Calculating amplifier + ADC total noise: design examples

TI Precision Labs – ADCs

Created by Chris Hall & Bryan Lizon

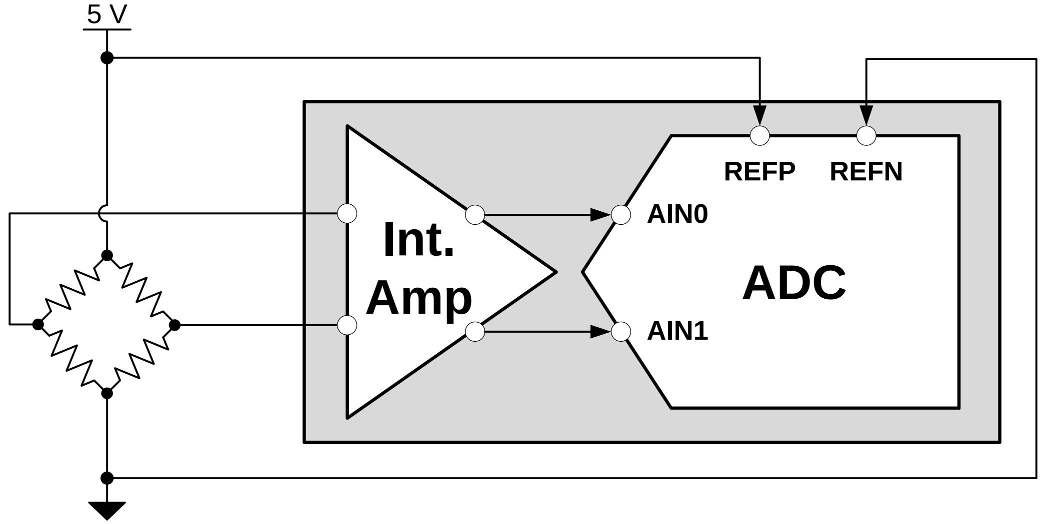
Presented by Alex Smith

DE#1: Internal vs external amplifiers

**For more information, watch the Precision Labs video on system noise parameters for low-speed delta sigma ADCs

Type	Parameter	Value
System specs**	Input voltage max (V_{IN})	10 mV
	Output data rate	60 SPS
	Noise target	250 nV
	Dynamic range	15.3 bits

ADC + internal amp (G_{MAX} = 128 V/V)



$$VREF = 5\,V$$

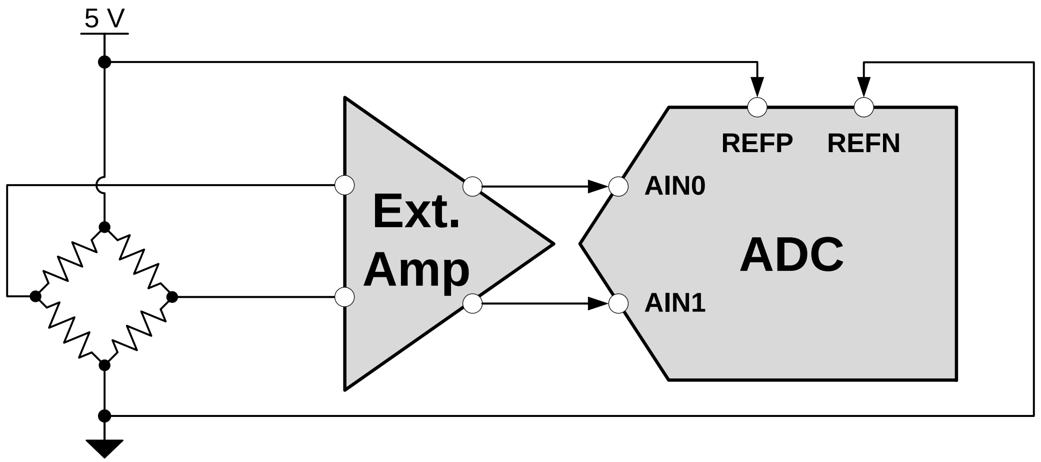
$$FSR_{ADC\ (G=128)} = \frac{\pm VREF}{Gain} = \pm 0.039\,V$$

$$\%\,Utilization\ (max) = \frac{V_{IN}}{FSR_{ADC\ (G=128)}} = \frac{10\ mV}{2 * 39\ mV} = 12.8\%$$

Is such low % utilization acceptable?

OR

ADC + external amp (G_{MAX} = 500 V/V)



$$VREF = 5\,V$$

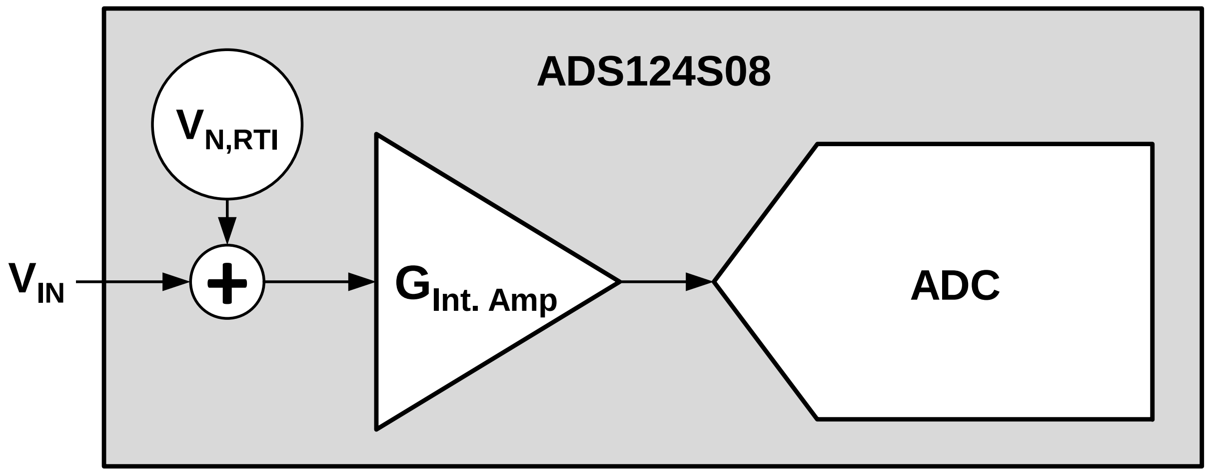
$$FSR_{ADC\ (G=1)} = \frac{\pm VREF}{Gain} = \pm 5\,V$$

$$Ext.amp\ gain\ (max) = \frac{FSR_{ADC\ (G=1)}}{V_{IN}} = \frac{5\ V}{0.01\ V} = 500\,{}^{V}/_{V}$$

Do you need such a large gain?

DE#1: Selecting components + calculating noise

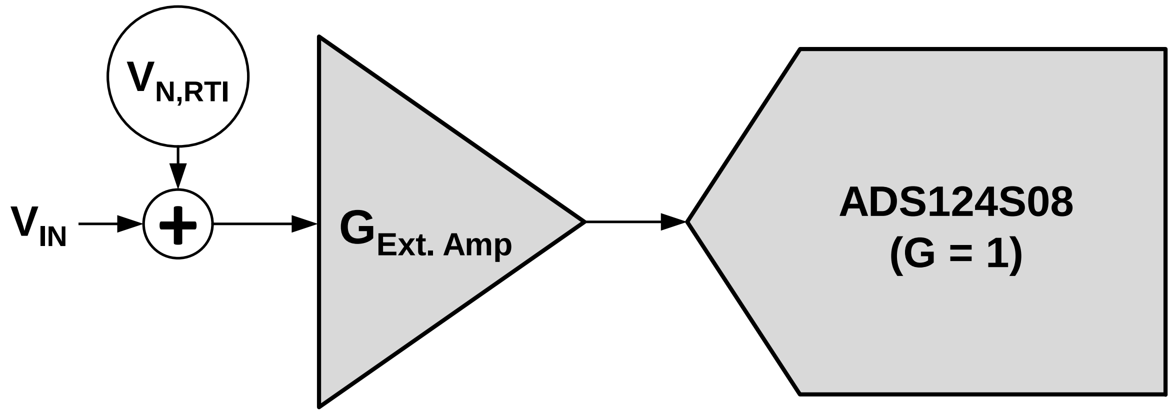
ADC + internal amp equivalent noise model



$$V_{N,RTI} = \sqrt{(V_{N,AMP})^2 + (V_{N,ADC}/G_{ADS124S08})^2}$$

Directly from ADC datasheet → calculations not required

ADC + external amp equivalent noise model



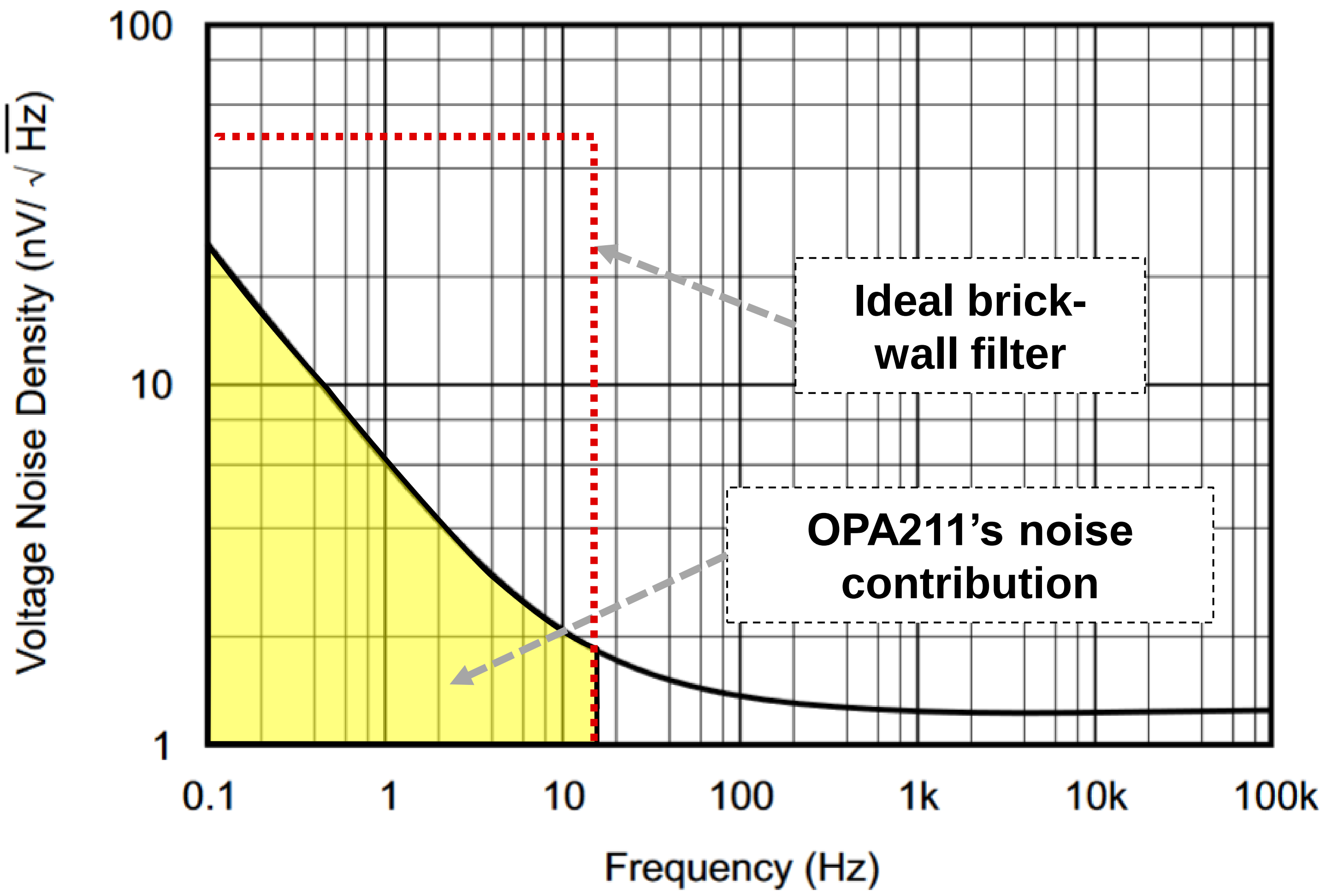
$$V_{N,RTI} = \sqrt{(V_{N,AMP})^2 + (V_{N,ADS124S08}/G_{Ext.\ AMP})^2}$$

Calculate using $V_{N,RTI}$ equation

Component voltage noise @ 60 SPS (ENBW = 16 Hz) (nV_{RMS})

Device	Gain							
	1	2	4	8	16	32	64	128
ADS124S08	1,400	700	370	210	120	110	100	89
OPA211	?							
OPA378	?							
OPA192	?							

DE#1: OPA211 system noise contribution



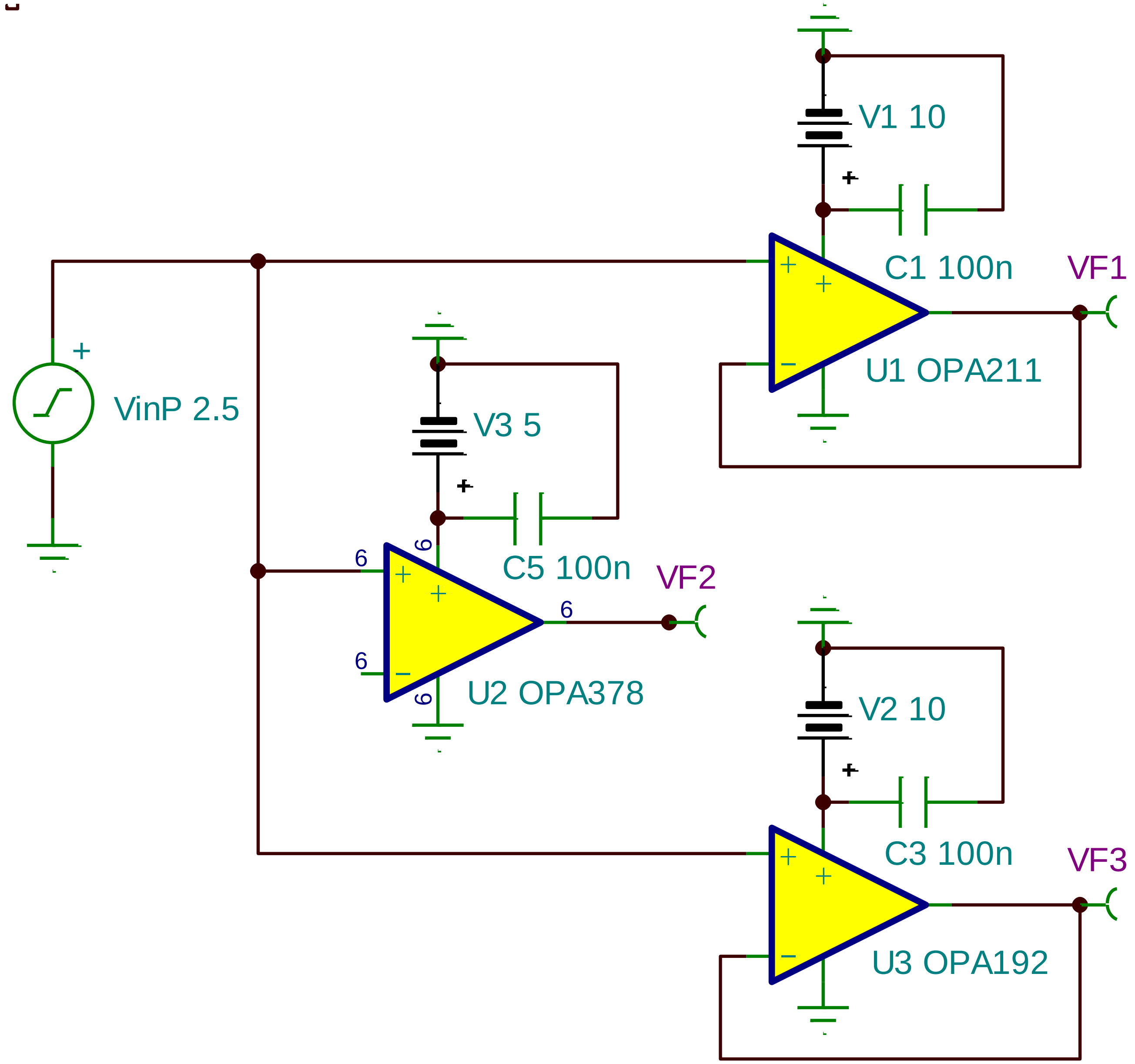
PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Input voltage noise	f = 0.1 to 10 Hz		80		nV_{PP}
Input voltage noise density	f = 10 Hz		2		nV/√Hz
	f = 100 Hz		1.4		nV/√Hz
	f = 1 kHz		1.1		nV/√Hz

$$V_{N,AMP} = 18.5\ nV_{RMS}$$

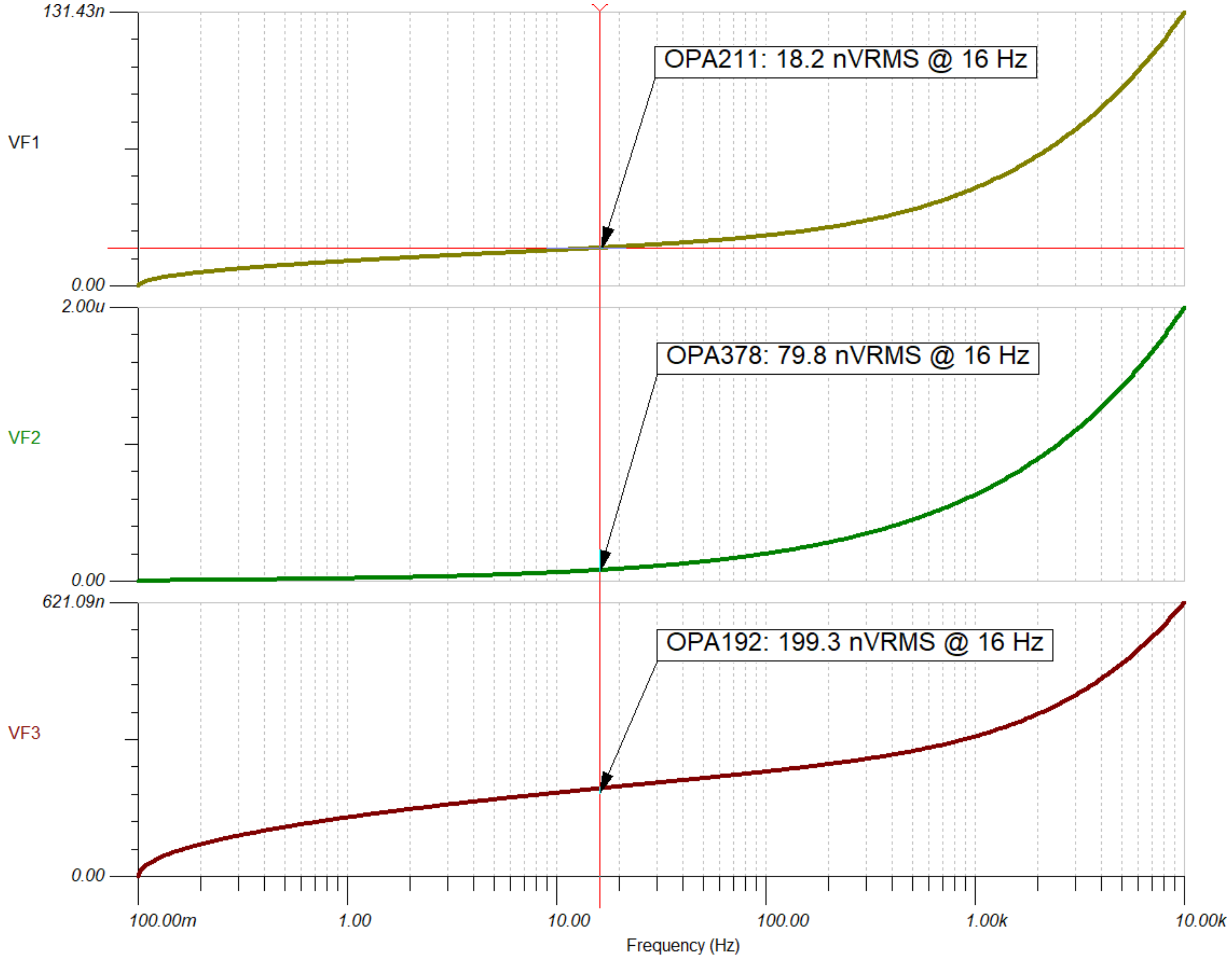
View the Precision Labs modules on amplifier noise to learn more

DE#1: Simulating amplifier noise

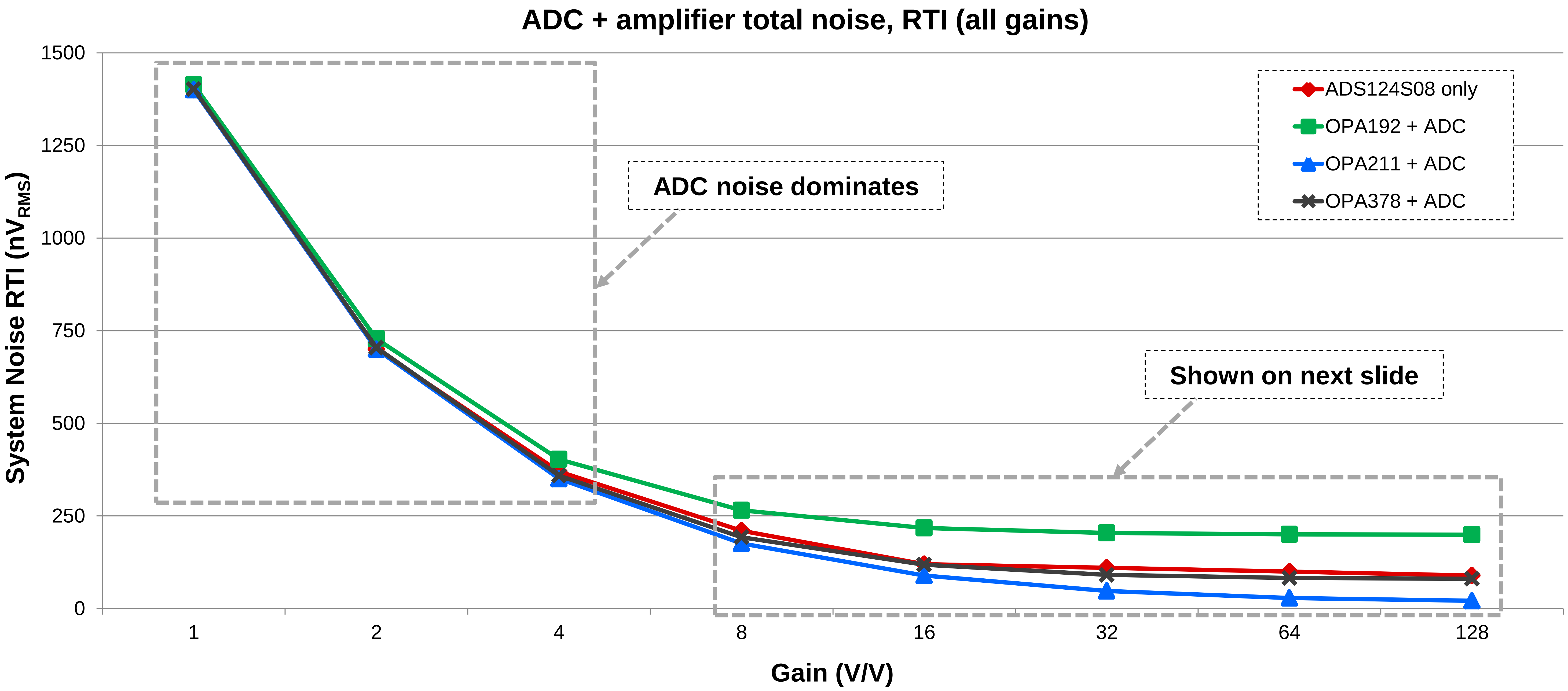
Simulated circuits



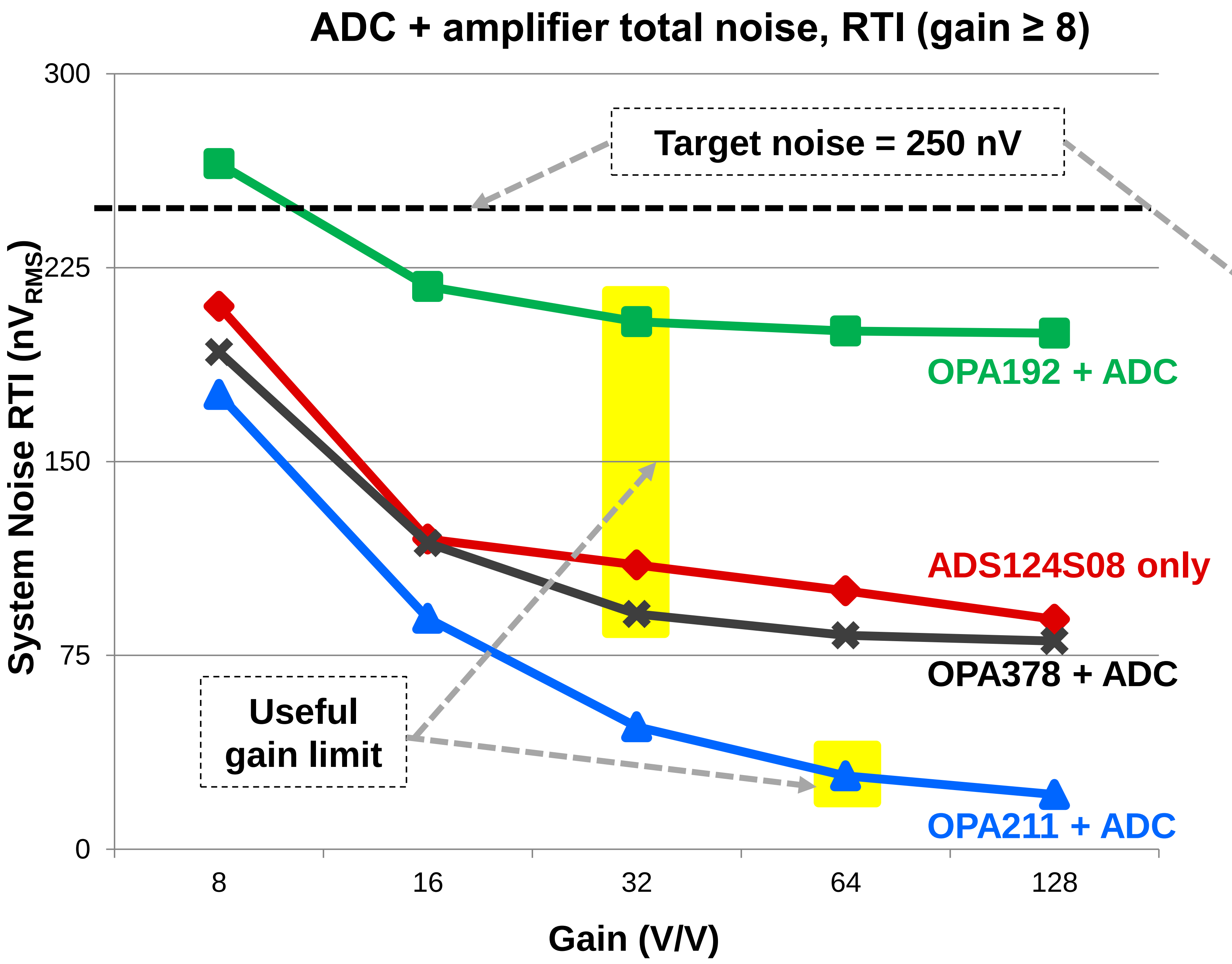
Total output noise



DE#1: ADC + amplifier total noise vs gain



DE#1: ADC + amplifier total noise vs gain

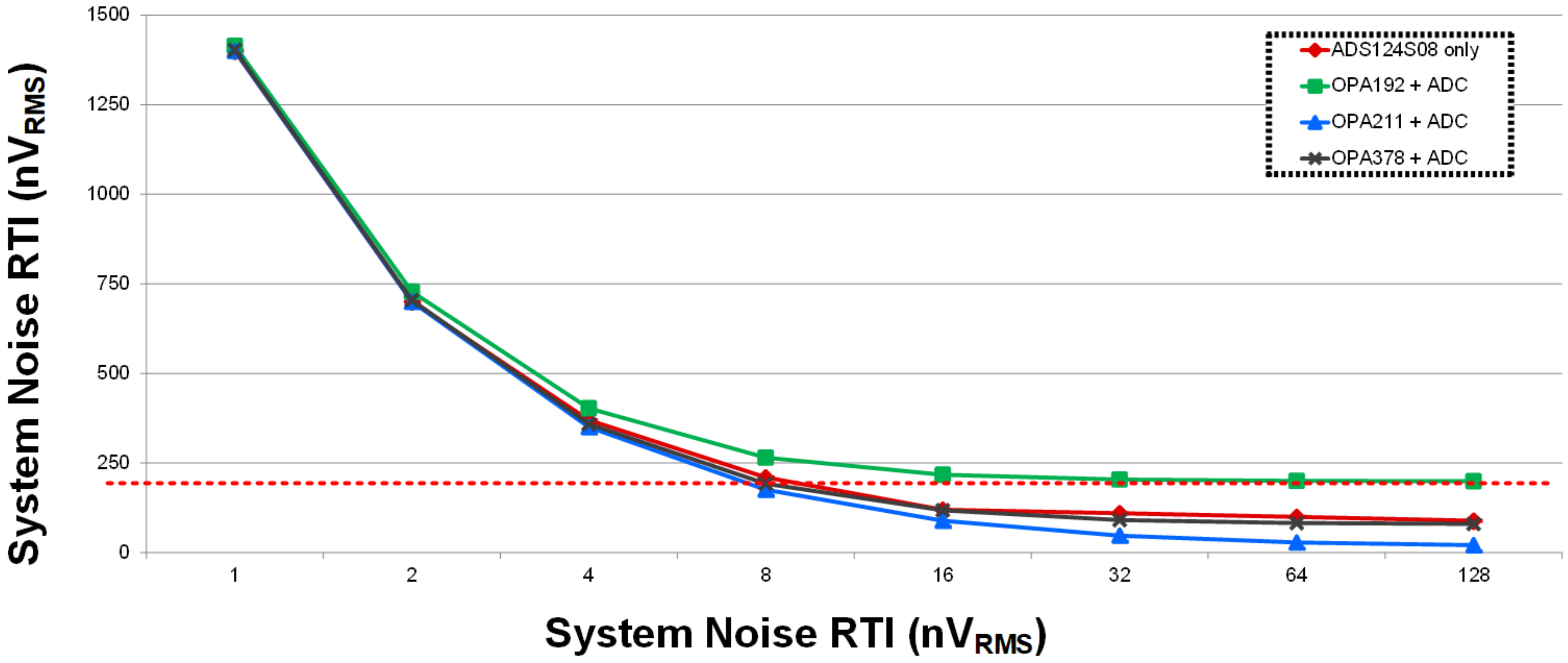


Type	Parameter	Value
System specs	Input voltage (max)	10 mV
	Output data rate	60 SPS
	Noise target	250 nV
	Dynamic range	15.3 bits

Thanks for your time!
Please try the quiz.

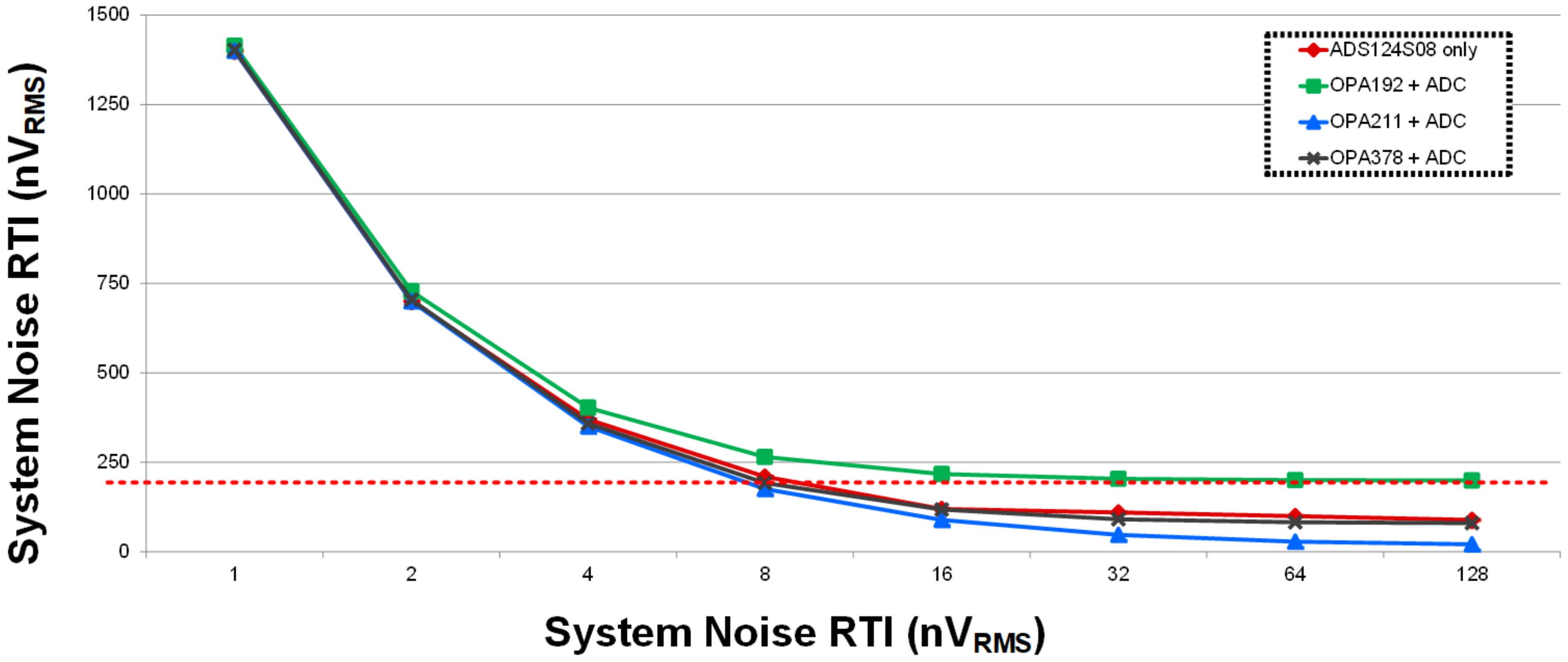
Quiz: Calculating amplifier + ADC total noise

1. For the figure below the system noise RTI for the OPA192 is constant for gains greater than 16V/V. Why?
   a) The system is limited by ADC noise performance at this point.
   b) The system is limited by amplifier noise at this point.



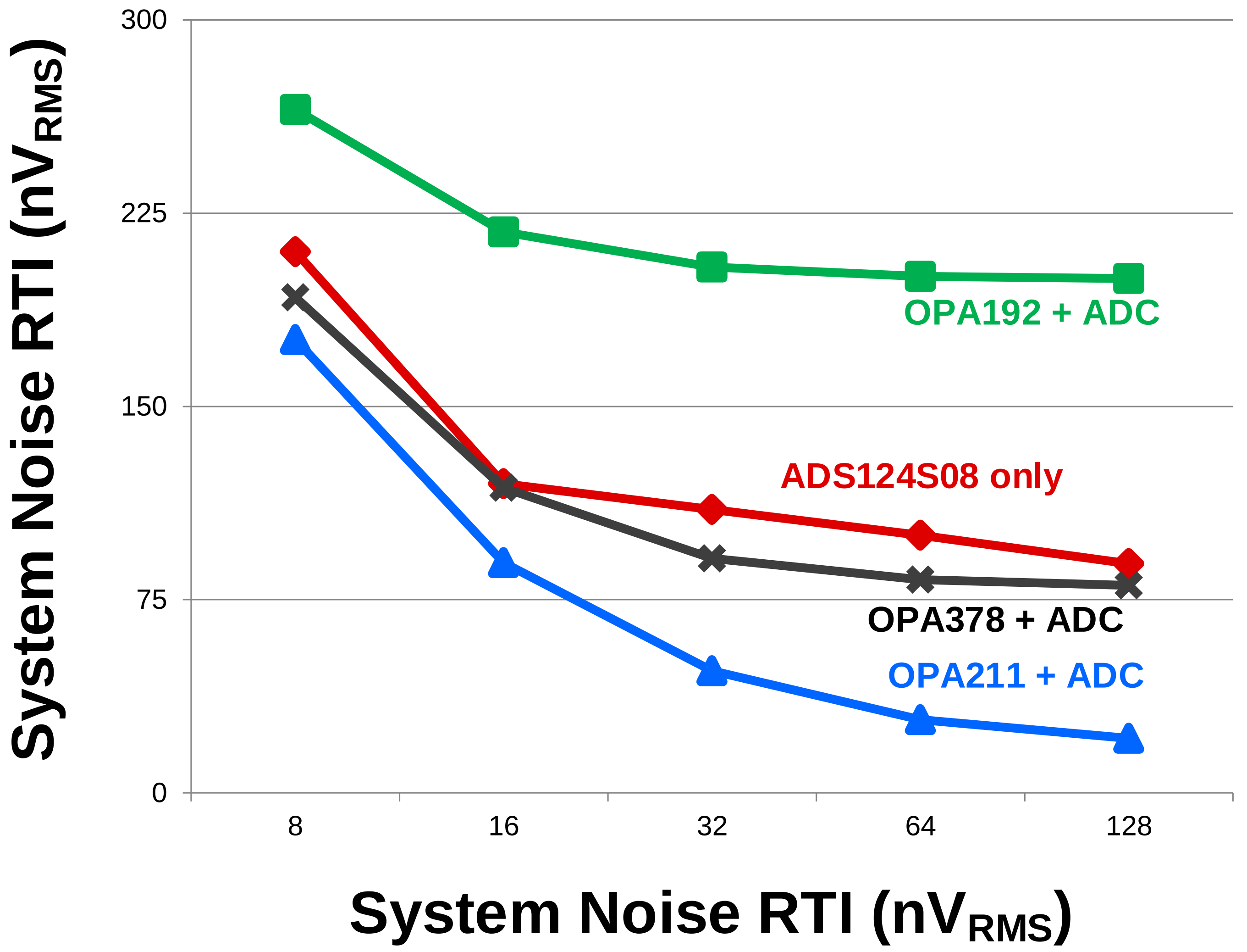
Quiz: Calculating amplifier + ADC total noise

1. For the figure below the system noise RTI for the OPA192 is constant for gains greater than 16V/V. Why?
   a) The system is limited by ADC noise performance at this point.
   b) The system is limited by amplifier noise at this point.



Quiz: Calculating amplifier + ADC total noise

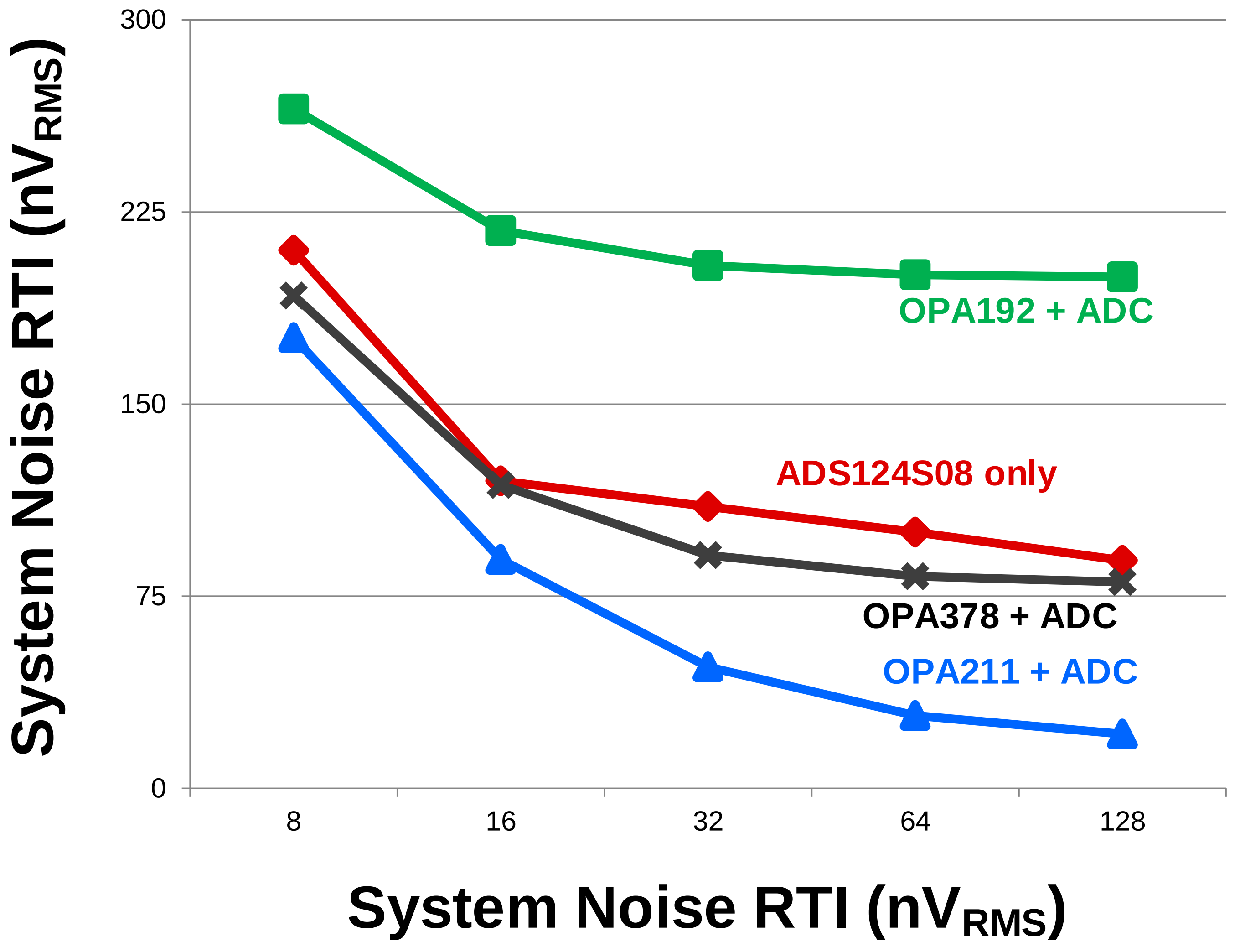
2. Assume the noise target is 150nVrms. Which amplifier cannot meet required performance for any gain value?
   a) OPA192
   b) ADS124S08 only
   c) OPA378
   d) OPA211



Quiz: Calculating amplifier + ADC total noise

2. Assume the noise target is 150nVrms. Which amplifier cannot meet required performance for any gain value?

   a) OPA192
   b) ADS124S08 only
   c) OPA378
   d) OPA211



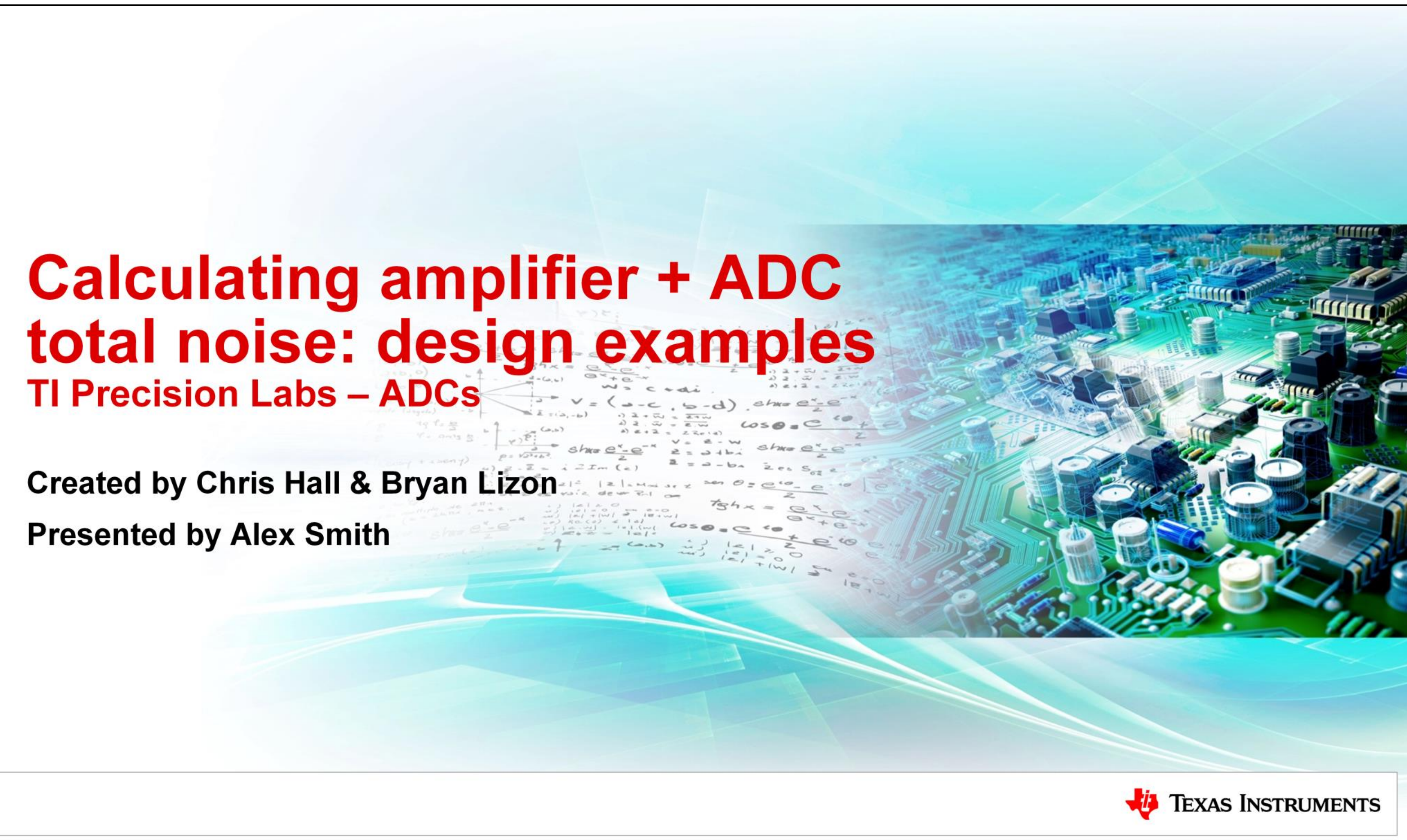
Quiz: Calculating amplifier + ADC total noise

3. (T/F) For DC precision delta sigma converters the internal PGA often has noise performance that is better than discrete amplifiers. Furthermore, discrete amplifiers that are better than the internal buffer are typically high performance op amps that will significantly increase the system cost.
   a) True
   b) False

Quiz: Calculating amplifier + ADC total noise

3. (T/F) For DC precision delta sigma converters the internal PGA often has noise performance that is better than discrete amplifiers. Furthermore, discrete amplifiers that are better than the internal buffer are typically high performance op amps that will significantly increase the system cost.
   a) True
   b) False

Thanks for your time!



Hello, and welcome to the TI Precision Lab discussing how to determine if an amplifier is required for your high-resolution ADC, and how this choice affects the system's noise performance.

In a previous Precision Lab module covering how gain affects ADC noise and dynamic range, we discussed ADC full-scale range versus input signals, input- and output-referred noise, total noise performance for single- and dual-stage amplifier systems, how gain affects lower resolution and higher resolution ADCs, and finally the impact gain has on dynamic range parameters

This module will expand upon that knowledge by walking through several design examples. These design examples will explore topics such as adding an external amplifier versus using an ADC with an integrated amplifier, how much gain is necessary for your system, using a low-noise amplifier with a higher-noise ADC, and noise calculations for low-level signals applied to a wide bandwidth ADC.

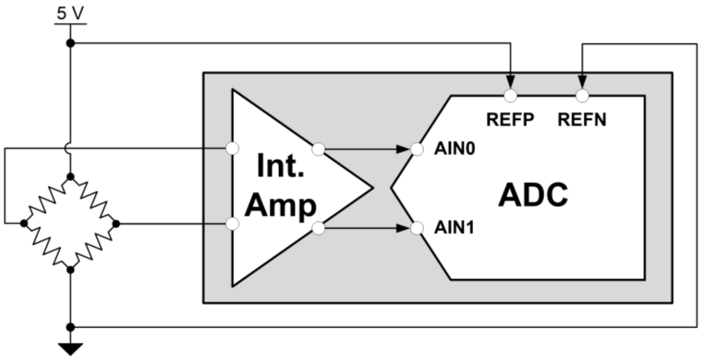
The first example covers selecting an ADC with integrated amplifier versus an ADC with an external amplifier

**For more information, watch t
Precision Labs video on systen
noise parameters for low-speed
delta sigma ADCs

DE#1: Internal vs external amplifiers

Type	Parameter	Value
System specs**	Input voltage max (V_{IN})	10 mV
	Output data rate	60 SPS
	Noise target	250 nV
	Dynamic range	15.3 bits

ADC + internal amp (G_{MAX} = 128 V/V)



$$VREF = 5\ V$$

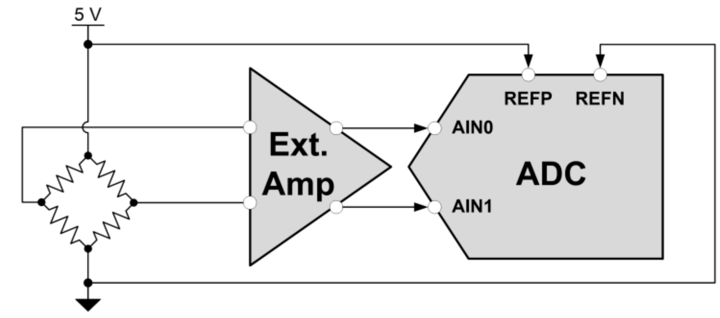
$$FSR_{ADC\ (G=128)} = \frac{\pm VREF}{Gain} = \pm 0.039\ V$$

$$\%\ Utilization\ (max) = \frac{V_{IN}}{FSR_{ADC\ (G=128)}} = \frac{10\ mV}{2 * 39\ mV} = 12.8\%$$

Is such low % utilization acceptable?

OR

ADC + external amp (G_{MAX} = 500 V/V)



$$VREF = 5\ V$$

$$FSR_{ADC\ (G=1)} = \frac{\pm VREF}{Gain} = \pm 5\ V$$

$$Ext.amp\ gain\ (max) = \frac{FSR_{ADC\ (G=1)}}{V_{IN}} = \frac{5\ V}{0.01\ V} = 500\ ^{V}/_{V}$$

Do you need such a large gain?

TEXAS INSTRUMENTS

For this example, let's use the same system specs presented in the Precision Labs module on system noise parameters for low-speed delta-sigma ADCs. These specs are restated in the table and they represent a 10 millivolt resistive bridge measurement that requires a 250 nanovolt noise floor and 15.3 bits of dynamic range.

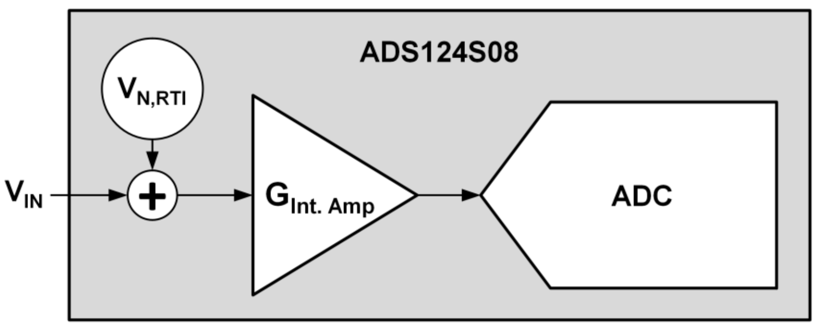
As you might guess, this application requires an amplifier. In this example, we will look at the choice of using an ADC with an integrated amplifier as shown on the left compared to an ADC with an external amplifier as shown on the right. You can see that each signal chain has its challenges. For example, ADCs with integrated amplifiers have limited gain settings that might not allow you to use the ADC's full-scale range. The equations on the left show that for these system specs, an ADC with a maximum integrated gain of 128 only allows you to use 12.8% of the ADC's FSR. On the other hand, the external amplifier gain can be set to virtually any value to help maximize ADC FSR. As the equations on the right show, you would need a gain of up to 500 to reach 100% utilization.

Ultimately, the goal is to be able to answer the questions at the bottom of this slide: is it acceptable to use such a small percentage of your ADC's FSR given the low noise, high dynamic range specs, or is it necessary to use an external amplifier with a high gain to achieve the required performance?

Now that we've discussed the intent of this design example, let's move on to selecting components.

DE#1: Selecting components + calculating noise

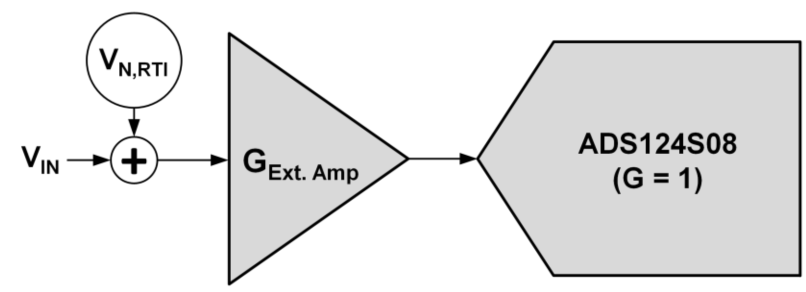
ADC + internal amp equivalent noise model



$$V_{N,RTI} = \sqrt{(V_{N,AMP})^2 + (V_{N,ADC}/G_{ADS124S08})^2}$$

Directly from ADC datasheet → calculations not required

ADC + external amp equivalent noise model



$$V_{N,RTI} = \sqrt{(V_{N,AMP})^2 + (V_{N,ADS124S08}/G_{Ext.\,AMP})^2}$$

Calculate using $V_{N,RTI}$ equation

Component voltage noise @ 60 SPS (ENBW = 16 Hz) (nV_{RMS})

Device	Gain							
	1	2	4	8	16	32	64	128
ADS124S08	1,400	700	370	210	120	110	100	89
OPA211	?							
OPA378	?							
OPA192	?							

TEXAS INSTRUMENTS

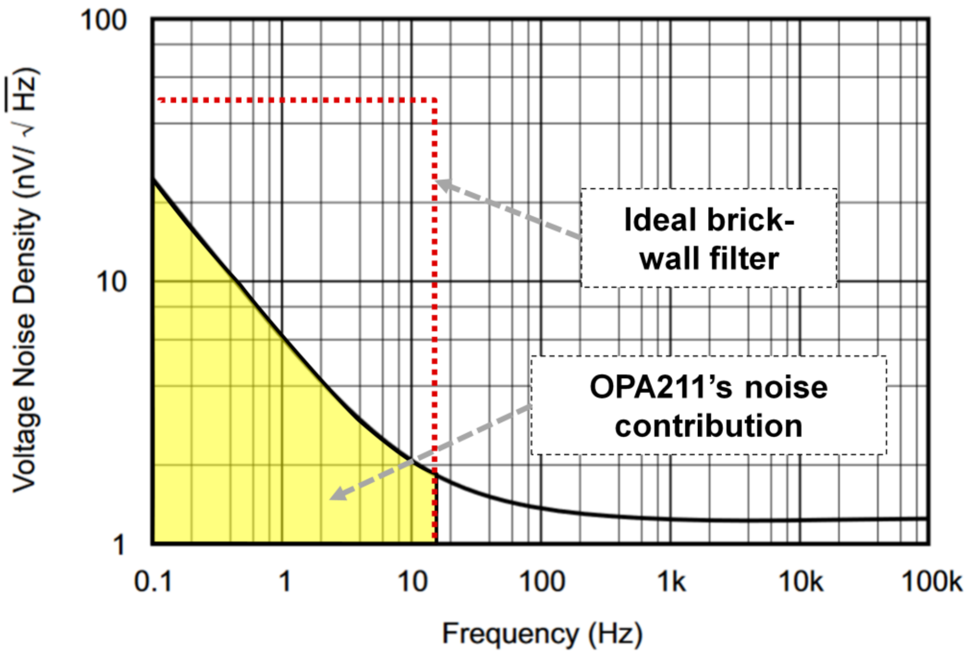
For this example, let's select the ADS124S08, a low-noise 24-bit delta-sigma ADC with an integrated gain stage, since we have used this device in previous Precision Labs noise modules. An equivalent noise model for this device is shown in the top left image. On the right is the equivalent noise model for the external amplifier plus ADC system, where the ADC noise is just the ADS124S08 noise at a gain of one. In each case, the ADC is the same and the only variable is the choice of using an integrated versus external amplifier.

Next, determine the total noise performance for each signal chain. In general, you would calculate the input-referred noise using the given equations. However, for the ADC with integrated gain, you can typically just copy the values directly from the datasheet. The table shows the ADS124S08 input-referred noise values across all available gains using a SINC 3 filter at the target output data rate of 60 samples per second. Note there is nothing calculate since these values include the combined ADC and integrated PGA noise. This simplifies system noise analysis compared to using a discrete amplifier with an ADC.

Comparatively, you do need the input-referred noise equation to calculate the ADC plus external amplifier total noise. The equation on the right is modified slightly to denote that the ADC noise is just the ADS124S08 noise at a gain of one. The OPA211, OPA378, and OPA192 are selected as the external amplifiers. Now you just need to determine each amplifier's noise voltage at 16 hertz noise bandwidth. Can this information be pulled directly from a datasheet without any calculation like the ADC with integrated gain? Let's look at the

OPA211 to find out.

DE#1: OPA211 system noise contribution



PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Input voltage noise	f = 0.1 to 10 Hz		80		nV_{PP}
Input voltage noise density	f = 10 Hz		2		nV/√Hz
	f = 100 Hz		1.4		nV/√Hz
	f = 1 kHz		1.1		nV/√Hz

$$V_{N,AMP} = 18.5\ nV_{RMS}$$

View the Precision Labs modules on amplifier noise to learn more

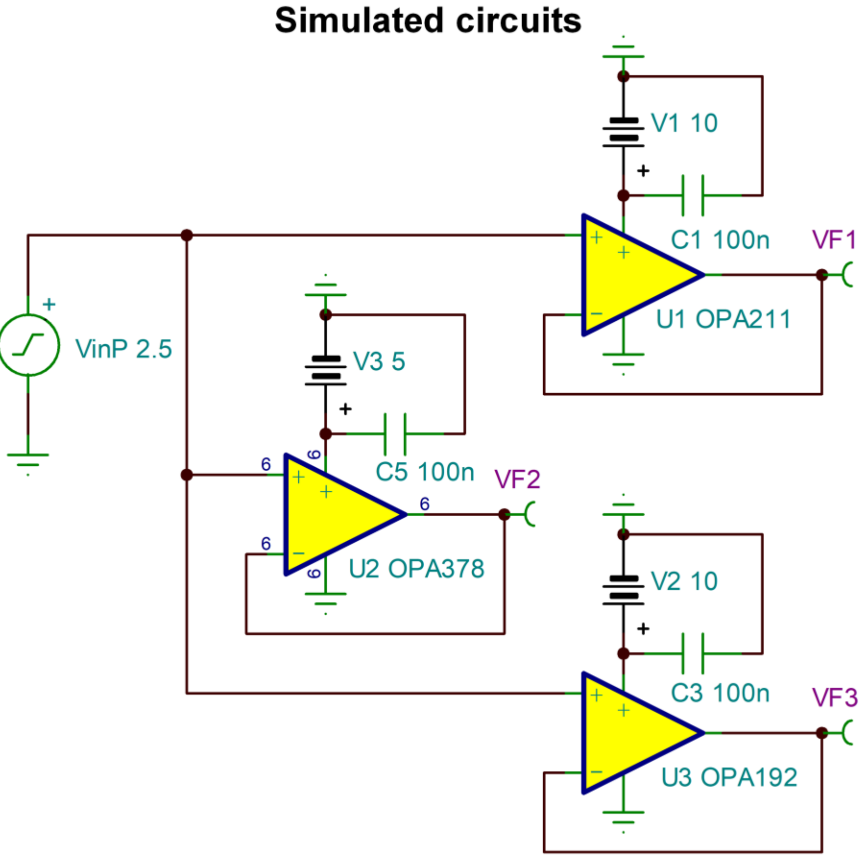
Texas Instruments

Shown here on the left is the voltage noise density curve for the OPA211, while the table on the right shows its noise specifications. Note that the OPA211 has a sharp increase in voltage noise density under 10 hertz, known as 1/f or pink noise. Additionally, the OPA211 has a relatively flat region known as broadband noise. In order to calculate the OPA211's noise contribution given a 16 hertz system effective noise bandwidth, you would need to integrate the area under the noise density curve up to the noise bandwidth. If you'd like more information on how to estimate the area under this curve, or to learn more about amplifier noise in general, please view the Precision Labs modules on amplifier noise

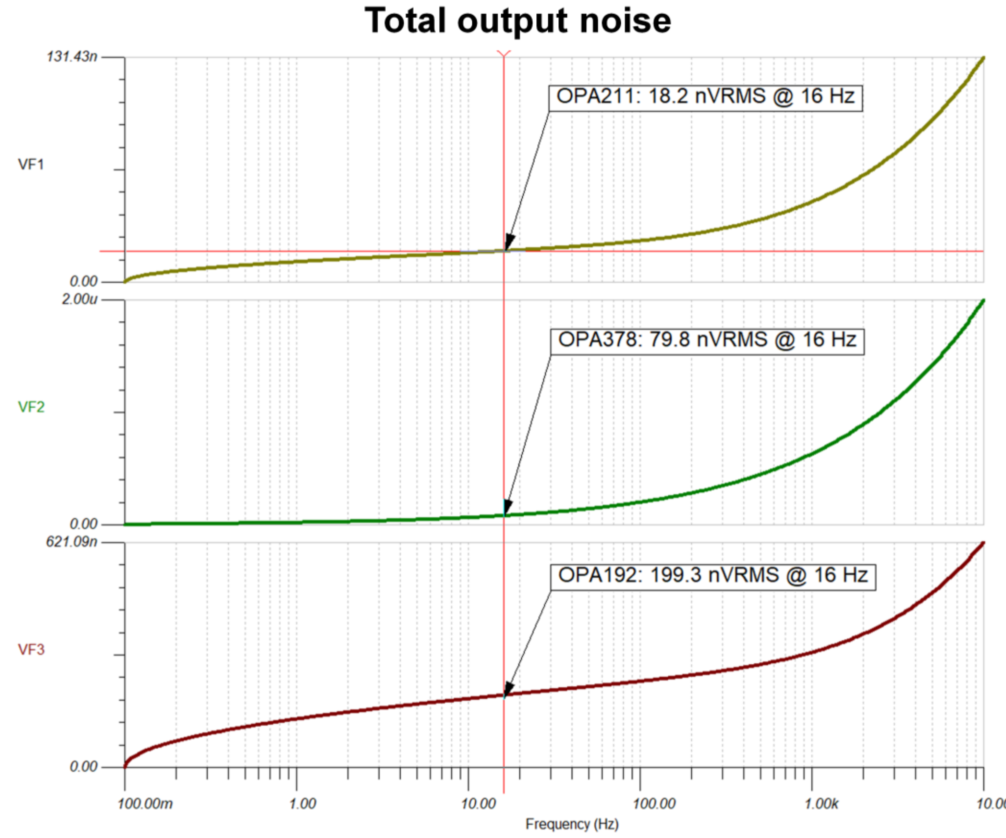
Using the methods from those Precision Labs modules, you can calculate that the OPA211 contributes 18.5 nanovolts RMS of noise to the system. To find the noise contribution for the other amplifiers, you can use this same method. Additionally, the next slide shows how you may also corroborate these noise values using simulation.

DE#1: Simulating amplifier noise

Simulated circuits



Total output noise

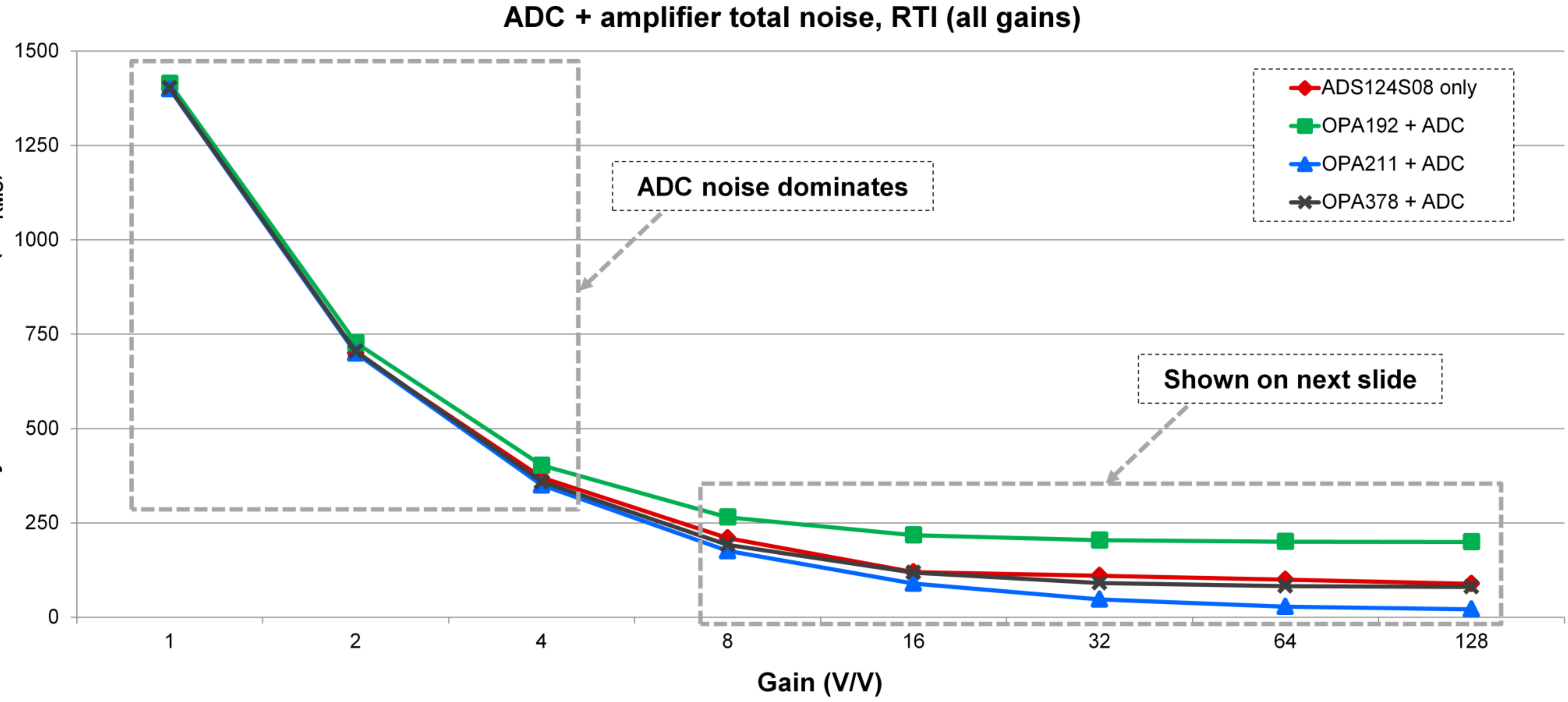


You can set up each component in a buffer configuration using a spice simulation tool to understand the baseline noise for your amplifiers. On the left, all three amplifiers are configured as buffers and connected to the same input source, which is a 500 millivolt peak to peak sinewave with a 2.5V DC offset. This signal keeps the input within the common-mode range of each amplifier.

Running a total noise analysis of the circuit on the left yields the plots on the right where the RMS voltage noise for each amplifier at 16 hertz is highlighted. Note that the OPA211 voltage noise is 18.2 nanovolts RMS, which is very close to the calculated value of 18.5 nanovolts RMS.

Now that you have determined each amplifier's noise voltages, you can calculate the total noise using the input-referred noise equation as well as the noise values from the ADS124S08's datasheet. On the next slide we will plot this noise as a function of gain and compare it to the ADS124S08's noise performance using its integrated PGA.

DE#1: ADC + amplifier total noise vs gain



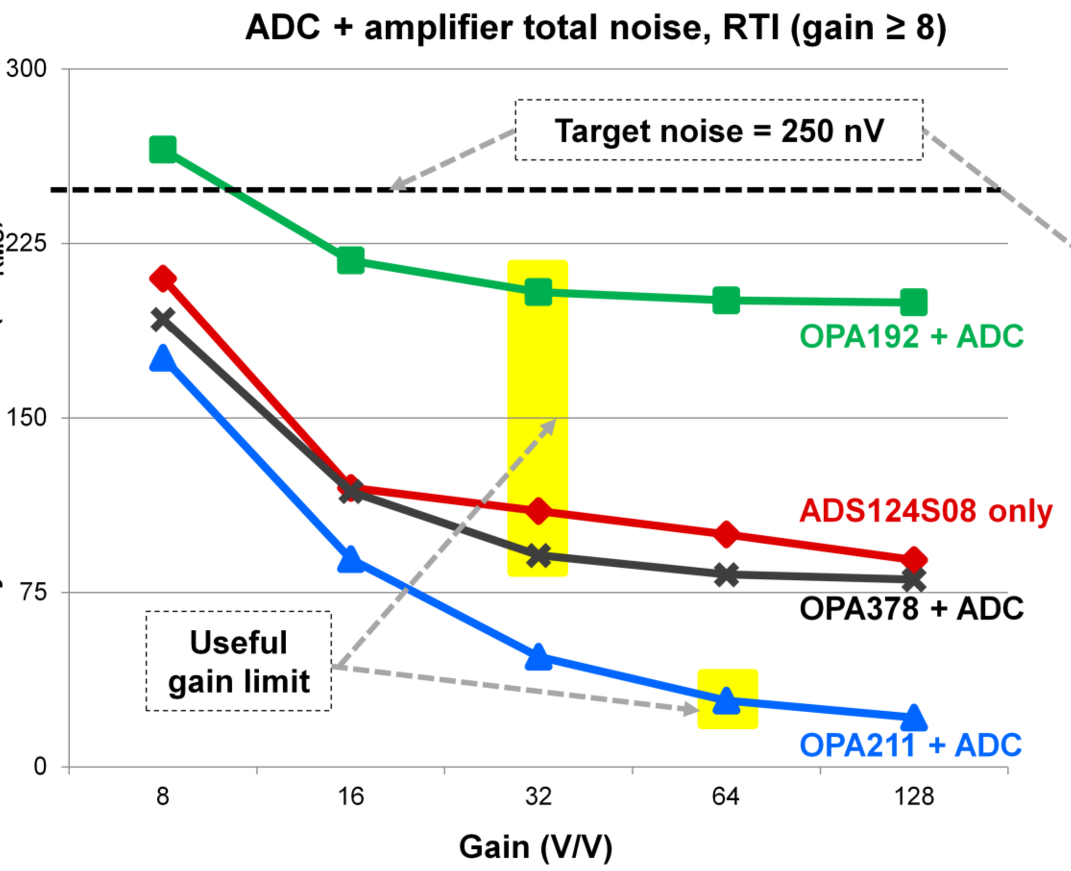
Texas Instruments

Shown here on the left are four plots representing each signal chain's voltage noise versus gain. The binary gains on the x-axis reflect the available options on the ADS124S08. The red line represents the ADS124S08 noise by itself, while the other three lines represent each discrete amplifier followed by the ADS124S08, with the ADC gain set to one volt per volt. Note that each system's noise is fairly similar for gains up to four volts per volt, since the ADC noise is still dominating. However, at a gain of eight and beyond, these plots start to diverge.

As you can see, adding the OPA192 to the ADS124S08 actually increases the noise floor compared to the ADC by itself. You can therefore conclude that this is not the best amplifier to pair with this specific ADC if your goal is **optimal noise performance** ~~**absolute best noise performance when measuring small input signals**~~. Comparatively, the OPA211 reduces the system noise floor. If you need better noise performance than the ADC plus integrated gain, the OPA211 is a good choice. Finally, the OPA378 offers approximately the same noise performance as the ADC by itself. If you need more gain than the ADS124S08 offers, this amplifier might be a good choice. Otherwise, the OPA378 is likely not worth the added cost and complexity as it offers no significant ~~**reduction**~~ **improvement** in noise performance. In general, amplifiers integrated into ADCs are are optimized to work well with the ADC core, and will generally offer the best combination of precision and accuracy compared to external amplifiers. Therefore, you should always first consider using an ADC with an integrated amplifier, assuming this device meets all of your other system specifications.

On the next slide we will zoom into the highlighted region of this plot to identify some other important takeaways from this design example

DE#1: ADC + amplifier total noise vs gain



Type	Parameter	Value
System specs	Input voltage (max)	10 mV
	Output data rate	60 SPS
	Noise target	250 nV
	Dynamic range	15.3 bits

Texas Instruments

This plot shows the same information that was presented on the previous slide, but only for gains greater than or equal to eight. There are several important points to note.

First, the data points highlighted in yellow signify the useful gain limit for each system. The useful gain limit concept was introduced in the previous Precision Labs module, and denotes the point at which adding more gain has no meaningful impact on the input-referred noise and results in constant dynamic range. This point occurs at a gain of 32 volts per volt for the OPA192 and OPA378 systems as well as the ADS124S08 by itself, and 64 volts per volt in the OPA211 system. Therefore, you can conclude that using a gain of 500 to maximize the ADC's dynamic range would not be beneficial to any of these systems, as the noise is constant and the dynamic range is effectively maximized by a gain of 64 volts per volt in all cases.

Second, all of these system meet the 250 nanovolt noise requirement at a gain of 16 volts per volts or less, as shown near the top of the plot. The dynamic range target is inherently met by this gain setting as well, since the dynamic range is derived from the noise performance. As a result, there is no reason to increase the gain beyond this point, even for the OPA192 where the overall noise floor increases compared to the ADC by itself. Ultimately, the best choice for this application is the ADS124S08 since its integrated amplifier is more than sufficient to meet the target system specs, even at low gains, and it would not add to the system cost or size.

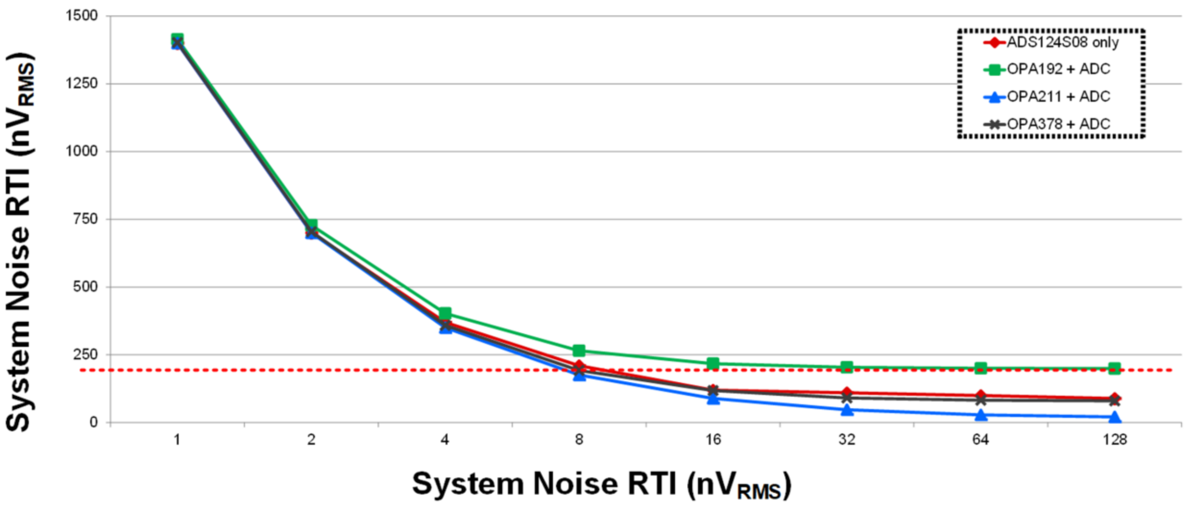
In other words, there are many applications where an external amplifier is necessary to meet your system's performance goals, but this in this case the requirements can be met using an ADC with integrated gain. However, the next module in this series will discuss two more design examples where external amplifiers are necessary to meet the system noise targets.

Thanks for your time! Please try the quiz.

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

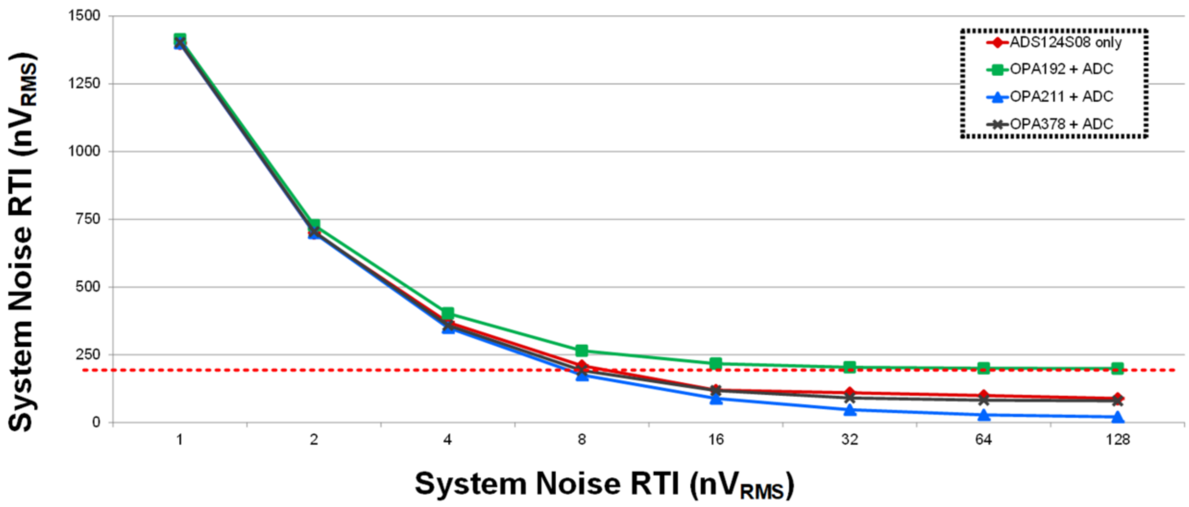
Quiz: Calculating amplifier + ADC total noise

1. For the figure below the system noise RTI for the OPA192 is constant for gains greater than 16V/V. Why?
   a) The system is limited by ADC noise performance at this point.
   b) The system is limited by amplifier noise at this point.



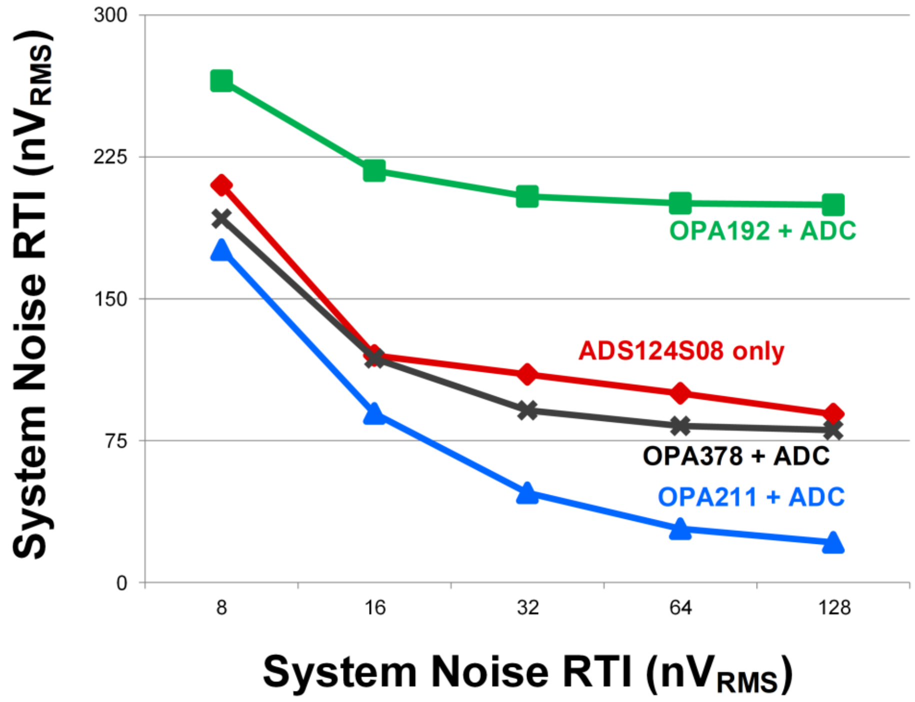
Quiz: Calculating amplifier + ADC total noise

1. For the figure below the system noise RTI for the OPA192 is constant for gains greater than 16V/V. Why?
   a) The system is limited by ADC noise performance at this point.
   b) The system is limited by amplifier noise at this point.



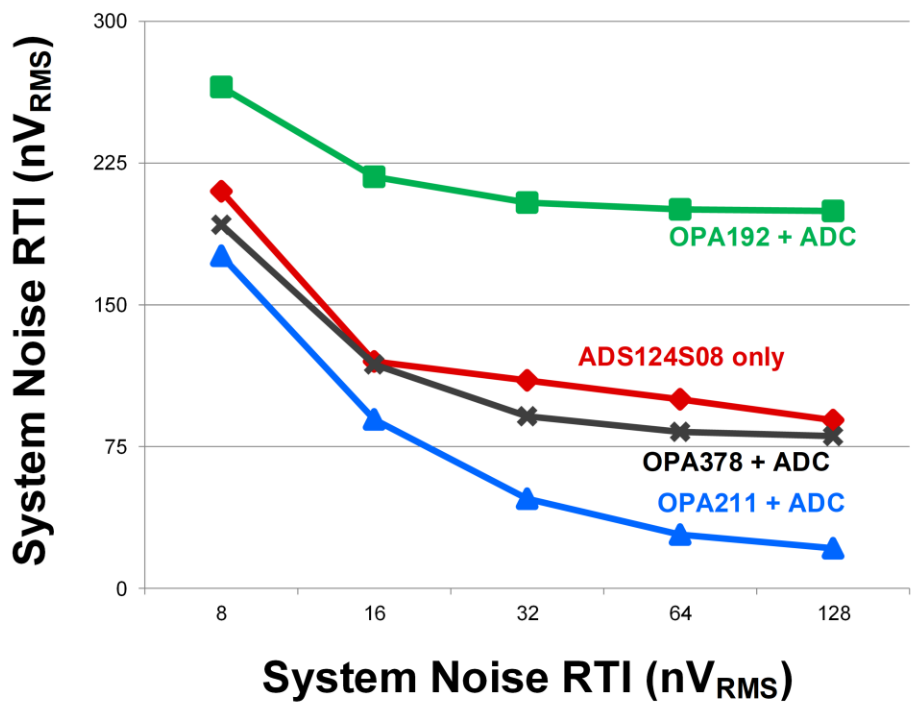
Quiz: Calculating amplifier + ADC total noise

2. Assume the noise target is 150nVrms. Which amplifier cannot meet required performance for any gain value?
   a) OPA192
   b) ADS124S08 only
   c) OPA378
   d) OPA211



Quiz: Calculating amplifier + ADC total noise

2. Assume the noise target is 150nVrms. Which amplifier cannot meet required performance for any gain value?
   a) OPA192
   b) ADS124S08 only
   c) OPA378
   d) OPA211



Quiz: Calculating amplifier + ADC total noise

3. (T/F) For DC precision delta sigma converters the internal PGA often has noise performance that is better than discrete amplifiers. Furthermore, discrete amplifiers that are better than the internal buffer are typically high performance op amps that will significantly increase the system cost.

   a) True

   b) False

TEXAS INSTRUMENTS

Quiz: Calculating amplifier + ADC total noise

3. (T/F) For DC precision delta sigma converters the internal PGA often has noise performance that is better than discrete amplifiers. Furthermore, discrete amplifiers that are better than the internal buffer are typically high performance op amps that will significantly increase the system cost.

   a) True

   b) False

Thanks for your time!