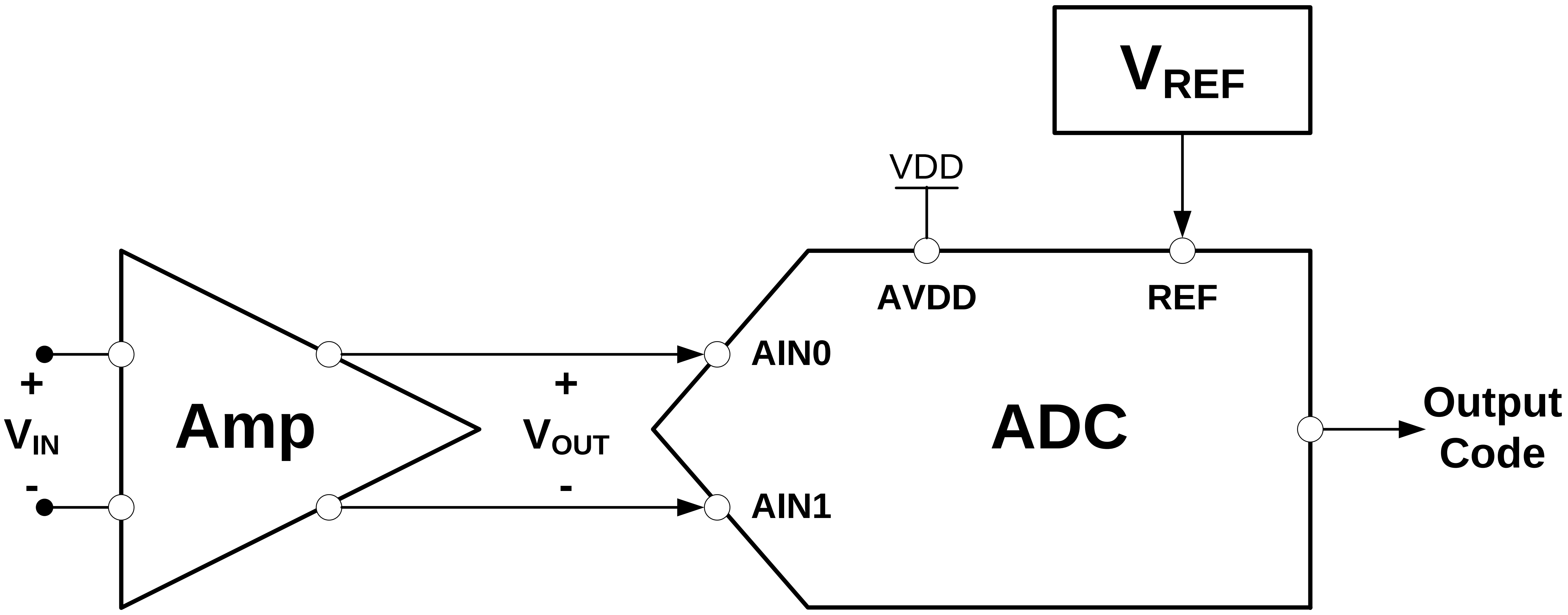
Types of noise in ADCs

TI Precision Labs – ADCs

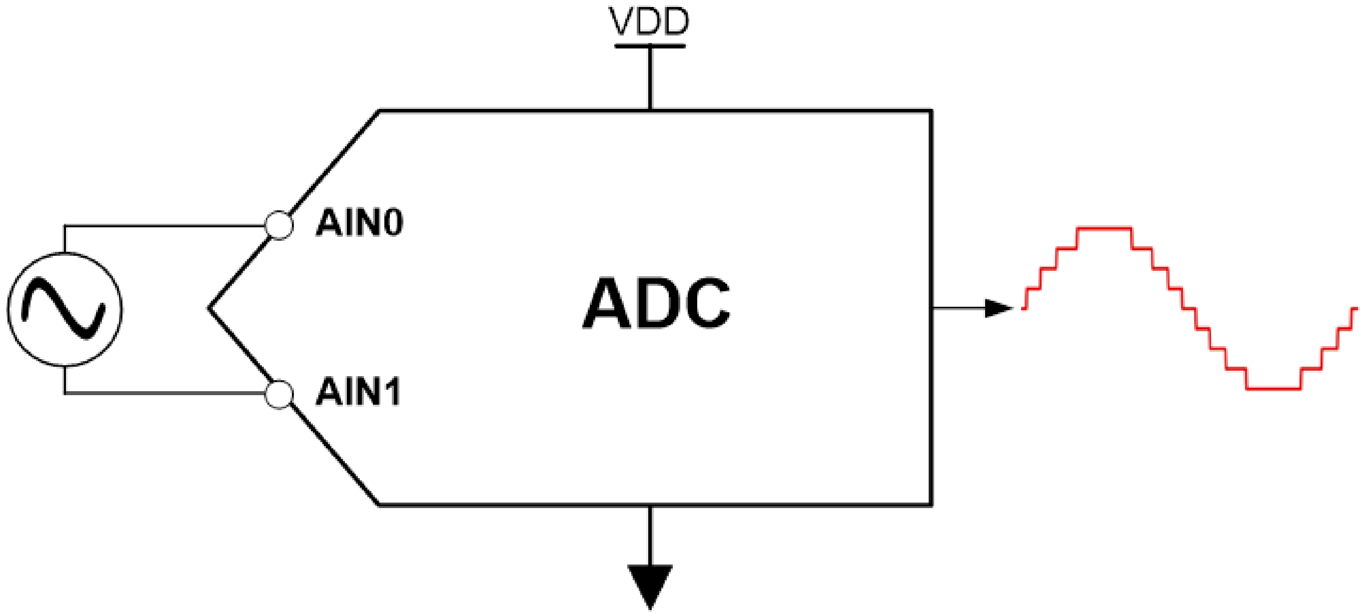
Created by Chris Hall & Bryan Lizon

Presented by Alex Smith

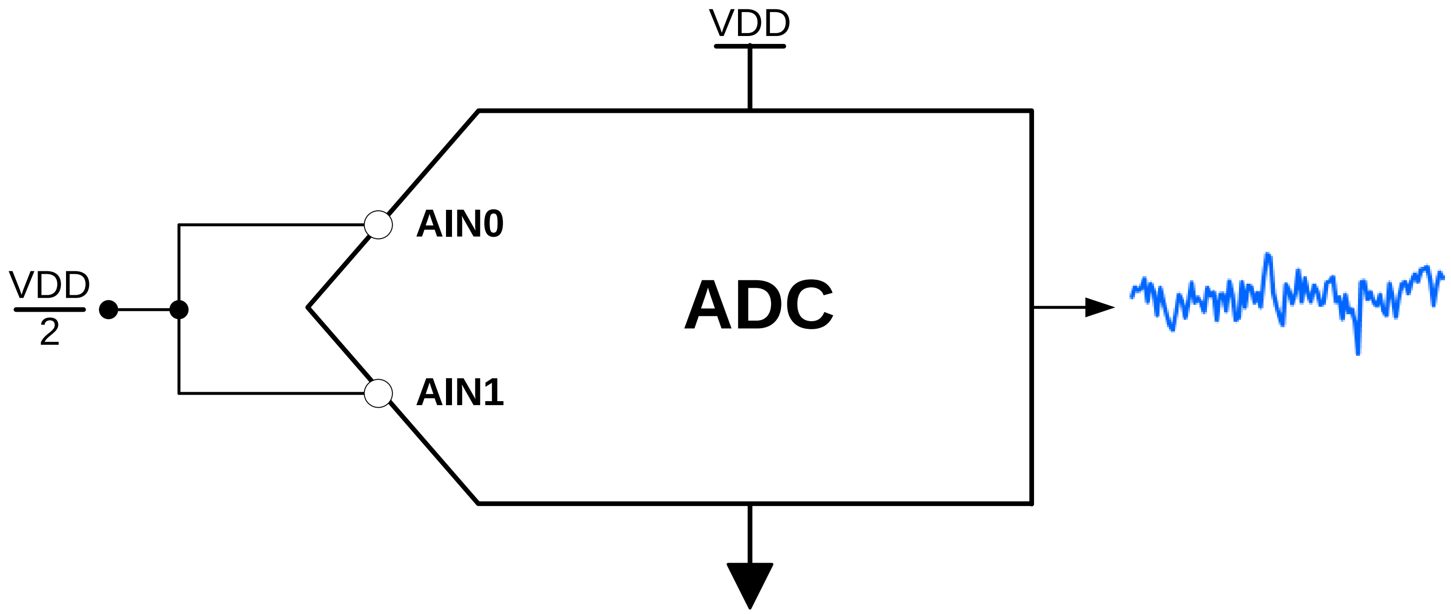
The goal of this Precision Labs series



Types of ADC noise

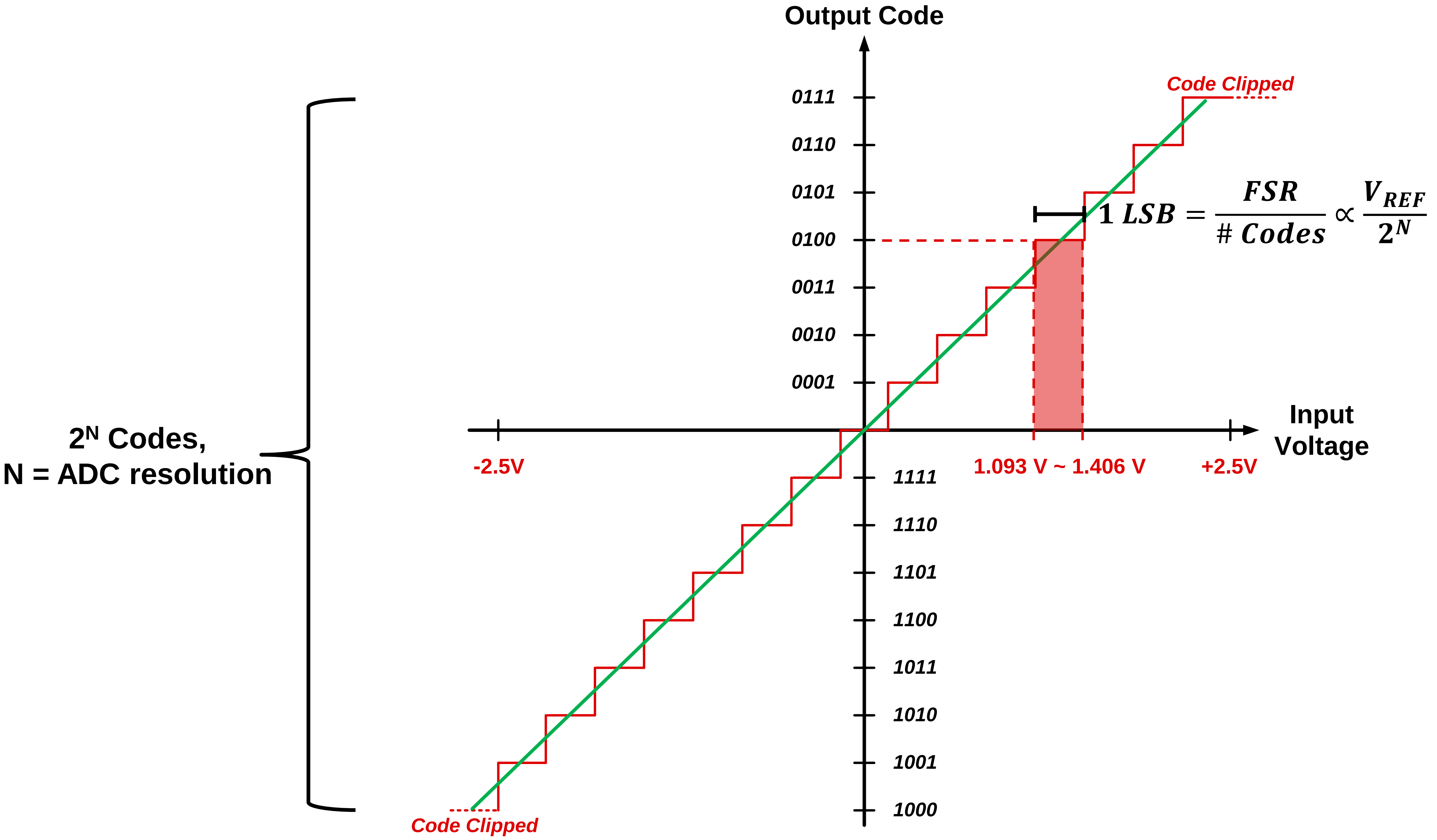


Quantization Noise

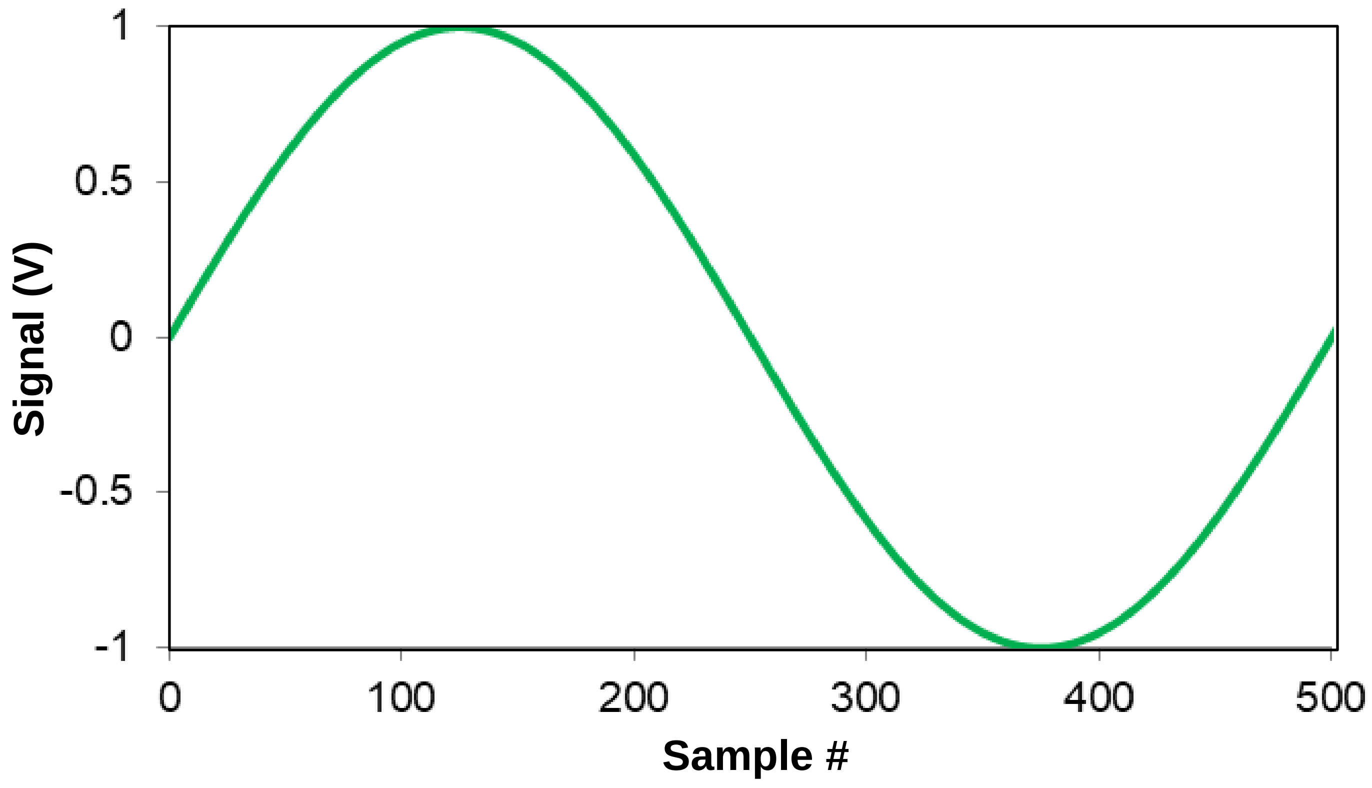


Thermal Noise

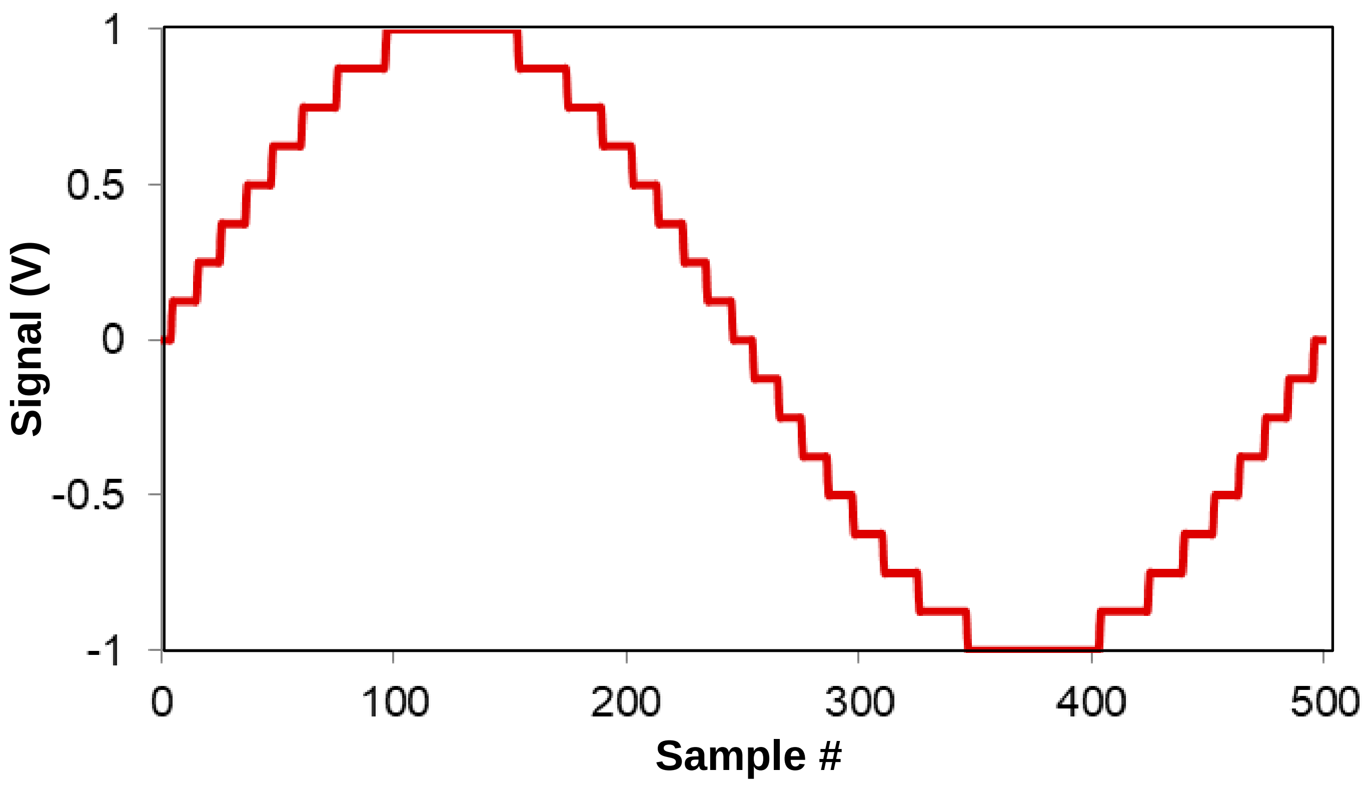
The ideal ADC transfer function



Quantization (Q) noise in the time domain

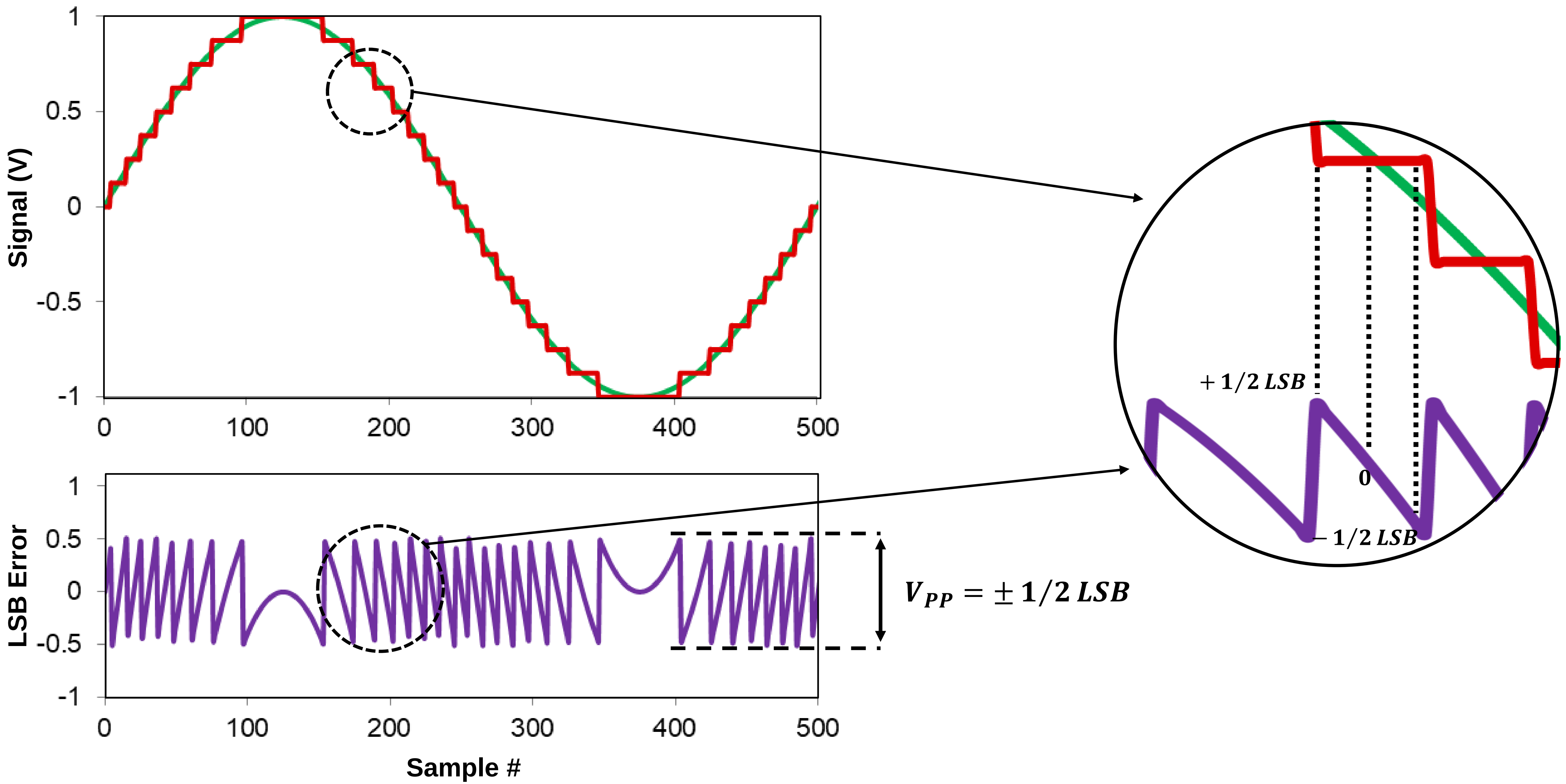


Analog Sinewave Input

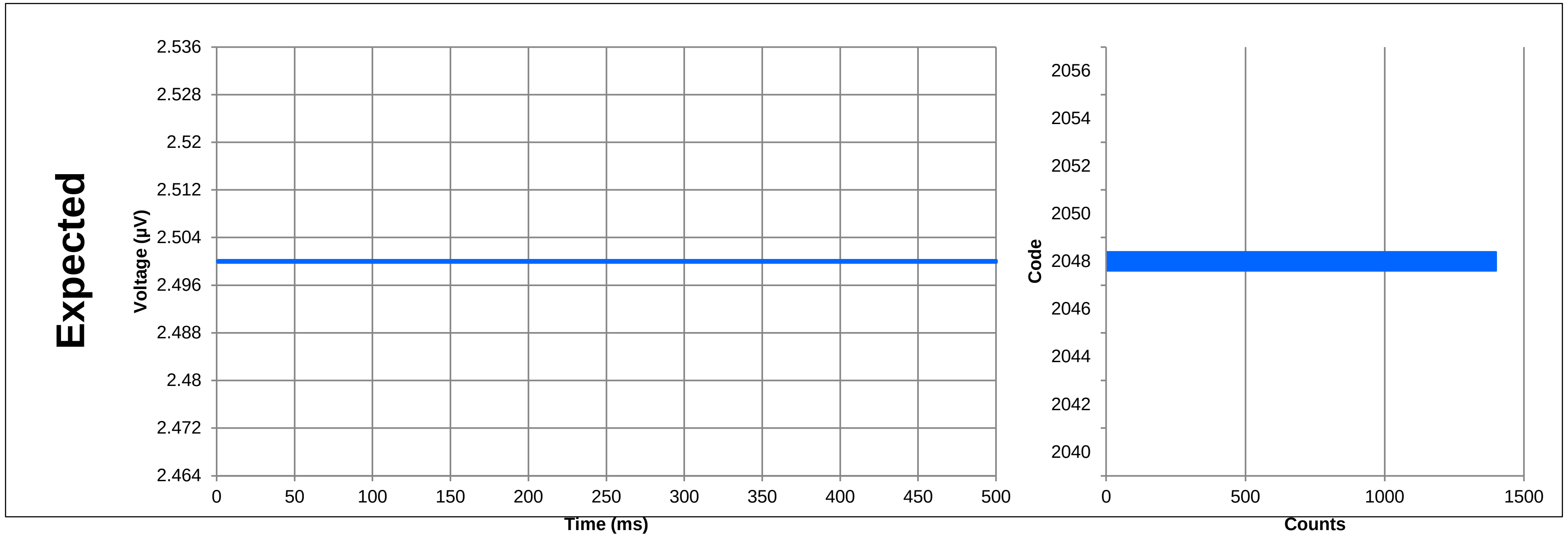


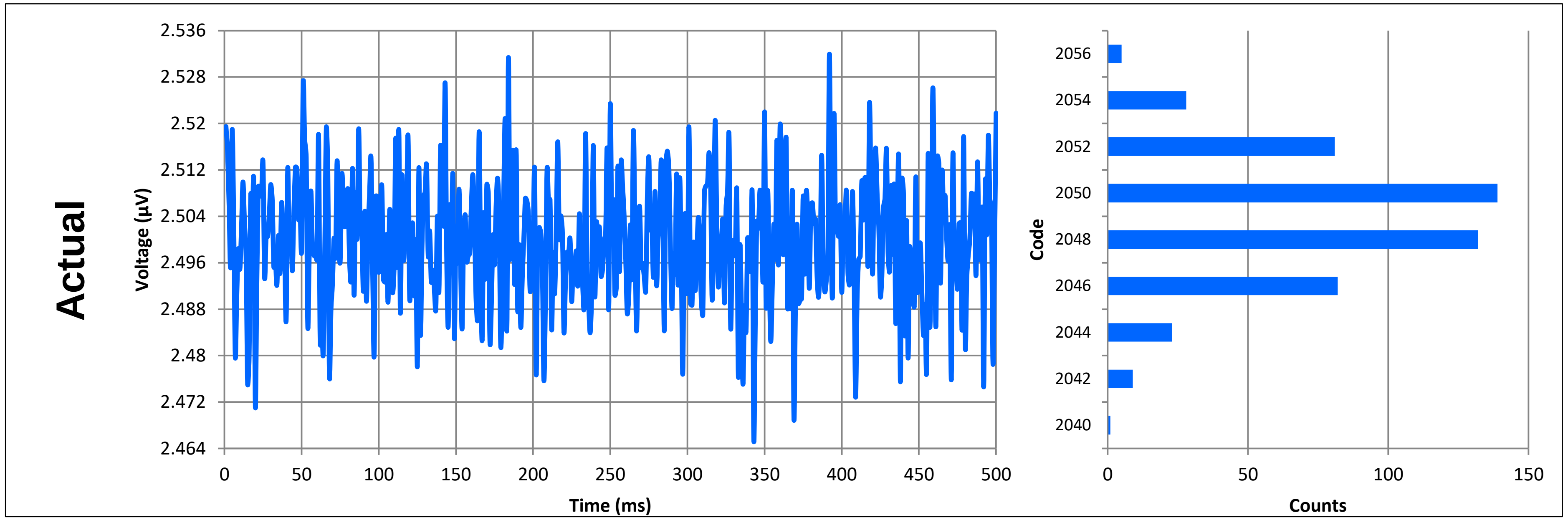
Quantized, Stair-Step Output (4-bit)

Q noise and LSB error



Thermal (T) noise in the time domain



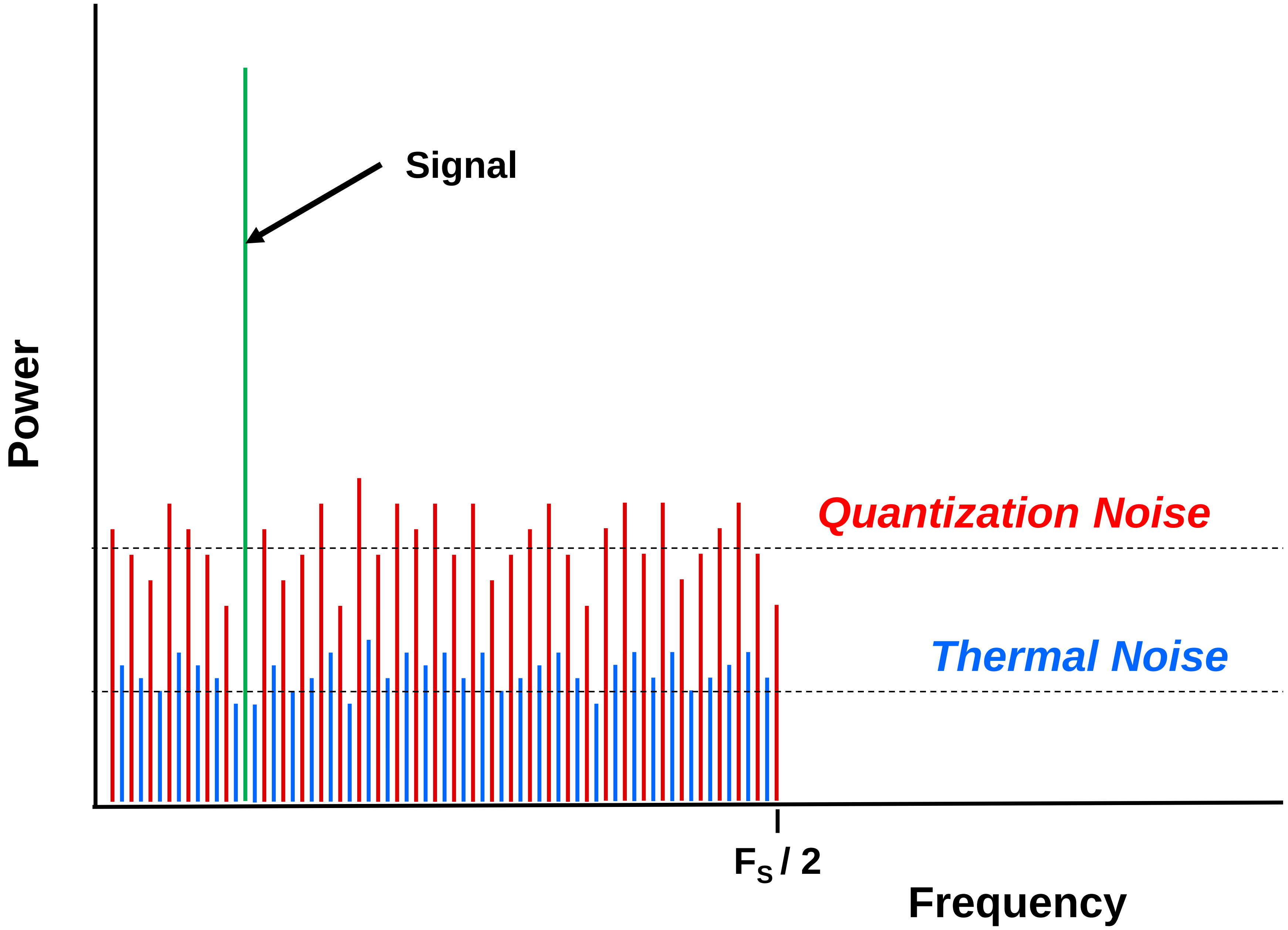


Thermal noise:

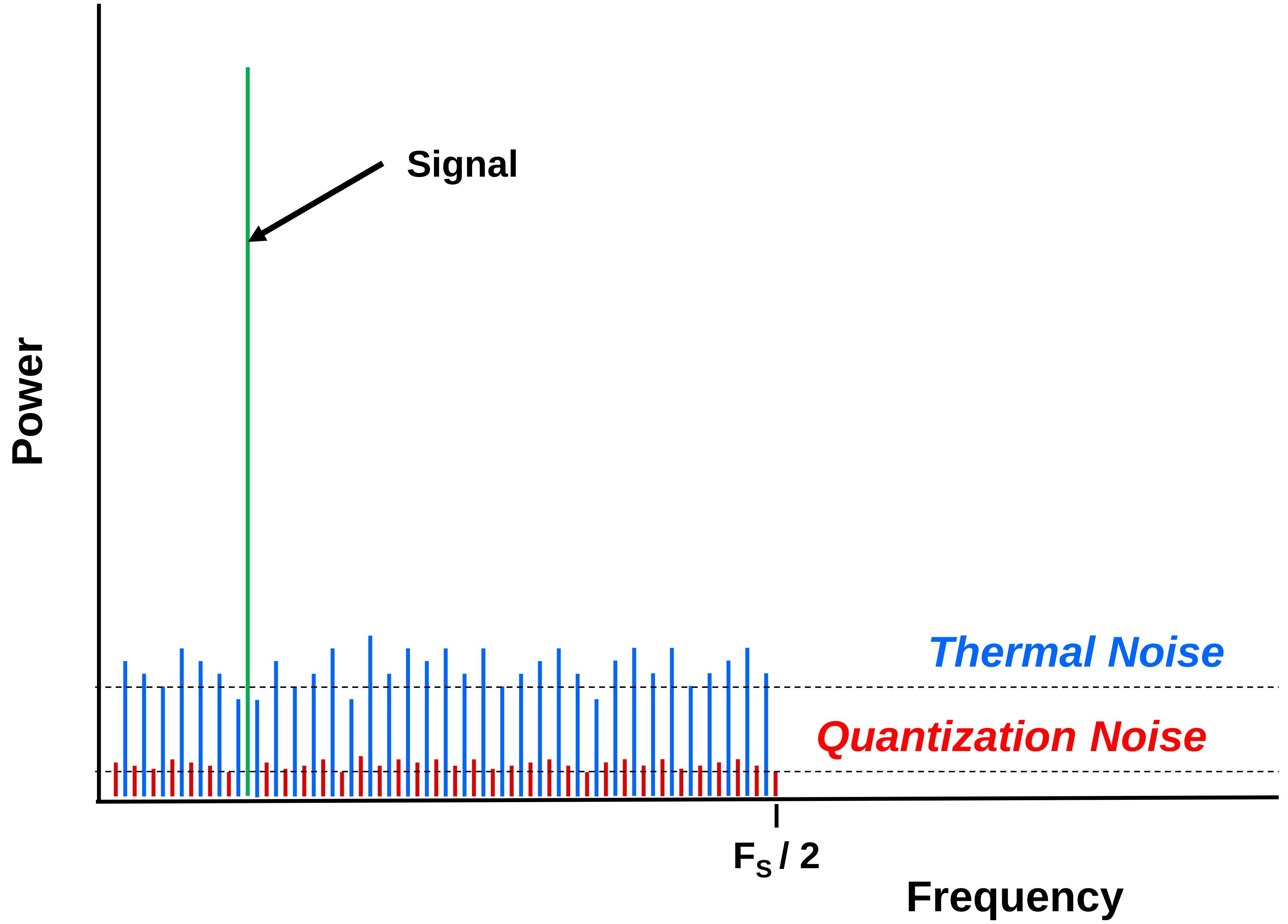
- **Is observable when LSB size is small**
- **A combination of all noise sources other than quantization noise**
- **Adds to quantization noise using root-sum-squares (RSS)**

For more information, watch the Precision Labs video on op amp noise

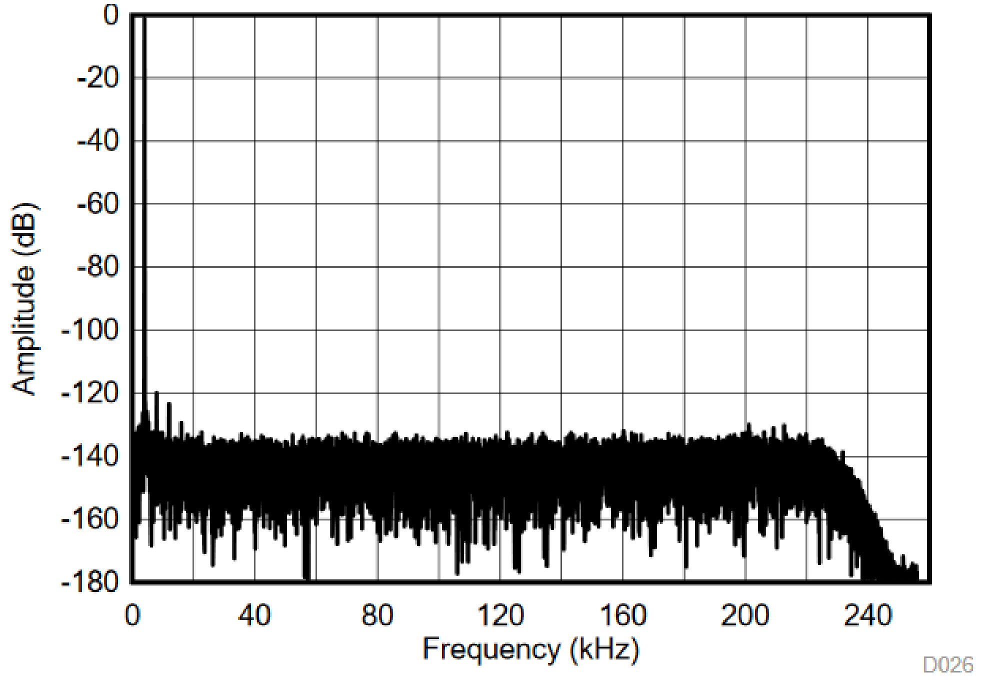
Frequency-domain noise (low-resolution ADC)



Frequency-domain noise (high-resolution ADC)

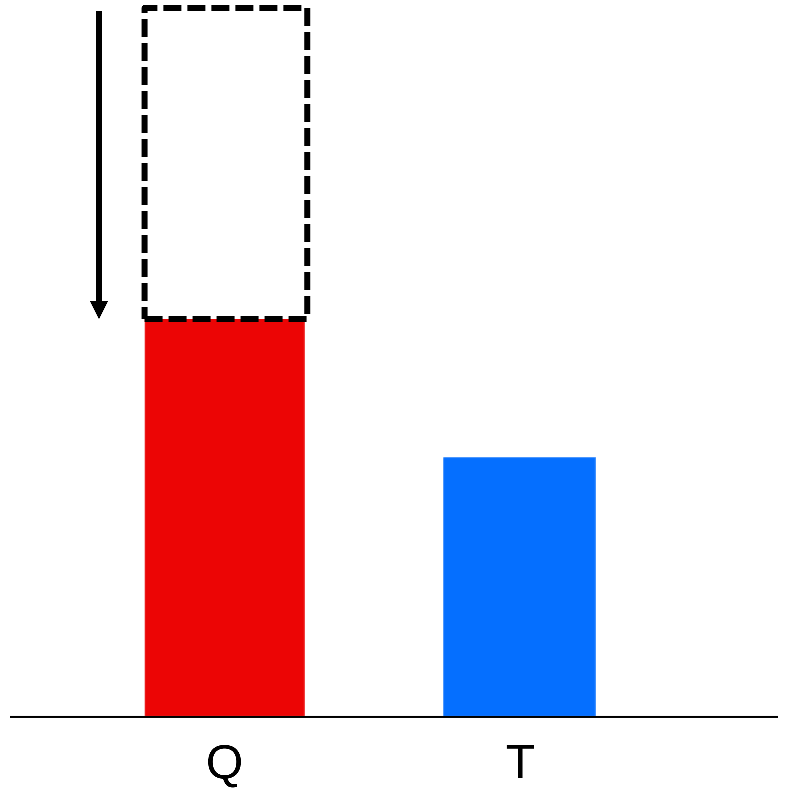


FFT (ADS127L01)



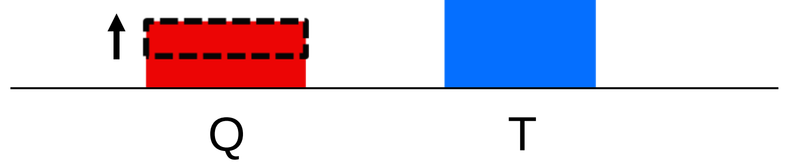
f_{IN} = 4 kHz, V_{IN} = –0.5 dBFS, HR mode, WB2, 512 kSPS, 32768 samples

How changing Q noise levels affects your system



Lower-resolution ADCs

<u>Resolution is limited by quantization noise</u>
*Use **smallest** acceptable reference*
(to decrease quantization noise)



Higher-resolution ADCs

<u>Resolution is limited by thermal noise</u>
*Use **largest** acceptable reference*
(to increase dynamic range)

Thanks for your time! Please try the quiz.

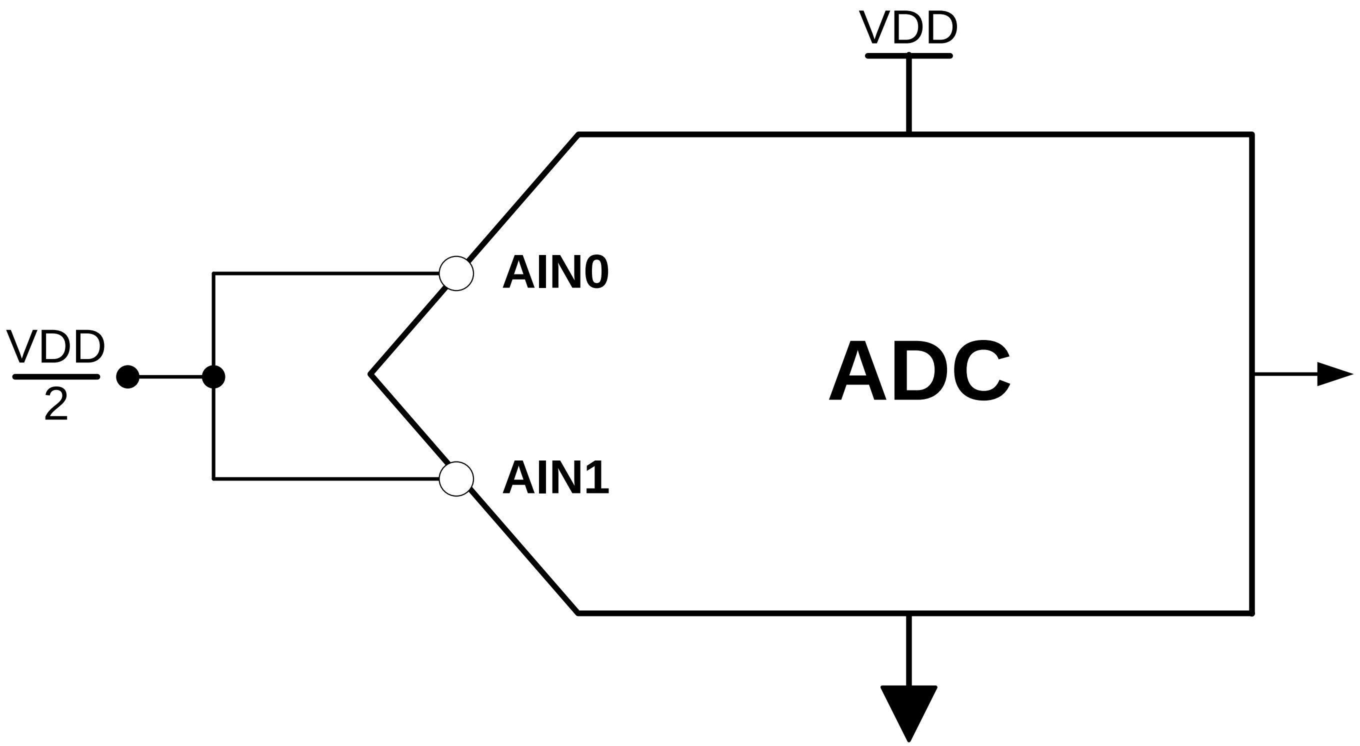
Quiz: Types of noise in ADCs

1. (T/F) Quantization noise will be reduced by increasing the ADC resolution.
   a. True.
   b. False.

2. (T/F) Thermal noise will be reduced by increasing the ADC resolution.
   a. True.
   b. False.

Quiz: Types of noise in ADCs

3. For the circuit below, which type of noise is being measured?
   a. Thermal Noise
   b. Quantization Noise



Quiz: Types of noise in ADCs

4. For a circuit where quantization noise dominates, should you increase, or decrease the reference voltage to reduce the total noise?
   a. Increase
   b. Decrease
   c. Total noise will not be impacted by the reference level.

5. For a circuit where thermal noise dominates, should you increase, or decrease the reference voltage to improve the system performance?
   a. Increase
   b. Decrease

Thanks for your time!

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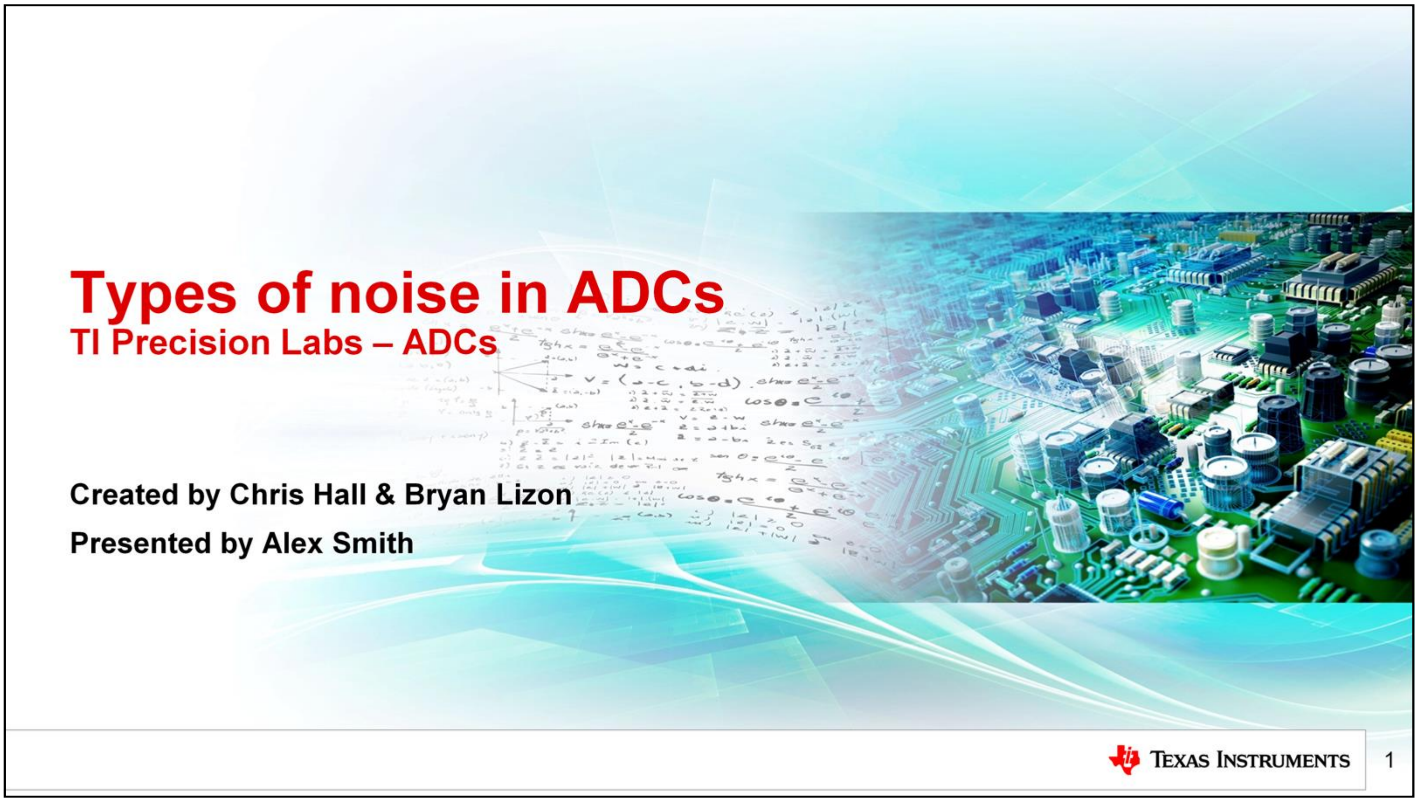
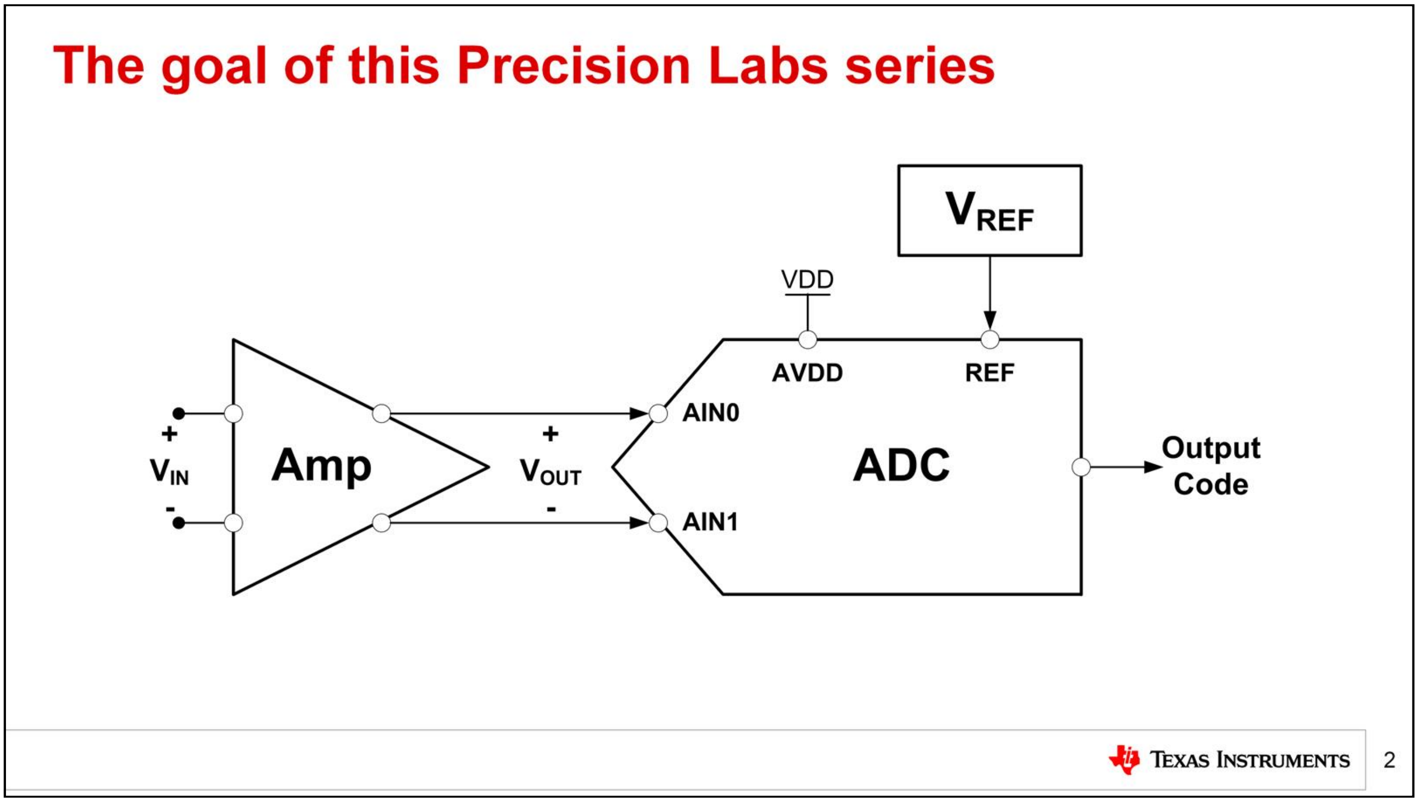


Hello, and welcome to the TI Precision Lab module discussing the different types of noise in ADCs. In this module you will learn about the two types of noise intrinsic to ADCs, where this noise comes from, and how each type affects lower- and higher-resolution ADCs.

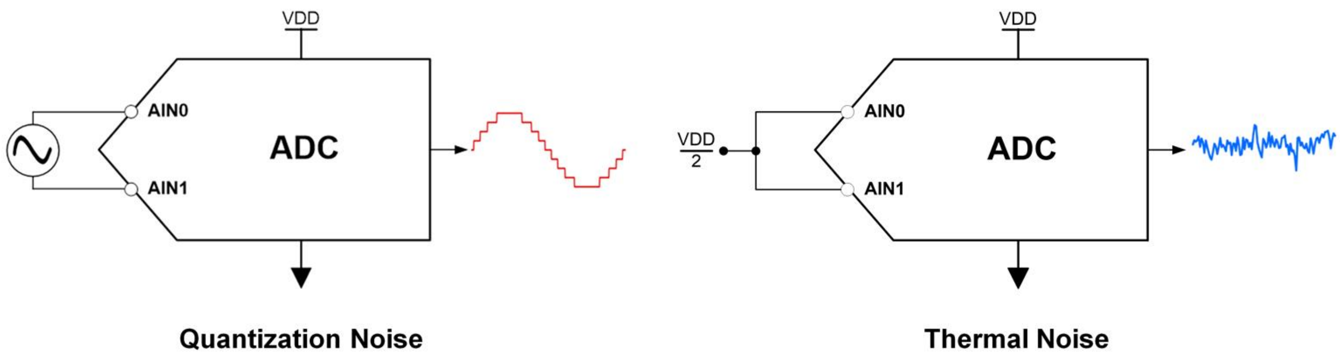
But first, let’s clarify the end goal of this presentation series



As stated in the introductory Precision Labs module in this section, the end goal of this series on ADC noise is be able to analyze the system shown here. In particular, you should be able to understand how noise enters this system, what the dominant noise sources are in a given application, how changing your system specifications affect the noise of each component as well as the overall system noise, and ultimately how to calculate the expected noise to determine if it meets your system requirements.

To accomplish this goal, we'll delve into each noise source at first, then bring all of that component-level knowledge together to analyze the entire system. And since this Precision Labs series focuses on how these components impact ADC performance, we'll begin by introducing the topic of intrinsic ADC noise.

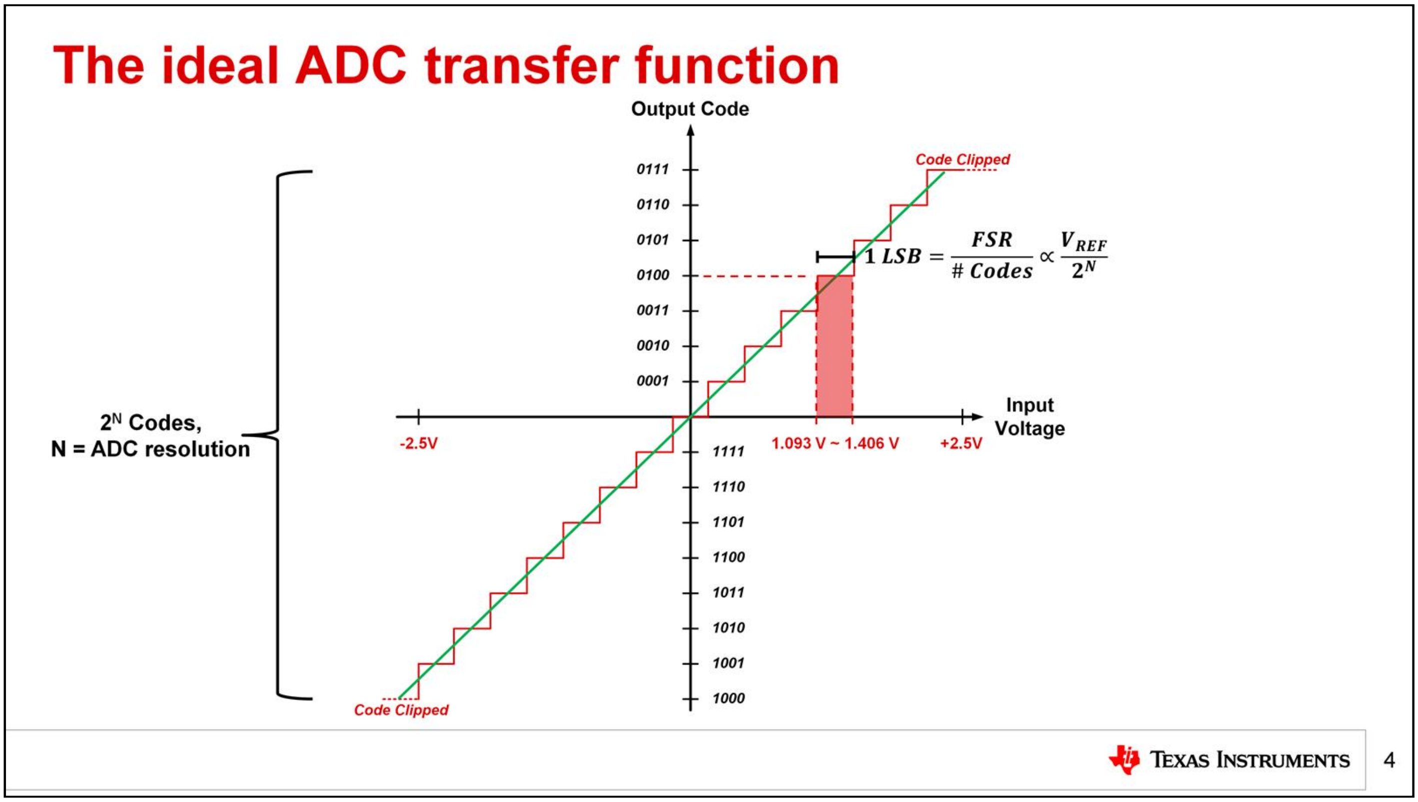
Types of ADC noise



Intrinsic ADC noise is made up of two components: the first is quantization noise, which is effectively a rounding error resulting from the need to map an infinite number of possible analog inputs to a finite number of digital output codes. This rounding error is what converts a smooth sinewave input into the stair-step shaped output shown in red in the figure on the left.

The second type of noise is thermal noise, which results from the inherent properties of electrical conductors. Since this type of noise is not a product of the analog to digital conversion process, it is still perceptible even when no input signal is present. This is shown in the image on the right where the ADC's inputs are shorted to mid-supply. The blue output signal is an example of what a thermal noise signal looks like in the time-domain

Both types of noise can be found in all ADCs, though one type typically dominates depending on the ADC’s resolution. Let’s discuss each in more detail, beginning with quantization noise



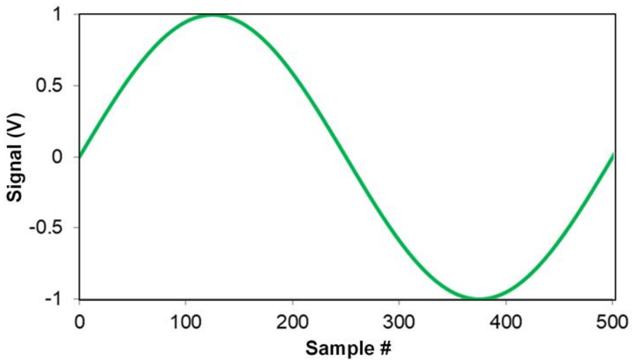
To better understand quantization noise, it helps to look at the ADC's ideal transfer function. If the green line on the plot shown here represents a pure analog signal, the red line represents the quantized output, unaffected by offset or gain error. Note that this transfer function extends into quadrants 1 and 3, which assumes an ADC using a binary two's complement coding format. This transfer function extends from the minimum input voltage to the maximum input voltage horizontally, which is ±2.5 V, and is divided vertically into a number of steps based off of the total number of ADC codes. This specific plot has 16 codes, or steps, representing a 4-bit ADC.

As stated previously, quantization noise results from the process of having to map an infinite number of analog input voltages to one of the finite number of available digital codes.

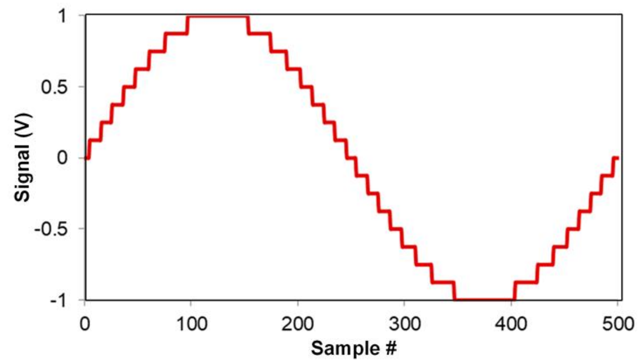
For example, given the full-scale input of ±2.5 V with this 4-bit ADC, the output code of 0100 could correspond to any analog input voltage between 1.093 and 1.406 V. For any ADC, this step width is know as the least significant bit, or LSB.

The value of one LSB is the smallest signal an ADC can theoretically resolve, though practical limitations often make it impossible for an ADC to actually resolve down to the level of one LSB. As the equation on the screen shows, LSB size is directly proportional to the ADC's reference voltage and indirectly proportional to the ADC's resolution. This relationship helps explain why higher resolution ADCs generally offer better noise performance – more available codes decrease LSB size which consequently decreases quantization noise. Let's further our understanding of quantization noise by looking at it in the time domain

Quantization (Q) noise in the time domain



Analog Sinewave Input



Quantized, Stair-Step Output (4-bit)

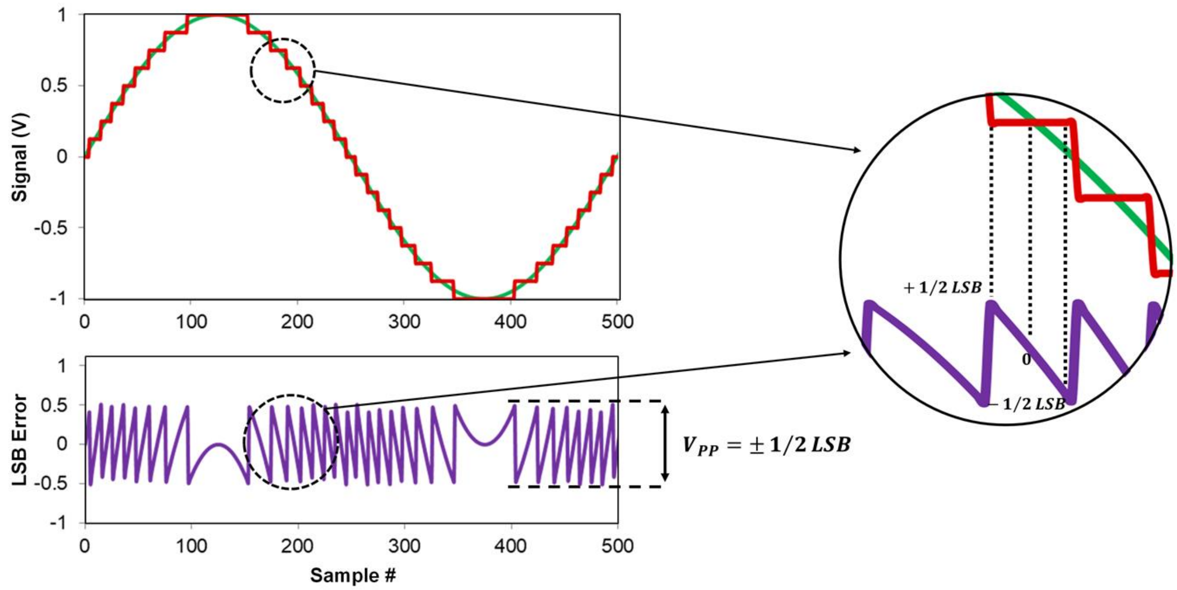
Shown on the left side of the screen is a generic sinewave input plotted in green. If you applied the 4-bit ADC transfer function from the previous slide to this sinewave, the output would be similar to the quantized result on the right side of the screen.

Like the ADC transfer function, the quantized output shown in red has a “stair-step” shape. Each step represents one ADC code, with each code correlating to an infinite number of possible analog input voltages that are bounded by the ADC’s LSB size.

One observation from these plots is that the quantized output is not necessarily a good reproduction of the input sinewave. Since we are using a 4-bit ADC in this example, the converter does not have sufficient resolution to precisely replicate the input signal. As stated on the previous slide, a higher resolution ADC – for example, a 20-bit device – would reduce both the width and the height of the “stairs” in the plot on the right, resulting in a quantized output that more closely resemble the sinewave.

Let’s overlay these plots to get a better idea of where quantization noise actually comes from

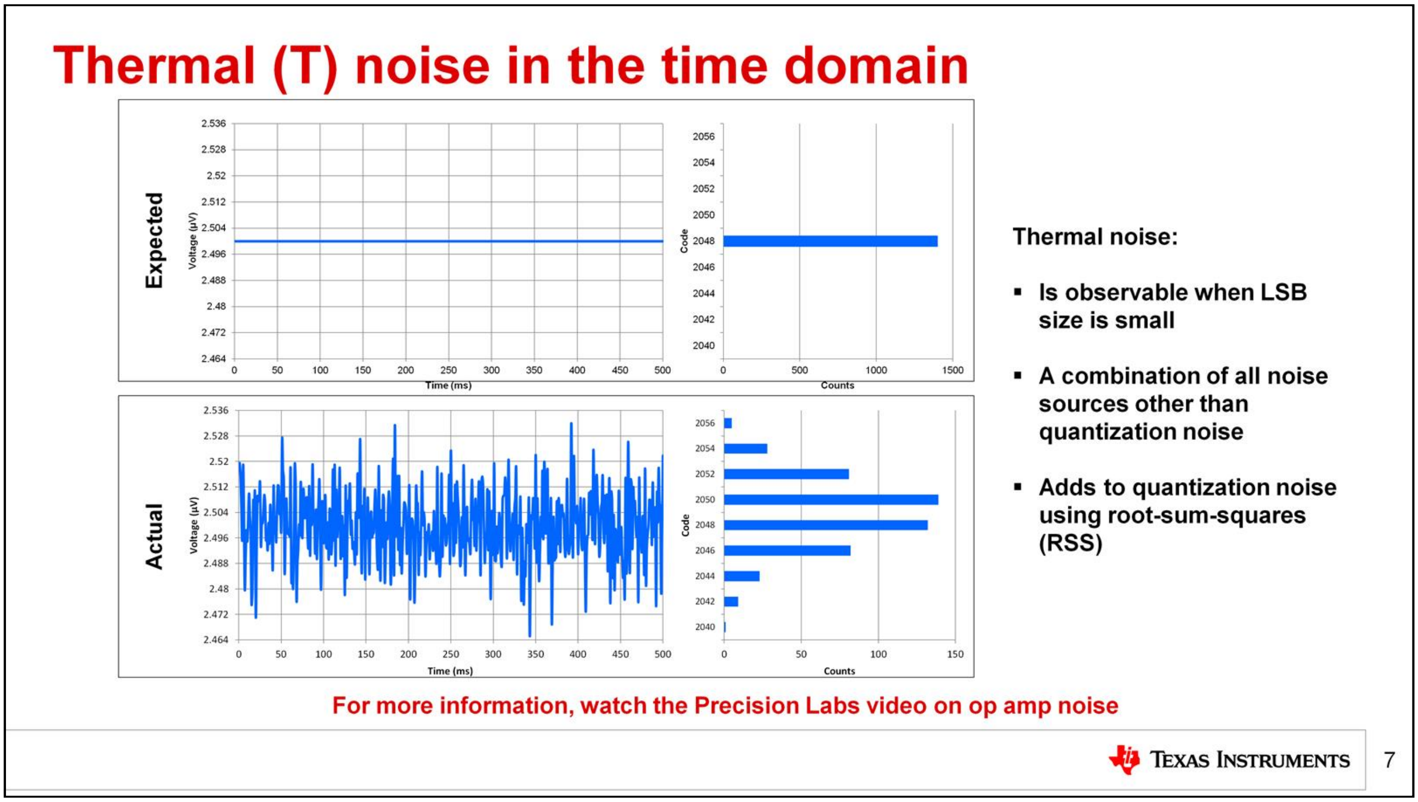
Q noise and LSB error



Shown here is the combined plot, with the red quantized output overlaid on the green analog sinewave input. Below this image is another graph plotting the difference between the analog input and quantized output. This purple chart represents the magnitude of the quantization noise at each point on the combined graph, and is referred to as a “saw-tooth” shaped error.

If you zoom in on a portion of the LSB error plot, you can see how the difference between the continuous analog input and the stair-step shaped output results in the saw-tooth waveform. Also note that the LSB error plot varies between plus or minus one-half of an LSB, similar to what was shown on the ADC’s transfer function slide. And as we discussed on that slide, within one LSB, the ADC can’t determine where the actual analog input voltage is, so this uncertainty appears as a “noise” in the result. This is true for DC signals as well, but with no frequency component, quantization “noise” actually appears as an offset error in the ADC output and is instead referred to as quantization error.

Now that you better understand what quantization noise is and where it comes from, let’s switch topics and learn about thermal noise

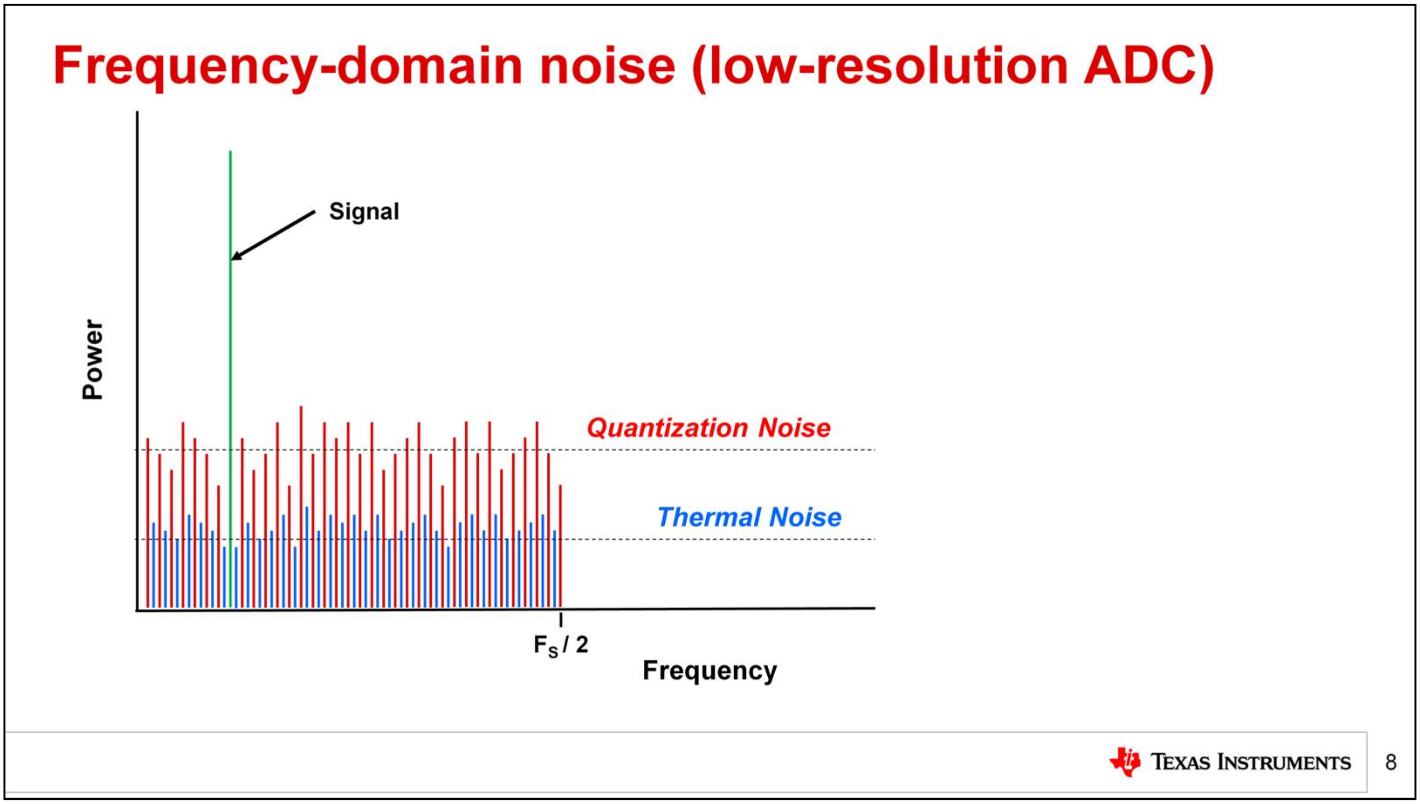


When you quantize a DC signal – for example, 2.5 V – you would ideally expect no quantization error and a single output code. This expected time-domain noise plot and histogram are shown at the top of this slide. And while these are considered ideal conditions, certain ADCs can exhibit this type of behavior.

However, for many ADCs you can observe noise even when no signal is present. For example, the thermal noise block diagram shown earlier in this presentation had the ADC's inputs shorted to mid supply. Noise measured under these circumstances is called thermal noise. Unlike quantization noise, which is specific to the analog to digital or digital to analog conversion process, thermal noise is inherent in all electrical components due to the random motion of charges within electrical conductors. The bottom image shows what thermal noise looks like in the time-domain, as well as a possible distribution of the ADC's output codes.

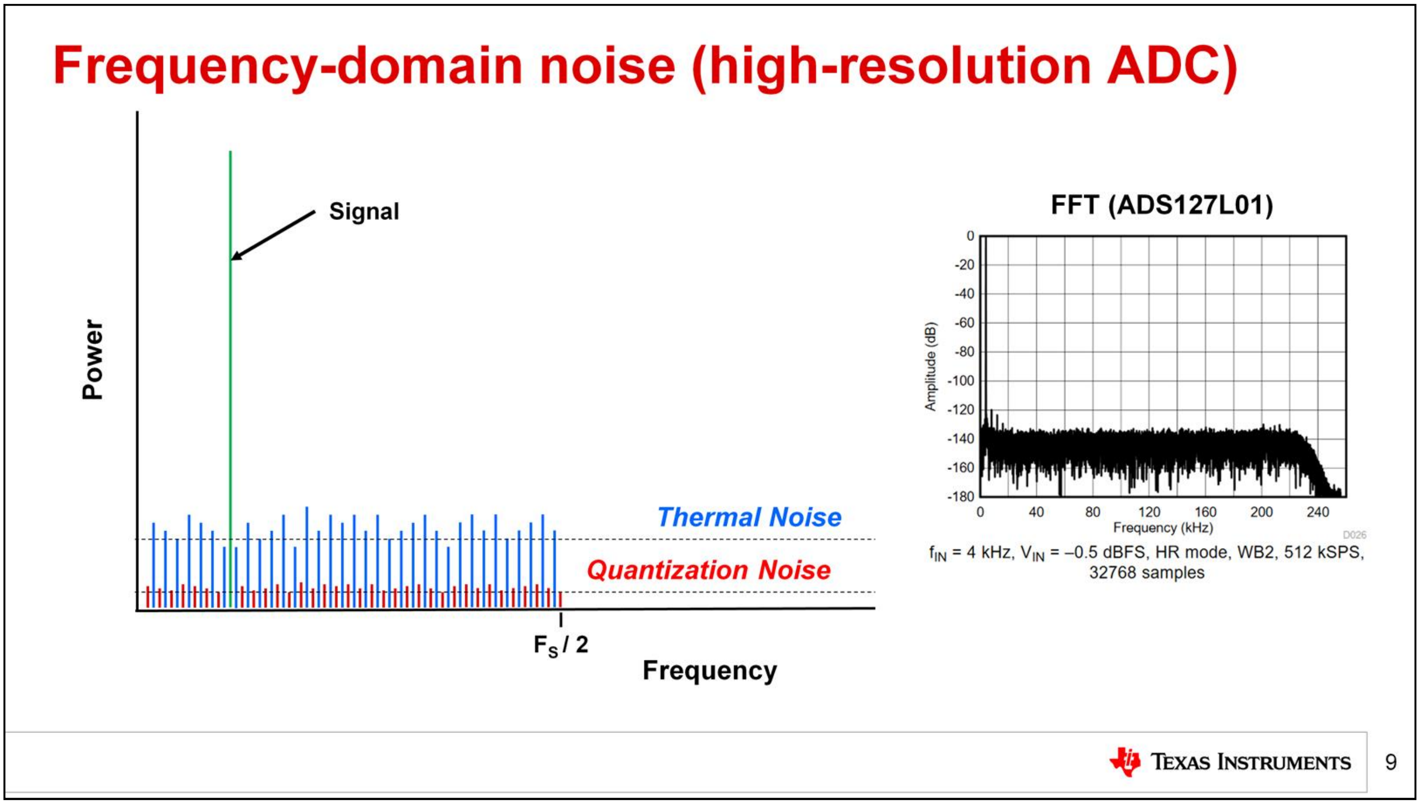
Since thermal noise is largely a result of the ADC's design and therefore unable to be changed by the end-user, we'll just make some general comments about thermal noise properties. First, thermal noise is observable when an ADC's LSB size is small, which is generally only in high resolution ADCs. For low-resolution ADCs, the time-domain noise plot would look more similar to the ideal case with a single output code and little to no quantization noise. You can see an example of this in a subsequent presentation. Second, thermal noise in ADCs is considered to be a combination of all other internal noise sources other than quantization noise. At a system level, other components including amplifiers and voltage references can contribute to the measured thermal noise. And finally, thermal noise frequency content is considered broadband with a Gaussian distribution, such that total ADC noise performance results from adding quantization and thermal noise using the root-sum of squares method. For more in-depth information about the properties of thermal noise, please review the Precision Labs modules on op amp noise

Since we've looked at quantization noise and thermal noise in the time domain, let's look at both in the frequency domain



In the frequency domain, both quantization noise and thermal noise generally appear uniform across frequency, as shown in the power vs frequency plot on the screen. As stated on the previous slide, thermal noise is typically broad spectrum, shown qualitatively as the blue frequency plot. Quantization noise, shown here in red, is also broadband due to the wide spectrum of the “saw-tooth” shaped waveform seen previously, folded or aliased back into the frequency range from 0 Hz to one-half the sampling frequency.

While the thermal noise is shown below the level of the quantization noise, this is not always the case. For many ADCs, thermal noise is greater in magnitude than quantization noise. For others, thermal noise and quantization noise could be approximately equal. As the slide title implies, the ADC's resolution generally defines the magnitude of the different noise levels. For this specific frequency plot, we can conclude that this is a low-resolution ADC, since the quantization noise dominates. In this case, the ADC must have a relatively large LSB size compared to the thermal noise.

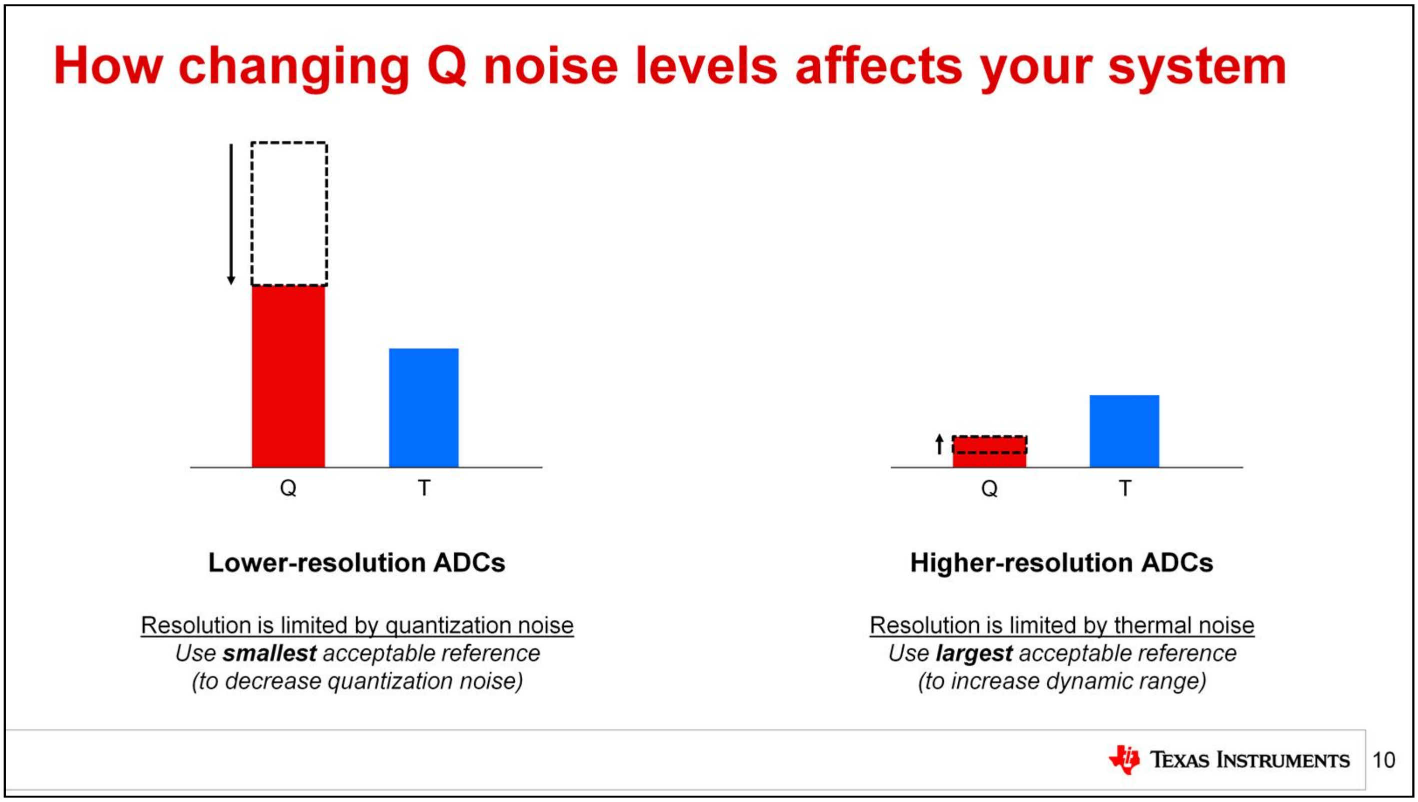


On the other hand, if you were looking at the noise levels in a high-resolution ADC, you'd see the quantization noise level drop below the thermal noise as shown. The lower levels of quantization noise are due to the much smaller LSB size in high-resolution ADCs. For example, the LSB size of a 24-bit delta-sigma ADC using a 5 volt reference and no gain is less than 300 nanovolts, which is far below the level of the ADC's thermal noise.

One important point to note here is that while these frequency plots may seem arbitrary, we are purposely looking at the qualitative difference between quantization and thermal noise. The frequency plots shown here and on the previous slide are used to help demonstrate how noise levels affect different ADCs, as well the frequency content of each type. If you were to look at an actual FFT, such as the one shown on the right side of screen from the 24-bit

ADS127L01's datasheet, you would not see a delineation between quantization and thermal noise. Instead, the ADC's noise floor would be a combination of both types of noise, with one typically dominating. To that end, we will explore the value of graphical representations of ADC noise, including FFTs, in a subsequent Precision Labs presentation on ADC noise parameters and measurement methods.

For now, let's explore how you can use the differences between quantization noise and thermal noise to your advantage.



As we've discussed throughout this presentation, the ADC's resolution generally defines which type of noise dominates. For lower resolution ADCs, the LSB size is large, resulting in higher levels of quantization noise compared to thermal noise, represented by the plot on the left. Conversely, in higher resolution ADCs, we can observe thermal noise due to the relatively low levels of quantization noise, represented by the plot on the right. It should be noted that the relative noise levels shown here for the lower and higher resolution ADC examples mirror the levels shown in the frequency domain plots.

So how do you take advantage of this information and apply it to your system? Unfortunately, thermal noise is a quality of the ADC and can't be changed by the end-user.

However, since quantization noise is a product of the ADC's resolution and reference voltage, you can affect change here to improve your system's performance. For example, if your system allows, you can use a smaller reference voltage with lower resolution ADCs to reduce the LSB size and subsequent quantization noise amplitude, as shown. This has the effect of lowering the ADC's total noise. For higher resolution ADCs where thermal noise dominates, you may actually use a larger reference voltage to increase the input range of the ADC, while ensuring that you keep the quantization noise level below the thermal noise. Assuming no other system changes, this increased reference voltage can enable a better signal-to-noise ratio. You can learn more about this topic in the Precision Labs module on reference noise.

Thanks for your time!
Please try the quiz.

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

Quiz: Types of noise in ADCs

1. (T/F) Quantization noise will be reduced by increasing the ADC resolution.
   a. True.
   b. False.

2. (T/F) Thermal noise will be reduced by increasing the ADC resolution.
   a. True.
   b. False.

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(T/F) Quantization noise will be reduced by increasing the ADC resolution.

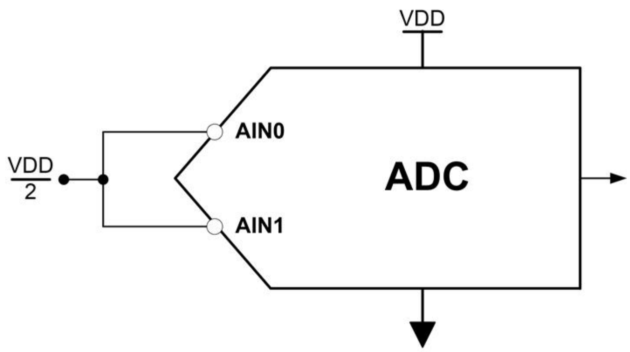
The correct answer is true. Increasing the ADC resolution makes the LSB smaller which reduces quantization noise.

(T/F) Thermal noise will be reduced by increasing the ADC resolution.

The correct answer is false. Thermal noise is independent of the ADC resolution. It depends on internal ADC components.

Quiz: Types of noise in ADCs

3. For the circuit below, which type of noise is being measured?
   a. Thermal Noise
   b. Quantization Noise



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For the circuit below, which type of noise is being measured?

The correct answer is “a”. In this example the input is connected to a DC voltage equal to the supply VDD/2. Quantization noise is normally measured by applying an AC sinusoidal waveform

Quiz: Types of noise in ADCs

4. For a circuit where quantization noise dominates, should you increase, or decrease the reference voltage to reduce the total noise?
   a. Increase
   b. Decrease
   c. Total noise will not be impacted by the reference level.

5. For a circuit where thermal noise dominates, should you increase, or decrease the reference voltage to improve the system performance?
   a. Increase
   b. Decrease

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For a circuit where quantization noise dominates, should you increase or decrease the reference voltage to reduce the total noise?

The correct answer is “b”, decrease. If quantization noise is dominant, reducing the reference voltage will make the LSB value smaller and hence reduce quantization noise.

For a circuit where thermal noise dominates, should you increase or decrease the reference voltage to reduce the total noise?

The correct answer is “a”, increase. Increasing the reference voltage will increase the full scale range of the device. If the reference noise level remains below the ADC’s noise, there is no net increase in system noise. Thus the signal amplitude is larger and the noise is the same so signal to noise ratio, noise free resolution and dynamic range will improve.

Thanks for your time!

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