Over-temperature calibration in RTD measurement systems

TI Precision Labs – ADCs

Created by Bryan Lizon

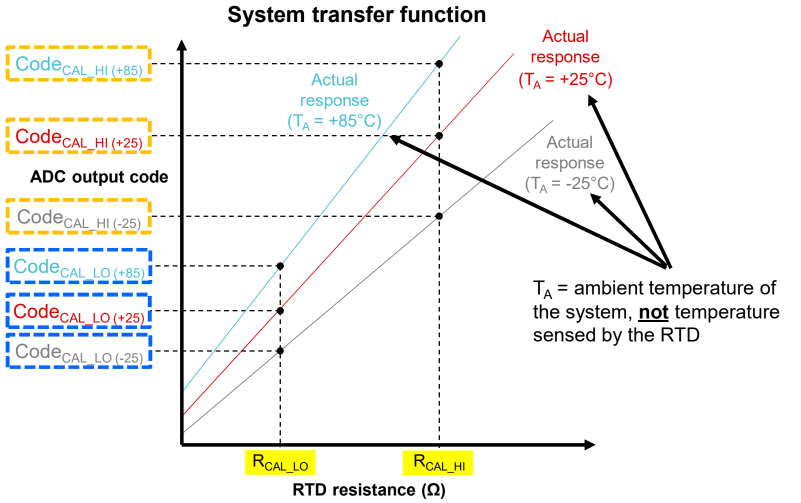
Presented by Josh Brown

TEXAS INSTRUMENTS

Hello, and welcome to the TI Precision Labs module discussing over-temperature calibration in RTD measurement systems. A previous Precision Labs module introduced general calibration methods, identified a process for removing initial errors through calibration, and discussed how much error is removed by this initial calibration process. This module expands on that information to include a procedure for calibrating over-temperature errors

To begin, let's review the system transfer function introduced in the previous Precision Labs module

System transfer function mapping over temperature

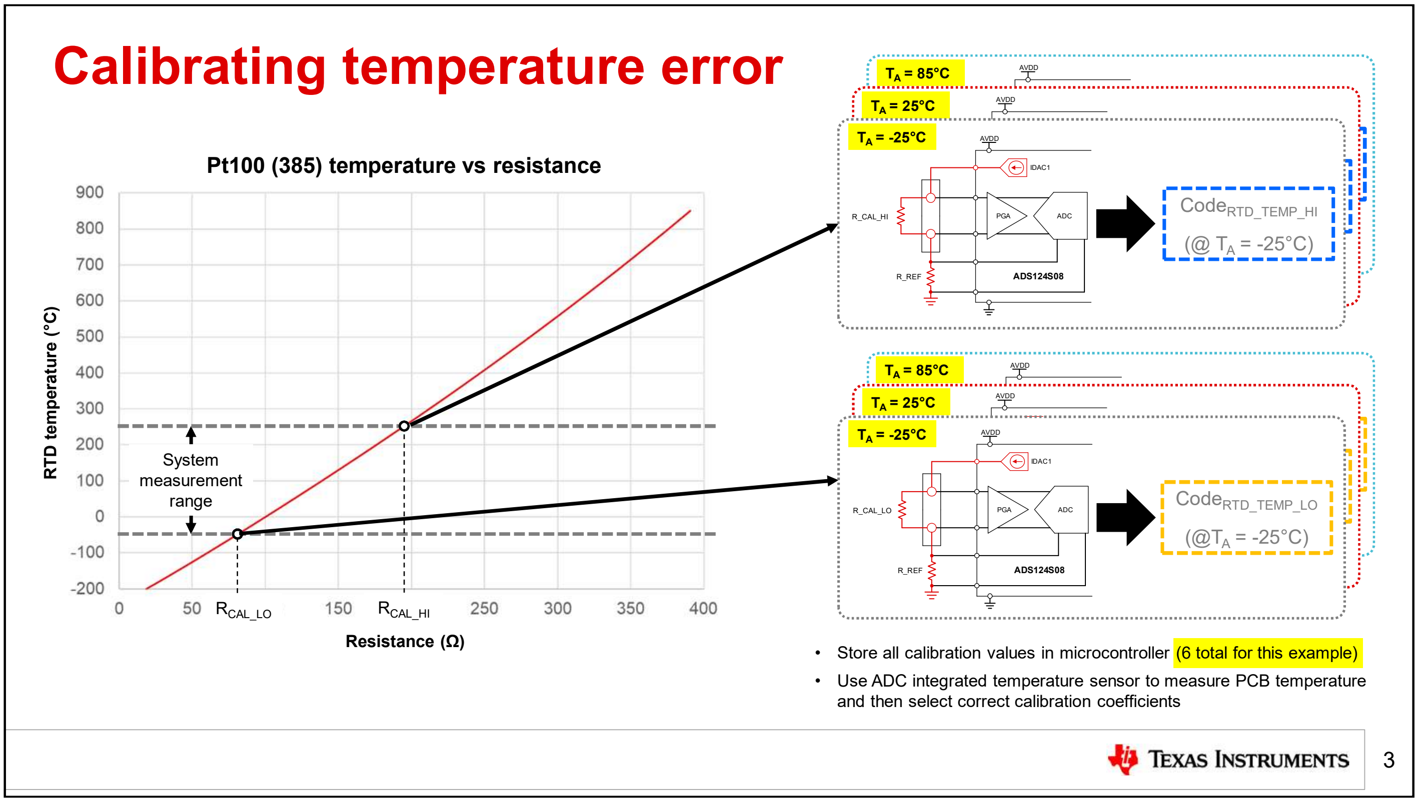


System transfer function changes with ambient temperature → must calibrate both resistors (R_{CAL_LO} and R_{CAL_HI}) at multiple temperature points to remove over-temperature error

Shown here is the standard system transfer function in red used extensively throughout this Precision Labs series. Specifically, in the previous module, we derived a method to calibrate this transfer function and remove the initial error. While not explicitly stated, the transfer function in red is the actual response of our system at a specific ambient temperature. In this example, the red plot corresponds to the initial error at an ambient temperature of 25 degrees Celsius, which should not be confused with the temperature sensed by the RTD. The corresponding ADC codes used to map the RTD curve to the transfer function are specific to this ambient temperature as well. However, as discussed in previous Precision Labs modules, the magnitude of each error source can change with temperature, which in turn changes the system transfer function

For example, hypothetical transfer functions at -25 degrees Celsius and 85 degrees Celsius are shown in gray and light blue, respectively. Since the transfer function is changing across ambient temperature, the code range corresponding to the RTD curve can change as well. Possible code ranges are shown on the left for the transfer functions in gray and light blue. These represent additional system error introduced by the change in temperature.

Since it is not possible to calibrate out the error at every individual temperature, we need to choose a few calibration temperatures and assume the temperature error is linear between these points. Importantly, we still use the same calibrated resistances, R_CAL_LO and R_CAL_HI, to generate these additional ADC codes. The next slide introduces the temperature calibration process

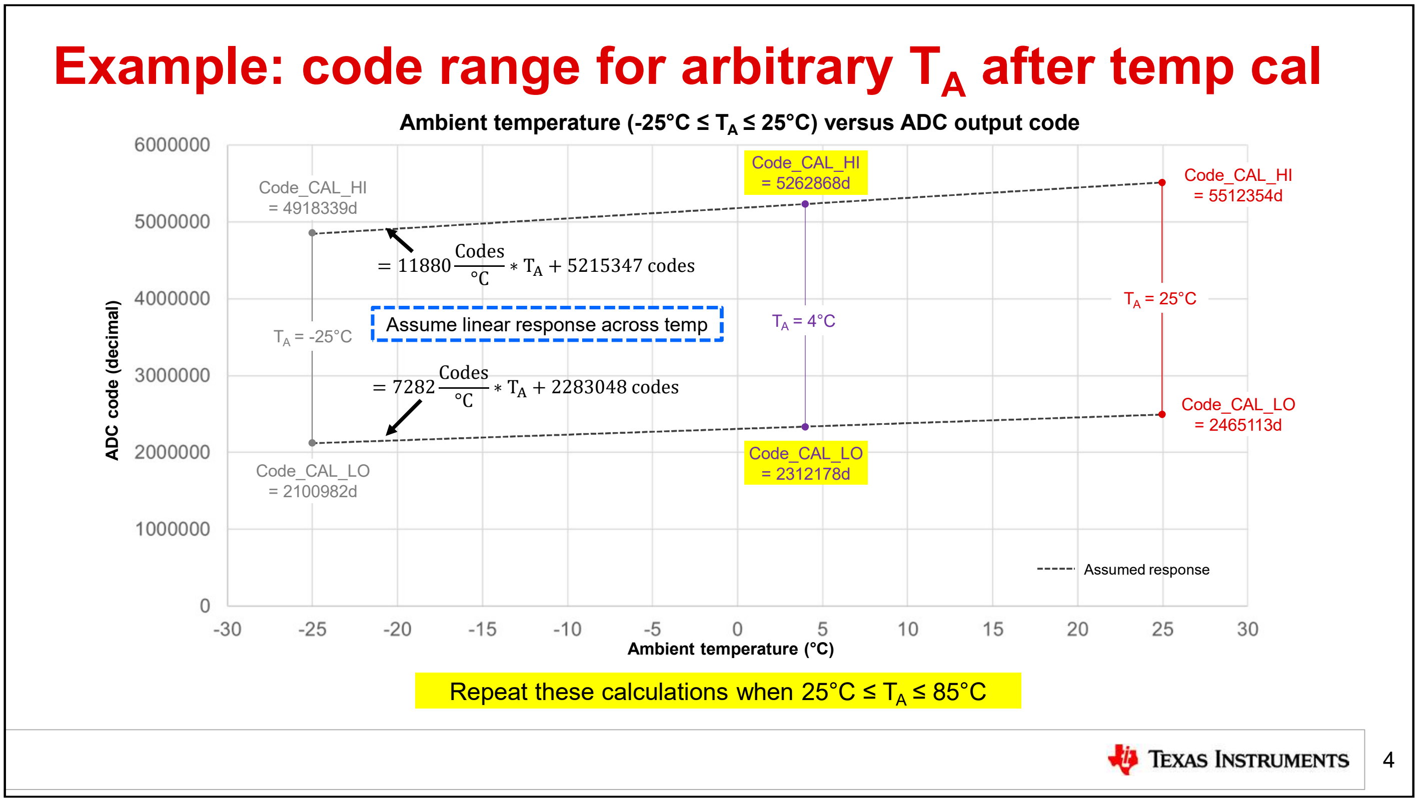


As an example, let's recall the Pt100 temperature versus resistance curve used throughout this module series. This is shown on the left. As stated previously, only two calibration resistors are needed as long as we just need to calibrate this specific RTD type. To calibrate, first perform an initial error calibration at the initial error temperature, typically 25 degrees Celsius. This was described in the previous Precision Labs module, and is shown for R_CAL_HI in the red box in the system on the top right

Then, expose the measurement system to the desired calibration temperatures using a controlled chamber or bath. Example parameters introduced in the previous presentation used a temperature range of -25 degrees Celsius to 85 degrees Celsius, so we will also calibrate at these two temperatures. However, more calibration points can be used, which improves the overall calibration results and can be useful for a nonlinear temperature response. The images in the top right show these additional two measurement points and resulting ADC output codes for R_CAL_HI. The images on the bottom right show how the process is repeated and the same three measurements are taken for R_CAL_LO

Ultimately, this example requires 6 different calibration values that can be stored in the controller. This information can be used to create two error profiles for the RTD measurement range. First, from -25 degrees Celsius to 25 degrees Celsius, and second, from 25 degrees Celsius to 85 degrees Celsius. Use a temperature sensor to measure the ambient temperature and determine which profile should be selected to correct the system error. Many ADCs integrate a temperature sensor that can be used for this purpose, thereby simplifying the design of the measurement system

Moreover, recall that this calibration profile is specific to the RTD curve. If the system needs to measure Pt1000 and Copper 50 RTDs in addition to the Pt100 shown here, it would be necessary to repeat this entire process for each RTD type. Now let's analyze how to use this information to calibrate out over-temperature error



First, let's assume we use the ADC's integrated temperature sensor to determine that the ambient temperature is 4 degrees Celsius. This value is shown in purple in the temperature versus ADC code plot shown on this slide. Since 4 degrees Celsius falls between the calibrated ambient temperatures of -25 degrees Celsius and 25 degrees Celsius from the previous slide, we need the calibrated ADC codes for these two temperatures. These are shown on the plot in gray and red, respectively. Note that the values shown on the plot have been arbitrarily chosen for this example, and do not necessarily correlate to any real system. On the contrary, these values would be measured and output by the ADC in a real system

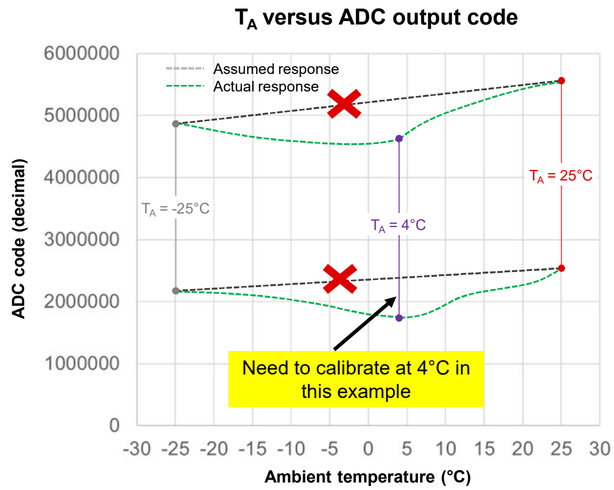
Next, using the assumption that the transfer function has a linear relationship with respect to temperature, calculate the equation for the line connecting Code_CAL_HI and Code_CAL_LO for each calibrated temperature as shown

Finally, use these equations to calculate the transfer function's code range at any ambient temperature between the calibrated values. Using the values provided, Code_CAL_HI and Code_CAL_LO at 4 degrees Celsius are shown on the plot in purple. Note that this process would need to be repeated for any additional sets of adjacent calibration codes, which would be 25 and 85 degrees Celsius in this example

The next slide discusses some challenges using this calibration method

Temperature calibration challenges

- Requires high-accuracy ambient temp measurement (T_A) for interpolation
- Minimal temperature gradient allowed → all devices exposed to same T_A
- Linear approximation only valid if the transfer function across T_A is actually linear
- Nonlinear behavior can require multiple calibration points to accurately map the transfer function across T_A



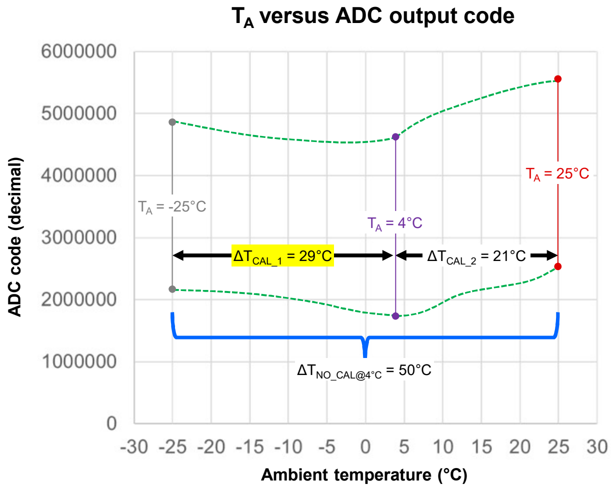
One important challenge with this temperature calibration process is that the ambient temperature must be known to be able to use the linearization equations introduced on the previous slide. This requires some method to accurately determine the system temperature, such as a discrete temperature sensor. This can increase the cost, power consumption, and complexity of the system

A second challenge involves ensuring that the entire system is subjected to the same temperature. In some cases, specific components can dissipate more power than others, causing temperature gradients across the PCB. As a result, different parts of the board can be at different temperatures, which can impact the accuracy of the calculated ADC code range

The most important challenge with this calibration method is that it relies entirely on the assumption that the error across temperature is linear. This was shown on the previous slide. However, it is possible that the error between the calibration points is nonlinear. For example, if the system actually had a response given by the green dotted lines, a linear approximation between -25 degrees Celsius and 25 degrees Celsius would not allow accurate determination of the system behavior at 4 degrees Celsius. Under these circumstances, it is necessary to calibrate at additional temperatures to accurately map the transfer function across ambient temperature. Since it is impossible to know the exact behavior of the system over temperature, choosing multiple, equally-spaced calibration points and limiting the ambient temperature range can help improve the calibrated results and reduce the temperature error

Estimating the potential reduction in temperature error by calibration is explored in more detail on the next slide

Calculating error after temperature calibration



- Maximum error can theoretically be anywhere between the calibration points
- Assume the error can only be reduced by the maximum temperature difference between adjacent calibration points
- Calculate reduced drift using drift error equation → Drift Error = Temp Drift · ΔT

$$\text{Drift}_{\text{NO\_CAL@4°C}} = 5\,\frac{\text{ppm}}{\text{°C}} \cdot 50\text{°C} = 250\text{ ppm}$$

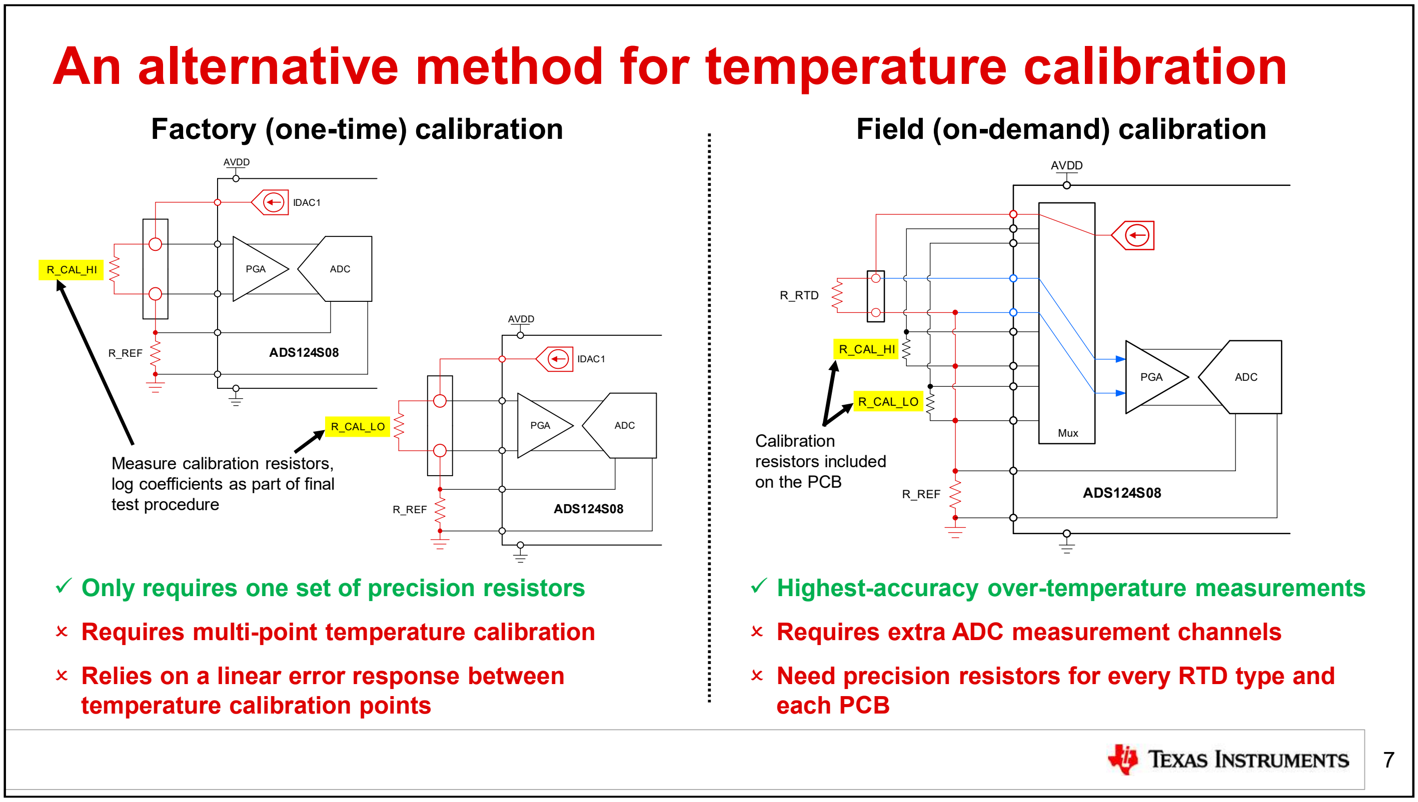
$$\text{Drift}_{\text{CAL@4°C}} = 5\,\frac{\text{ppm}}{\text{°C}} \cdot 29\text{°C} = 145\text{ ppm}$$

Reduces drift by up to 42% in this example

This plot was introduced on the previous slide, and shows how multiple calibration points can be required for systems with nonlinear behavior over temperature. Let’s make some observations about the behavior of temperature error so we can estimate how much the calibration process reduces it

First, the maximum drift error can theoretically occur anywhere between the calibration points because temperature error is not necessarily linear. This is presented in detail in the Precision Labs module on error sources in RTD measurement systems. Therefore, assume that the error can only be reduced by the maximum ambient temperature difference between adjacent calibration points. Assuming this example system is calibrated at -25, 4, and 25 degrees Celsius, the maximum ambient temperature difference is delta T_CAL_1, or 29 degrees Celsius. The reduced drift error can then be calculated using the equation shown on the right, which is just the temperature drift multiplied by the maximum change in ambient temperature. As an example, assume that the temperature drift is 5 ppm per degrees Celsius and that calibration is only performed at -25 degrees Celsius and 25 degrees Celsius. This is indicated by the blue bracket in the plot on the left. In this case, the maximum ambient temperature delta is 50 degrees Celsius and the drift error is equal to 250 ppm

Comparatively, the calibration at 4 degrees Celsius reduces the maximum ambient temperature delta to 29 degrees Celsius, which can reduce the calibrated temperature error to 145 ppm. As a result, the additional calibration at 4 degrees Celsius could theoretically reduce the temperature error by 42% in this example. As mentioned on the previous slide, choosing multiple, equally-spaced calibration points and limiting the ambient temperature range can help improve the calibrated results and reduce the temperature error. The next slide introduces an alternative calibration method that avoids some of the challenges presented in the last few slides



The last few slides presented a method that performs calibration over temperature for an RTD measurement system. As shown on the left, this method uses two high-accuracy resistors to correlate the ADC's transfer function to the relevant portion of the RTD resistance to temperature curve. These precision resistors are individually applied to each board at the factory to calibrate the system. The benefit of this approach is that it only requires one set of precision resistors no matter how many systems are produced

The challenge with this approach, as discussed previously, is that each system needs to be subjected to all of the different calibration temperatures. It can be time consuming to measure multiple calibration points, as well as expensive to generate different high-accuracy temperatures using a thermal bath or oven. Additionally, the error between calibration points must be linear for the interpolation process to work. Otherwise, the error cannot be calibrated out using this method

To eliminate some of these errors, it is possible to design a system similar to the image on the right. The main difference with this system is that the calibration resistors are now included as part of the RTD measurement board, as opposed to being applied externally at the factory

This enables on-demand calibration at any temperature using the same initial error calibration procedure described in the previous presentation. This method therefore does not require multi-point temperature calibration, does not rely on linear behavior between calibration points, and does not involve the external generation of high-accuracy ambient temperatures using precision equipment. Instead, run the calibration procedure at any time to re-calibrate the system to the current ambient temperature, whatever that may be.

The challenge with the on-demand calibration method is that it requires dedicated ADC channels to measure the calibration resistors, as well as high-precision calibration resistors installed on each PCB. Moreover, since the precision calibration resistors only apply to one specific RTD type and temperature range, this method can be difficult to implement for systems that have to measure different RTD types

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: Over-temperature error calibration

1. (T/F) More precision resistors are required for over-temperature calibration compared to initial error calibration.
   a. True
   b. False

2. (T/F) Temperature error will always be linear so calibrating at two different temperatures will eliminate drift errors between the two temperatures.
   a. True
   b. False

Question 1, true or false. More precision resistors are required for over-temperature calibration compared to initial error calibration

The correct answer is B, false. For a given RTD type and measurement range, only two precision resistors are required for either initial error or over-temperature error calibration

Question 2, true or false. Temperature error will always be linear so calibrating at two different temperatures will eliminate drift errors between the two temperatures

The correct answer is B, false. Temperature error can be nonlinear such that calibration can reduce error between two calibration points, but not necessarily eliminate it