*设计指南：**TIDA-070004***

使用集成式数字输出温度传感器的航空级温度检测参考设计

说明

本参考设计阐述了若干航天器项目通过提供系统的健康状态遥测功能，实现了对地面人员的实时监测。此参考设计展示了数字输出温度传感器使用耐辐射 MSP430FR5969-SP 微控制器 (MCU) 获取子系统上的温度数据的示例。此系统实现了一个基于 SPI 的从器件，可以利用简单的寄存器读取/写入协议响应主机对温度数据的请求。该参考设计还包括 TMP461-SP，该器件具备 ADC12D1620QML-SP 的本地温度检测和远程二极管温度检测功能。此参考设计使用 TSW12D1620EVM-CVAL 板。可将此方法视作基础，用于子系统温度和运行状态远程监测。

资源

TIDA-070004	设计文件夹
TMP461-SP	产品文件夹
MSP430FR5969-SP	产品文件夹
ADC12D1620QML-SP	产品文件夹
TSW12D1620EVM-CVAL	EVM 工具文件夹

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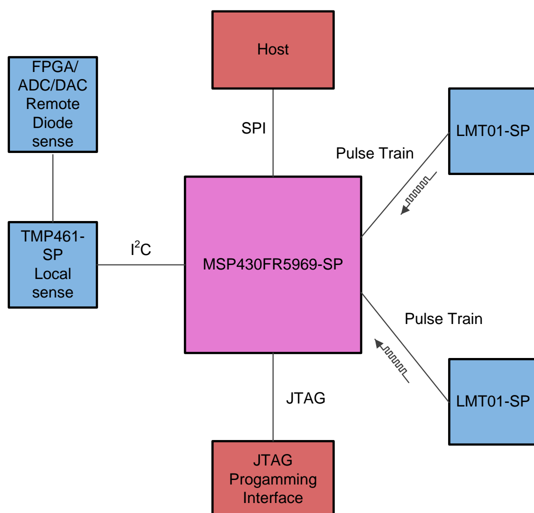
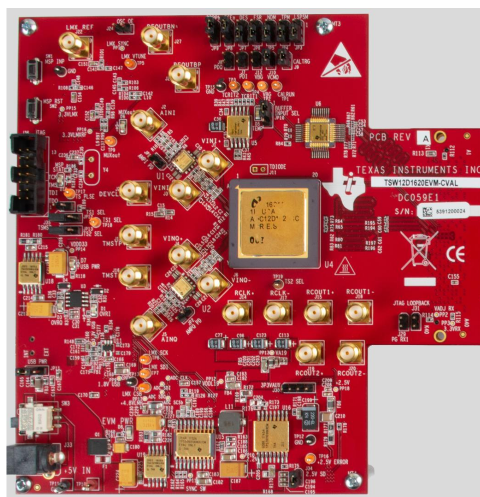
特性

- 准确度为 ±2°C 的本地温度检测功能
- 准确度为 ±1.5°C 的远程温度检测功能
- 超低功耗耐辐射 MCU
- I²C 温度传感器输出 (TMP461-SP)
- 基于 SPI 的从器件与主机连接

应用

- 命令和数据处理
- 卫星电力系统 (EPS)
- 光学成像有效载荷
- 雷达成像有效载荷
- 通信有效载荷





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1 System Description

The MSP430FR5969-SP based temperature sensing system is comprised of two LMT01-SP devices located on the bottom side of the board, along with the TMP461-SP on the topside of the board. The TMP461-SP has two temperature sensors. There is one internal sensor, and also a remote sensor that is made via a connection to a temperature sensing diode in the ADC12D1620QML-SP ADC converter. This allows temperatures to be evaluated from four unique locations on the TSW12D1620EVM-CVAL. The remote sense diode within the ADC12D1620QML-SP is most significant, as it represents the largest source of heat on the board that needs to be dissipated. With both input channels enabled and operating with a 1.6-GHz input clock, the ADC12D1620QML-SP will dissipate approximately 4 W.

The ability to monitor board temperature has multiple value propositions, and can be critical for maintaining reliable system operation in many applications. From a system health perspective, the ability to have accurate temperature data for a board can be an effective and relatively simple approach to get a relative metric on the health of a board. Changes in temperature over time could indicate failure, or potential for failure, of some components. Another use case is operation with temperature sensitive components such as many ADCs. The MCU can monitor the temperature of the ADC and trigger a recalibration if the temperature deviates over a preset threshold from the last temperature at which a calibration was performed. For example, an ADC with a similar architecture to the ADC12D1620QML-SP has an ENOB post calibration of approximately 9.2 at 25°C. The ENOB decreases to approximately 8.5 as the device heats up to 125°C. The ENOB performance change is linearly decreasing with change in temperature from the temperature at which calibration was performed. By applying the calibration at the increased temperature, the ENOB returns to near 9.2. Other performance metrics are similarly impacted by the temperature deviation from calibration temperature.

1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	PART NUMBER	KEY SPECIFICATIONS
Ultra low power space rated MCU	MSP430FR5969-SP	Wide supply voltage range (1.8 V to 3.6 V)
		Active mode current 100 µA/MHz
Temperature sensor with remote diode sense	TMP461-SP	Remote temperature accuracy ±1.5°C
		Local temperature accuracy ±2°C
Small accurate low power 2-pin temperature sensor	LMT01-SP	Temperature accuracy 0.7°C
		34-µA conversion current
		Package body 3.0 × 5.5 mm

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2 System Overview

2.1 Block Diagram

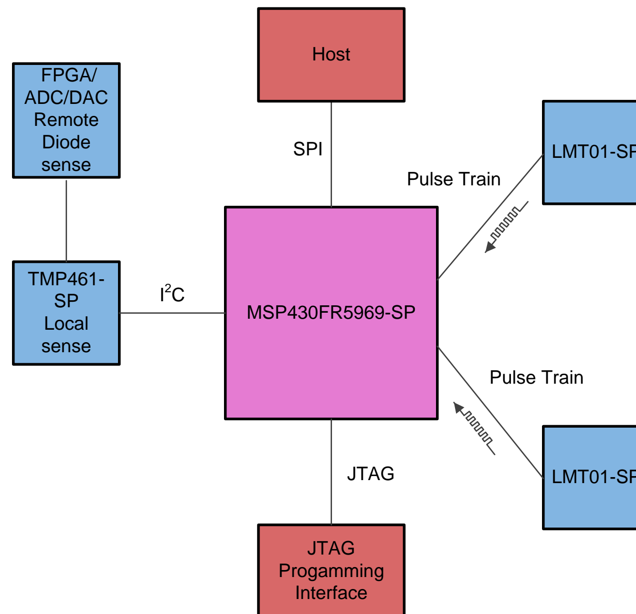

图 1. TIDA-070004 Block Diagram

2.2 Design Considerations

The primary design considerations used in this reference design are usage of low power space grade components to achieve accurate and flexible board and device temperature measurements. In this design, the MCU firmware is only taking care of reading each temperature sensor and saving into a register. An external host is responsible for requesting the temp sensor reading from the MCU. However, the MSP430FR5969-SP is a very capable MCU and can implement in firmware additional capability depending on the end systems requirements.

Potential design enhancements based on system needs:

- Evaluate temperature variation and execute an ADC calibration autonomously.
- Implement a temperature control loop with PWM signal to Peltier device to maintain a specified temperature.
- Manage register configurations of other system devices, such as the ADC configuration.

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2.3 Highlighted Products

This reference design features the following TI devices:

- MSP430FR5969-SP
- TMP461-SP
- LMT01-SP

For more information on these devices, see their respective product folders at www.ti.com.

2.3.1 MSP430FR5969-SP

- Radiation Performance
  - TID = 50 krad(Si)
  - SEL immune to LET = 72 MeV·cm^2/mg at 125°C
- Hardened for space and radiation environments
- 16-MHz, 16-bit RISC CPU
- Wide supply voltage range 1.8 V to 3.6 V
- Ultra low power consumption: Shutdown Mode (LPM4.5): 0.32 uA
- Wake up from Standby Mode in 7 µs
- 64KB FRAM with free program code / data memory partitioning
  - Nearly infinite (10^{15}) write cycles
  - 160x faster than Flash (> 2MB/s)
  - 250x less power in writes
- 2KB SRAM
- Signal conditioning
  - ADC 12 bit, 16 channel: 200 ksps and 150-uA consumption
  - PWM output
  - Analog comparator 15 channels, voltage hysteresis, reference generator
- Package: 48-pin TQFP and QFN

2.3.2 TMP461-SP

- Radiation Performance
  - TID = 50-krad(Si) HDR (50 rad(Si)/s), 100-krad(Si) LDR (10 mrad(Si)/s)
  - SEL immune to LET = 76 MeV·cm^2/mg at 125°C
- Remote diode accuracy: ±1.5°C (50 krad(Si))
- Local temp accuracy: ±2°C (50 krad(Si))
- Eliminates offset error due to series resistance
- Programmable non-ideality factor
- Programmable digital filtering
- Resolution: temp changes to 0.0625°C
- Alert pin can provide overtemperature trip signal
- V_S = 1.7 V to 3.6 V, 35-µA operating current

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- Ceramic 10-lead HKU package

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2.3.3 LMT01-SP

- Radiation Performance
  - TID = 100-krad(Si) RHA
  - SEL Immune to LET = 90 MeV·cm^2/mg at 125°C
- High accuracy ±0.7°C (max error across temperature, –55°C to +125°C)
- +1.5°C (max error at 100-krad(Si) LDR)
- 2-pin digital pulse-count output interface
- Wide supply range of 2 V to 5.5 V
- 2-pin ceramic package: 5.57 mm × 3.00 mm

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3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The following details the required hardware and software for TIDA-070004.

3.1.1 Hardware

- TSW12D1620EVM-CVAL rev E1 or newer.
- With revision E1 hardware, two LMT01-SP or /EM units are required to be mounted to the bottom side of TSW12D1620EVM-CVAL.
- With revision E1, two wires need to be added to the schematic and board for proper I^2C connection to the TMP461-SP. Future revisions will include these modifications:
  - Add net connecting U20 pin 31 to U12 pin 28.
  - Add net connecting U20 pin 32 to U12 pin 26.
  - Add 10-kΩ pullup resistor from U11 pin 1 to VDDD33. This is not strictly required, as the FTDI driver will properly bias this when driven from the GUI.

These modifications connect the MSP430 as a I^2C master in parallel with the FTDI device being used as a I^2C master. The software GUI will program the FTDI lines as high impedance including the SCL pin to prevent any contention from the multi-master setup.

3.1.2 Software

- TSW12D1620EVM-CVAL GUI and the MSP430FR5969-SP Firmware. These are available in the TSW12D1620EVM-CVAL product folder. The installer will install both.
  - Revision E1 of the TSW12D1620EVM-CVAL does not have the firmware loaded in the MCU. It is required to load the firmware with a compatible JTAG emulator along with the required board modifications noted in the hardware section.
  - After installing *Setup_TSW12D1620EVM.exe*, follow instructions located in the installation directory to program the firmware in the MSP430FR5969-SP. If default location is chosen, this information will be located at *C:\Program Files (x86)\Texas Instruments\TSW12D1620EVM\MSP430 Firmware\Firmware_Updater*

The MSP430FR5969-SP firmware is implemented as a SPI slave device communicating to a host. In this application, the host is the Microsoft Windows based GUI driving a pattern to an FTDI USB to parallel device FT4232HL. The SPI host will communicate with the MCU via a pre-defined register set.

表 2. MSP430FR5969-SP Firmware Register Map

Register Address	Register Name	Description
0x00	TEMP_SENSOR_EN_REG	Control register to enable / disable temperature measurement
0x01	LMT01_D1_REG	LMT01-SP device1 pulse count
0x02	LMT01_D2_REG	LMT01-SP device2 pulse count
0x03	TMP461_LOCAL_REG	TMP461-SP local temperature
0x04	TMP461_REMOTE_REG	TMP461-SP remote temperature
0x05	ERR_STATUS	TMP461-SP error and status information
0x06	FIRMWARE_VERSION	Firmware version

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The firmware has the ability to enable or disable any of the temperature reads for either the TMP461-SP or the two LMT01-SP devices via the TEMP_SENSOR_EN_REG register. The MCU continuously and sequentially reads all enabled temperature sensors and updates the respective register. When the host requests a temperature read, the current value in the respective register is sent to host. The LMT01-SP temperature measurement is accomplished by first enabling the respective LMT01-SP by driving the GPIO connected to the VP terminal to the high level (3.3 V). At this point the LMT01-SP begins acquisition and then outputs the temperature correlated pulse train. The VN terminal is shared between both LMT01-SP devices, and is connected to a comparator resource through a biasing resistor to GND and connected to port P1.3. See 图 2 for biasing schematic. Each positive going pulse detected causes an Interrupt Service Routine (ISR) to increment a counter. Determining the LMT01-SP's temperature reading is implemented using a 10-ms interrupt timer. A timer is programmed in the MCU to execute an ISR at 10-ms intervals. At the servicing of each 10-ms time, the MCU checks to see if the currently enabled LMT01-SP has updated its pulse count. If the count has changed in the last 10 ms, then the new count is stored in a variable and the routine exited. If the count is the same, then this indicates that the LMT01-SP has completed its count, and we now have a new measurement. This is stored in the SPI register, and the next device in sequence is read (or measured in the case of the LMT01-SP). See 图 3 for MSP430FR5969-SP firmware flow diagrams.

The TMP461-SP is read from the main loop of the program every 200 ms. At each 200-ms interval, the enabled TMP461-SP remote or local temp sensors are read via I^2C and stored in the SPI register set. Since the ADC12D1620QML-SP diode is not a standard diode, the calibration technique described in TI application note SBOA173 was used. Three temperatures (25°C, 50°C, and 70°C) were chosen to calculate the calibration data. The board was placed in a thermal chamber with ±1°C of chamber uniformity at each setpoint. The values obtained with this methodology resulted in an nFactor correction of 0xEE and an offset correction of 0x05 to be loaded into the TMP461-SP.

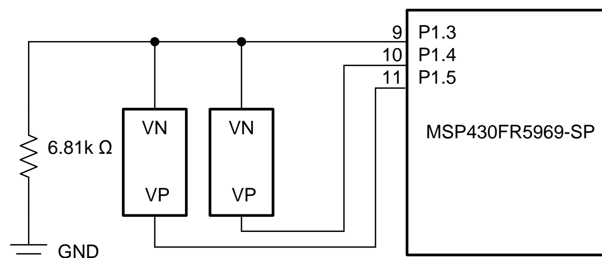

图 2. LMT01-SP to MSP430FR5960-SP Biasing

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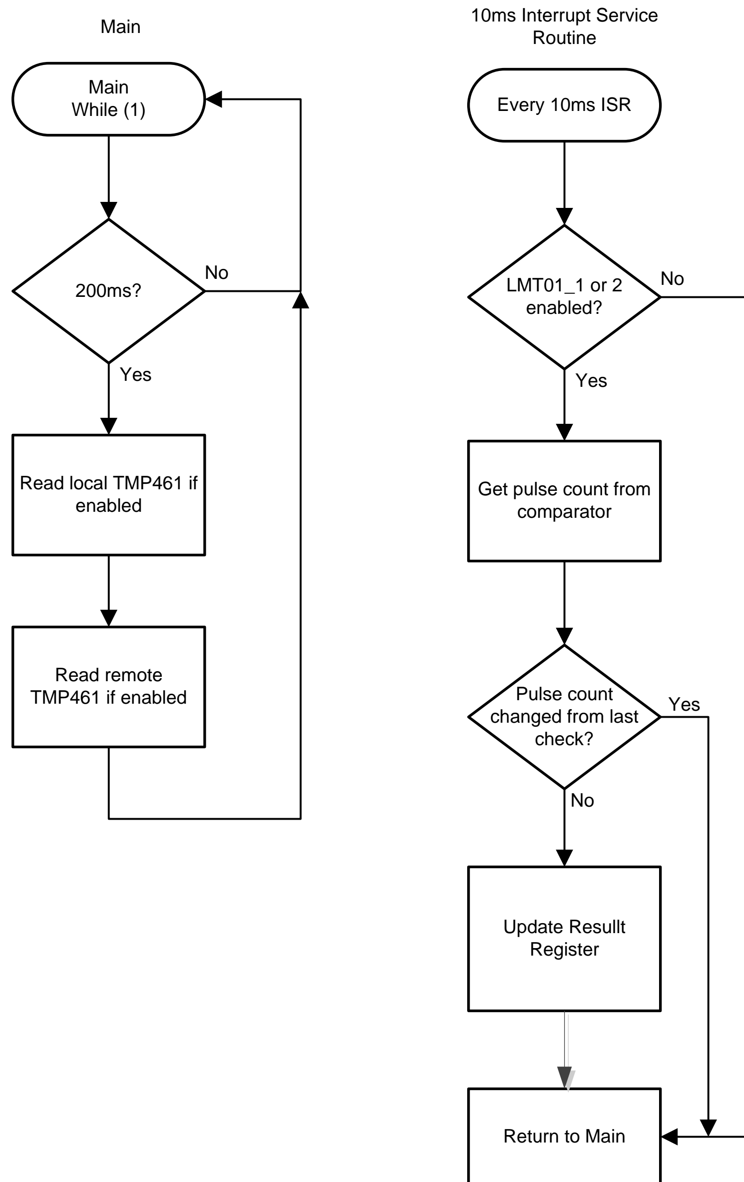

图 **3. MSP430FR5969-SP Firmware Flow Diagrams**

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3.2 Testing and Results

3.2.1 Test Setup

An automated LabVIEW™ routine was created to execute the TSW12D1620EVM GUI to obtain temperature measurements at periodic intervals. Several tests were run to evaluate the temperature change of both the board and the ADC12D1620QML-SP junction temperature under two conditions. Both conditions tested used the maximum input clock rate of 1.6-GHz. The first tested condition had both channels active, and the second condition had only a single channel active. It is estimated that the ADC will be dissipating approximately 4 W with both channels active, and approximately 2 W with a single channel. Both tests start with board powered at thermal equilibrium and ADC disabled. The acquisition of temperature reads is started and the ADC is then enabled with either the single or two channels active. The tests were setup to run for 600 s. At the end of 600 s, each of the board's temperature sensors had nearly reached thermal equilibrium in both cases. 图 4 shows the locations of the sensors placed on the TSW12D1620EVM-CVAL.

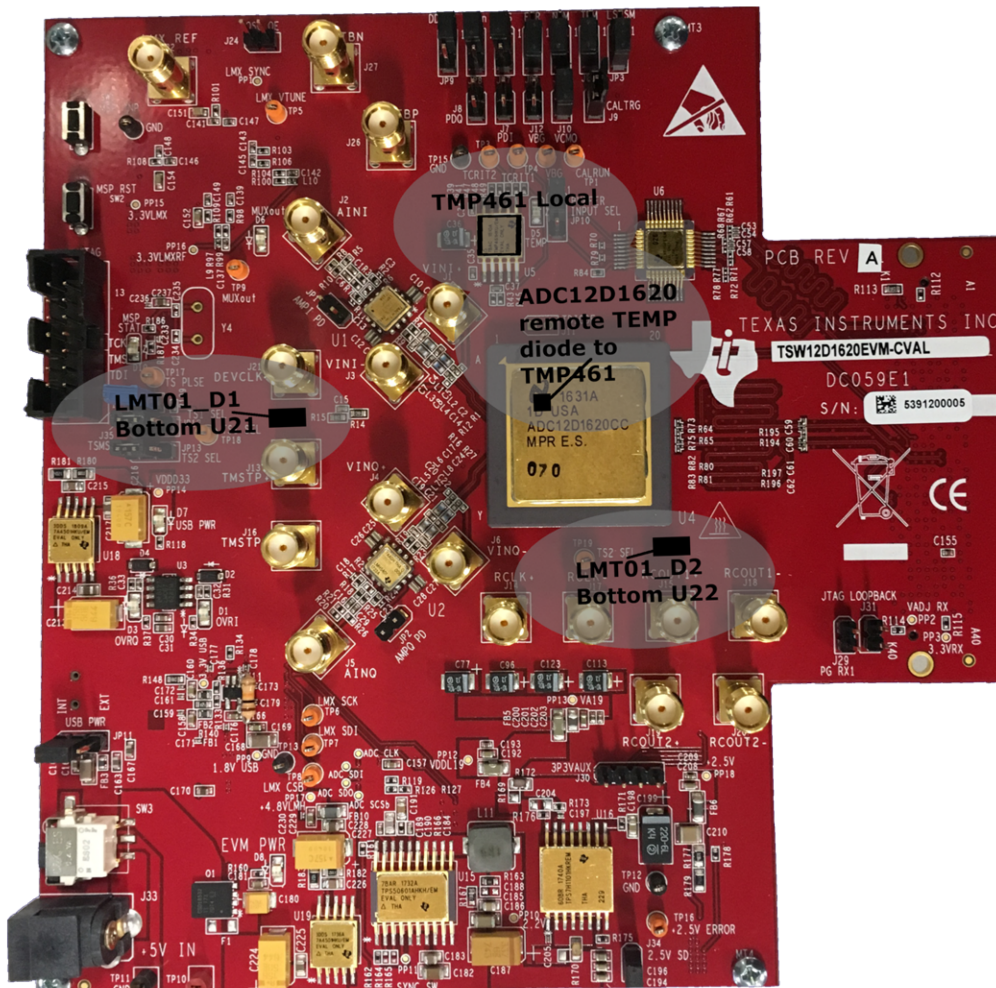

图 4. TSW12D1620EVM-CVAL Temperature Sensor Locations

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3.2.2 Test Results

The initial temperature reads for the LMT01_D1 (U21) start at a slightly elevated temperature when compared to the other sensors. This is due to its proximity to the active power devices on the board. After enabling the ADC, the temperature readings from LMT01_D2 (U22) rapidly exceed the temperature reading of LMT01_D1. This is due to its proximity to the ADC. See 图 5 for temperature results with ADC operating at 4 W. 图 6 shows temperature results with ADC dissipating ~2 W. 图 7 is a composite image of the TSW12D1620EVM overlaid with an infrared thermal image showing temperature gradients around the board. The board was operating in a ~22°C lab environment with board operating at max power ~4 W at thermal equilibrium. Note, that the thermal image of the gold lids and leads do not accurately reflect the temperature due to emissivity errors associated with the thermal imager. The spot and peak temperatures recorded by the thermal camera matches very closely to the ADC diode temperature recorded by the TMP461-SP.

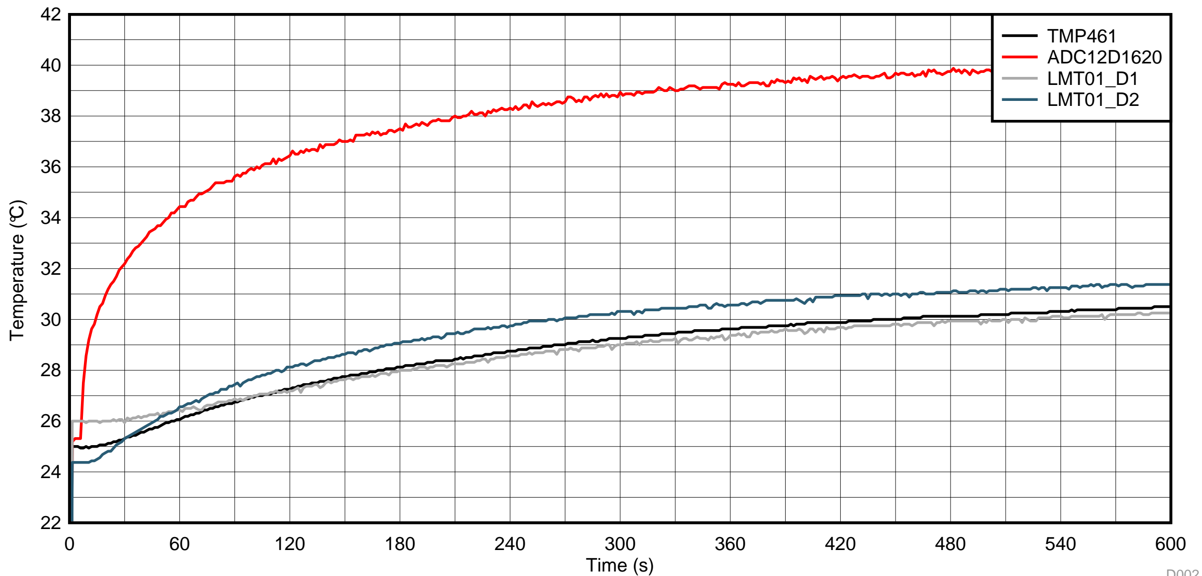

图 5. TSW12D1620EVM-CVAL Board Temperatures Operating at 4 W

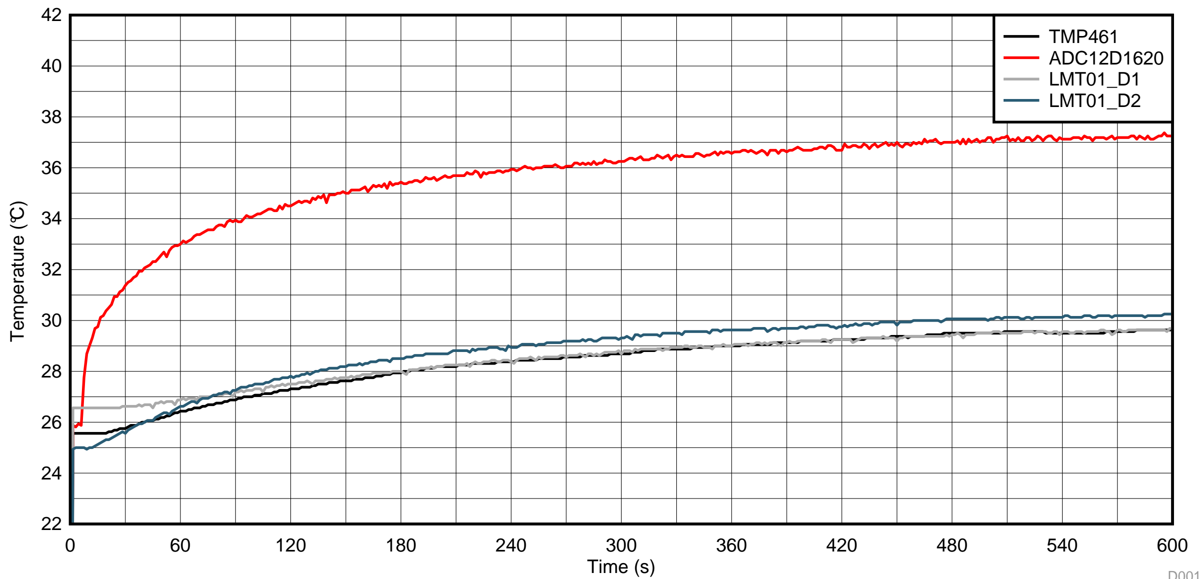

图 6. TSW12D1620EVM-CVAL Board Temperatures Operating at 2 W

TIDUEM2 — http://www-s.ti.com/sc/techlit/TIDUEM2
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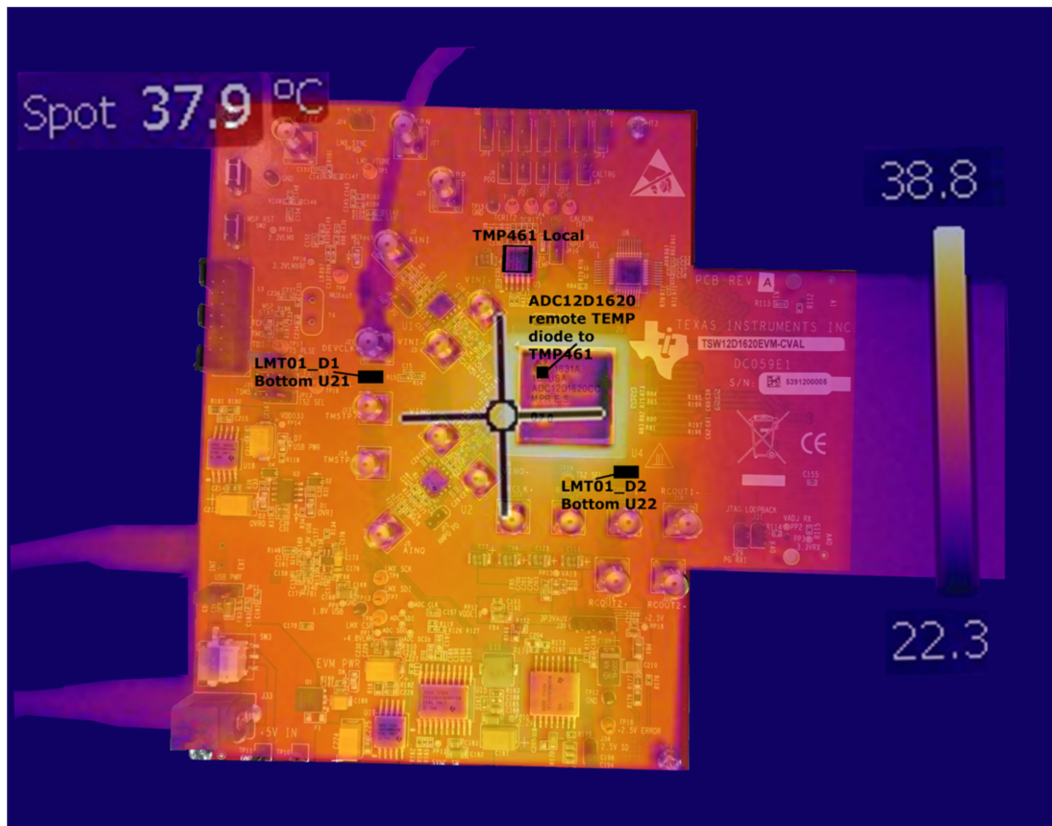

图 7. TSW12D1620 Thermal Infra-Red Composite Board Image

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4 Design Files

4.1 Schematics

To download the schematics, see the design files in the TIDA-070004 folder.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files in the TIDA-070004 folder.

4.3 PCB Layout Recommendations

- **MSP430FR5969-SP**
  - For MSP430FR5969-SP layout recommendations, please reference the *Applications, Implementation, and Layout* section of the MSP430FR5969-SP data sheet (SLASEK0).
- **LMT01-SP**
  - For LMT01-SP layout recommendations, please reference the *Layout* section of the LMT01-SP data sheet (SNIS205).
- **TMP461-SP**
  - For TMP461-SP layout recommendations, please reference the *Layout* section of the TMP461-SP data sheet (SBOS876).

4.3.1 Layout Prints

To download the layer plots, see the design files in the TIDA-070004 folder.

4.4 Gerber Files

To download the Gerber files, see the design files in the TIDA-070004 folder.

4.5 Assembly Drawings

To download the assembly drawings, see the design files in the TIDA-070004 folder.

5 Software Files

To download the software files, see the design files in the TIDA-070004 folder.

6 Related Documentation

1. *Optimizing remote diode temperature sensor design*

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修订历史记录

注：之前版本的页码可能与当前版本有所不同。

Changes from Original (March 2019) to A Revision **Page**

- 已更改 将标题从"卫星温度检测参考设计"更改为"使用集成式数字输出温度传感器的航空级温度检测参考设计" 1
- 已更改 说明 段落 1
- 已删除 删除了"电路板/系统健康监控"和"电路板/系统温度和性能优化" 1
- 已添加 添加了"命令和数据处理"、"卫星电力系统 (EPS)"、"光学成像有效载荷"、"雷达成像有效载荷"以及"通信有效载荷". 1

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