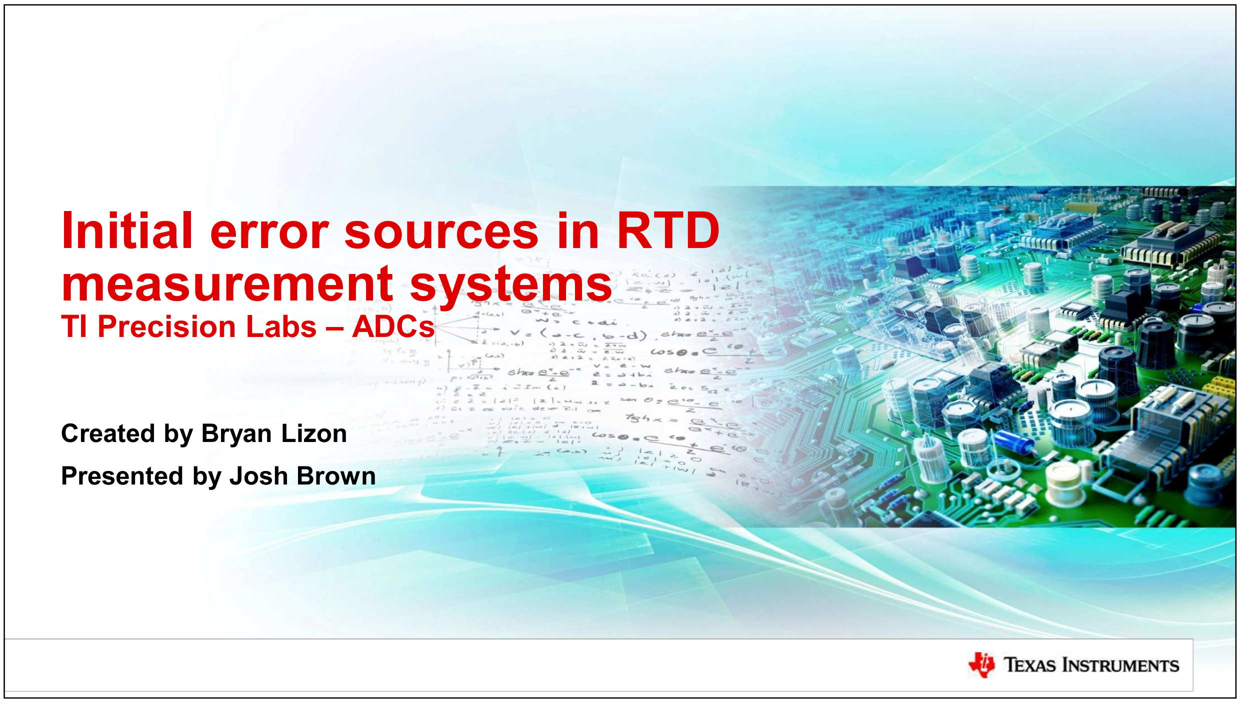


Initial error sources in RTD measurement systems

TI Precision Labs – ADCs

Created by Bryan Lizon

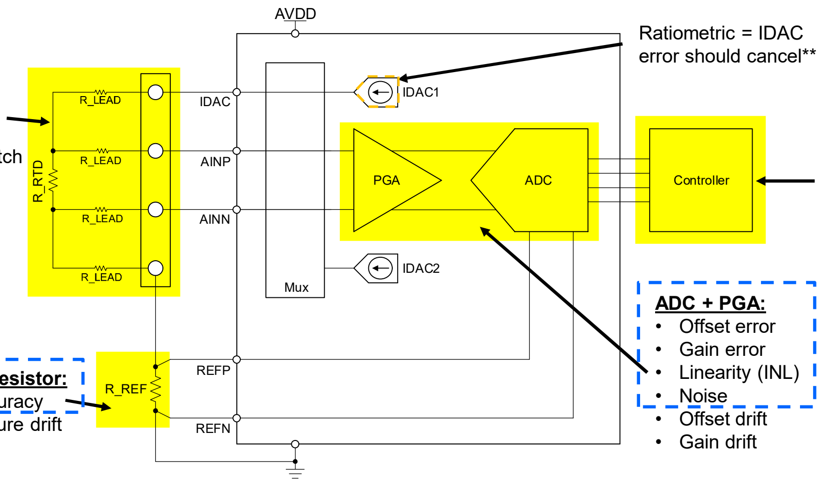
Presented by Josh Brown

Hello, and welcome to the TI Precision Labs module introducing initial error sources in RTD measurement systems. An initial error source is defined at a specific temperature, typically 25 degrees Celsius. This module identifies each initial error source in an RTD measurement system as well as its effect on the measurement. A follow-up presentation discusses how these errors are affected by a change in temperature, as well as additional system error sources

To begin, let’s identify the types of errors

Discussed in this presentation

Common errors in a typical RTD system



RTD errors:
- Sensor accuracy
- Self-heating
- Lead wire mismatch

Ratiometric = IDAC error should cancel**

Conversion / computational errors

ADC + PGA:
- Offset error
- Gain error
- Linearity (INL)
- Noise
- Offset drift
- Gain drift

Reference resistor:
- Initial accuracy
- Temperature drift

**3-wire RTD systems using 2x IDACs must consider the IDAC error

Shown here is a typical RTD measurement system that includes a 4-wire RTD connected to a terminal block, a low-side reference resistor, an ADC with an integrated PGA and current sources, and a controller to perform the resistance to temperature conversion. This system has several common error sources

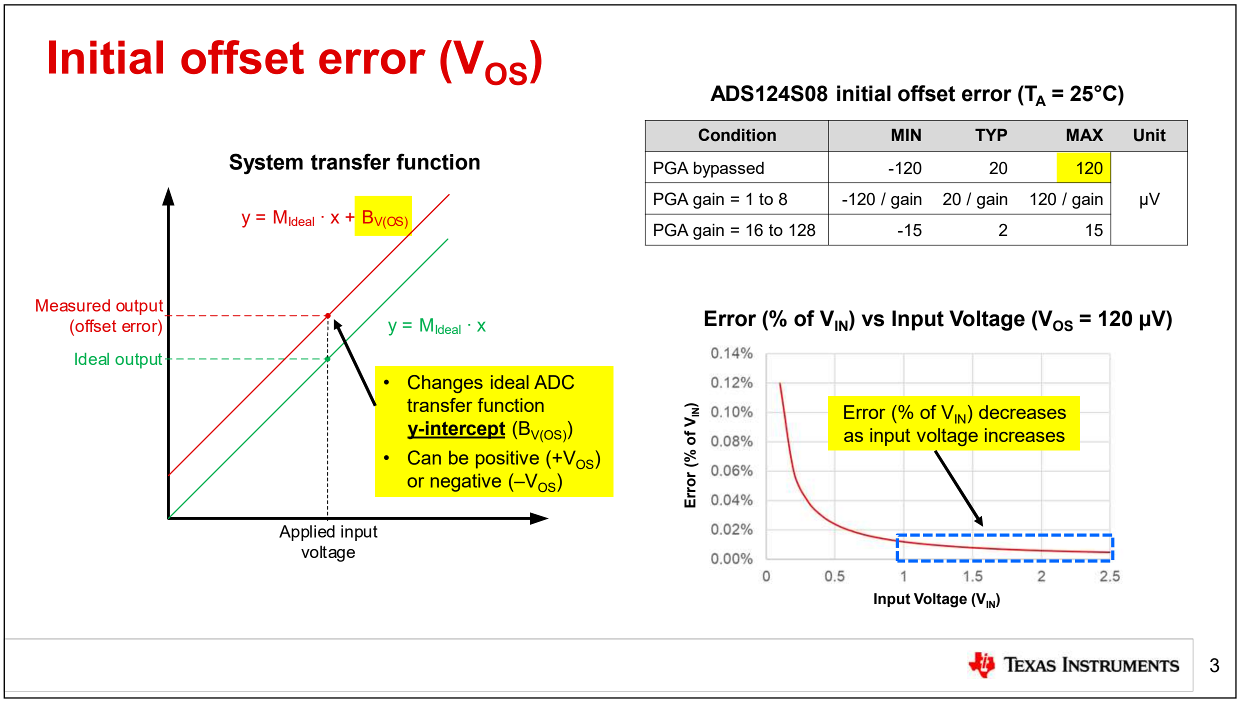
The ADC and amplifier can contribute multiple types of error. In this image, the amplifier is integrated into the ADC package, but the same error analysis applies for a discrete amplifier. In either case, the amplifier and ADC can contribute offset and gain error, linearity errors, and drift errors. While both components can also contribute noise, this topic is not discussed further in this presentation. Instead, refer to the Precision Labs series on ADC noise for a detailed noise analysis

The precision resistor used to establish a ratiometric reference voltage can contribute initial accuracy and temperature drift errors. We will assume there is no IDAC error because of the ratiometric reference configuration. However, IDAC mismatch error does need to be considered for 3-wire RTD measurement systems using two IDACs. This topic is covered in detail in a previous Precision Labs module discussing challenges with 3-wire RTD systems. Please review that module for more information about errors related to IDAC mismatch

The RTD itself can contribute error in the form of variation in the sensor accuracy, self-heating, and lead wire mismatch. Finally, the controller can introduce computational errors in the resistance-to-temperature conversion process

Given the complexity of the different error sources, this topic will be split into two parts. This presentation focuses on initial errors, which are highlighted by the blue boxes. A subsequent presentation will explore the remaining error sources as well as temperature drift errors

Let's begin by analyzing initial offset error



Initial offset error (V_{OS})

ADS124S08 initial offset error (T_A = 25°C)

Condition	MIN	TYP	MAX	Unit
PGA bypassed	-120	20	120	µV
PGA gain = 1 to 8	-120 / gain	20 / gain	120 / gain	
PGA gain = 16 to 128	-15	2	15	

System transfer function

- Changes ideal ADC transfer function **y-intercept** ($B_{V(OS)}$)
- Can be positive ($+V_{OS}$) or negative ($–V_{OS}$)

Error (% of V_{IN}) vs Input Voltage (V_{OS} = 120 µV)

Error (% of V_{IN}) decreases as input voltage increases

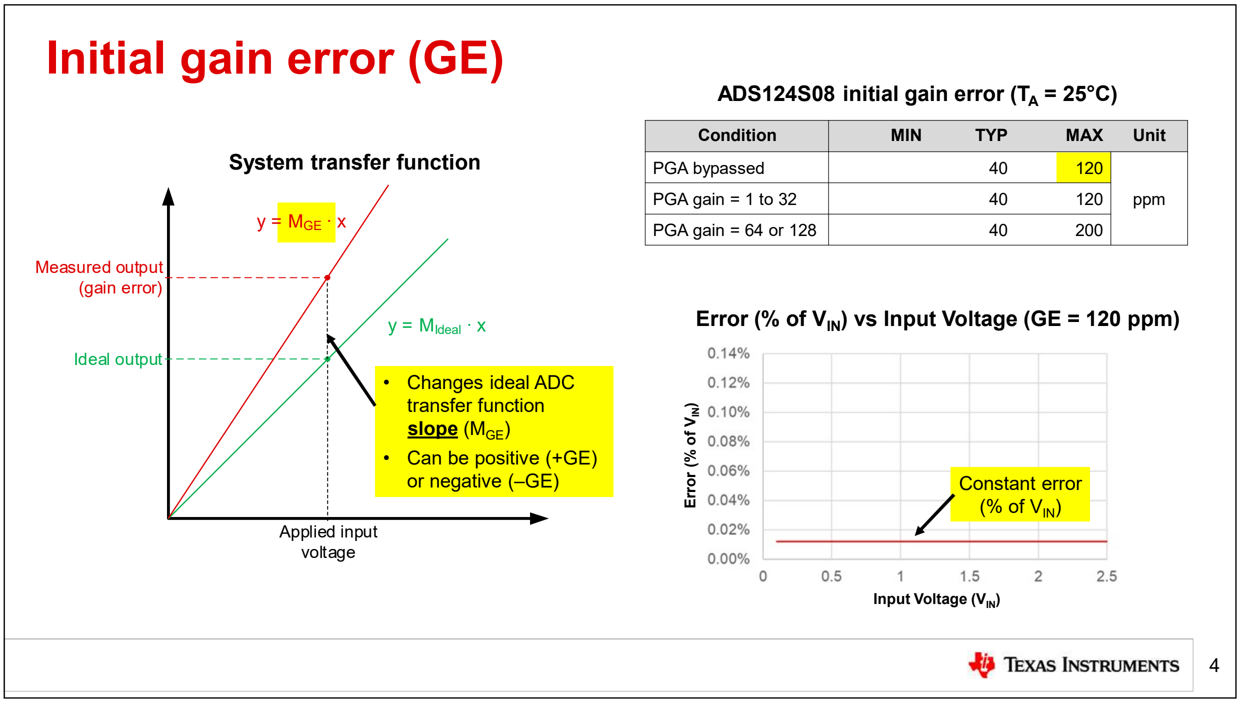
Shown on the left in green is the transfer function for an ideal, error-free system. This transfer function has some slope, M_IDEAL, that generates an ideal output code from an applied input voltage. Notably, the equation for this curve has a y-intercept of zero

Offset error introduces a nonzero y-intercept to this curve, shifting it up or down if the offset is positive or negative, respectively. The red curve represents the system transfer function with a positive offset error. Note that this plot assumes no other errors are present in the system to keep the analysis simple. Now that the system has an offset error, the applied input voltage produces a different measured output compared to the ideal transfer function. This different output code correlates to a different measured RTD resistance, which results in the wrong calculated temperature. Fortunately, the typical RTD measurement system calibration process removes offset error

As an example of offset error in a real ADC, the table in the upper right shows the offset error specifications in microvolts for the ADS124S08. This ADC is a 24-bit, 13 channel delta-sigma ADC with an integrated amplifier that is commonly-used for RTD measurements. Due to the integrated amplifier, the offset specifications for this ADC represent the combined offset of both the ADC and the amplifier, and can vary depending on the selected gain. Note that offset is typically specified referred to the input of the amplifier, which is the case for this ADC.

To understand how offset affects the measurement, the graph in the bottom right plots the percent change in input voltage contributed by offset as the input voltage sweeps from 100 mV to 2.5 V. The plot uses an offset error specification of 120 µV, which is the offset error when the PGA is bypassed. Importantly, the % error decreases as the input voltage increases. For example, the error is 0.12% when the input voltage is 100 mV, while the error is approximately zero when the input voltage is 2.5 V. These results indicate that offset error is an absolute parameter, or one that does not scale with input voltage. Therefore, offset error tends to dominate the overall error budget when the input signals are small

Let’s move on to discuss gain error



Initial gain error (GE)

System transfer function

- Changes ideal ADC transfer function **slope** (M_{GE})
- Can be positive (+GE) or negative (–GE)

ADS124S08 initial gain error (T_A = 25°C)

Condition	MIN	TYP	MAX	Unit
PGA bypassed		40	120	ppm
PGA gain = 1 to 32		40	120	
PGA gain = 64 or 128		40	200	

Error (% of V_{IN}) vs Input Voltage (GE = 120 ppm)

Constant error (% of V_{IN})

Shown on the left in green is the same plot of the error-free system transfer function presented on the previous slide

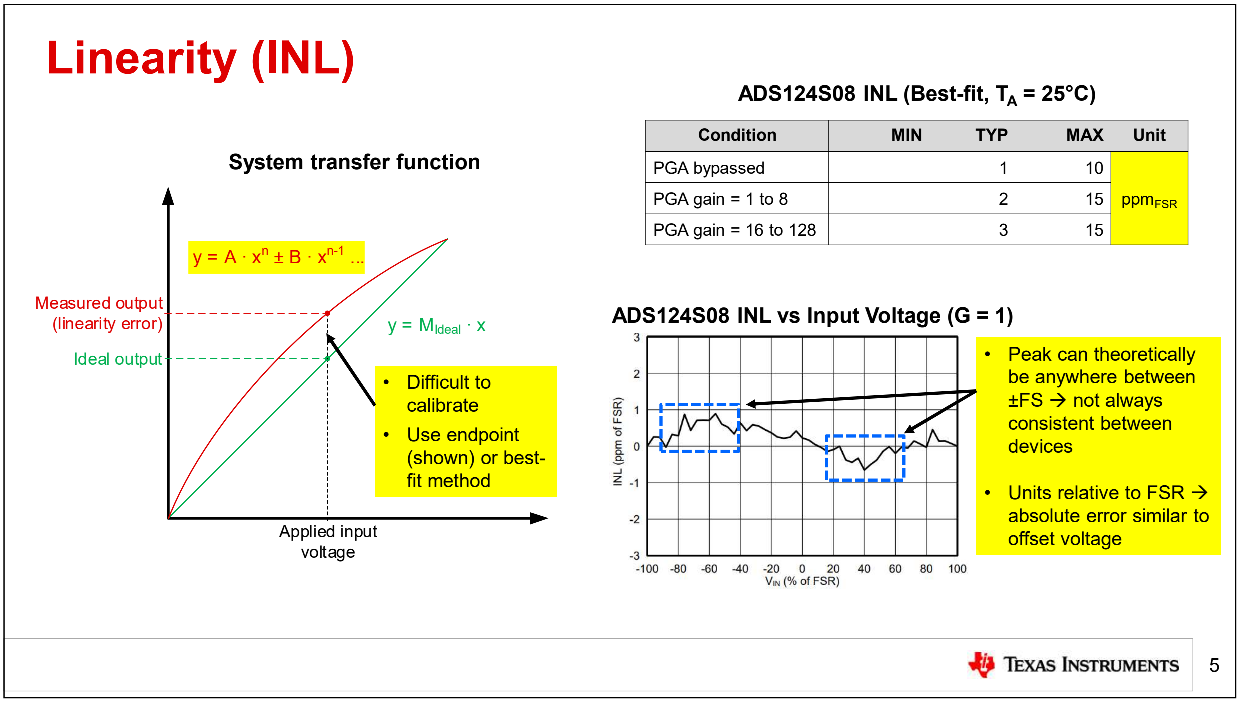
Gain error changes the slope of this curve, rotating it up or down if the gain error is positive or negative, respectively. The red curve represents the system transfer function with a positive gain error. Note that this plot assumes no other errors are present in the system to keep the analysis simple

Now that the system has an gain error, the applied input voltage produces a different measured output compared to the ideal transfer function. This different output code correlates to a different measured RTD resistance, which results in the wrong calculated temperature. Fortunately, the typical RTD measurement system calibration process removes gain error

As an example of gain error in a real ADC, the table in the upper right shows the gain error specifications in ppm for the ADS124S08, the 24-bit delta-sigma ADC introduced on the previous slide. Similar to offset error, the gain error for this ADC is the combined gain error of both the ADC and the amplifier, and can vary depending on the selected gain

To understand how gain error affects the measurement, the graph in the bottom right plots the percent change in input voltage contributed by gain error as the input voltage sweeps from 100 mV to 2.5 V. The plot uses a gain error specification of 120 ppm, which is the gain error when the PGA is bypassed. Unlike offset error, gain error as a percent of the input voltage remains constant as the input voltage increases. These results indicate that gain error is a relative parameter, or one that scales with input voltage. This makes sense because gain error is specified in ppm, which is defined as a percentage of the input signal. Therefore, gain error tends to dominate the overall error budget when the input signals are closer to full scale

Let’s now discuss linearity error



Linearity (INL)

System transfer function

- Difficult to calibrate
- Use endpoint (shown) or best-fit method

ADS124S08 INL (Best-fit, T_A = 25°C)

Condition	MIN	TYP	MAX	Unit
PGA bypassed		1	10	ppm_{FSR}
PGA gain = 1 to 8		2	15	
PGA gain = 16 to 128		3	15	

ADS124S08 INL vs Input Voltage (G = 1)

- Peak can theoretically be anywhere between ±FS → not always consistent between devices
- Units relative to FSR → absolute error similar to offset voltage

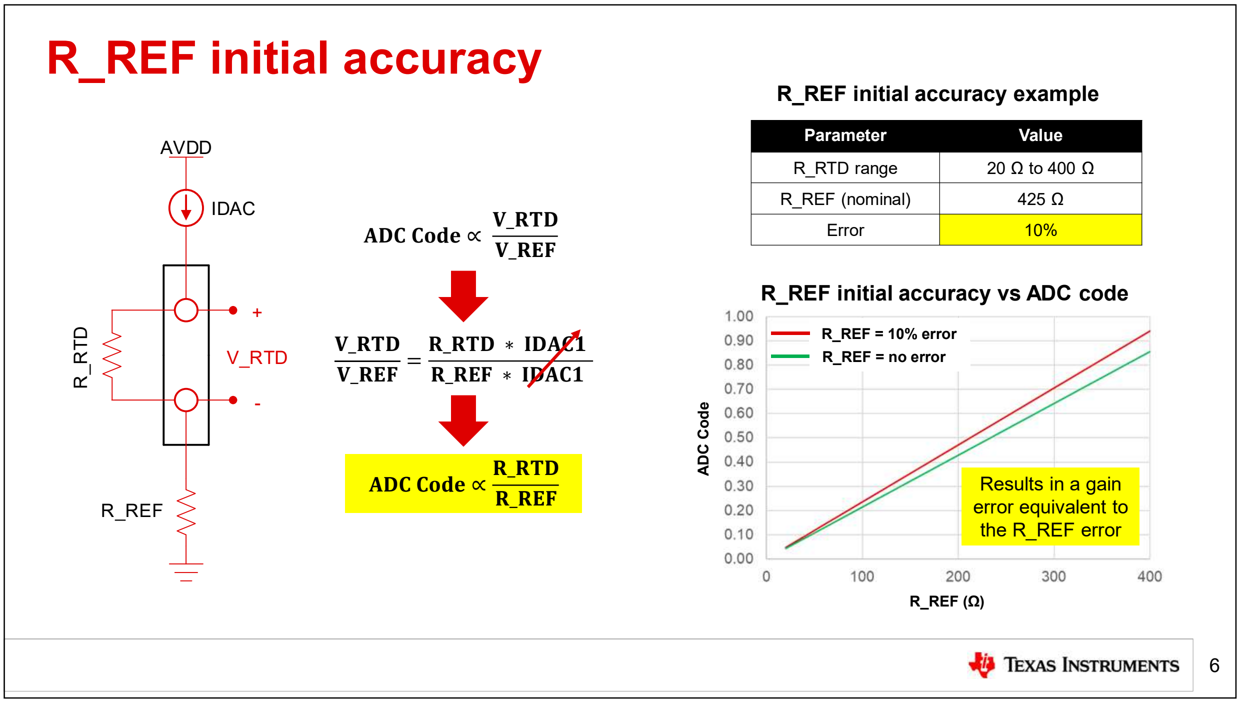
Shown on the left in green is the same plot of the error-free system transfer function presented on the previous slide. As its name implies, a linearity error causes the ideal, linear curve in green to become the nonlinear curve shown in red. As a result, nonlinearity error is very difficult to calibrate

Linearity error can be found in both ADCs and amplifiers. The red plot shows an ADC error called integral non linearity, or INL, which is specified using the endpoint method. This method represents the maximum deviation of the actual transfer function from the ideal, endpoint curve after an offset and gain error calibration. INL can also be specified using the best-fit method, which determines the remaining linearity error after a multi-point calibration across input voltage

As an example of linearity error in a real ADC, the table in the upper right shows the INL specifications for the ADS124S08. Note that the INL for this ADC is specified in ppm of FSR and uses the best-fit method. Similar to the previous errors we've discussed, the INL specifications shown here are the combined linearity error of both the ADC and the amplifier, and can vary depending on the selected gain

To understand how INL affects the measurement, the curve in the bottom right plots the ADS124S08 INL versus input voltage at a gain of one. Let's review some key characteristics of this graph. First, the peak value can theoretically be anywhere within the full-scale range, and the location of this peak and the general shape of the INL curve can vary from device to device. These two factors make INL difficult to calibrate as previously mentioned. Also, since INL is given in units of ppm of FSR, it is considered an absolute error similar to offset voltage. In other words, the specified INL error is a fixed voltage that is relative to the full-scale range. Therefore, INL uses a larger percentage of the error budget when the input signals are small

Next, let's consider how the reference resistor error impacts the system



R_REF initial accuracy

$$\text{ADC Code} \propto \frac{\text{V\_RTD}}{\text{V\_REF}}$$

$$\frac{\text{V\_RTD}}{\text{V\_REF}} = \frac{\text{R\_RTD} * \cancel{\text{IDAC1}}}{\text{R\_REF} * \cancel{\text{IDAC1}}}$$

$$\boxed{\text{ADC Code} \propto \frac{\text{R\_RTD}}{\text{R\_REF}}}$$

R_REF initial accuracy example

Parameter	Value
R_RTD range	20 Ω to 400 Ω
R_REF (nominal)	425 Ω
Error	10%

R_REF initial accuracy vs ADC code

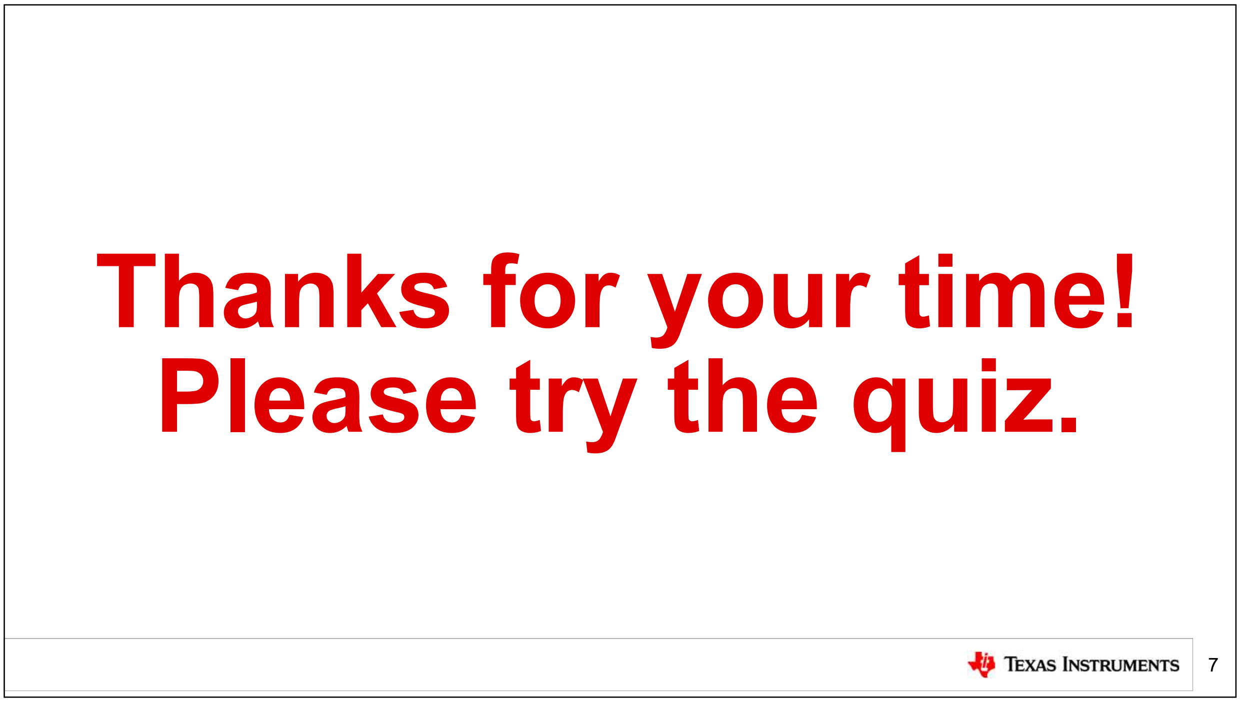
Results in a gain error equivalent to the R_REF error

One of the most important non-ADC errors to consider in an RTD measurement system is the error of the reference resistor, R_REF. As these equations show, the ADC code is directly related to the reference voltage. In the ratiometric reference configuration shown on the left, any error in the IDAC bias current is eliminated, and the ADC code depends only on the ratio of the RTD resistance to the R_REF resistance. However, this means any change in the resistance of R_REF has a direct impact on the measurement result

For example, the table in the top right provides some theoretical values for R_REF, including a nominal resistance of 425 Ω and an error of 10%. While this error is large, it helps visualize the effect R_REF error has on the total error. In a practical circuit however, it is common to choose a component that has a 0.1% accuracy specification or better

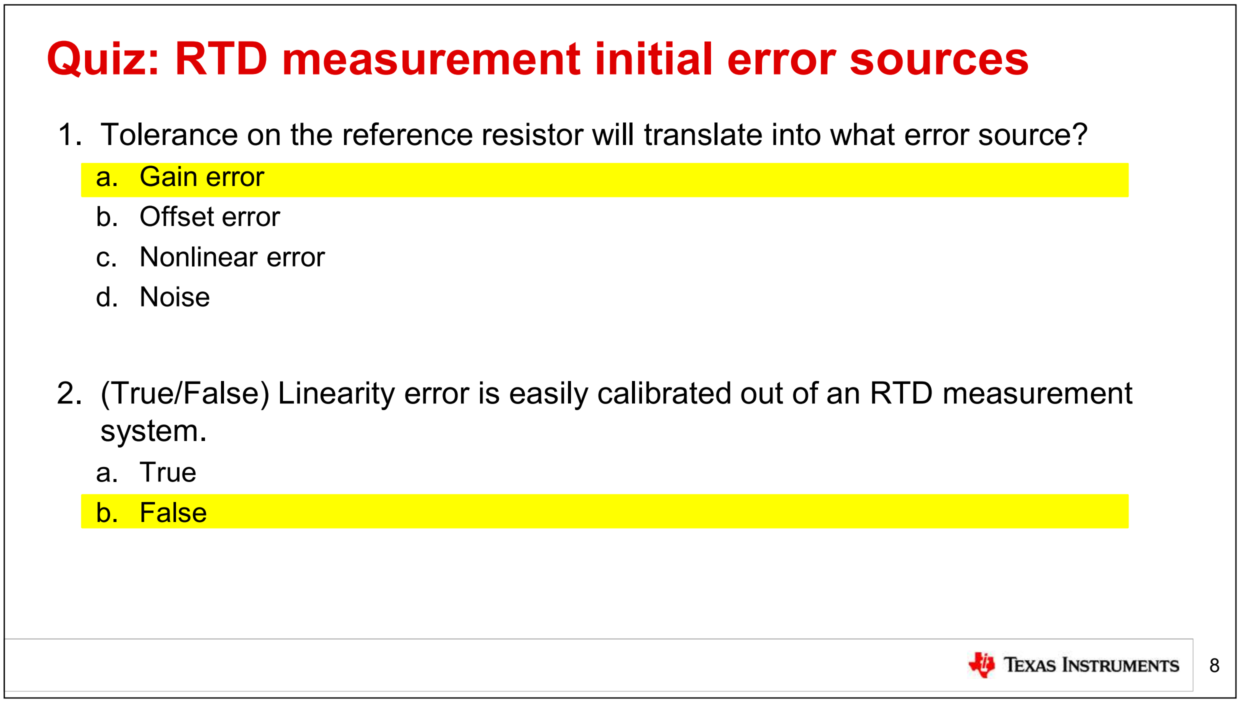
To understand how R_REF error affects the measurement, the plot on the bottom right shows the ideal response in green and the response with error in red, both with respect to the RTD measurement range given in the table. Importantly, the deviation between the two curves increases linearly as R_REF increases. Since the error scales linearly with the input signal, R_REF error becomes another gain error whose magnitude is equivalent to the R_REF error. In many real-world RTD measurements system, R_REF error dominates the overall system error because it directly changes the reference voltage used by the ADC. Fortunately, the typical RTD measurement system calibration process removes initial reference resistor error

For analysis regarding additional RTD measurement system error sources, as well as over-temperature errors, review a subsequent Precision Labs module series



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: RTD measurement initial error sources

1. Tolerance on the reference resistor will translate into what error source?
   - [✓ a. Gain error]
   - b. Offset error
   - c. Nonlinear error
   - d. Noise
2. (True/False) Linearity error is easily calibrated out of an RTD measurement system.
   - a. True
   - [✓ b. False]

Question 1. Tolerance on the reference resistor will translate into what error source?

The correct answer is A, gain error

Question 2, true or false. Linearity error is easily calibrated out of an RTD measurement system

The correct answer is B, false. Linearity error typically has a third order relationship with input voltage, making it very difficult to remove through calibration. However, linearity error is typically small such that it does not significantly impact the error budget

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