TI Designs
Automotive High-Temperature Sensor (HTS) Reference Design

Description

The TIDA-01235 reference design provides a multichannel, low-cost, and accurate thermocouple-based solution for temperature measurement. The protection strategies involved in the design protect the analog front end (AFE) from coupling transients. This design meets the requirements of automotive-exhaust gas temperature sensors.

Resources

TIDA-01235	Design Folder
ADS1118-Q1	Product Folder
LMT01-Q1	Product Folder
MSP430G2553-Q1	Design Folder

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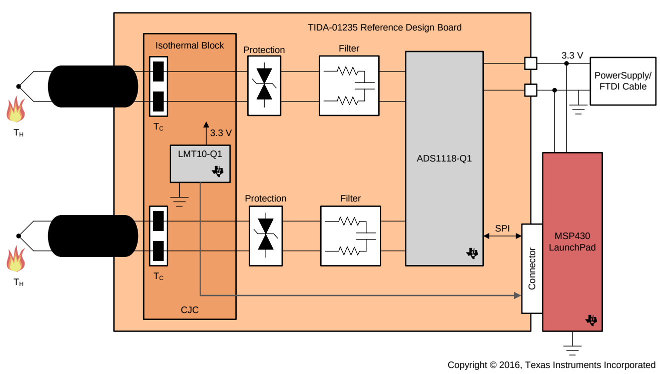
Features

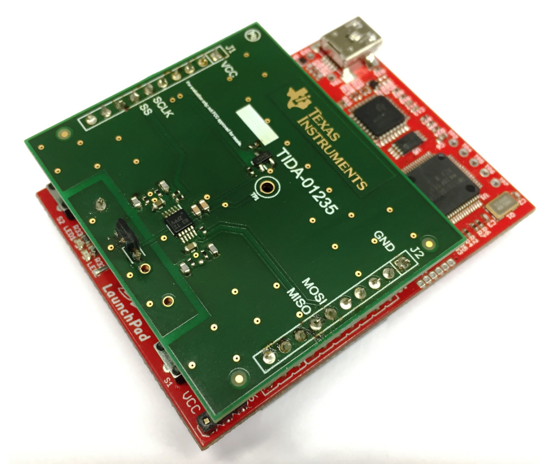
- Compatible With Type N Thermocouple Probes
- Design Specifications Compatible for –40°C to 1300°C (Temperature Range of Thermocouple)
- Accuracy of < ±1°C Over Temperature Range –40°C to 1300°C
- Implements Cold Junction Compensation (CJC) Using LMT01-Q1 Based
- Protection Against Coupling Transients, Surge Transients on Thermocouple Front End
- Operating Temperature Range: –40°C to 125°C

Applications

Thermocouple-Based Temperature Measurements in:

- Exhaust Gas Systems
- Engine Management
- Transmission Management
- HEV-EV Temperature Sensors
- Body Modules





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1 System Overview

1.1 System Description

The sole objective of this reference design is to provide comprehensive details on how to design a simple, robust, and accurate analog front end (AFE) circuit for making precision temperature measurements with thermocouple sensors. This reference design explains the theory, operation, and test results.

This reference design provides a conceptual understanding and practical implementation of topics like antialiasing filters, biasing resistors for sensor diagnostics, cold junction compensation (CJC), and the design challenges of printed-circuit boards (PCBs). Furthermore, the external protection circuitry complies to automotive standards such as coupling transients requirements. Electromagnetic compatibility (EMC) compliance is necessary to ensure that the design not only survives but performs as intended in an automotive exhaust environment.

This reference design provides a system solution for precision N-type thermocouple measurements in exhaust gas systems. This design is intended as an evaluation model for users to fast prototype and develop end products at a fast rate to speed up in the automotive market. Potential challenges with thermocouples as a temperature sensor include tiny voltage outputs, low sensitivity, and nonlinearity. In addition, the design files include design considerations, block diagrams, schematics, bill of materials (BOM), layer plots, Altium files, Gerber Files, and Texas Instrument's (TI) MSP430™ microcontroller (MCU) firmware.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Sensor type	Thermocouple: Type-N
Temperature range	–40°C to 1300°C
Cold junction compensation type	LMT01-Q1 temperature sensor
Power supply voltage range	3.3-V power supply from MSP430™ debugging or external power supply
Thermocouple temperature linearization	–40°C to 1300°C look-up table with 1°C resolution implemented in the MSP430™ firmware to resolve nonlinearity
LMT01-Q1 based temperature linearization	–40°C to 125°C data sheet equation implemented in the MSP430™ firmware to resolve nonlinearity
Protection on signal lines	Coupling transient protection
Operating temperature range	–40°C to 125°C (temperature of the board including the cold junction)

1.3 Block Diagram

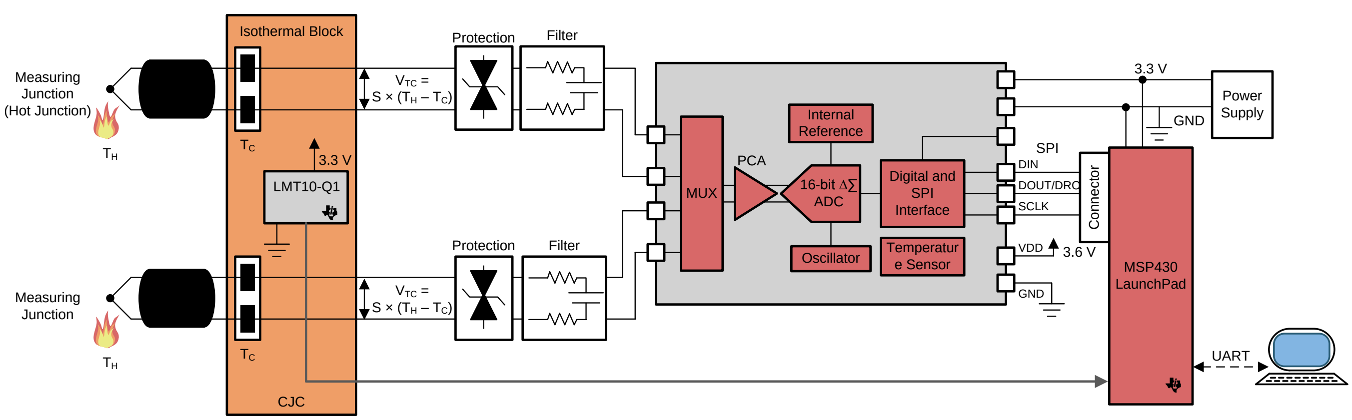

Figure 1. TIDA-01235 Block Diagram

The front-end circuit biases a N-type thermocouple, filters out of bandwidth noise, reads the generated signal, amplifies the signal, and then converts analog input voltages into CJC and linearized, 16-bit digital temperature readings. The module uses the National Institute of Standards and Technology (NIST) linearization tables based on the International Temperature Scale of 1990 (ITS-90) for thermocouple linearization.

The AFE circuit offers a solution for CJC, using an LMT01-Q1 sensor. The use of LMT01-Q1 reduces the influence of temperature from other electronics in the systems to effectively provide good accuracy, which is also useful when placing an isothermal block in the vicinity of thermocouples. The MPS430 MCU provides the key computation of this AFE design. The MSP430 contains all of the software that enables the MCU to perform all of the intended functions. The MCU interfaces with the ADS1118-Q1 device through the serial peripheral interface (SPI). Immediately after power up, the MCU performs the necessary initializations required to run, such as setting up the system clock, I/O port settings, enable and disable interrupts, and the initialization of SPI engines to begin communication with the ADC. After self-initialization, the MCU initializes the internal registers of the ADC as per the design requirements already captured and implemented in software. The preceding Figure 1 shows the components of the design.

1.3.1 Highlighted Products

1.3.1.1 ADS1118-Q1

The ADS1118-Q1-Q1 is a precision, low-power, 16-bit analog-to-digital converter (ADC) that provides all the features necessary to measure the most common sensor signals. The ADS1118-Q1-Q1 integrates a programmable gain amplifier (PGA), voltage reference, oscillator, and high-accuracy temperature sensor. These features, along with a wide power-supply range from 2 V to 5.5 V, make the ADS1118-Q1-Q1 ideally suited for thermocouple sensor-measurement applications. The ADS1118-Q1-Q1 performs conversions at data rates up to 860 samples per second (SPS).

The PGA offers input ranges from ±256 mV to ±6.144 V allowing both large and small signals to be measured with high resolution. An input multiplexer (MUX) allows measurement of two differential or four single-ended inputs. The high-accuracy temperature sensor also can be used for system-level temperature monitoring, or cold junction compensation for thermocouples. The ADS1118-Q1-Q1 operates either in continuous-conversion mode, or in a single-shot mode that automatically powers down after a conversion. Single-shot mode significantly reduces current consumption during idle periods. Data is transferred through an SPI. The ADS1118-Q1-Q1 is specified from –40°C to +125°C.

1.3.1.2 LMT01-Q1

The LMT01-Q1 is a high-accuracy, two-pin temperature sensor with an easy-to-use pulse count interface which makes it an ideal digital replacement for PTC or NTC thermistors both on and off board in the automotive market. The LMT01-Q1 digital-pulse count output and high accuracy over a wide temperature range allow pairing with any microcontroller (MCU) without concern for integrated ADC quality or availability while minimizing software overhead. The LMT01-Q1 from TI achieves a flat ±0.5°C accuracy with very fine resolution (0.0625°C) over a wide temperature range of –20°C to 125°C without system calibration or hardware and software compensation.

Unlike other digital integrated circuit (IC) temperature sensors, the single-wire interface of the LMT01-Q1 is designed to directly interface with a general purpose input/output (GPIO) or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01-Q1s integrated electromagnetic interference (EMI) suppression and simple two-pin architecture makes it ideal for onboard and offboard temperature sensing. The LMT01-Q1 offers all the simplicity of analog NTC or PTC thermistors with the added benefits of a digital interface, wide specified performance, EMI immunity, and minimum processor resources.

2 Thermocouple Theory

2.1 Thermocouple Theory

In the automotive market, temperature is the most required parameter to measure in many places in automotive, requires continuous measurement, monitoring, and control. The current automotive market demands a temperature sensor, which has a higher integration of many thermocouples in one unit at a reasonably low cost to reduce the overall production costs. All temperature sensors measure temperature by sensing a change in the material physical characteristics as a function of temperature. Temperature sensors are available in wide varieties:

- Thermocouple
- Resistance temperature detector (RTD)
- Thermistor
- Semiconductor temperature sensor integrated circuit

The use of thermocouples in the exhaust gas temperature is increasing because of its lower cost and ability to withstand higher temperatures. Thermocouples are of a simple construction, rugged, inexpensive, and one of the most commonly-used temperature transducers covering a wide range of temperatures. A thermocouple is formed when two dissimilar metal wires bind together electrically to form two junctions, as Figure 2 shows.

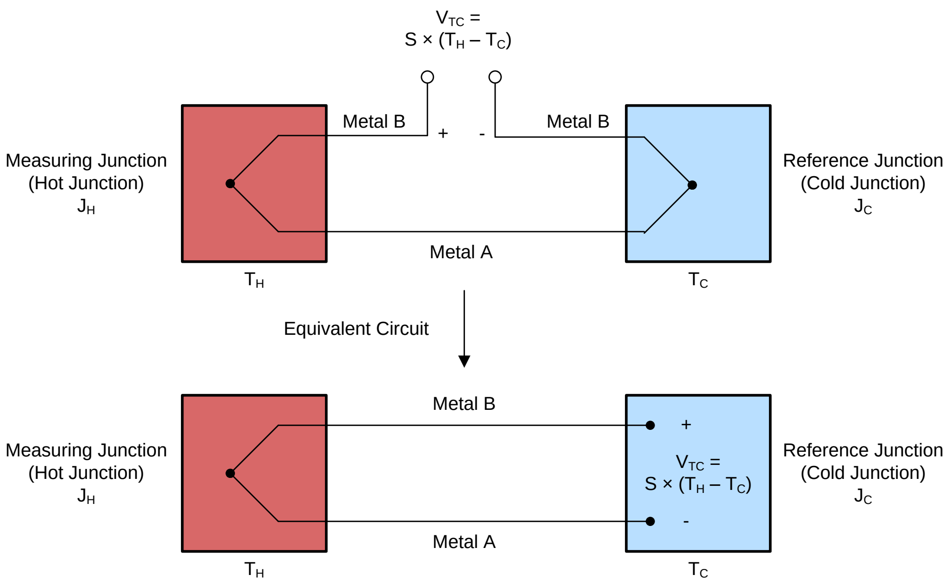

Figure 2. Simple Thermocouple

Whenever the two junctions formed by joining two dissimilar metals experience a temperature gradient, an open-circuit voltage develops. The produced voltage, first discovered by the German scientist Thomas Johann Seebeck in 1821, is called “Seebeck Voltage" and this phenomenon is called the “Seebeck Effect”. Modern physics provides an explanation of the Seebeck phenomenon: The voltage potential develops because free-electrons at the hot end are more thermally agitated than the free-electrons at the cooler end. The more thermally agitated electrons on the hot end begin to diffuse toward the cooler end. This redistribution of electrons creates a negative charge at the cooler end and an equal positive charge at the hot end. The result is the production of an electrostatic-voltage between the two ends. The magnitude and direction of the open-circuit voltage developed between the two ends is proportional to the temperature difference; refer to the following Equation 1.

$$V_{TC} = S \times (T_H - T_C) \quad (1)$$

where

- V_{TC} is the Seebeck voltage in mV
- S is the Seebeck coefficient or thermoelectric sensitivity in µV/ºC
- T_H is the temperature of hot junction or measuring junction in ºC
- T_C is the temperature of reference junction or cold junction in ºC.

When designing with thermocouples, understanding that thermocouples are bipolar is important. A bipolar thermocouple indicates a capability to produce a positive or negative voltage depending on whether or not the measured temperature is higher or lower than the system temperature, respectively. Unlike other temperature sensors, thermocouples do not require excitation due to their inherent voltage output.

Theoretically, all dissimilar metals exhibit the Seebeck effect, but only a few specific metal combinations are used to make most practical thermocouple sensors. These combinations have been categorized and characterized into different calibration types by the National Institute of Standards and Technology (NIST). Each calibration type is designated by the capital letters indicating the composition and other different characteristics, as Figure 3 shows. Based on calibration type, the thermocouple has an individual sensitivity of 40 µV/°C (for a type-N thermocouple), a temperature range, accuracy, life-span, and nonlinearity over a temperature range.

The Seebeck coefficient is a nonlinear function of temperature that causes nonlinearity in the thermocouple output voltage over the operating temperature range. Thermocouples are not uniformly linear across a temperature range, as Figure 3 shows. Always choose a thermocouple with less variation in the Seebeck coefficient. Also note that the use of type-N thermocouples is preferable in the majority of the automotive market because of stability issues.

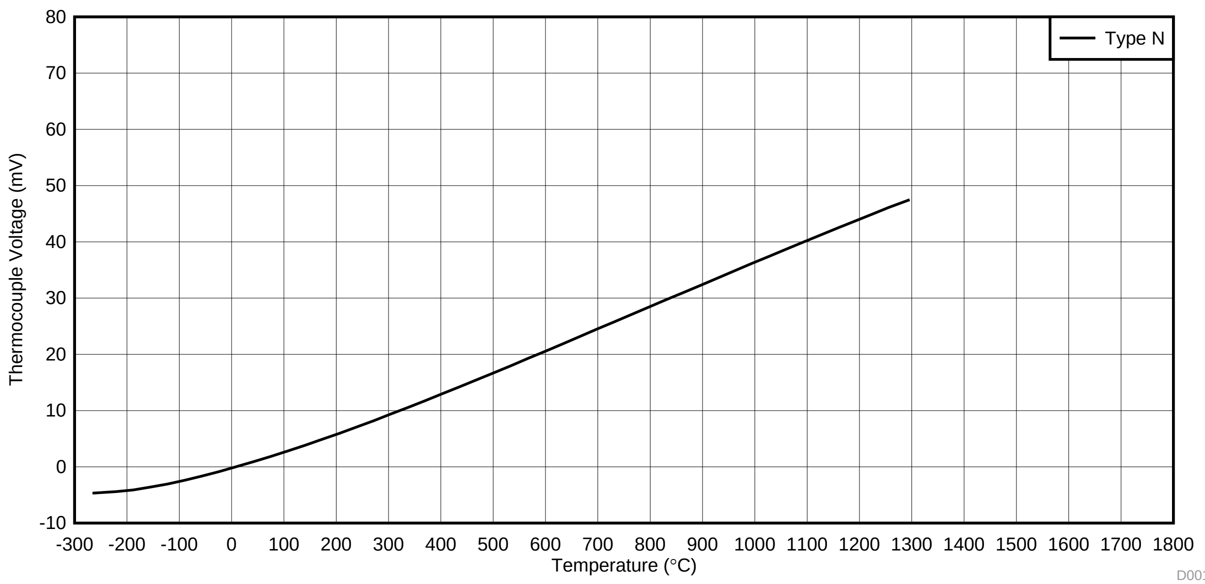

Figure 3. Thermocouple Voltage as Function of Temperature

2.2 Cold Junction Compensation (CJC)

Thermocouples measure the temperature difference between hot and cold junctions. Thermocouples do not measure the absolute temperature at one junction, as Figure 4 shows. The cold junction is also referred to as a reference junction.

Thermocouples are created with leads at the meter connection. In the printed-circuit board (PCB), these unwanted thermocouples are one of the biggest concerns. Each dissimilar metal connection creates a new thermocouple as one proceeds from measuring end to wire connector, to solder, to copper PCB trace, to IC pin, to bonding wire, and to chip or die contact. However, if the signal is differential, and each of the thermocouple pairs are at the same temperature, then the thermocouple voltages cancel out and have no net effect on the measurement. Therefore, the net voltage error added by these connections is zero.

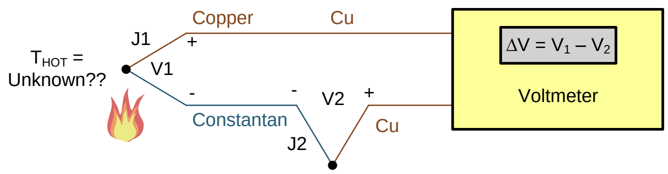

Figure 4. Unwanted Thermocouple Junction

The next step is to determine what is required to calculate the temperature (T_{HOT}) of measuring junction J1.The following Equation 2 indicates that to find out the temperature of hot junction of a thermocouple requires knowing the temperature of the cold junction. The cold junction of a thermocouple usually is kept in an ice bath (see Figure 5) to keep it at a known reference temperature of 0°C, which is another reason it is called as cold junction. In reality, it is impractical and inconvenient in most applications to provide a true ice-point reference. The NIST thermocouple reference table also assumes that the cold junction is at 0°C.

$$T_{HOT} = (\Delta V / S) + T_{COLD} \tag{2}$$

For example, if a T-type thermocouple produces an open circuit voltage of 3.4 mV with its cold junction reference temperature maintained at 0°C. The next step is to determine the temperature of its hot junction. Assume that a Seebeck coefficient of a T-type thermocouple is 40 µV/°C (see Equation 3).

$$T_{HOT} = \left(3.4\ \text{mV} / \left(40\ \mu\text{V} / {}^\circ\text{C}\right)\right) + 0^\circ\text{C} = 85^\circ\text{C} \tag{3}$$

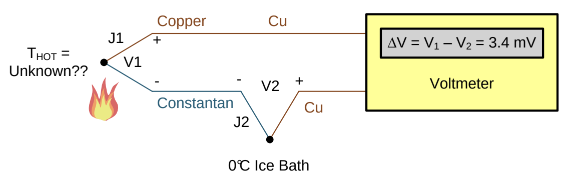

Figure 5. Measuring Absolute Temperature Using 0°C Ice Bath

Knowing the cold junction reference temperature is necessary to determine the correct absolute temperature at the measuring junction. An additional measurement is then mandatory to determine the cold junction reference temperature because practically it is not possible to provide ice bath. The more practical and logical approach is to use some other type of direct-reading, temperature sensor means capable of absolute measurements (not relative measurements as with an RTD). Use a thermistor or sensor IC to measure the temperature at the reference junction and then use it to compute the temperature at the measuring junction of a thermocouple. This technique is called cold junction compensation (CJC). This design uses a sensor IC (LMT01-Q1) for the compensation.

2.3 Thermocouple Input Signal Conditioning

The use of thermocouples, despite their prevalence in the field of engineering, is often misunderstood and can result in many design challenges due to issues such as small output voltage, low sensitivity, and nonlinearity across the temperature range. Achieving an overall system accuracy of ±1ºC or better is difficult because of these signal-conditioning issues. Users must design the interface of a thermocouple sensor analog front-end (AFE) with extreme care to achieve a sufficient level of accuracy. A thermocouple signal chain consists of a thermocouple sensor in the front, a thermocouple connector, an isothermal block, overvoltage protection, biasing resistors, an antialiasing filter, an amplifier, an ADC, and sensor data linearization in the software. This AFE circuit addresses all of the challenges associated with the measuring of thermocouple temperature.

2.3.1 Input Filter Design

The main goal of the filter design is to keep the filter initial error contribution to the total error comparable to or smaller than the initial error of the thermocouple sensor. Because of the manufacturing limitations of the type-N thermocouple, which is mainly related to the purity of materials, the initial error of the thermocouple sensor (tolerance class 1) is typically less than 1.5°C and from –40°C to 1300°C. The initial error is also better than 0.4% up to 1300°C, which is the maximum range of thermocouple temperatures.

Signal conditioning is critical in any design. Any ADC, regardless of architecture, requires some amount of filtering on the inputs to reduce noise in the system, which is because of the effects of aliasing. The digital filter in delta-sigma (ΔΣ) ADCs significantly reduces the requirements of an external analog filter, but still requires some filtering. A simple filter, such as the one that shows, creates a balanced differential filter.

The filter design using the ADS1118-Q1-Q1 device employs a simple first-order filter. The use of this first-order filter is due to the expected small-form factor and cost requirements of this reference design. Users implementing this filter can easily sequence the filter into higher-order filters to provide a greater immunity to high-frequency noise.

Refer to the TIDA-00168 reference design [3] for a detailed description of the input filter design.

2.3.1.1 Selecting Differential-Mode and Common-Mode Capacitor Ratio

The differential filter is also great for reducing both common-mode and differential noise components. The resistors used to develop the filter also serve to limit current to the inputs of any device that follows the filter. When sized accordingly, the resistors enable better functionality to the inputs, protection against electrostatic discharge (ESD), and long-term overvoltage conditions. The filter shown in is an example of a structure commonly used for differential signals. A few important points require consideration when selecting components. To avoid differential noise caused by mismatches in the common-mode capacitors, industry standards recommend using a differential capacitor that is at least ten times greater than the common-mode capacitors.

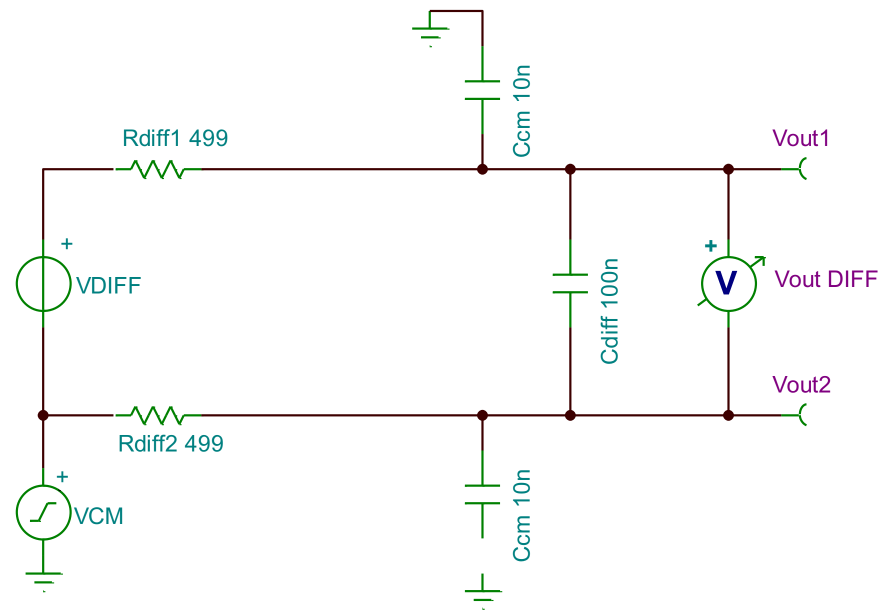

Figure 6. Mismatch in Common-Mode Capacitors

As shown in Figure 7, because there is a good match in two common mode capacitors the Vout DIFF voltage is a plane signal with no noise components in it.

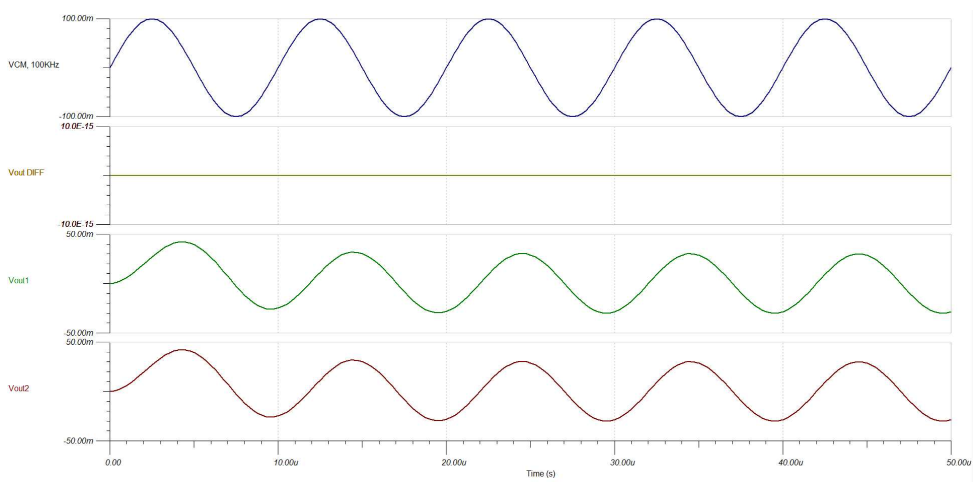

Figure 7. Differential Noise Due to Mismatches in Common-Mode Capacitors

2.3.1.2 Filter Cutoff frequency

Normally, the actual signal does not change quickly for a thermocouple (sensor bandwidth < 1 Hz). Therefore, using low cutoff filters is not unreasonable and generates a sufficient noise performance if quality capacitors are used; however, using low cutoff filters causes a reduced channel update rate. Use of the filter is important for the rejection of any noise that may be subjected to the ADC inputs, which are near the modulator sampling speed. The modulator sampling speed is usually hundreds or even thousands of times higher than the actual ADC output data rate. The data converter cannot digitally reject noises of higher frequencies. The use of analog input filtering is required to reject noises of higher frequencies. ΔΣ ADCs specify the sampling frequency of the modulator to allow external filters to be designed accordingly. The ADS1118-Q1-Q1 device, for example, has a modulator sampling frequency of 256 kHz.

The input filter also performs as an antialiasing filter. In most systems, users can calibrate out errors introduced through input filters. However, for this uncalibrated example, the ADS1118-Q1-Q1 device has roughly 10 MΩ of differential input impedance, which increases the gain error as the sensor output and filter impedances increase. When selecting the filter for this design there is a trade-off between lowering the cutoff and using small-value components. Ideally, due to the low bandwidth of the sensor (<1 Hz), users prefer a thermocouple design with a lower cutoff frequency and a higher-order filter. However, designing a high-order passive filter that is aggressive introduces large resistances in front of the ADC, which interacts with the differential input impedance of the ADS1118-Q1-Q1 device.

The inside digital filter cannot dispose of the aliasing signal brought on by the modulator; however, the input filter can act as an antialiasing filter. The goal of this design is to keep the signal rejection at 256 kHz and at least –80 dB. The –80 dB attenuation is arbitrary and depends on the expected noise in the environment where the system is deployed. The –80 dB shows that the injected undesirable signal of 5 mV attenuates to 0.5 μV.

The filter must be able to reduce noise to 256 kHz by a factor of 10000. The desired rejection is at 256 kHz of 80 dB. Calculate a cutoff frequency to achieve this rejection. Because the first-order filter in this design rejects at 20 dB per decade, the corresponding –3-dB frequency would be four decades down from 256 kHz or 25.6 Hz. The transfer function of the filter is calculated in Equation 4:

$$\ddot{A} = \frac{\ddot{U}_O}{\ddot{U}_1} = \frac{1}{1 + j\varpi R_{DIFF}\left(C_{DIFF} + \frac{1}{2}C_{CM}\right)}$$

$$\frac{1}{\sqrt{1 + \left(\varpi R_{DIFF}\left(C_{DIFF} + \frac{1}{2C_{CM}}\right)\right)^2}} = \frac{1}{10000}$$

- $\varpi = 2\pi \times 256\ \text{kHz}$
- $R_{DIFF} = (R_{F1} + R_{F2})$

$$\frac{1}{2\pi \times 256\ \text{kHz} \times (R_{F1} + R_{F2}) \times \left(C_{DIFF} + \frac{C_{CM}}{2}\right)} = \frac{1}{10000}$$

$$\frac{1}{2\pi \times 25.6\ \text{kHz} \times (R_{F1} + R_{F2}) \times \left(C_{DIFF} + \frac{C_{CM}}{2}\right)} = 1 \quad (4)$$

So, the cutoff frequency of the filter is 25.6 Hz.

where

- R_{DIFF} = differential resistance
- C_{DIFF} = differential capacitance
- C_{CM} = common-mode capacitance
- R_{F1} = resistance on single end
- R_{F2} = resistance on other single end.

2.3.2 PGA Operation and Common-Mode Voltage Limitation

The PGA offers input ranges from ±256 mV to ±6.144 V, allowing both large and small signals to be measured with high resolution. The ADS1118-Q1-Q1 performs conversions at data rates up to 860 samples per second (SPS). An input multiplexer (MUX) allows measurement of two differential or four single-ended inputs. A type N thermocouple couple gives out the voltages from –1.269 mV to 47.477 mV, so select the range in such a way to match this range. Choosing ±256 mV is clearly a better choice that allows the designer to make the most of this specification.

2.3.3 Biasing Resistors

In the case of a floating signal source and differential measurement, take care to ensure that the common-mode voltage level of the signal remains in the common-mode input range of the measurement device with respect to the measurement system ground. In the input stage of a data acquisition device, the input bias currents can move the voltage level of the floating source out of the valid range. Use resistors to bias this voltage to a reference, as Figure 8 shows.

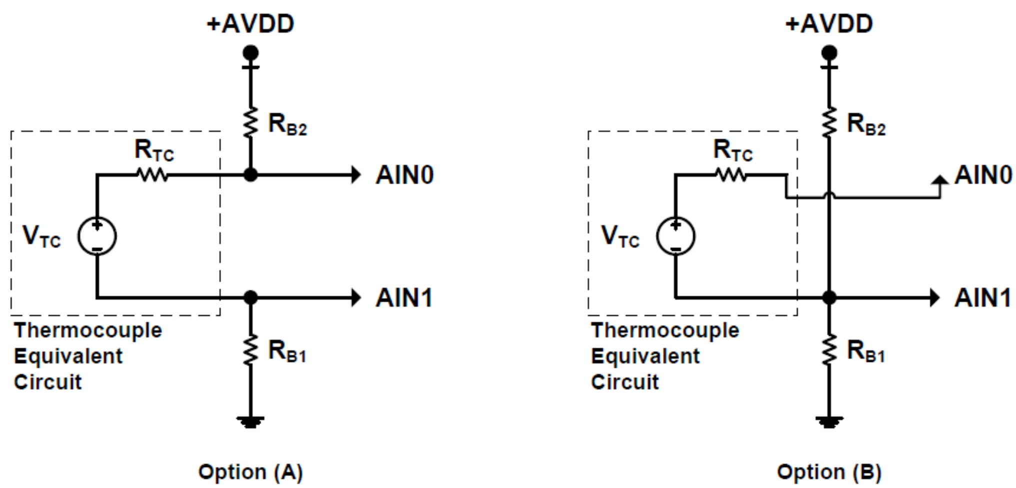

Figure 8. Thermocouple Biasing Options Using Pullup and Pulldown Resistors

The +AVDD = 3.3 V of system voltage.

These resistors are called bias resistors and provide a DC path from the device inputs to the measurement system ground. Bias resistors must have a large enough value to allow the source to float with respect to the measurement system ground and not load the signal source. Likewise, the biasing resistors R_{B1} and R_{B2} are used to set the common-mode voltage of the thermocouple within the specified common-mode voltage range of the PGA (in this example, to mid-supply AVDD / 2). Mid-supply AVDD / 2 is often an ideal common-mode voltage for most devices like ADCs, operational amplifiers, and PGAs. If the application requires the thermocouple to be biased to GND, a bipolar supply (for example, AVSS = –2.5 V and AVDD = +2.5 V) must be used for the ADS1118-Q1-Q1 device to meet the common-mode voltage requirement.

Understanding the consequence of not using biasing resistors is important. Without the biasing resistors, the thermocouple output-voltage is differential. If not biased to any reference level, the common-mode voltage can be anywhere from AVSS to AVDD (in this example, 0 V to 3.3 V), thus indicating that the condition for common-mode voltage can be violated. Consequently, the non-ideal common-mode rejection ratio (CMRR) of the device results in an input offset voltage error.

To determine the common-mode input voltage set by the design, replace the thermocouple by its Thevenin's equivalent circuit where V_{TC} is a function of the Seebeck coefficient and the temperature difference (ΔT) between the two junctions, as the preceding Figure 8 shows. R_{TC} is the thermocouple wire resistance, which is a function of wire resistivity, length, and gauge. This design has two options for connecting the biasing resistors to the thermocouple lead wires, as Figure 8 shows. Both options offer different advantages and disadvantages. The current design uses option A. Refer to the TIDU574 reference design[3] for a detailed description of why to choose option A.

2.4 Cold Junction Compensation (CJC)

The current design uses LMT01-Q1 for CJC. To measure the temperature of the cold junction, place the LMT01-Q1 device in close vicinity to the thermocouple connector ends, as Figure 9 shows. A ground isolation barrier is provided to share the effect of the isothermal block from the other components thermal behavior. The voltage measured across the temperature sensor (LMT01-Q1) is proportional to the temperature of the isothermal block, which is determined by the characteristic equation of LMT01-Q1. As Figure 10 shows, one end of LMT01-Q1 is connected to ground to have at least one potential to maintain the isothermal condition chosen for this configuration. Output resistor 100K along with the transistor level-shifter configuration; the LMT01-Q1 output pulses in the range of 3.3 V. Pulsing can be achieved with the help of the MCUs GPIO and timers or Interrupts.

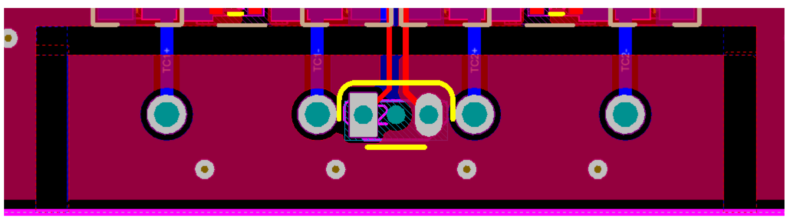

Figure 9. Placement of LMT01-Q1 in Isothermal Block for CJC

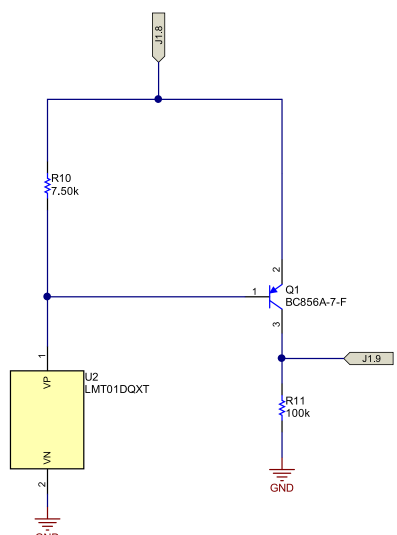

Figure 10. LMT01-Q1 Connection Schematic

2.5 PCB Guidelines

One of the challenges for the thermocouple design is to design an optimal layout. Section 2.4 describes the CJC block layout considerations. As Figure 11 and Figure 12 show, ADC input sections must be symmetrical to nullify the effects of unwanted, small thermocouples junctions and EMI noise. The isothermal block is completely separated from the other section of the board to nullify the effect of temperature on the isothermal block. The bottom layer has most of the components and the designer must ensure that none of the components are in the vicinity of the isothermal block.

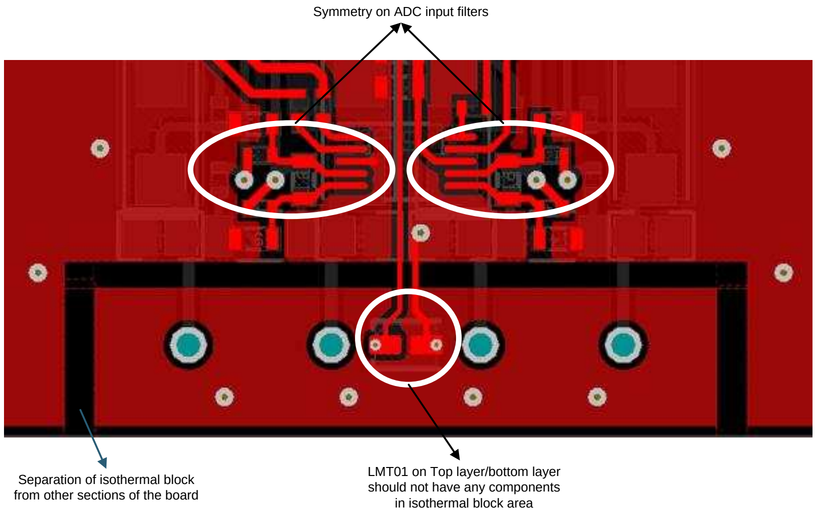

Figure 11. Top Layer

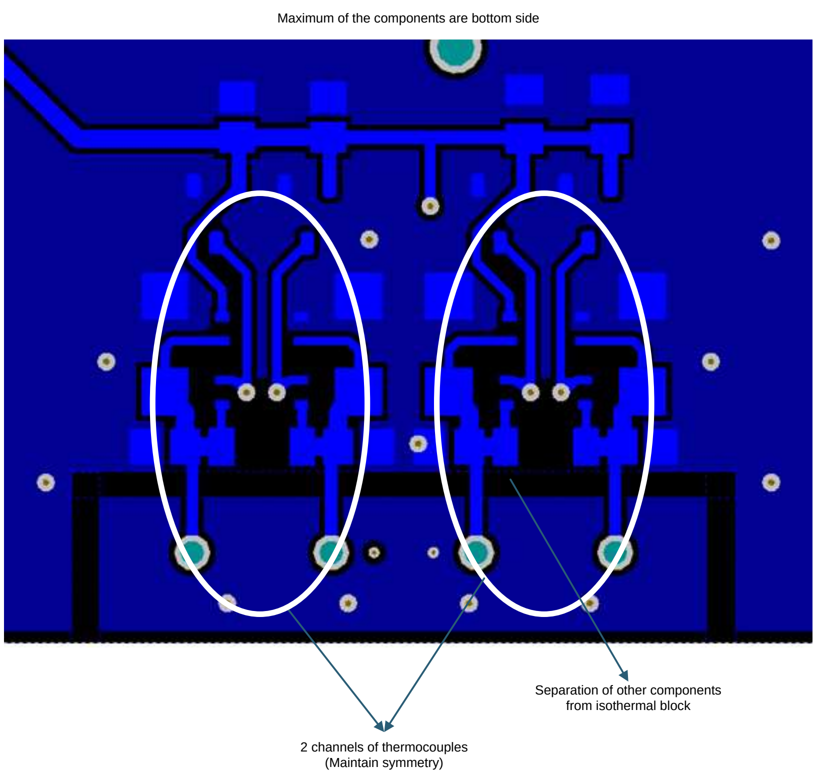

Figure 12. Bottom Layer

3 Getting Started Hardware and Software

3.1 Hardware

Figure 13 shows the complete hardware board of the thermocouple measurement system. Two boards are stacked on top of another. The bottom board (red) is a TI MSP430™ LaunchPad™ development kit, which is used for programming, testing, and evaluation purposes only. The top board (green) is the TIDA-01235 device, which comprises the ADC, CJC temperature sensor, filter, and protection circuits. The ADS1118-Q1-Q1 device is responsible for converting thermocouple temperature signals to digital signals (SPI) there to connect to the MSP430G2553 LaunchPad for programming. The LMT01-Q1 device is directly connected to the MSP430G2553 LaunchPad.

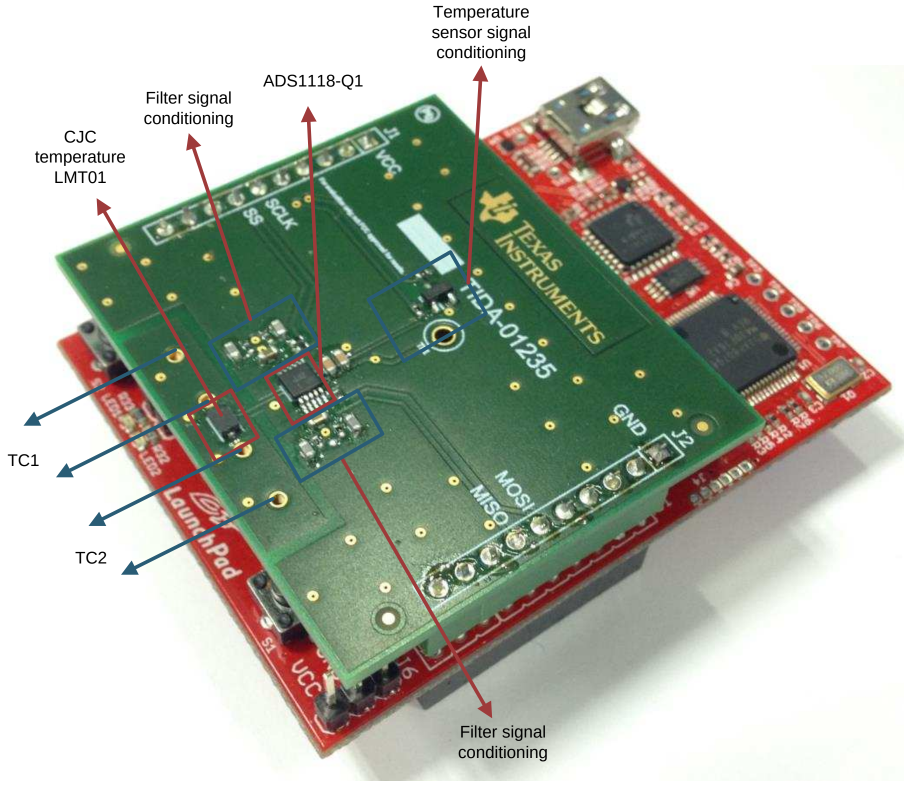

Figure 13. TIDA-01235 Board Components Description (TC1: Thermocouple 1, TC2: Thermocouple 2)

The following equipment is required for the initial board setup:

- TIDA-01235 board with the MSP430 device preprogrammed
- 3.3-V battery or power supply (optional: can also take the supply from MSP LaunchPad)
- Keysight B2912A SourceMeter® to provide the temperature equivalent voltage (preferably, but other source meters can be used)
- HP 3458A 8½ digit multimeter (preferably)

Connections:

- Connect Keysight source meter to the input terminals of the TIDA-01235, as Figure 15 shows
- Connect HP3458A 8½ multimeter across the terminals of thermocouple to measure the exact thermocouple voltage across ADC terminals, as Figure 15 shows
- Connect computer through USB to the MSP430 LaunchPad for debugging and programming purposes
- Connect FTDI cable across P1.1 and P1.2 for Tx and Rx signals for universal asynchronous receiver/transmitter (UART) communication
- Complete setup can be placed in temperature chamber for sweeping the maturement results for a grade 1 range of automotive temperatures

3.2 Software

An MSP430G2553 LaunchPad is used to program in the Embedded C language. TI recommends to use Code Composer Studio™ (CCS) software when dealing with MSP430 LaunchPads. CCS is an integrated development environment (IDE) for TI embedded processor families. CCS comprises a suite of tools used to develop and debug embedded applications. CCS includes compilers for each of TI's device families, source code editor, project build environment, debugger, profiler, simulators, real-time operating system, and many other features. The intuitive IDE provides a single-user interface that guides through each step of the application development flow.

Figure 14 shows the flow diagram of the working program. The ADC on the TIDA-01235 converts the thermocouple voltage to equivalent SPI codes and, using look-up tables, these codes are converted into real temperature values (T_{TC}). By using a characteristic equation, the LMT01-Q1 pulse information is converted into temperature (T_{CJC}). Add both thermocouple temperature (T_{TC}) and cold junction temperature (T_{CJC}) to obtain the final, actual temperature (T_{Actual}) value.

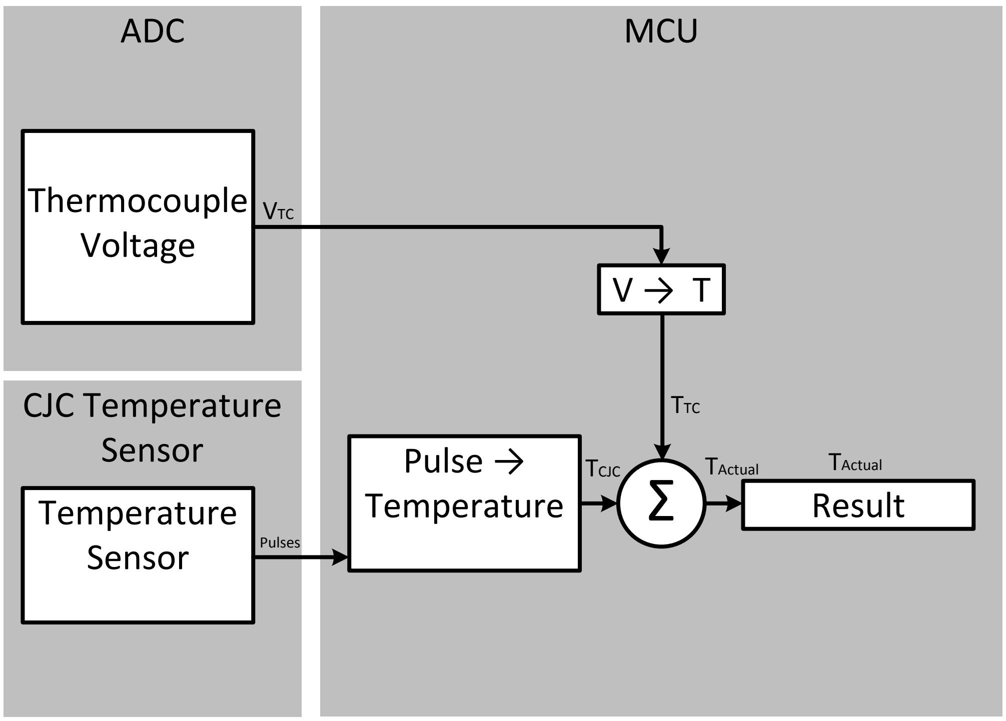

Figure 14. Software Flow Diagram

4 Testing and Results

4.1 Test Setup

Figure 15 shows the test setup. connect the diagram as shown to start the setup. All the test results are performed using channel 1 of the ADC.

Thermocouple equivalent voltages are provided using a Keysight Source meter; connect this meter to channel 1 of the ADC, as Figure 15 shows. An 8½ digit multimeter is used to measure the exact amount of voltage applied, so connect the multimeter to the same terminals of ADC channel 1.The complete setup is then placed inside a temperature chamber and UART signals are transmitted to the PC through an FTDI cable.

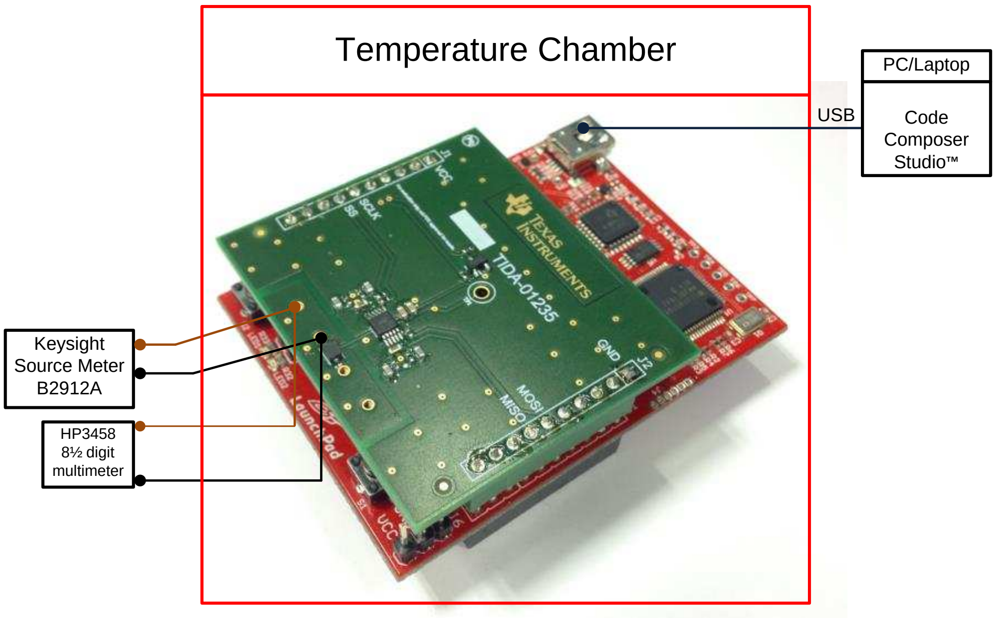

Figure 15. Testing Equipment Connection

4.2 Test Plan

The main purpose of thermocouple testing is to estimate the accuracy of ADC and CJC channels. Every thermocouple system generally has two channels, namely a thermocouple channel and an external temperature sensor channel. The total error of a thermocouple is the sum of these errors. As previously addressed, this reference design has two boards: the MSP430 LaunchPad and TIDA-01235 reference design board. When taking temperature measurements, the MSP430 is kept outside and the temperature chamber and the TIDA-01235 board is kept inside. Both boards are connected through SPI. The MSP communicates with the computer through UART.

The MSP430 provides the pure temperature cycle (TC) temperature without the calculation of the cold junction. Section 4.3 shows all of the tests. Use the test setup as shown in Figure 15. The equivalent thermocouple voltages are applied from –1.269 mV to 47.477 mV in several steps.

The test plan is divided into three cases to calculate the thermocouple accuracy:

- Thermocouple channel accuracy (ADS11118-Q1 accuracy)
- Thermocouple channel accuracy (ADC1118-Q1 accuracy) plus CJC channel accuracy (LMT01-Q1 accuracy)
- CJC channel accuracy (LMT01-Q1 accuracy)

4.2.1 Thermocouple Channel Accuracy (ADS11118-Q1 Accuracy)

To test the accuracy along the thermocouple channel, thermocouple temperature equivalent voltages (–1.269 mV to 47.477 mV) are provided in several steps with an SMU on channel 1 of the ADC. The ADS1118-Q1-Q1 device interprets these voltages and converts SMU voltages into respective temperatures using look-up tables. The MSP430 delivers the temperature values through UART. The difference between the SMU input voltage and MSP430 output voltage estimates for the error.

4.2.2 Thermocouple Channel Accuracy (ADC1118-Q1 Accuracy) Plus CJC Channel Accuracy (LMT01-Q1 Accuracy)

To test the accuracy along the thermocouple channel plus CJC channel, thermocouple temperature equivalent voltages (–1.269 mV to 47.477 mV) are provided with an SMU on channel 1 of the ADC. The ADS1118-Q1-Q1 device interprets these voltages and uses the MSP430 converts these voltages into temperature using look-up tables. The MSP430 through UART delivers the temperature values. The difference between the SMU input voltage and MSP430 output voltage estimates for the error. LMT01-Q1 pulses are converted into temperature using the characteristic equation provided in the LMT01-Q1 datasheet.

TC temperature is added with the CJC temperature and can estimate the error using input and output temperature values.

4.2.3 CJC Channel Accuracy (LMT01-Q1 Accuracy)

LMT01-Q1 pulses are converted into temperature using the characteristic equation provided in the LMT01-Q1 datasheet. The temperature chamber is maintained at various temperatures (from –40°C to 125°C), and per measurement, 30 samples have been taken to estimate the LMT01-Q1 error. A graph is plotted between the LMT01-Q1 temperature and the deviation from the original value.

4.3 Temperature Error of Thermocouple Channel With and Without CJC

A thermocouple type N over a temperature range of –40ºC to +1300ºC produces a corresponding output voltage from –1.269 mV to 47.477 mV. Voltage is applied across thermocouple input channels and the output is recorded in the computer. The TIDA-01235 board remains in the temperature chamber and estimates errors from –40ºC to +125ºC. Figure 16 shows the test setup. The source meter and multimeter are automated in such a way to feed the thermocouple voltage from –1.269 mV to 47.477 mV in different steps.

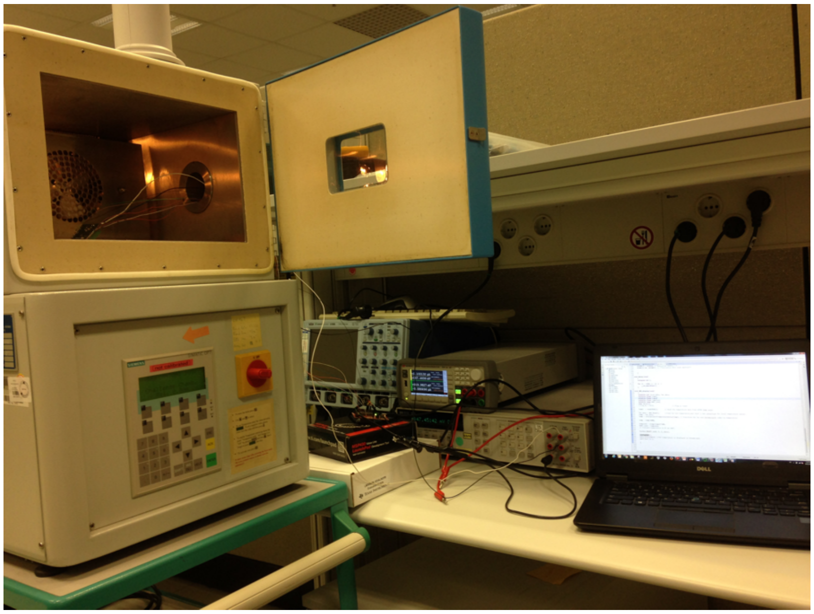

Figure 16. Test Setup

The temperature chamber is set to –36ºC, 0ºC, 25ºC, 75ºC, and 125ºC and the thermocouple temperature accuracy is analyzed at intermittent temperatures between the temperature range from –40ºC to +1300ºC at equivalent voltages of –1.269 mV to 47.477 mV.

Graphs terminology

Error (TC): Error_TC is defined as the total ADC channel error. Error_TC includes the ADC gain, offset, and linearity error but excludes the error due to CJC from the LMT01-Q1 device. The exact temperatures are calculated from the thermocouple output voltage using look-up tables.

Error (TC + CJC): Error_TC + CJC is defined as the total error including ADC channel error and LMT01-Q1 error. Error_TC includes the ADC gain, offset, and linearity error, which also includes the error due to CJC from the LMT01-Q1 device. The corresponding temperatures are calculated from the thermocouple output voltage using look-up tables and the LMT01-Q1 characteristic equation.

The system accuracy can be further improved by performing a gain calibration. The easiest method of calibration is a one-point gain calibration, which is performed by finding the fraction between the maximum output and maximum input and then multiplying the total set of results with this number. This one-point calibration is performed at room temperature. Additional calibration points at different ambient temperatures increase the accuracy of the results; however, this step has not been performed in this guide. For the gain calibration, several measurements were taken for a thermocouple temperature of 1300°C. The resulting ADC codes were averaged and compared with the ideal, expected ADC code.

Figure 17 through Figure 27 show the measurement results. A voltage from –1.269 mV to 47.477 mV is applied across the thermocouple output terminals when the LMT01-Q1 device is maintained at a constant temperature.

In Figure 17 and Figure 18, the temperature error at 25°C with a gain and offset correction factor (Error_TC) has improved compared to the error without the gain and offset calibration factor (Error_TC + CJC). The error of the thermocouple channel at 25°C is now minimized across the entire input range (–40°C to +1300°C), comparing the results without gain and offset calibration with the results with gain and offset calibration. As is visible in the plots, the graphs have been rotated by the calibration factor around the crossing point of the curves, which is just calibrated for 25°C. The same process can now also be done for other temperature points.

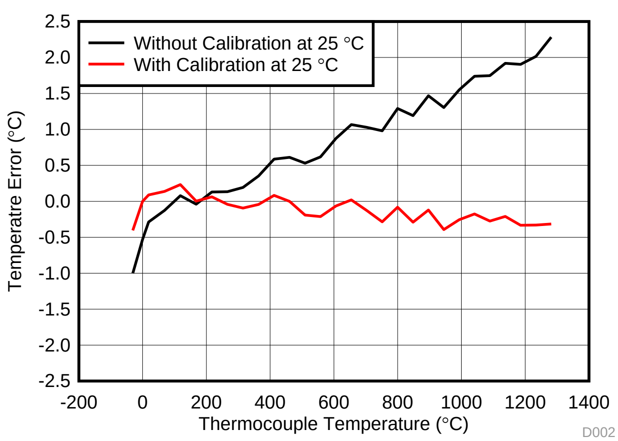

Figure 17. Temperature Error at 25°C for TC Channel

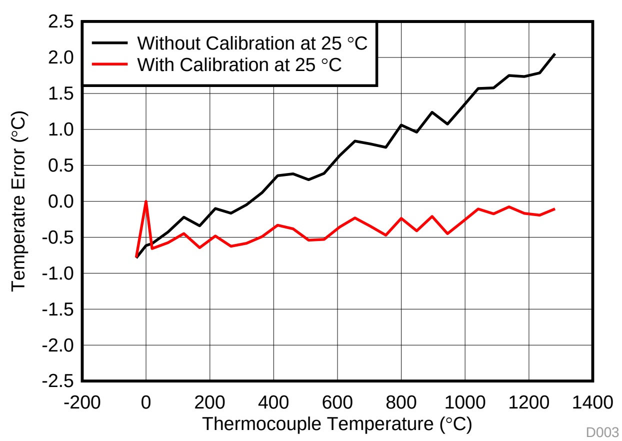

Figure 18. Temperature Error at 25°C for TC + CJC Channel

In Figure 19 and Figure 20, the temperature error at 0°C with gain and offset correction factor (Error_TC) has improved in comparison to the error without the gain and offset correction factor (Error_TC + CJC). The error of the thermocouple channel at 0°C is now minimized across the entire input range (–40°C to +1300°C), comparing the results without gain and offset calibration with the results with gain and offset calibration. As is visible in the plots, the graphs have been rotated by the calibration factor around the crossing point of the curves.

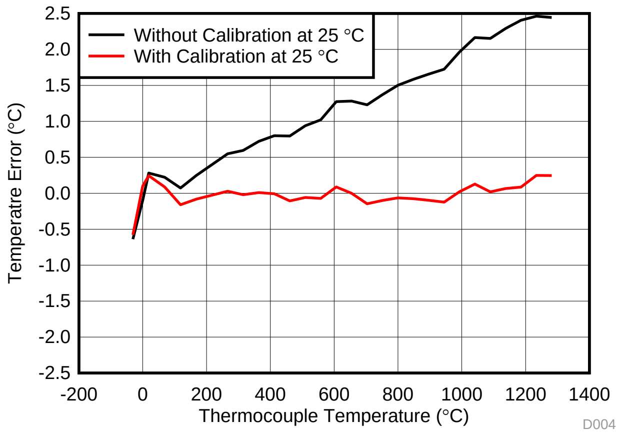

Figure 19. Temperature Error at 0°C for TC Channel

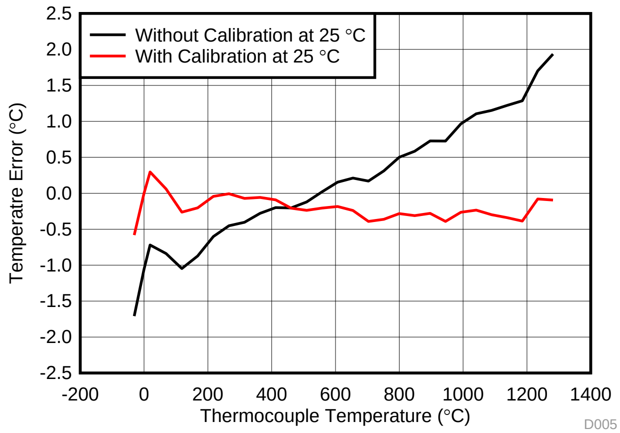

Figure 20. Temperature Error at 0°C for TC + CJC Channel

In Figure 21 and Figure 22, the temperature error at 75°C with gain and offset correction factor (Error_TC) has improved in comparison to the error without the gain and offset correction factor (Error_TC + CJC). The error of the thermocouple channel at 75°C is now minimized across the entire input range (–40°C to +1300°C), comparing the results without gain and offset calibration with the results with gain and offset calibration. As is visible in the plots, the graphs have been rotated by the calibration factor around the crossing point of the curves.

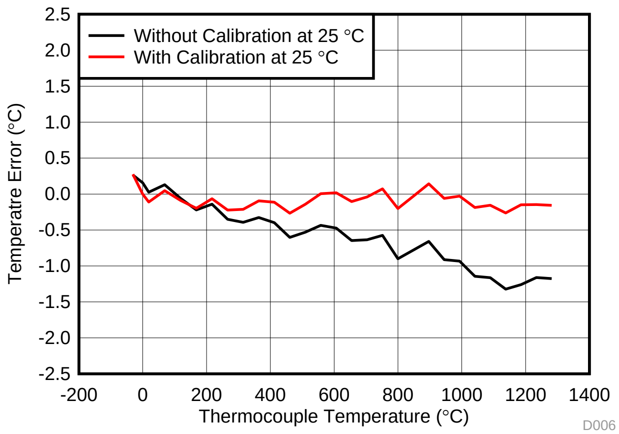

Figure 21. Temperature Error at 75°C for TC Channel

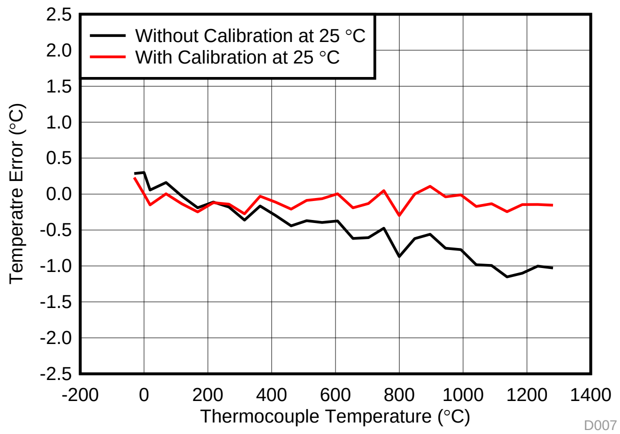

Figure 22. Temperature Error at 75°C for TC + CJC Channel

Figure 23 represents the thermocouple channel error for a temperature range from –40°C to +125°C without gain and offset calibration.

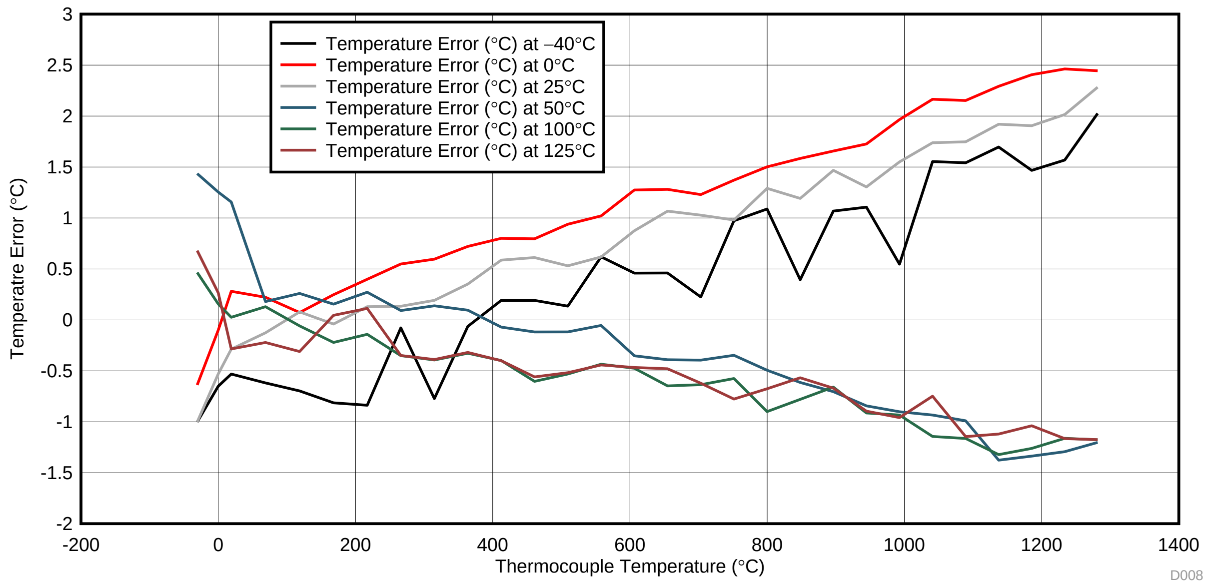

Figure 23. Thermocouple Channel Error in ºC Without Gain and Offset Calibration

Figure 24 represents the thermocouple channel error for a temperature range from –40°C to +125°C with gain and offset calibration.

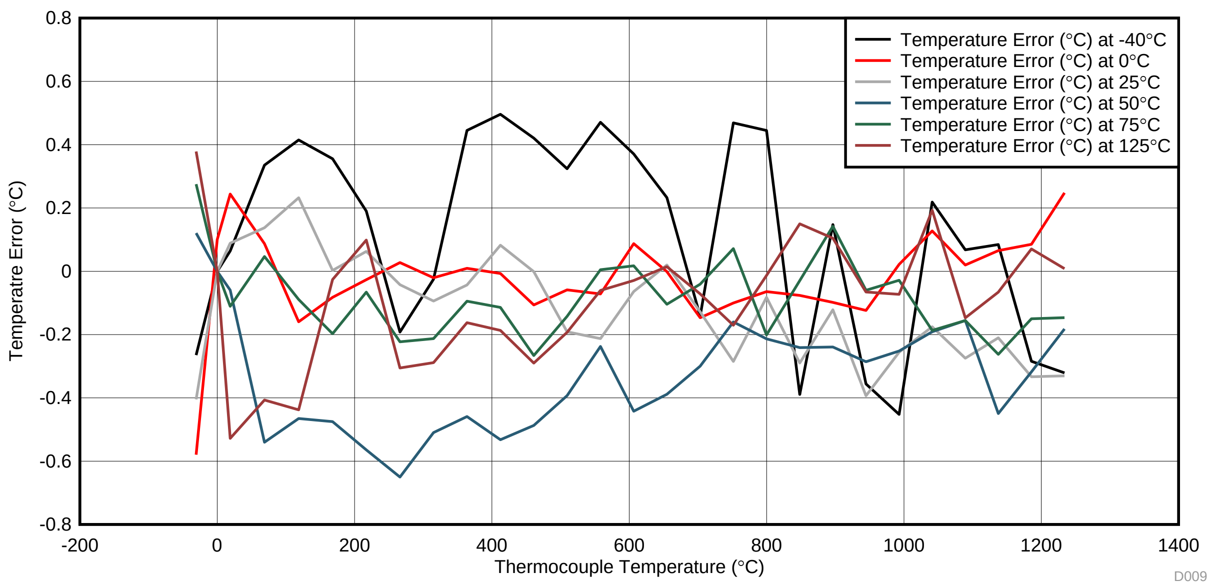

Figure 24. Thermocouple Channel Plus CJC Error in ºC With Gain and Offset Calibration

The preceding Figure 23 and Figure 24 show the error by taking the entire set of data again over the ambient temperature –40°C to +125°C; however, with a gain and offset correction factor, the resulting temperature error can be seen in Figure 24. Comparing the results without gain calibration (Figure 23) with the results with gain and offset calibration (Figure 24), it is visible that the graphs have been rotated by the calibration factor around the crossing point of the three curves and with an observable that error is less than ±1°C.

4.4 Temperature Error of LMT01-Q1 Channel

Plot the temperature error for the LMT01-Q1 channel by placing the temperature chamber at a particular temperature and measuring the performance of LMT01-Q1 for about 30 sample points. In this design, multiple readings of ambient temperature were taken at –36°C, 0°C, and 25°C. The LMT01-Q1 channel error directly impacts the overall system accuracy. The temperature error graphs in Figure 25, Figure 26, and exclusively show the error due to the measurement system.

Figure 25 shows the LMT01-Q1 error when the temperature chamber temperature has been placed at –36ºC

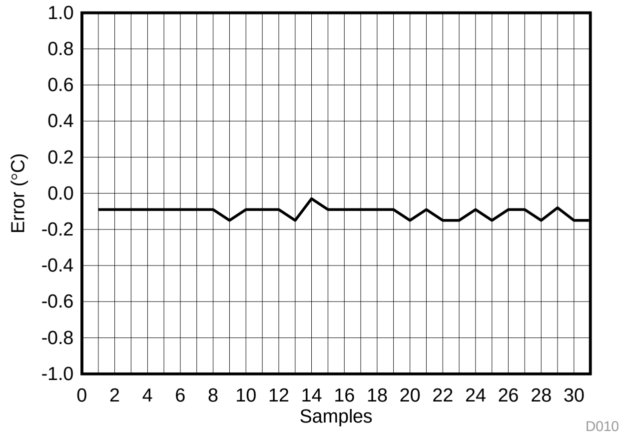

Figure 25. LMT01-Q1 Temperature Error at –35ºC

Figure 26 shows the LMT01-Q1 error when the temperature chamber temperature has been placed at 0ºC.

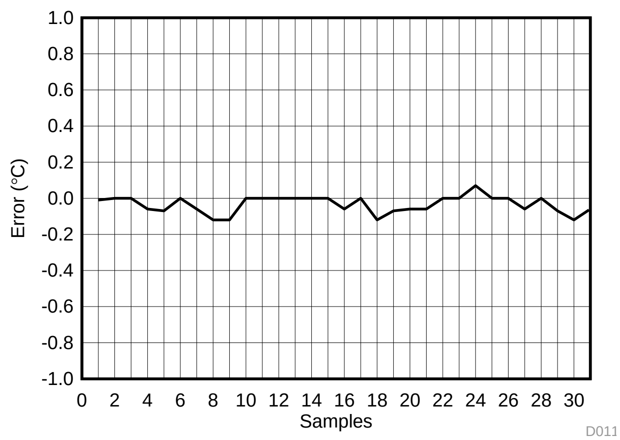

Figure 26. LMT01-Q1 Temperature Error at 0ºC

Figure 27 shows the LMT01-Q1 error when the temperature chamber temperature has been placed at 25ºC.

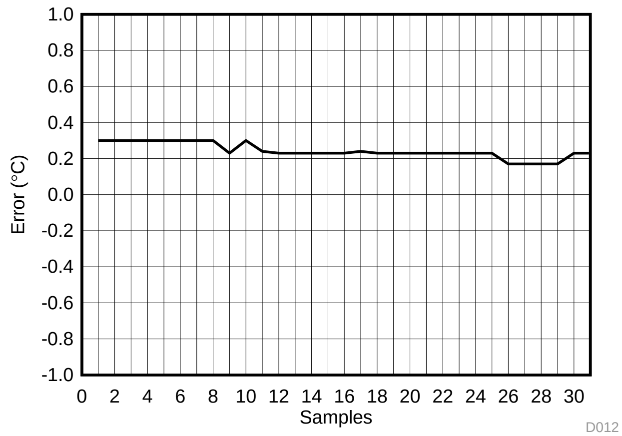

Figure 27. LMT01-Q1 Temperature Error at 25ºC

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01235.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01235.

5.3 PCB Layout Recommendations

5.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01235.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01235.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01235.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01235.

6 Software Files

To download the software files, see the design files at TIDA-01235.

7 Related Documentation

1. Texas Instruments, *Precision Thermocouple Measurement with the ADS1118-Q1*, Application Report (SBAA189)
2. Texas Instruments, *Isolated Loop Powered Thermocouple Transmitter*, TIDA-00189 Design Guide (TIDU449)
3. Texas Instruments,*Thermocouple AFE Using RTD or Integrated Temperature Sensor for Cold Junction Compensation (CJC)* TIDA-00168 Design Guide (TIDU574)

7.1 Trademarks

8 About the Author

SANDEEP TALLADA is a systems engineer at Texas Instruments. As a member of the Automotive Systems Engineering team, Sandeep focuses on powertrain end-equipment and creating subsystem reference designs. He brings to this role experience in sensor systems technology. Sandeep earned his master of science in sensor systems technology from the University of Applied Sciences Karlsruhe, Germany.

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