Estimating total error in RTD measurement systems

TI Precision Labs – ADCs

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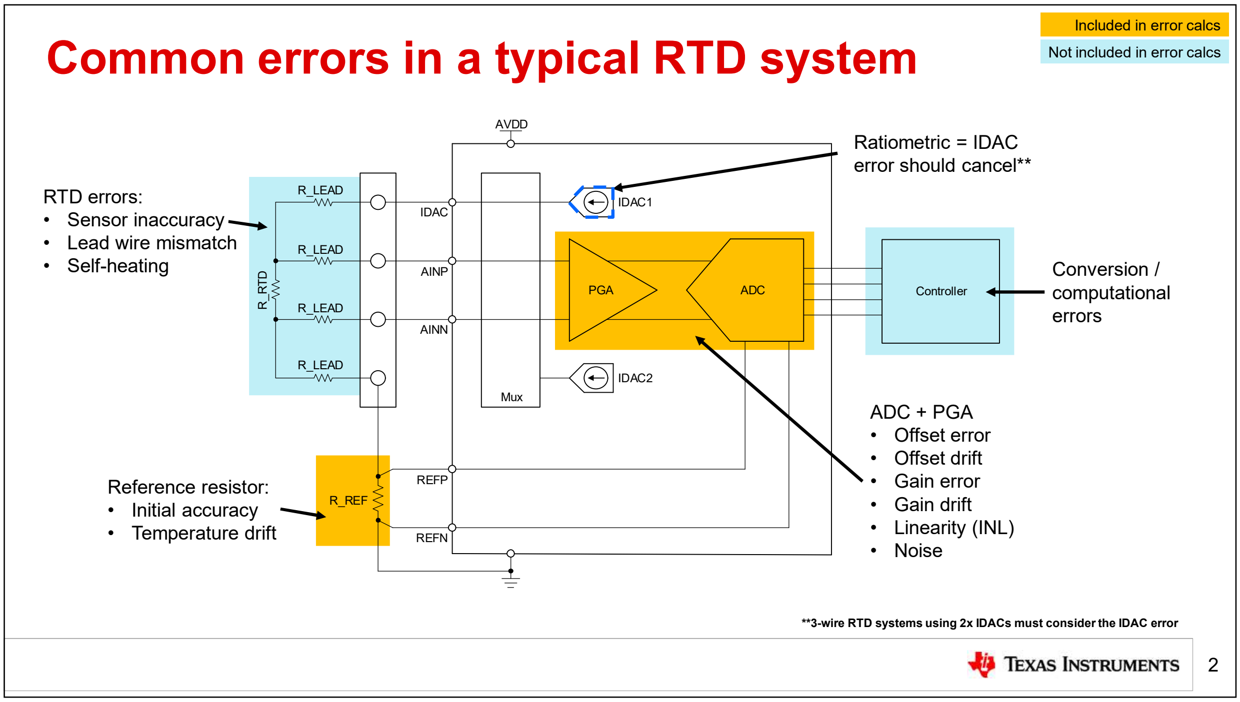
Hello, and welcome to the TI Precision Labs module discussing how to estimate total error in RTD measurement systems. This module provides a methodology for estimating initial error, temperature drift error, and total error, as well as describes how to convert errors to different units such as percent or degrees Celsius

To begin, let's revisit the common error sources found in RTD measurement systems that were introduced in a previous Precision Labs module



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. As discussed in a previous Precision Labs module, 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. While all of these errors are important, the total error calculations only include those errors that come from the signal chain. These errors include the ADC, PGA, and reference resistor errors, and are highlighted in orange. Errors coming from the sensor or from the conversion process are not included in the total error calculations. These types of errors are highlighted in blue

Now that we have identified which error sources are used in the total error calculations, let’s step through an example to learn how to estimate total error for a specific ADC

Example: how to estimate total error @ RTD_MAX

ADS124S08 & RTD system parameters

Parameter	Value	Units
Data rate	100	SPS
Filter type	Low-latency	
Gain	8	V/V
IDAC	1	mA
R_REF	1.6	kΩ
Temp range	-25 to +85	°C
RTD type	Pt100	
RTD range	-50 to +250	°C
	80.31 to 194.10	Ω
V_REF	1.6	V
FSR	0.4	V
VIN_MAX	0.1941	V

Error sources

Parameter	TYP	MAX	Units
ADC offset error	20 / gain	120 / gain	µV
ADC offset drift	15	200	nV/°C
ADC gain error	40	120	ppm
ADC gain drift	1	4	ppm/°C
ADC INL	2	15	ppm_{FSR}
ADC noise	0.45	2.9	µV
R_REF accuracy	0.1	0.5	%
R_REF drift	5	15	ppm/°C

$$V\_REF = IDAC * R\_REF = 1\ mA * 1.6\ k\Omega = 1.6\ V$$

$$FSR = 2 * \frac{V\_REF}{Gain} = 2 * \frac{1.6\ V}{8\ V/V} = 0.4\ V$$

$$VIN\_MAX = IDAC * RTD\_MAX = 1\ mA * 194.10\ \Omega = 0.1941\ V$$

For this example, we will select the ADS124S08 to measure the RTD. This ADC is a 24-bit, 13 channel delta-sigma ADC with an integrated amplifier and current sources that is commonly-used for RTD measurements.

Next, we need to identify our design specifications. The top-left table defines the system parameters assuming we use the ADS124S08 to measure a Pt100 RTD. The bottom-left table lists the errors that result from the selected system parameters. Before we can begin the error analysis however, we need to calculate three more system parameters

First, we need the reference voltage, V_REF. This value is the product of the IDAC current and the R_REF resistance, which is 1.6 V. One important note about this calculation, as well as subsequent calculations, is that we are using the ideal absolute IDAC current to keep the analysis simple. In practice, the measured voltage could be slightly higher or lower depending on actual IDAC current, but this is acceptable because we are trying to estimate the total error. We will use this convention throughout the rest of this error estimation

Next, we need the full scale range, or FSR. The specific FSR equation for the ADS124S08 is shown, and the calculated result is 0.4 V

Third, our estimated error is always calculated at a specific RTD resistance, which in this case is RTD_MAX. Later in this presentation we will extrapolate these calculations to plot the total error across the entire RTD resistance range. For now, we just need to calculate maximum input voltage to the ADC, V_IN_MAX. This value is the product of the ideal IDAC current and the maximum RTD resistance, which is 0.1941 V

Finally, we can add these values to the system parameters table as shown. Now we can begin estimating the total initial error

**Refer to the Precision Labs module on *Statistics Behind Error Analysis* for more information

Estimating initial error @ RTD_MAX (T_A = 25°C)

ADS124S08 & RTD system parameters

Parameter	Value	Units
Data rate	100	SPS
Filter type	Low-latency	
Gain	8	V/V
IDAC	1	mA
R_REF	1.6	kΩ
Temp range	-25 to +85	°C
RTD type	Pt100	
RTD range	-50 to +250	°C
	80.31 to 194.10	Ω
V_REF	1.6	V
FSR	0.4	V
VIN_MAX	0.1941	V

Error sources

Parameter	TYP**	MAX	Units
ADC offset error	20 / gain	120 / gain	µV
ADC offset drift	15	200	nV/°C
ADC gain error	40	120	ppm
ADC gain drift	1	4	ppm/°C
ADC INL	2	15	ppm_{FSR}
ADC noise	0.45	2.9	µV
R_REF accuracy	0.1	0.5	%
R_REF drift	5	15	ppm/°C

$$\text{Offset error} = \frac{20\ \mu V}{\text{Gain}} = 2.5\ \mu\text{V}$$

$$\text{Gain error} = 40\ \text{ppm} * \text{VIN\_MAX} = 7.76\ \mu\text{V}$$

$$\text{INL} = 2\ \text{ppm} * \text{FSR} = 0.8\ \mu\text{V}$$

$$\text{Noise} = 0.45\ \mu\text{V}$$

$$\text{R\_REF accuracy} = 0.1\% * \text{VIN\_MAX} = 194.10\ \mu\text{V}$$

Dominant error source

To estimate the initial error, let's calculate each error source individually and convert to microvolts. Where applicable, relative errors will be referenced to the maximum input voltage, VIN_MAX. Moreover, the initial error is specified at an ambient temperature of 25 degrees Celsius. Also note that for this example we will use typical errors because these represent the most statistically likely set of conditions. Refer to the Precision Labs module on statistics behind error analysis for more information about the difference between typical and maximum errors

Typical offset error is specified in microvolts and is given by the equation 20 divided gain, or 2.5 µV for this example

Typical gain error is specified as 40 ppm. Since gain error varies with input voltage, we need to multiply the gain error by V_IN_MAX. The typical gain error is 7.76 µV for this example

Typical INL is specified as 2 ppm of FSR. Since INL is an absolute error similar to offset, we just need to multiply the INL error in ppm by the FSR. The typical INL is 0.8 µV for this example

The ADC noise at the system settings in this example is 0.45 µV

Finally, the typical R_REF accuracy is 0.1%. Similar to gain error, we can convert this to ppm and multiply by V_IN_MAX to determine that the typical R_REF accuracy is 194.1 µV for this example

Reviewing all of these different error sources, it is clear that the R_REF accuracy is the dominant initial error

Now let's discuss how to calculate total initial error

Total initial error (T_A = 25°C)

ADS124S08 & R_REF error summary @ RTD_MAX

Error type	Parameter	Value	Units
Initial errors	ADC offset error	2.5	µV
	ADC gain error	7.76	
	ADC INL	0.8	
	ADC noise	0.45	
	R_REF accuracy	194.10	

- Assume errors are uncorrelated
- Use root sum-of-squares (RSS) method:

$$\sqrt{x_n^2 + x_{n-1}^2 + x_{n-2}^2 \dots + x_1^2}$$

- Similar procedure for typical or maximum errors (typical errors shown)

$$\text{Initial error @ RTD\_MAX} = \sqrt{2.5\ \mu V^2 + 7.76\ \mu V^2 + 0.8\ \mu V^2 + 0.45\ \mu V^2 + 194.10\ \mu V^2} = 194.27\ \mu V$$

The table on the left summarizes the errors calculated in the previous slides. Use the following information to calculate total initial error

First, we assume the errors are uncorrelated. This is generally true for the types of errors presented in this module. Operating under this assumption allows us to use the root sum of squares method to calculate total error. The general form of this equation is shown on the right. We can use this formula to calculate a total initial error of 194.27 microvolts at the maximum RTD resistance

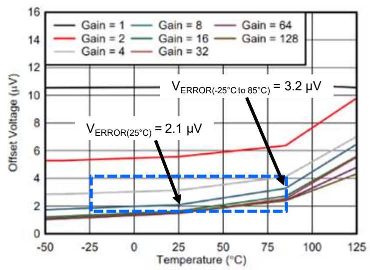
Finally, a similar procedure can be used for typical or maximum errors. As noted previously, typical errors are used in this example because this represents the most statistically likely set of conditions

Let's now discuss how to calculate over-temperature errors

Two methods to calculate temperature drift error

Datasheet error plots

ADS124S08 offset drift



- Determine values directly from the plot
- Not available in all datasheets
- Use largest value in error calculations

$$\text{Error}_{\text{Drift}} = \text{Error}_{\text{Total}} - \text{Error}_{\text{Initial}} = 3.2\ \mu\text{V} - 2.1\ \mu\text{V}$$

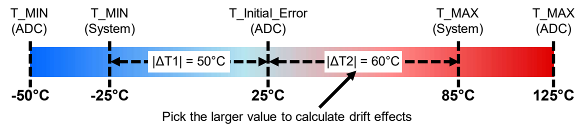
$$\text{Error}_{\text{Drift}} = 1.1\ \mu\text{V}$$

Electrical characteristics table

- Linear approx over/under estimates error
- Available in all datasheets = most common method

ADS124S08 offset specs (G = 8)

Condition	MIN	TYP	MAX	Unit
Offset error (T_A = 25°C)	-15	2.5	15	µV
Offset drift (T_A = -50°C to +125°C)	-0.2	0.015	0.2	µV/°C



$$\text{Error}_{\text{Drift}} = \text{Offset}_{\text{Drift}} * \Delta T = 0.015\ \mu\text{V}/°\text{C} * 60°\text{C}$$

$$\text{Error}_{\text{Drift}} = 0.9\ \mu\text{V}$$

A previous Precision Labs module discussing error sources in RTD measurement systems introduced two methods to calculate temperature drift error. The first method uses the datasheet error plots to directly determine the error magnitude at any given temperature. The example plot on the left shows the ADS124S08 offset over the specified temperature range of -50 degrees Celsius to 125 degrees Celsius, where the initial error is given as 2.1 microvolts at a gain of 8. One of the challenges with this method is that these types of plots are not available in all datasheets, requiring use of alternative methods to estimate temperature error

When these plots are available, it is possible to directly determine the drift error within the system temperature range. The blue box highlights the temperature range used in this example, which is -25 degrees Celsius to 85 degrees Celsius. The largest offset error within this range is 3.2 microvolts. We can then use the equations in the bottom left to back-calculate the error due to temperature drift, which is 1.1 microvolts. Differentiating between initial and drift errors allows the user to understand how much error each source contributes. This information can then be used to determine if calibration is necessary to achieve the system accuracy targets. Calibration is discussed in more detail in a subsequent Precision Labs module

The second method uses the specifications given in the electrical characteristics table to determine temperature errors. Example offset and offset drift specifications at a gain of 8 are given in the table on the right. One challenge with this method is that the datasheet drift specifications represent a linear approximation of the error over temperature. If the actual error response is nonlinear, the electrical characteristics method can under- or overestimate the error. Review the Precision Labs presentation on error sources to learn more. The benefit of the second method is that these error specifications are available in all datasheets, allowing a fair comparison between different devices or systems. Therefore, estimating temperature error using the electrical specifications is the most common method. We will use this method throughout the rest of this presentation

To calculate temperature errors using the second method, we first need to identify the error calculation temperature range using the temperature gradient on the right. This plot includes the specified temperature range of the ADS124S08, the system measurement range, and the initial error temperature. To identify the error calculation temperature range, subtract T_initial_error from T_MIN system and T_MAX system, resulting in delta T1 and delta T2, respectively. Taking the absolute value of these numbers and then choosing the larger of the two yields the error calculation temperature range. Applying the resultant values to the equation at the bottom right yields a calculated drift error of 0.9 microvolts.

Now let’s apply this information to calculate all of the drift errors in this example

Estimating error over temperature (typical)

ADS124S08 & RTD system parameters

Parameter	Value	Units
Data rate	100	SPS
Filter type	Low-latency	
Gain	8	V/V
IDAC	1	mA
R_REF	1.6	kΩ
Temp range	-25 to +85	°C
RTD type	Pt100	
RTD range	-50 to +250	°C
	80.31 to 194.10	Ω
V_REF	1.6	V
FSR	0.4	V
VIN_MAX	0.1941	V

Error sources

Parameter	TYP	MAX	Units
ADC offset error	20 / gain	120 / gain	µV
ADC offset drift	15	200	nV/°C
ADC gain error	40	120	ppm
ADC gain drift	1	4	ppm/°C
ADC INL	2	15	ppm_{FSR}
ADC noise	0.45	2.9	µV
R_REF accuracy	0.1	0.5	%
R_REF drift	5	15	ppm/°C

Calculate ΔT:

$$|\Delta Tx| = |T_{System\_x} - T_{Initial}|$$

$$|\Delta T1| = |-25°C - 25°C| = 50°C$$

$$|\Delta T2| = |85°C - 25°C| = 60°C$$

$$\Delta T2 > \Delta T1 \rightarrow \Delta T = 60°C$$

Calculate over-temperature errors:

$$\text{Offset drift} = 15\frac{\text{nV}}{°\text{C}} * 60°\text{C} = 0.9\ \mu\text{V}$$

$$\text{Gain drift} = 1\frac{\text{ppm}}{°\text{C}} * 60°\text{C} * \text{VIN\_MAX} = 11.65\ \mu\text{V}$$

$$\text{R\_REF drift} = 5\frac{\text{ppm}}{°\text{C}} * 60°\text{C} * \text{VIN\_MAX} = 58.23\ \mu\text{V}$$

Dominant error source

On the previous slide we calculated the maximum temperature change, delta T, for the system parameters included in the table on the top left. These calculations are shown on the top right, where delta T is 60 degrees Celsius. Now let's calculate the over temperature errors

Typical offset drift is specified as 15 nanovolts per degree Celsius. Multiplying this value by delta T and converting to microvolts yields a typical offset drift value of 0.9 microvolts for this example.

Typical gain drift is specified as 1 ppm per degree Celsius. Multiplying this value by delta T and V_IN_MAX yields a typical gain drift value of 11.65 microvolts for this example

Typical R_REF drift is specified as 5 ppm per degree Celsius. Multiplying this value by delta T and V_IN_MAX yields a typical R_REF drift value of 58.23 microvolts for this example

Reviewing all of these different error sources, it is clear that the R_REF drift dominates the total system error across temperature

The next slide summarizes these results

Total error (initial + temperature)

ADS124S08 & R_REF error summary @ RTD_MAX

Error type	Parameter	Value	Units
Initial errors	ADC offset error	2.5	µV
	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	
	R_REF drift	58.23	

Initial error @ RTD_MAX:

$$= \sqrt{2.5\ \mu V^2 + 7.76\ \mu V^2 + 0.8\ \mu V^2 + 0.45\ \mu V^2 + 194.10\ \mu V^2}$$

$$= 194.27\ \mu V$$

Total error (initial + temp) @ RTD_MAX:

$$= \sqrt{\begin{pmatrix} 2.5\ \mu V^2 + 7.76\ \mu V^2 + 0.8\ \mu V^2 + 0.45\ \mu V^2 \\ + 194.10\ \mu V^2 + 0.9\ \mu V^2 + 11.65\ \mu V^2 + 58.23\ \mu V^2 \end{pmatrix}}$$

$$= 203.15\ \mu V$$

R_REF accuracy and drift dominate the overall error budget – **NOT** the ADC!

→ Choose high accuracy, low-drift R_REF for best performance e.g. 0.1%, 5 ppm/°C

Before calculating total error, let's recall the initial error values and the total initial error derived previously in this presentation. The initial error values are highlighted in purple in the table on the left, while the total initial error is shown in the equation on the top right.

Next, let's include the temperature errors calculated on the previous slide. These values are highlighted in blue in the table on the left. We calculate the total error at the maximum RTD resistance using the same root sum of squares formula that was used to calculate the total initial error. This is shown on the bottom right as 203.15 microvolts

The key takeaway from this analysis is that the R_REF errors dominate the overall error budget in this example, not the ADC. Therefore, it is imperative to choose a high accuracy, low drift R_REF for best system performance. A 0.1% accurate component with a 5 ppm per degree Celsius drift specification is recommended

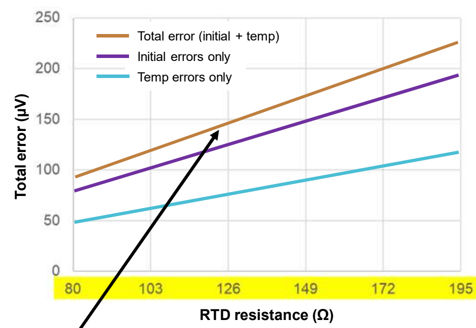
Next, let's extrapolate this analysis to include the entire RTD resistance range, not just the maximum value

Total error over entire input range

ADS124S08 & RTD system parameters

Parameter	Value	Units
Data rate	100	SPS
Filter type	Low-latency	
Gain	8	V/V
IDAC	1	mA
R_REF	1.6	kΩ
Temp range	-25 to +85	°C
RTD type	Pt100	
RTD range	-50 to +250	°C
	80.31 to 194.10	Ω
V_REF	1.6	V
FSR	0.4	V
VIN range	80.31 to 194.10	mV

Total error (µV) across RTD resistance



Total error across input voltage looks like gain error because R_REF error dominates

On the left are the ADC and system settings we have been using throughout this example. In the last slide we calculated the initial error, temperature error, and total error at the maximum RTD resistance of 194.1 ohms. Let's perform that same analysis across the entire input range

On the right is a plot of the error in microvolts with respect to RTD resistance. The blue plot represents the total temperature drift error only, the purple plot represents the total initial error only, and the brown plot shows the total combined initial and over-temperature errors

Interestingly, all of these plots just look like a typical gain error plot. However, this makes sense because the R_REF error dominates the overall error budget both initially and over temperature. Therefore, the resulting total error across RTD resistance can just be approximated as the R_REF error

That concludes the error estimation portion of this presentation. The final topic discussed on the next slide introduces how to convert error in microvolts to different units

Converting error (µV) to error (%) and error (°C)

$$\text{Error (\%)} = \frac{\text{Error (V)}}{\text{Input Voltage (V)}} * 100$$

$$\text{Error (\%)} = \frac{194.27\ \mu\text{V} * 10^{-6}}{0.1941\ \text{V}} * 100$$

$$\text{Error (\%)} = 0.100\%$$

$$\text{Error (°C)} = \frac{\text{Error } (\mu\text{V})}{\text{Sensitivity}\left(\frac{\Omega}{°\text{C}}\right) * \text{IDAC } (\mu\text{A})}$$

$$\text{Sensitivity}\left(\frac{\Omega}{°\text{C}}\right) = \left|\frac{RTD_{T2}\ (\Omega) - RTD_{T1}(\Omega)}{\text{T2 (°C)} - \text{T1 (°C)}}\right|$$

Calculating Pt100 sensitivity

Pt100 temperature (°C)	Pt100 resistance (Ω)	Sensitivity (ΔΩ/°C)
247	193.010	0.36
248	193.370	0.36
249	193.740	0.37
250	194.100	0.36

$$\text{Error (°C)} = \frac{194.27\ \mu V}{0.36\frac{\Omega}{°\text{C}} * 1000\ \mu\text{A}}$$

$$\text{Error (°C)} = 0.540°\text{C}$$

Throughout this presentation we've talked about error using different units, including microvolts and percent. Now let's discuss how to convert between these units. We'll also identify how to calculate error in degrees Celsius, which is a common requirement in RTD measurement systems

First, the formula on the top left calculates the error in percent by taking the error in volts and dividing by the input voltage, then multiplying by 100. Note that this formula can be reversed if the error is given in percent and needs to be converted to back to a voltage. As an example, we previously calculated a total initial error of 194.27 µV for an input voltage of 0.1941 V. This is equivalent to a 0.1% error, which is highlighted in yellow in the top right

Comparatively, the equation for converting error in microvolts to error in degrees Celsius is shown on the bottom left. This equation divides the error in microvolts by the product of the ideal IDAC current in microamps and the RTD sensitivity to generate the error in degrees Celsius.

Since sensitivity is a new parameter, let's discuss it in more detail. The equation for sensitivity is also shown on the bottom left. Sensitivity is the absolute difference between two RTD resistances divided by the difference in their corresponding temperatures. These RTD resistances and temperatures are determined using polynomial equations or look up tables, as described in a previous Precision Labs module

For example, several values for a Pt100 RTD are given in the table on the right. These values are taken from a standard look-up table that has a resolution of 1 degree Celsius. Inputting two sets of adjacent values into the sensitivity equation produces the sensitivity numbers in the last column. Note that the values do not need to be adjacent to calculate the sensitivity. Also note that a Pt100 generally becomes more sensitive as temperature increases

Applying the average sensitivity value from the table to the error equation yields an error of 0.54 degrees Celsius. If this result is unacceptably high, calibration is necessary. Please review a subsequent Precision Labs module on calibration techniques to learn more

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.

Questions: Estimating total error in RTD

1. Why is the square root sum of the squares (RSS) used to add error sources?
   a. This represents a worst case method of combining errors
   b. The errors are random and uncorrelated so this is a good statistical method to calculate total error
   c. This approach simplifies the error computation

2. Calculating drift error using the data sheet drift specification assumes that the drift is linear over temperature. Is this assumption always true?
   a. Yes
   b. No

Question 1. Why is the square root sum of the squares used to add error sources?

The correct answer is B, the errors are random and uncorrelated so this is a good statistical method to calculate total error

Question 2. Calculating drift error using the data sheet drift specification assumes that the drift is linear over temperature. Is this assumption always true?

The correct answer is B, no. Drift error cannot assumed to be linear over temperature