

Example Temperature Measurement Applications Using the ADS1247 and ADS1248

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High-Performance Analog

ABSTRACT

This document discusses the use of the [ADS1247](#) and [ADS1248](#) precision analog-to-digital converters (ADCs) together with a resistive temperature device (RTD) and thermocouple to measure temperature. Included are detailed examples of the most common configurations of a two-wire RTD, a three-wire RTD, a four-wire RTD, and a thermocouple with cold junction compensation. This document provides sufficient information to enable several alternate configurations to be implemented.

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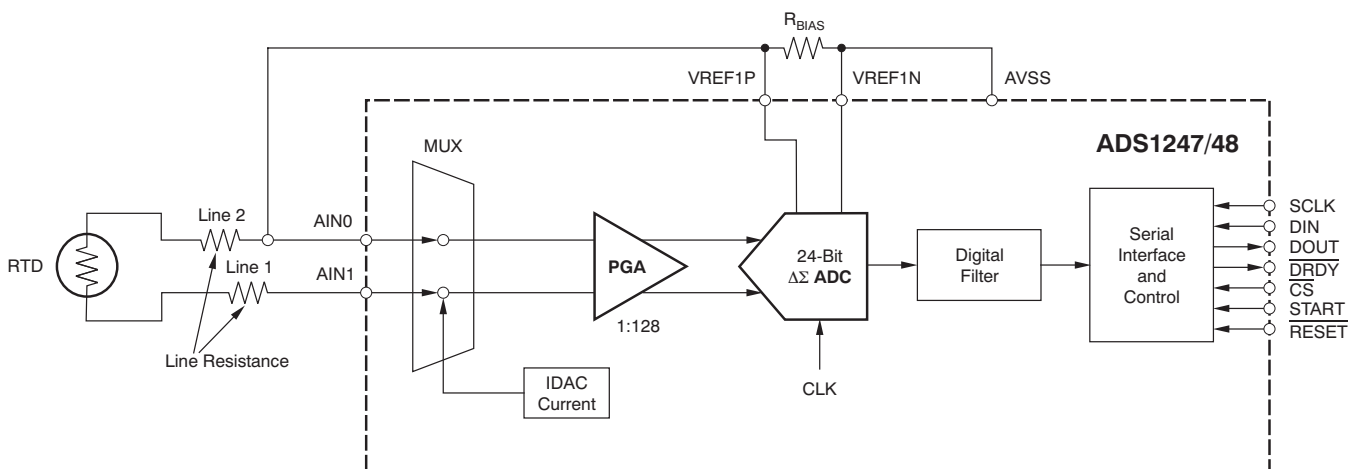
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1 Introduction

Whenever measurement of various industrial sensors are required, accuracy of measurement can be significantly improved by characterizing the sensor performance over the range of temperatures in which it is expected to operate. This principle requires an accurate sensor temperature measurement. This application report is intended for designers who want to use TI's ADS1247 and ADS1248 devices to measure temperatures with RTD and thermocouple temperature sensors. By using a high-resolution, 24-bit ADC such as the ADS1247 or ADS1248, accurate temperature measurement is greatly simplified because of the device architecture, integrated input multiplexer, and current-source digital-to-analog converters (DACs). This document provides example temperature measurement configurations, with and without cold temperature compensation, for optimal accuracy.

2 Two-Wire RTD Application

Figure 1 shows an example of a two-wire resistance temperature detector (RTD) application using either the ADS1247 or ADS1248 device.



NOTE: R_{BIAS} must be as close to the ADC as possible.

Figure 1. Two-Wire RTD Application Example

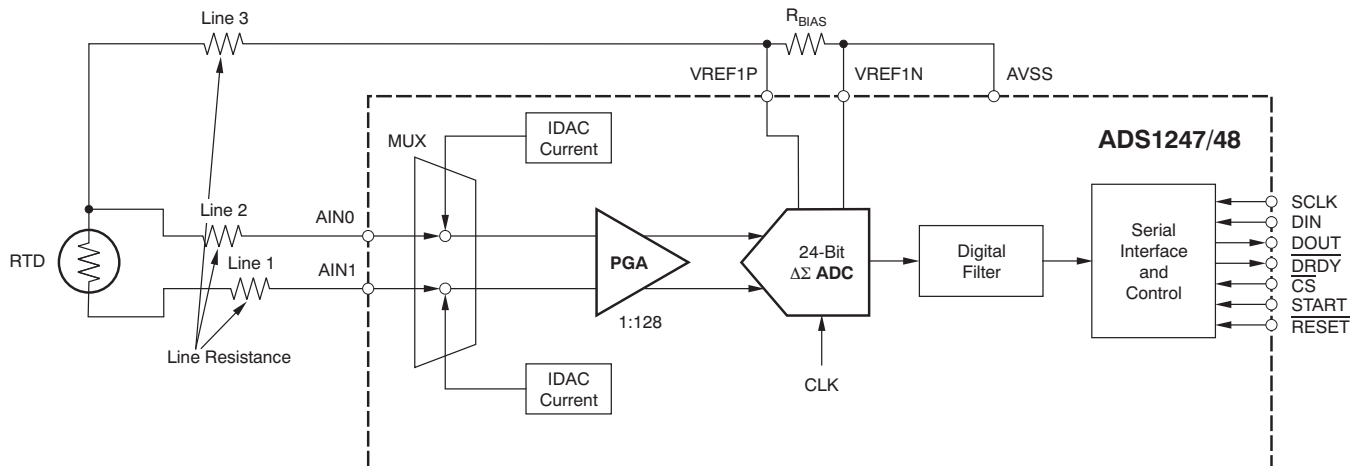
The two-wire RTD connection is the simplest method for a remote connection. Figure 1 presents one such possible RTD application. The ADS1247 and ADS1248 current sources are connected to one of the terminals of the RTD lines by setting the appropriate bits in the IDAC1 register. The value of the current can be chosen by setting the ISELT bits in the IDAC0 register. The internal band-gap reference must be turned on by setting the VREFCON bits in the MUX2 register. The internal reference must also be turned on for the IDAC to function, even though the reference to the device is supplied externally. The voltage developed across the RTD is measured by connecting the RTD through the PGA to the ADC.

The voltage measured across the RTD is proportional to temperature (determined by the characteristics of the RTD). The R_{BIAS} value is selected according to the IDAC current source setting. The reference to the device is also derived from the IDAC. The appropriate external reference must be selected by setting the VREFSELT bits in the MUX2 register. R_{BIAS} determines the reference voltage to the ADC as well as the input common mode of the PGA. Both the reference as well as the input to the device are functions of the IDAC current in this topology. This ratiometric approach ensures a greater effective number of bits (ENOB) because the noise in the IDAC reflects in the reference as well as in the input, and thus tends to cancel off.

The effect of the IDAC current temperature drift is also cancelled out in this ratiometric topology. However, a major limitation of the two-wire method is that the voltage drop across the line resistances adds up to the voltage drop across the RTD; therefore, the sensor cannot be very far away from the measurement setup. For best performance with the ratiometric approach, do not add filtering capacitance to either the signal path or the reference path. The IDAC current mismatch drift in this topology also does not matter, because there is only one current path.

3 Three-Wire RTD Application

Figure 2 shows an example of a three-wire RTD application using either the ADS1247 or ADS1248.



NOTE: R_{BIAS} must be as close to the ADC as possible.

Figure 2. Three-Wire RTD Application Example

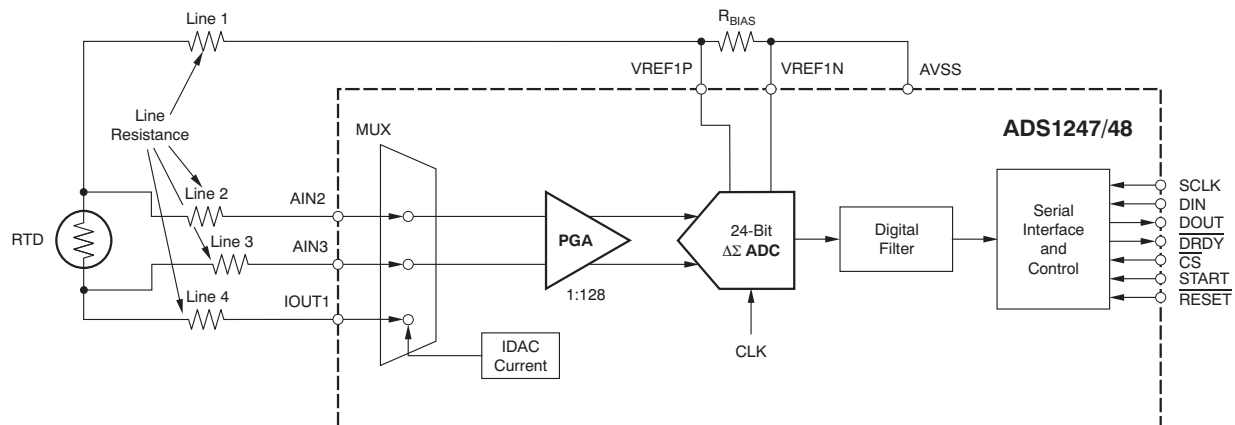
For optimum performance in three-wire RTD applications, the two ADS1247 and ADS1248 current sources have been extremely closely matched. In the possible 3-wire example given in Figure 2, two selectable current sources are used to provide symmetry and compensate for mismatch through the RTD wiring. The ADS1247 and ADS1248 current sources are connected to the two channels configured with the two RTD terminals by setting the appropriate bits in the IDAC1 register. The current value can be chosen by setting the ISELT bits in the IDAC0 register. The internal band-gap reference must be turned on by setting the VREFCON bits in the MUX2 register. The internal reference must be turned on for the IDAC to function, even though an external reference channel is used. The voltage measured across the RTD is proportional to temperature (determined by the characteristics of the RTD).

The R_{BIAS} value is selected according to the IDAC current source setting. R_{BIAS} also determines the reference voltage to the ADC as well as the input common mode of the PGA. The reference and the input to the device are both functions of the IDAC current in this topology. The noise in the IDAC reflects in the reference and in the input, and thus tends to cancel off. This ratiometric approach also ensures a greater ENOB. Additionally, the effect of the IDAC current temperature drift is cancelled out in this approach.

We are only concerned with the IDAC current mismatch drift. The IDAC current mismatch drift contributes to the offset drift of the measurement. The sensitivity of the offset drift to the IDAC current mismatch is directly proportional to the line resistance. For best performance with the ratiometric approach, do not add filtering capacitance to either the signal path or the reference path. The limitation of the two-wire method (see Section 2) has been avoided in this topology, and therefore the sensor can be very far away from the measurement setup as long as noise coupling into the wire does not degrade overall noise performance. This setup applies less than half of the dynamic range of the ADC because the input to the ADC is never negative.

4 Four-Wire RTD Application

The four-wire RTD approach (illustrated in Figure 3) provides the highest level of accuracy because it isolates the excitation path of the RTD from the sensing path. The ADS1247 and ADS1248 current sources are connected to one of the RTD line terminals by setting the appropriate bits in the IDAC1 register. Line 4 of the RTD has been tied to the IOUT1 terminal of the device because Line 4 is not a sensing line, thus saving an input channel in the device for other sensors. The current value can be chosen by setting the ISELT bits in the IDAC0 register. The internal band-gap reference must be turned on by setting the VREFCON bits in the MUX2 register. The internal reference must be turned on for the IDAC to function, even though the reference to the device is supplied externally. The voltage developed across the RTD is measured by also connecting the RTD through the PGA to the ADC. The voltage measured across the RTD is proportional to temperature (determined by the characteristics of the RTD). The value of R_{BIAS} is selected according to the IDAC current source setting.



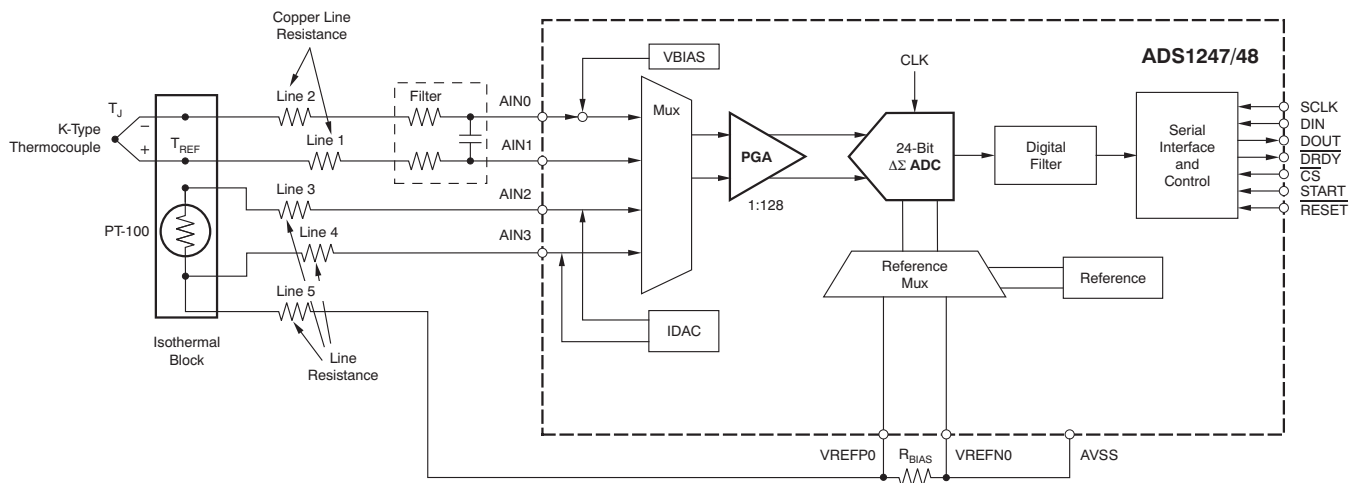
NOTE: R_{BIAS} must be as close to the ADC as possible.

Figure 3. Four-Wire RTD Application Example

The reference to the device is also derived from the IDAC. The appropriate external reference must be selected by setting the VREFSELT bits in the MUX2 register. R_{BIAS} determines the reference voltage to the ADC as well as the input common mode of the PGA. Both the reference and the input to the device are functions of the IDAC current in this topology. The noise in the IDAC reflects in the reference as well as in the input, and therefore tends to cancel out. The IDAC current drift does not matter because we follow the ratiometric topology. The IDAC current mismatch drift does not matter either, because there is only one current path. For best performance with the ratiometric approach, do not add filtering capacitance to either the signal path or the reference path. This setup, similar to that discussed in [Section 3](#), uses less than half of the dynamic range of the ADC; the input to the ADC is never negative.

5 Thermocouple Application with RTD-Based Cold Junction Compensation

A thermocouple, unlike the RTD, needs no excitation source and generates a potential difference across its terminals, which is proportional to the temperature ($T_J - T_{REF}$). The thermocouple consists of a two-metal junction that produces a voltage difference proportional to T_J , the junction temperature which must be measured. These two metals must be connected to the copper line; consequently, two more junctions are created. These two metal junctions must be placed at the same temperature, T_{REF} . Placing them at the same temperature creates a voltage proportional to T_{REF} , which is opposite that produced by the thermocouple junction. If the temperature T_{REF} is known, then T_J can be calculated by adding T_{REF} to it. But if T_{REF} cannot be forced to a known temperature, it can be measured with an RTD. A three-wire RTD method for junction temperature compensation is shown in [Figure 4](#).



NOTE: R_{BIAS} must be as close to the ADC as possible.

Figure 4. Thermocouple-Based Application Example

When measuring the temperature using the thermocouple approach, the output of the thermocouple must be biased. The ADS1247 and ADS1248 provides a bias voltage generator for this purpose. The bias voltage is equal to the mid-supply voltage [that is, $AVSS + (AVDD - AVSS) / 2$] and must be tied to one of the terminals of the thermocouple; see [Figure 4](#). The internal reference measures the voltage from the thermocouple. A filter may be used to suppress noise in the thermocouple voltage as a result of noise coupling to the lines. When measuring the temperature of the junction using the RTD, the external reference must be selected to obtain the optimal noise performance using the ratiometric approach; this technique is explained in detail in [Section 3](#).

6 Three-Wire RTD Measurement: Design Example

This section describes designing a circuit for measuring temperatures in the range of -200°C to $+850^{\circ}\text{C}$ using a three-wire PT-100 RTD and the ADS1247 (although this design applies to the ADS1248 as well). The two excitation current sources (IDACs) of the ADS1247 are ideally suited for implementing the three-wire RTD topology. A ratiometric configuration where the reference is derived from the IDAC currents improves performance. [Figure 5](#) shows the circuit topology for the ratiometric three-wire RTD measurement.

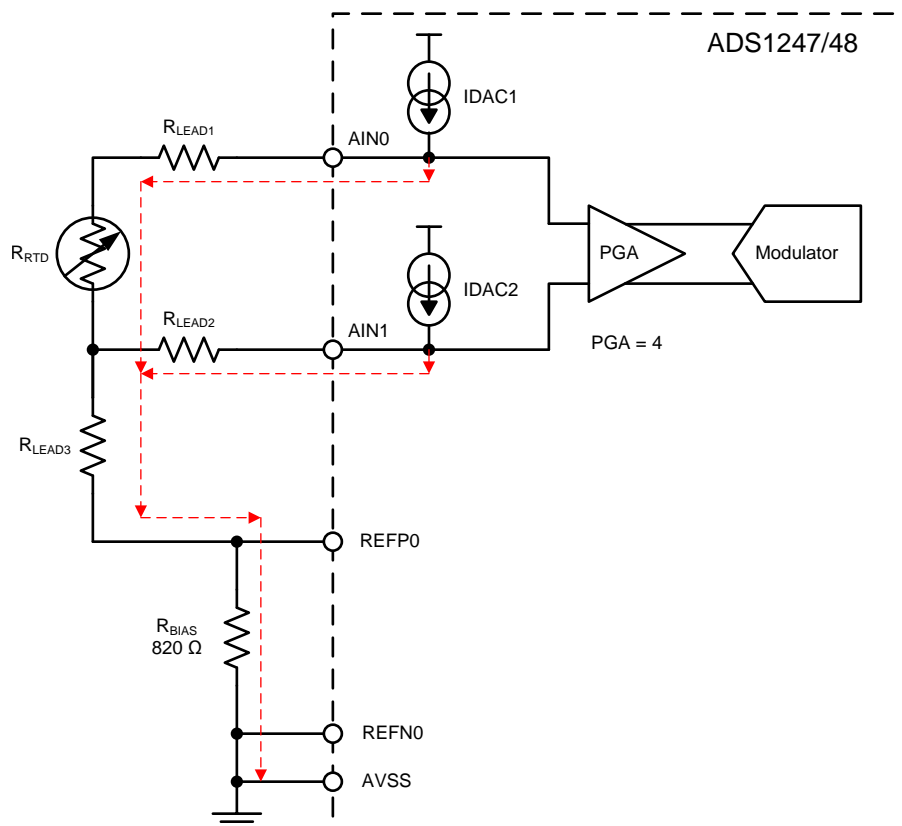


Figure 5. Three-Wire RTD Application Design Example

The matched excitation current sources integrated in the ADS1247 are used to implement lead-wire cancellation. IDAC1 provides excitation of the RTD element. IDAC2 has the same current setting as IDAC1, providing cancellation of lead-wire resistance by generating a voltage drop across lead-wire resistance R_{LEAD2} equal to the voltage drop across R_{LEAD1} . The voltage drops across the lead-wire resistances, R_{LEAD1} and R_{LEAD2} , cancel because the RTD is measured differentially at ADC pins AIN0 and AIN1. The ADC reference voltage (pins REFPO and REFNO) is derived from the voltage across R_{BIAS} with the currents from IDAC1 and IDAC2, providing ratiometric cancellation of current-source drift. R_{BIAS} also level shifts the RTD signal to within the ADC specified common-mode input range.

By calculating the voltages from the input and the reference, the output code is proportional to [Equation 1](#):

$$\text{Code} \propto (I_{IDAC1} \cdot (R_{RTD} + R_{LEAD1}) - (I_{IDAC2} \cdot R_{LEAD2})) / ((I_{IDAC1} + I_{IDAC2}) \cdot R_{BIAS}) \quad (1)$$

If the lead resistances and excitation currents match, such that $R_{LEAD1} = R_{LEAD2}$ and $I_{IDAC1} = I_{IDAC2}$, the lead wire voltages cancel out. Equation 1 reduces to the result in Equation 2, maintaining a ratiometric measurement.

$$\text{Code} \propto R_{RTD} / (2 \cdot R_{BIAS}) \quad (2)$$

R_{LEAD3} is not part of the measurement, because it is not in the input measurement path or in the reference measurement path. However, if filtering is used in the analog inputs, take care to avoid routing the excitation currents through the series filter resistors. The voltage from excitation currents reacting with series resistance creates error in the measurement. The excitation currents must be routed through separate IDAC outputs, to bypass the series resistance at the analog inputs.

Equation 1 and Equation 2 show that the two current sources must be matched to cancel the lead resistances of the RTD wires. If the current sources do not match, they may be swapped or chopped to reduce the mismatch error. With the first measurement, IDAC1 first drives the RTD and the first lead wire, while IDAC2 drives the second lead wire. Then the excitation current sources are swapped. With the second measurement, IDAC2 drives the RTD and the first lead wire, while IDAC1 drives the second lead wire. Taking measurements in both configurations and averaging the results reduces the error of mismatched current sources. The multiplexer in the ADS1247 is used to implement this chopping technique to remove the error between IDAC1 and IDAC2.

The PT-100 RTD measures temperatures between -200°C and $+850^{\circ}\text{C}$. The RTD resistance is defined by the Callendar-Van Dusen (CVD) equations and the temperature of the RTD is determined from the measured resistance. The PT100 RTD has an impedance of $100\ \Omega$ at 0°C and roughly $0.385\ \Omega$ of resistance change per 1°C in temperature change. The RTD resistance at -200°C is $18.590\ \Omega$ and the resistance at 850°C is $390.48\ \Omega$.

An IDAC current setting of $1\ \text{mA}$ and a reference resistor of $820\ \Omega$ are chosen to obtain the best possible temperature resolution while weighing several circuit considerations as follows.

The common-mode input voltage is set near mid-supply to keep the input within the common-mode input range of the PGA. The voltage across R_{BIAS} sets the input range. Equation 3 shows that the input voltage is just below mid-supply. For $AVDD = 3.3\ \text{V}$, the input voltage is near mid-supply.

$$V_{REF} = R_{BIAS} \cdot (I_{IDAC1} + I_{IDAC2}) = 820\ \Omega \cdot 2\ \text{mA} = 1.64\ \text{V} \quad (3)$$

The excitation current sources operate properly to a maximum IDAC compliance voltage. Above this compliance voltage, the current sources lose current regulation. In this example, the output voltage of the excitation current source is calculated from the sum of the voltages across the RTD and R_{BIAS} as shown in Equation 4.

$$V_{IDAC1\ \text{MAX}} = R_{RTD\ \text{MAX}} \cdot I_{IDAC1} + (R_{BIAS} \cdot (I_{IDAC1} + I_{IDAC2})) = 0.4\ \text{V} + 1.64\ \text{V} = 2.04\ \text{V} \quad (4)$$

Subtracting $2.04\ \text{V}$ from $3.3\ \text{V}$, the IDAC compliance voltage of $1.26\ \text{V}$ is sufficient for operation as shown in the Typical Characteristics figures in the ADS1247 datasheet.

The PGA in the ADS1247 amplifies the RTD signal to utilize the full-scale range of the ADC. Starting with the reference voltage, the ADC is able to measure a differential input signal of $\pm 1.64\ \text{V}$. The maximum allowable PGA gain setting is based on the reference voltage, the maximum RTD resistance, and the excitation current.

As mentioned previously, the maximum resistance of the RTD is seen at 850°C . This case provides the largest voltage measurement of the ADC. The RTD voltage when $R_{RTD@850^{\circ}\text{C}}$ is $390.48\ \Omega$ as shown in Equation 5.

$$V_{RTD\ \text{MAX}} = R_{RTD@850^{\circ}\text{C}} \cdot I_{IDAC1} = 390.48\ \Omega \cdot 1\ \text{mA} = 390.48\ \text{mV} \quad (5)$$

The maximum gain for the PGA, without over-ranging the ADC, is shown in Equation 6. Selecting a PGA gain of 4 gives a maximum measurement of 95% of the positive full-scale range at 850°C .

$$\text{Gain}_{\text{MAX}} = V_{BIAS} / V_{RTD\ \text{MAX}} = 1.64\ \text{V} / 390.48\ \text{mV} = 4.2\ \text{V/V} \quad (6)$$

With the component values and PGA gain selected, the common-mode input range is verified to ensure that the ADC and PGA are operating in a linear region. The maximum input voltage has the most restriction in the common-mode input range. At the maximum input voltage, the common-mode input voltage seen by the ADC is shown in Equation 7.

$$V_{CM} = V_{BIAS} + (V_{RTD\ \text{MAX}} / 2) = 1.64\ \text{V} + (390.48\ \text{mV} / 2) = 1.835\ \text{V} \quad (7)$$

The common-mode input range of the device is shown in [Equation 8](#).

$$AVSS + 0.1 \text{ V} + (V_{\text{RTD MAX}} \cdot \text{Gain}) / 2 \leq V_{\text{CM}} \leq AVDD - 0.1 \text{ V} - (V_{\text{RTD MAX}} \cdot \text{Gain}) / 2 \quad (8)$$

After substituting in the appropriate values, the common-mode input range is found in [Equation 9](#) and [Equation 10](#).

$$0 \text{ V} + 0.1 \text{ V} + (390.48 \text{ mV} \cdot 4) / 2 \leq V_{\text{CM}} \leq 3.3 \text{ V} - 0.1 \text{ V} - (390.48 \text{ mV} \cdot 4) / 2 \quad (9)$$

$$881 \text{ mV} \leq V_{\text{CM}} \leq 2.42 \text{ V} \quad (10)$$

When the RTD is at the maximum voltage, the input common-mode voltage, $V_{\text{CM}} = 1.835 \text{ V}$, is within the limits of [Equation 10](#); therefore, the RTD measurement is within the input common-mode range of the ADC and PGA. At the minimum RTD voltage ($V_{\text{RTD MIN}} = 18.59 \text{ mV}$), a similar calculation can be made to show that the input is within the common-mode voltage range as well.

7 Conclusion

The preceding discussion shows how both the ADS1247 and ADS1248 can be used with RTD and thermocouples in different configurations. This information must provide sufficient examples to show how other temperature measurement methods can be tested and implemented.

8 Related Documentation

For related documentation see the following:

- ADS124x Data Sheet, [SBAS426](#)
- ADS114x Data Sheet, [SBAS453](#)
- *RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248 Family of Devices*, [SBAA201](#)
- *3-Wire RTD Measurement System Reference Design, -200°C to 850°C*, [SLAU520](#)
- *A Glossary of Analog-to-Digital Specifications and Performance Characteristics*, [SBAA147](#)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from A Revision (May 2015) to B Revision	Page
• Deleted <i>Three-Wire RTD Application with Hardware Compensation</i> section	3
• Deleted <i>Hardware-Compensated Three-Wire RTD Measurement: Design Example</i> section	5
• Added <i>Related Documentation</i> section.....	7

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