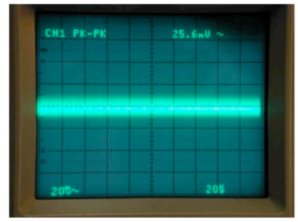
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 7.

Up to this point in the noise video series we have learned how to predict amplifier noise output using calculation and simulation. In this video we will cover techniques for measuring noise. There are two common types of test equipment that are used to measure noise: the oscilloscope and the spectrum analyzer. In this video we will discuss the theory of operation of this equipment, as well as some tips and tricks to optimize performance.

Oscilloscope Noise Measurements



- **Do not** use 10x probes for low noise measurements
- Use direct BNC cable connection (10x better noise floor)
- Use male BNC shorting cap to measure noise floor of oscilloscope
- Use bandwidth limiting (if appropriate)
- Use digital scope in dc coupling mode for 1/f noise measurements (ac coupling has a 60Hz high pass filter)
- Use ac coupling for broadband measurements (if necessary)

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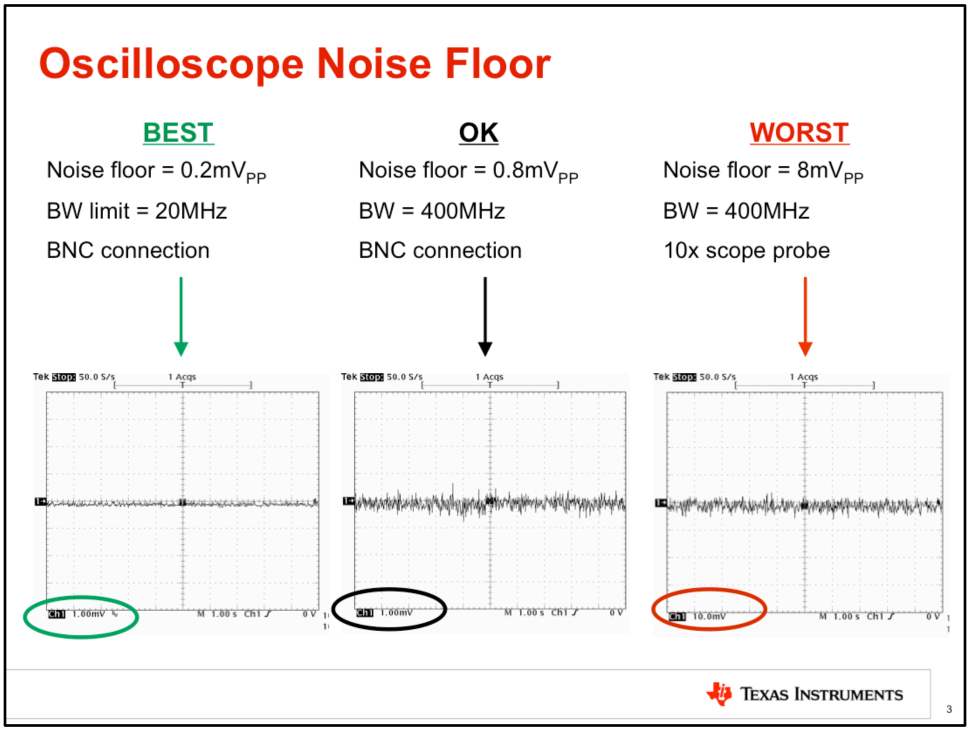
Let's start by looking at the oscilloscope, which is probably the most common way engineers measure noise. Typically, the scope is connected to the circuit output and the peak-to-peak noise voltage level is observed. This slide lists some tips and tricks to ensure that the observed noise reading is as accurate as possible.

The first tip relates to the type of probe connected to the scope. Most scope probes are "10x" probes. This means that there is a "divide by 10" attenuator in the probe. This attenuation will reduce the noise floor by a factor of 10, so don't use this type of probe! Use a direct connection to the scope, without any attenuation, for a 10 times better noise floor.

Always check the noise floor of any instrument before making noise measurements. In the case of an oscilloscope, it is common to use a BNC shorting cap to determine the instrument's noise floor.

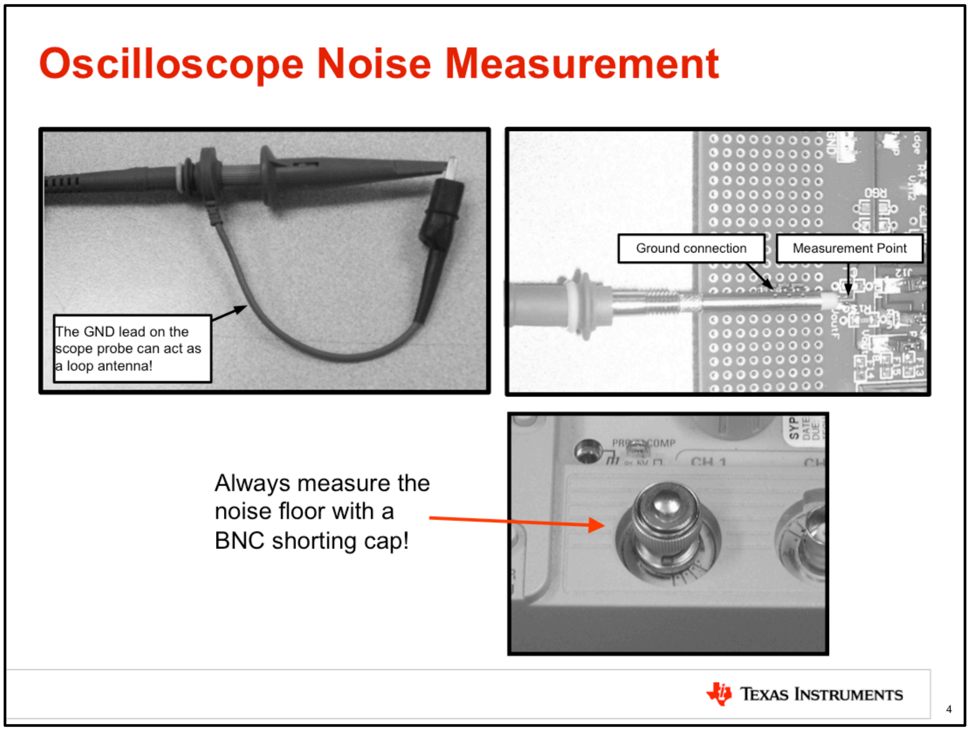
Many oscilloscopes have bandwidth that is much wider than your systems bandwidth. For example, you may use a 400MHz scope to observe the noise of a 100kHz amplifier. The problem with doing this is that the scope noise floor includes a lot of extra high frequency noise that is not relevant to your application. Most scopes have a bandwidth limiting feature that significantly reduces bandwidth and consequently improves the noise floor.



This slide shows a typical digitizing oscilloscope, measuring its noise floor in three different configurations. The worst configuration, shown on the right, has a noise floor of 8mVpp. In this case, a 10x scope probe is used and the scope bandwidth is set to the full 400MHz.

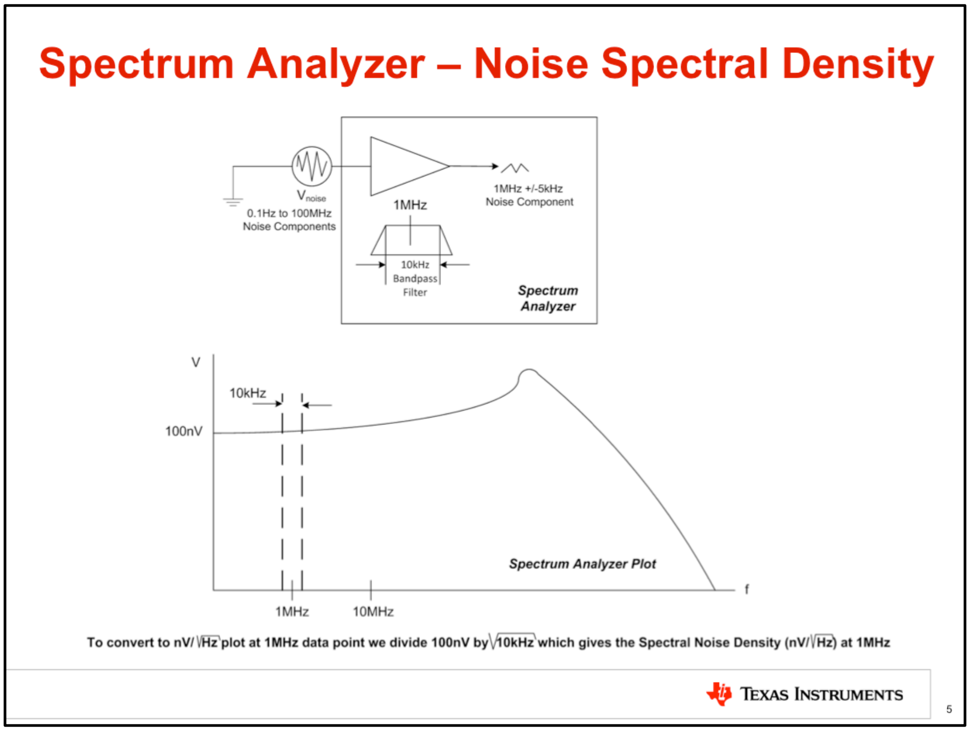
A significant improvement can be achieved by replacing the 10x scope probe with a direct BNC connection or 1x scope probe. Making this change effectively decreases the noise floor by a factor of 10, as shown in the center image. Notice that the vertical range changed from 10mV per division to 1mV per division.

The best noise floor occurs when a BNC connection is used along with the bandwidth limiting feature, as shown on the left. In this example, limiting the bandwidth to 20MHz reduces the noise from 0.8mV to 0.2mV or less.



This slide shows a few additional tips that can help improve the performance of your scope measurements. First, you should avoid using the scope probe's GND lead. It can act as a loop antenna and receive extrinsic noise, giving you errors in your measurements. If possible, remove the scope probe cap and use a direct GND connection (as shown on the top right). Note that the internal shaft on the scope probe is connected to ground. Also, it is important to always measure the noise floor of your scope. One way to do this is by using a shorting cap as shown in the figure on the bottom right. Another method is to short the end of your scope probe or measurement cable. However, as was mentioned previously, your cable or scope probe can act as an antenna. Using a shorting cap will tell you the noise floor of the scope without adding any noise pick-up on the cable. It may be useful to try both methods to determine if you are picking up noise on your cable.

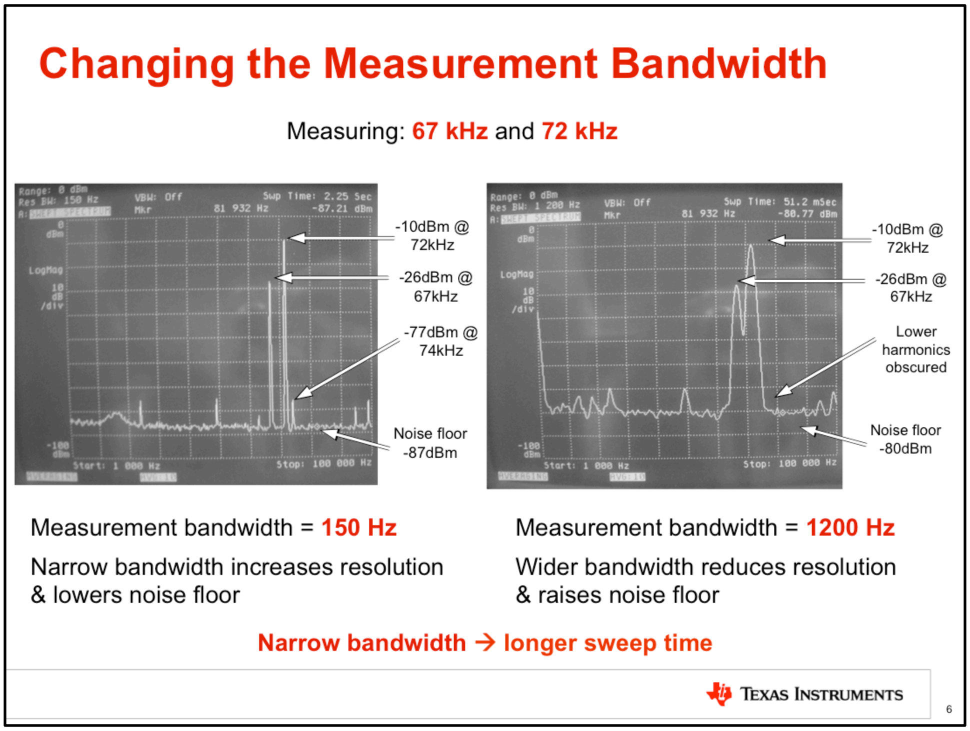
Once you have properly configured your oscilloscope, measuring noise is done by adjusting the time scale to match the bandwidth of your circuit. Later we will show an example measurement of the circuit that we did hand calculation and simulation for.



Let’s now discuss spectrum analyzers.

The spectrum analyzer is a very useful instrument for measuring noise, because it can show you the shape of the noise spectral density curve. The oscilloscope, on the other hand, does not give information as to the frequency content of your system noise. Using a spectrum analyzer can be very helpful for detecting unexpected extrinsic noise signals that are picked up. For example, you may see a spike at 60Hz indicating that ac power line noise is being picked up.

Conceptually, the spectrum analyzer works by sweeping a band pass filter across frequency and plotting the filter’s output. The width of the band pass filter is referred to as the measurement bandwidth. Averaging is also used by the instrument to improve measurement accuracy. In the next few slides we will cover some tradeoffs associated with changing the measurement bandwidth and averaging settings.

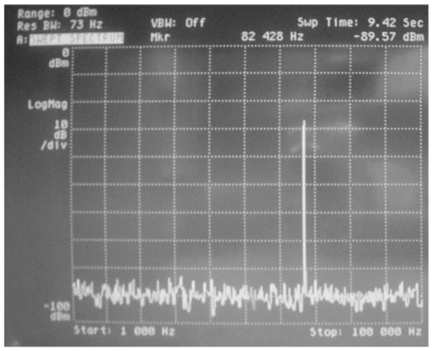


The images above show a spectrum analyzer being used to measure signals at 67 kHz and 72 kHz. The two spectrum analyzer results are run using different measurement bandwidth settings of 150Hz and 1200Hz.

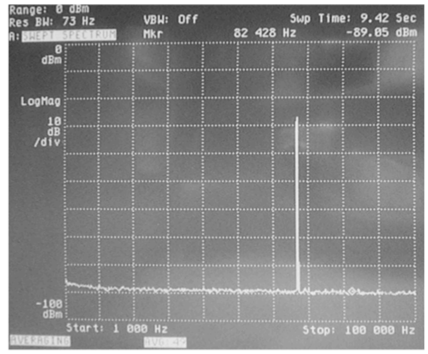
The measurement that used the narrow measurement bandwidth of 150Hz is better at resolving the discrete signals. Also, the narrow measurement bandwidth reduces the noise floor because the amount of noise captured inside of the band pass filter is smaller with a narrow bandwidth.

The measurement with the wide resolution bandwidth of 1200Hz loses information about each signal because the wider band pass filter captures both signals at once. So. when making noise measurements, take care to use a measurement bandwidth that provides good resolution. Note that decreasing measurement bandwidth will increase the sweep time, essentially trading test time for improved accuracy. In some cases for very high accuracy measurements, test times can take several hours! Thus, it is not always practical to use an extremely narrow measurement bandwidth.

Changing Averaging



No averaging



49x averaging

More averaging to reduce noise floor → longer measurement time

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Another way to improve measurement accuracy is to use averaging, which combines the results of multiple noise sweeps. In order to achieve accurate results, the device conditions need to remain constant. Averaging is not good for measuring transients, but it does work well for measuring spectral density.

Averaging has the same trade-off as with measurement bandwidth, so increasing the amount of averages for better accuracy will increase the measurement time. In the examples above, you can see the results with no averaging on the left and the results with 49x averaging on the right. Without averaging, the spectral density measurement shows significant variation. Using averaging, you get a more accurate overall average value.

Convert dBm to nV/√Hz

$$V_{spect\_anal} = \sqrt{\left(10^{\frac{NdBm}{10}}\right)\cdot(1mW)\cdot R} \qquad (5.4)$$

$$V_{spect\_den} = \frac{V_{spect\_anal}}{\sqrt{K_n \cdot RBW}} \qquad (5.5)$$

Where
NdBm -- the noise magnitude in dBm from the spectrum analyzer
R -- the reference impedance used for the dBm calculation
V_{spect_anal} -- noise voltage measured by spectrum analyzer per resolution bandwidth
RBW -- resolution bandwidth setting on spectrum analyzer
V_{spect_den} -- spectral density in (nV/rt-Hz)
K_n – conversion factor that changes the resolution bandwidth to a noise bandwidth

Filter type	Application	K_n
4-pole sync	Most analog spectrum analyzers	1.128
5-pole sync	Some analog spectrum analyzers	1.111
Typical FFT	FFT-based spectrum analyzers	1.056

TEXAS INSTRUMENTS

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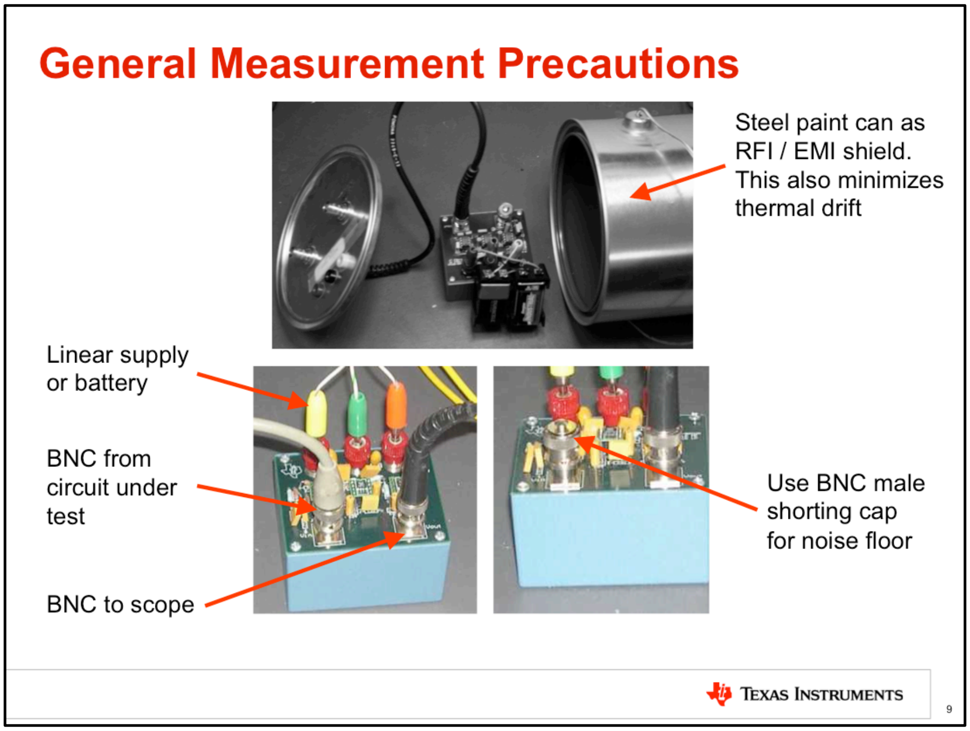
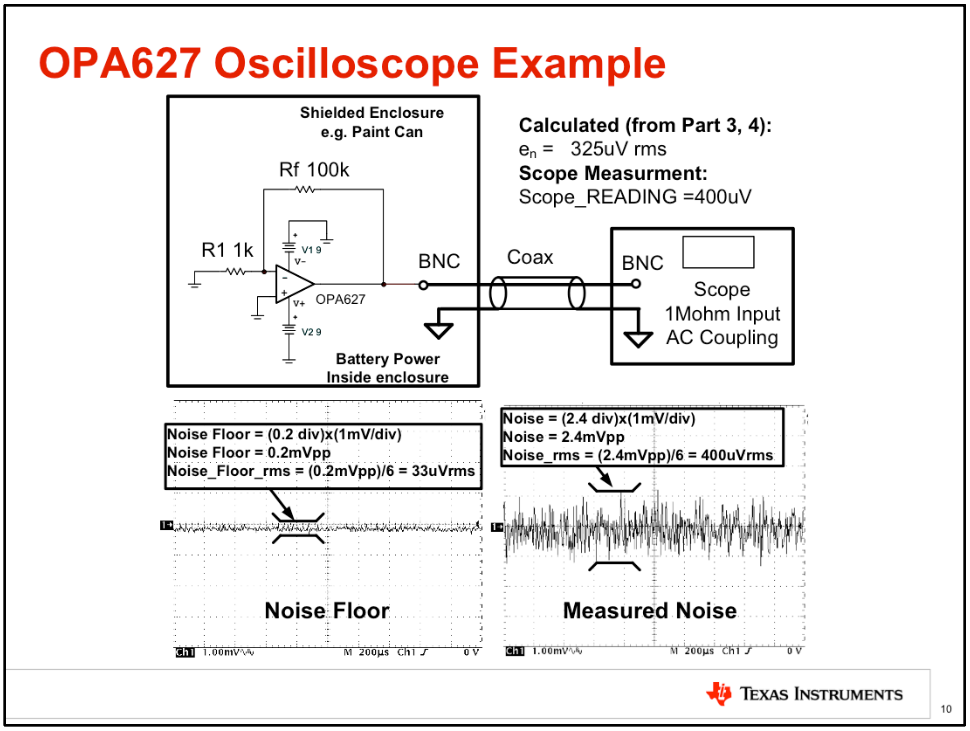
When doing noise analysis, it is useful to display measurement results as a voltage spectral density in units of nV/√Hz. However, spectrum analyzers often display the measurement as decibel-milliwatts or dBm. The formula above shows how to convert dBm to nV/√Hz. We will not discuss the math in detail here, but suffice it to say that we are converting the noise power delivered to the instrument's 50Ω input impedance to a noise spectral density. In some cases, it may be useful to have a calibrated noise source to confirm that the conversion to dBm to spectral density was done accurately.



In addition to the proper configuration of oscilloscopes and spectrum analyzers, other aspects of your test setup can also have a huge impact on the quality of your noise measurement.

1. First, use a well shielded and grounded environment. Make sure that the shield is grounded, and any gaps in the shield are minimized. Copper and steel are good choices for shielding material. We often use a modified steel paint can as a shield for our noise circuits.
2. As mentioned before, if possible, make all circuit connections directly and with BNC cables.
3. Use batteries or linear power supplies in order to provide the lowest-noise power possible.
4. A BNC shorting cap is useful when measuring the noise floor. Don't leave un-terminated or floating inputs on your devices, as these will tend to pick up extrinsic noise.

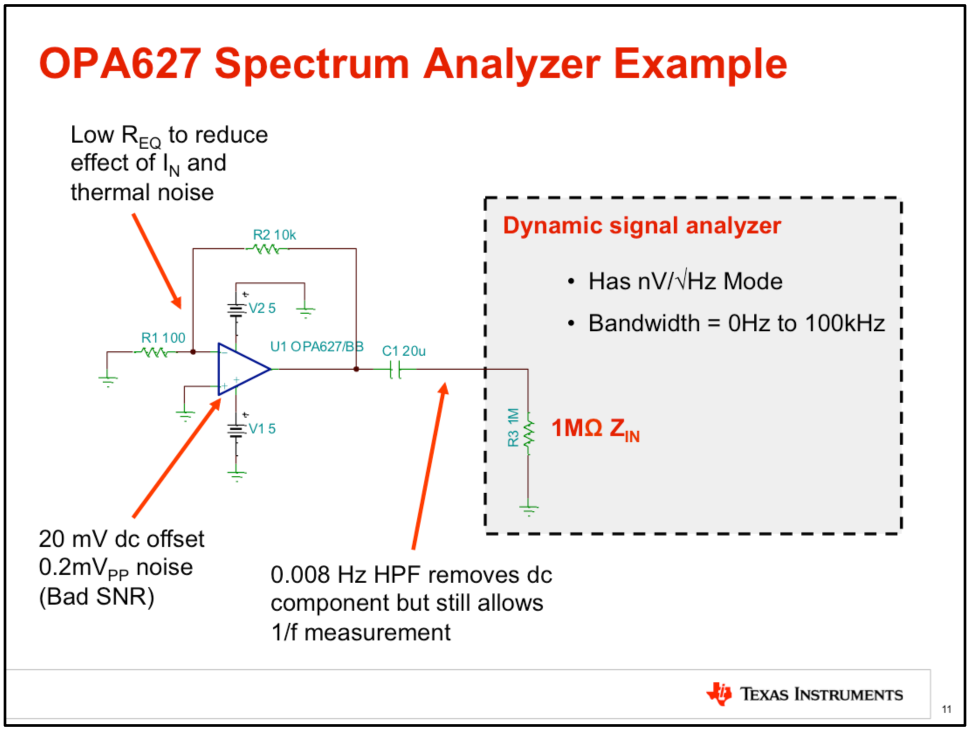
Remember, the goal of this testing is to measure the intrinsic noise, so these precautions are focused on eliminating sources of extrinsic noise.



Let's now apply all of these real-world techniques to the OPA627 example circuit from our hand calculations and simulations. This circuit was connected directly to an oscilloscope with a BNC cable. As previously mentioned, the direct BNC connection is better than a 10x scope probe because the noise floor is ten times better.

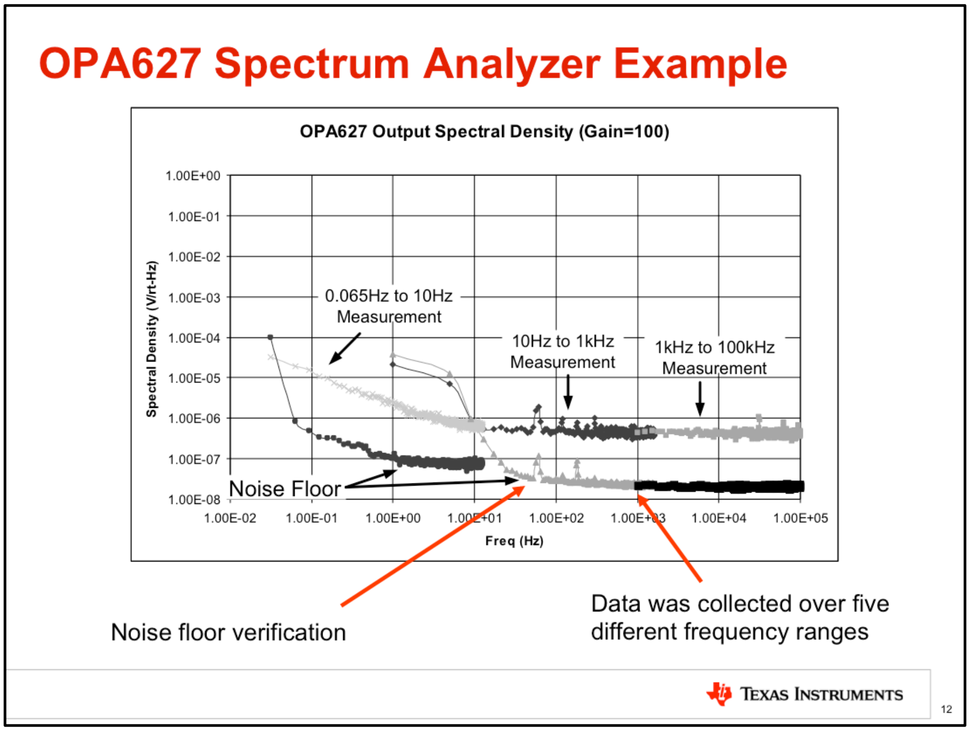
The measured output noise voltage was $400uV_{RMS}$ while the calculated result from an earlier video was $325uV_{RMS}$. There is some discrepancy in the measurement, which is typical for scope measurements. The discrepancy results from process variations in the device as well as measurement accuracy limitations of the test equipment. In general, the agreement between measured and calculated noise should be on the order of ±20%.

If the discrepancy is large, first confirm that the device is connected properly and is functional. Next, make sure that the equipment is configured properly. Always confirm that the system noise floor is low enough to allow for accurate results. Assuming that there are no functionality or equipment issues, the next thing to consider is extrinsic noise. Try improving the shielding environment. If you still see large discrepancies after thoroughly troubleshooting the circuit, you should try a noise measurement with a spectrum analyzer to get a deeper understanding of the system's noise characteristics. You may discover, for example, that switching noise at

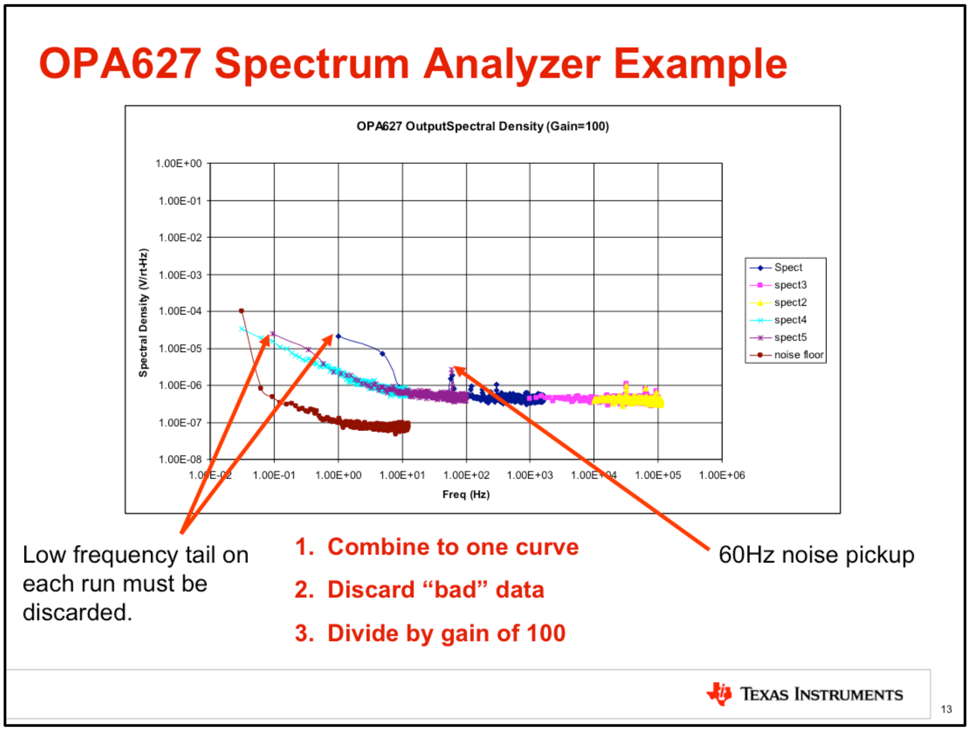


Let's now use a spectrum analyzer to measure the voltage noise spectral density curve for OPA627. For this example, we will try to reproduce the curve given in the OPA627 data sheet. The circuit connection is shown above.

First, note that the parallel combination of R1 and R2 is low in order to minimize the thermal noise. Also note that a large value ceramic capacitor C1 is used to ac couple the signal into the spectrum analyzer. The input impedance and the coupling capacitor form a high pass filter with a very low cutoff frequency of 0.008Hz. This is important for proper 1/f characterization. The capacitive coupling is required because the op-amp has a large dc offset compared to the noise level; so the dc offset would saturate the input. Note that the spectrum analyzer may have an AC coupled mode; however, the cutoff frequency is often too high for adequate 1/f measurements.

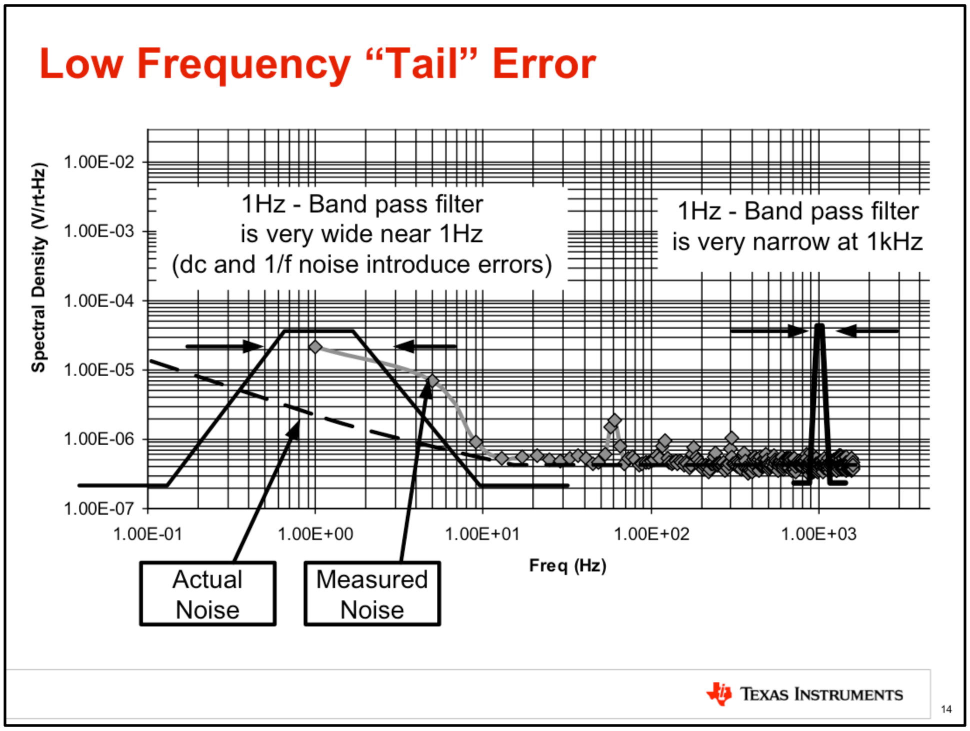


Here we give the spectral density curve results using the circuit from the previous slide. Note that the data was collected over several ranges. For each frequency range, the spectrum analyzers measurement bandwidth is adjusted to optimize accuracy. At low frequencies, for example, the measurement bandwidth is very narrow, where as at high frequencies it is wider. This allows us to get good accuracy and also keep the measurement time reasonable. Also note that the system noise floor was measured. Checking the noise floor is important, regardless of the test equipment used. Remember, if the noise floor is higher than the signal you are trying to measure you cannot get a valid result.

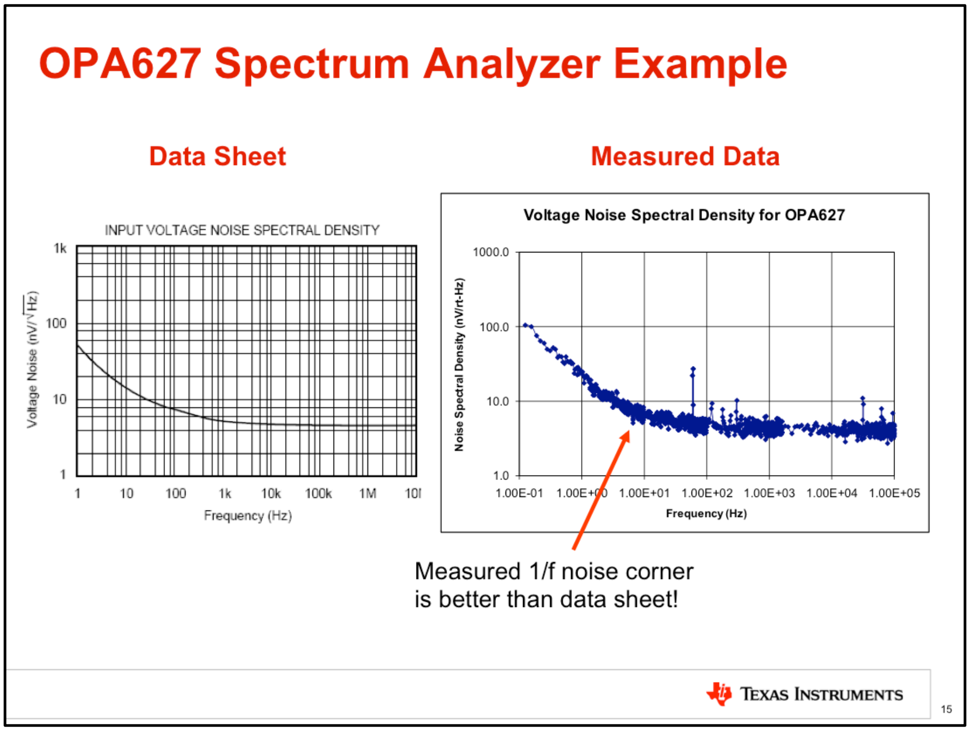


After the data is collected, you will need to make some adjustments to get the spectral density curve.

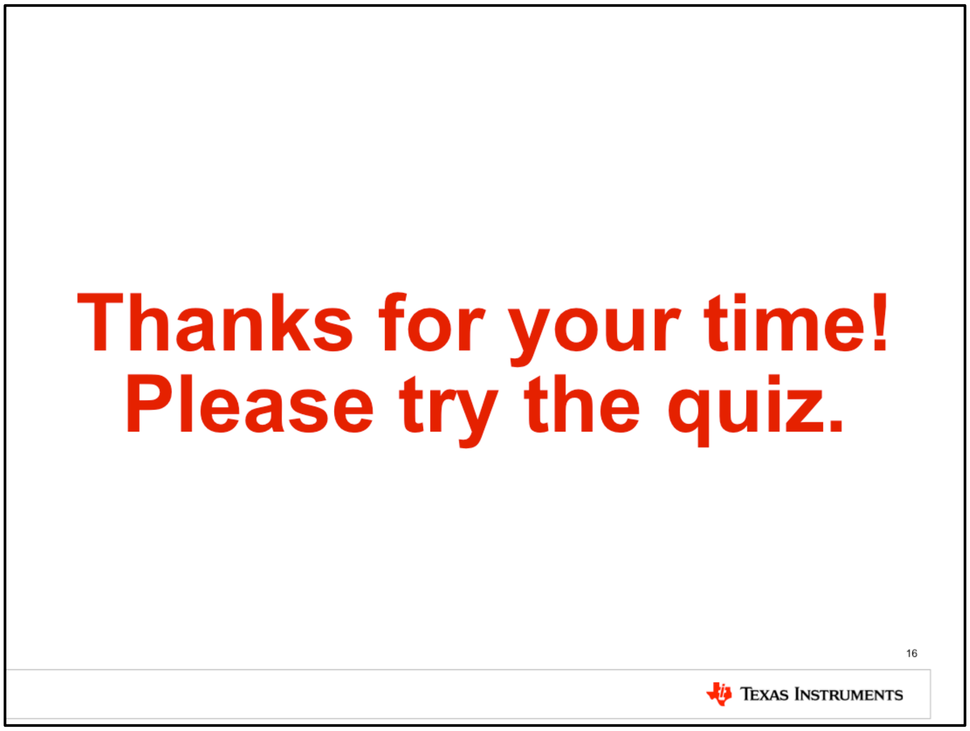
First, combine the separate frequency ranges into one curve. Second, you will notice that the curves have a strange “tail” at low frequencies. This is a common anomaly associated with spectrum analyzers which we will discuss in more detail in the next slide. For now, just know that this data should be eliminated. Also, you may see some extrinsic noise in your spectral density curve. In this example you can see 60Hz noise pick-up and some harmonics of 60Hz. Ideally this pick-up can be eliminated through proper shielding, but this is not always possible. Finally, you will need to divide the measured results by the circuit’s noise gain in order to refer the noise back to the amplifier input.



This slide gives further explanation into the cause of the low frequency tail. First, keep in mind that the spectral density curve is shown on a logarithmic axis, so the measurement bandwidth as a percentage of frequency is much wider at low frequency then at high frequency. As a result, at low frequency the measurement bandwidth band pass filter captures some unwanted dc content as well as the 1/f noise beyond the frequency that is being measured. This pushes the spectrum higher than it should be and creates the low frequency "tail." As mentioned before, this information should be eliminated. A good practice is to measure one decade lower than you need and simply discard the low frequency points.



Here we compare the final combined voltage spectral density curve measurement with the data sheet curve. Notice that the 1/f noise corner is different then the data sheet. This is not unusual. The 1/f noise corner changes with process variations, and the data sheet curve shows typical performance only. Also notice that the broadband spectral density compares well between the measured result and the data sheet curve. The measured noise curve could have been improved with additional averaging and shielding, but overall provides an excellent depiction of the device's noise spectral density.



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

Noise 7

Multiple Choice Quiz

TI Precision Labs – Op Amps

Quiz: Noise 7

1. (T/F) A 10x scope probe is better than a 1x scope probe for noise measurements.

a. True
b. False

2. (T/F) The bandwidth limiting feature can be used to improve the noise floor.

a. True
b. False

3. Which of the following is NOT a recommended procedure for measuring 1/f noise?

a. Set scope in ac coupling mode
b. Use a 0.001Hz high pass filter.
c. Set time scale to 1 sec per division.

4. (T/F) Ac coupling should be used for broadband noise measurements.

a. True
b. False

Quiz: Noise 7

5. What advantage does a spectrum analyzer have over an oscilloscope in noise measurements?

a. Operation of the spectrum analyzer is fast and simple.
b. The spectrum analyzer is more accurate
c. The spectrum analyzer makes it easy to see if you have high frequency content at a specific frequency.
d. The spectrum analyze can operate to low frequencies.

6. Which is NOT an important precaution for noise measurements?

a. Use shield cables to connect to the circuit under test.
b. Use low ESR capacitors for coupling the circuit under test to the test equipment.
c. Use linear power supplies or batteries.
d. Test the noise floor of your equipment.

7. (T/F) The maximum frequency that a spectrum analyzer can measure is called it's measurement bandwidth.

a. True
b. False

Quiz: Noise 7

8. Using a narrow measurement bandwidth will _________.

a. Improve accuracy and increase the test time.
b. Degrade accuracy and decrease the test time.

9. (T/F) The averaging feature on a spectrum analyzer will improve the accuracy of noise measurements.

a. True
b. False

Input Offset Voltage (V_{OS}) & Input Bias Current (I_B)

Multiple Choice Quiz: Solutions

TI Precision Labs – Op Amps

Quiz: Noise 7

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