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TI Precision Designs: Verified Design

Precision Thermocouple Measurement with the ADS1118

TEXAS INSTRUMENTS

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Circuit Description

This Thermocouple measurement Verified Design provides a very simple and accurate way to implement a thermocouple measurement. This design outlines the necessary anti-aliasing filters and biasing resistors to provide sensor diagnostics. This example also provides a novel way of accomplishing cold junction compensation for the system using the ADS1118's onboard temperature sensor. For thermocouple linearization the design also provides a very simple algorithm that can be implemented on most microcontrollers.

Design Resources

Design Archive	All Design files
TINA-TI™	SPICE Simulator
ADS1118	Product Folder

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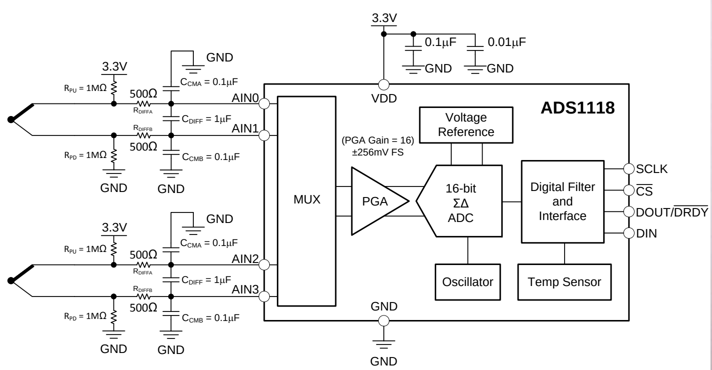

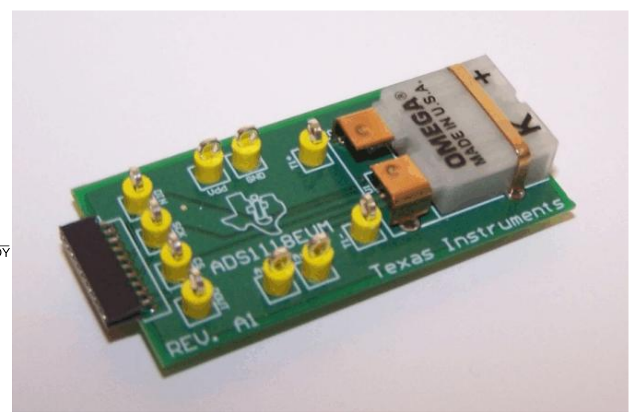

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1 Design Summary

The design requirements are as follows:

- Supply Voltage: 2.0 V to 5.5 V
- Input: Passive filter with less than 5kΩ of series resistance to minimize error
- Verified with K-Type thermocouple with up to 260°C service temperature (sensor end)
- Capable of interfacing with any thermocouple type
- Verified signal chain only accuracy of ±1°C from 0°C to 70°C system temperature (signal chain includes connector, cold junction and ADC with K-type TC error removed)
- Operating system temperature range for connector, cold junction and ADC -40°C to 125°C
- Verified system accuracy of ±2.5°C from -40°C to 150°C thermocouple service temperature (sensor end temperature)
- Verified system repeatability better than 0.25°C
- 60dB of signal chain noise rejection at 250kHz
- 5 V continuous overvoltage protection on inputs above supply and below ground
- 50 V momentary overvoltage protection on inputs above supply and below ground
- Microcontroller with 16 or 32-bit accumulator and SPI port

The design goals and performance are summarized in Table 1. Figure 2 depicts the measured error of the final design.

Table 1. Comparison of Design Goals, Simulation, and Measured Performance

	Goal	Calculated	Measured
Un-calibrated Signal Chain Accuracy (sensor error removed)	±1°C	±0.54°C	±0.4°C
Un-calibrated System Accuracy (sensor error dominant)	±2.5°C	±2.27°C	±1.3°C
System Repeatability	0.25°C	0.25°C	0.25°C

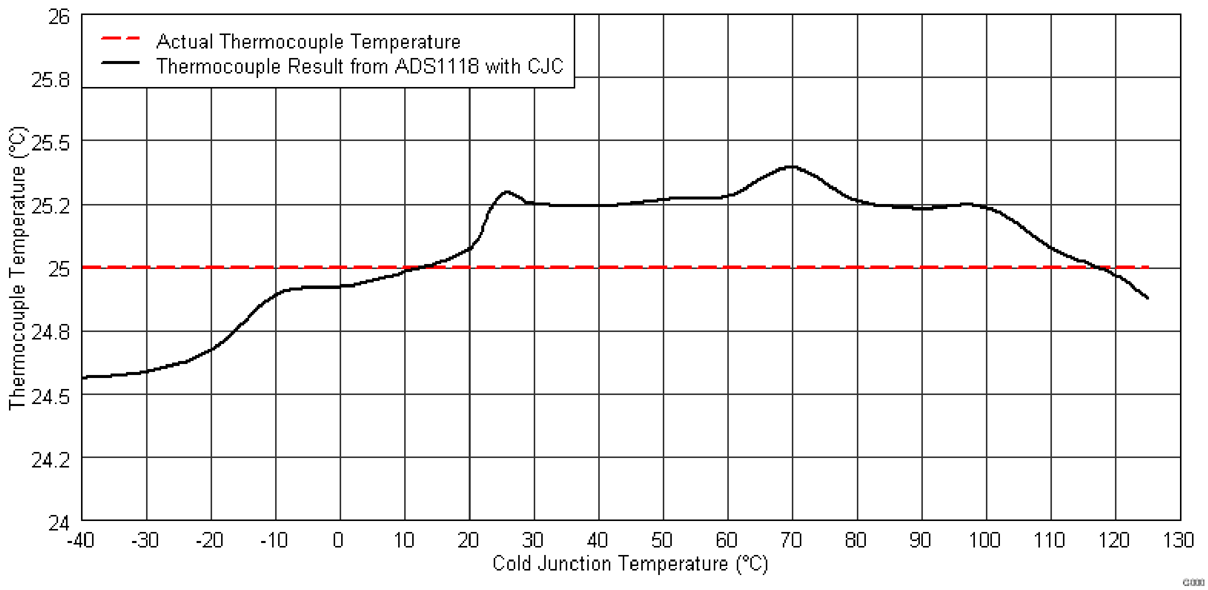

Figure 1: Fixed Thermocouple Accuracy with Varying Cold Junction Temperature

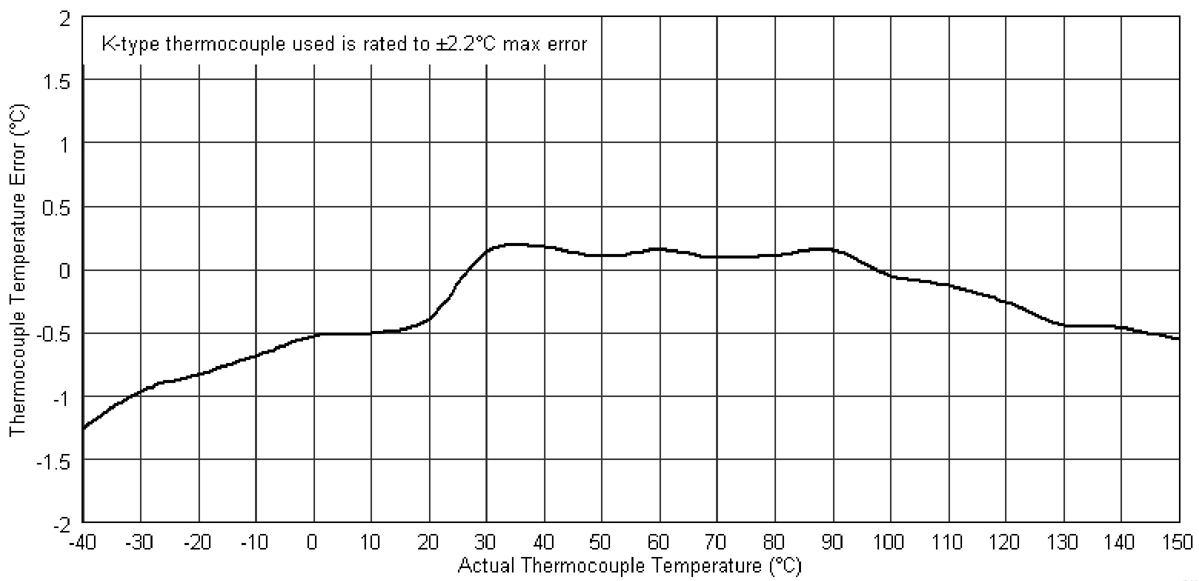

Figure 2: Total Error with Ambient Cold Junction with varying Thermocouple Service Temperature (T_{CJC} = 25°C ± 5°C)

2 Design Theory

Thermocouples are a popular type of temperature sensor. A relatively low price, wide temperature range, long-term stability, and suitability with contact measurements make these devices very common in a wide range of applications. While achieving extremely high accuracy with a thermocouple can be more difficult than a resistance temperature detector (RTD), the low cost and versatility of a thermocouple often make up for this difficulty in accuracy. Additionally, in contrast with thermistors and RTDs, the use of thermocouples often simplifies application circuitry because they require no excitation. That is, these sensors generate their own voltage and therefore only need a reference and some form of ice point or cold junction compensation.

A thermocouple is a length of two wires made from two dissimilar conductors (usually alloys) that are soldered or welded together at one end, as show in Figure 3. The composition of the conductors used varies widely, and depends on the required temperature range, accuracy, lifespan, and environment that is being measured. However, all thermocouple types operate based on the same fundamental theory: the thermoelectric or Seebeck effect. Whenever a conductor experiences a temperature gradient from one end of the conductor to the other, a voltage potential develops. This voltage potential arises because free electrons within the conductor diffuse at different rates, depending on temperature. Electrons with higher energy on the hot side of the conductor diffuse more rapidly than the lower energy electrons on the cold side. The net effect is that a buildup of charge occurs at one end of the conductor and creates a voltage potential from the hot and cold ends. This effect is illustrated in Figure 4.

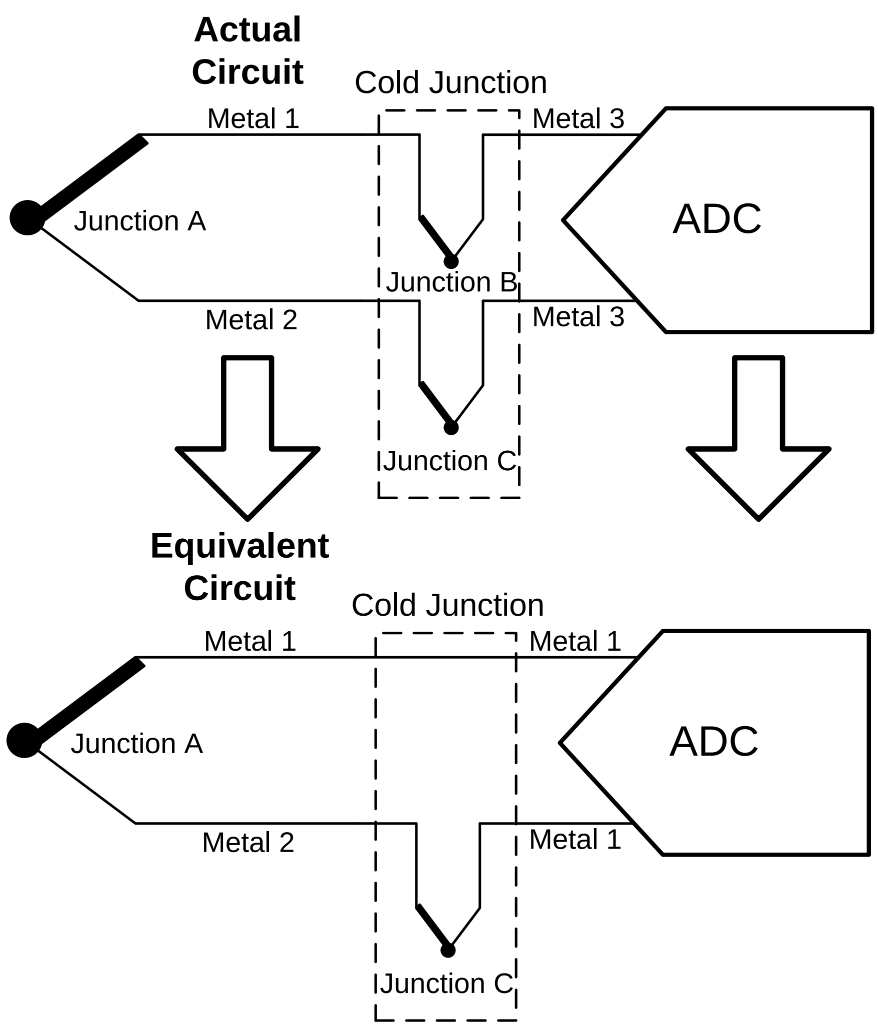

Figure 3: Thermocouple Junction Diagram

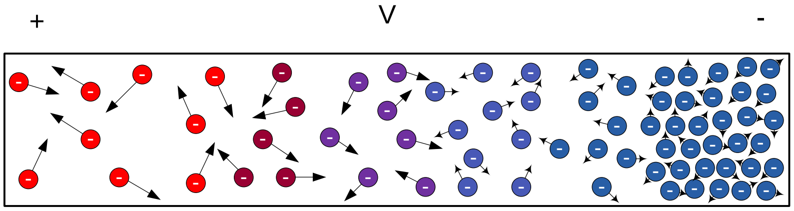

Figure 4: Illustration of the Seebeck Effect

Different types of metals exhibit this effect at varying levels of intensity. When two different types of metals are paired together and joined at a certain point (junction A in Figure 3), the differences in voltage on the end opposite of the short (junctions B and C) are proportional to the temperature gradient formed from either end of the pair of conductors. The implication of this effect is that thermocouples do not actually measure an absolute temperature; they only measure the temperature difference between two points, commonly known as the hot and cold junctions. Therefore, in order to determine the temperature at either end of a thermocouple, the exact temperature of the opposite end must be known.

In a classical design, one end of a thermocouple is kept in an ice bath (junctions B and C in Figure 3) in order to establish a known temperature. In reality, for most applications, it is not practical to provide a true ice point reference. Instead the temperature of junctions B and C of the thermocouple are continuously monitored and used as a point of reference to calculate the temperature at junction A at the other end of the thermocouple. These junctions are known as the cold junctions or ice point for historical reasons, although they do not need to be kept cold or near freezing.

These endpoints are referred to as junctions because they connect to some form of terminal block that transitions from the thermocouple alloys into the traces used on the printed circuit board, or PCB (usually copper). This transition back to copper is what creates the cold junctions B and C. Because of the law of intermediate metals, junctions B and C can be treated as a single reference junction, provided that they are held at the same temperature or isothermal. Once the temperature of the reference junction is known, the absolute temperature at junction A can be calculated. Measuring the temperature at junctions B and C and then using that temperature to calculate the temperature at junction A is known as cold junction compensation.

In many applications, the temperature of junctions B and C are measured using a diode, thermistor, or RTD. As with any form of cold junction compensation, it is important that two conditions are met to achieve accurate thermocouple measurements:

- **Junctions B and C must be kept isothermal or be held at the same temperature.** This condition can be achieved by keeping junctions B and C in very close proximity to each other and away from any sources of heat that may exist on a PCB. Many times, isothermal blocks are used to keep the junctions at the same temperature. A large mass of metal offers a very good form of isothermal stabilization. For other applications it may be sufficient to maximize the copper fill around the junctions. By creating an island of metal fill on both top and bottom layers, joined with periodically placed vias, a simple isothermal block can be created. It is important to ensure that this isothermal block cannot be impacted by parasitic heat sources from other areas in the circuit, such as power conditioning circuitry.
- **The isothermal temperature of junctions B and C must be accurately measured.** The closer that a temperature sensor (such as a diode, RTD, or thermistor) can be placed to the isothermal block, the better. Air currents can also act to reduce the accuracy of the cold junction compensation measurement. To achieve the best performance, it is recommended to ensure that the cold junction be kept within an enclosure and that air currents be kept to a minimum near the cold junction. In applications where air currents are unavoidable, it may be useful to find a mechanical method to cover the sensor measuring the cold junction in the form of some type of shielding that protects the cold junction from air currents. It is also important to remember that the orientation of the PCB can

impact the accuracy of the cold junction compensation. If there are heat-generating elements physically below the cold junction, for example, inaccuracies can become significant as heat from those elements rises.

Input Signal Conditioning: The importance of signal conditioning is critical in any design. Due to the effects of aliasing, any ADC, regardless of architecture, need some amount of filtering on its inputs to reduce noise in the system. Because of the digital filter in delta sigma ADCs, the requirements of an external analog filter are significantly reduced, but some filtering is still needed. A simple filter, such as the one shown in Figure 5 will offer a great balanced differential filter design. These filters are important for rejecting any noise that might be subjected to the ADC inputs that 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. Noises at these frequencies have no way of being rejected digitally by the data-converter and must be rejected through analog input filtering. Delta sigma ADCs will specify the frequency that the modulator samples at to allow external filters to be designed accordingly.The ADS1118, for example, has a modulator sampling frequency of 250kHz.

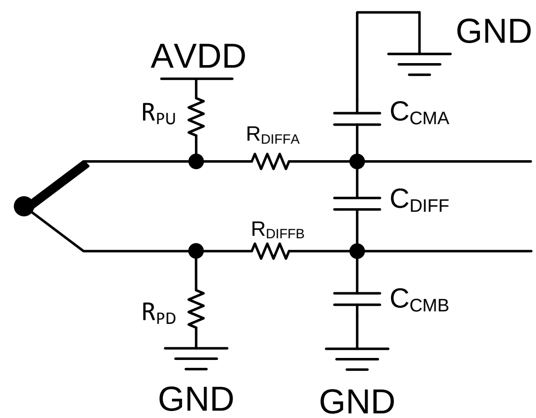

Figure 5: Signal conditioning with first order low-pass filter

The input signal conditioning circuit in Figure 5 has some very desirable properties. It offers filtering, biasing, overvoltage protection and sensor open detection. It includes a simple bias generation through R_{PU} and R_{PD}, which will center the thermocouple between supply and ground. This is often an ideal common-mode for most input devices such as ADCs, Opamps and PGAs. Additionally, in this application if a thermocouple is disconnected these resistors will automatically drive both inputs to supply and ground giving an obvious sensor disconnect condition to an ADC. These resistors do add a small amount of noise so for very high precision designs that thermal noise should be accounted for when choosing the size of these resistors. Alternatively, some products such as the ADS1247/8 have a built in bias generation and burnout current sources that remove the need for these resistors.

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, this can allow significant robustness to the inputs and protect from ESD and long term overvoltage conditions. The filter shown in Figure 5 is a very commonly used structure for differential signals. However, there are a few important points to keep in mind when selecting components.

1. Because mismatches in the common-mode capacitors cause differential noise, it is recommended that the differential capacitor be at least 10x greater than the common-mode capacitors.

2. To achieve good electromagnetic interference (EMI) immunity, it is important to remember that simply placing large capacitors in the signal path and supply are not effective at attenuating high noise frequency components. Using small (10nF and lower) capacitors with low equivalent series resistance (ESR) and low dielectric absorption (DA) in parallel with another higher capacitance capacitor on sensitive supply and signal paths can offer significant improvements to EMI immunity.

3. Additional EMI protection can further be realized by incorporating a ferrite bead or common-mode choke to the inputs. If there is significant concern that there may be frequent exposure to electrical overstress or electrostatic discharge (ESD), Schottky clamp diodes or TVS diodes can be added to the exposed inputs before the input filter. These components can all impact performance and their leakages should be considered before adding them to a signal chain.

Selecting actual filter values is pretty straight forward. For a thermocouple, the actual signal is not expected to change quickly, so very low cutoff filters <10Hz are not unreasonable and will offer very good noise performance if quality capacitors are used. For a very low cutoff low-pass filter, it would be preferred to use as large of a differential capacitor as possible, with the smallest possible resistor values to achieve the lowest possible frequency cutoff and in-band noise. However, the required component values may not be practical. For example, the differential filter shown in Figure 5 has the following equation for calculating the low frequency cutoff.

$$f_{C-DM} = \frac{1}{2\pi\left(R_{DIFFA} + R_{DIFFB}\right)\left(C_{DIFF} + \frac{C_{CM}}{2}\right)} \tag{1}$$

As an example, consider a design where a 10Hz filter cutoff is desired. Additionally, consider that there may be a certain constraint to how high the series resistances can be, perhaps 500Ω. To create a filter with 500Ω of series resistance, C_{DIFF} would need to be 15µF and C_{CM} would need to be 1.5µF. For many applications capacitors of this size are not practical and instead higher resistances or moving to a higher bandwidth would be needed. However, higher resistances can cause significant errors when the input impedance of the ADC is small. Also, R_{DIFFA} and R_{DIFFB} should be kept the same so that any common mode currents are cancelled out. For applications in noisy environments a second or third stage filter will help make sure that more adequate high frequency rejection occurs. For example, using the structure in Figure 6, which is essentially a duplication of the filter in Figure 5 and reducing R_{DIFFA}, R_{DIFFB}, R_{DIFFC} and R_{DIFFD} to 250Ω would yield a similar, although slightly higher 3-dB cutoff, but would significantly improve the filter roll-off. This effect can be seen in Figure 7. Figure 7 also shows the result from adding a 3rd stage and reducing the R_{DIFF} resistors to 150Ω.

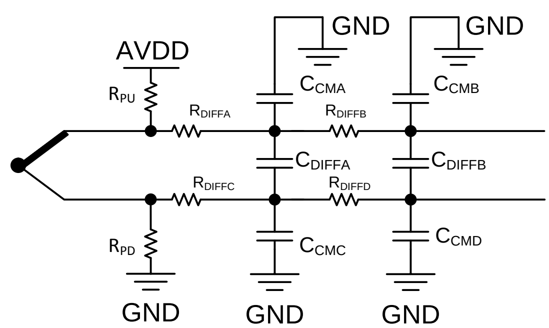

Figure 6: Signal conditioning with second order low-pass filter

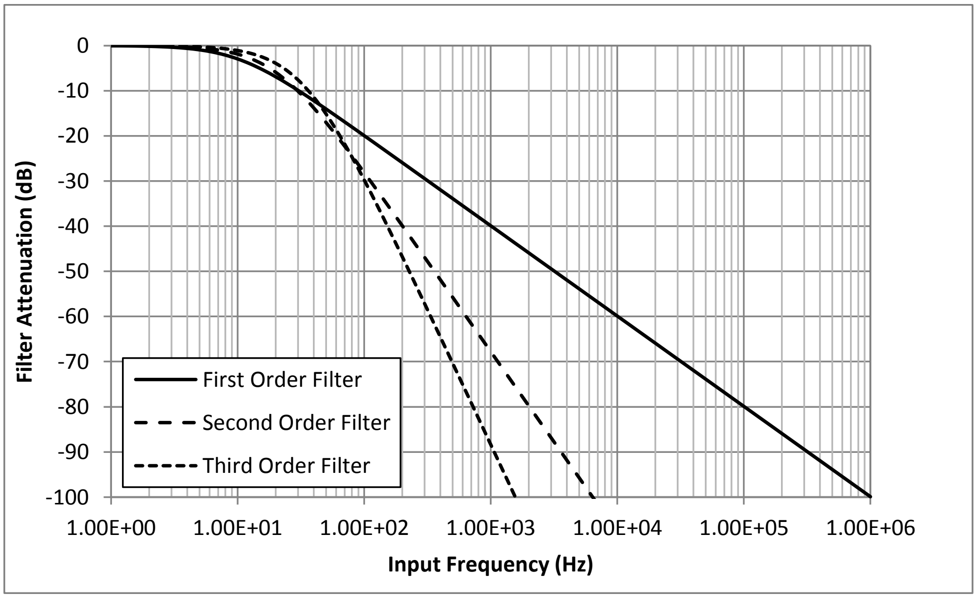

Figure 7: Bode plot of varying filter orders

3 Component Selection

Before designing and laying out an actual system, first examine the overall requirements of the system and begin component selection based on the design targets. Carefully analyzing these parameters will help reveal which error sources contribute to the majority of the total error of the system. For this design, the total thermocouple temperature range is limited to -40°C to 150°C due to equipment measurement limitations of a thermal bath used in this experiment. The actual design is capable of temperatures much greater, although a more advanced system would need to be employed to verify the accuracy at high temperatures. Also, all calculations are based on a standard K-type thermocouple with ±2.2°C of un-calibrated accuracy. Accuracy will depend on the type of thermocouple used and the amount of calibration used to remove thermocouple errors.

ADC Selection: There are many different types of ADCs that can interface well with thermocouples and offer varying performance levels. However, the ADS1118 is the smallest and lowest cost precision implementation of thermocouple measurement. The integration of an internal voltage reference, multiplexer, and temperature sensor make the ADS1118 an ideal option for this design, however there are other options to choose from which offer even greater performance. For added resolution, gain and a buffer the ADS1220 or ADS1247 can offer significantly better repeatability, precision and allows more aggressive input filters to further reduce noise by having higher series resistances on the inputs. However, for the purposes of the design targets, the intention is to utilize as few components as possible and limit performance only to what is needed to accomplish the design goals. Table 2 shows a comparison of a few of TIs ADCs designed for thermocouple measurement.

Table 2. ADC Comparison

	ADS1118	**ADS1220**	**ADS1248**
Resolution	16-bit	24-bit	24-bit
Gain	8	128	128
Input Noise @20SPS	2uVrms	120nVrms	90nVrms
Differential Input Impedance	710kΩ	>100MΩ	>100MΩ
Reference Drift	7	7	2
CJC Sensor	Internal	Internal	External
Power (3.3V Supply)	0.5mW	1.55mW	2.2mW
Price	$2.30	$3.95	$4.45

Filter Component Selection: For the filter design using the ADS1118, a very simple first order filter is being used. This is due to the expected small form factor and cost requirements for this reference design. This filter could easily be cascaded into higher order filters to provide greater higher frequency noise immunity.

Errors introduced through input filters can be, and are usually calibrated out in most systems. However, for this uncalibrated example, the ADS1118 has roughly 710kΩ of differential input impedance. This increases gain error as sensor output and filter impedances increase. In selecting the filter for this design there will be a tradeoff between lowering the cutoff and using small value components. Ideally, a lower cutoff frequency and a higher the order filter is preferred for a design with a thermocouple due to the low bandwidth of the sensor (<1Hz). However, designing an extremely aggressive high order passive filter will introduce large resistances in front of the ADC, which will interact with the differential input impedance of the ADS1118. For this design the constraint is on keeping the signal rejection at 250kHz below 60dB. The 60dB used for this design is somewhat arbitrary and depends on the expected noise environment the system will be deployed in. In this case, 60dB corresponds to less than 1LSB peak-to-peak of noise from 4mV peak-to-peak of direct differential mode noise injected directly to the filter inputs at the limited bandwidth around 250kHz.

Given that:

$$-60dB = 20\log[10^{-3}] \tag{2}$$

The filter will need to reduce noise at 250kHz by a factor 1000. If 1LSB at a full scale range of ±0.256mV for a 16-bit ADC is:

$$LSB = \frac{FSR}{2^{16}} \tag{3}$$

$$= \frac{0.512V}{65536}$$

$$= 7.8125\mu V$$

Because 7.8125µV is equivalent to 1LSB, it can be expected that 7.8125mV of noise within the limited bandwidth around 250kHz will be rejected to less than 1 LSB. Now that the rejection at 250kHz of 60dB is desired, a cutoff frequency to achieve this can easily be calculated. Since the first order filter in this design rejects at 20dB per decade, the corresponding -3dB frequency would be simply be 3 decades down from 250kHz or 250Hz.

With a desired cutoff frequency in mind, actual component values can be selected. Because of how common and physically small in ceramic form they are C_{DIFF} and C_{CM} are selected as 1µF and 0.1µF respectively. With these components selected, Equation 1 can be re-arranged to solve for R_{DIFF}.

$$R_{DIFF} = \frac{1}{4\pi f_{C-DM}\left(C_{DIFF} + \frac{C_{CM}}{2}\right)} \tag{4}$$

$$= \frac{1}{4\pi \times 250Hz \times \left(1\mu F + \frac{0.1\mu F}{2}\right)}$$
$$= 303.152\,\Omega$$

This means that as long as R_{DIFF} is greater than or equal to around 300Ω, there will be at least 60dB of filter attenuation at 250kHz. In addition to the filter cutoff, this design needs to be able to withstand up to 5V above supply or below ground. To select a suitable resistance for the protection, look to the Absolute Maximum Ratings section of the ADS1118 datasheet. This is present on all TI data-converter datasheets.

ABSOLUTE MAXIMUM RATINGS(1)

	VALUE	UNIT
VDD to GND	–0.3 to +5.5	V
Analog input current	100, momentary	mA
	10, continuous	mA

Figure 8: Absolute Maximum Ratings table from ADS1118 datasheet

Notice that the ADS1118 can withstand up to 10mA of continuous current on any of its inputs. That means that in order to limit the current to less than 10mA, the series resistance would need to be:

$$R_{DIFF} = \frac{\text{Overvoltage amount (V)}}{\text{Maximum rated continuous input current (A)}} \tag{5}$$

$$= \frac{5V}{10mA}$$

$$= 500\Omega$$

Also note that this also satisfies the 50V momentary overvoltage according to the datasheet maximum ratings. Given that 500Ω satisfies both the input filter cutoff requirements and the overvoltage requirements, it can serve as the baseline for calculating the amount of error it will introduce into the system. Figure 9 shows the final filter profile. The actual filter cutoff with these values is 132Hz with a 250kHz filter rejection of 64.3dB.

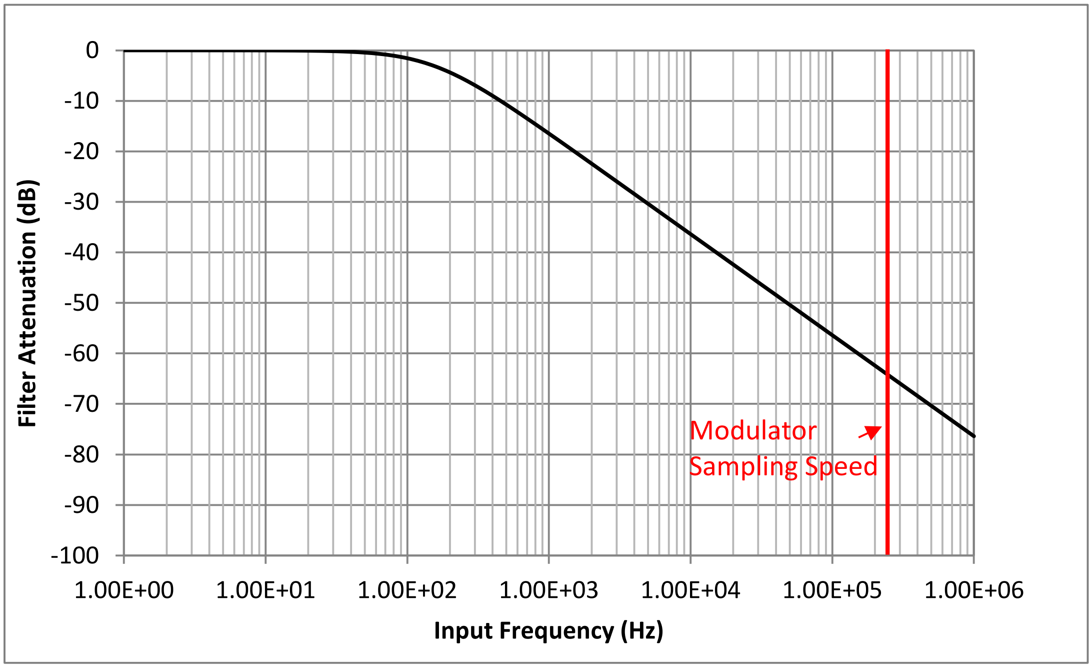

Figure 9: Final signal chain filter bode plot

R_{PU} and R_{PD} should be sized as high as possible without introducing too much additional noise. For this design, they will be sized to keep their noise contribution to 1LSB peak to peak or less. A small amount of noise from these resistors will become useful later to employ some dithering to the system to obtain higher resolution. They are perfect for this because the noise they generate is very statistically Gaussian and very easy to average out. From equation 3, 1LSB was calculated to be 7.8125uV. Using the Johnson-Nyquist equation for resistor noise:

$$v = \sqrt{4kTR} \tag{6}$$

Where

$$k = 1.38 \times 10^{-23} \mathrm{J/K}$$

A simple calculation can be made to put a bound on R. For this calculation, the bandwidth of noise is to be limited within the passband of the filter used on the input, which is 132Hz from the previous filter discussion. Since v in equation 6 has units of nV/rtHz, the target value for v is:

$$v = \frac{8.125\mu V}{\sqrt{132}} = 707nV/\sqrt{Hz} \tag{7}$$

This means that the total R_{PD} and R_{PU} should be:

$$R_{PU} + R_{PD} \leq \frac{v^2}{4kT} \tag{8}$$

$$R_{PU} + R_{PD} \leq 30.2\ M\Omega$$

Since there is no need to use a value that large, a 1MΩ resistor for each is sufficient to accomplish the task without adding too much noise.

System Error Calculations

- **Filter Errors:** The anti-aliasing filter is the largest source of un-calibrated systematic error. It presents a significant source of gain error to the system and is calibrated out of most systems. Given that 1000Ω of total series input resistance has been added to the signal chain, it will interact with the 710kΩ differential input impedance of the ADS1118. This will manifest itself as a gain error in the system. Based on these values, it can be expected that the filter will cause the following error to the DC signal:

$$\mathrm{Error\%} = \frac{\mathrm{R_{DIFF}}}{\mathrm{R_{DIFF}} + \mathrm{InputZ}} \tag{9}$$

$$= \frac{1\ k\Omega}{1\ k\Omega + 750\ k\Omega} \times 100\%$$

$$= 0.133\%$$

  This error will scale with input signal, so at 0V differential input, there will be no error. However at the largest thermocouple voltage from the Omega K-type thermocouple of 260°C a 10.561mV signal will be attenuated to:

$$\mathrm{V_{Actual}} \times (1 - \mathrm{Error\%}) = \mathrm{V_{Measured}} \tag{10}$$

$$10.561mV \times (100\% - 0.133\%) = 10.547mV$$

  This 14µV of error corresponds to roughly 0.34°C of error at 260°C and scales linearly with temperature. As a benchmark, this indicates that at 260C, every 0.1% of error contributes about 0.29°C of total system error.

- **Passive component inaccuracies and drift:** Much like any active IC in a system, passive components also suffer from temperature drift. In this design, they will introduce a negligible amount of error. That said, the series filter resistors will present the largest passive drift error in the system. A typical surface mount resistor will have roughly 100ppm/°C drift. This drift will change the amount of error that the series resistors normally introduce, which makes this error source very difficult to calibrate out. Fortunately, at 100ppm/°C, they don't introduce very much variance in the gain error. For a 0°C to 70°C signal chain that corresponds to 7ppm or a resistor variance of 0.7%. It is essentially changing the error from the above filter error by 0.7%. This is obviously a very small variation and can be ignored in this implementation.

- **ADC Gain Error and drift:** The ADS1118 also has some amount of error that is introduced in the form of gain error and drift due to the ADC. Fortunately, the ADS1118 is already calibrated to a typical value of 0.01% gain error and 7ppm/°C of drift. Although these specifications are tighter in comparison to the passive component errors, they play a much greater role in determining the overall accuracy of the system. A 0.01% gain error translates to around 0.029°C of error at 260°C based on the previous benchmark. At 7ppm/°C within a range of 0°C to 70°C corresponds to about 0.049% error shown in equation 11.

$$\frac{7ppm}{°\mathrm{C}} \times (70°\mathrm{C} - 0°\mathrm{C}) \times 10^{-6} \times 100\% = 0.049\% \tag{11}$$

  Based on the previous benchmark, this means that at 260°C at the thermocouple service end the reference drift will contribute roughly 0.15°C of error. Since the initial accuracy at 25°C is so small, and the drift dominates the accuracy, the combination of these two errors yields an error of around 0.16°C. Because this error is almost entirely due to drift, it cannot be easily calibrated out.

- **ADC Linearity Error:** For this design, the non-linearity of the ADC can be ignored. All ADCs have some amount of non-linearity with respect to the input signal. For the ADS1118, the actual non-linearity is less than 1LSB or around 15ppm of full scale. Since in this experiment only a small portion (2%) of full scale will be used, it is likely that the actual linearity will be much better than 15ppm, but even at 15ppm the total temperature error due to non-linearity is roughly 0.005°C. Because this is not a dominant error source, it can be ignored.

- **ADC Offset and drift:** Offset and offset drift can be calibrated out of this system, but will impact accuracy, especially at low temperatures. For the K-type thermocouple used in this example, the manufacturer’s look-up table indicates that at -40°C only 3µV separates 1°C of variation. That means that 10µV of offset specified in the ADS1118 datasheet will correspond to an error of around 0.3°C of error.

- **CJC Error:** The ADS1118 has a high-accuracy delta sigma modulator, onboard temperature sensor, a very small size, and minimal signal path requirements. In addition, with only 500µW of power consumption, the effects of the ADS1118 self-heating are negligible, making the ADS1118 very capable of performing cold junction temperature measurement. The ADS1118's built in linearized temperature sensor has a 0.5°C maximum error from 0°C to 70°C. A 0.25°C 3-sigma maximum can be derived from Figure 26 in the ADS1118 datasheet. This CJC error correlates to a direct 1:1 error with the calculated temperature from the thermocouple.

With all of these primary error sources identified a total system typical error can be calculated for the ADS1118. Because linearity was much smaller than other error sources it will be ignored in this calculation. Keep in mind that errors cannot be directly added; instead they must be added as a root-sum square. This is due to the Gaussian statistical nature of errors that may have both positive and negative magnitudes.

Table 3. Table of System Errors

	Total Unadjusted Error (TUE) varying CJC	Calibrated TUE varying CJC
Input Impedance and Filter Errors	0.34°C	Negligible
Gain Drift Errors	0.16°C	0.16°C
Offset Errors	0.3°C	Negligible
CJC Temp Sensor Error	0.25°C	0.25°C
Total Signal Chain Error	0.54°C	0.3°C
Total System Error (with 2.2°C accurate K-type Thermocouple)	2.27°C	2.22°C

These calculations indicate that the signal chain and ADS1118 can be expected to introduce roughly 0.54°C of un-calibrated error while using the ADS1118's internal temperature sensor for CJC. This can be further reduced by calibrating the systematic gain error introduced by the input filter to 0.3°C. Both of these errors are small enough that they make a very small impact on the total system error because the thermocouple error is the dominant contributor. Clearly to improve performance of this system, a higher accuracy thermocouple or a thermocouple specific calibration would yield the biggest improvement.

There are other places where errors can be introduced, for instance, a non-ideal layout can increase the effect of stray thermocouples, where small parasitic thermocouples form at passive component junctions. When inputs are kept close to each other and isothermal, these errors generally cancel each other out.

Finally, the actual precision or repeatability of the measurement needs to be considered. Precision is different from accuracy, in the sense that a system can be very precise or repeatable, but not necessarily accurate. For this calculation all static errors (non-linearity, offset, gain errors) are removed and only errors that change with time will be included. For precision the predominant error source is noise. Table 4 shows the calculated repeatability based on the ADS1118 specified noise and the corresponding conversion to thermocouple temperature based on the manufacturers look-up table for the K-type thermocouple used in this design. Also, because the peak-to-peak noise is higher than 1LSB, there is enough noise to successfully dither and average readings to reduce the noise.

Table 4. Calculated Repeatability

	Noise Error in µVpp	Noise Error µVpp with a 4 average dither	Noise Error in °C	Noise Error °C with a 4 average dither
8 SPS	10	5	0.25°C	0.125°C
128 SPS	20	10	0.5°C	0.25°C
860 SPS	51.5	25.75	1.25°C	0.625°C

The final schematic with the filter and bias implemented is shown in Figure 10. Although for this design, only one thermocouple channel will be implemented, Figure 10 shows how this could be connected with two separate thermocouple channels. Also, take note of the 0.1µF and 0.01µF capacitors on the supply. These are intended to maintain a consistent voltage when fast current spikes burden the supply. These have a strong impact on performance and should be kept as close to the device as possible. The smaller 0.01µF capacitor provides better immunity for higher frequency noise and is intended to be a lower ESR capacitor than the 0.1µF ceramic.

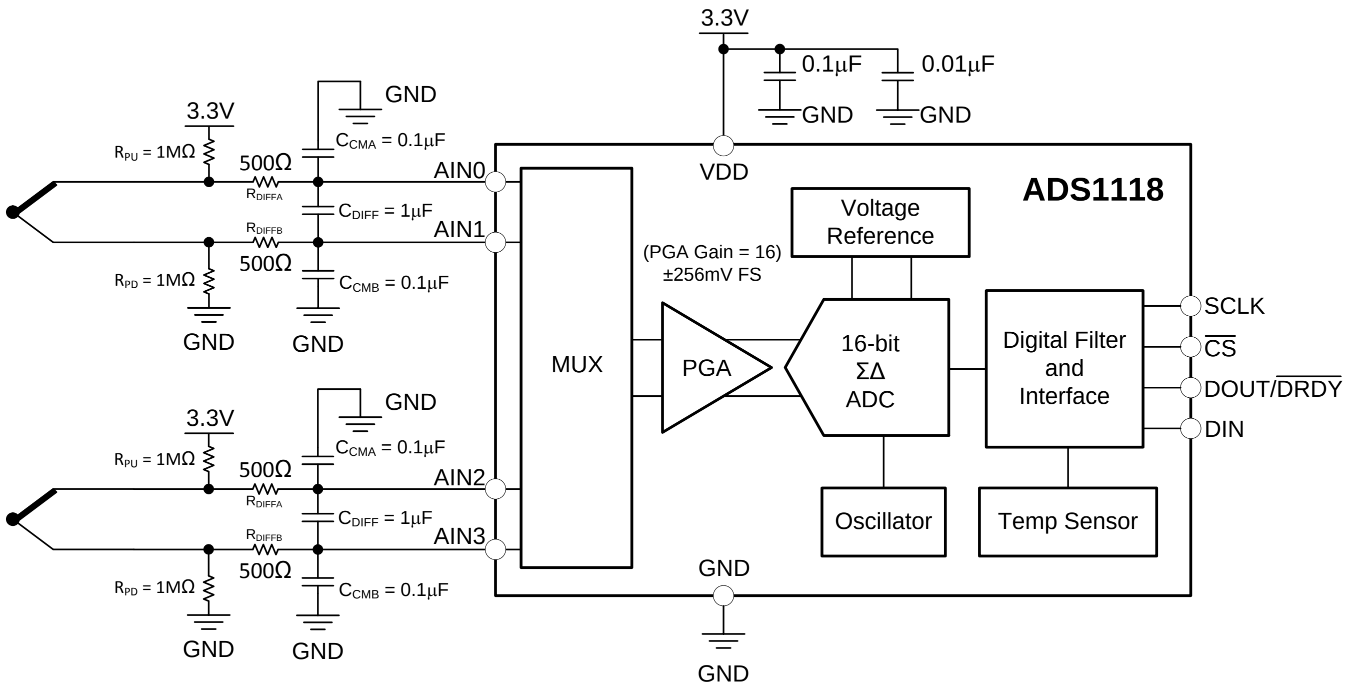

Figure 10: Final signal chain and ADC implementation

4 PCB Design

The PCB schematic and bill of materials can be found in the Appendix.

The layout is designed in a modular way that allows an interfacing board with a microcontroller. In an actual system, a microcontroller, power conditioning, and some form of interface transceiver is likely to be present. In order to achieve optimal noise and thermal performance, it is important to isolate the ADS1118 away from digital components as well as any heat-generating components. Because there are no digital or heat-generating ICs on this board, there is very little error because of noise and parasitic thermal gradients on the board. However for many systems, careful consideration regarding the parasitic heat generated by other components should be carefully considered when performing system layout. Figure 11 shows a good component placement diagram for thermocouple systems using the ADS1118 in addition to commonly-used components within a typical thermocouple system. Notice that the ADS1118 is kept as close to the thermocouple connection as possible. Also note that there is a ground fill around the device and connector.

In the example of Figure 11, several vias are shown that connect to another ground fill on the other side of the board. Having an additional layer helps to improve the temperature consistency of the board. The metal fill not only conducts the temperature of the cold junction to the ADS1118 very well, it also helps ensure that both junctions are kept isothermal. Furthermore, there is a ground fill cut that isolates all other active components from the ADS1118 and the thermocouple cold junction. This layout helps avoid parasitic heat transfer from other active components in the system and can greatly improve noise performance.

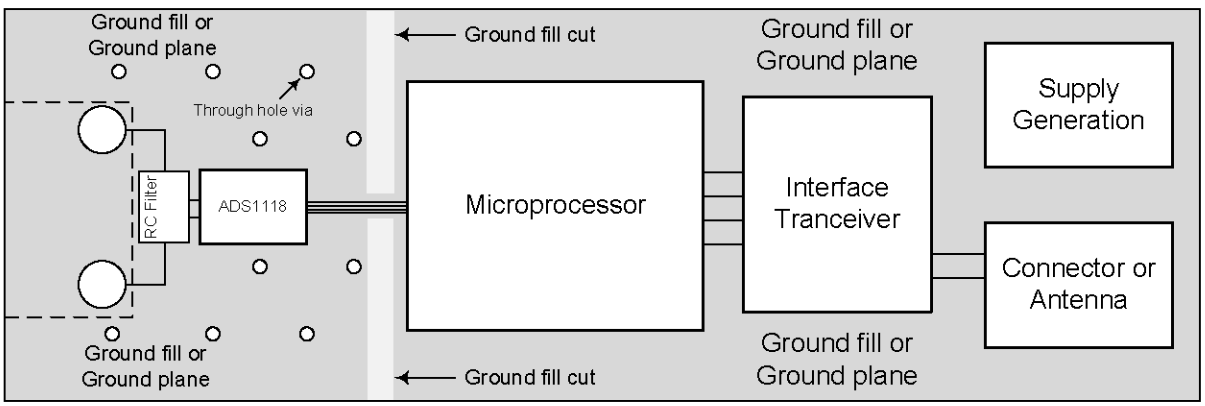

Figure 11: Typical ADS1118 thermocouple application component placement

Because the accuracy of the overall temperature sensor depends on how accurately the ADS1118 can measure the cold junction, careful PCB layout considerations must be employed when designing an accurate thermocouple system. This thermocouple application provides a good starting point and offers an example of one way to achieve good cold junction compensation performance. The design uses the same schematic shown in Figure 10, except with only one thermocouple channel connected. The layout for the design is shown in Figure 12 and Figure 13. In the layout diagram in Figure 12, C10 corresponds to C_{DIFF}, C2 corresponds to C_{CMA}, C3 corresponds to C_{CMB}, R3 corresponds to R_{DIFFA}, R4 corresponds to R_{DIFFB}, R1 corresponds to R_{PU} and R2 corresponds to R_{PD}.

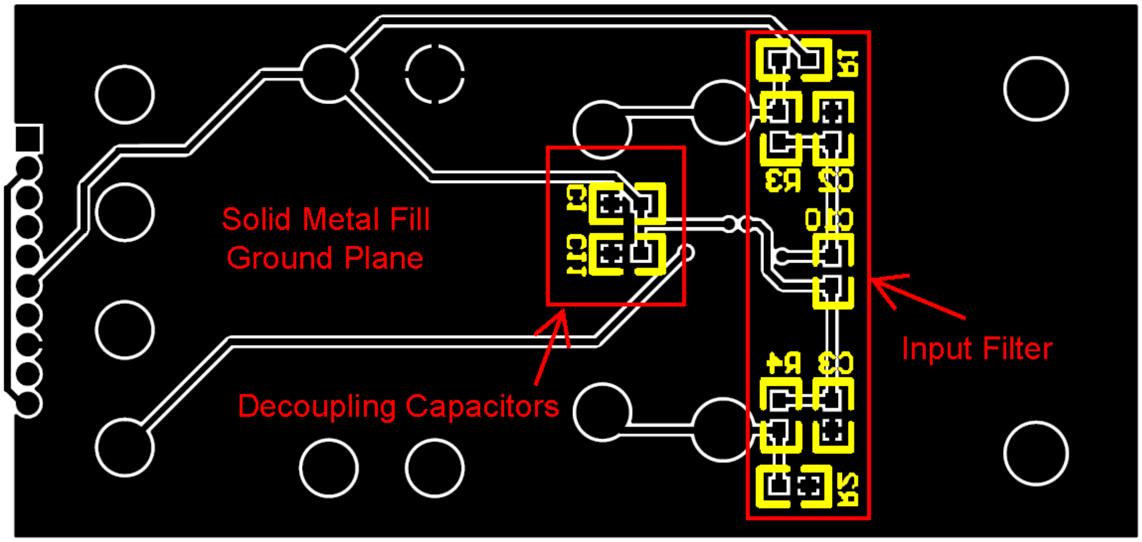

Figure 12: ADS1118EVM Bottom Side Layout

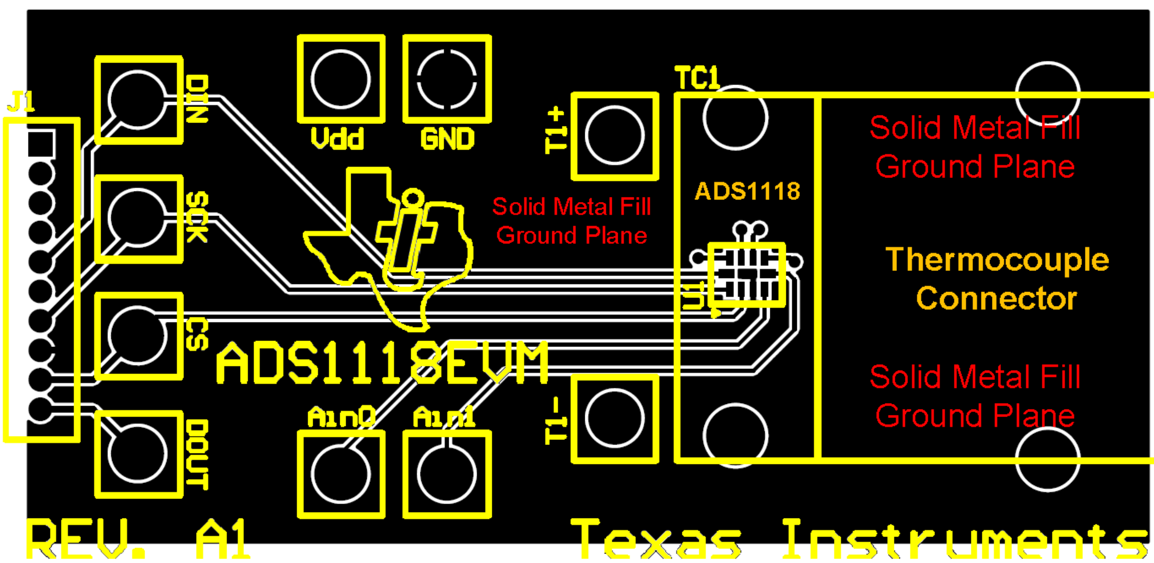

Figure 13: ADS1118EVM Top Side Layout

6 Software Flow

The calculation procedure to achieve cold junction compensation is simple and can be done in several ways. One typical way is to interleave readings between the thermocouple inputs and the temperature sensor. That is, acquire one on-chip temperature result for every thermocouple ADC voltage measured. If the cold junction is in a very stable environment, more periodic cold junction measurements may be sufficient. These operations, in turn, will yield two results for every thermocouple measurement and cold junction measurement cycle: the thermocouple voltage or V_{TC}, and the on-chip temperature or T_{CJC}. In order to account for the cold junction, the temperature sensor within the ADS1118 must first be converted to a voltage that is proportional to the thermocouple currently being used, to yield V_{CJC}. This process is generally accomplished by performing a reverse lookup on the table used for the thermocouple voltage-to-temperature conversion. Adding the two voltages then yields the thermocouple-compensated voltage V_{Actual}, where $V_{CJC} + V_{TC} = V_{Actual}$. V_{Actual} is then converted to temperature using the same lookup table from before, and yields T_{Actual}. A block diagram showing this process is given in Figure 14.

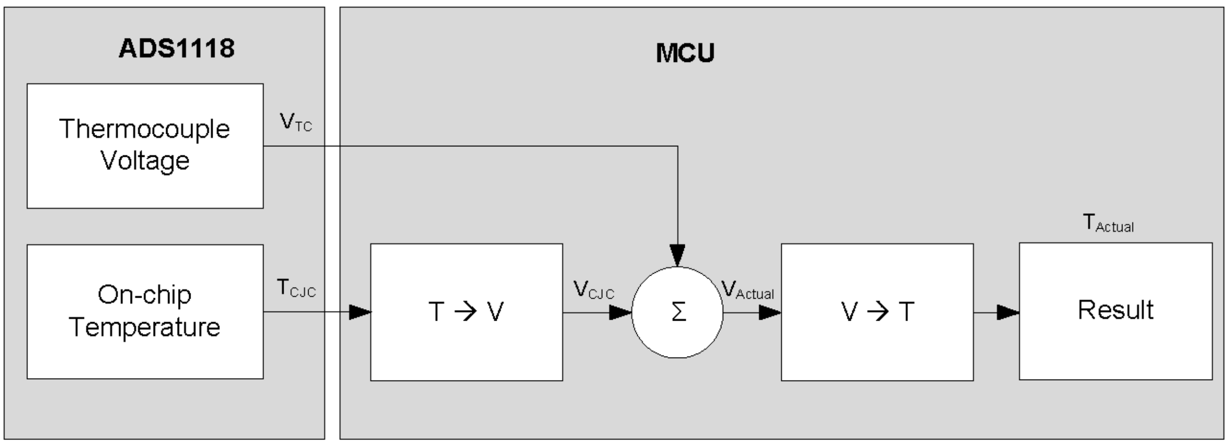

Figure 14: Software Flow Block Diagram

For example, consider the following condition:

- ADC cold junction reports 26.2°C
- ADC measured K-type thermocouple voltage of 6.62mV

To convert this to a final temperature first convert the measured on-chip temperature into the corresponding thermocouple voltage of the type being used. According to the manufacturers thermocouple look-up table 26.2C corresponds to 1.049mV.

$$V_{Actual} = V_{CJC} + V_{TC} \tag{12}$$

$$= 1.049mV + 6.62mV$$

$$= 7.669mV$$

Next convert the newly calculated voltage back into a temperature from the thermocouple look-up table. In this example the manufacturers thermocouple look-up table indicates that 7.669mV is equivalent to 188.05°C.

From a software point of view, the conversion from thermocouple temperature to voltage and voltage to temperature can be performed in two ways. First, the coefficients can be programmed into the microcontroller from the high-order polynomial, and then the calculation can be performed on each reading. While this method offers the smallest introduced error during the conversion, it is extremely processor-intensive and is not practical for some applications. The second and way to perform the conversion is through the use of a lookup table. Thermocouple manufacturers usually provide a lookup table with their respective thermocouple devices that offer excellent accuracy for linearization of a specific type of thermocouple. The granularity on these lookup tables is also very precise—approximately 1°C for each lookup value. To save microcontroller memory and development time, an interpolation technique applied to these values can be used. An example of this method when converting from voltage to temperature with eight look-up table entries is shown in Figure 15.

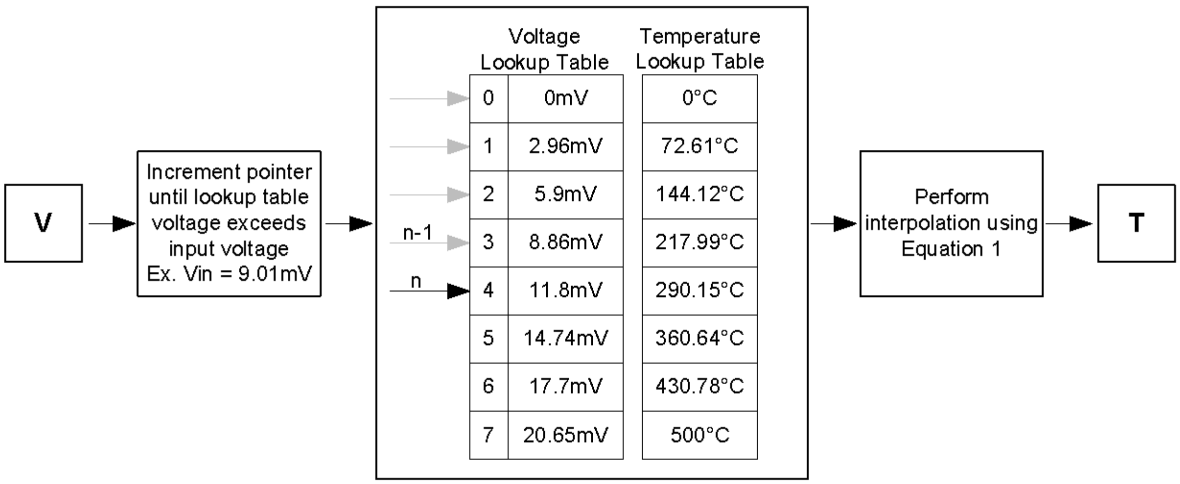

Figure 15: V-to-T Conversion Block Diagram

To perform a linear interpolation using a lookup table, first compare the value that must be converted to values in the lookup table, until the lookup table value exceeds the value that is being converted. Then, use Equation 12 to convert to temperature, where V_{LT} is the voltage lookup table array and T_{LT} is the temperature lookup table array. This operation involves four additions, one multiplication, and one division step, respectively. This operation can be done easily on most 16- and 32-bit microcontrollers. Converting from temperature to voltage is the same, except that the lookup tables and the temperature variables are reversed, as shown in Equation 13.

$$T = T_{LT}[n-1] + \left(T_{LT}[n] - T_{LT}[n-1]\right)\left(\frac{V_{IN} - V_{LT}[n-1]}{V_{LT}[n] - V_{LT}[n-1]}\right) \tag{13}$$

$$V = V_{LT}[n-1] + \left(V_{LT}[n] - V_{LT}[n-1]\right)\left(\frac{T_{IN} - T_{LT}[n-1]}{T_{LT}[n] - T_{LT}[n-1]}\right) \tag{14}$$

The number of entries used for a lookup table will affect the accuracy of the conversion. For the majority of applications, 16 to 32 lookup table entries should be sufficient. Also, the lookup table entries do not need to equally spaced. By carefully placing them in highly nonlinear portions of the thermocouple transfer functions, the number of required lookup table entries can be minimized. Furthermore, they also do not need to be incorporated in powers of 2, as shown in the examples within this document. Figure 16 shows the conversion error that can be expected from linear interpolation using a lookup table for a K-type thermocouple from 0ºC to +500ºC. Because the number of lookup table entries exceeds 16, the improvement in accuracy become smaller and smaller.

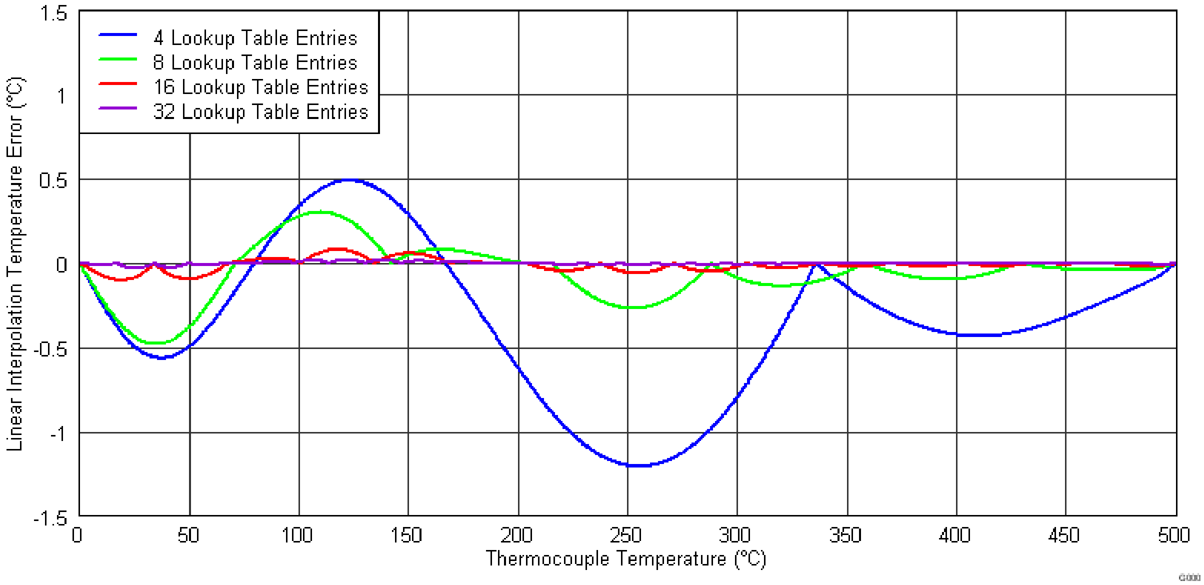

Figure 16: Comparison of Interpolation Errors Using Various Lookup Table Entries

7 Verification & Measured Performance

An excellent way to test the accuracy of the on-chip cold junction compensation with the completed board is to place the ADS1118 and cold junction into a temperature-controlled environment, and place the other end of the thermocouple into a known constant temperature source such as a thermal bath. This experimental setup is shown in Figure 17. When performing this experiment, it is best to try and mimic the actual environment in which the system board is to be used. If the ADS1118 and cold junction are within an enclosure that does not have significant air currents present, a simple oven should be sufficient. However, in applications that must endure high air currents, a temperature-forcing system with aggressive air currents may be useful to benchmark the system performance. The accuracy of the oven or temperature-forcing system used on the ADS1118 system board and cold junction does not need to be highly accurate. The other end of the thermocouple, however, must be held at a very constant and accurate temperature. One of the best ways to achieve this constant temperature is by using a thermal bath or a well-insulated bath of ice water.

In order to perform this experiment, the temperature of the ADS1118 PCB and thermocouple cold junction is swept, while the temperature of the end of the thermocouple is held constant in the thermal bath. The temperature measurements of the thermocouple are recorded and plotted against the cold junction temperature (oven temperature). Figure 17 shows the set-up using the ADS1118 board and a K-type thermocouple. The SM-USB-DIG Platform and USB cable remain outside the oven.

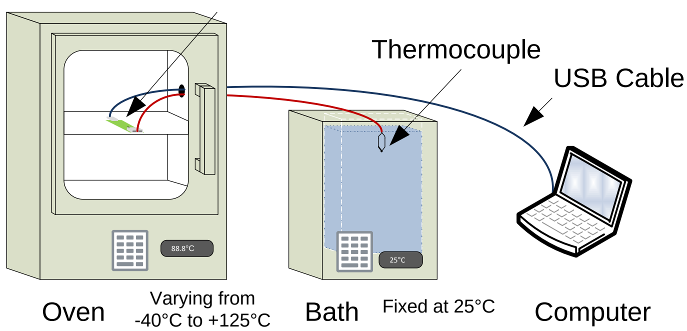

Figure 17: Experimental Setup With Varying Cold Junction Temperature

Figure 18 shows the plot of the thermocouple measurements against the cold junction temperature obtained in this experiment. This setup is intended to reveal inaccuracies that arise because of changes to the system board temperature, cold junction temperature, and ADS1118 temperature. The results indicate an approximately 0.4ºC drift when the system is drifted from 0ºC to +70ºC and around 0.9ºC variation over the complete specified temperature range of –40ºC to +125ºC for the ADS1118. These results were obtained with a factory-trimmed ADS1118 with no additional calibrations, and include all errors as a result of ADS1118 internal reference drift, internal temperature sensor error, and isothermal errors.

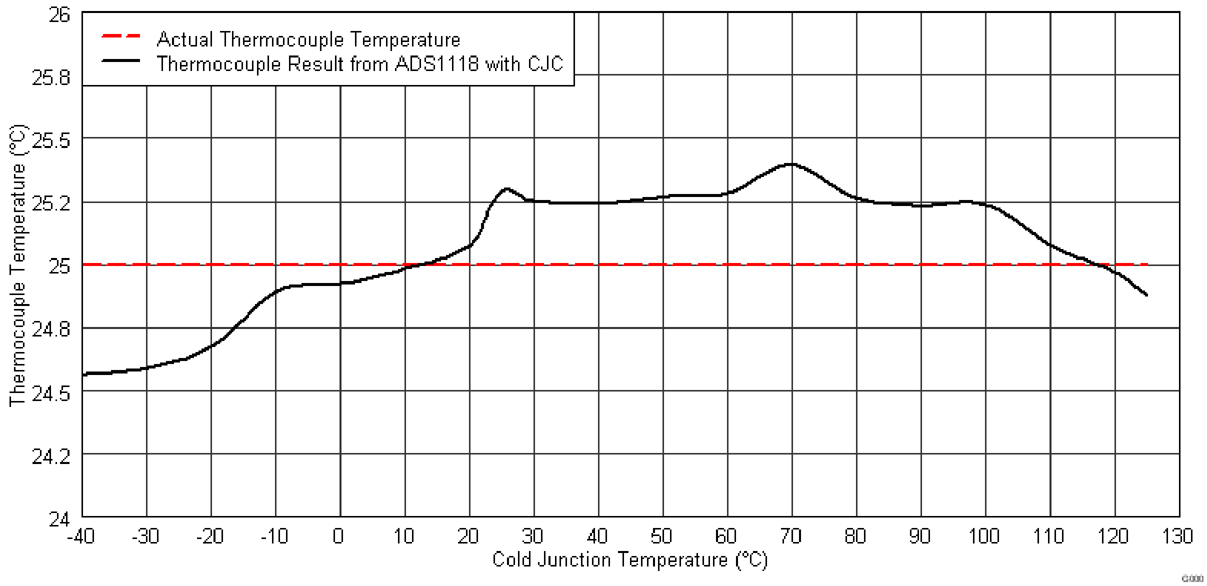

Figure 18: Thermocouple Accuracy with Varying Cold Junction Temperature on ADS1118 EVM

A second experiment that tests the overall system performance by verifying the accuracy of the thermocouple temperature measurement system is to sweep the temperature of the thermocouple using a very stable, uniform, and accurate temperature source. A calibrated thermal bath is a good temperature source for this test. The setup for this test is shown in Figure 19. This experiment is specifically intended to reveal inaccuracies in the thermocouple itself and any errors that occur because of the analog-to-digital conversion process. The cold junction is held at a relatively constant ambient temperature (room temperature) with no temperature forcing. The results in Figure 20 indicate approximately 1.5ºC of error from –40ºC to +150ºC. This result is well within the accuracy limitations of the K-type thermocouple used (also included with the ADS1118EVM), which is specified to be accurate to within 2.2°C. More precise tests can be performed using a calibrated thermocouple.

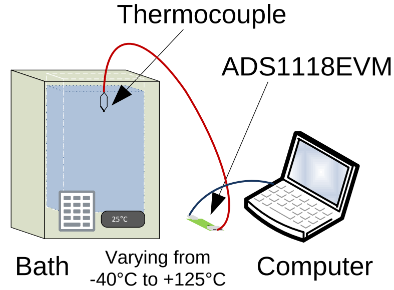

Figure 19: Experimental Setup with Varying Thermocouple

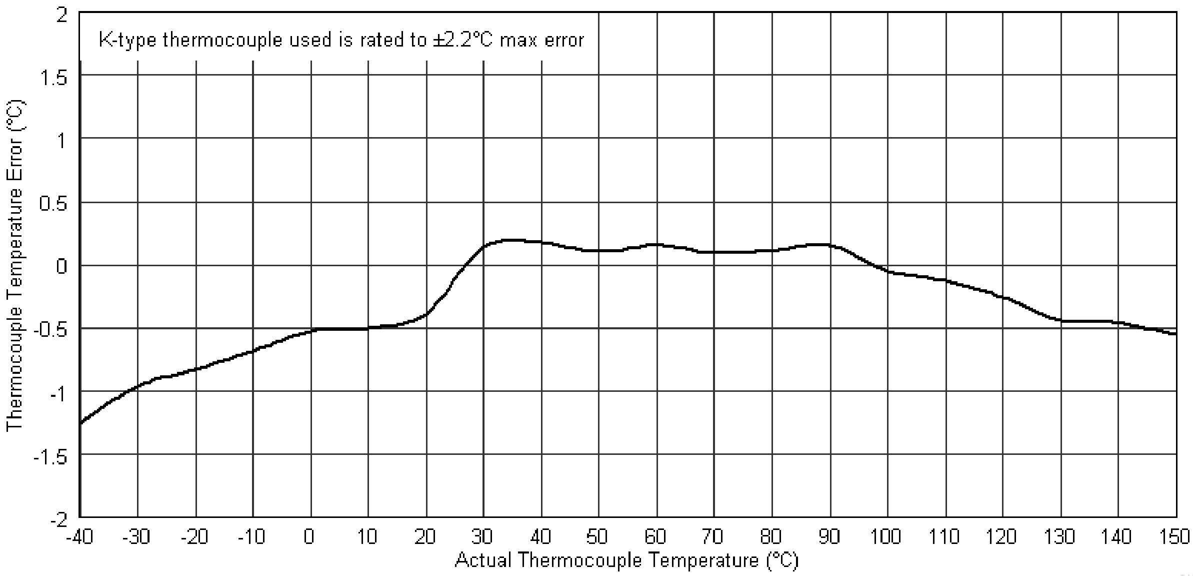

Figure 20: Experimental Temperature Error for Cold Junction Compensation on ADS1118EVM

The results shown in Figure 18 and Figure 20 are typical results using the ADS1118EVM and the thermocouple provided with the EVM. The actual performance in a given system may be different and depends on many variables, including (but not limited to) the application schematics, PCB layout, temperature-forcing system accuracies, and environmental noise contributions, among other factors. TI offers no assurance of system performance other than the performance parametrics detailed in the Electrical Characteristics section of the ADS1118 product data sheet.

8 Modifications

There are several ways to improve this design. Currently, it is a minimalist approach to thermocouples. The following are a few great ways to improve upon this design.

1. Add a second order RC filter. Using the same series resistances, but splitting them into to two separate cascaded filters would give a significant amount of added high frequency noise immunity. This simple addition is likely the biggest improvement to the design to improve the system robustness.
2. Adding low leakage TVS diodes to the inputs after the series resistors would add additional path for current to flow. It would not only improve the ESD performance of the system, but it would also improve the overvoltage protection.
3. Using a higher performance ADC such as the ADS1220 would allow more gain to be used as well as employ higher resolution. Precision and repeatability would improve nearly 10x by moving to the ADS1220. The ADS1220 would also be able to accept higher series resistances as well due to its extremely high input impedance.
4. Custom thermocouple calibration would also drastically improve performance. For many systems, a mixture of lookup tables and polynomial fitting are augmented by either a single or multipoint calibration of a thermocouple. Once calibrated, the accuracy of the system would be much better.

9 About the Author

Mike Beckman graduated from the Iowa State University, where he earned a Bachelor and Master of Science in Electrical Engineering. He joined Texas Instruments as a Systems Engineer. At the time of this writing he manages TI's Delta Sigma ADC product line.

Luis Chioye received his Bachelor of Science in Electrical Engineering from the University of Arizona, and his Master of Science in Electrical Engineering from Walden University/NTU School of Engineering and Applied Science. He is an applications engineer with TI’s Precision Analog group, where he is responsible for precision data converters.

10 Acknowledgements & References

1. *“Revised Thermocouple Reference Tables.” Omega. Web. 15 Jun. 2013 <http://www.omega.com/temperature/Z/pdf/z204-206.pdf>*

2. *INA826EVM Users Guide (SBOU115C)*

3. *ADS1118 Product Datasheet (SBAS457C)*

Special thanks to Pete Semig, Collin Wells, Art Kay and Tim Green for their support in contributing insight and experience into this TI Precision Design.

Appendix A.

A.1 Electrical Schematic

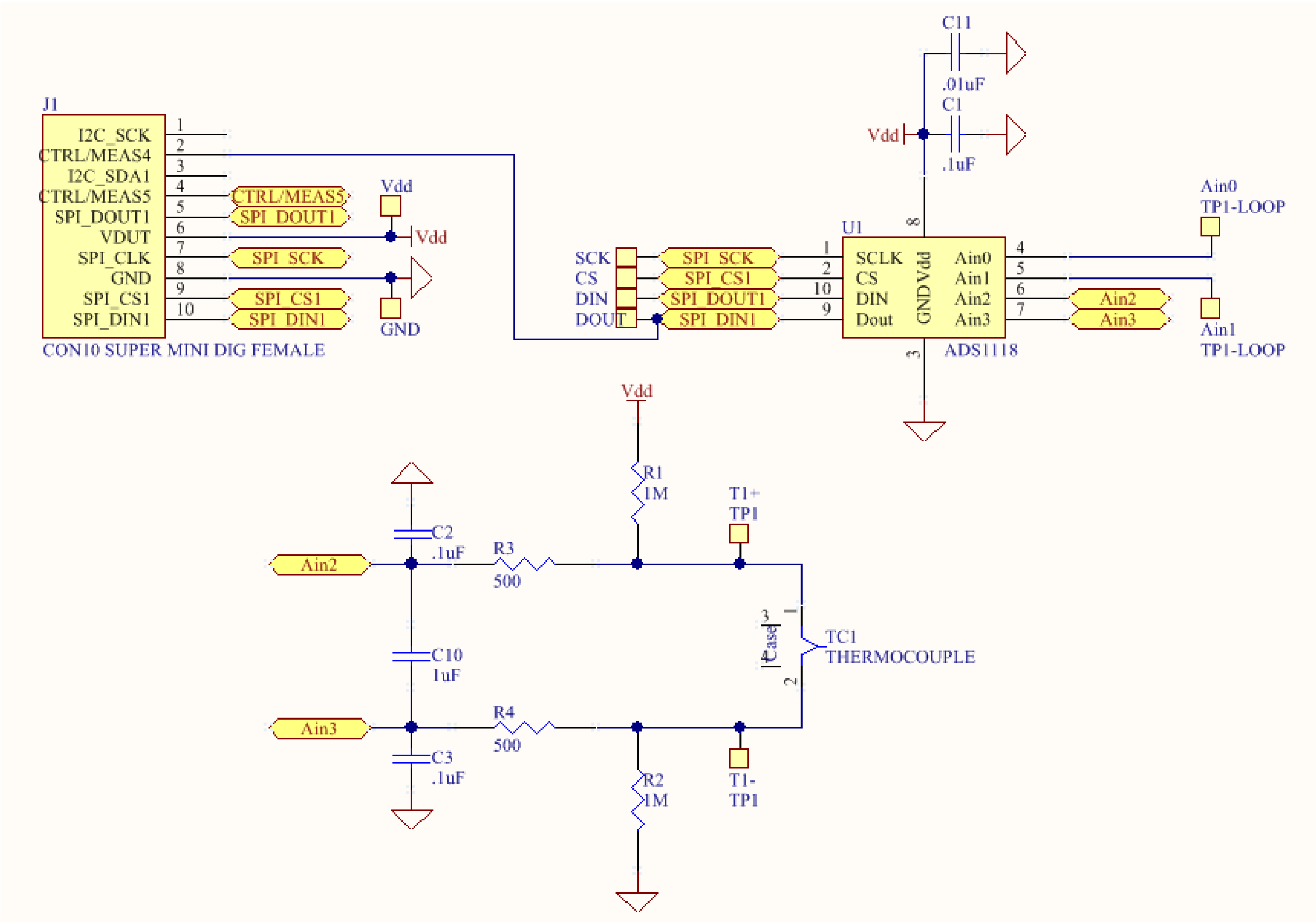

Figure A-1: Electrical Schematic

A.2 Bill of Materials

NOTE: All components should be compliant with the European Union Restriction on Use of Hazardous Substances (RoHS) Directive. Some part numbers may be either leaded or RoHS. Verify that purchased components are RoHS-compliant. (For more information about TI's position on RoHS compliance, see the TI web site.)

Reference Designator	Description	Vendor	Supplier	Supplier Part Number	Manufacturer Part Number
TC1	Thermocouple connector	Omega	Omega	PCC-SMP-K-5	PCC-SMP-K-5
N/A	Thermocouple	Omega	Omega	5SRTC-TT-K-24-36	5SRTC-TT-K-24-36
J1	Connector, Socket 10-pin .050 R/A Sngl	Mill-Max Manu. Corp.	Mill-Max Manu. Corp.	851-43-010-20-001000	851-43-010-20-001000
R1, R2	Resistor, 1MΩ 1/16W 5% 0402 SMD	Stackpole Electronics Inc	Digi-Key	RMCF0402JT1M00 CT-ND	RMCF0402JT1M00
C11	Capacitor, ceramic .010 µF 25 V X7R 0402	Yageo	Digi-Key	311-1337-1-ND	CC0402KRX7R8BB103
C1-3	Capacitor, ceramic .10 µF 16 V X7R 0402	TDK Corporation	Digi-Key	445-4952-1-ND	C1005X7R1C104K
C10	Capacitor, ceramic 1.0 µF 16 V X5R 0402	TDK Corporation	Digi-Key	445-4978-1-ND	C1005X5R1C105K
R3, R4	Resistor, 510 Ω 1/16W .5% 0402 SMD	Susumu	Digi-Key	RR05P510DCT-ND	RR0510P-511-D
CS, DIN, DOUT, GND, SCK, Vdd, T1+, T1-, Ain0, Ain1	Test point PC Compact .063"D YLW	Keystone Electronics	Digi-Key	5009K-ND	5009
1, 2	Bumpon Hemisphere .50 x .14 Clear	3M	Digi-Key	SJ5312-7-ND	SJ-5312 (CLEAR)
U1	ADS1118, RUG Package	Texas Instruments	Texas Instruments	ADS1118RUGT	ADS1118

Figure A-2: Bill of Materials