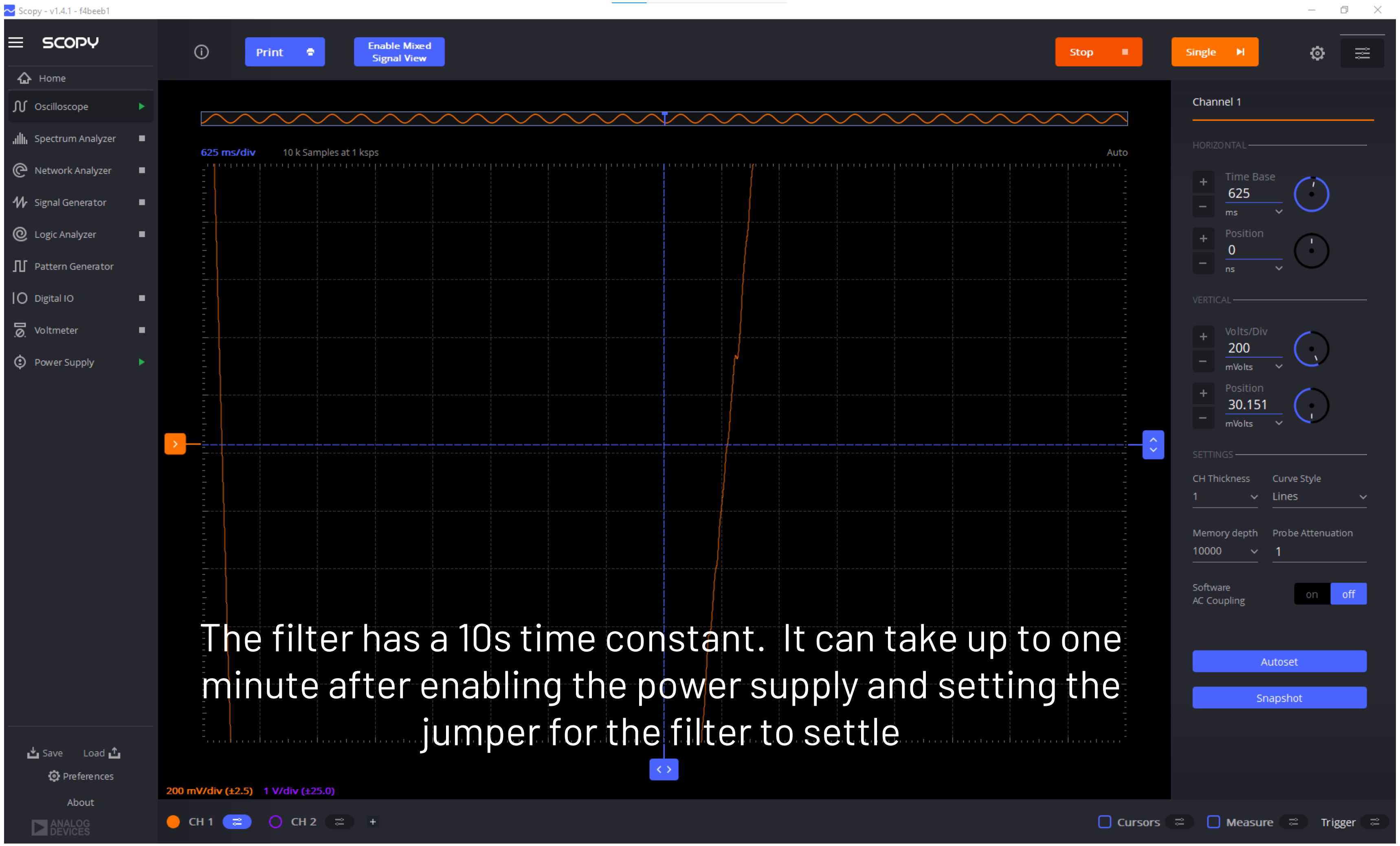


Figure 60. 0.1 Hz to 10 Hz Noise, V_{SY} = ±5 V

Estimate:

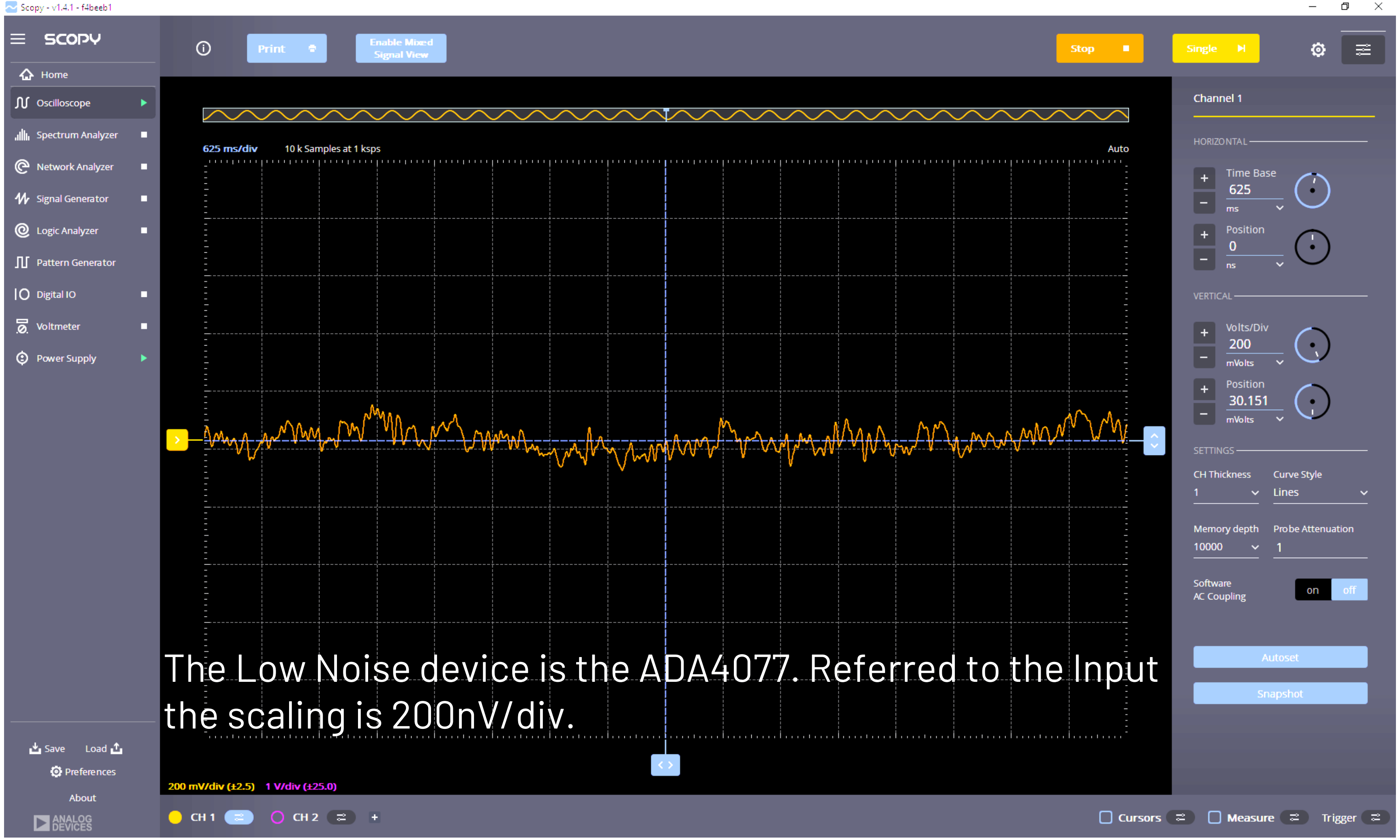
$$V_{\frac{1}{f}} = 6.6 \times e_{1Hz} \times \sqrt{\ln\left(\frac{f_{HIGH}}{f_{LOW}}\right)} = 6.6 \times 13e^{-9} \times \sqrt{\ln\left(\frac{10}{0.1}\right)} = 0.18\mu V_{PP}$$

Wait for Filter to Settle



The filter has a 10s time constant. It can take up to one minute after enabling the power supply and setting the jumper for the filter to settle

Typical Result for the Low Noise Device



The Low Noise device is the ADA4077. Referred to the Input the scaling is 200nV/div.

Set the Jumper to “Zero Drift”

Let's Estimate the 1/f Noise for the ADA4522

While the filter is settling, let's take a minute to estimate the low frequency noise

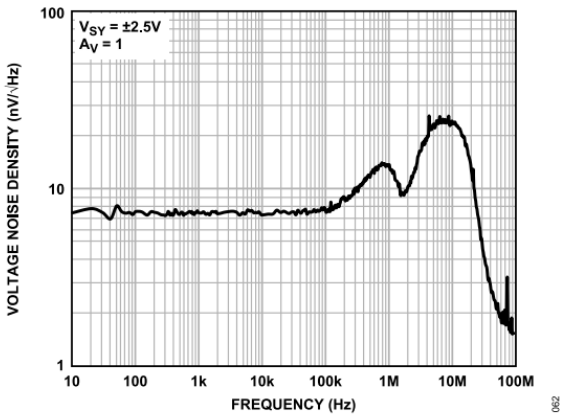


Figure 60. Voltage Noise Density vs. Frequency, V_{SY} = ±2.5 V

Because the ADA4522 is a Zero-Drift device, it has no 1/f noise, so we must calculate the broadband noise from 0.1 Hz to 10 Hz using 5.8nV/SQRT-Hz

We will use a noise bandwidth of 10 Hz

Calculation:

$$V_n = 6.6 \times NSD\sqrt{Noisebandwidth} = 6.6 \times 5.8e^{-9}\sqrt{10} = 0.12\mu V_{PP}$$

Let's Compare our Estimate to the ADA4522 Datasheet

Data Sheet:

NOISE PERFORMANCE				
Total Harmonic Distortion Plus Noise	THD + N	A_V = 1, f = 1 kHz, V_{IN} = 6 V rms		
BW = 80 kHz			0.0005	%
BW = 500 kHz			0.004	%
Peak-to-Peak Voltage Noise	$e_{N\ p\text{-}p}$	A_V = 100, f = 0.1 Hz to 10 Hz	117	nV p-p
Voltage Noise Density	e_N	A_V = 100, f = 1 kHz	5.8	nV/√Hz
Peak-to-Peak Current Noise	$i_{N\ p\text{-}p}$	A_V = 100, f = 0.1 Hz to 10 Hz	16	pA p-p
Current Noise Density	i_N	A_V = 100, f = 1 kHz	0.8	pA/√Hz

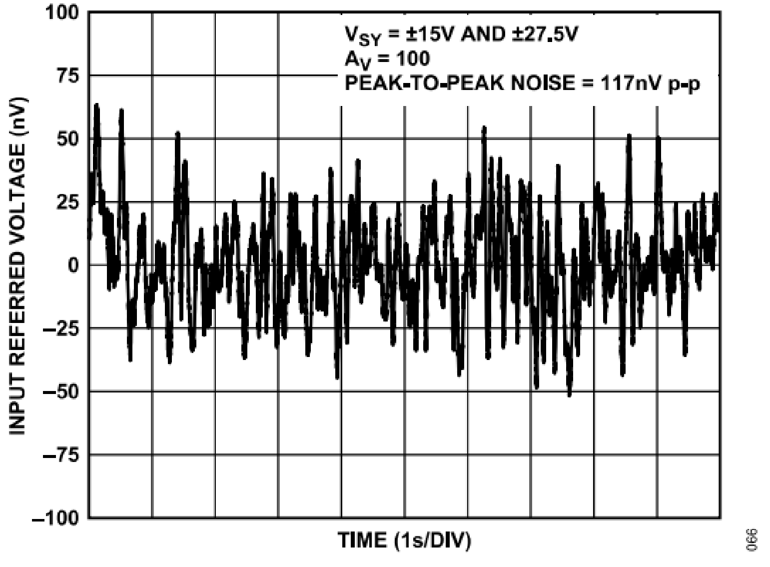
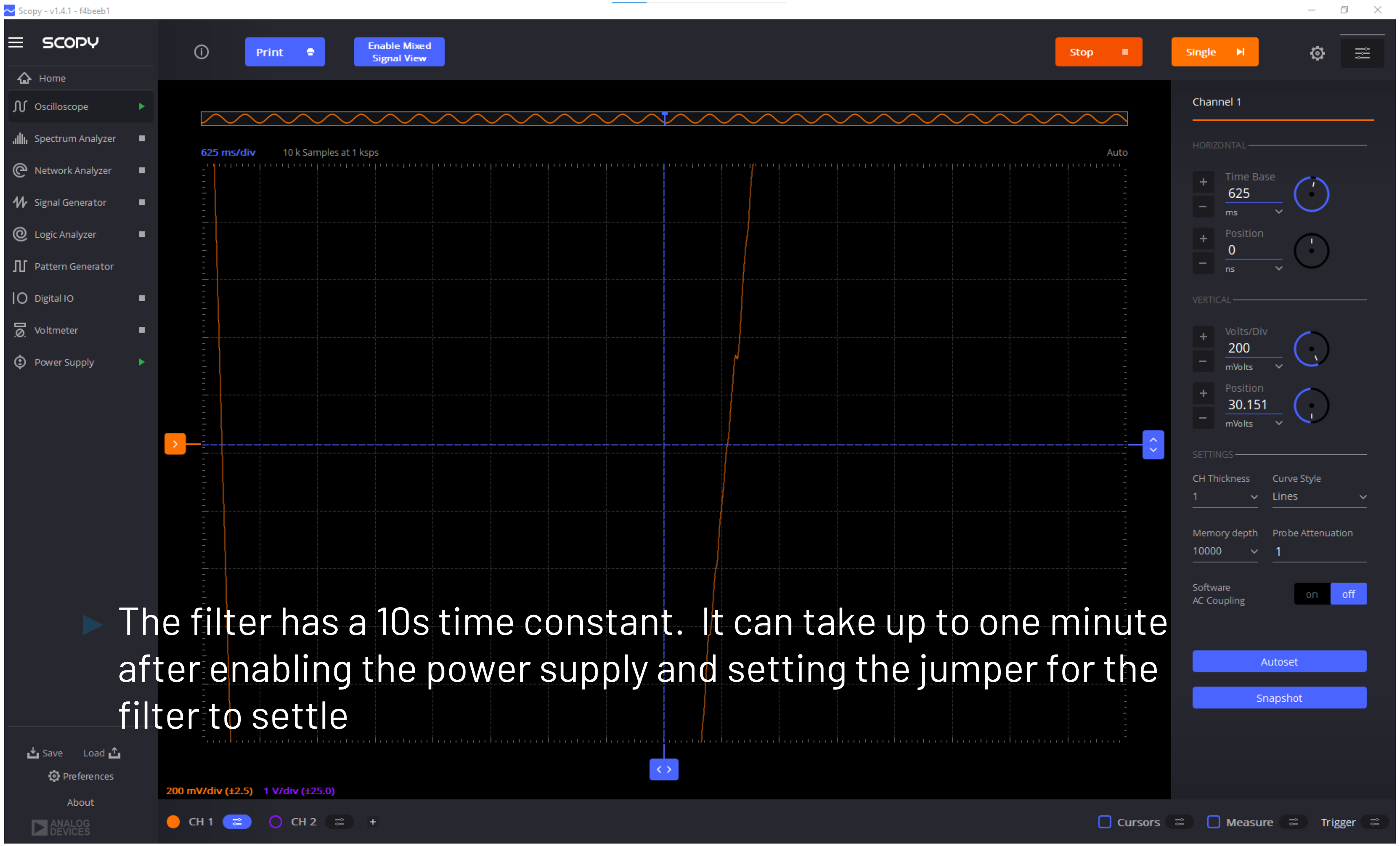


Figure 64. 0.1 Hz to 10 Hz Noise

Estimate:

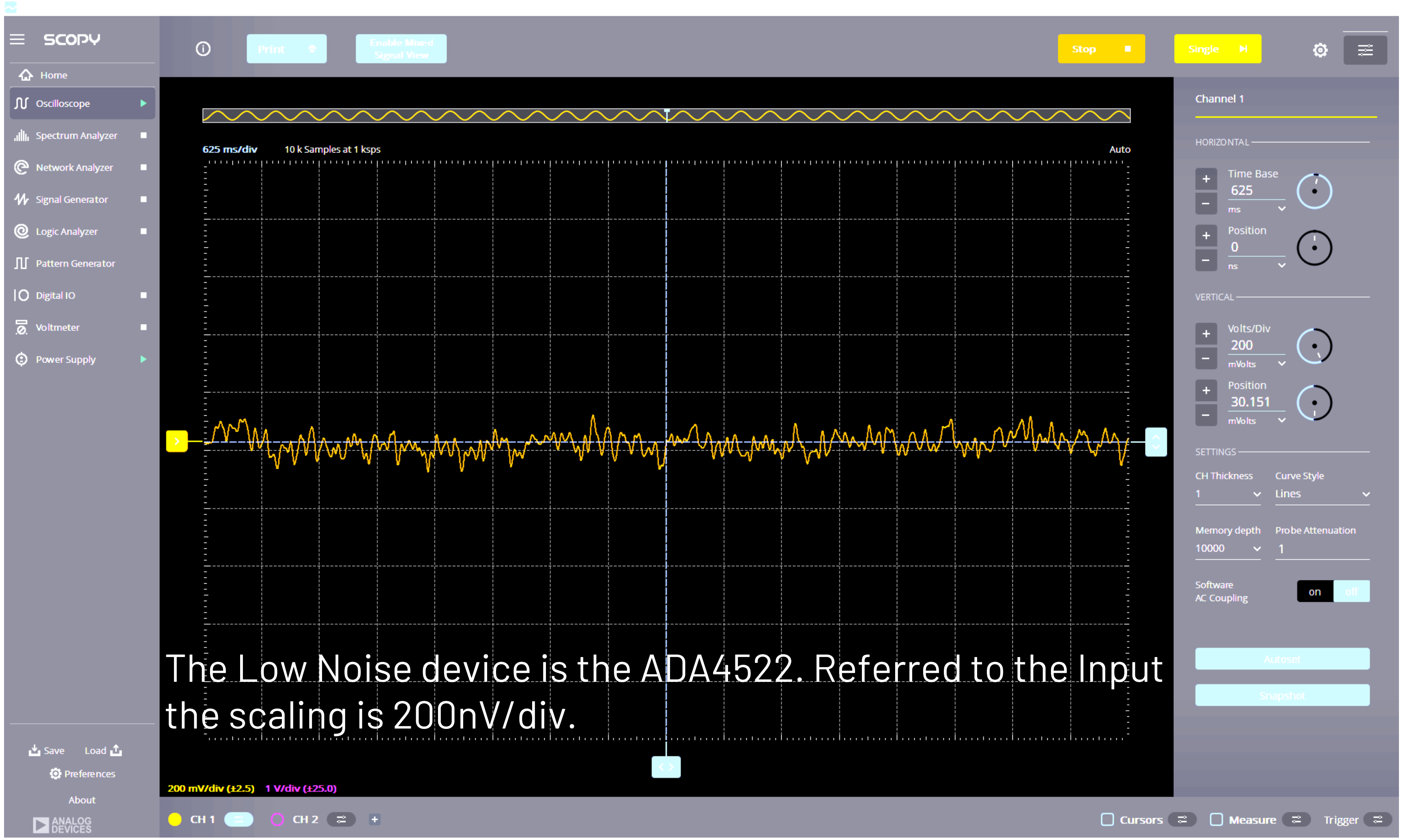
$$V_n = 6.6 \times NSD\sqrt{Noisebandwidth} = 6.6 \times 5.8e^{-9}\sqrt{10} = 0.12\mu V_{PP}$$

Wait for Filter to Settle



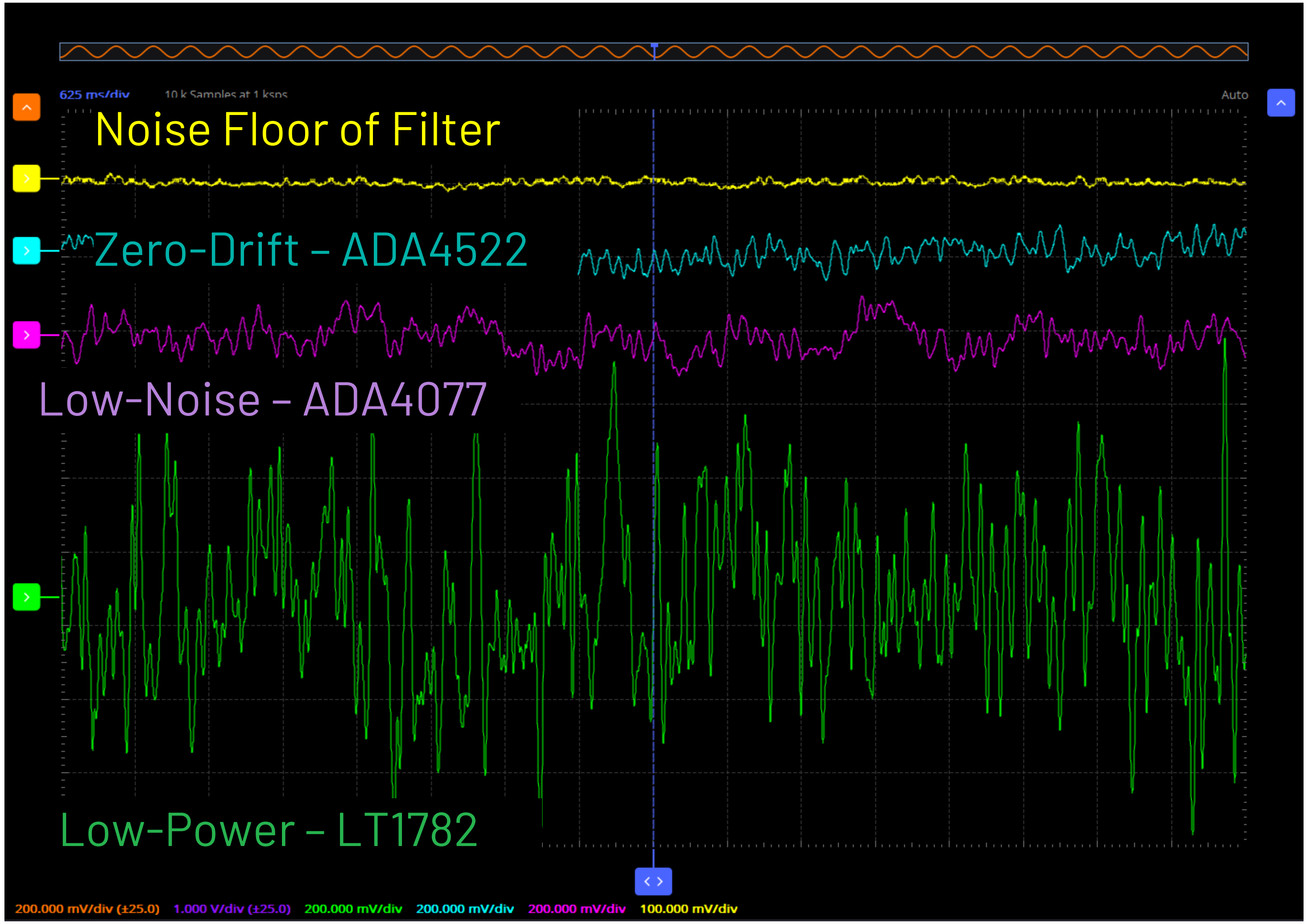
- The filter has a 10s time constant. It can take up to one minute after enabling the power supply and setting the jumper for the filter to settle

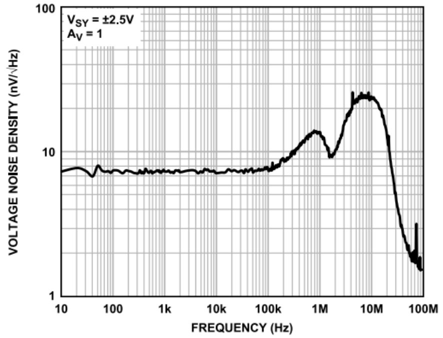
Typical Result for the Zero-Drift Device

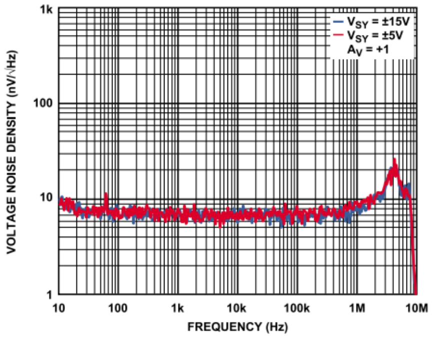


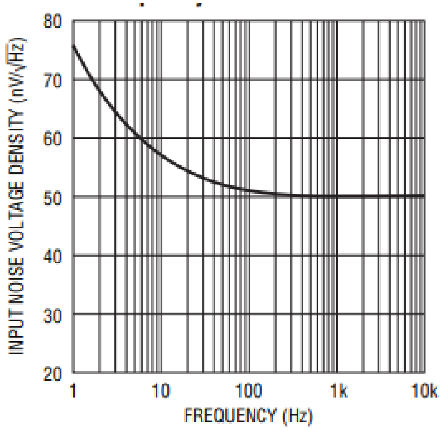
The Low Noise device is the ADA4522. Referred to the Input the scaling is 200nV/div.

Results Summary

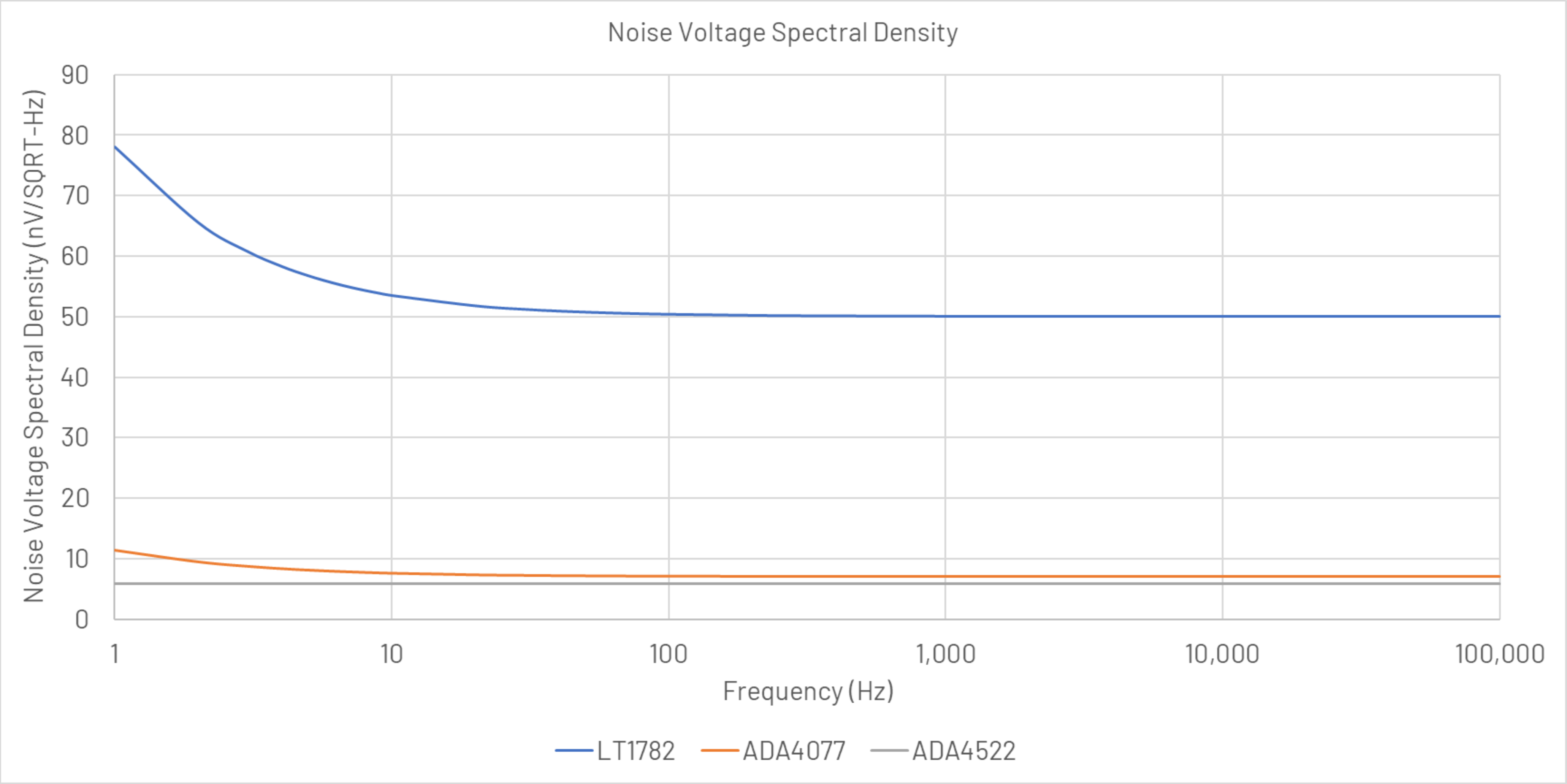






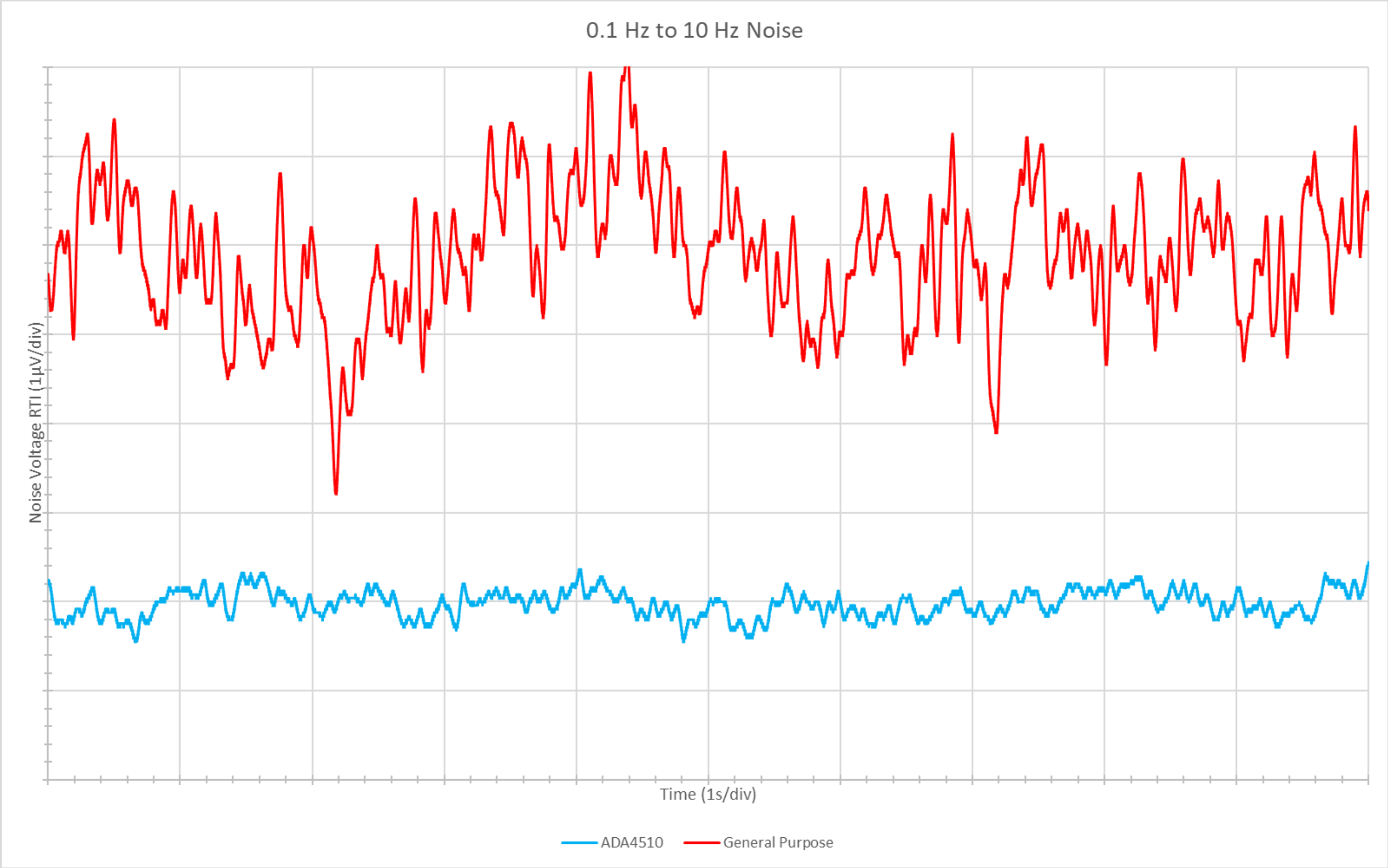


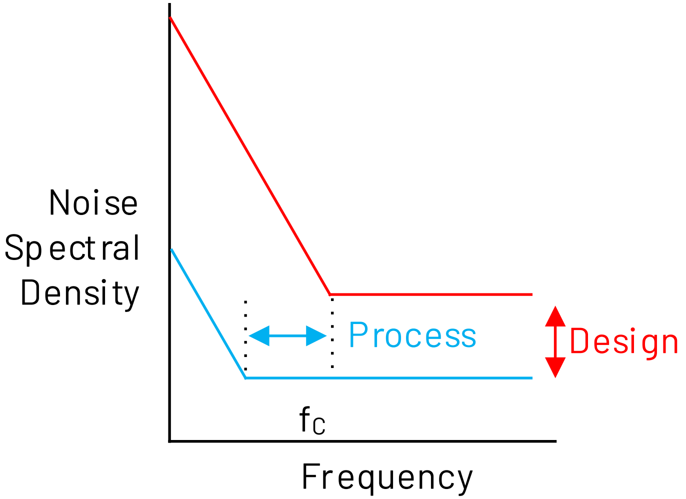
Recap - NSD for all three Opamps Included in this Demo

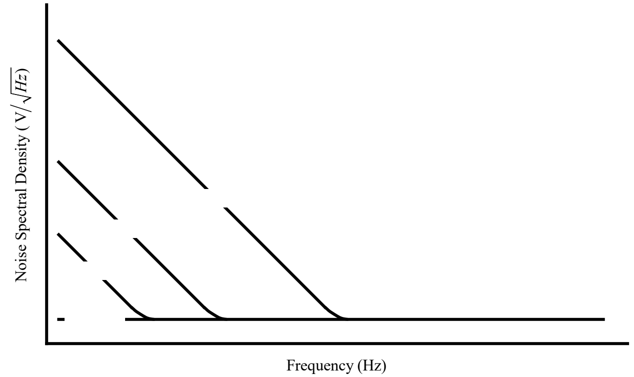


Recap - Low Frequency Noise Comparison

Low Noise Technology vs Standard Technology

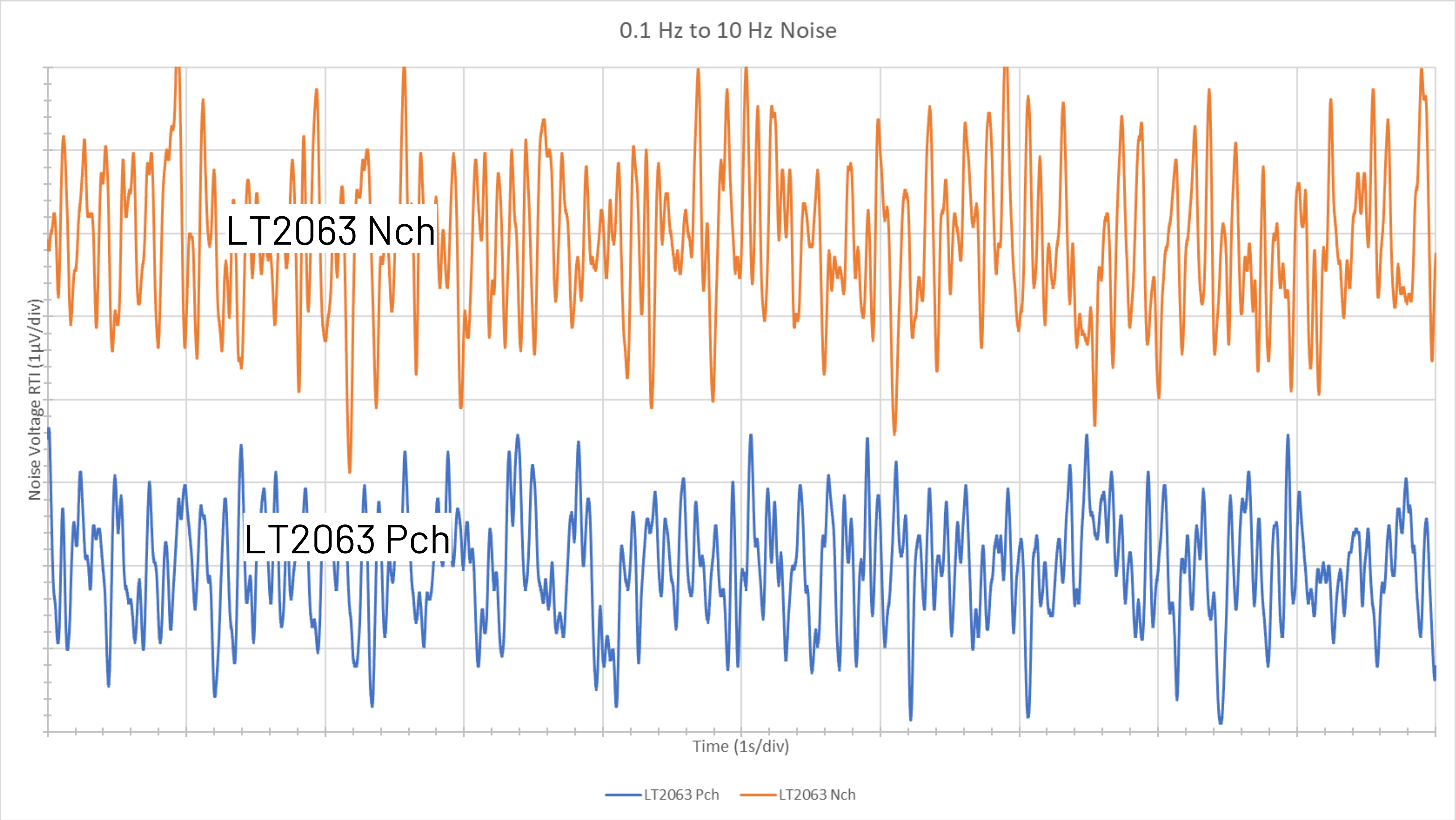






Rail-to-Rail Input Stages

0.1 Hz to 10 Hz Noise



Rail-to-Rail Input Stages

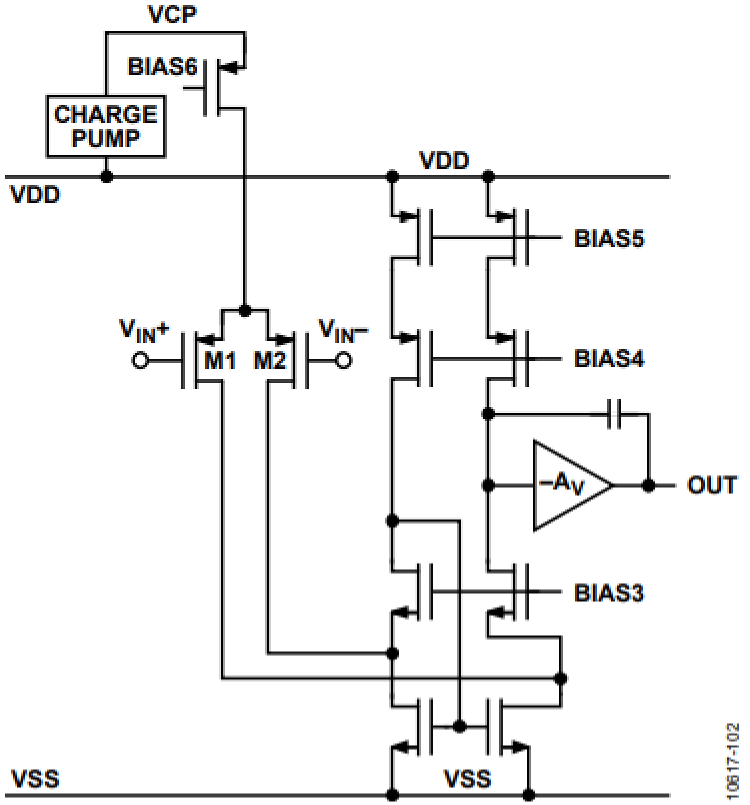
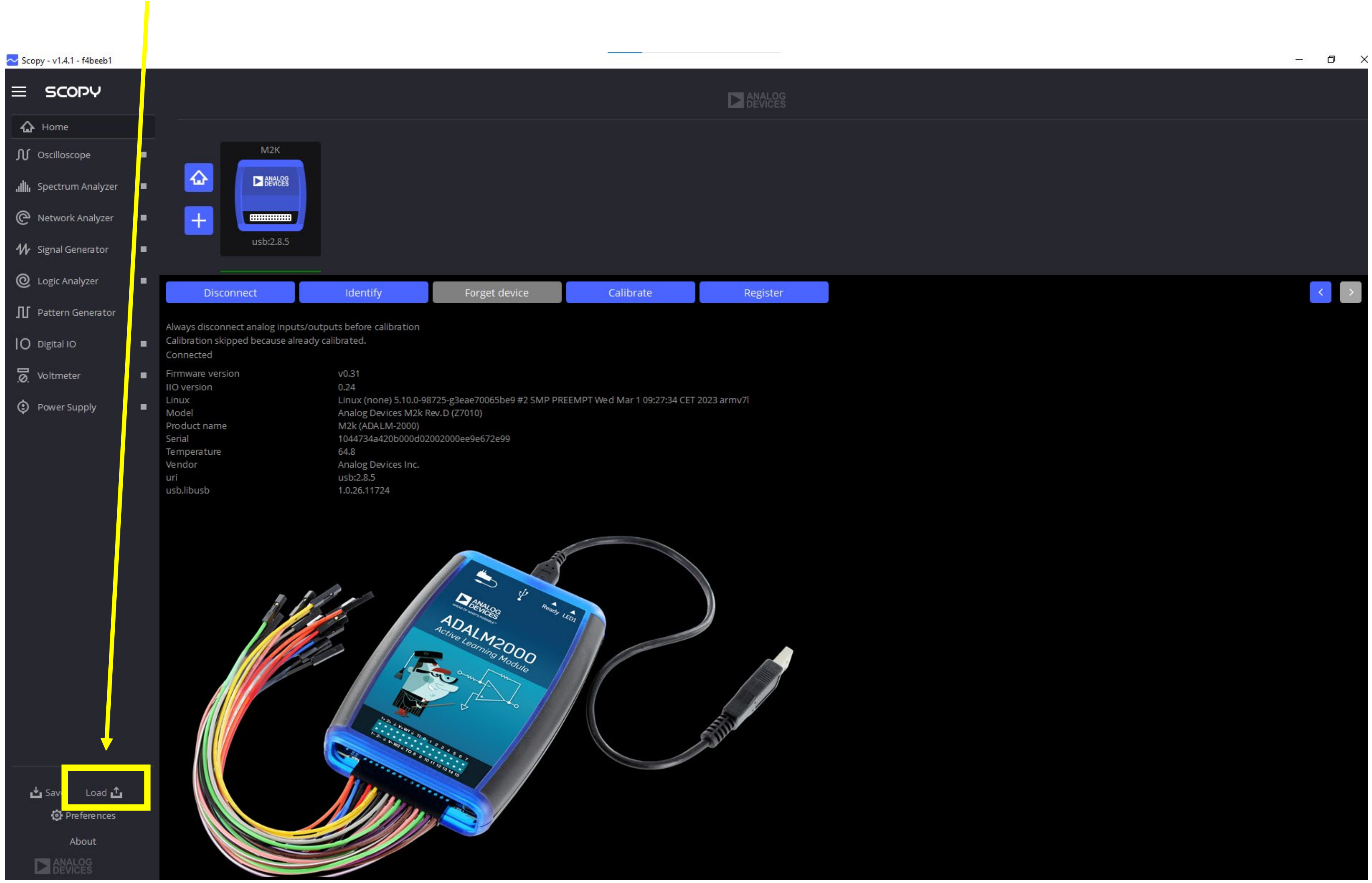


Figure 61. ADA4500-2 Input Structure

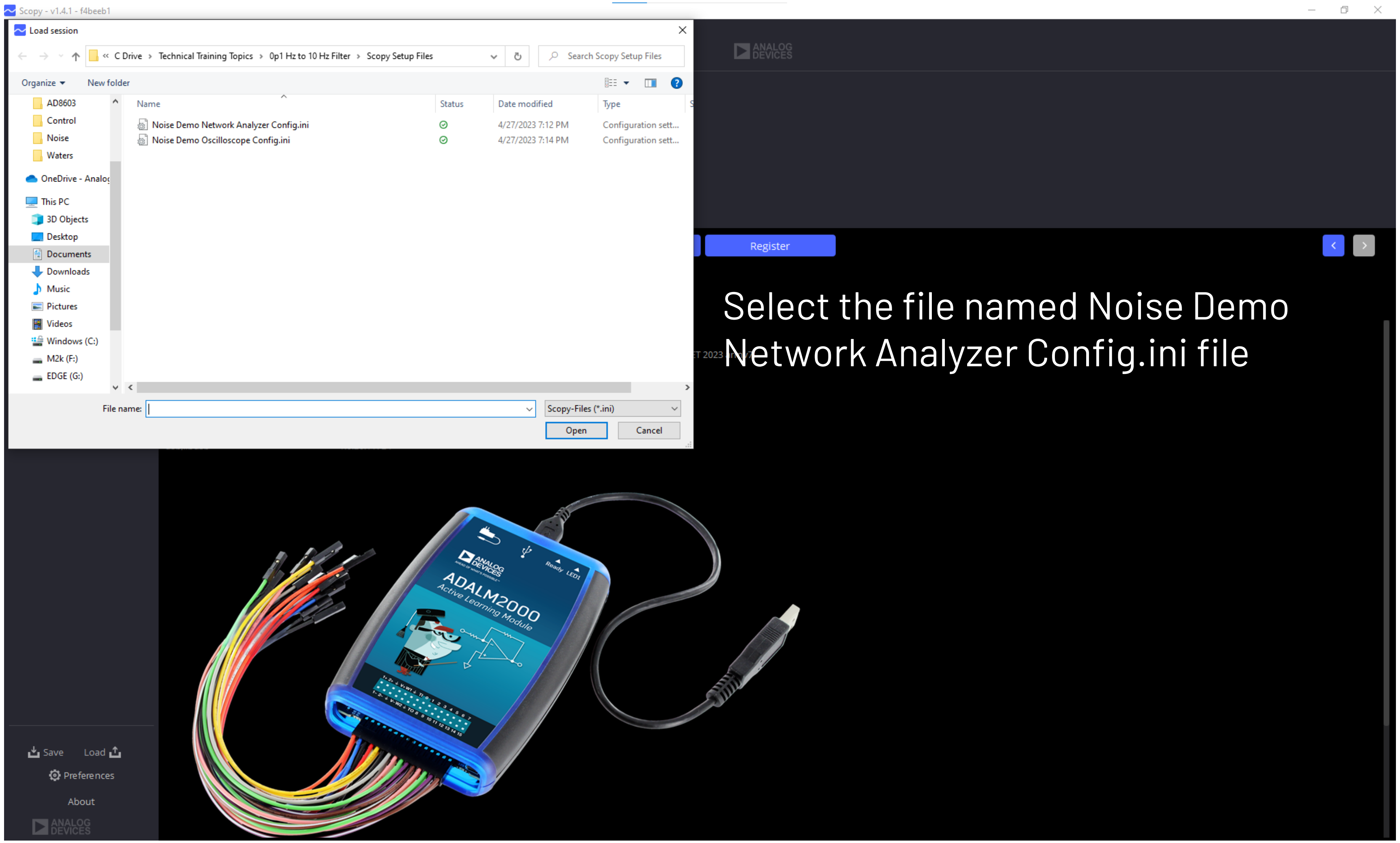
Let's use the Network Analyzer Feature of the ADALM2000 to Measure the Filter Response

Set the Jumper to "Network Analyzer"

Load the Config Files



Navigate to the Config File Location

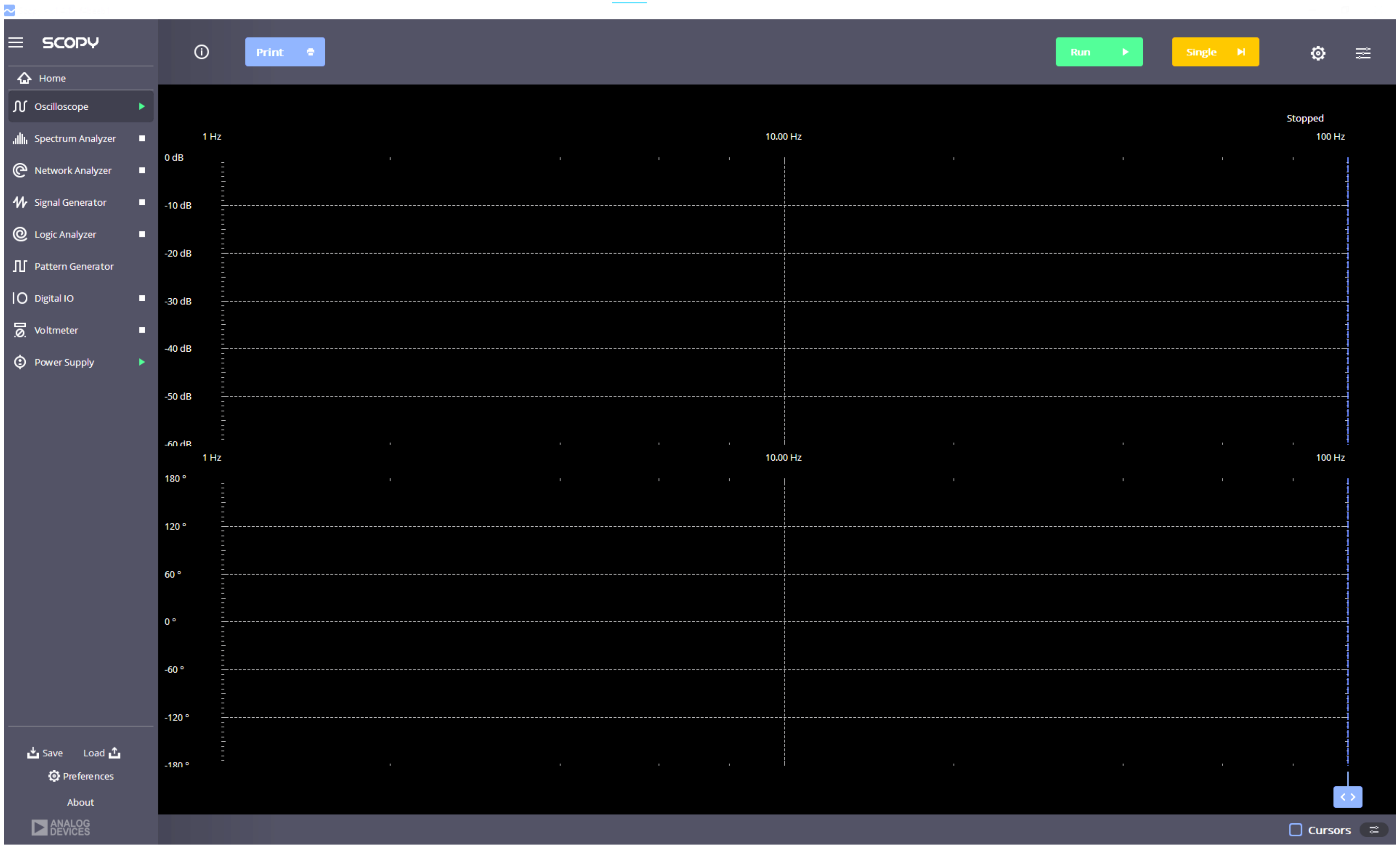


Noise Demo Network Analyzer Config.ini

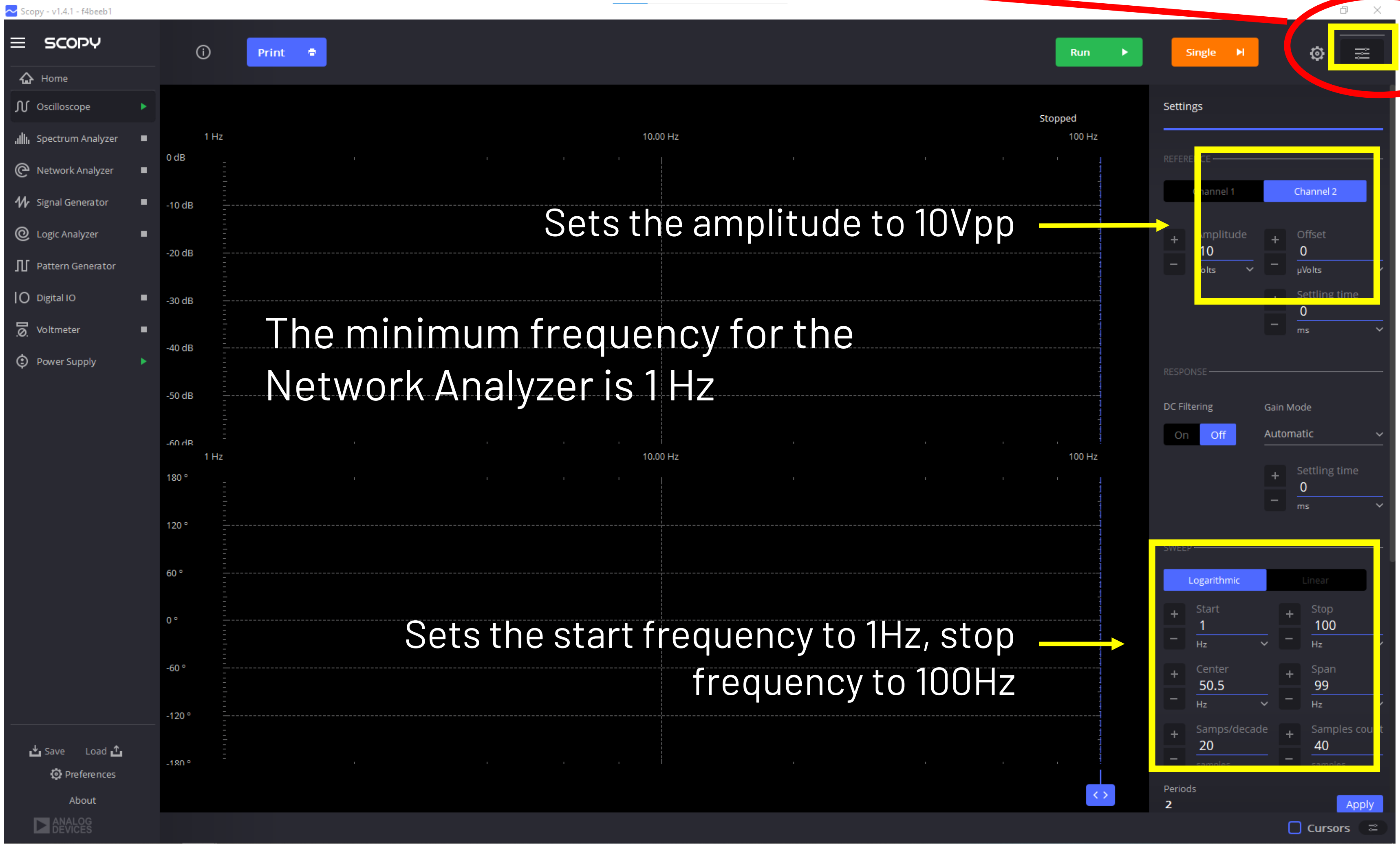
DO THIS FIRST

Double-click on the icon above and save to your preferred location on your laptop

The Network Analyzer Panel is Opened and Configured



Click Here to see the Relevant Settings

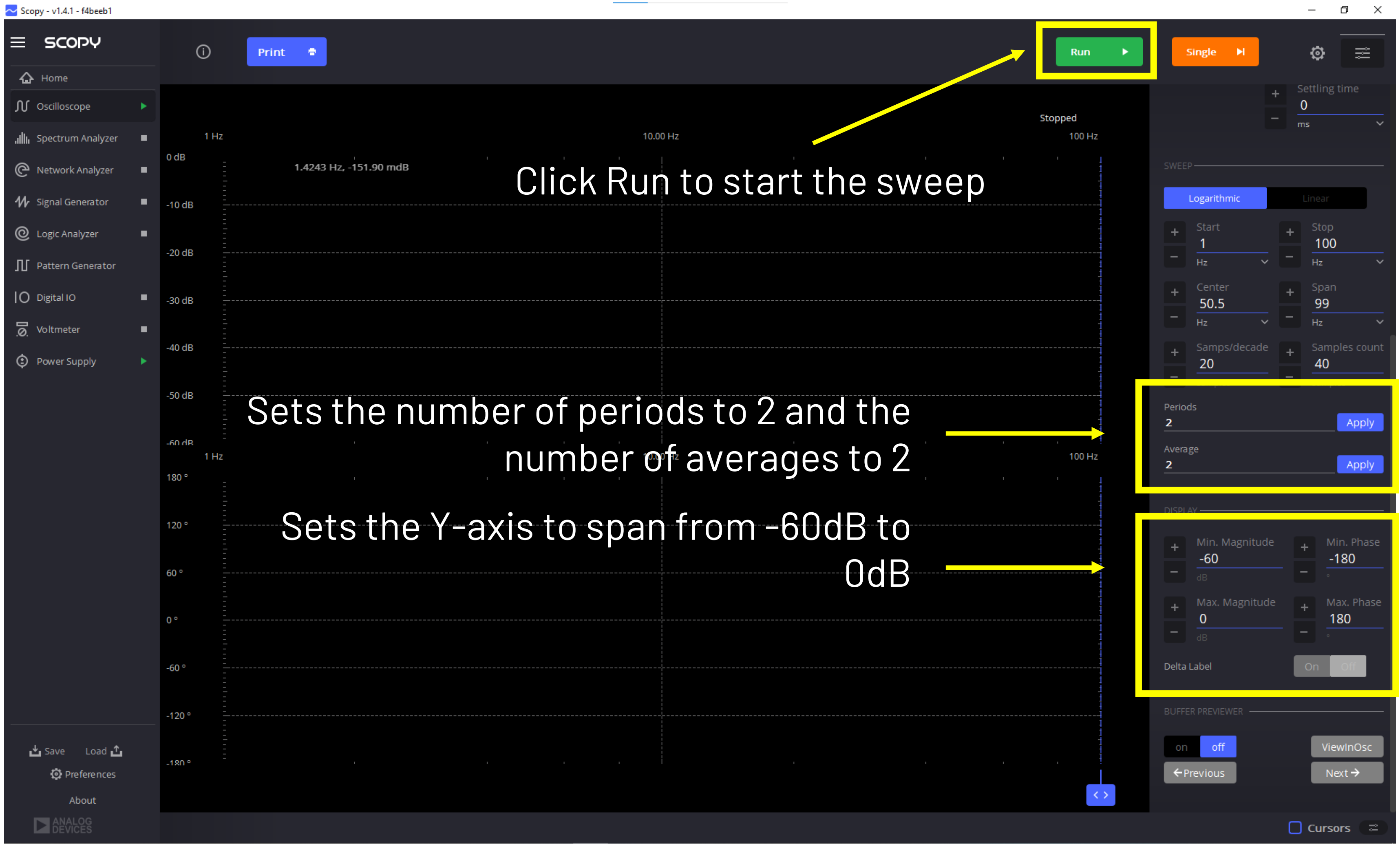


Sets the amplitude to 10Vpp

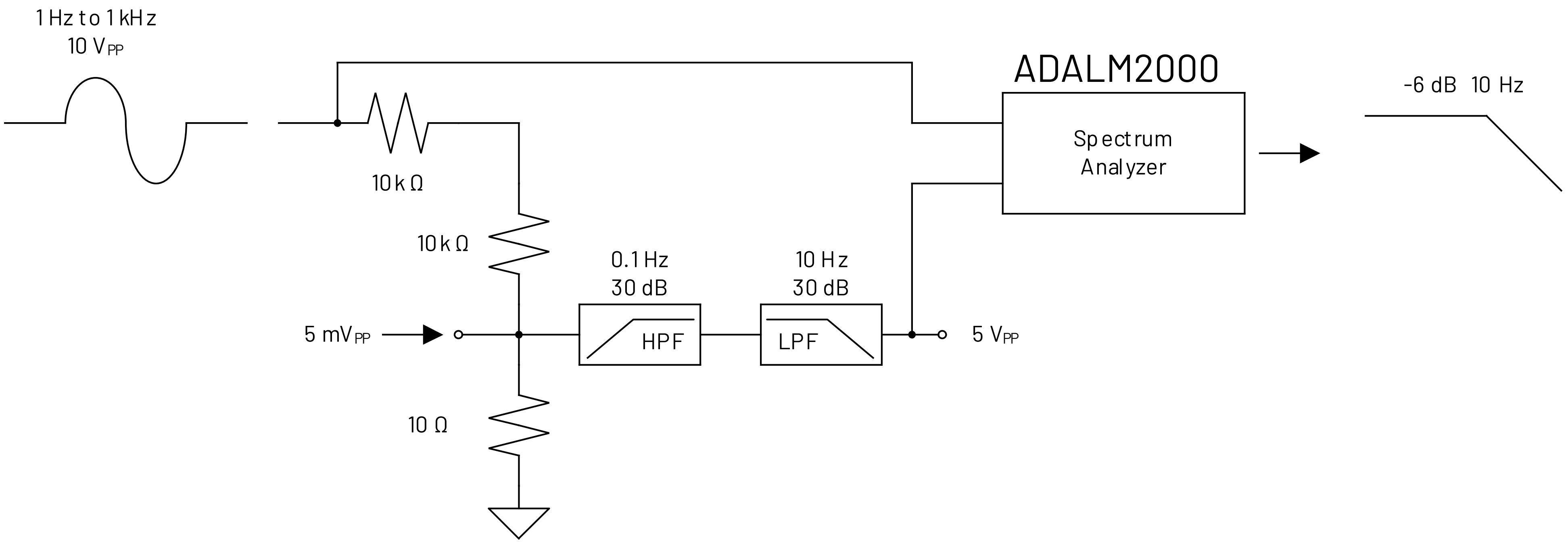
The minimum frequency for the Network Analyzer is 1 Hz

Sets the start frequency to 1Hz, stop frequency to 100Hz

Scroll Down to See Additional Config Settings

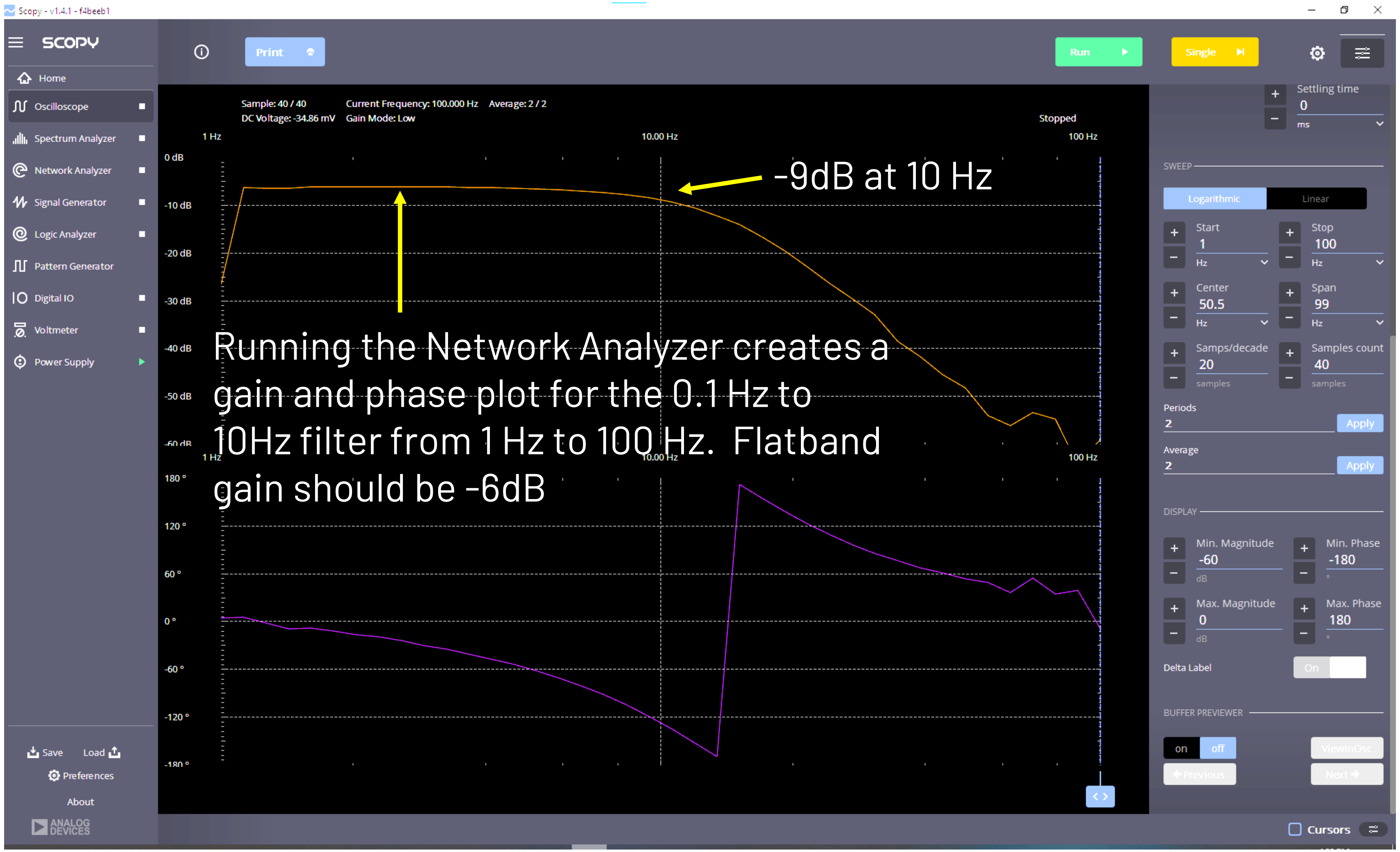


What Do We Expect to See?



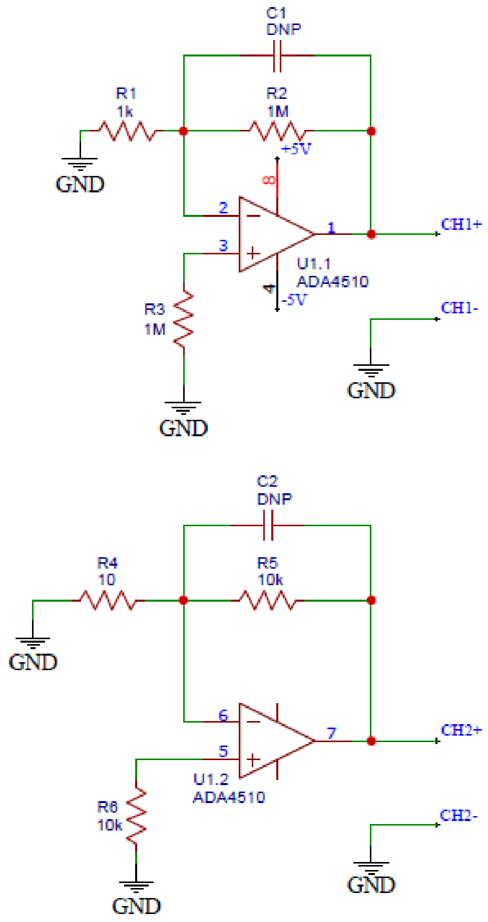
We are applying a 10 V_{PP} sinewave at the input, dividing it by 2000, multiplying by 60dB (1000) and measuring the ratio ➔ -6 dB

Typical Result for the Network Analyzer Demo

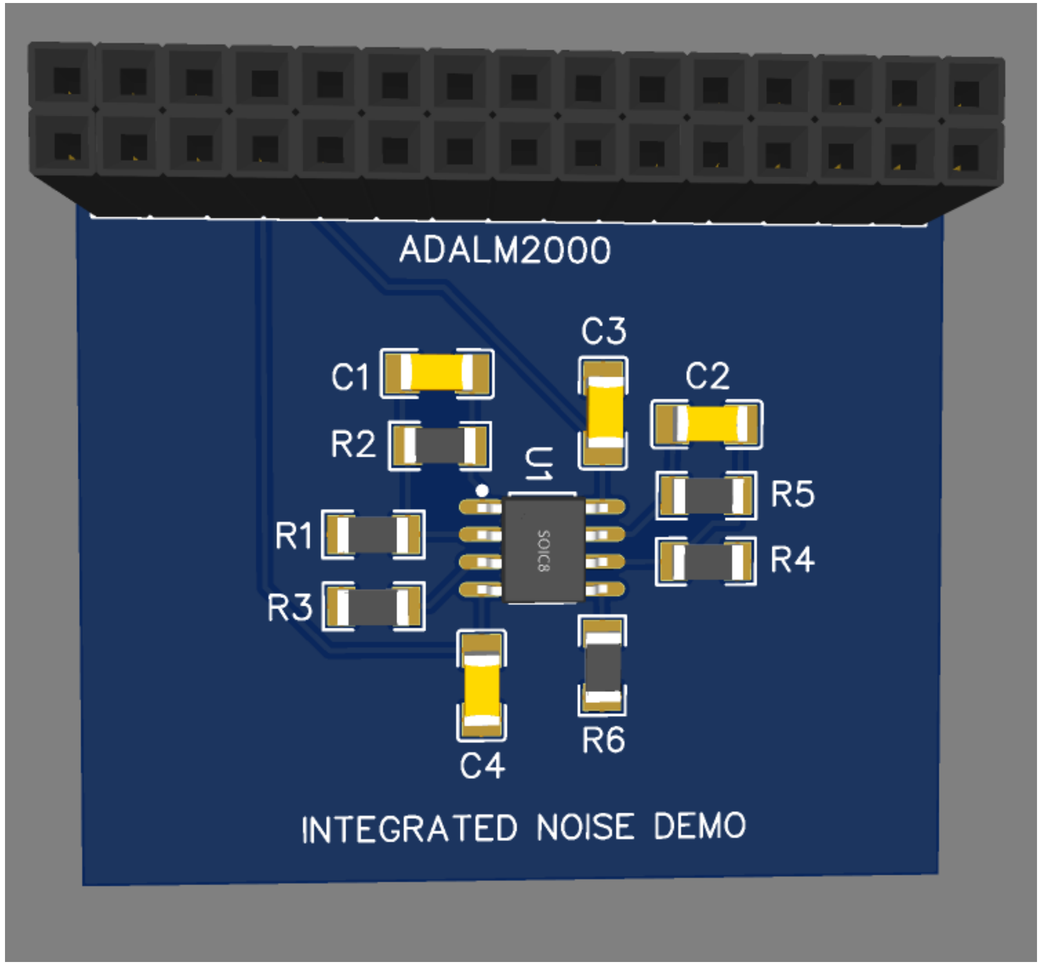


Integrated Noise Demo

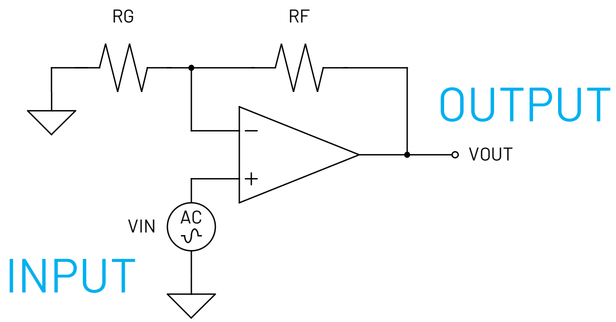
Integrated Noise Demo Board Schematic



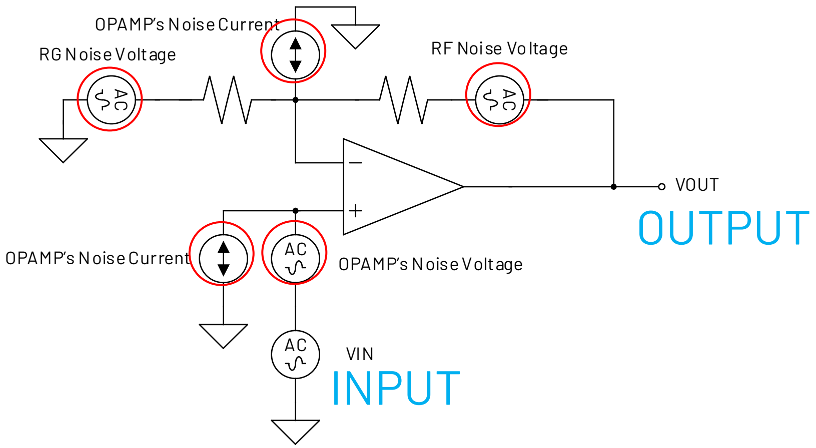
Integrated Noise Demo Board Top Side



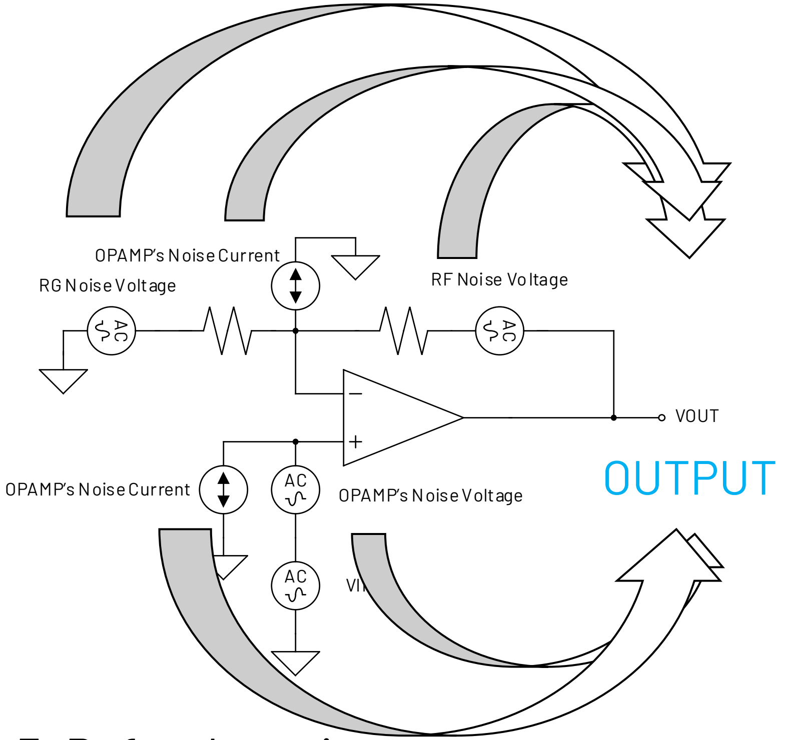
Estimate the Noise



1. Start with your circuit



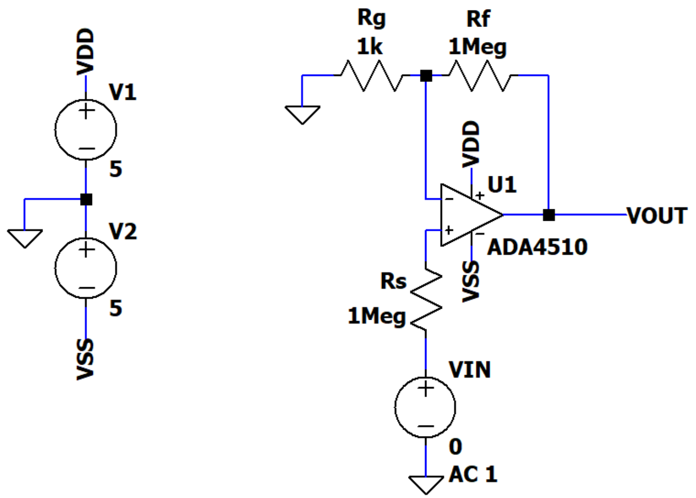
2. Add the noise sources



3. Refer the noise sources to the output

Noise Bandwidth and Noise Sources

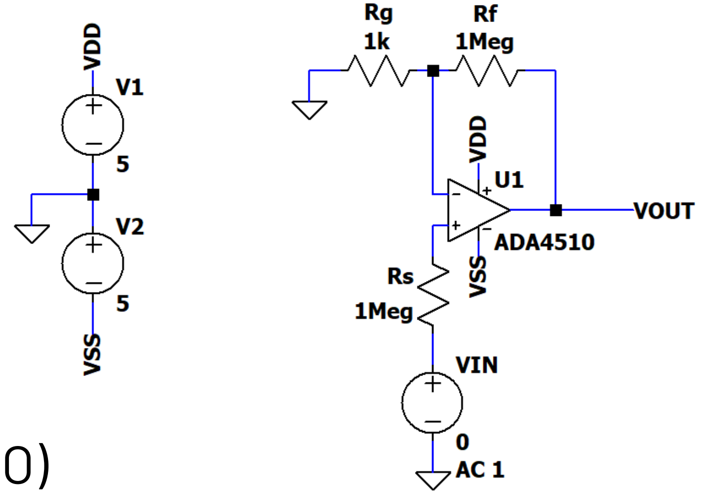
- Identify the noise Bandwidth
  - ADA4510 configured in G = 1001
    - Small-signal bandwidth = 10.4Mhz/1001 = 10.4kHz
    - Noise bandwidth = 10.4Khz * 1.57 = 16.3kHz



- Identify each noise source:
  - Rg = 1k ➔4nV/SQRT-Hz
  - Rf = 1M➔127nV/SQRT-Hz
  - Rs = 1M➔127nV/SQRT-Hz
  - ADA4510 ➔Vn = 5nV/SQRT-Hz (@16.3kHz)
  - ADA4510 ➔ In- = 200fA/SQRT-Hz (@16.3kHz)
  - ADA4510 ➔ In+ = 200fA/SQRT-Hz (@16.3kHz)

Refer to the Output

- Refer each Noise Source to the Output:
  - Rg = 1k ➔4nV/SQRT-Hz*1000 = 4µV/SQRT-Hz (RTO)
  - Rf = 1M➔127nV/SQRT-Hz*1 = 127nV/SQRT-Hz (RTO)
  - Rs = 1M➔127nV/SQRT-Hz*1001 = 127µV/SQRT-Hz (RTO)
  - ADA4510 ➔Vn = 5nV/SQRT-Hz (@16.3kHz)*1001 = 5µV/SQRT-Hz (RTO)
  - ADA4510 ➔ In- = 200fA/SQRT-Hz (@16.3kHz) *1M= 200nV/SQRT-Hz (RTO)
  - ADA4510 ➔ In+ = 200fA/SQRT-Hz (@16.3kHz)*1M*1001 = 200µV/SQRT-Hz (RTO)



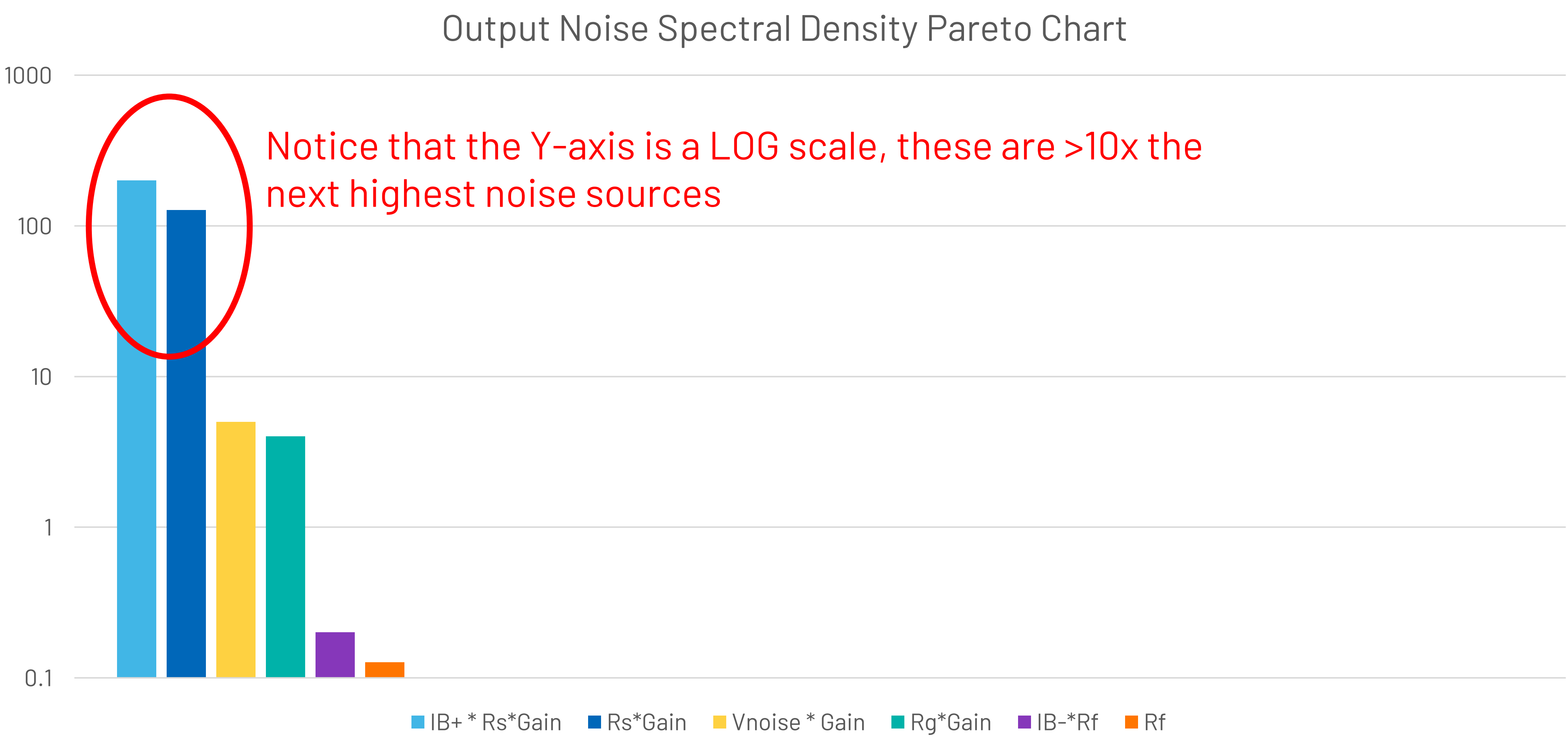
Sum the NSD at the output:

$$V_{OUT_{NSD@16.3kHz}} = \sqrt{\left(4\mu V/\sqrt{Hz}\right)^2 + \left(127nV/\sqrt{Hz}\right)^2 + \left(127\mu/\sqrt{HzV}\right)^2 + \left(5\mu V/\sqrt{Hz}\right)^2 + \left(200nV/\sqrt{Hz}\right)^2 + \left(200\mu V/\sqrt{Hz}\right)^2} = 237\mu V/\sqrt{Hz}$$

Estimate the Total Noise:

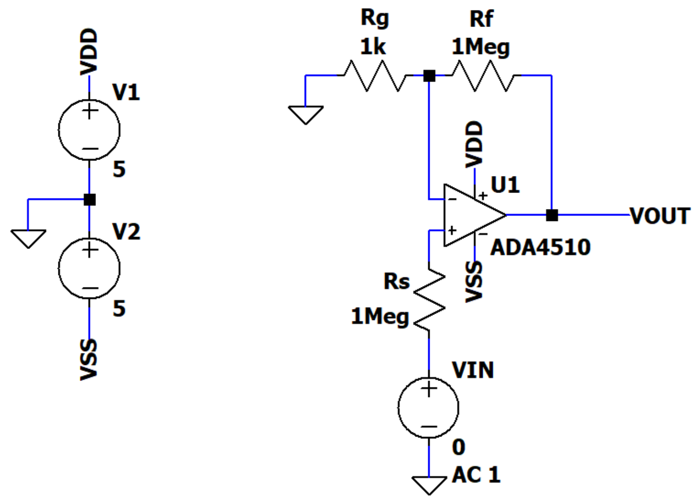
$$V_{OUT_{TOTALNOISE V_{PP}}} = 6.6 \times 237\mu V/\sqrt{Hz} \times \sqrt{16.3kHz} = 200mV_{PP}$$

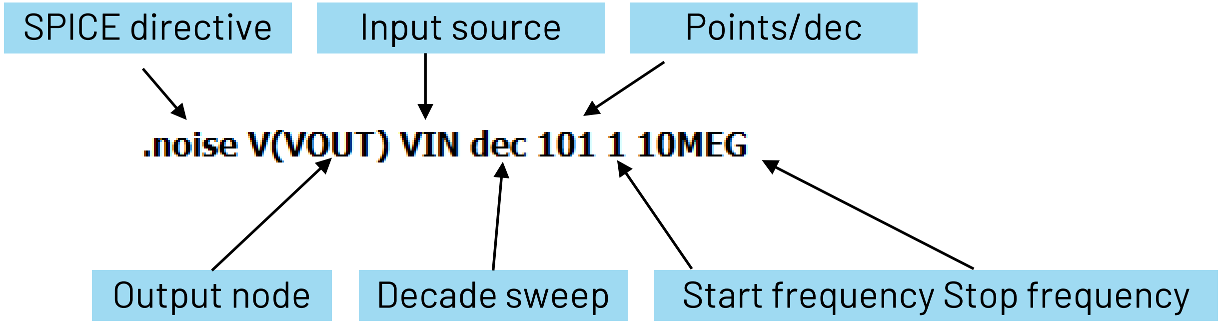
Identify Dominant Noise Sources



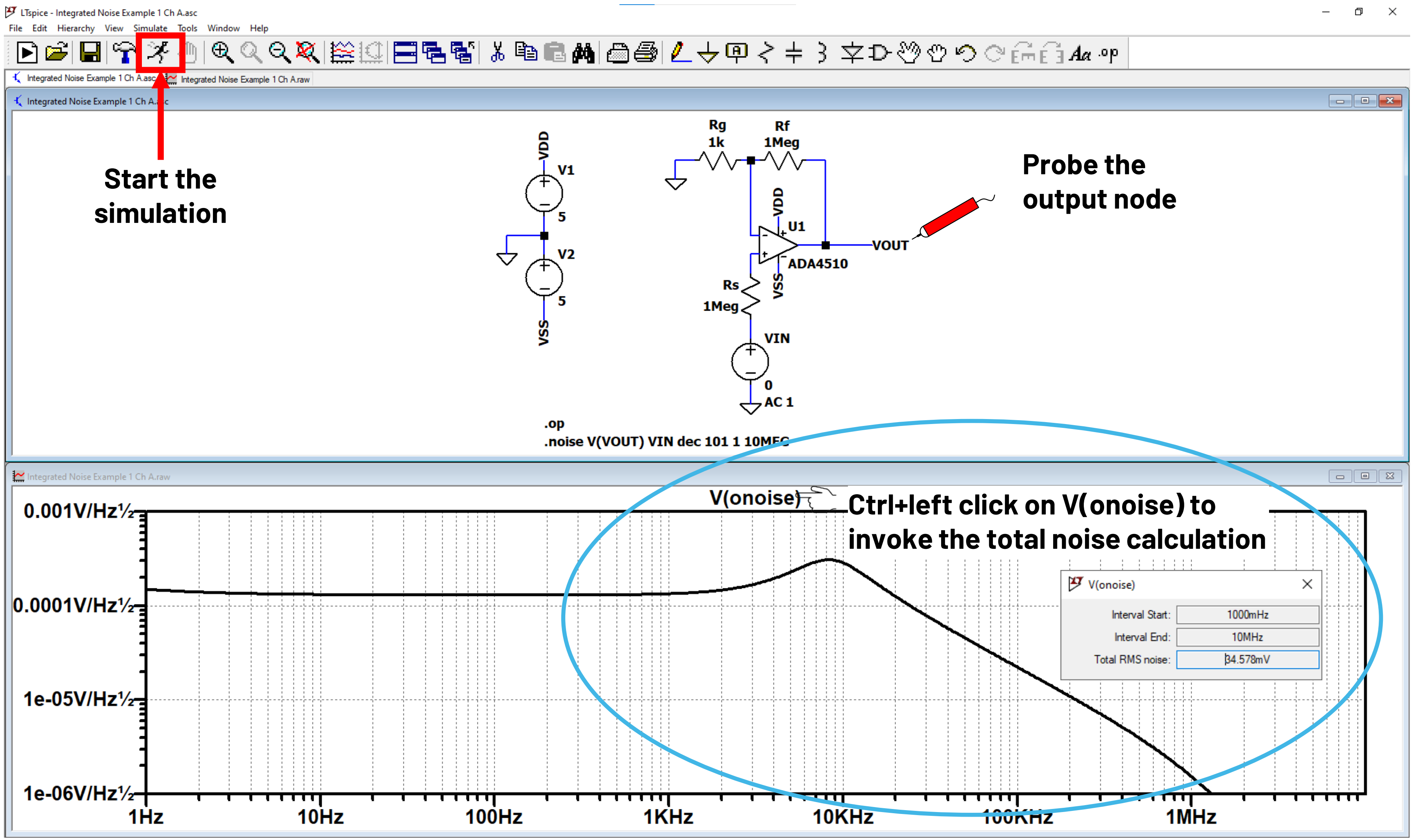
Simulating Noise in LTSpice

- Add the .noise command as a SPICE directive with the listed arguments:
  - Output: The **node** where you want to examine the ***output referred noise***
  - Input: The **source** where you want to examine the ***input referred noise***
  - Type of sweep: octave, decade, linear or list
  - Number of points: per octave, per decade, etc
  - Start Frequency: Lowest frequency in the sweep in Hz
  - Stop Frequency: Highest frequency in the sweep in Hz

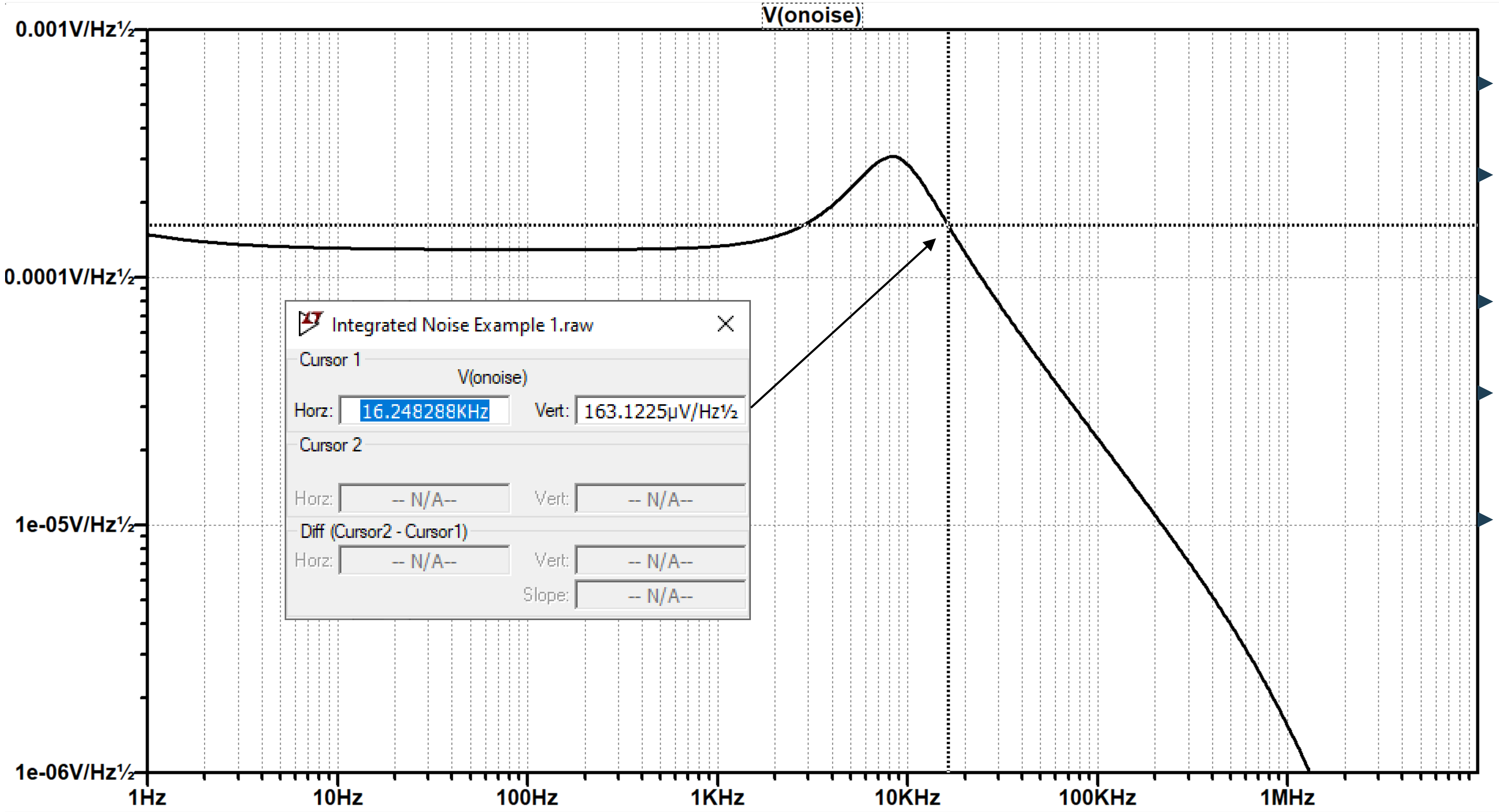




Simulating Noise in LTSpice

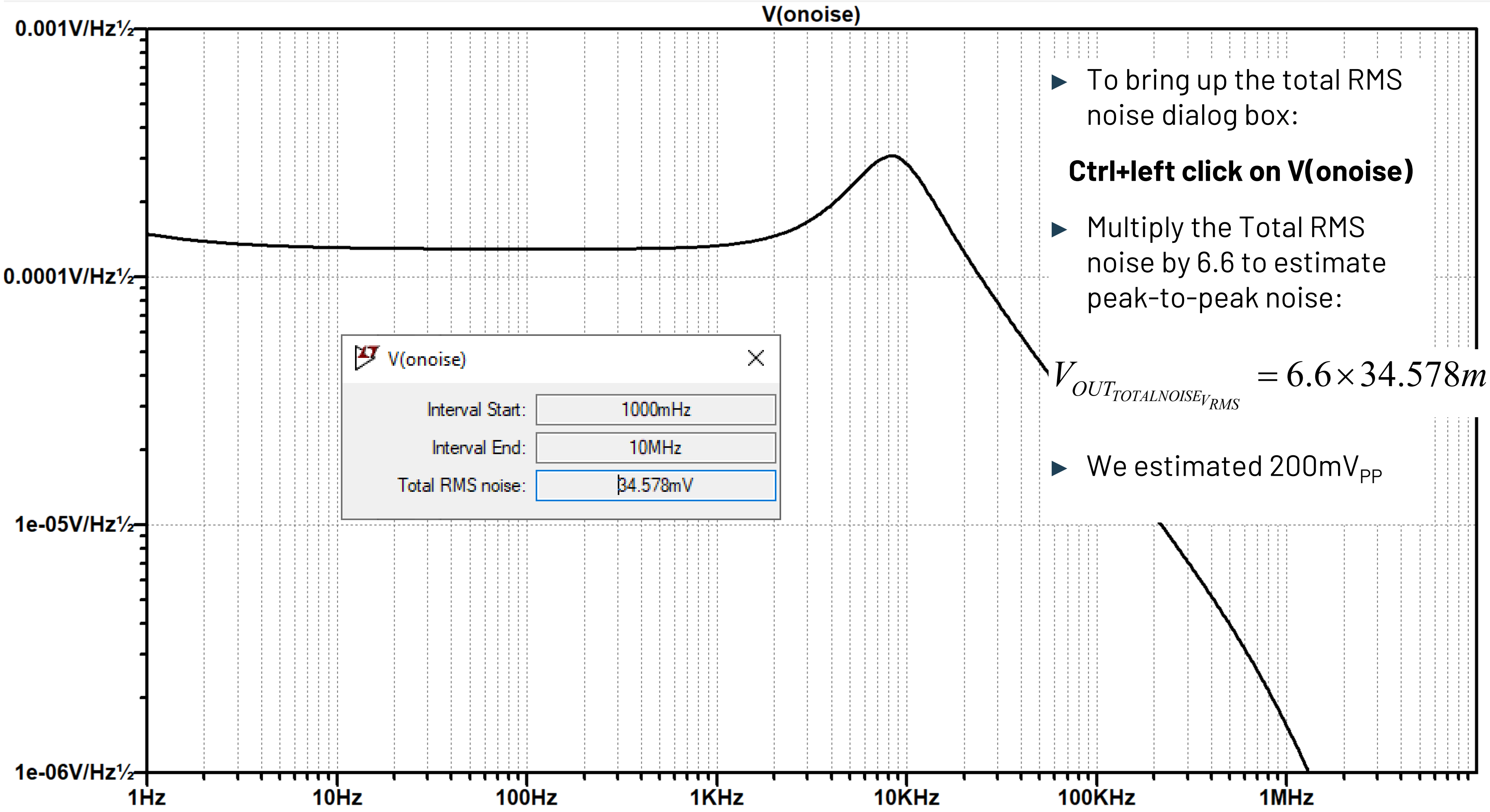


Output Referred Noise Spectral Density



- Place the cursor at the noise bandwidth of 16.3kHz
- We estimated 237 µV/√Hz at the noise bandwidth of 16.3 kHz
- This is slightly past the -3dB point
- Calculating ~3dB down from our estimate we would expect 167 µV/√Hz
- The simulation shows 163 µV/√Hz

Total Noise



- To bring up the total RMS noise dialog box:

Ctrl+left click on V(onoise)

- Multiply the Total RMS noise by 6.6 to estimate peak-to-peak noise:

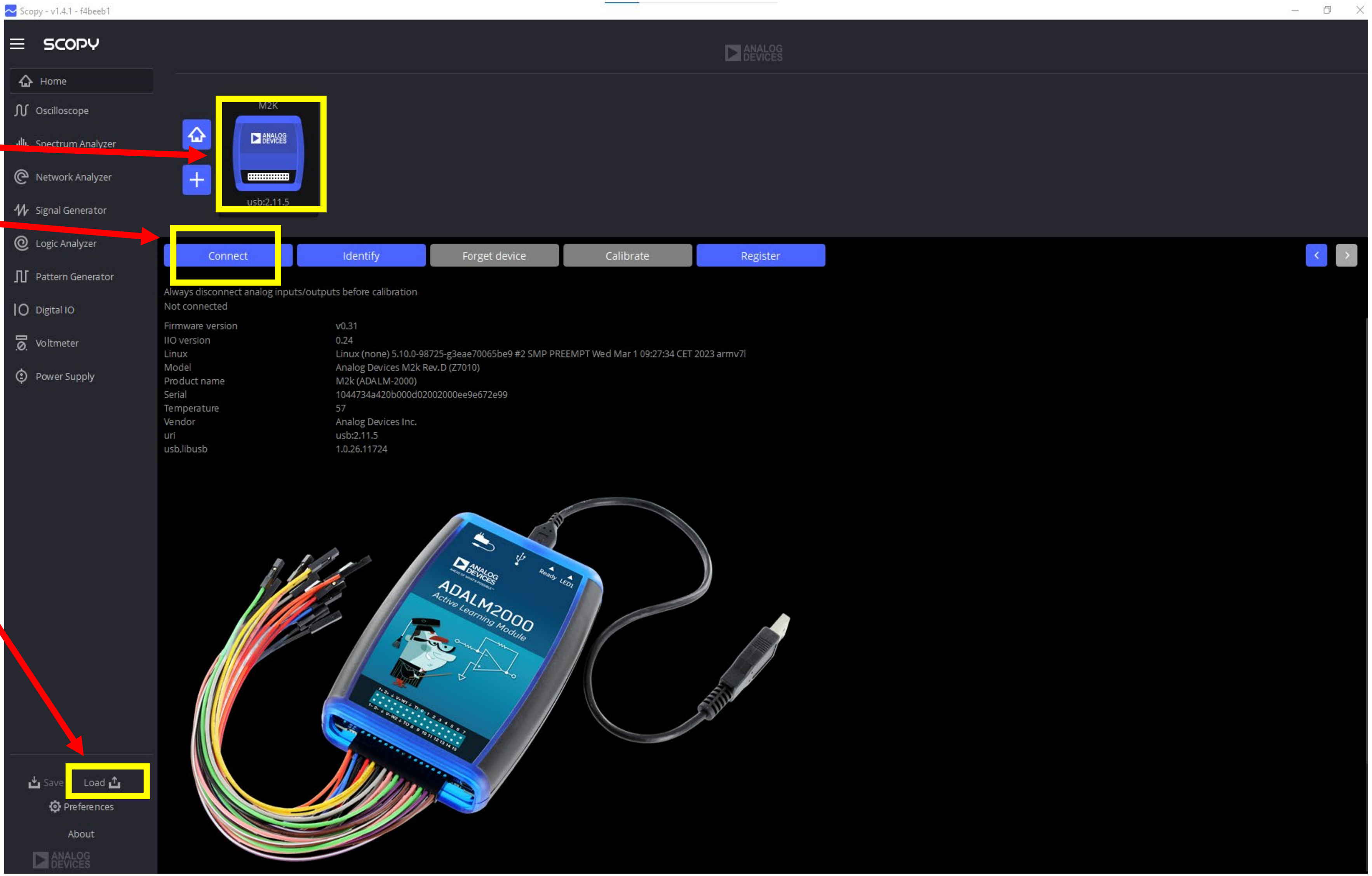
$$V_{OUT_{TOTALNOISE_{V_{RMS}}}} = 6.6 \times 34.578mV = 228mV_{PP}$$

- We estimated $200mV_{PP}$

Launch Scopy and Load Config File

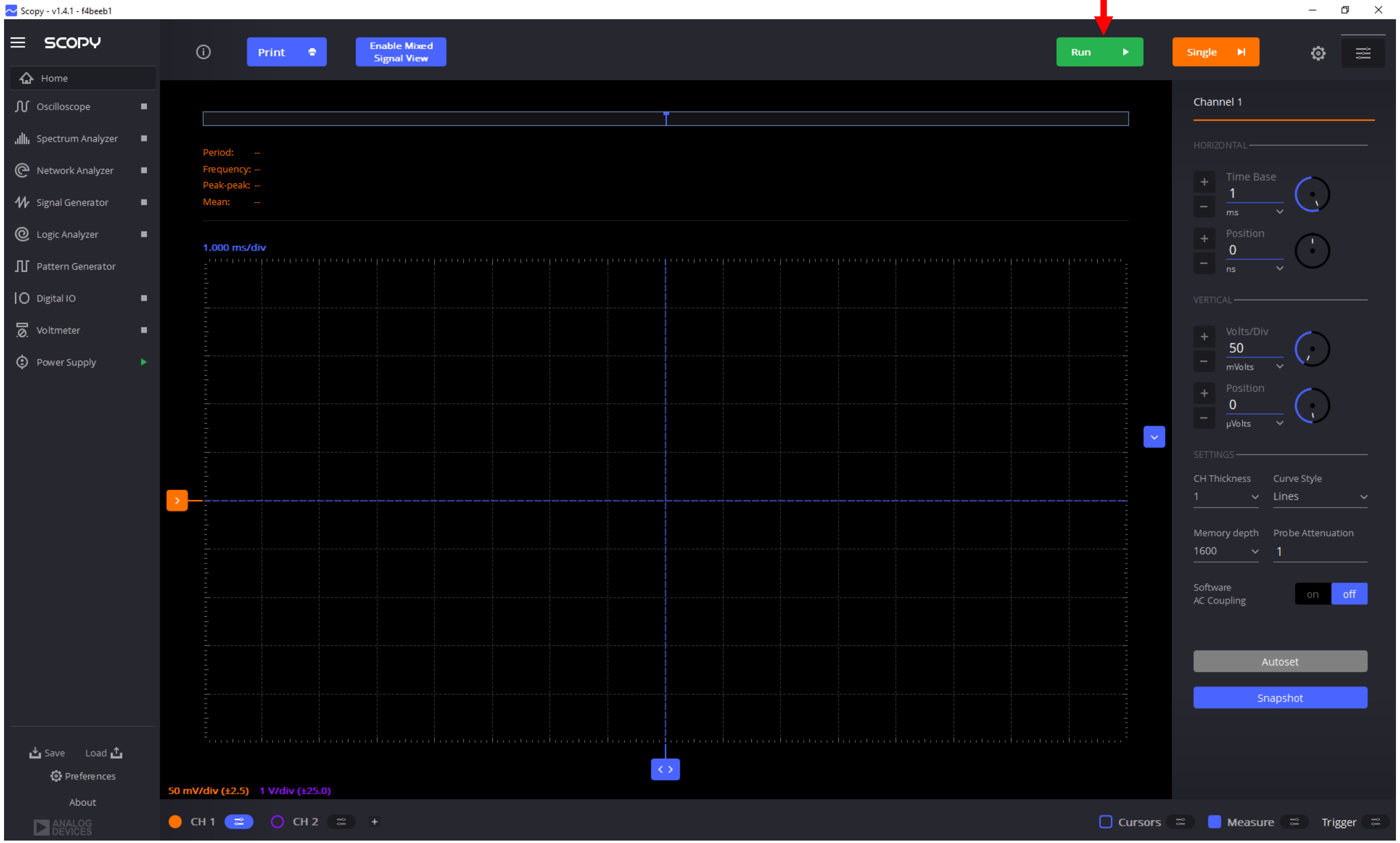
- Connect the ADALM2000 to your laptop and launch Scopy
- Click on the M2K icon
- Click connect
- Once connected click on load and load the file named:

"**Integrated Noise Scopy Config.ini**"



Let’s Have a Look at the Total Noise

- Click “Run” to start the oscilloscope

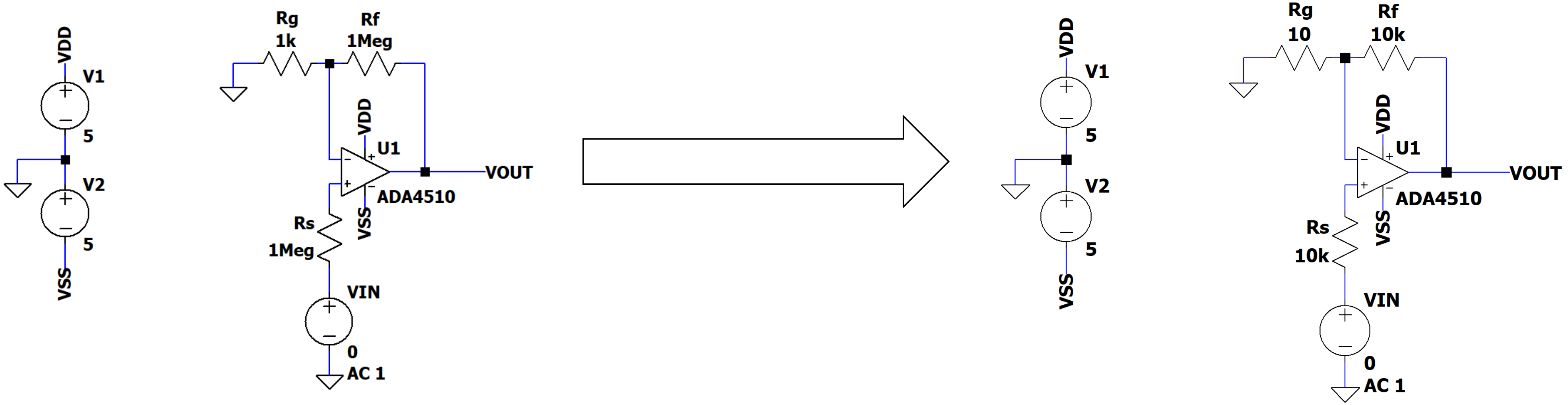


Review the Result…is it about what you expected?

- You can click the stop button and look at the peak-to-peak measurement
- Try running and stopping a few times…you will notice some variation in the result…this is the nature of noise
- *If your result seems too high, you might be picking up external noise (the circuit has very high impedances and is in a high gain) try moving the board or rotating it to reduce any external interference* ☺

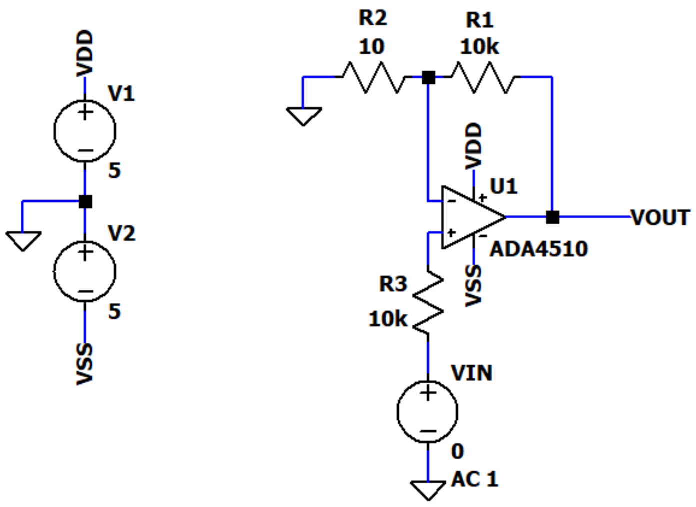
Reducing the Noise

- In the previous example we saw that the dominant sources of noise were the IB+ noise current multiplied by the source impedance multiplied by the gain and the voltage noise of the source resistance multiplied by the gain
- Let's reduce all the impedance values by 100, keeping the same gain, but with less noise contribution from IB+ and Rs



Example for a Simple Non-Inverting Amplifier

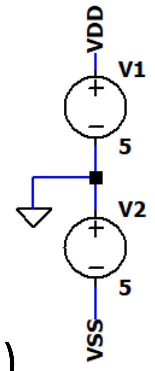
- Identify the noise Bandwidth
  - ADA4510 configured in G = 1001
    - Small-signal bandwidth = 10.4Mhz/1001 = 10.4kHz
    - Noise bandwidth = 10.4Khz * 1.57 = 16.3kHz

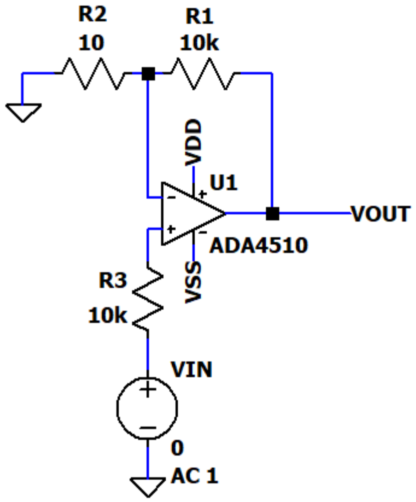


- Identify each noise source:
  - Rg = 10 ➔0.4nV/SQRT-Hz
  - Rf = 10k➔12.7nV/SQRT-Hz
  - Rs = 1k➔12.7nV/SQRT-Hz
  - ADA4510 ➔Vn = 5nV/SQRT-Hz (@16.3kHz)
  - ADA4510 ➔ In- = 200fA/SQRT-Hz (@16.3kHz)
  - ADA4510 ➔ In+ = 200fA/SQRT-Hz (@16.3kHz)

Example for a Simple Non-Inverting Amplifier

- Refer each Noise Source to the Output:
  - Rg = 10 ➔0.4nV/SQRT-Hz*1000 = 0.4µV/SQRT-Hz (RTO)
  - Rf = 10k➔12.7nV/SQRT-Hz*1 = 12.7nV/SQRT-Hz (RTO)
  - Rs = 10k➔12.7nV/SQRT-Hz*1001 = 12.7µV/SQRT-Hz (RTO)
  - ADA4510 ➔Vn = 5nV/SQRT-Hz (@16.3kHz)*1001 = 5µV/SQRT-Hz (RTO)
  - ADA4510 ➔ In- = 200fA/SQRT-Hz (@16.3kHz) *10k= 2nV/SQRT-Hz (RTO)
  - ADA4510 ➔ In+ = 200fA/SQRT-Hz (@16.3kHz)*10k*1001 = 2µV/SQRT-Hz (RTO)





Sum the NSD at the output:

$$V_{OUT_{NSD@16.3kHz}} = \sqrt{\left(0.4\mu V/\sqrt{Hz}\right)^2 + \left(12.7nV/\sqrt{Hz}\right)^2 + \left(12.7\mu/\sqrt{Hz}V\right)^2 + \left(5\mu V/\sqrt{Hz}\right)^2 + \left(2nV/\sqrt{Hz}\right)^2 + \left(2\mu V/\sqrt{Hz}\right)^2} = 14\mu V/\sqrt{Hz}$$

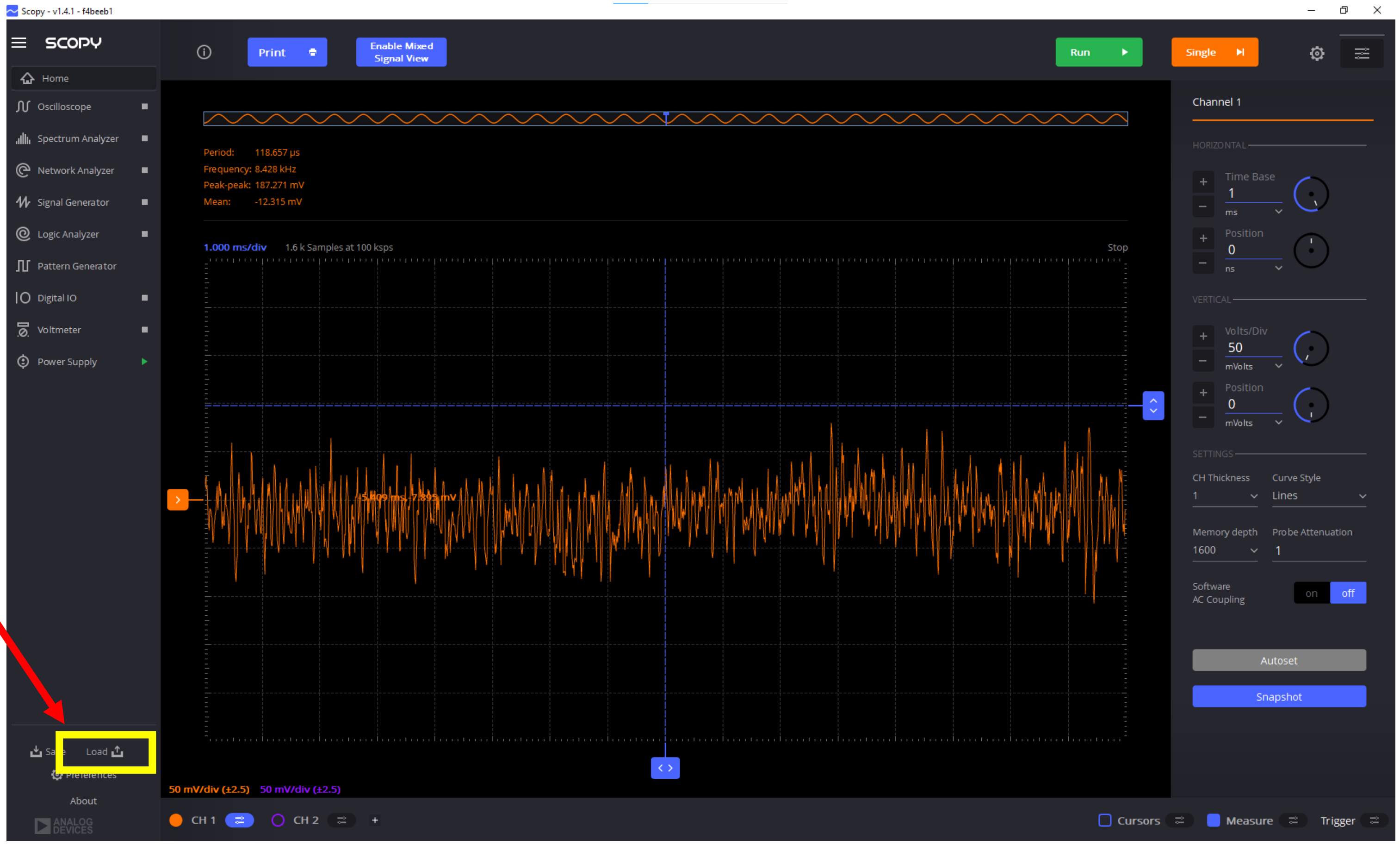
Estimate the Total Noise:

$$V_{OUT_{TOTALNOISE_{V_{PP}}}} = 6.6 \times 14\mu V/\sqrt{Hz} \times \sqrt{16.3kHz} = 12mV_{PP}$$

Load Config File

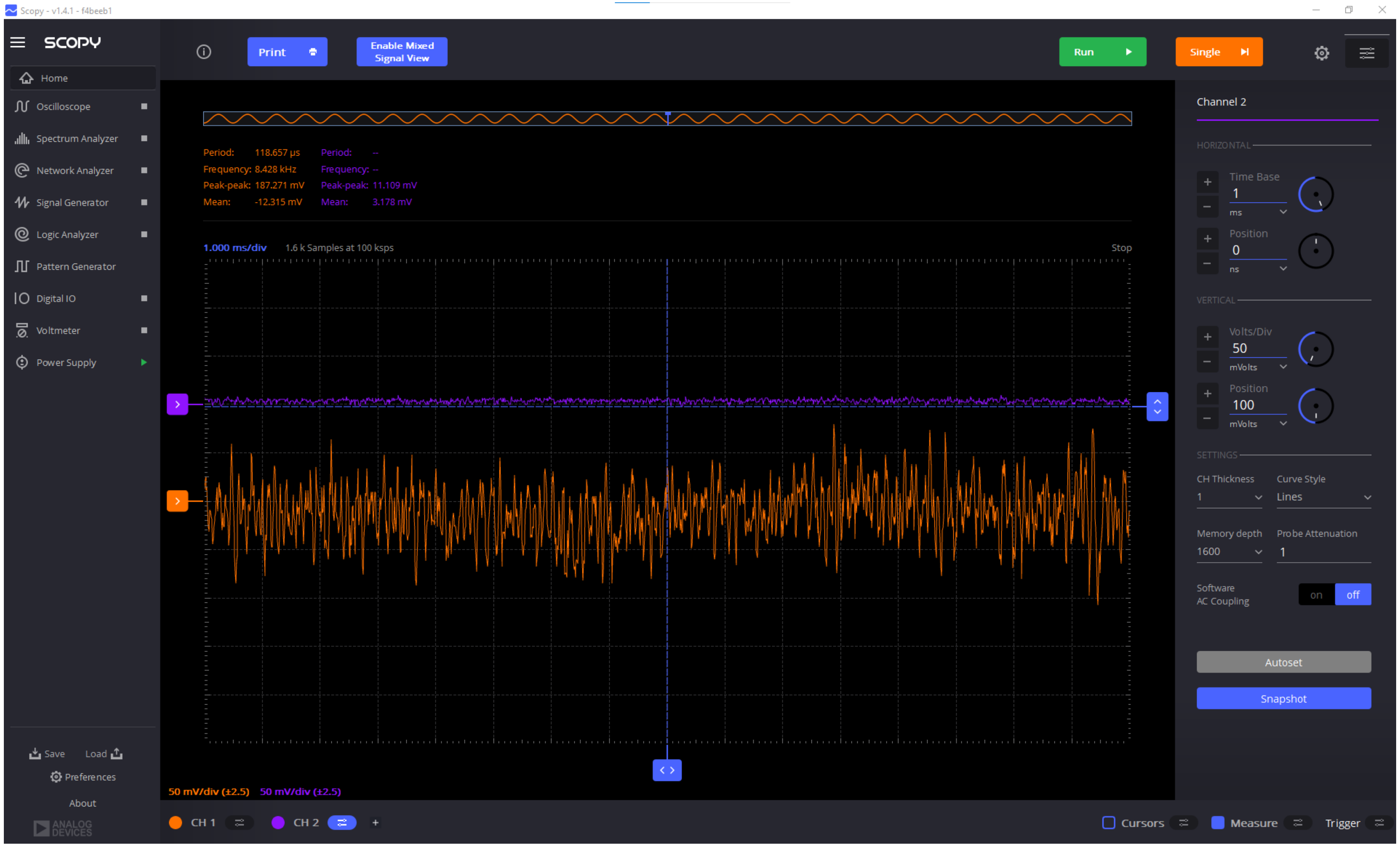
- Load the file named:

“Integrated Noise Scopy Config Ch B.ini”



Let’s Have a Look at the Total Noise

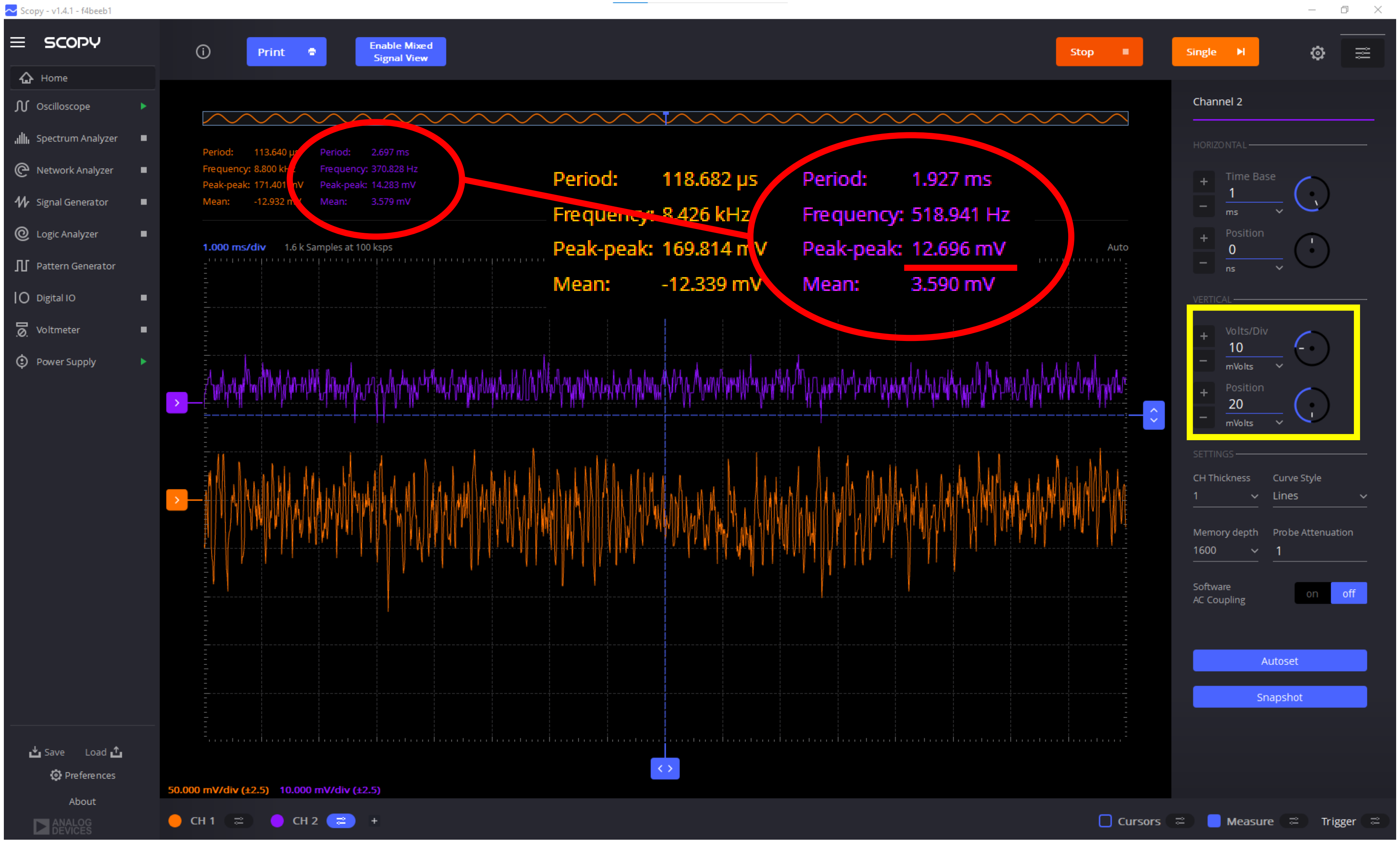
- Click “Run” to start the oscilloscope



- Click “Run” to start the oscilloscope
- Notice both Ch1 and Ch2 are on the same scale
- You see how much the noise is reduced

Let's Zoom In and Measure

- Click "Run" to start the oscilloscope



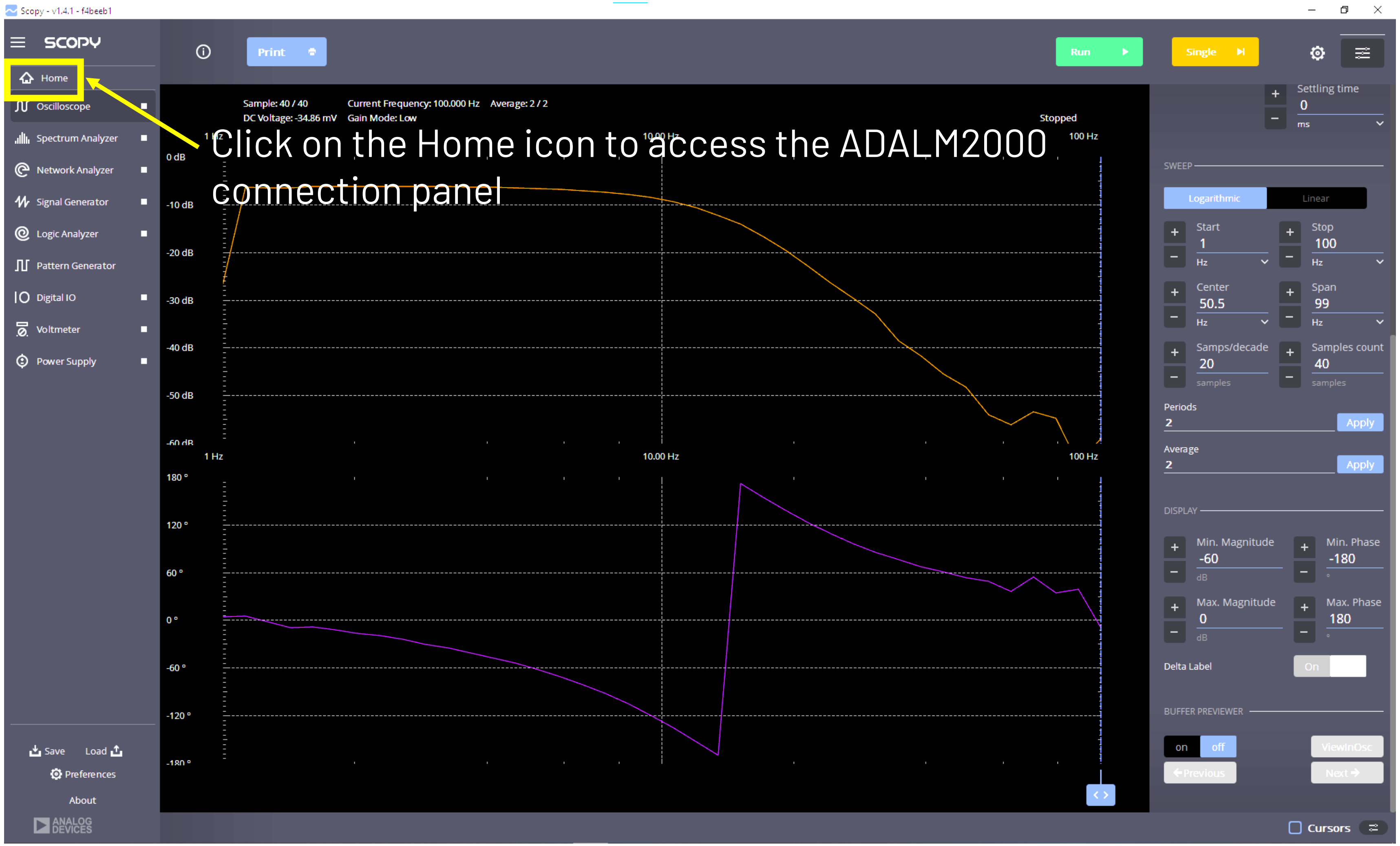
- Change Ch 2 to 10mV/Div
- Change Ch2 Position to 20mV
- Measure the peak-to-peak noise

Shutting Down

Shutting Down

Click on the green triangle icon next to the Power Supply label…it will turn into a grey box. It is now safe to disconnect the PCB from the ADALM2000

Shutting Down



Click on the Disconnect Button

You may first need to click on this icon if the option to disconnect does not automatically appear

Click on the Disconnect button. It is now safe to disconnect the ADALM2000 from your laptop

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Thank You!