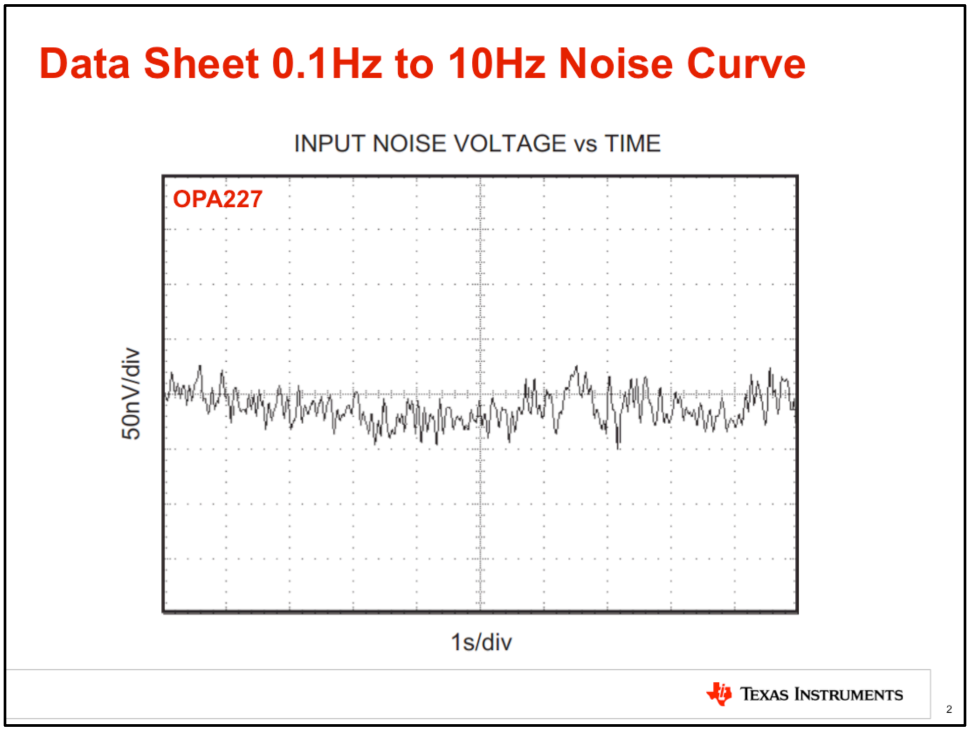
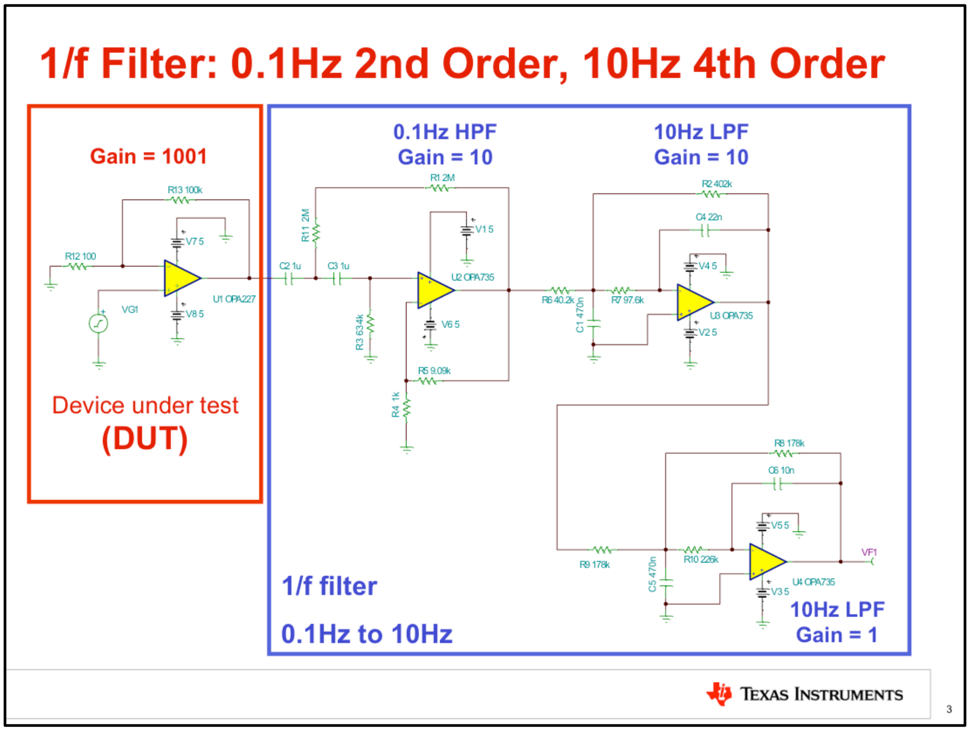
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 8.

In the previous videos we introduced methods for calculating, simulating, and measuring noise. In this video we will dive a little deeper into the topic of 1/f, or flicker, noise. Specifically, we will discuss the 0.1Hz to 10Hz noise plots that are included in most op amp data sheets. We will cover how these plots are generated and explain their significance, and we'll also discuss the differences between long-term noise measurements in standard amplifiers compared to zero-drift amplifiers.



Throughout this video series on noise, we have mainly discussed op amp noise spectral density curves. Most amplifiers also have a 0.1Hz to 10Hz noise plot. Some data sheets also list the 0.1Hz to 10Hz peak-to-peak noise in the electrical characteristics table. The objective of these curves and specs is to provide a quick and easy to understand representation of 1/f noise, which occurs at low frequency. Sometimes engineers use this curve as the basis for comparing the noise performance of amplifiers to each other. However, this is only a good comparison if low frequency noise is the dominant factor. In general, it is better to directly compare the op amps' spectral density curves, or do a full analysis to find the lowest noise solution.

It is important to note that 1/f noise curves are always referred to the input. The output noise can then be determined by multiplying by your circuit's noise gain.



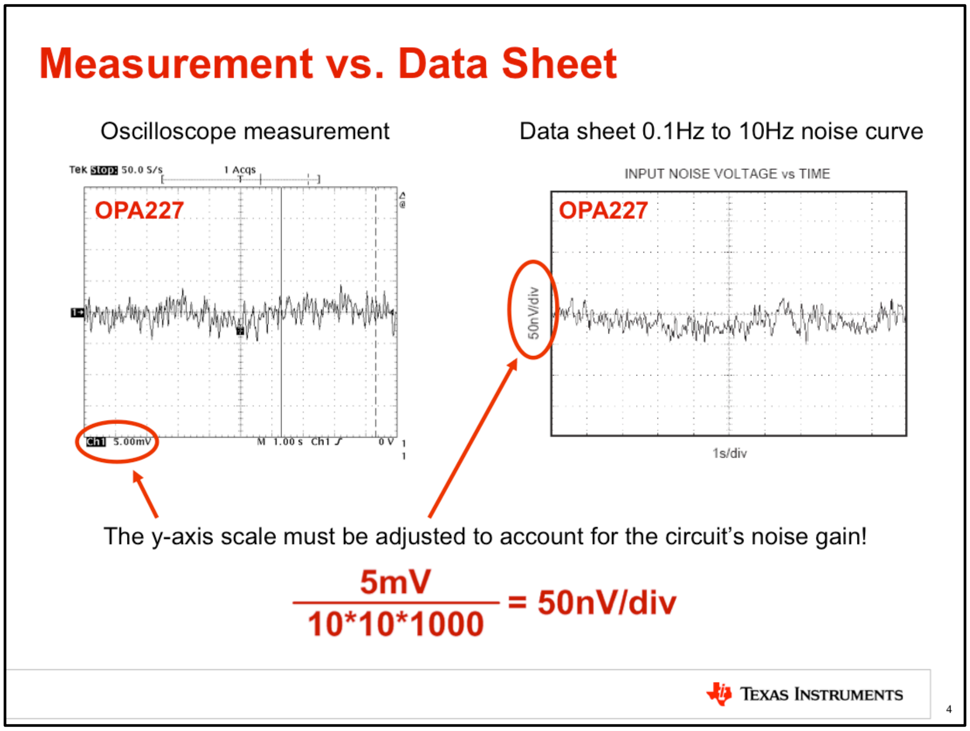
This circuit illustrates a common test configuration used to measure the 0.1Hz to 10Hz noise plot.

The device under test, commonly called a DUT, is normally configured in high gain in order to increase the amplitude of the noise to a level that can be easily measured by an oscilloscope. The test circuit contains three active filters:

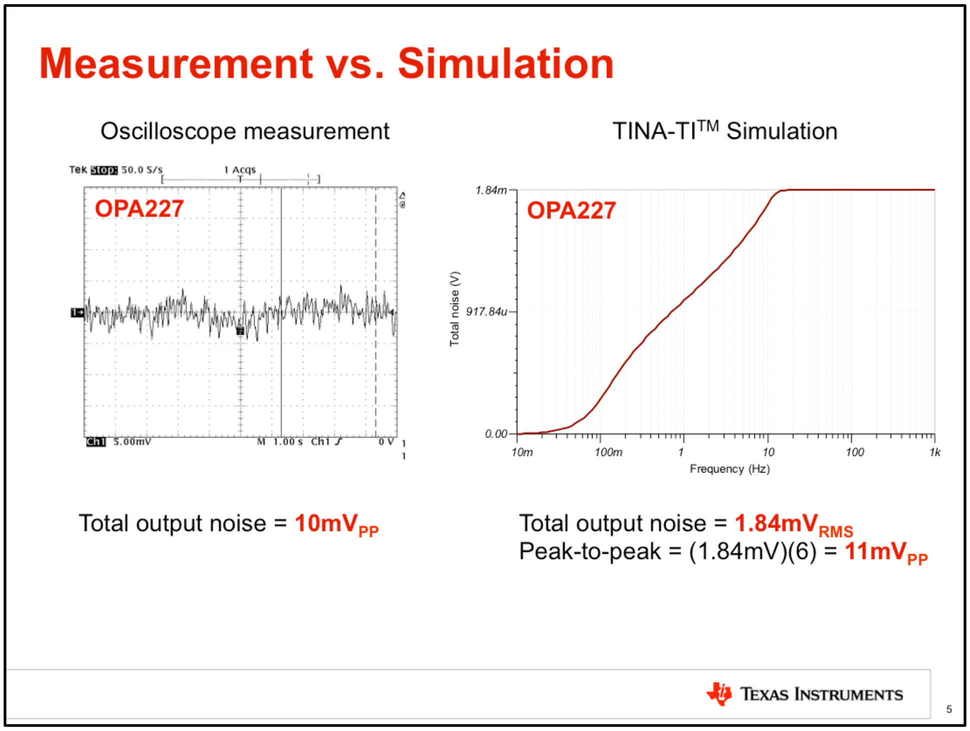
The first stage of the active filter is a 0.1Hz high pass filter in a gain of 10.
The second stage of the amplifier is a 10Hz low pass filter in a gain of 10.
The third stage is another 10Hz low pass filter in a gain of 1.

The overall gain of this system is very high at 100,000V/V, or 100dB. The combined filter response is a second order 0.1Hz high pass filter and a fourth order 10Hz low pass filter. The objective is to have a “brick wall” band pass filter from 0.1Hz to 10Hz, and although this filter is not a true brick wall filter, it is close enough to get the desired effect.

This circuit is documented in detail as a free TI Precision Design. More information and a link to the design is given at the end of this presentation.

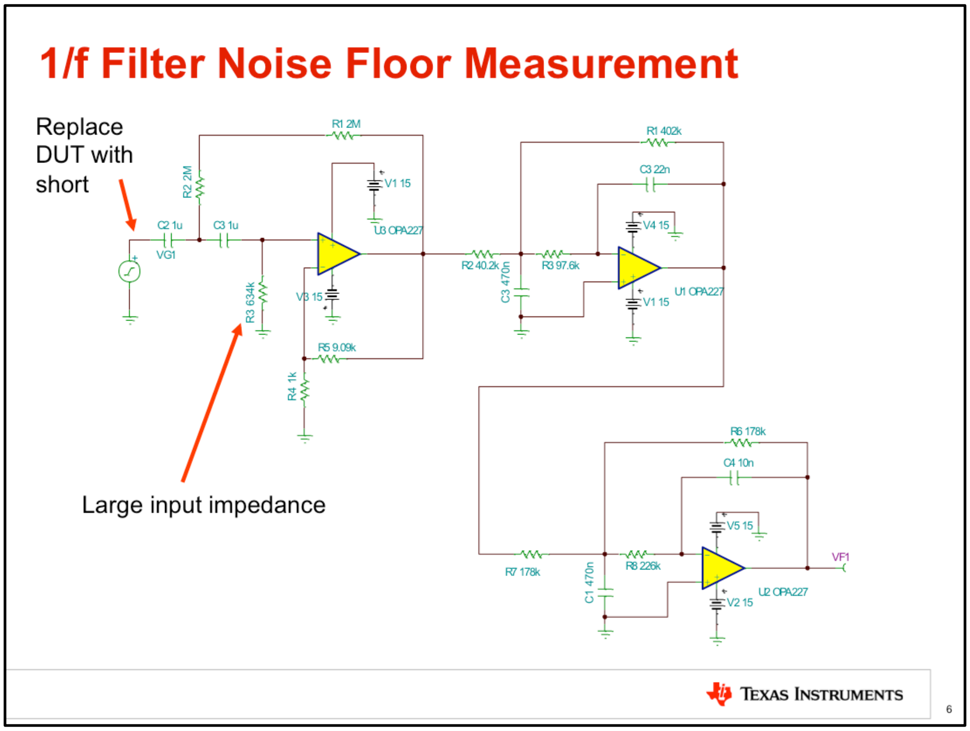


The plot on the left shows the measurement made using the circuit from the previous slide. The figure on the right is from the OPA227 data sheet. Note that the data sheet curve is referred to the input. To make the plot on the left referred to the input, divide by the noise gain of 100,000. In this example, the measured result is very similar to the data sheet curve after the y-axis scale is adjusted.



Of course, the circuit's noise can also be simulated using TINA-TI. If you need a refresher on how to simulate op amp noise in TINA, watch part 5 and 6 of this video series.

The TINA noise analysis gives the total noise to be 1.84mVrms. We can convert to peak-to-peak noise by using the 6 x RMS relationship. Note that the results are quite close - 10mVpp with measurement, and 11mVpp in simulation.



In order to be confident that a noise measurement is accurate, it is always important to look at the test circuit's noise floor. In this case, the device under test should be replaced with a short circuit. Note that the type of op-amp used in the filter can affect the noise floor, since some amplifiers are optimized for low-noise performance. How do we determine which amplifier would work best for this application? Lets consider a few alternatives.

1/f Filter Noise Floor Measurement

Which op amp will give us the lowest noise floor?

Op amp	General description	V_N (nV/√Hz)	I_N (fA/√Hz)
OPA227	Low noise Bipolar	3.5 @10Hz 6 @1Hz 20 @0.1Hz	2,000 @10Hz 6,000 @1Hz 20,000 @0.1Hz
OPA132	Low noise CMOS	23 @10Hz 80 @1Hz 228 @0.1Hz	3
OPA735	Auto zero CMOS	135	40

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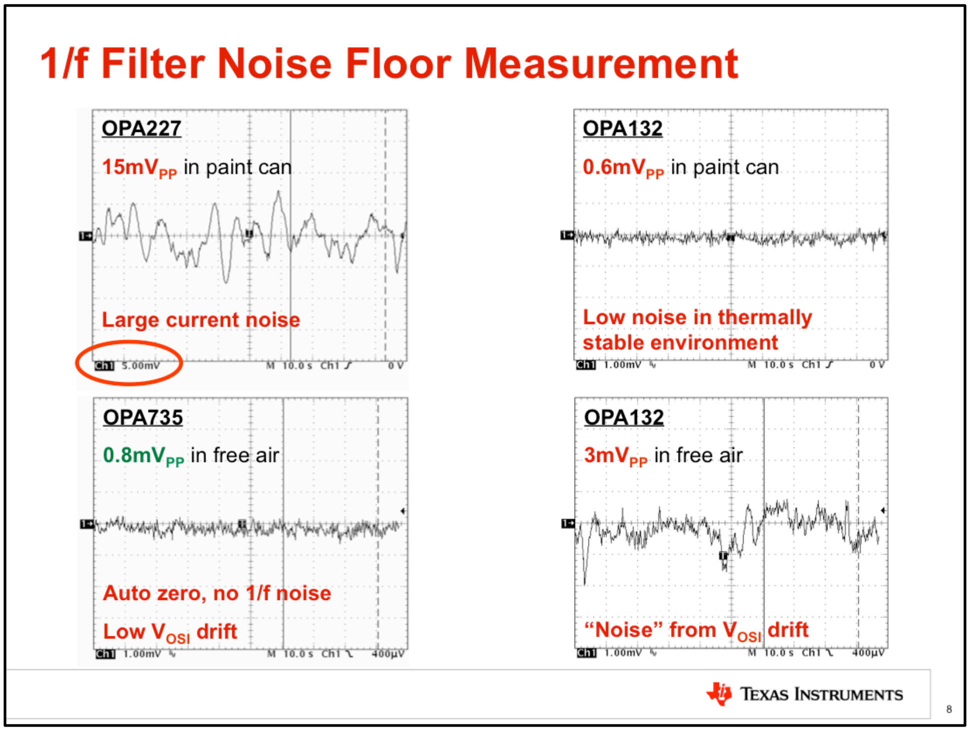
The OPA227 is a low noise, bipolar op amp. Intuitively, this seems like the best choice because of the low voltage noise; however, the current noise on this device is relatively high, especially at very low frequency. This application has high input impedance, so current noise may be significant.

The OPA132 has higher voltage noise than the OPA227, but relatively low current noise .

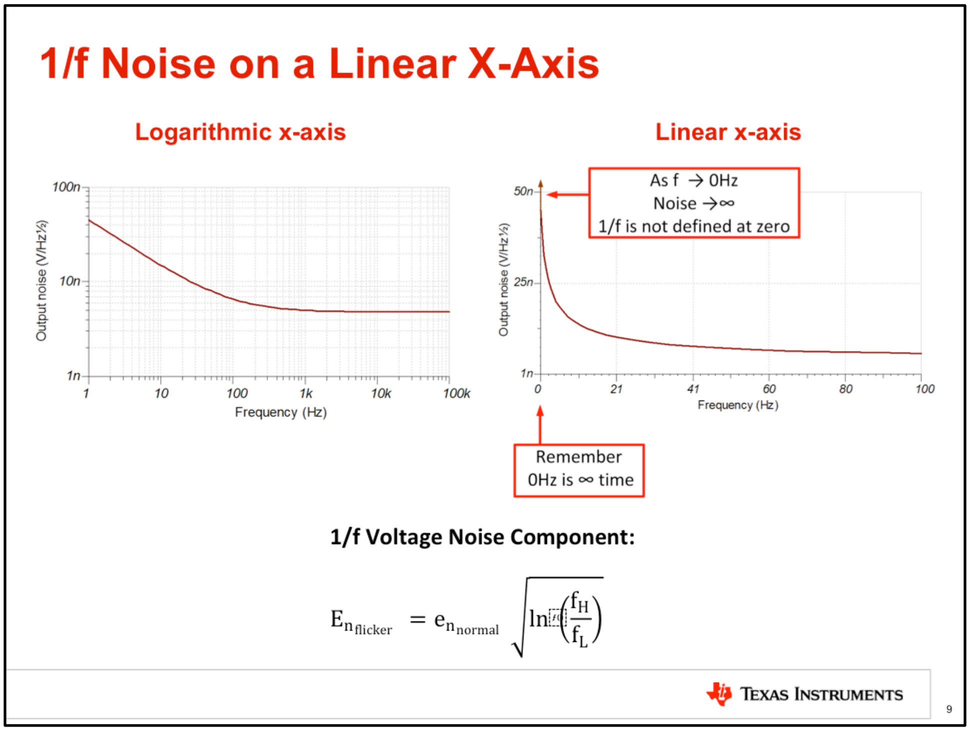
The OPA735 has higher voltage and current noise than the OPA132, so it doesn't seem like a good option at first, however, it is an auto-zero amplifier. On the next slide, we will see that the auto-zero topology offers some significant benefits in this application.



Surprisingly, the OPA227 has the worst noise, as shown on the top left. This is primarily because of the high current noise from the amplifier being converted to voltage noise through the large input impedance. For low impedance applications, however, the OPA227 would likely be the best choice.

The OPA132, on the other hand, is a CMOS amplifier and therefore has very low current noise. The voltage noise of the OPA132 is fairly good as well. The OPA132 noise floor is shown in two plots. The device being measured in a steel paint can, which is a noise-free and thermally stable environment, has excellent noise performance as shown on the top right. However, when placed in free air, the noise increases significantly as shown on the bottom right. This is not caused by an increase of intrinsic or extrinsic noise, but caused by the drift of the input offset voltage, or V_{OSI}, as the op amp temperature changes in free air. Even one or two degrees C of temperature drift can cause large offsets, especially in high gain.

The last device considered, the OPA735 has relatively low current noise, but the voltage noise is the highest of the three devices. However, this device has extremely low V_{OSI} drift and so it is not affected by ambient temperature variations, as shown on the bottom left. So, for this example, the OPA735 is the best choice overall.



Let’s conclude our deep dive into 1/f noise by investigating what happens over long time intervals.

First, we must remember that we normally look at noise spectral density on a graph with a logarithmic x-axis. If we instead consider the spectral density curve with a linear x-axis, it becomes clear that noise increases to infinity at 0 Hz. The fact that noise is infinite at 0 Hz sounds alarming, until you consider that 0 Hz corresponds to infinite time. Infinite time is not practical to consider, so we use 0.1Hz for the 1/f noise low frequency cutoff. 0.1Hz corresponds to 10 seconds. This might seem like a long time with respect to electronics, but some applications require even longer time intervals. What happens if we measure noise over the course of days, months, or years?

OPA336 Long-term 1/f Noise Calculations

f_H	f_L	$1/f_L$ Sec.	$1/f_L$ Days	$1/f_L$ Years	Noise Calculation	Noise
10	1	1	1.1×10^{-5}	3.1×10^{-8}	$200nV \cdot \sqrt{\ln\left(\frac{10Hz}{1Hz}\right)}$	303nV
10	0.1	10	1.1×10^{-4}	3.1×10^{-7}	$200nV \cdot \sqrt{\ln\left(\frac{10Hz}{0.1Hz}\right)}$	429nV
10	1×10^{-6}	1×10^{6}	11	0.032	$200nV \cdot \sqrt{\ln\left(\frac{10Hz}{1\mu Hz}\right)}$	808nV
10	1×10^{-9}	1×10^{9}	1.1×10^{4}	32	$200nV \cdot \sqrt{\ln\left(\frac{10Hz}{1nHz}\right)}$	960nV

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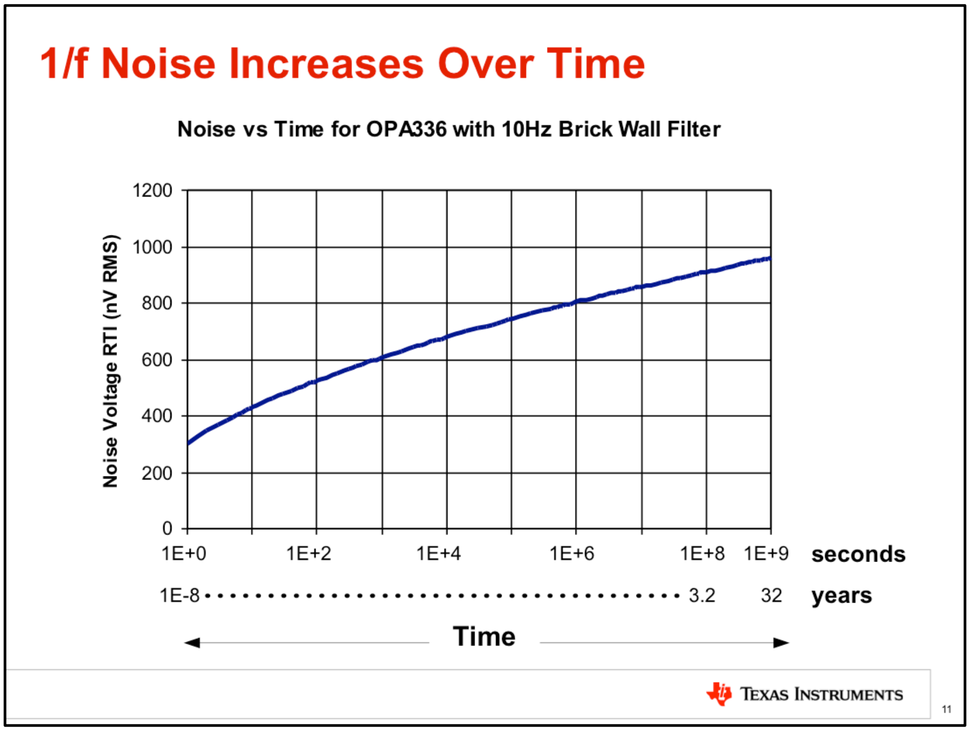
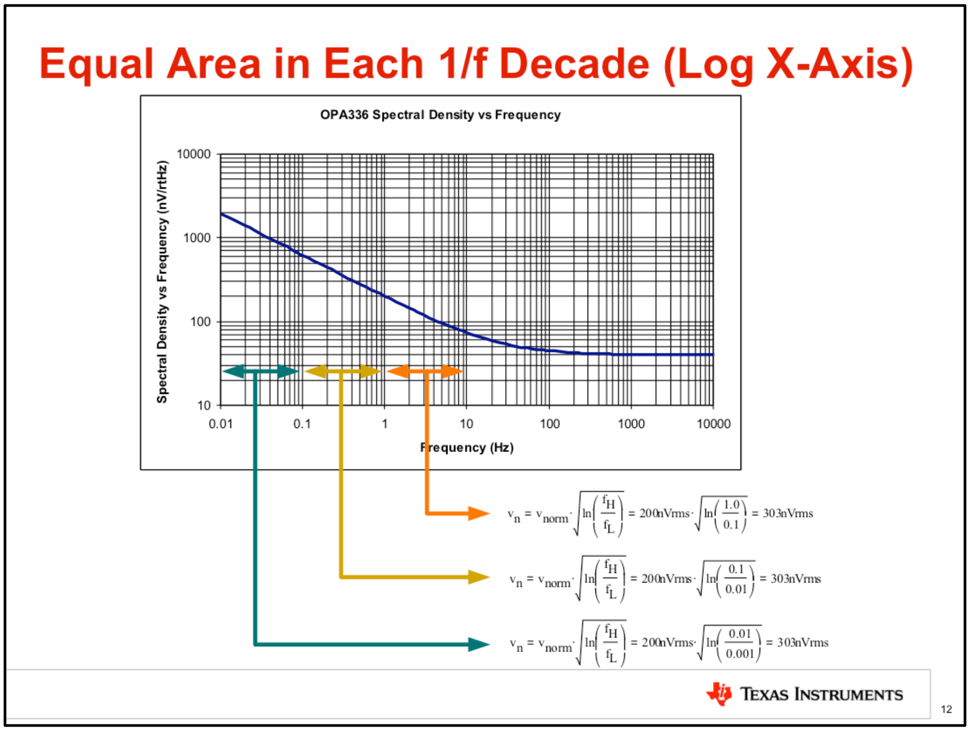
This table gives 1/f noise calculations for the OPA336, a standard CMOS op amp, at increasingly low cutoff frequencies. The lower cut frequency is set by the noise observation time. Remember, typical 1/f noise calculations use 0.1Hz, or 10 seconds, as the lower cutoff. However, the same calculation can be made for any time period. Note that a frequency of 0Hz corresponds to infinite time and, consequently, is not practical. Other extremely low frequencies, such as 1nHz, correspond to years of time.

In this example the 1/f noise increases from 303nVrms to 960nVrms when the lower cutoff is changed from 1Hz to 1nHz. Notice that 1nHz corresponds to 32 years, so this means that if you observe noise for 32 years you will see noise levels of 960nV.

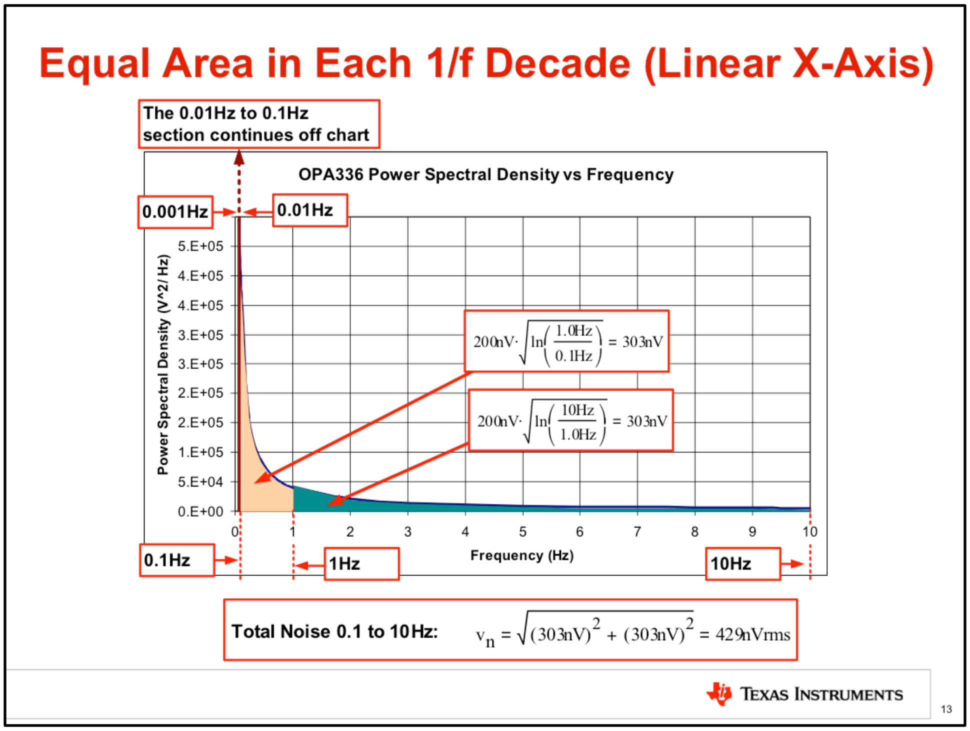


This plot is another way of looking at the data from the previous slide. The horizontal axis is the time duration, and the vertical axis indicates the RMS input noise measured over the time interval. Notice that the noise increases over time, but over the course of many years the increase in noise is not excessive. Let's take a look at the noise contribution from each decade of frequency.



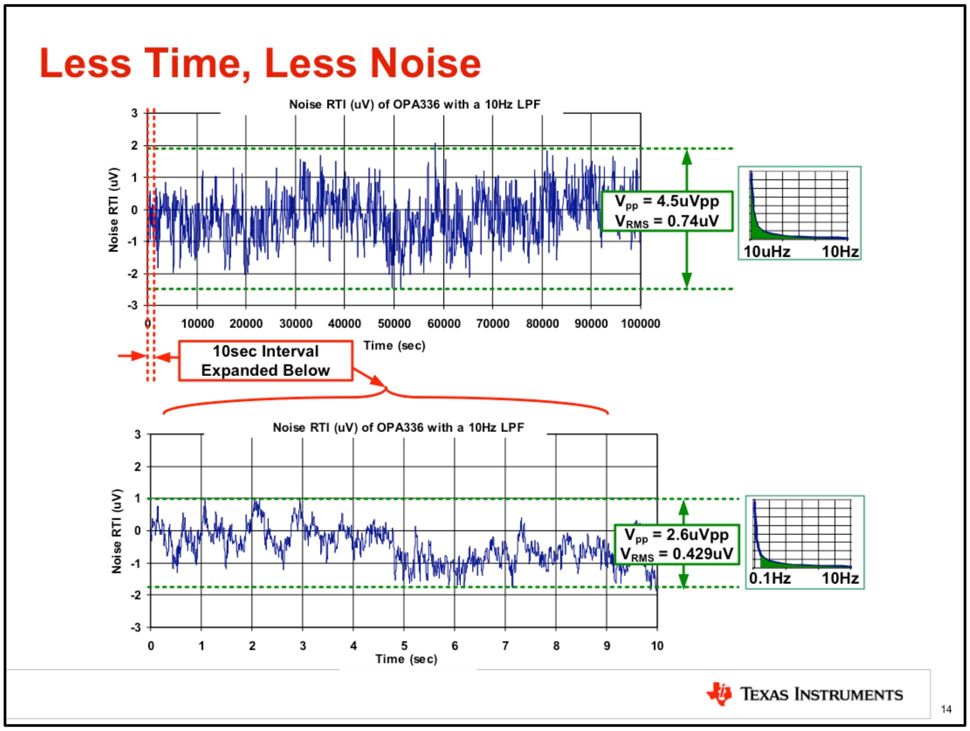
The total noise contribution from 1/f noise is equal over each decade change in frequency. For example, the total noise in the interval from 1Hz to 10Hz is the same as in the interval from 0.1Hz to 1Hz. This is shown mathematically in the figure, using the formula developed earlier in the video.

This fact is often confusing to engineers because the area under the curve appears to be significantly larger at lower frequencies. However, keep in mind that spectral density curves are usually shown with a logarithmic x-axis. When you look at the area of two different decade-wide intervals on a logarithmic axis, they do not look equivalent. However, if you change to a linear x-axis, you see that as 1/f noise gets larger the width of the interval gets smaller.



This figure shows the noise power spectral density curve on a linear axis to illustrate the equivalent area of decade-wide intervals. Note that the interval from 0.1Hz to 1Hz is tall and narrow, but the interval from 1Hz to 10Hz is short and wide. The total noise, or area, for these two regions is equivalent.

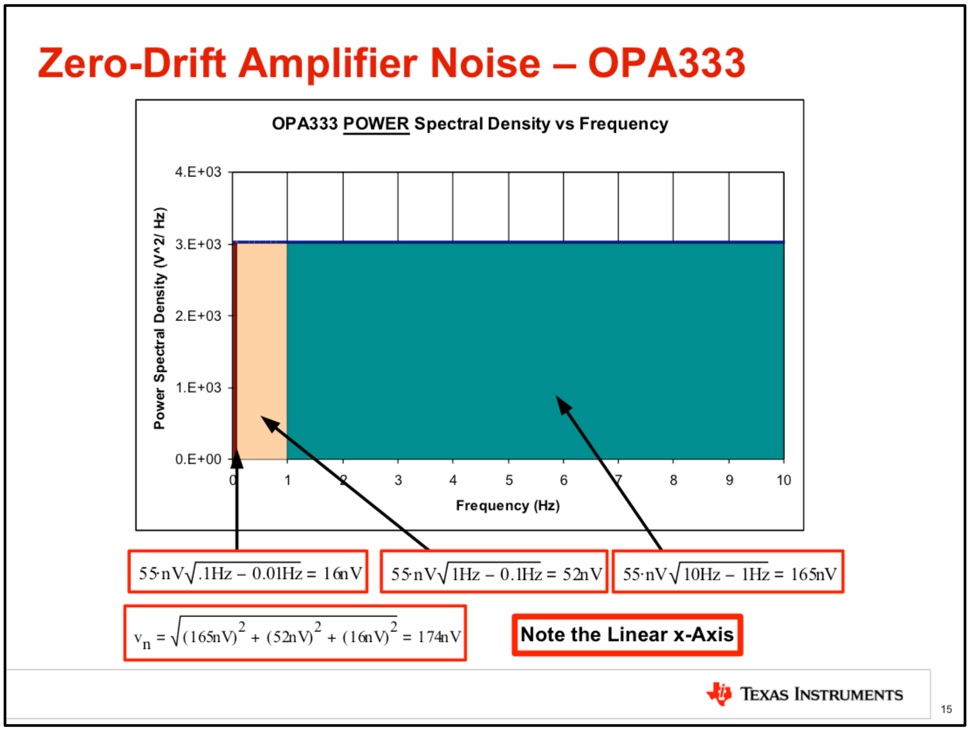
Now that we have a deeper understanding of flicker noise spectral density, let's look at the time domain.



This slide shows the time domain noise of the OPA336 for two different observation periods . Notice that the total peak to peak noise increases for longer observation time periods.

The top waveform shows the noise over a 100,000 second interval, or 10uHz. The upper cut frequency for this signal is 10Hz, so the noise bandwidth is from 10uHz to 10Hz. The total rms noise over the entire interval is 0.74uV.

If you choose any sub-interval of time, the total rms noise will be smaller. In this example, a 10 second sub-interval is shown to have a total noise of 0.43uV rms. The sub-interval in this example was taken from the first 10 seconds, but any 10-second interval will have the same total rms noise. Remember that a smaller time period corresponds to a larger lower-cut frequency, and less area under the 1/f curve.



Despite our deep dive into 1/f noise, not all amplifiers have this type of noise. The most common type of amplifiers with this behavior called zero-drift amplifiers. The OPA333 is an example of a zero-drift amplifier.

For these devices, total noise is always computed using the same method used for broadband noise. Since the noise spectral density is flat, it is possible to integrate noise down to 0Hz. Remember, it is not possible to integrate down to 0Hz with 1/f noise because the noise spectral density is infinite at 0Hz.

In standard amplifiers, the total 1/f noise is equal for each decade-wide sub-interval. With broadband noise and in zero-drift amplifiers, however, the total noise dramatically decreases at lower sub-intervals. Looking at the power spectral density curve on a linear axis, as shown here, helps to visualize this point.

OPA333 Long-term Noise Calculations

f_H	f_L	$1/f_L$ Sec.	$1/f_L$ Days	$1/f_L$ Years	Noise Calculation	Noise
10	1	1	1.1×10^{-5}	3.1×10^{-8}	$55\cdot nV\sqrt{10Hz - 1Hz}$	165nV
10	0.1	10	1.1×10^{-4}	3.1×10^{-7}	$55\cdot nV\sqrt{10Hz - 0.1Hz}$	173nV
10	1×10^{-6}	1×10^{6}	11	0.032	$55\cdot nV\sqrt{10Hz - 1\mu Hz}$	174nV
10	1×10^{-9}	1×10^{9}	1.1×10^{4}	32	$55\cdot nV\sqrt{10Hz - 1nHz}$	174nV

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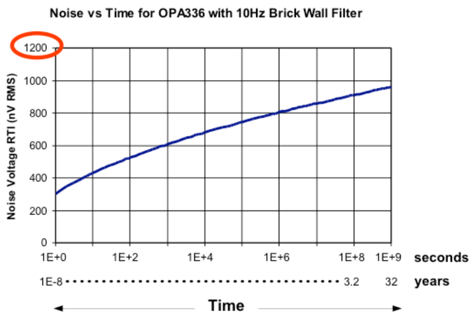
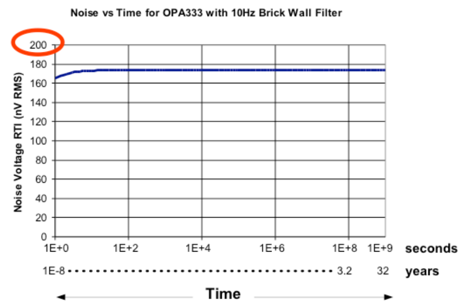
We can predict the long-term noise of the OPA333, similar to what was done before with the OPA336. This table shows the results of those calculations at the same lower cutoff frequencies. Note that the there is very little change in total noise with time. Because the noise spectral density curve is flat, the lower frequency sub-intervals have very little area, so their total noise contribution is insignificant. This is an advantage of the zero-drift topology compared to standard devices with 1/f noise.

Long-term Noise – Standard vs. Zero-drift



Standard op amp with 1/f noise



Zero drift op amp

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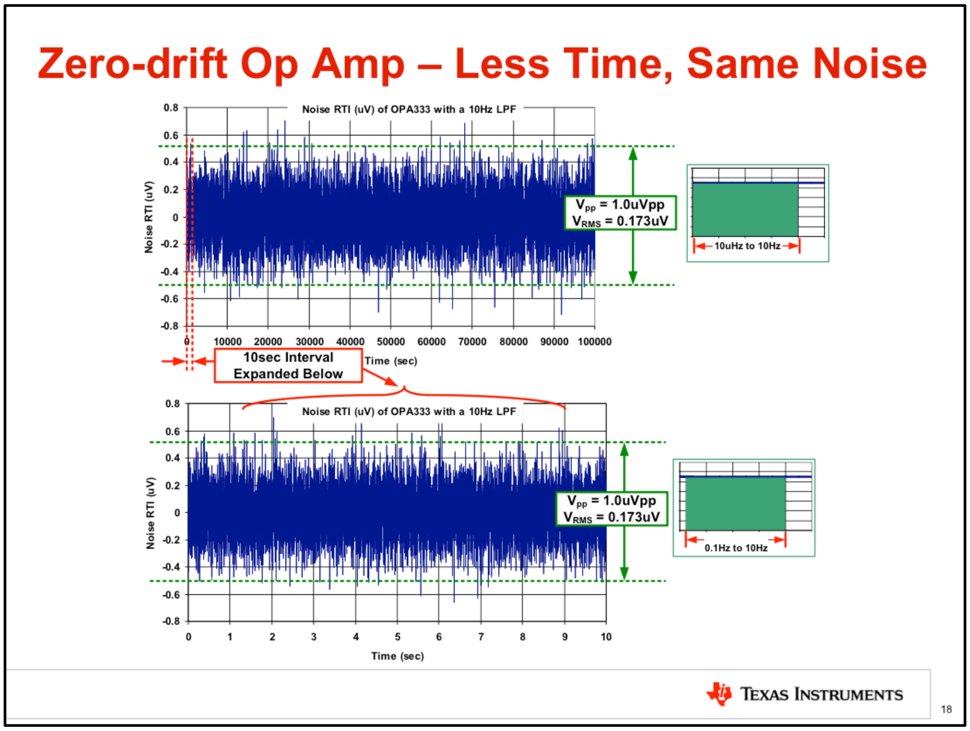
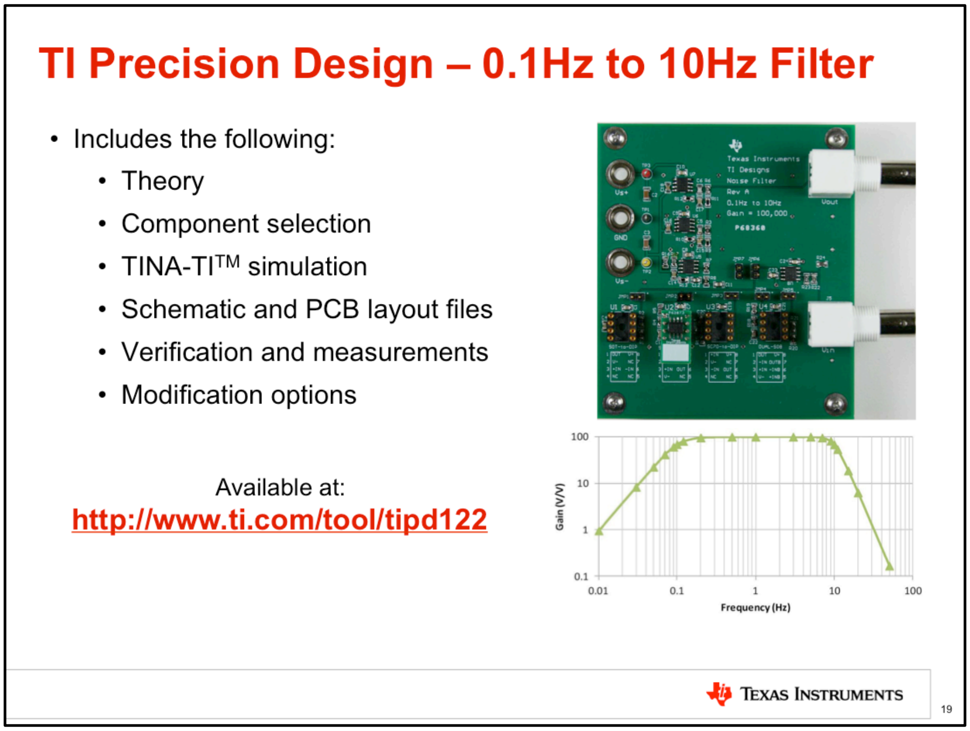
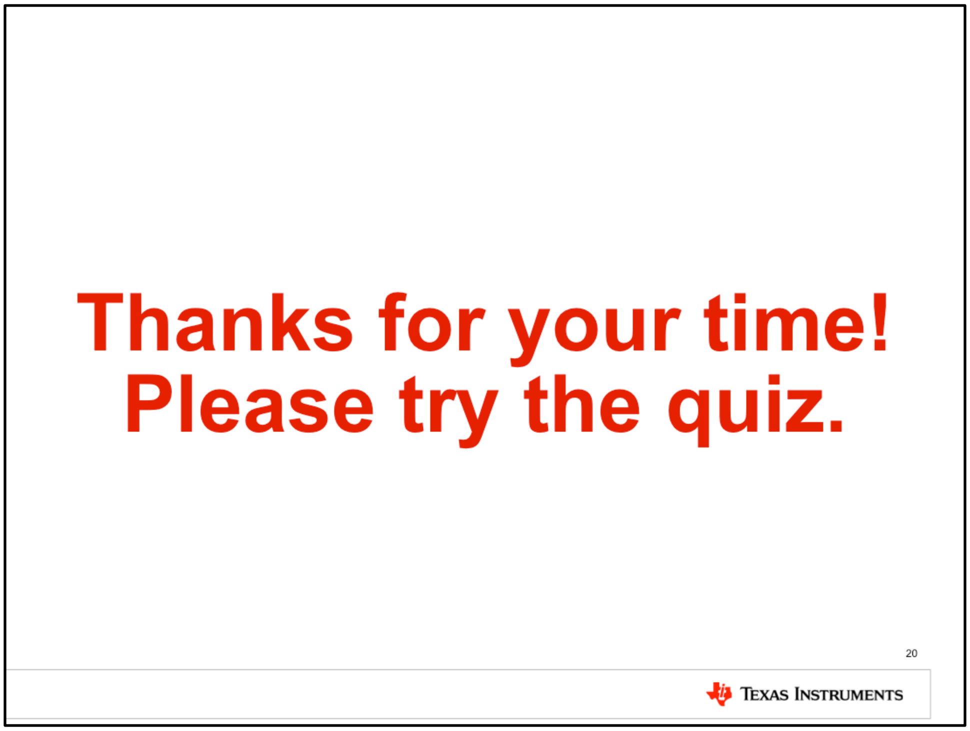
Here we compare the long-term noise of the OPA336 with the zero-drift OPA333. Remember, the OPA336 has 1/f noise, while the OPA333 does not. Again, note that the total noise increases with time for the OPA336, but remains relatively constant for the OPA333. Keep in mind that the y-axis scale on these plots is different – the OPA336 plot has a maximum of 1200nVrms, while the OPA333 plot has a maximum of only 200nVrms.



Finally, let's look at the time domain for the zero drift amplifier. Again, the total noise for zero-drift amplifiers remains relatively constant for different observation periods. The waveform in the figure above illustrates the OPA333 noise over a 100,000 second interval, or 10uHz. The upper cutoff frequency for this signal is 10Hz, so the noise bandwidth is from 10uHz to 10Hz. The total rms noise over the entire interval is 0.173uV. If you choose any sub-interval of time, the total rms noise will be the same. Here, a 10-second sub-interval is shown to also have a total noise of 0.173uV rms. The sub-interval in this example was taken from the first 10 seconds, but any 10-second interval will have the same total rms noise.



As mentioned previously, the 0.1Hz to 10Hz filter circuit used for low-frequency noise measurements is freely available as a TI Precision Design. The design document goes into every detail necessary for you to fully understand the theory, simulation, and measurements behind the circuit design. Circuit schematics, PCB layout files, and bill of materials are also provided if you would like to build and test this circuit yourself. Many other high-quality Precision Designs are available as well, covering a variety of useful applications.

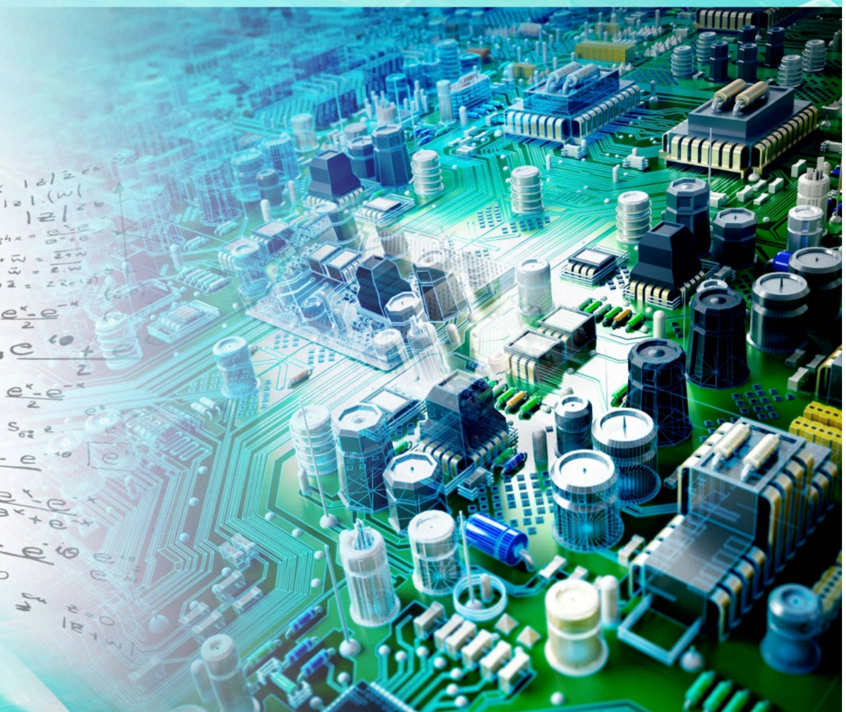


That concludes this video – thank you for watching! Please try the quiz to check your understanding of this video's content.

Noise 8

Multiple Choice Quiz

TI Precision Labs – Op Amps



Quiz: Noise 8

1. (T/F) The 0.1Hz to 10Hz waveform is another way of considering the low frequency voltage noise for a device.

a. True
b. False

2. (T/F) A few degrees of ambient temperature shift can cause offset drift that looks like noise.

a. True
b. False

3. (T/F) The 0.1Hz to 10Hz noise plot is generated using a spectrum analyzer.

a. True
b. False

4. Assume that an amplifier has 1/f noise. Increasing the measurement period will ____.

a. Increase rms noise.
b. Decrease rms noise.
c. Have very little affect on rms noise.

Quiz: Noise 8

5. Assume that an amplifier does not have 1/f noise. Increasing the measurement period will ____.

a. Increase rms noise.
b. Decrease rms noise.
c. Have very little affect on rms noise.

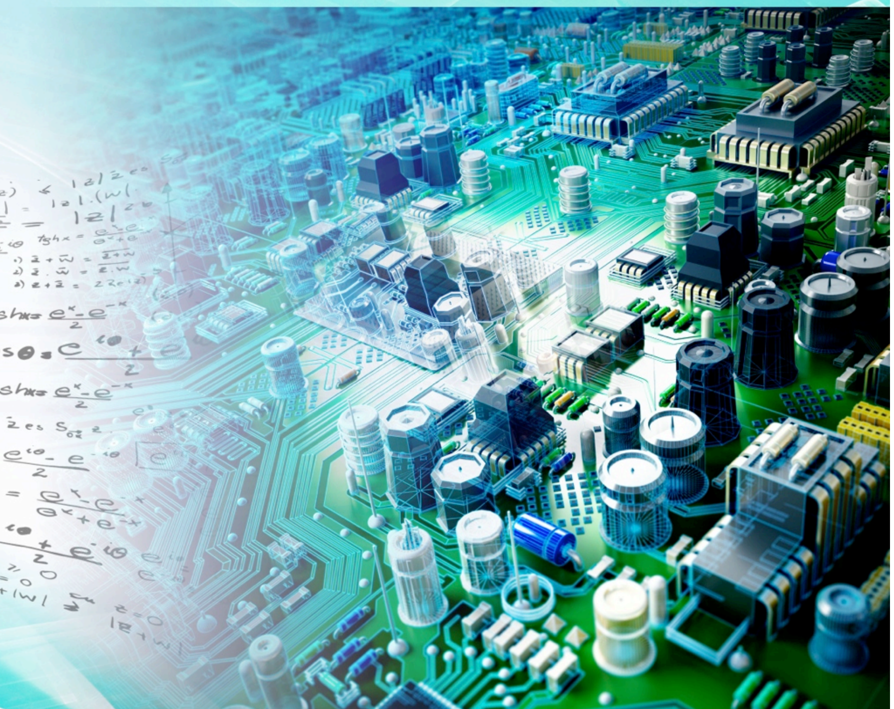
6. (T/F) Flicker noise is infinite at zero hertz, but zero hertz corresponds to infinite time which is not practical.

a. True
b. False

Noise 8

Multiple Choice Quiz: Solutions

TI Precision Labs – Op Amps



Quiz: Noise 8

1. (T/F) The 0.1Hz to 10Hz waveform is another way of considering the low frequency voltage noise for a device.

a. True
b. False

2. (T/F) A few degrees of ambient temperature shift can cause offset drift that looks like noise.

a. True
b. False

3. (T/F) The 0.1Hz to 10Hz noise plot is generated using a spectrum analyzer.

a. True
b. False

4. Assume that an amplifier has 1/f noise. Increasing the measurement period will ____.

a. Increase rms noise.
b. Decrease rms noise.
c. Have very little affect on rms noise.

Quiz: Noise 8

5. Assume that an amplifier does not have 1/f noise. Increasing the measurement period will ____.

a. Increase rms noise.
b. Decrease rms noise.
c. Have very little affect on rms noise.

6. (T/F) Flicker noise is infinite at zero hertz, but zero hertz corresponds to infinite time which is not practical.

a. True
b. False