Application Note

How to Optimize Space-Grade Temperature Sensing Designs

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ABSTRACT

This article presents an in-depth guide to integrating Texas Instruments (TI) temperature sensors into space systems, with a particular emphasis on remote temperature sensors, which comprise a significant portion of TI's space portfolio. This begins by reviewing common temperature sensing designs used in space applications, then shifts to the various use cases for remote temperature sensing and outlines essential design considerations for successful system integration. Additionally, the article explores how radiation exposure influences the performance of remote temperature sensors. The findings demonstrate the ease and effectiveness of embedding TI remote temperature sensors within space system architectures, supporting the development of robust and reliable electronics for space missions.

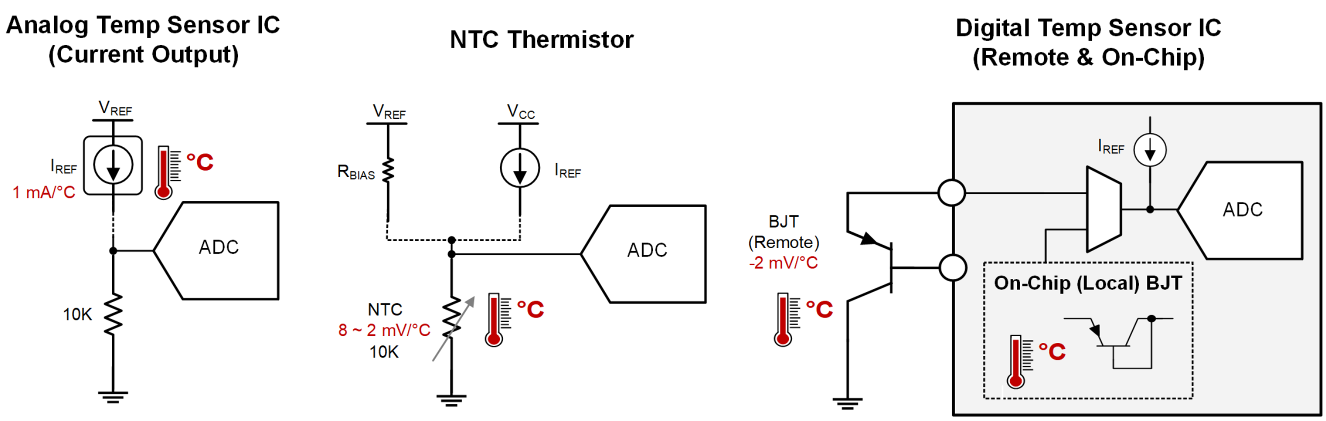

Figure 1-1. Comparing Temperature Design

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1 Introduction

Designing with space-grade integrated circuits (ICs) is a crucial component in developing reliable electronic systems for the challenging space environment. Space ICs require passing radiation exposure to the system. When considering options for temperature sensing, space ICs provide a more integrated design that comes with verified radiation performance data. This article offers a comprehensive overview of the key information required to integrate a Texas Instruments (TI) Space Temperature Sensor into a system. There are three popular choices customers tend to use for a temperature design for a space system: temperature transducer, thermistor, and an IC/remote junction. A temperature transducer provides an output current proportional to absolute temperature. A thermistor is a temperature-sensitive resistor whose resistance changes significantly with temperature. A remote junction is a bipolar junction transistors (BJT) where the base-emitter voltage changes with temperature. In our TI temperature portfolio, the company sells IC temperature designs. Within the TI space portfolio there are remote temperature sensors. Remote temperature sensors provide digital temperature measurements from the local die and external channels that can connect to both PNP and NPN transistors. This setup allows for the measurement of multiple hotspots throughout the system using a single integrated circuit. Our remote sensors includes an integrated analog-to-digital converter (ADC) and the required biasing to accurately measure the temperature of external BJTs. Remote temperature sensors present a range of designs for various applications, and this document details the most common use cases. By the end of this article, the ease of embedding a remote temperature sensor into system architectures is clearly evident.

2 Comparisons

When selecting temperature sensor technologies for use in space environments, engineers often compare integrated circuit temperature sensors with traditional thermistors. Both sensor types have distinct advantages and limitations:

Table 2-1. Remote vs Thermistor Comparison

Digital Remote Sensor	Thermistors	Temperature Transducer (Current Output)
Known radiation performance data for the product	Further testing must be performed to understand functionally under radiation	Known radiation performance data for the product
Higher integration reducing component and engineering costs	More components needed to measure temperature including a current source and ADC	More components needed to measure temperature including a resistor and ADC
Linearization across a large temperature range	Non-linear and provides low accuracy at hot temperatures.	Linearization across a large temperature range
No additional biasing is required	Biasing is needed	Biasing is needed
Integrated ADCs for temperature reading with programmable sampling	Implementing a large number of thermistors for multiple hot spots on the board is demanding (more ADCs or IOs on MCU)	Implementing a large number of thermistors for multiple hot spots on the board is demanding (more ADCs or IOs on MCU)
Integrated Alerts	Comparator circuit for alert functionally must be implemented	Comparator circuit for alert functionally must be implemented

3 Remote Application Use Cases

There are three primary applications for a remote temperature sensor: measuring the temperature of the circuit board, measuring the temperature of nearby components, and measuring the temperature of integrated diodes for on-chip temperature readings. There are many integrated circuit components, such as FPGAs, ADCs, and other System On Chips (SoCs), that include diodes for temperature measurement within the product. TI remote temperature sensors connect directly to these diodes for accurate temperature readings. When there is a need to measure temperature for multiple locations around the board outside of SoCs, discrete BJT-based diodes can be used as external temperature sensing elements. Up to nine different locations can be measured with one single remote IC with the TMP9R00-SP. Using a single IC simplifies the design process by providing an integrated analog-digital converter to read all nine different locations. The remote temperature sensor can also be used only as a digital local temperature sensor. To do so, there is an option to short the D+ and D- pins together and not use the remote. A single temperature IC can be used to measure board temperature and other hot spots around the system. Examples of these applications are listed below for reference.

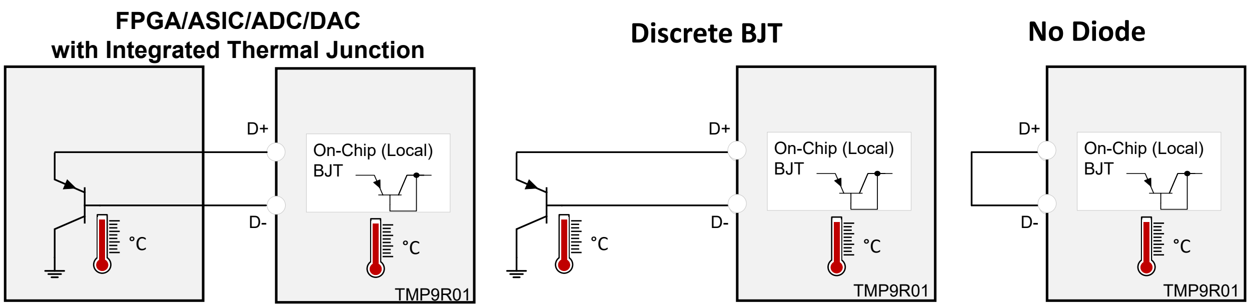

Figure 3-1. Remote Temperature Sensor Applications

Table 3-1. Integrated BJT Monitoring Examples

Example	Device	Monitoring Remote Connection
ALPHA-3P-ADM-VA601-SPACE	TMP9R01-SEP	XQRVC1902 ACAP
ALPHA-3P-VB630-SPACE	TMP9R01-SEP	XQRVE2302 ACAP
ALPHA-XILINX-KU060-SPACE	TMP461-SP	XQRKU060 FPGA
TSW12D1620EVM-CVAL	TMP461-SP	ADC12DJ1620
TIDA-070004	TMP461-SP	ADC12DJ1620
App Note: RTG4 FPGA: Temperature Monitor	TMP461-SP	RTG4 FPGA

Table 3-2. Discrete BJT Monitoring Examples

Example	Device	Monitoring Remote Connection
TIDA-010197	TMP461-SP	Satellite Health Monitoring
TIDA-010191	TMP461-SP	Health Monitoring
TIDA-010931	TMP9R00-SP	Battery Management

4 Default Remote Considerations

Default Remote Design Considerations

Engineers must account for design parameters for remote sensors. TI remote design is based on the diode current-voltage relationship shown in Equation 2. This provides a simplified equation to how to measure temperature. Calculate temperature using proprietary methods. Remote temperature sensors are designed to match with BJT transistors. For more information about selecting transistors, see *Remote Temperature Sensor Transistor Selection Guide*.

$$\Delta V_{BE} = \left(\frac{\eta k T}{q}\right)\ln\left(\frac{I_{C2}}{I_{C1}}\right) \quad (1)$$

$$T = \frac{q \Delta V_{BE}}{\eta k \ln\left(\frac{I_{C2}}{I_{C1}}\right)} \quad (2)$$

Table 4-1. List of Variables

Variable	Definition
ΔV_{BE} (3)	Voltage measurement across the BJT between the base and the emitter
η (4)	N-factor correction parameter
q (5)	Charge of an Electron
k (6)	Boltzmann's Constant
$\frac{I_{C2}}{I_{C1}}$ (7)	Current methodology of chosen remote sensor. This varies between device.

TI remotes force either three or four currents on the D+ line to measure the delta Vbe across the remote junction. The currents from the D+ line are designed into our remote sensors and contribute to how temperature is collected from the remote BJT. The ideal D+ signal is shown below highlighting the different currents during an active conversion. Ideally, TI recommends directly connecting the D+ and D- to the remote BJT with no additional resistance; however, with long traces, TI recommends adding filtering to the D+ and D- signal lines. Be cautious in what to choose for a cap and resistor. A large capacitance or resistor can add error to the temperature measurement. More details about the maximum values of capacitance and resistance can be viewed with the datasheet of the desired remote temperature sensor.

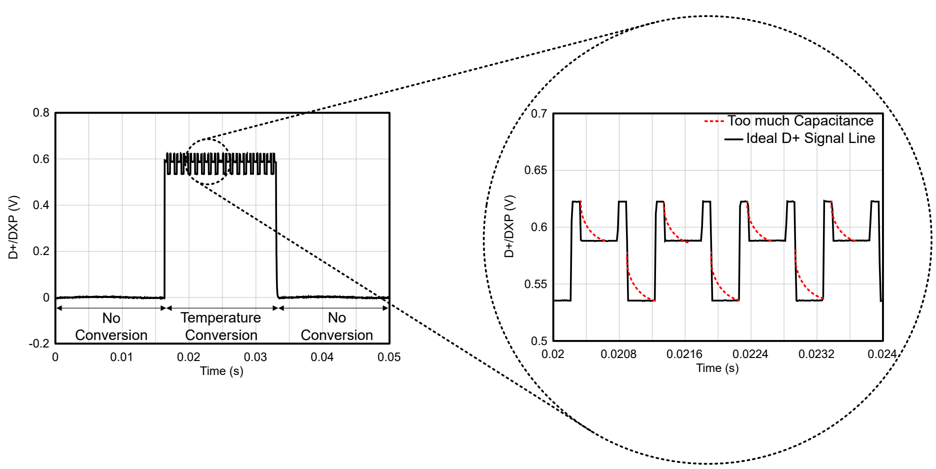

Figure 4-1. D+ Waveform

Selecting a transistor can affect the accuracy of the remote sensor. The key temperature characteristics of the remote BJT junction are n-factor, beta, and Vbe. N-factor, or otherwise known as ideality factor, is a parameter that reflects how closely the base emitter junction follows the ideal diode equation. Beta is the current ratio between the collector and base. Beta represents the error present when the collector current leaks through the base. Ideally, a transistor whose collector current equals the emitter current with no leakage, provides stronger performance as a remote junction. Transistors can vary in n-factor, forward current gain, and size. TI remote temperature sensors can calibrate these parameters to match with different transistors. Most of TI temperature sensors are designed to meet transistors with a n-factor of 1.008 with no changes to the configuration settings. The n-factor is specified in the datasheet. Any variant of 3904 and 3906 PNP/NPN transistors are preferred to match with our remote sensors without calibration. Errors within the remote junctions can be from a different ideality factor, large variations in beta, large resistance or capacitance on the D+ D- lines, or noise interface from long D+ D- cabling.

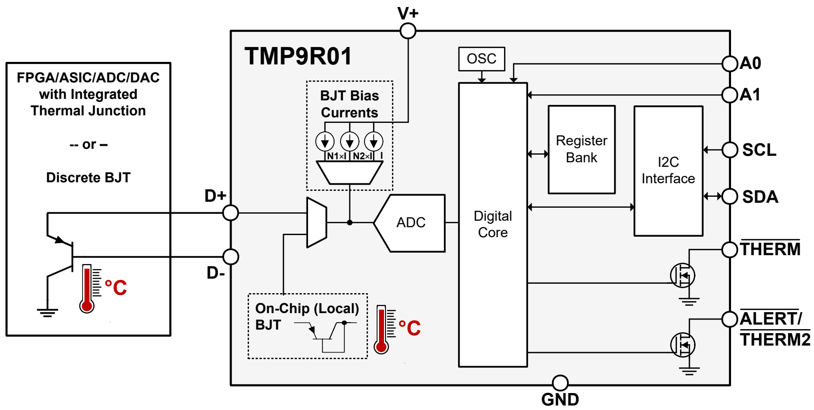

Figure 4-2. Remote Block Diagram

Diode connected is when the base is connected to the collector within the NPN or PNP BJT. NPN diodes have to be diode connected. The preference is to connect PNP with all pins available. Diode connected diodes restrict usage of the automatic beta correction feature.

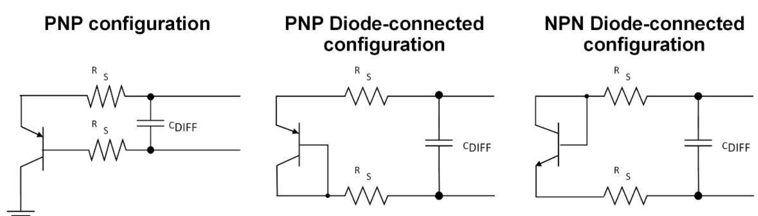

Figure 4-3. Proper PNP and NPN Connections

Radiation can affect temperature sensors by introducing errors in temperature readings and overtime degrade their performance. All TI temperature sensors have gone through Single Event Effects (SEE) and Total Ionizing Dose Effects (TID) radiation testing. All radiation reports are located on the respective device's product page. A large portion of our space portfolio are digital. TMP9R01-SP is a digital space grade remote temperature sensor that passes TID up to 100krad(Si) Radiation Hardness Assured (RHA) and Single Event Latchup (SEL) immune to a LET of 75MeV-cm2/mg. Since TMP9R01-SP is digital with registers, any bit change in the registers can cause a shift in temperature accuracy. Data within the registers include configuration, n-factor, offset, and high/low limit settings. Within the SEE report, data was collected in the registers and the alert pin signal was used to understand the complete functionally of the device under radiation conditions. A remote or local temperature output with an error larger than 1.5°C was recorded as a transient. A SEFI was recorded when the Alert/THERM signal was tripped. Any bit that was changed within any of the I2C registers outside of the temperature reading registers was recorded as an upset.

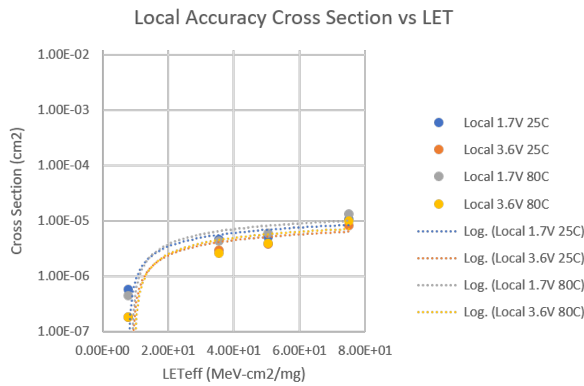

Figure 4-4. Weibull Plot for Local Temperature Accuracy Events

5 Beta Error

Beta can be a factor of error when measuring temperature from a remote junction. Not all transistors have a beta issue. Beta is the current ratio between the collector and base. Beta represents the error present when the collector current leaks through the base. Low beta error tends to be with smaller technologies. As mentioned, the core design of TI remote temperature sensors forces either three or four currents on the D+ line to measure the delta Vbe across the remote junction. Different currents result in a different beta measurements. Equation 8 highlights the relationship between betas and the temperature result for a two-current architecture.

$$\Delta V_{be} = \eta V_T \ln\left(\frac{I_{e1} \times \beta_1/(\beta_1+1)}{I_{e2} \times \beta_2/(\beta_2+1)}\right) \quad (8)$$

When the beta terms equal each other, the terms cancel out leading to no additional error due to Beta. Error comes from variations of beta from different current values. Adding radiation exposure to the remote temperature must not add additional beta errors to the BJT remote temperature result. The Gummel Plot highlights the most preferred beta characteristics for a BJT to match with the remote temperature sensors. When matching the transistors, TI recommends the BJT to follow the characteristics within the linear region shown in Figure 5-1. The blue line represents the Beta ratio following the right secondary y-axis. The red and gray lines follows the primary left y-axis.

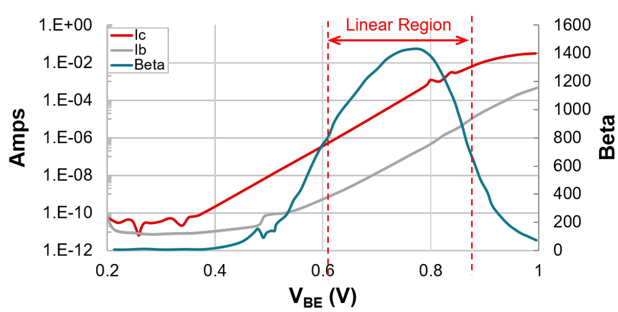

Figure 5-1. Gummel Plot

When designing BJTs, the following plot can be useful when sizing the BJTs to match with our remote junctions. When sizing transistors to match with the remote sensors, TI recommends small delta beta measurements across the set D+ current values on the remote as highlighted in Figure 5-2.

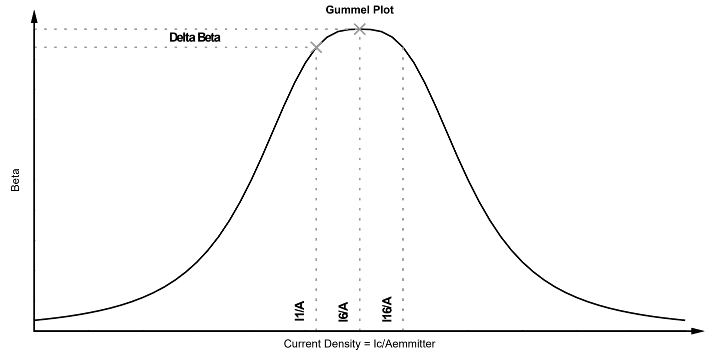

Figure 5-2. Recommended BJT Sizing

Table 5-1. D+ Output Current Values

Name	Current
I1	7.5uA
I6	6x7.5uA
I16	16x7.5uA

6 Calibration

TI remote temperature sensors can correct for errors through calibration registers. This feature allows to match with a variety of different BJTs. As stated previously, n-factor represents the error of how closely the base emitter junction follows the ideal diode equation. N-factor and offset can be corrected within the I2C registers of TI remote temperature sensors. To reduce these errors, the following steps must be performed. The equipment needed for adjusting the n-factor and the offset are the following: a controlled temperature environment, a reference temperature measurement, and the remote/junction setup.

1. Verify the connection pins to confirm the presence of a diode by measuring the forward voltage drop, which can be approximately 0.7V.
2. Place remote/junction setup in a controlled temperature environment like an Oil Bath or an Oven. A reference temperature reference needs to be setup within the environment. Oil bath or an oven reference must not be used. The preferred reference is to use a Platinum Resistance Thermometer (PRT) or a Resistance Temperature Detector (RTD) as close to the remote junction as possible. Another reference option is the using the local temperature die of the remote sensor.
3. Collect temperature of remote, local, and reference data across temperature within the controlled environment. The range of temperature needs to be users desired range of the product.
4. Load collected data into the Remote Calibration Tool to optimize the value needed for n-factor and offset.
5. Write new n-factor and offset values into I2C registers.
6. Confirm improved performance by repeating step three.

An example of improved accuracy with the Remote Calibration Tool is shown, first highlighting the raw data with no changes in the configuration, then, highlighting the improvement in accuracy with changes in the configuration.

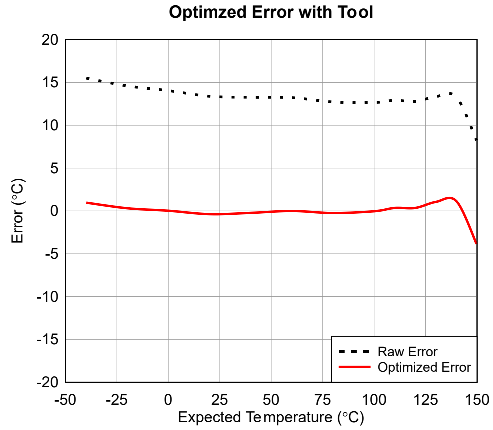

Figure 6-1. Effects from Changing Offset and N-factor

Table 6-1. Calibration Settings

Nfactor	Offset
0.994661626	-17.875C
0x1C	0xF710

When n-factor and offset are the only sources of error, the following equations can also be used to optimize the remote device. $N_{expected}$ value is 1.008.

$$Error = (T + 275.15) \times \frac{N_{actual} - N_{expected}}{N_{expected}} \quad (9)$$

$$Reported\ T = (T + 273.15) \times \frac{N_{actual}}{N_{expected}} - 273.15$$

$$N_{actual} = \frac{(T_{reported} + 273.15) \times N_{expected}}{T + 273.15}$$

Our temperature sensors also have, automatic series resistance cancellation. Series resistance cancellation in remote temperature sensors is an important technique used to enhance measurement accuracy, especially in applications where long cable runs are involved and connecting to SOCs. When sensors are placed at a distance from the measurement system, the resistance of the connecting wires can introduce errors in temperature readings due to voltage drops along the wire. Any resistance in the junction signal path can cause a voltage drop between the actual VBE at the transistor and the measured VBE at the temperature sensor, which results in a temperature offset. To mitigate this effect, internally remotes can cancel resistance on the DXP/DXN signals to cancel out resistance error from the wire and allow the addition of noise filtering without increasing the temperature error. A total of up to 1kΩ of series resistance can be canceled by the device. Series resistance cancellation allows direct connections to embedded and discrete junctions. The equation below highlights the additional error to the Vbe measurement when resistance in in the D+ and D- path. The first term is the added error from the series resistance.

$$\Delta V_{BE} = I_S R_S + \left(\frac{\eta k T}{q}\right) \ln\left(\frac{I_{C2}}{I_{C1}}\right) \quad (10)$$

7 Layout Techniques

Remotes measure very small voltages using very low currents; therefore, noise at the device inputs must be minimized. Sources of errors include Electromagnetic Interference (EMI) or inductive coupling, incorrect calibration, and PCB trace resistance. To reduce errors please consider the following conditions:

1. Place the remote device as close to the remote junction sensor as possible
2. Route the D+ and D– traces next to each other and shield them from adjacent signals through the use of ground guard traces. If a multilayer PCB is used, bury these traces between the ground or V+ planes to shield them from extrinsic noise sources. TI recommends 5-mil (0.127mm) PCB traces.
3. Minimize additional thermocouple junctions caused by copper-to-solder connections. If these junctions are used, make the same number and approximate locations of copper-to-solder connections in both the D+ and D– connections to cancel any thermocouple effects.
4. Use a 0.1µF local bypass capacitor directly between the V+ and GND of the remote temperature sensor. For optimum measurement performance, minimize filter capacitance between D+ and D– to 1000pF or less. This capacitance includes any cable capacitance between the remote BJT and the temperature sensor.
5. If the connection between the remote temperature sensor and the remote sensor is wired and is less than eight inches (20.32 cm) long, use a twisted-wire pair connection. For lengths greater than eight inches, use a twisted, shielded pair with the shield grounded as close to the remote IC device as possible. Leave the remote sensor connection end of the shield wire open to avoid ground loops and 60Hz pickup.
6. Thoroughly clean and remove all flux residue in and around the pins of the device to avoid temperature offset readings as a result of leakage paths between D+ and GND, or between D+ and V+.

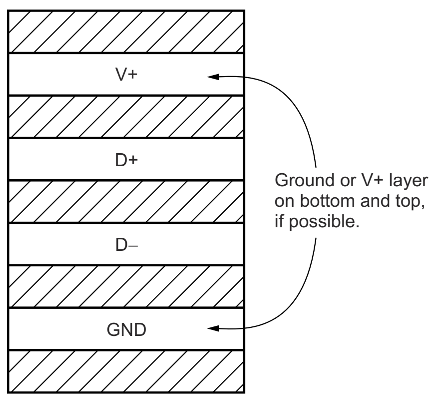

Figure 7-1. Recommendation for Layering the D+ and D- Trace

With a multichannel EVM, data was collected to determine the ratio between the trace length and the accuracy of the temperature sensor. The EVM shown in Figure 7-2 was placed in an oil bath with a controlled temperature environment at 25C. Data was collected with the online GUI and reported in the document. Shielded cabling was used for the remote wiring. As shown through this experiment, there was not an evident relationship between the length of the wire and the accuracy of the remote channel. Noise can still interfere through the D+ and D- and all recommendations listed above should take place.

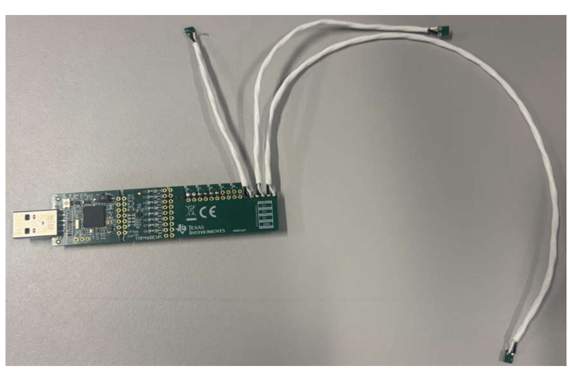

Figure 7-2. Test Setup With Multichannel Remote EVM

Table 7-1. Error Across Different Remote Lengths

	Ch1 Error	Ch2 Error	C3 Error	C4 Error	C5 Error	C6 Error	C7 Error	C8 Error
Max Error	1.125	1.1875	1.125	1	1.0625	1.125	1.0625	1.25
Extra Trace Length	On PCB					3in	6in	12in

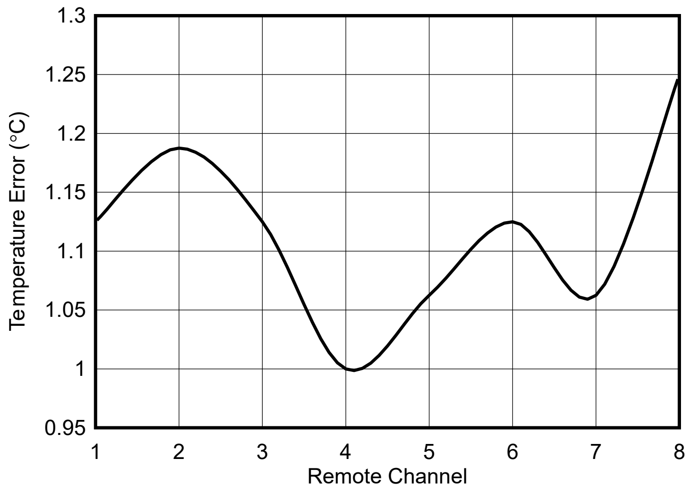

Figure 7-3. Error Across Different Remote Lengths

8 Summary

In conclusion, the integration of Texas Instruments remote temperature sensors offers a reliable and effective design for monitoring critical thermal environments in space applications. By addressing remote temperature sensor common use cases with an overview of all design consideration, there must a clear understanding of how to embed a space remote temperature sensor into a system. The validated radiation tolerance and design flexibility of these sensors contribute significantly to the development of robust, mission-ready electronics. As space missions continue to grow in complexity and duration, the adoption of proven remote temperature sensing designs remains essential for verifying system reliability and operational success.

9 References

- Texas Instruments, *Optimizing Remote Diode Temperature Sensor Design*, application note.
- Texas Instruments, *Remote Temperature Transistor Sensor Selection Guide*, application note.
- Texas Instruments, *TMP9R01-SP Single-Event Effects (SEE) Radiation Test Report*, radiation report.
- Texas Instruments, *TIDA-070004*, product folder.
- Texas Instruments, *Remote Calibration Tool*, software.