Application Report
SBAA180 – January 2011

Example Temperature Measurement Applications Using the ADS1247 and ADS1248

Robert Burnham and Nagaraj Ananthapadamanabhan
Data Acquisition Products

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 (with and without hardware compensation), a four-wire RTD, and a thermocouple with cold junction compensation. This document provides sufficient information to enable several alternate configurations to be implemented.

Contents

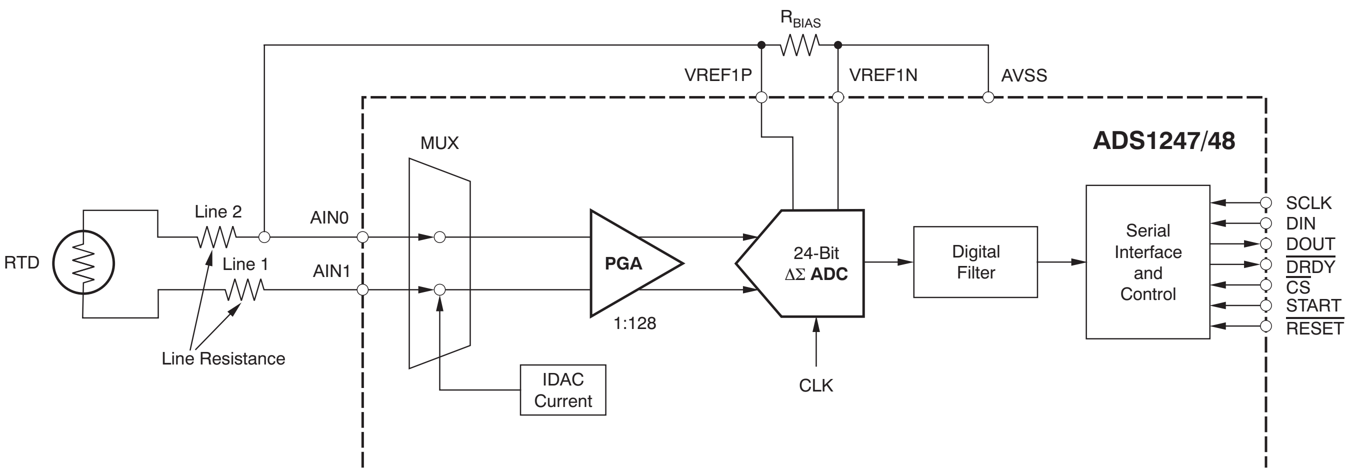
List of Figures

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} should be as close to the ADC as possible.

Figure 1. Two-Wire RTD Application Example

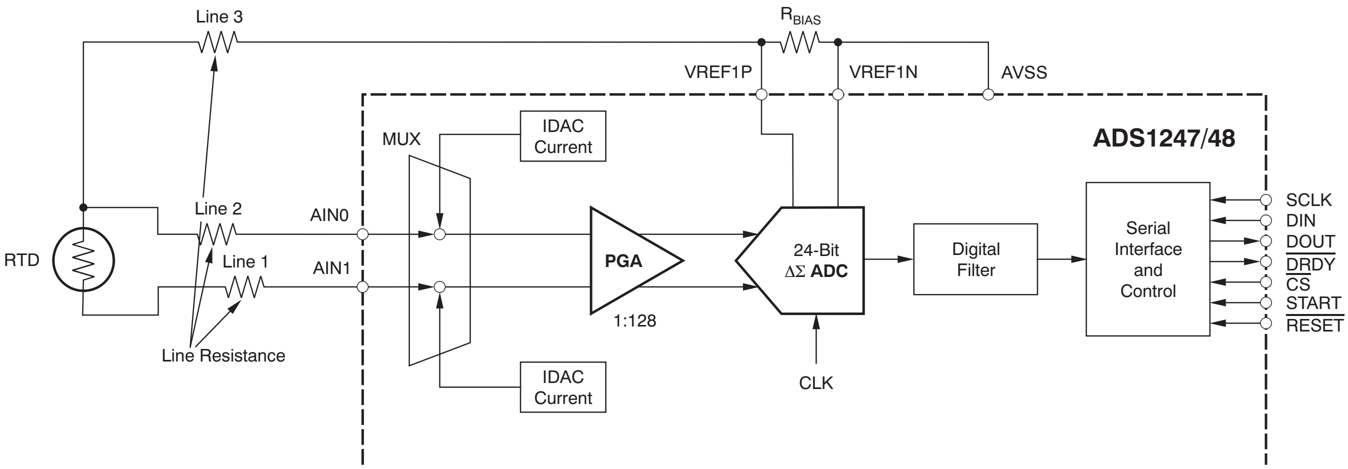
The two-wire RTD connection is the simplest method for a remote connection. Figure 1 presents one such possible RTD application. The ADS1247/8 current sources are connected to one of the terminals of the RTD lines by setting the appropriate bits in the IDAC1 register. The value of the current can be 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, no filtering capacitance should be added 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 illustrates an example of a three-wire RTD application using either the ADS1247 or ADS1248.



Note: R_{BIAS} should be as close to the ADC as possible.

Figure 2. Three-Wire RTD Application Example

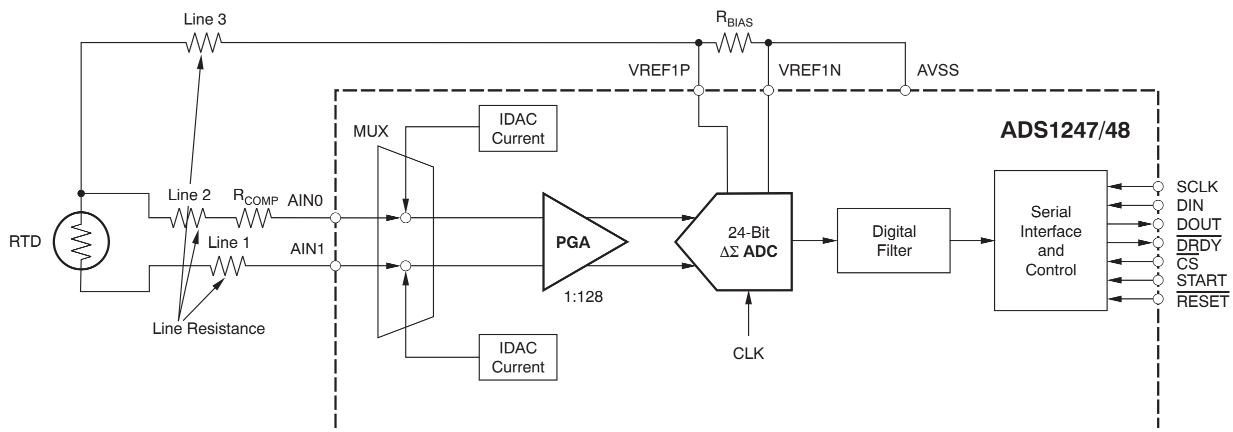
For optimum performance in three-wire RTD applications, the two ADS1247/8 current sources have been extremely closely matched. In the possible 3-wire example given in Figure 2, two selectable current sources are used to provide symmetry and compensate for mismatch through the RTD wiring. The ADS1247/8 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, no filtering capacitance should be added 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 Three-Wire RTD Application with Hardware Compensation

An alternate three-wire topology, shown in Figure 3, allows the circuit to completely use the input dynamic range of the device by adding a compensation resistor, R_{COMP}, in the second arm of the RTD. The voltage drop across R_{COMP} subtracts from the voltage drop across the RTD. The value of R_{COMP} is chosen such that it is equal to the RTD resistance at the middle of the temperature measurement range. For best results, R_{COMP} should be chosen as a precision resistor with a very low temperature coefficient. In this topology, the IDAC current mismatch drift affects the offset drift of the measurement in the same way as it does in the previous example. The sensitivity of the offset drift to the IDAC current in this case, however, is directly proportional to the sum of the line resistance and compensation resistance, R_{COMP}.

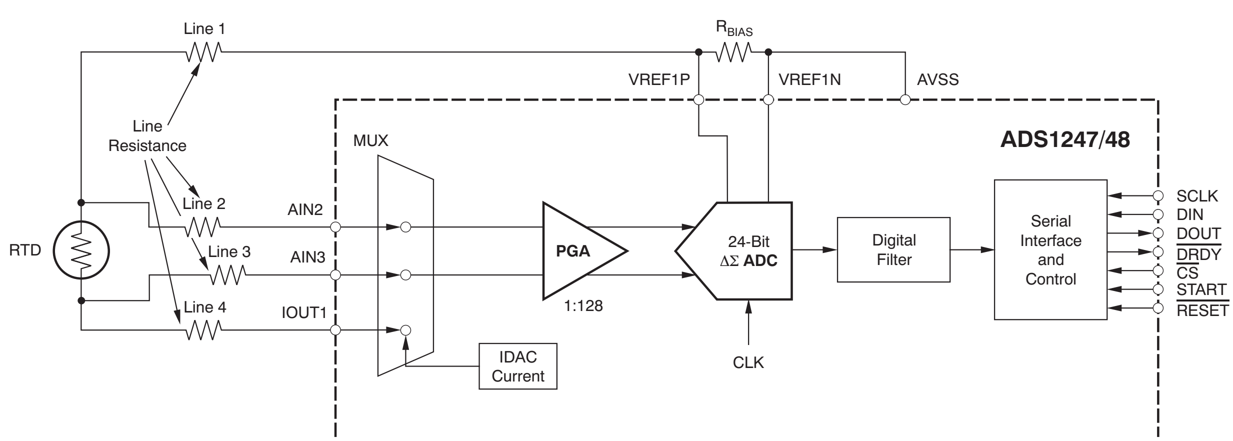


Note: R_{BIAS} and R_{COMP} should be as close to the ADC as possible.

Figure 3. Three Wire RTD Application Example with Hardware Compensation

5 Four-Wire RTD Application

The four-wire RTD approach (illustrated in Figure 4) provides the highest level of accuracy because it isolates the excitation path of the RTD from the sensing path. The ADS1247/8 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.



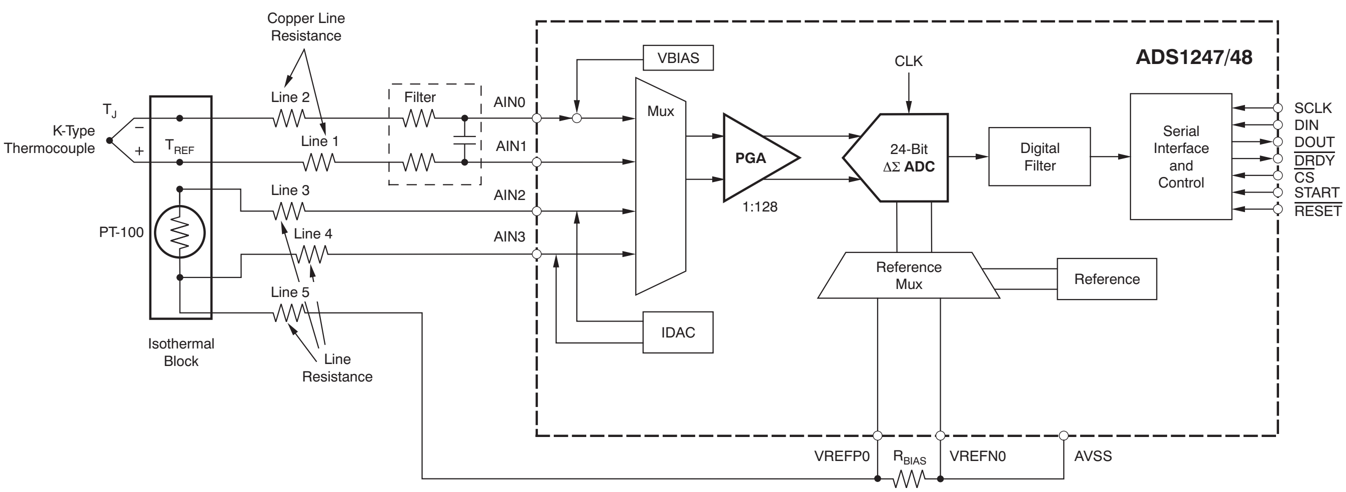
Note: R_{BIAS} should be as close to the ADC as possible.

Figure 4. 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, no filtering capacitance should be added 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.

6 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 5.



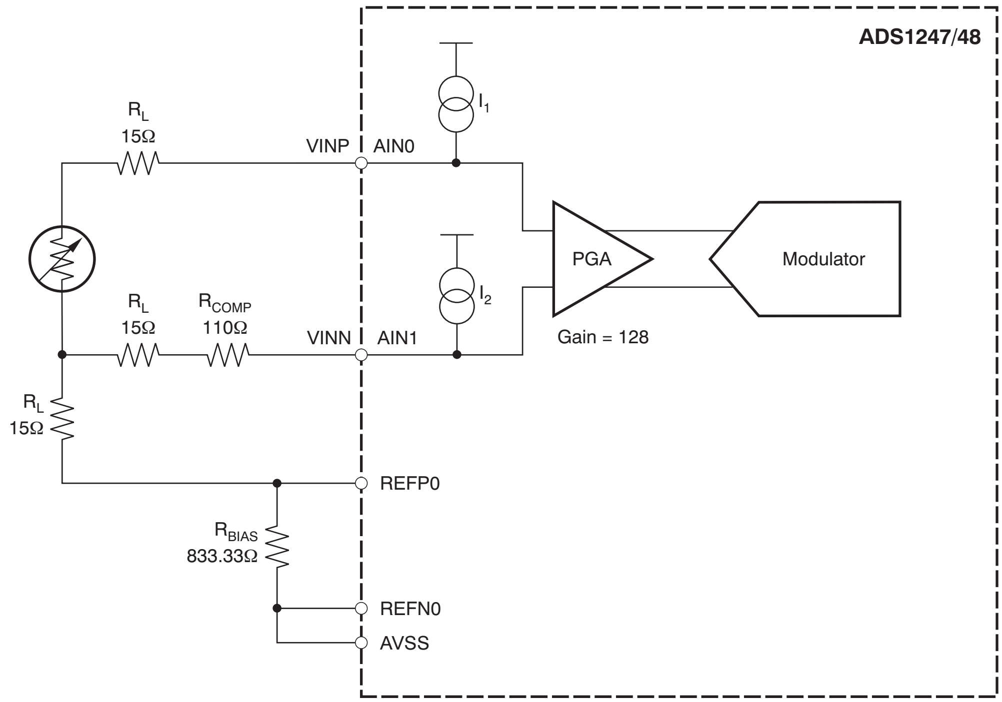
Note: R_{BIAS} should be as close to the ADC as possible.

Figure 5. Thermocouple-Based Application Example

When measuring the temperature using the thermocouple approach, the output of the thermocouple must be biased. The ADS1247/8 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 as shown in Figure 5. 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. The three-wire RTD measurement with hardware compensation may also be used.

7 Hardware-Compensated Three-Wire RTD Measurement: Design Example

This section describes designing a circuit for measuring temperatures in the range of 0°C to +50°C using a PT-100 RTD and the ADS1248 or ADS1247. The PT-100 has a temperature coefficient of 0.392Ω/°C between 0°C and +100°C. Its resistance at 0°C is 100Ω. The two onboard, matched-current DACs of the ADS1247/8 are ideally suited for implementing the three-wire RTD topology. A ratiometric approach where the reference is derived from the IDAC currents improves the noise performance considerably. Figure 6 shows the circuit topology for the ratiometric three-wire RTD method with hardware compensation.



Note: R_{BIAS} and R_{COMP} should be as close to the ADC as possible.

Figure 6. Three-Wire RTD Application Example with Hardware Compensation

The temperature range of the circuit is 0°C to +50°C. The resistance of the PT-100 changes from 100Ω at 0°C to 119.6Ω at +50°C. By choosing a compensating resistor, $R_{COMP,}$ which is equal to the resistance of the PT-100 sensor at +25°C, the voltage variation at the input of the ADC can be made to swing equally in both the negative and positive directions. The resistance of the PT-100 at +25°C is 109.8Ω. Thus, R_{COMP} is chosen to be 110Ω. For optimal results, R_{COMP} should be chosen as a precision resistor with very low temperature coefficient in order to minimize the overall temperature offset drift. The line resistance R_L depends on the distance of the sensor from the measurement setup. R_L has been assumed to be equal to 15Ω. The positive resistance swing about 109.8Ω is 9.8Ω. The maximum differential input to the modulator is equal to 2.5V ([AVDD – AVSS]/2) when [AVDD – AVSS] is 5V. The PGA gain is chosen to be 128 in order to achieve the best noise performance. Thus, the maximum differential input to the PGA is 2.5/128 = 19.53mV. The IDAC current should be set to less than 19.53mV/9.8Ω = 1.99mA. The highest IDAC current setting of 1.5mA is chosen to obtain the best possible temperature resolution while allowing some headroom to measure even temperatures that fall outside the range of 0°C to +50°C.

The input to the ADC is:

$$V_{INP} - V_{INN} = I_1(R_L + R_{RTD}) - I_2(R_L + R_{COMP})$$
$$= I(R_{RTD} - R_{COMP})$$

with $I_1 = I_2 = I$

The maximum differential input to the PGA is (V_{INP} – V_{INN}) and is equal to 1.5mA × 9.8Ω; that is, 14.7mV. The maximum differential input voltage to the modulator is 128 × (V_{INP} – V_{INN}) and is equal to 1.881V in our example. So the reference voltage must be chosen to be greater than or equal to 1.881V. The reference voltage, V_{REF}, is chosen to be 2.5 V. The voltage across R_{BIAS} serves as the reference voltage and sets the input common-mode voltage for the channels AIN0 and AIN1. The current flowing through R_{BIAS} is 3mA. Setting R_{BIAS} to 833.33Ω sets the V_{REF} at 2.5V.

For best results, R_{BIAS} should be a high precision resistor with a very low temperature coefficient. The initial error in R_{BIAS} contributes to the gain error of the measurement, and the temperature coefficient of R_{BIAS} contributes to the gain drift of the measurement.

The input common-mode voltage is given by Equation 1:

$$\begin{aligned} V_{CMI} &= \frac{[I_1(R_L + R_{RID}) + I_2(R_L + R_{COMP})]}{2} + (I_1 + I_2)(R_L + R_{BIAS}) \\ &= IR_L + I\,\frac{(R_{RTD} + R_{COMP})}{2} + 2I(R_L + R_{BIAS}) \end{aligned} \tag{1}$$

The output common mode of the PGA, V_{CMO}, is the same as the input common mode V_{CMI}. The PGA output can swing between 0.1V and 4.9V. The maximum output differential voltage is 2.5V. Thus, the output common mode of the PGA can vary from (0.1V + 1.25V) = 1.35V to (4.9V – 1.25V) = 3.65V, such that the output does not saturate. The input common mode can vary between 1.35V and 3.65V. In this case, the V_{CMI} varies between 2.7245V to 2.7395V, which is well within the range of 1.35V to 3.65V.

8 Conclusion

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