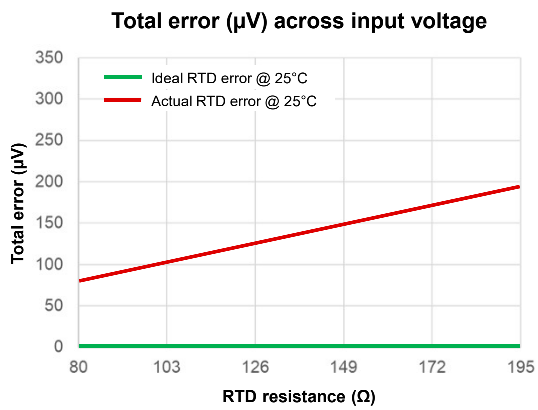
Hello, and welcome to the TI Precision Labs module discussing calibration techniques for RTD measurement systems. Previous Precision Labs modules discussed common error sources and calculating total error. This module focuses on removing that error through calibration. Topics covered in this presentation include a discussion on general calibration, identifying a process for removing initial errors through calibration, and how much error is removed by this initial calibration process.

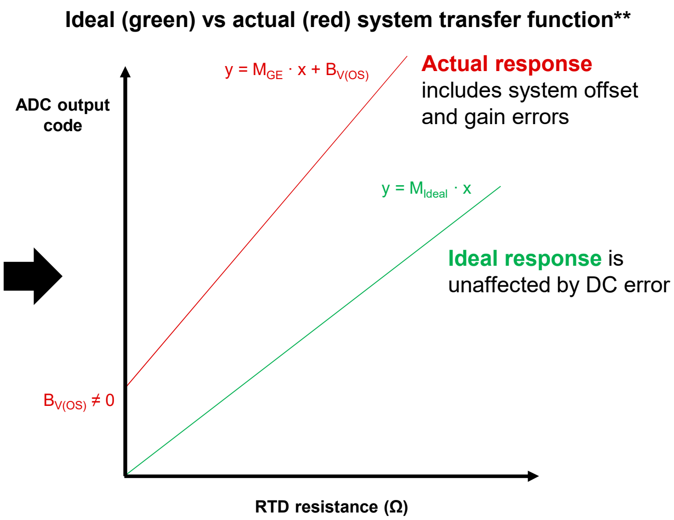
A follow-up presentation introduces a method to calibrate over-temperature error

To begin, let's discuss how the error estimation techniques introduced in previous Precision Labs modules affect the system transfer function

**Ignores linearity errors

How error impacts the system transfer function

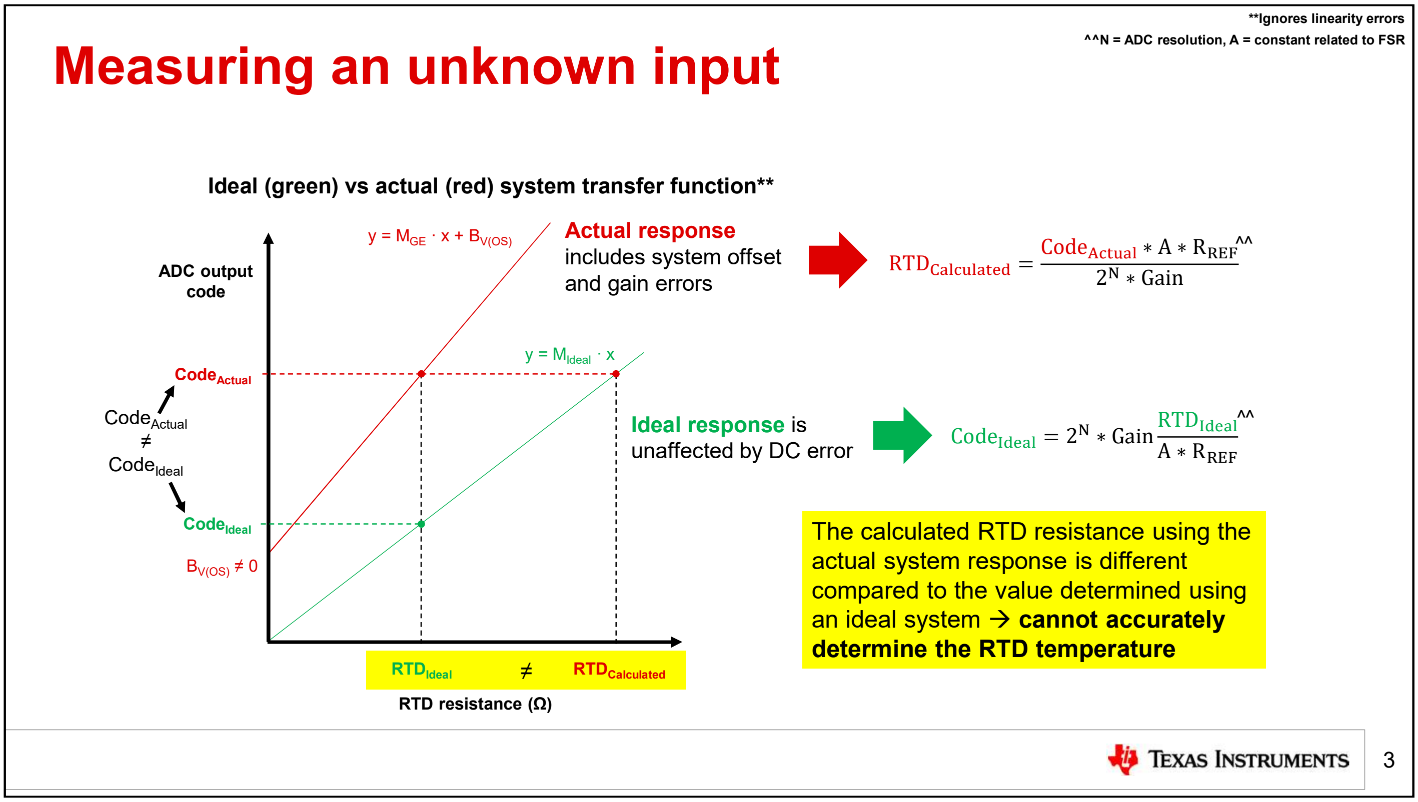




Under ideal conditions, an RTD measurement system has no error. This is represented by the horizontal green line in the plot on the left. An error-free system yields the green transfer function shown on the right. This response is considered ideal because it is unaffected by DC error.

However, a previous Precision Labs module discussing error estimation plotted the actual error of an example system. This response is given by the red line on the left. The red error plot on the left translates to the actual response on the right, also in red. Note how the error across input voltage changes the slope and y-intercept of the actual response on the right, which corresponds to the gain error and offset error, respectively. Also note that to keep the analysis simple, we assume the actual response is linear. This assumption is valid because linearity errors are typically a small percentage of the total error, so excluding them from this analysis will not significantly impact the results. Refer to the previous Precision Labs module on calculating error in RTD measurement systems for more information

Next, let's discover what happens when we try to use this example system to measure some unknown input



On the left are the same ideal and actual transfer functions shown on the previous slide. When we apply an unknown input signal, RTD_Ideal, to the system, the generated ADC output is Code_Ideal as shown. Using the green equation on the right, we can determine that this ADC code corresponds to the RTD resistance given by RTD_Ideal. We can then use a look up table or polynomial to accurately determine the temperature from that resistance

When we apply the same unknown input signal to the system in red, the ADC output is given as Code_Actual. Since the behavior of the actual system transfer function is unknown at this point, we assume it follows the green, ideal response. However, it is clear that Code_Actual and Code_Ideal are not equal. As a result, we can use the red equation on the top right to determine that Code_Actual corresponds to RTD_Calculated, which is very is different from RTD_ideal

When we use a look up table or polynomial to correlate RTD_Calculated to a temperature, our final result would be completely wrong compared to the temperature that corresponds to RTD_Ideal. Calibration is therefore necessary to understand the behavior of the actual response so we can accurately determine the RTD temperature from the measured resistance

The next slide discusses which errors can be removed by calibration

Which errors are removed by calibration?

ADS124S08 & R_REF error summary @ RTD_MAX

Error type	Parameter	Value	Units
Initial errors	ADC offset error	2.5	
	ADC gain error	7.76	
	ADC INL	0.8	
	ADC noise	0.45	
	R_REF accuracy	194.10	
Over-temperature errors	ADC offset drift	0.9	
	ADC gain drift	11.65	µV
	R_REF drift	58.23	
Total errors	ADC offset	3.4	
	ADC gain	19.41	
	ADC INL	0.8	
	ADC noise	0.45	
	R_REF	252.33	

- Linearity error is difficult to calibrate, but typically insignificant for RTD measurements
- Noise cannot be removed, but potentially can be reduced by averaging
- Calibrated errors are reduced to the level of the signal chain noise

Reduced by initial calibration

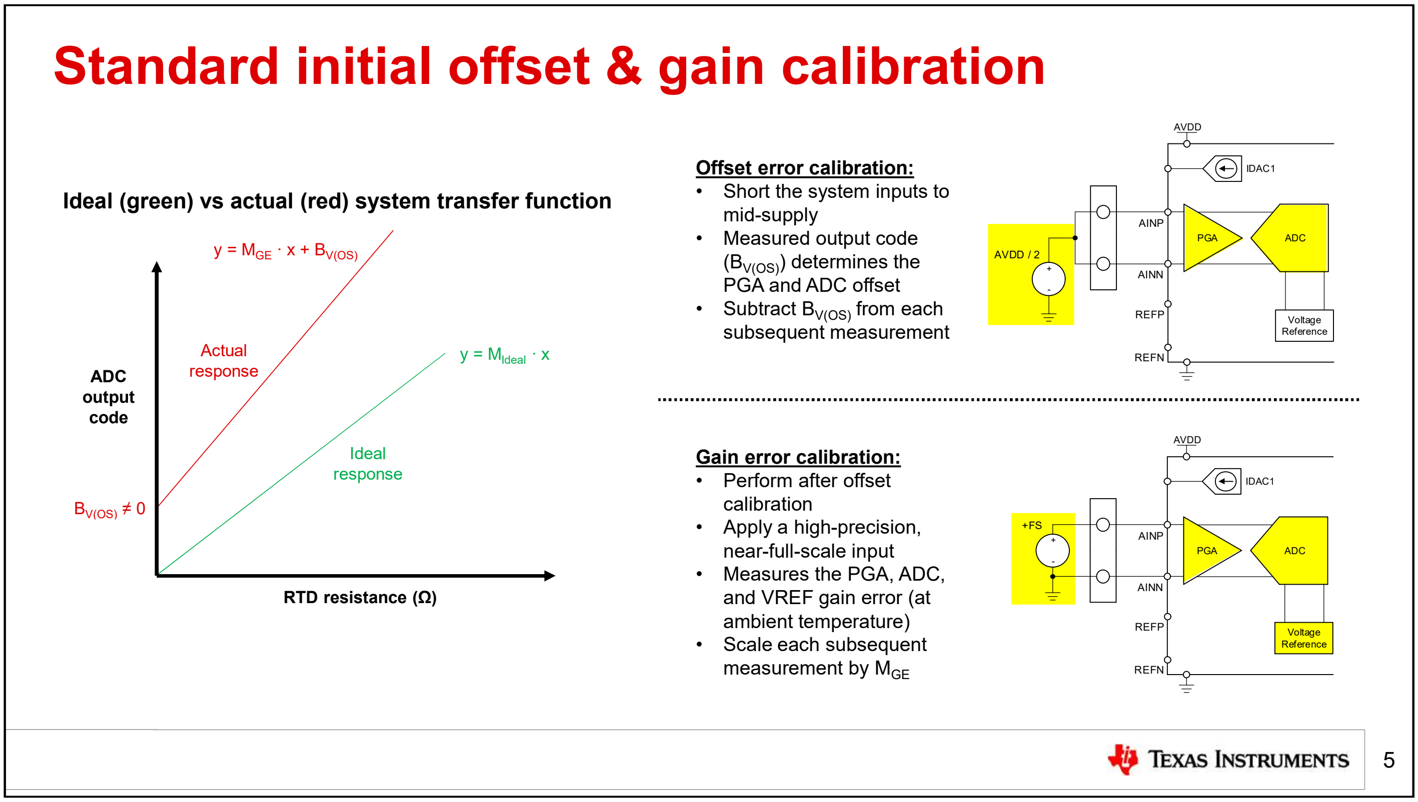
Reduced by over-temp calibration

The errors in this table come from an example introduced in a previous Precision Labs module discussing how to estimate the total error for RTD measurement systems. This table groups the different ADC and reference resistor error sources into initial errors in purple, over-temperature errors in light blue, and total error in brown. In the example, these errors were calculated with respect to the maximum RTD resistance, which was 194.1 ohms, and used the ADS124S08 as the ADC. The ADS124S08 is a 24-bit, 13 channel delta-sigma ADC with an integrated amplifier and current sources that is commonly-used for RTD measurements.

Let’s make some general comments about which of the errors shown in this table can be removed by calibration. As mentioned on the previous slide, linearity error is not removed by the standard calibration process. This is acceptable because the linearity error is typically small, which is the case in this example. A multi-point calibration can be performed to remove linearity, but this is a very time-intensive, cost prohibitive process

ADC noise is inherent to the device and cannot be removed by calibration. Averaging multiple samples can help reduce noise in some cases. Please see the Precision Labs series on ADC noise for more information about noise mitigation techniques

The remaining offset and gain error sources can be reduced by the calibration process, though only to the level of the signal chain noise. The orange boxes indicate those errors that can be reduced by the initial calibration process, while the darker blue box indicate those errors that can be reduced by an over-temperature calibration. Over-temperature calibration will be discussed in a subsequent Precision Labs module. The next slide steps through a generic calibration procedure that can remove initial offset and gain errors

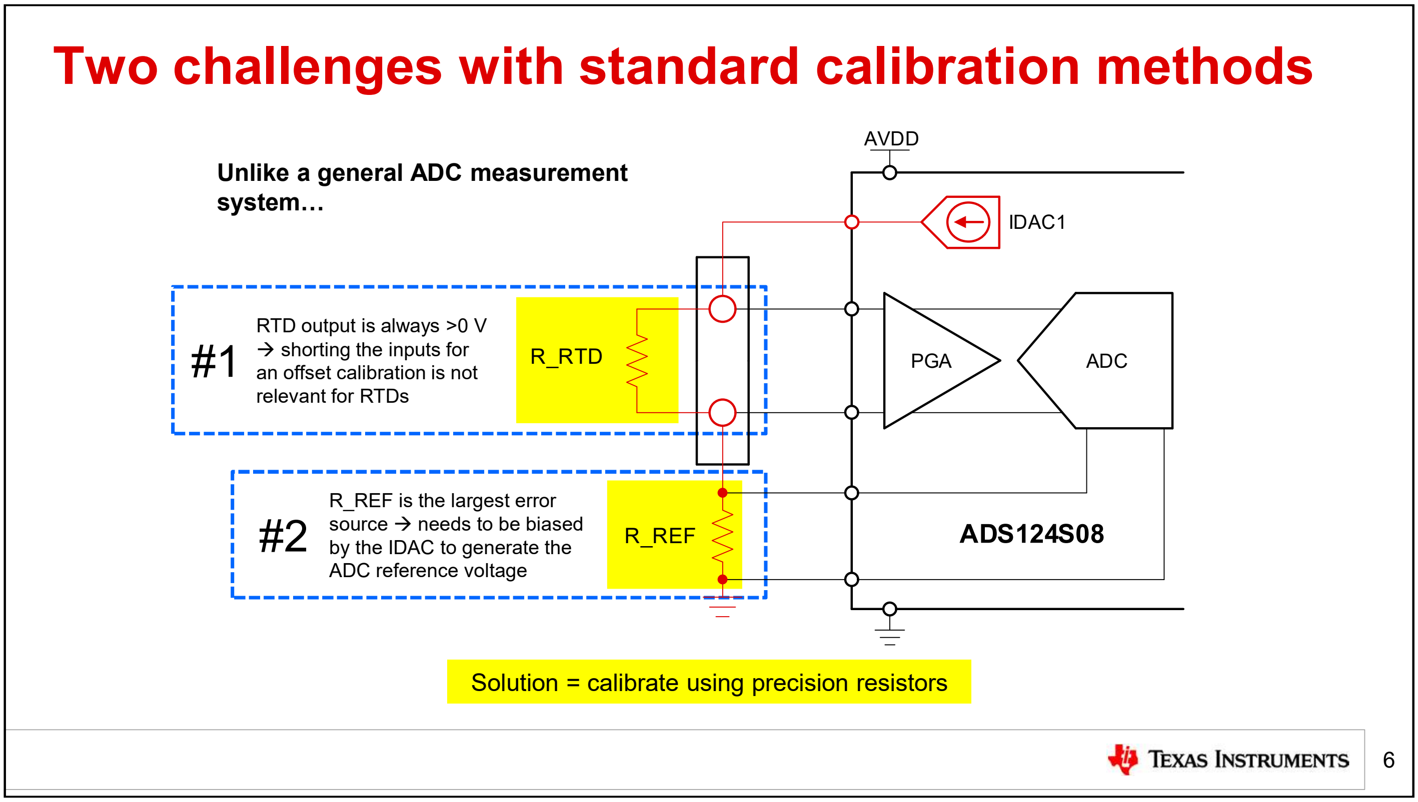


Shown on the left are the ideal and actual transfer functions introduced on the first slide in this presentation. We determined that the actual response has both offset and gain errors, which we can remove by calibration.

The first step in the initial error calibration procedure is to remove the offset. As shown in the top right, the offset calibration involves shorting the ADC differential inputs together, typically to a mid-supply voltage. This helps keep the input voltage at the center of the PGA common-mode range. Then, the measured output code corresponds to the combined offset of the PGA and the ADC. Averaging multiple conversions can help reduce noise in the offset voltage measurement. Finally, the offset voltage is subtracted from each subsequent measurement. Performing this action shifts the actual response in red down toward the ideal response in green. Each response still has a different slope, but both now have the same y-intercept

After offset calibration is complete, perform a gain calibration by applying a high precision, near-full scale input to the system. Typically a signal that is 95% of full-scale is sufficient. Then, the measured output code corresponds to a scaling factor that is relative to the slope of the combined gain error of the PGA, the ADC, and the voltage reference at the initial error temperature. Averaging multiple conversions can help reduce noise in the gain error measurement. Finally, each subsequent measurement is multiplied by the scaling factor derived from this process. Performing this action rotates the actual response in red toward the ideal response in green. Now both responses have the same slope and y-intercept, and the system is calibrated.

While this method works well for general data acquisition systems, measuring an RTD creates distinct challenges that requires this process to be modified



As mentioned on the previous slide, the generic RTD measurement system shown on the right has several unique features that make standard offset and gain calibration less effective

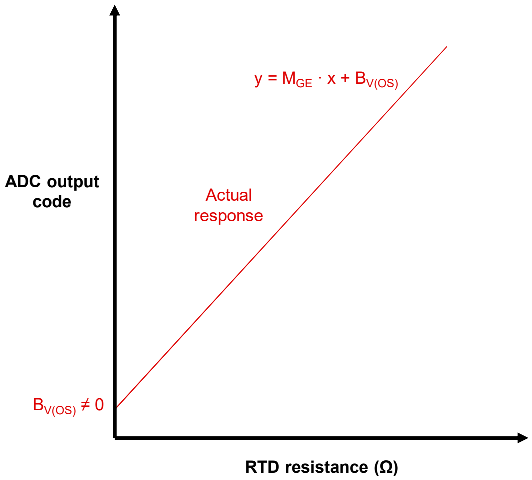
First, the RTD output is always greater than 0 volts, so shorting the inputs for an offset calibration is not relevant for an RTD measurement. Second, an RTD measurement system uses a ratiometric reference, where R_REF is often the largest source of error. Calibrating a ratiometric reference would require an additional, higher-precision voltage reference to be able to calibrate the R_REF error. Moreover, R_REF must be biased by an IDAC to generate the ADC reference voltage. This bias path flows through R_RTD, making it impractical to also apply a full-scale signal from a precision source

Ultimately, a better way to calibrate an RTD measurement system is to use precision resistors to mimic the behavior of a real RTD. This enables us to determine the shape of the actual system transfer function strictly within the RTD measurement range, providing more accurate results

The next slide introduces the initial error calibration process for RTD measurement systems

RTD initial error calibration process

System transfer function



<u>For a specific RTD type:</u>

1. Identify the RTD measurement range for the system
2. Choose two precision resistors (R_{CAL_LO} and R_{CAL_HI}) to represent the extremes of the RTD curve:
    - Choose high-accuracy (0.01% max), low-drift (≤5 ppm/°C max) resistors so they don't contribute significant error to the system
3. Connect R_{CAL_LO} and R_{CAL_HI} to the RTD measurement system and bias each resistor using the ADC IDAC
4. Correlate each resistor's ADC output with ideal resistance value → this maps the system transfer function, including all errors, to the RTD curve

The goal of the RTD initial error calibration process is the same as the standard gain and offset calibration procedure. The system has an unknown transfer function similar to the one shown on the left, and we are trying to determine how the measured resistance maps to the ADC output. In this case however, we only care about a limited subset of the actual response that corresponds to the RTD measurement range

Therefore, the first step in the process is to identify the RTD measurement range of the system for a specific RTD type. For example, the system needs to measure a Pt100 from -50 to 250 degrees Celsius. Importantly, this process only works for this specific set of conditions. If different RTD types need to be measured, or the temperature range changes, the calibration process needs to be repeated

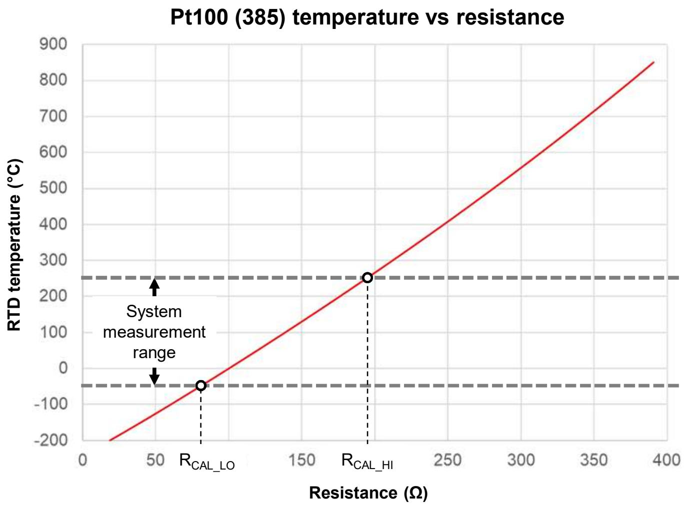
Next, choose two precision resistors to represent the extremes of the RTD curve. These resistors should be very high accuracy and very low drift, because the calibrated accuracy cannot be better than the accuracy of these resistors. In other words, if you choose 1% calibration resistors, the best calibrated accuracy you could achieve is 1%

Then, connect each resistor to the RTD measurement system as though it were a real RTD, bias it with the ADC IDAC, and take a measurement. Averaging multiple conversions can help reduce any noise in the measurement

Finally, correlate the averaged, measured value from each calibration resistor with the ideal resistance value from a look-up table or polynomial. This maps the relevant portion of the previously unknown system transfer function, including errors, to the known RTD curve

The next few slides step through an example

Example: initial error calibration for a Pt100



1. Identify the RTD measurement range for the system:

RTD specifications

Parameter	Value	Units
RTD type	Pt100	
RTD range	-50 to +250	°C
	80.31 to 194.10	Ω

2. Choose two precision resistors (R_{CAL_LO} and R_{CAL_HI}) near the extremes of the RTD curve

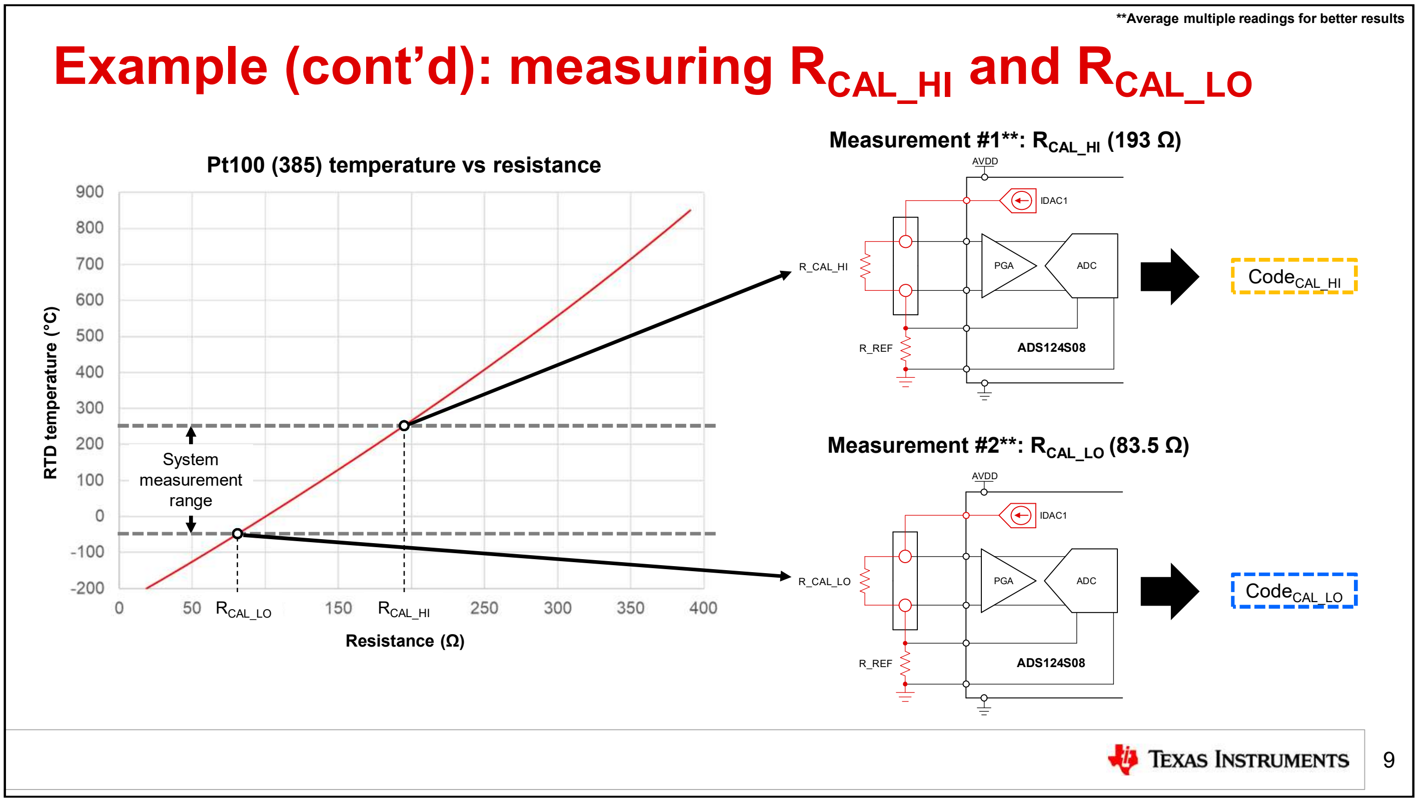
e.g. R_{CAL_LO} = 83.5 Ω and R_{CAL_HI} = 193 Ω

For this example, let's calibrate a Pt100 that has an alpha value of 385. The temperature versus resistance curve for this RTD is plotted on the left, and is derived from a look-up table or calculated using a polynomial. Note that while this simplified calibration process assumes the system transfer function is linear, the RTD response can be nonlinear and calibration will still work. Let's identify the RTD measurement range

This example will use the same system parameters we defined for the examples in the error sources and error estimation Precision Labs modules. These parameters are shown in the table on the right and include a temperature range from -50 to 250 degrees Celsius, which corresponds to an RTD resistance range of 80.31 to 194.1 ohms, respectively. The relevant portion of the RTD curve is denoted by the gray dotted lines on the plot on the left. Though not shown on this slide, we will also select the ADS124S08 as the ADC in this example.

Next, we need to choose two precision resistors near the extremes of the RTD curve. We will refer to these resistors as R_CAL_LO and R_CAL_HI. Note that the actual resistance of these components does not need to cover the entire measurement range because we know the response of the RTD curve. Instead it is recommended to select the closest standard resistance values because these components are easier to find and therefore more cost effective. Two possible values for the calibration resistors that can be used in this example are highlighted in yellow on the right

Let's move on the step three



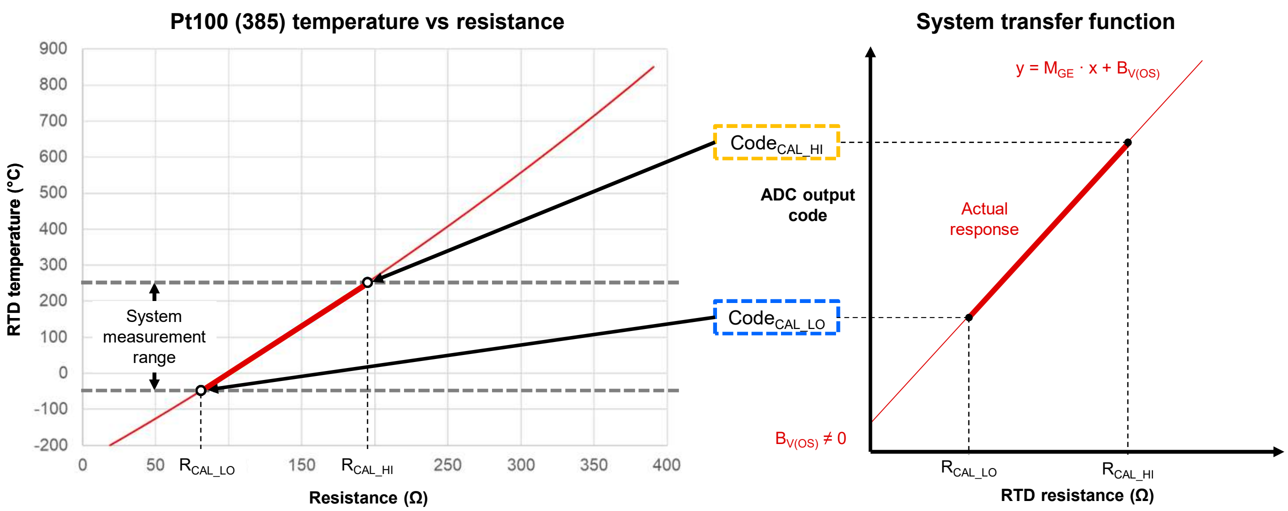
Step 3 requires us to connect each resistor to the RTD measurement system as though it were a real RTD, bias it with the ADC IDAC, and take a measurement.

The measurement system for R_CAL_HI is shown in the top right. The ADC output code for this measurement is given as Code_CAL_HI, which is highlighted in orange. Note that averaging multiple conversions can help reduce any noise in the measurement

Next, replace R_CAL_HI with R_CAL_LO. The measurement system for R_CAL_LO is shown in the bottom right. The ADC output code for this measurement is given as Code_CAL_LO, which is highlighted in blue.

Finally, we are now able to map the ADC output to the RTD curve

Example (cont'd): system transfer function mapping



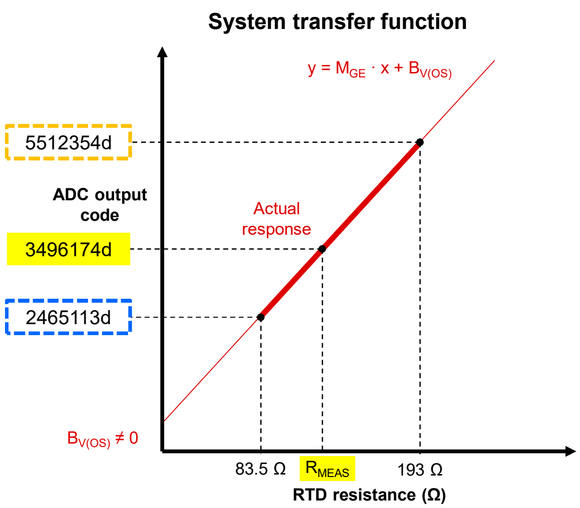
System transfer function – including gain and offset errors – is now mapped to RTD temperature curve

This slide shows the RTD curve on the left and the system transfer function on the right

Our measured values, Code_CAL_HI and Code_CAL_LO, allow us to map the RTD curve to the system transfer function, including all errors, as shown

Now we know which segment of the ADC code range corresponds to the RTD curve. This allows us to accurately determine the value of any measured RTD resistance using these ADC codes and their corresponding resistance values

Example (cont'd): calculating an unknown R_RTD



Equation of a line: $R_x = M * Code_x + B$

Calculate the slope: $M = \frac{R2 - R1}{C2 - C1}$

$$= \frac{193\ \Omega - 83.5\ \Omega}{5512354 - 2465113} = 3.59 * 10^{-5} \frac{\Omega}{Code}$$

Calculate y-intercept: $B = R_x - M * Code_x$

$$= 193\ \Omega - 3.59 * 10^{-5} \frac{\Omega}{Code} * 5512354 = -5.08\ codes$$

Calculate R_{MEAS}: $R_{MEAS} = 3.59 * 10^{-5} \frac{\Omega}{Code} * Code_{MEAS} - 5.08\ codes$

$$= 3.59 * 10^{-5} \frac{\Omega}{Code} * 3496174 - 5.08\ codes$$

$$= 120.55\ \Omega$$

To determine the value of any arbitrary measured RTD resistance after calibration, we need to determine the equation for the transfer function within our calibrated range. This requires the general equation for a line, which is the first formula shown on the right

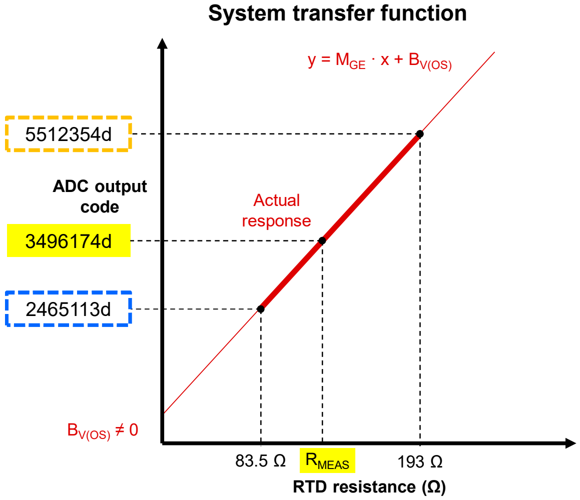
Next, we can replace the variables R_CAL_LO and R_CAL_HI with their values in this example. These are 83.5 ohms and 193 ohms, respectively. Because this is an arbitrary example, we need to choose values for the calibrated ADC codes. In a real system however, these values would be measured and output by the ADC. In this example, let's choose Code_CAL_LO to be 2465113 and Code_CAL_HI to be 5512354, both in decimal

Now we can calculate the slope of the transfer function using the second equation on the right. Entering R1, R2, C1, and C2 into the equation yields a slope of 3.59 times 10 to the negative fifth Ohms per Code. With the slope calculated, determine the y-intercept by applying either resistance-code pair to the equation for a line. R2 and C2 are used in this example, which results in a y-intercept of -5.08 codes

Finally, we can derive an equation for any arbitrary measured resistance, R_MEAS

If we assume that the unknown resistance R_MEAS yields an ADC output code of 3496174 in decimal, we can then calculate that R_MEAS is 120.55 ohms. Now let's convert this to a temperature

Example (cont'd): converting R_MEAS to T_MEAS



$R_{MEAS} = 120.55\ \Omega$

Pt100 (385) look-up table (LUT)

	Temperature in °C									
°C	0	1	2	3	4	5	6	7	8	9
	Resistance in Ω									
-50	80.31									
-40	84.27	83.87	83.48	83.08	82.69	82.29	81.89	81.50	81.10	80.70
-30	88.22	87.83	87.43	87.04	86.64	86.25	85.85	85.46	85.06	84.67
-20	92.16	91.77	91.37	90.98	90.59	90.19	89.80	89.40	89.01	88.62
-10	96.09	95.69	95.30	94.91	94.52	94.12	93.73	93.34	92.95	92.55
0	100.00	99.61	99.22	98.83	98.44	98.04	97.65	97.26	96.87	96.48
0	100.00	100.39	100.78	101.17	101.56	101.95	102.34	102.73	103.12	103.51
10	103.90	104.29	104.68	105.07	105.46	105.85	106.24	106.63	107.02	107.40
20	107.79	108.18	108.57	108.96	109.35	109.73	110.12	110.51	110.90	111.29
30	111.67	112.06	112.45	112.83	113.22	113.61	114.00	114.38	114.77	115.15
40	115.54	115.93	116.31	116.70	117.08	117.47	117.86	118.24	118.63	119.01
50	119.40	119.78	120.17	120.55	120.94	121.32	121.71	122.09	122.47	122.86
60	123.24	123.63	124.01	124.39	124.78	125.16	125.54	125.93	126.31	126.69
70	127.08	127.46	127.84	128.22	128.61	128.99	129.37	129.75	130.13	130.52
80	130.90	131.28	131.66	132.04	132.42	132.80	133.18	133.57	133.95	134.33
90	134.71	135.09	135.47	135.85	136.23	136.61	136.99	137.37	137.75	138.13
100	138.51	138.88	139.26	139.64	140.02	140.40	140.78	141.16	141.54	141.91

$T_{MEAS} = 50°C + 3°C = 53°C$

For this example, let's convert the measured resistance to a temperature using a look-up table similar to the one shown on the right. As described in a previous Precision Labs module that introduced RTDs, a look-up table is easier to use compared to a polynomial because it is computationally simple

After locating the resistance value in the table, use the temperature values on the left and the top of the table to determine the temperature. If the exact value is not included in the table, use linear interpolation to calculate the corresponding temperature

In this example, the measured ADC code of 3496174 in decimal corresponds to a measured resistance of 120.55 ohms and a calibrated temperature of 53 degrees Celsius

That completes the initial error calibration process. Let's now consider how this process affects the error sources introduced at the beginning of this presentation

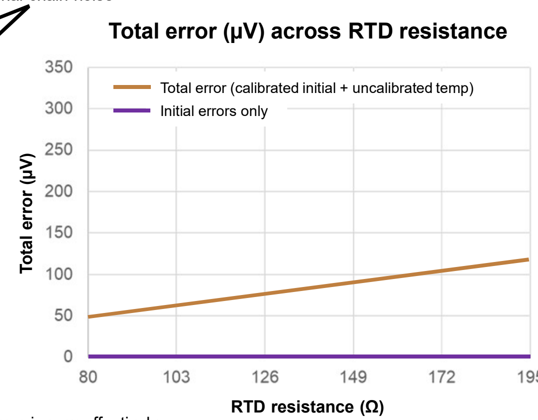
Total error after initial error calibration

ADS124S08 & R_REF error summary @ RTD_MAX

Error type	Parameter	Value	Units
Initial errors	ADC offset error	0.45	
	ADC gain error	0.45	
	ADC INL	0.8	
	ADC noise	0.45	
	R_REF accuracy	0.45	
Over-temperature errors	ADC offset drift	0.9	
	ADC gain drift	11.65	µV
	R_REF drift	58.23	
Total errors	ADC offset error	1.35	
	ADC gain error	12.10	
	ADC INL	0.8	
	ADC noise	0.45	
	R_REF accuracy	58.23	

Calibrated errors are reduced to the level of the signal chain noise

Total error is now effectively just the uncalibrated temp error



Implement temp calibration if necessary

Reduced by initial calibration

Reduced by over-temp calibration

The error table on the left was introduced earlier in this presentation, where the errors are calculated at the maximum RTD input resistance, RTD_MAX. The plot on the right graphs these errors across the entire RTD resistance range used in this example, which was from 80 ohms to 195 ohms

After completing the initial calibration, the offset, gain, and R_REF errors can be reduced to the level of the noise as shown. The purple plot on the right reduces to effectively 0 microvolts of error at any measured RTD resistance. The total error then just becomes the over-temperature error as shown in the table on the left and the brown plot on the right

If further error reduction is necessary, calibrate across temperature. This topic is discussed in a subsequent Precision Labs module

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: Calibrating an RTD measurement system

1. Which of the following errors is not removed by the calibration process described in this presentation?
   a. Nonlinearity
   b. Offset
   c. Gain Error

2. What is typically the largest error source in an RTD temperature measurement system?
   a. ADC gain error
   b. ADC offset error
   c. Tolerance in external reference resistor
   d. ADC noise error

Question 1. Which of the following errors is not removed by the calibration process described in this presentation?

The correct answer is A, nonlinearity

Question 2. What is typically the largest error source in an RTD temperature measurement system?

The correct answer is C, tolerance in the external resistor