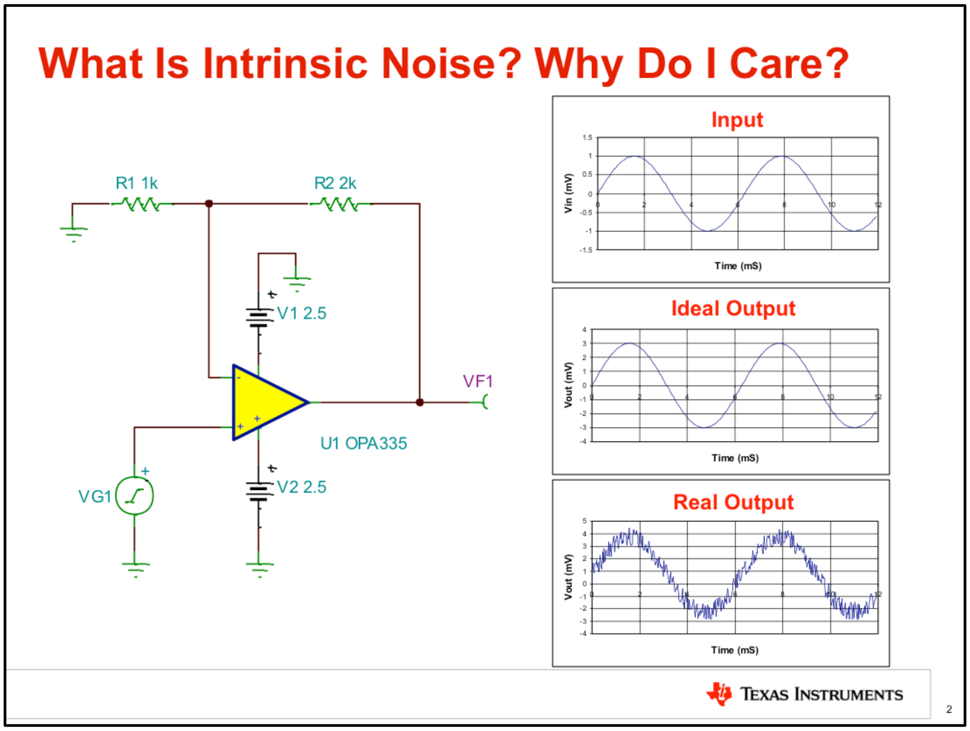
Hello, and welcome to the TI Precision Lab discussing intrinsic op amp noise, part 1.

Overall, this video series will show how to predict op amp noise with calculation and simulation, as well how to accurately measure noise.

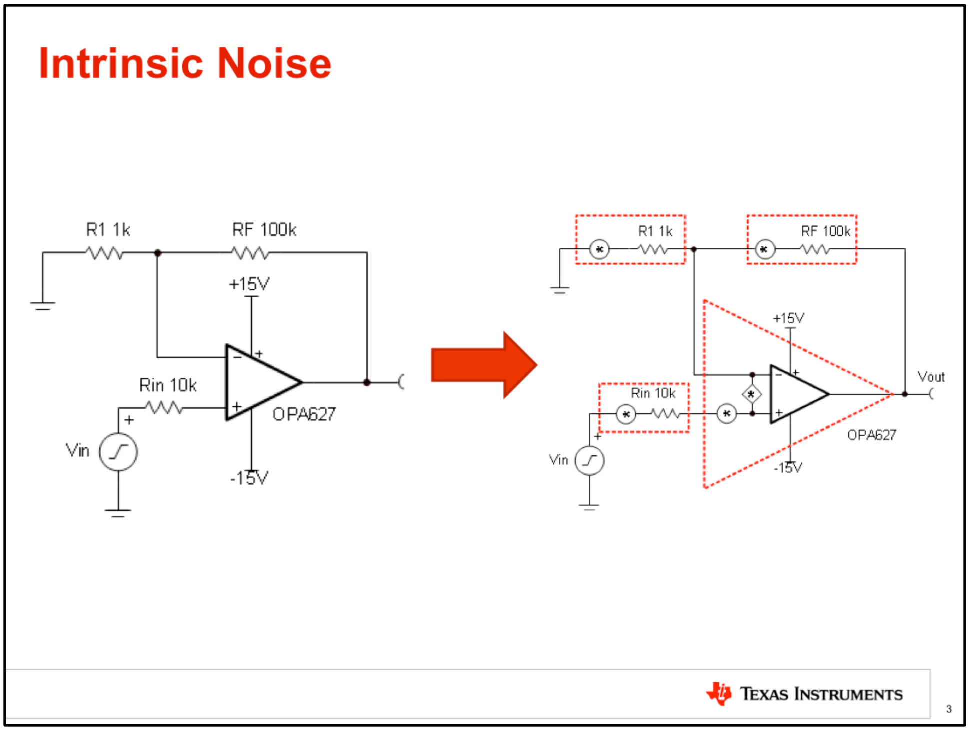
In part 1 we will define intrinsic noise, introduce the different types of noise, and discuss noise spectral density.



Noise can be defined as an unwanted signal that combines with a desired signal to result in an error. In audio, for example, noise can be noticed as a hiss or popping sound. In a sensor system, noise can be an error in the measured sensor output, such as pressure or temperature.

Noise can be categorized into two basic groups: extrinsic and intrinsic. Extrinsic noise is noise produced from some external circuit or natural phenomena. For example, 60Hz power line noise and interference from mobile phones are common examples of extrinsic noise. Cosmic radiation is another example of a natural phenomenon that causes extrinsic noise. Intrinsic noise is caused by components within a circuit. Resistors and semiconductor devices generate noise, for example.

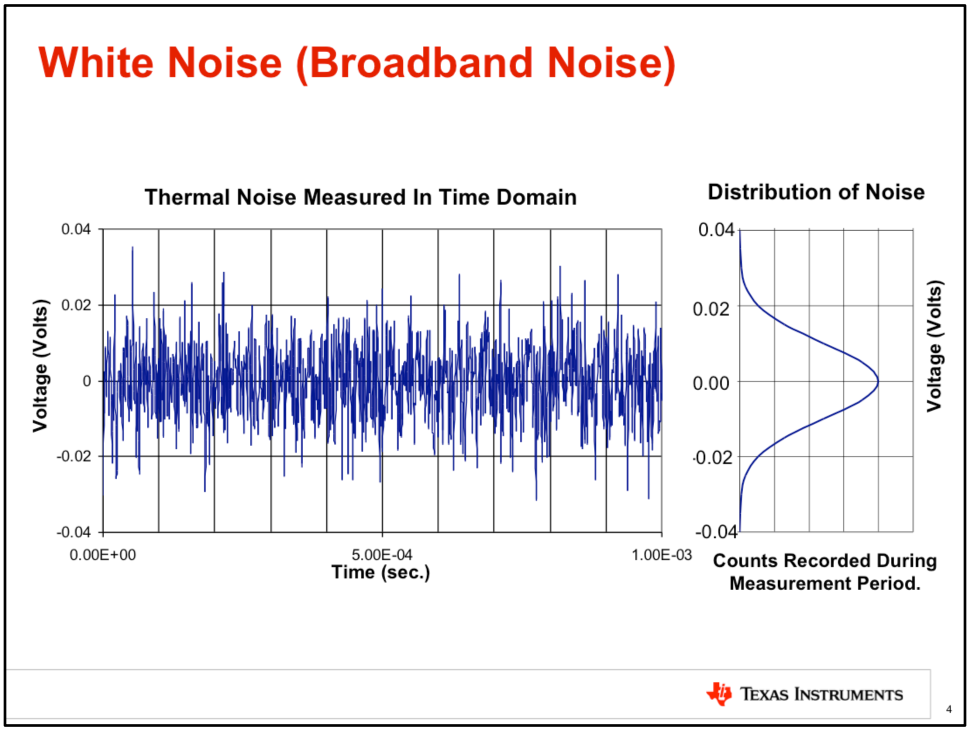
Intrinsic noise is very predictable, where as extrinsic noise is typically difficult to predict. In this noise video series, we will focus on intrinsic noise. As we mentioned before, our discussion will focus on how to calculate, simulate, and measure noise. We will also discuss techniques for reducing noise.



This slide illustrates how an amplifier circuit can be translated into a noise equivalent circuit.

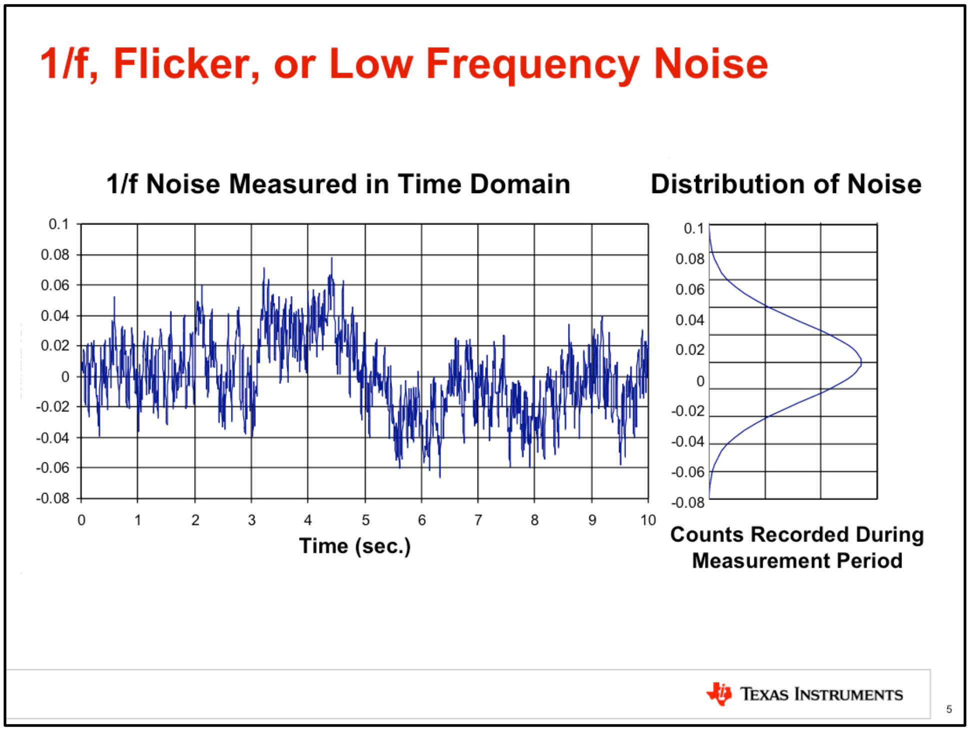
Each resistor has a noise voltage source associated with it. The noise voltage source is denoted by a circle with an asterisk inside. The amplifier also has a noise voltage source and a noise current source. The noise current source is denoted by a diamond with an asterisk inside. The magnitude of the noise sources inside the amplifier is given in the amplifiers data sheet. The magnitude of the noise associated with the resistor is dependent on the resistance value and can be calculated.

We will soon learn how to combine the effects of all the noise sources to determine the total output noise. But first, lets look at some general categories of noise.

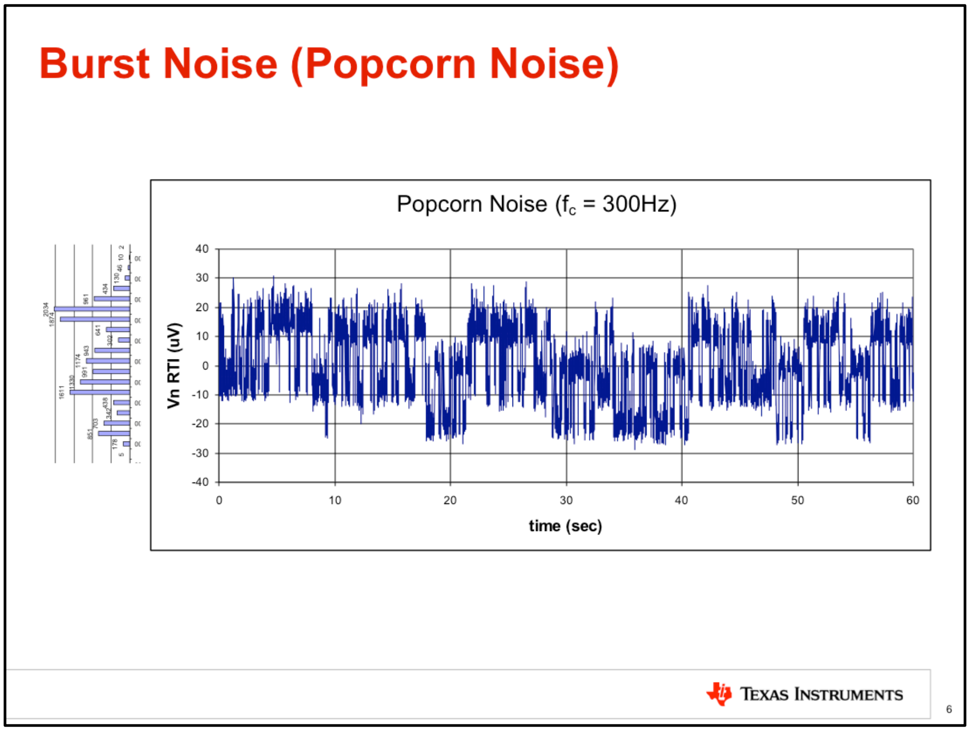


This slide shows the time domain waveform for white noise, also known as broadband noise. The time domain waveform is what you would see if you measured noise with an oscilloscope. Notice that the horizontal axis is 1ms, full scale. Taking the reciprocal of the full-scale time gives a frequency of 1kHz. In general, broadband noise is considered to be in the middle to high frequency range; that is, frequencies greater than 1kHz. In the next slide we'll consider lower frequency noise sources.

Also notice the statistical distribution to the right hand side of the slide. The distribution is Gaussian, with a mean value of 0V and the skirts of the distribution at approximately ±40mV. The distribution indicates that the probability of measuring noise near 0V is high, where as the probability of measuring noise near the skirts of the distribution is relatively low. Later we will see how the distribution can be used to estimate the peak-to-peak value of the noise signal.

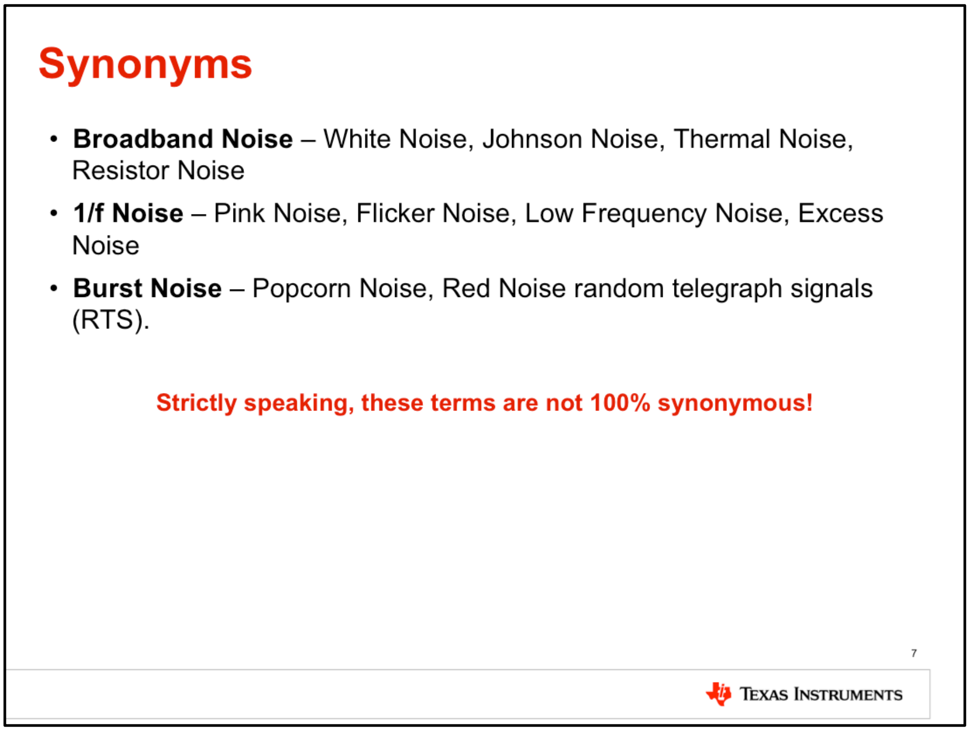


Flicker noise, also known as 1/f or low frequency noise, is another category of noise. This slide shows the time domain waveform, as well as the statistical distribution for 1/f noise. The time domain waveform is what you would see if you measured noise with an oscilloscope. Notice that the horizontal axis is 10s full scale. Taking the reciprocal of the full scale time gives a frequency of 0.1Hz. In general, 1/f noise is considered to be in the low frequency range; that is, frequencies less than 1kHz.



Another category of noise is called burst, or popcorn noise. Popcorn noise is a sudden change (or step) in voltage or current. It does not follow a Gaussian distribution - instead it has a bimodal or multi-modal distribution. The example above jumps between three discrete modes of operation.

Popcorn noise is low frequency, from 0.1 to 1kHz. Popcorn noise sounds like popping popcorn when played on a speaker or headphones. Popcorn noise is caused by defects in a device, and unfortunately it cannot be mathematically predicted. This presentation does not give further details on popcorn noise.

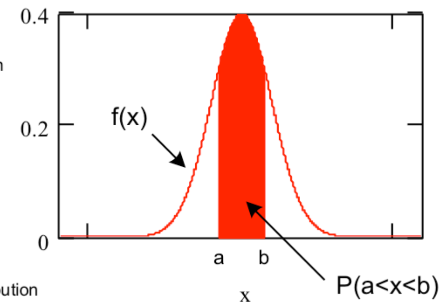


As we have already seen, the various categories of noise have many synonyms. For example, broadband noise is also called white noise, Johnson noise, thermal noise, and resistor noise. It can become very confusing to engineers that are new to this subject when literature and presentations switch between these different terms.

Statistics Review – PDF

Probability **Density** function for Normal (Gaussian) distribution

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]}$$



Probability **Distribution** function for Normal (Gaussian) distribution

$$P(a < x < b) = \int_a^b f(x)\, dx = \int_a^b \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]} dx$$

Where
$P(a < x < b)$ -- the probability that x will be in the interval (a, b
x-- the random variable. In this case noise voltage.
μ -- the mean value
σ -- the standard deviation

For example, if P(-1<x<+1) = 0.3, then there is a 30% chance that x is between -1 and 1.

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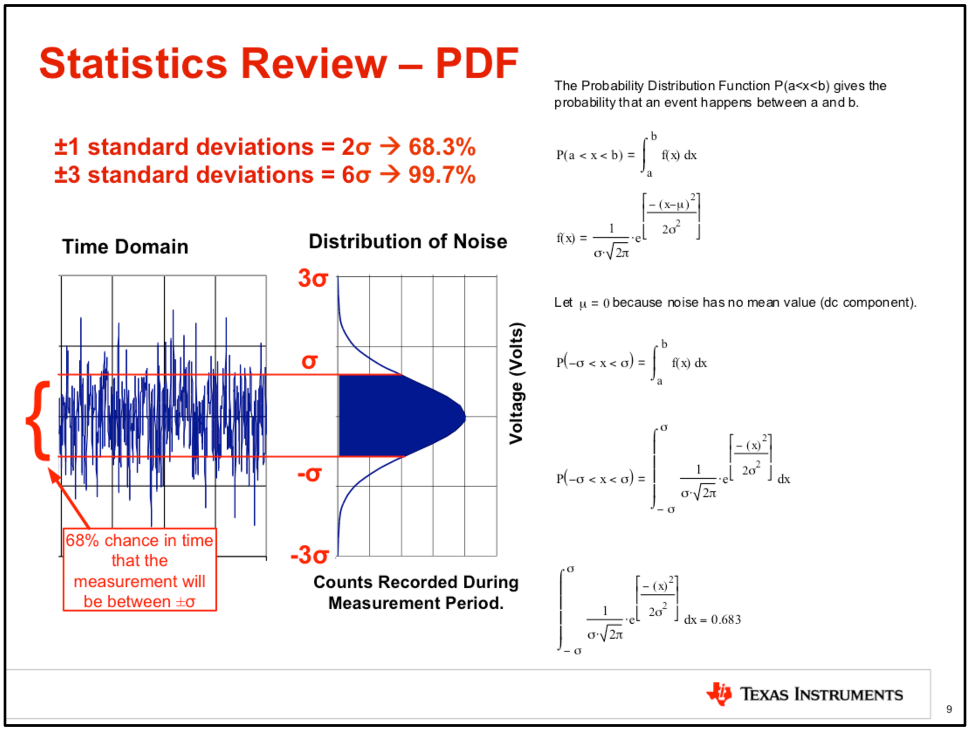
A brief background in statistics is helpful with noise analysis, because most noise has a Gaussian distribution. The probability **density** function creates the outline of the Gaussian curve. The probability **distribution** is derived by integrating the probability density function.

The probability distribution function gives the probability that an event will occur in a certain interval. So, for example, if the probability distribution function is equal to 0.3 for x in the range of -1 to 1, then there is a 30% chance that x will be between – 1 and +1 at any instant in time. In the case of noise, we will use the probability distribution function to estimate peak-to-peak noise.



The probability **distribution** function indicates that there is a 68% chance that a peak will occur between ±1 standard deviation, or 2σ. For ±3 standard deviations, (or 6σ) the probability increases to 99.7%. This is often used as an estimate of peak-to-peak noise. Keep in mind, however, that the tails of the Gaussian curve are infinite, so there is always a finite probability that noise can be measured outside of the interval of ±3σ.

STDEV Relationship to Peak-to-Peak

Number of Standard Deviations	Percent chance of measuring voltage
2σ (same as ±1σ)	68.3%
3σ (same as ±1.5σ)	86.6%
4σ (same as ±2σ)	95.4%
5σ (same as ±2.5σ)	98.8%
6σ (same as ±3σ)	**99.7%**
6.6σ (same as ±3.3σ)	**99.9%**

Is standard deviation the same as RMS?

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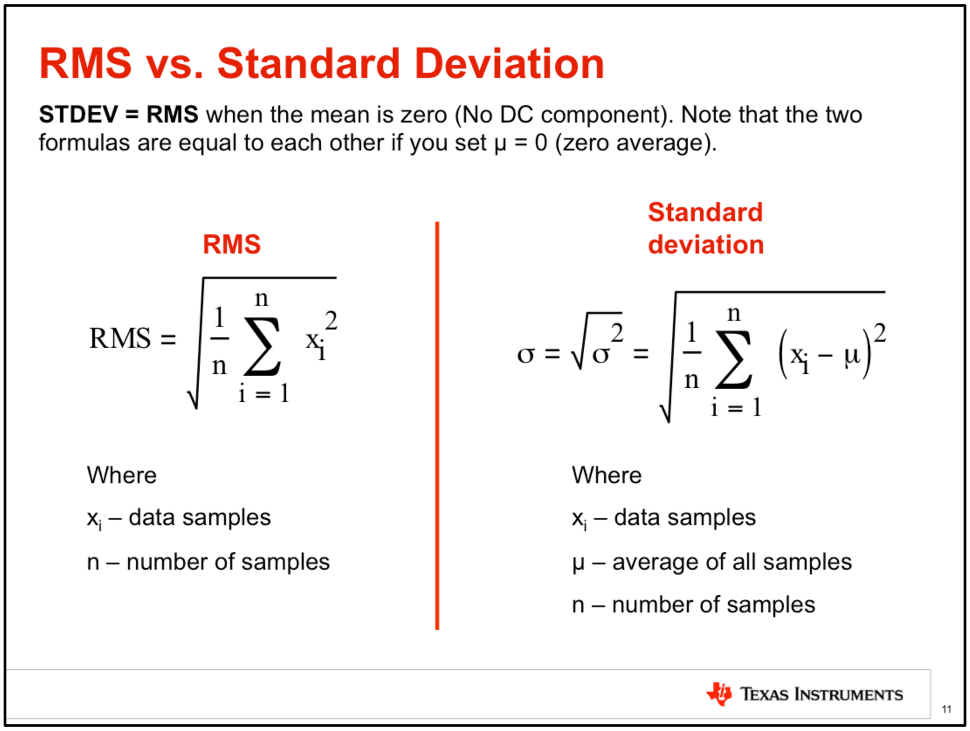
The table shown here relates the number of standard deviations to the probability that a measurement is bounded by this range. For example, there is a 68% chance that any instantaneous noise measurement will be in the range of 2σ, or ±1 standard deviation. 6σ and 6.6σ are common ways of estimating the peak-to-peak noise. In the case of 6σ, for example, there is a 99.7% chance that any instantaneous measurement will occur within that range. Thus, the chance that a noise reading is outside this limit at any instant in time is only 0.3%. The 0.3% probability is considered to be negligible, so 6σ is often used as an approximation for peak-to-peak noise.

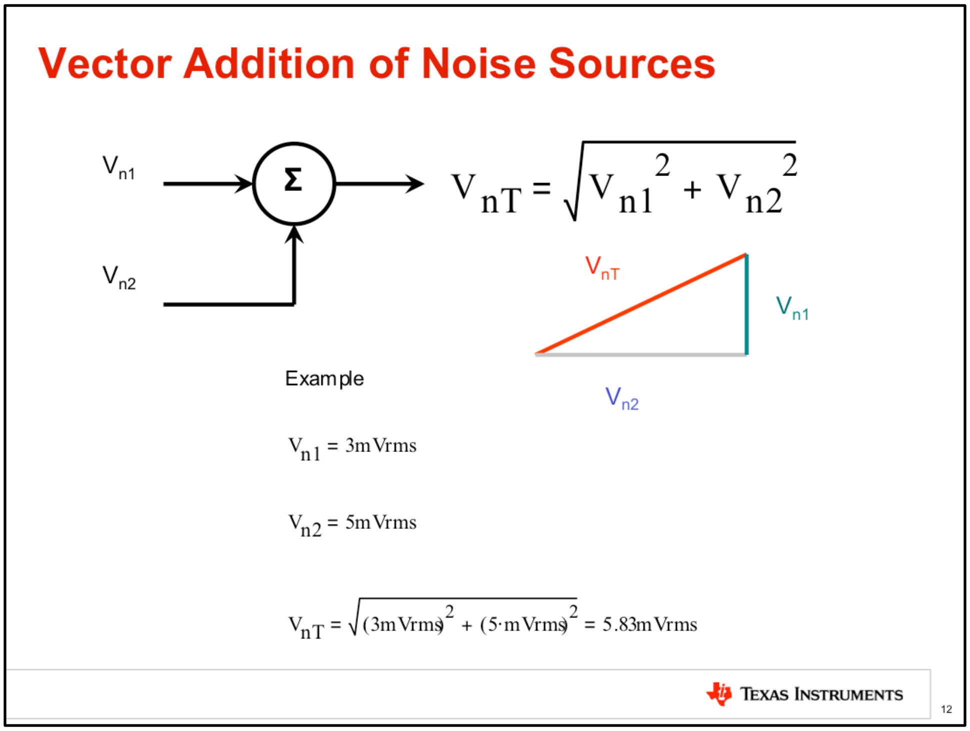
If you are familiar with noise analysis, you may have heard the terms standard deviation and RMS used interchangeably. This leads one to wonder, is RMS equivalent to standard deviation?



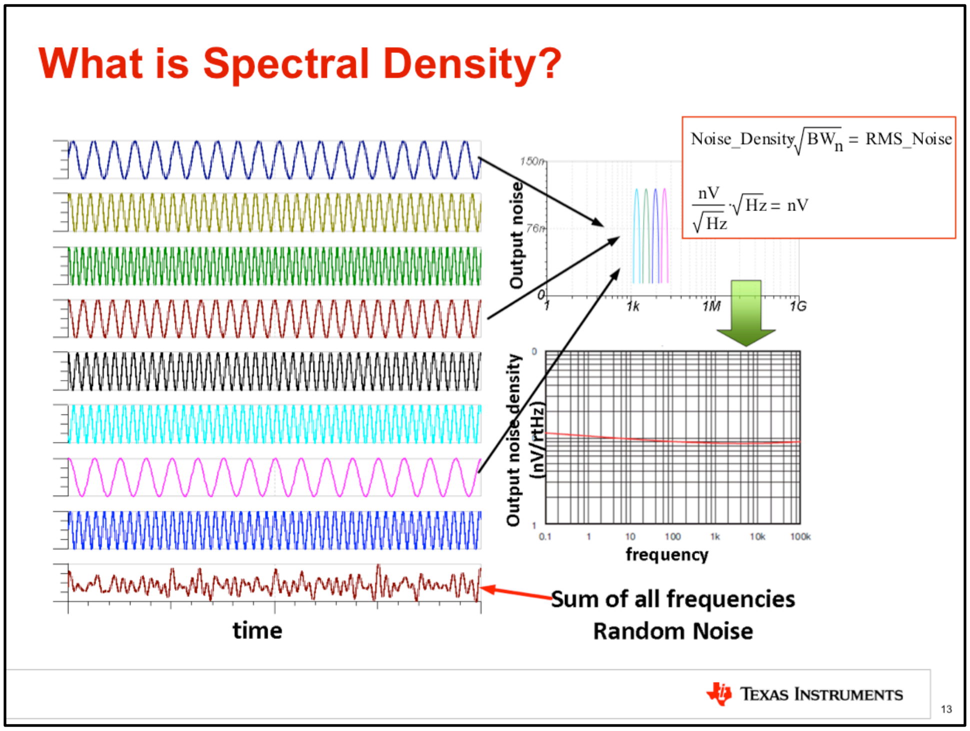
So, the question is does RMS = standard deviation?

The answer is both yes and no! If the signal has no DC offset, the answer is yes. This is the case for most noise signals. Notice that the equation for RMS and standard deviation are the same, except that the standard deviation equation subtracts out the average, or dc offset.

In the case where a signal has a DC offset, RMS will not be equal to the standard deviation. Fortunately, op-amp and resistor noise do not have a DC offset, so we can consider RMS to be equivalent to the standard deviation in these cases. Some extrinsic noise, such as digital switching noise, may not be symmetrical and thus will have a DC offset. It is important to note, however, that some instruments or simulation tools will report RMS noise including the offset term (AC + DC) and others will report RMS without the offset term (AC only).



An important concept in nose analysis is adding noise values. Noise cannot be added algebraically, for example, 3+5=8. Noise must be added as a vector as shown here, where we take the square root of 3mVrms squared plus 5mVrms squared for a result of 5.83mVrms. It is important to note that this relationship applies only to uncorrelated ,random noise. If the noise source is correlated, a different formula applies.



Do you remember that white light is the combination of all colors? Well, white noise is the combination of all frequencies. This figure shows that when you add several signals of different frequencies together in the time domain, the result is a random looking signal. In the frequency domain, each one of these signals looks like an impulse. Combining an infinite number of these signals across all frequencies creates what is called a noise spectral density curve.

Voltage Noise Spectral Density is often a confusing parameter to engineers who are not familiar with noise analysis. Spectral density has units of nV per square root Hertz. Multiplying spectral density by the square root of the noise bandwidth gives the RMS noise as shown in the equation on the top right. Looking at the units in the equation, you can see how the square root Hertz cancels out.

The spectral density curve is the main amplifier specification used to describe an amplifier's noise characteristics. In this video series we will use the spectral density curve extensively in noise calculations.

Resistor Thermal Noise

The mean- square open-circuit voltage (e_n) across a resistor (R) is:

$$e_n = \sqrt{(4kT_K R\Delta f)}$$

where:

T_K → Temperature (K)
R → Resistance (Ω)
f → frequency (Hz)
k → Boltzmann's constant (1.381E-23 joule/K)
e_n → volts (V_{RMS})

$$T_K = T_C + 273.15$$

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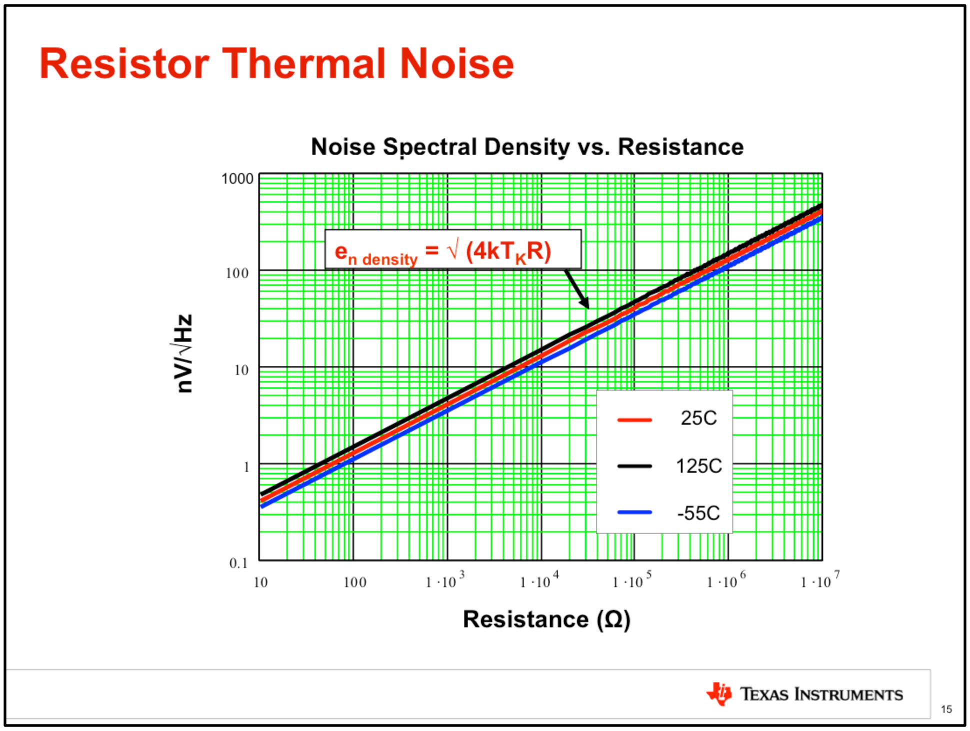
At this point we have introduced many of the fundamentals needed to understand noise.

This slide shows how to calculate the noise produced by a resistor. This noise is generated by the random motion of charges within the resistor.

The equation shown above gives the total RMS noise generated by a resistor. Notice that the equation requires the temperature in Kelvin, the resistance, the bandwidth, and Boltzmann's constant. Dividing both sides of the equation by the square root of the bandwidth yields the voltage spectral density equation.

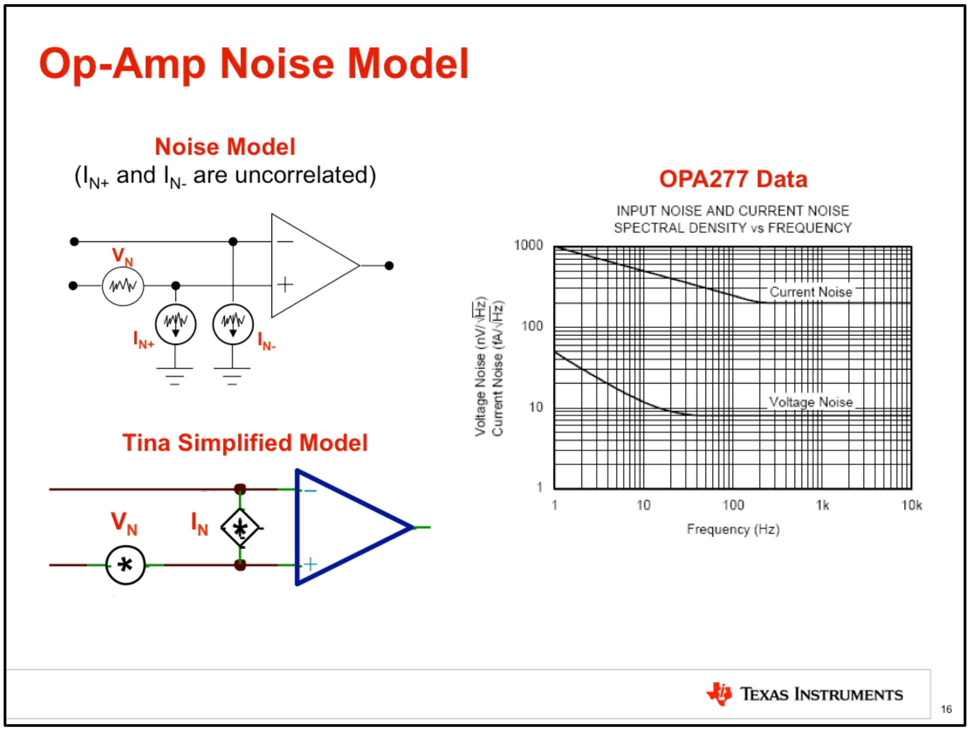
Remember that amplifiers' noise specifications are usually given in terms of spectral density. Determining the noise spectral density for a resistor is useful, because it allows for easy comparison of the noise generated by resistors and the noise generated by amplifiers.



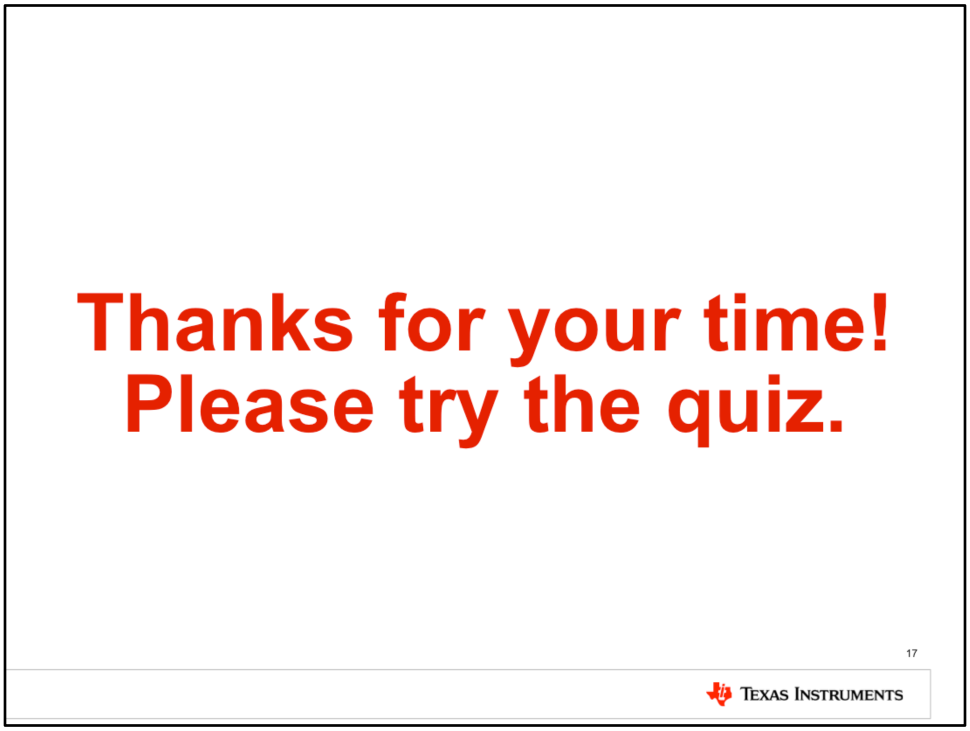
This plot was generated using the equation given in the last slide. Note that the equation was divided by the square root of bandwidth to give a spectral density, which is useful because it provides a quick way of comparing resistor noise to op-amp noise. Remember, most op-amps specify noise in nV/√(Hz).

A very low noise amplifier may have intrinsic noise of 1nV/√(Hz) noise. Comparing to this plot, 1nV/√(Hz) corresponds to a resistor value of approximately 70 ohms. Thus, for this example, op-amp you should try to use resistors of 70 ohms or less. For best performance, it's recommended for the amplifier in a circuit to generate more noise than the resistors. Low noise amplifiers can be expensive, and you would not want to pay extra for an expensive low noise amplifier and have resistor noise dominate the circuit's noise performance.

Neglecting resistor noise is a very common oversight of engineers who are new to noise analysis. For this reason, it is useful to have this chart available for quick reference.



This slide show the typical op-amp noise model. In some cases, it is important to have two separate current noise sources, as shown in the upper left. In other cases, the simplified model with a single noise source between the inputs is adequate. The noise sources represent the spectral density curves. In the following videos discussing noise, we will learn how to use the op amp noise model to predict the total peak-to-peak output noise for different amplifier configurations.



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