

# Radiation-Hardened Space Battery Management System (BMS) Reference Design



## Description

This reference design demonstrates a space-graded battery management system. The circuit measures eight battery cells in series to monitor battery health, state of charge, and temperature.

## Resources

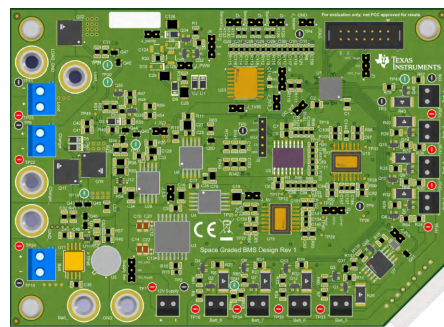
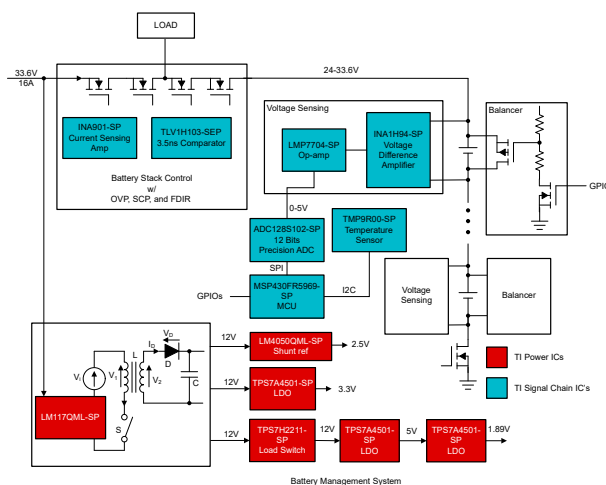
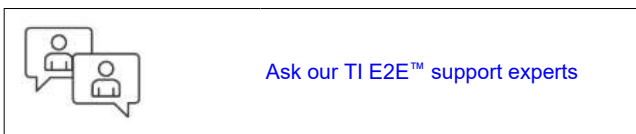
<a href="#">TIDA-010931</a>	Design Folder
<a href="#">MSP430FR5969-SP</a>	Product Folder
<a href="#">ADC128S102QML-SP</a>	Product Folder
<a href="#">TLV1H103-SEP</a>	Product Folder
<a href="#">TPS7H2211-SP</a>	Product Folder
<a href="#">TPS7A4501-SP</a>	Product Folder
<a href="#">LM4050QML-SP</a>	Product Folder
<a href="#">INA901-SP</a>	Product Folder
<a href="#">INA1H94-SP</a>	Product Folder
<a href="#">LMP7704-SP</a>	Product Folder
<a href="#">TMP9R00-SP</a>	Product Folder
<a href="#">LM117QML-SP</a>	Product Folder

## Features

- Radiation performance – 75krad / 72MeV
- Manage eight 4.2V Li-ion batteries
- Battery monitoring accuracy:  $\pm 1\text{mV}$  (Battery= 3V to 4.2V)
- GPIO controlled battery balancing circuit
- Scalability to measure up to 28 batteries
- Low leakage current capabilities:  $0.02\mu\text{A}$
- Board dimensions: 5.5in  $\times$  4in

## Applications

- Spacecraft battery management system (BMS)
- [Satellite electrical power system \(EPS\)](#)



## 1 System Description

As [Table 2-1](#) and [Figure 2-1](#) illustrate, the TIDA-010931 reference design is composed of numerous subsystems including:

- A battery cell voltage monitoring system
- A battery cell balancer to maximize battery capacity
- Temperature sensors to monitor battery cells
- A battery stack control to protect battery and load from overcharging and short circuiting

The ability to monitor battery voltage, current, and temperature has many value propositions. Battery management systems (BMS) provide key information regarding battery state of health and state of charge which is crucial for satellites to maintain a reliable energy source. Today, lithium-ion batteries act as the key to reduce the cost and weight of satellites, yet still come with safety concerns.

The combination of the high energy density of Li-ion and flammable material associated with batteries can be hazardous due to thermal runaway, overcharging, improper balancing, and the chance of experiencing a short. Currently, there are no known radiation-hardened balancer ICs or monitor ICs with the ability to sense battery state of health and state of charge. To reduce the amount of batteries and weight, a higher amount of cell voltage sensing accuracy in applications is needed. BMS in space require low leakage current from batteries to survive the lead time of rocket launches. This design is a discrete, autonomous, and reliable BMS approach that provides high radiation performance, precise cell voltage monitoring, fast overcurrent protection, temperature sensing, and balancing capabilities.

The MSP430FR5969-SP MCU measures battery cell characteristics including current, voltage, and temperature and communicates with the BMS graphical user interface (GUI). The MSP430FR5969-SP is also used to provide timing and logic for the power sequencing and provides a PWM switching signal for the boost circuit. The MSP430FR5969-SP can be programmed with pre-written firmware for compatibility with the BMS GUI.

The power design for this reference design enables power control to allow for low leakage current abilities. The different power rails can be enabled and disabled by the MSP430FR5969-SP.

A 12V external power supply or an eight cell battery pack is required to power the TIDA-010931 reference design. The device has an integrated power supply to power each subcomponent using the LM117QML-SP, TPS7H2211-SP, LM4050QML-SP, and TPS7A4501-SP to create different step-down voltages. Details on exact voltages and power sequencing can be found in the [Design Considerations](#) section.

## 2 System Overview

Table 2-1 details the system specifications.

**Table 2-1. System Specifications**

PARAMETER	VALUE	UNIT
Power Supply	12 or from battery pack	V
# of Battery Cells	8	–
Battery Cell Voltage	3–4.2	V
Leakage Current	0.02	μA
Battery Cell Voltage Accuracy	±1	mV
Balancer Current	120 to 169	mA

Table 2-2 lists the jumpers and headers descriptions.

**Table 2-2. Jumpers and Headers Descriptions**

PARAMETERS	NET NAME	DESCRIPTION
Power Supply	12V Supply	12V power supply
	Supply Sel	Select input supply from battery output or external 12V supply
JTAG	JTAG	JTAG connection
PWM Control	J_PWM	PWM input
Input/Output Controls	J Pump	Pump input
	Charger	Charger input
	Batt	Eight-cell battery pack input
	Load	Load output
Voltage Supply	J_LS	Enables load to rest of circuit
	J4	12V or 5V supply for battery pump
	J_5V	Separates LDO and 5V load
	J_1V85	Separates LDO and 1.85V load
	J_3V3	Separates 3.3V LDO output and MSP430FR5969-SP
	J_3V3_2	Separates 3.3V LDO and ADC128S102-SP
	J_2V5	Separates LDO and 2.5V load
J_heater	GPIO assigned for turning the battery heater on or off	
Communications	J6	Temperature control communications
	J2	ADC communication to connect to a digital analyzer
	J5	Voltage balancing with calibration with 2.5Vref
Battery Monitoring	Batt 1	Connect to battery cell 1
	Batt 2	Connect to battery cell 2
	Batt 3	Connect to battery cell 3
	Batt 4	Connect to battery cell 4
	Batt 5	Connect to battery cell 5
	Batt 6	Connect to battery cell 6
	Batt 7	Connect to battery cell 7
	Batt 8	Connect to battery cell 8
Temperature Monitoring	Sensor 1	Temperature sensor 1
	Sensor 2	Temperature sensor 2
	Sensor 3	Temperature sensor 3
	I2C_pull	Enable TMP9R00-SP I2C 3.3V pullup

Table 2-3 lists the test points and the expected value.

**Table 2-3. Test Point Descriptions and Expected Values**

NET NAME	DESCRIPTION	EXPECTED VALUE
TP1	12V supply	12V
TP2	Ground	0V
TP3, TP4, TP5, TP6, TP8, TP9, TP10, TP43	Ground	0V
TP7	Battery 4 sensing amplifier output	0.565V–4.552V
TP11	Load voltage	24V
TP12	Battery 7 sensing amplifier output	0.565V–4.552V
TP13	Battery 3 sensing amplifier output	0.565V–4.552V
TP14	Battery 6 sensing amplifier output	50.565V–4.552V
TP15	Battery 2 sensing amplifier output	0.565V–4.552V
TP16	Battery output voltage	33.6V
TP17	Battery 8 sensing amplifier output	0.565V–4.552V
TP18	Battery 1 sensing amplifier output	0.565V–4.552V
TP19	Gate voltage	27V
TP20	Short-circuit protection gate voltage	30mV
TP21	Gate voltage	5V
TP22	Charger voltage in	28V
TP23	Load voltage	28V
TP24	Battery output voltage	33.6V
TP25	Battery 8 sensing first amplifier output	2.5V
TP26	Battery 4 sensing first amplifier output	2.5V
TP27	Battery 7 sensing first amplifier output	2.5V
TP28	Battery 3 sensing first amplifier output	2.5V
TP29	Battery 6 sensing first amplifier output	2.5V
TP30	Battery 2 sensing first amplifier output	2.5V
TP31	Gate voltage	26.88V
TP32	Battery 5 sensing amplifier output	5V
TP33	Battery 5 input voltage	21V
TP34	Battery 7 input voltage	29.4V
TP35	Battery 6 input voltage	25.2V
TP36	Battery 4 input voltage	16.8V
TP37	Battery 3 input voltage	12.6V
TP38	Battery 2 input voltage	8.4V
TP39	Battery 1 input voltage	4.2V
TP40	Battery 5 sensing first amplifier output	2.5V
TP41	Battery 7 balancer	29.4V
TP43	Ground	0V
TP45	INA901-SP output	0.6V
TP46	INA901-SP output	0.6V

## 2.1 Block Diagram

Figure 2-1 illustrates the TIDA-010931 system block diagram.

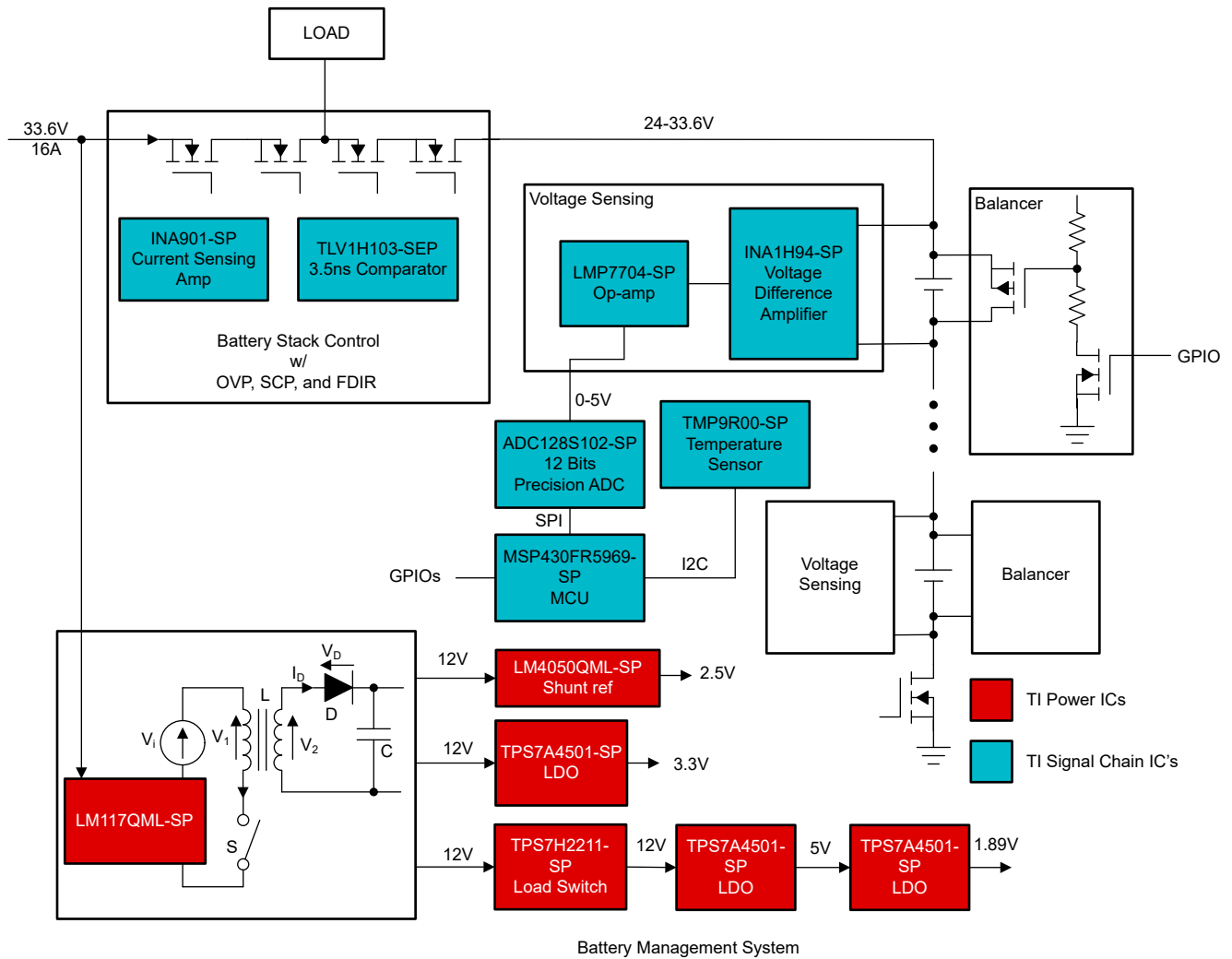


Figure 2-1. Block Diagram

## 2.2 Design Considerations

The following sections describe fundamental design considerations utilized for subsystems of the reference design based on end-use applications.

### 2.2.1 System Control and Processing

The TIDA-010931 system control and processing is based on the feature set and capabilities of the MSP430FR5969-SP MCU. The MSP430FR5969-SP interfaces with different dedicated devices to sense battery temperature, current, and voltage and adjusts system functionality based on measurements.

The MSP430FR5969-SP also provides the PWM switching signal for an unregulated boost controller circuit. A boost circuit is implemented with N-MOSFETs for quick turn off ability. The right gate voltage for the boost regulator can use the N-MOS to short to ground.

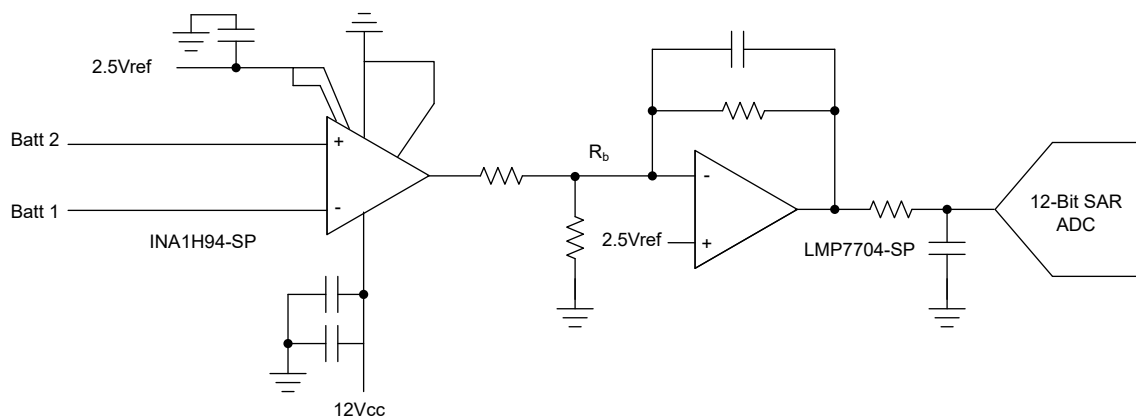
### 2.2.2 Battery Cell Monitoring

This reference design was created to support eight standard Lithium-Ion 4.2V batteries. The LM117QML-SP linear regulator is used in the reference design to step down a 33.6V battery output to 12V. LM117QML-SP has a maximum input rating of 40V. If more battery cells are desired, a different step-down buck is required.

The battery cell monitoring is designed to monitor battery cell voltages in the range of 3V to 4.2V. A wider range can be accommodated by changing the gain of the LMP7704-SP amplifier circuit following the INA1H94-SP. This resistor change also needs to be reflected in the BMS GUI through the SCISwitchValueChanged function.

The battery-monitoring circuit (see [Figure 2-2](#)) functions by first utilizing the INA1H94-SP, a precision unity-gain difference amplifier, to accurately measure the voltage from two batteries. The INA1H94-SP can measure small differential voltages in the presence of common-mode signal up to 150V. The R97 resistor functions to change the gain. The LMP7704-SP is used to adjust the common mode and range of the signals to maximize the dynamic range of the ADC input. The output is sent to the MCU and displayed on the GUI.

The INA1H94-SP is in a single-supply operation for this design, leading to the addition of a 2.5V reference. This IC does not have a rail-to-rail input or output, requiring a reference to satisfy the common-mode range. The data sheet specifies that the voltages at the internal amplifier are within 1.5V of the supply voltage. A 2.5V reference was chosen to satisfy this, but a reference as low as 1.5V is acceptable.



**Figure 2-2. Battery Monitoring**

### 2.2.3 Temperature Sensing

Temperature sensing plays a vital role in monitoring battery lifetime and proper operation. [Figure 2-3](#) shows the temperature sensing circuitry. The TMP9R00-SP can locally monitor temperature ranging from  $-55^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  and remotely monitor temperature ranging from  $-55^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ . TMP9R00-SP can support eight remote channels with a combined maximum voltage of 6V. The temperature measurement is represented as a 12-bit digital code for both local and remote sensors

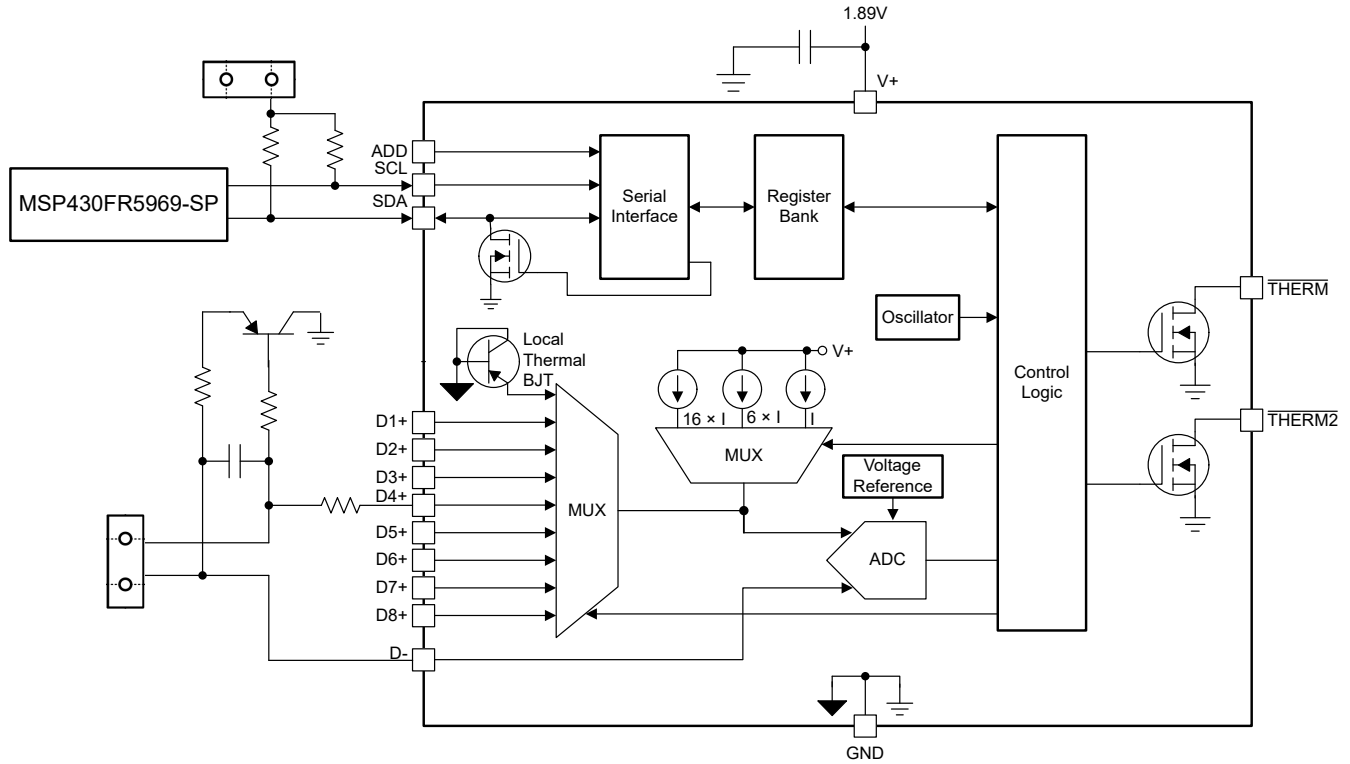


Figure 2-3. Temperature Sensing

### 2.2.4 Battery Stack Control

The INA901-SP, a current-sense amplifier, has a built-in gain of 20V/V allowing for a smaller current sense resistor which minimizes the drop and power loss across the sense resistor. The INA901-SP is paired with the TLV1H103-SEP voltage comparator to drive the MCU (see Figure 2-4).

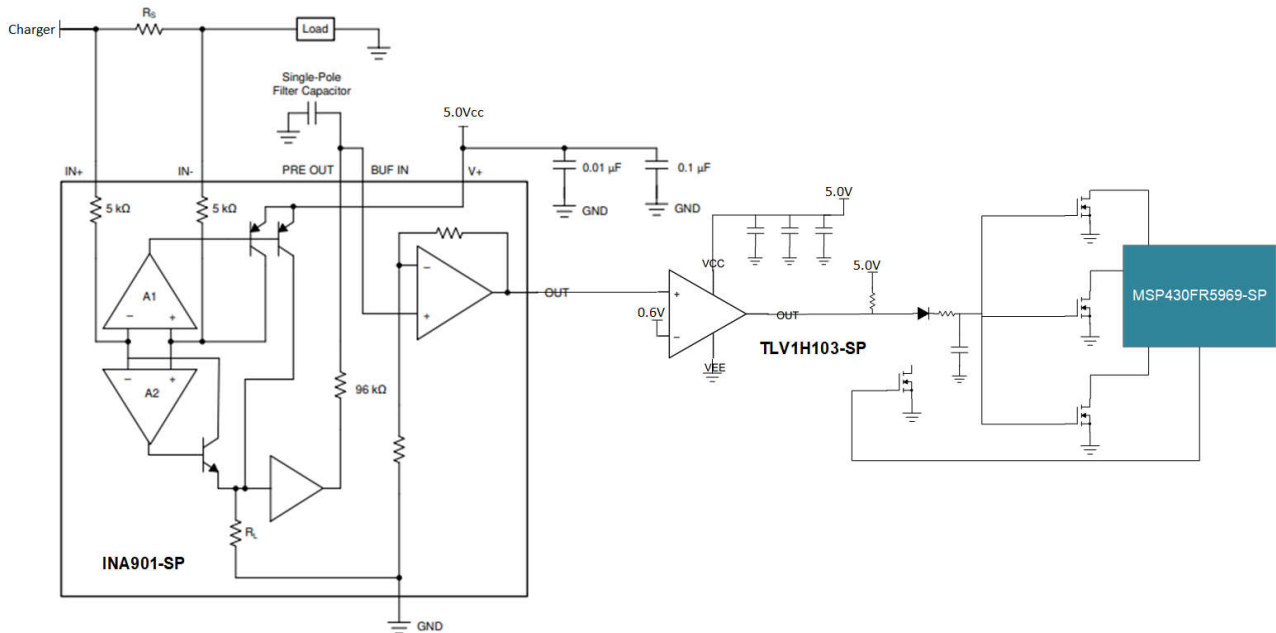
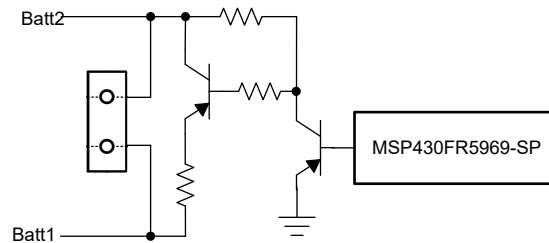


Figure 2-4. Short-Circuit Protection

## 2.2.5 Battery Balancing

Battery cell balancing plays a role in the capacity and performance of each battery cell. This system (see [Figure 2-5](#)) involves a low-complexity passive balancing design. When the GPIO from the MCU is low there is no balancing occurring; therefore, no current is drawn from the battery cell. When the GPIO from the MCU is high, the transistor gets turned on and around 15mA is drawn from the battery cell.

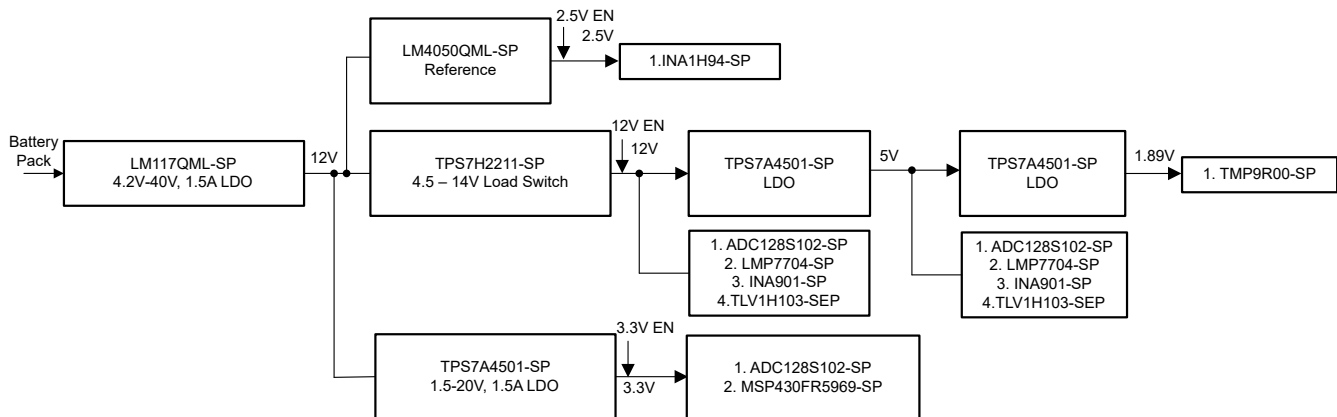


**Figure 2-5. Battery Balancing**

## 2.2.6 Power Tree and Power Sequencing

[Figure 2-6](#) illustrates the power tree consisting of four main components: TPS7H4010-SEP, LM4050QML-SP, TPSH2211-SP, and TPS7A4501-SP.

The LM117QML-SP integrated circuit converts voltage from the battery pack (33.6V) to 12V. The LM117QML-SP is an easy-to-use, wide-input range, 1.5A linear regulator designed for various applications. The LM4050QML-SP is a space-graded 2.5V shunt voltage reference that is used to supply low-noise reference for battery cell monitoring. The TPS7A4501-SP is an adjustable low-dropout regulator used to convert voltage from 12V to 3.3V, 12V to 5V, and 5V to 1.89V. Each section of the power supply can be enabled or disabled from the MSP430 to reduce current consumption when not in use.



**Figure 2-6. Power Management**



## 2.3 Highlighted Products

This section describes the highlighted products used in the reference design for battery stack control, processing, balancing, temperature sensing, and monitoring.

<a href="#">TIDA-010931</a>	Design Folder
<a href="#">MSP430FR5969-SP</a>	Product Folder
<a href="#">ADC128S102QML-SP</a>	Product Folder
<a href="#">TLV1H103-SEP</a>	Product Folder
<a href="#">TPS7H2211-SP</a>	Product Folder
<a href="#">TPS7A4501-SP</a>	Product Folder
<a href="#">INA901-SP</a>	Product Folder
<a href="#">INA1H94-SP</a>	Product Folder
<a href="#">LMP7704-SP</a>	Product Folder
<a href="#">TMP9R00-SP</a>	Product Folder
<a href="#">LM117QML-SP</a>	Product Folder
<a href="#">LM4050QML-SP</a>	Product Folder

### 2.3.1 MSP430FR5969-SP

The MSP430™ ultra-low-power (ULP) FRAM platform combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing innovators to increase performance at lowered energy budgets. FRAM technology combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash at much lower power.

The ultra low-power architecture of the MSP430FR5969-SP showcases seven low-power modes, optimized to achieve power efficient distributed telemetry and housekeeping systems.

The integrated mixed-signal features of the MSP430FR5969-SP make the device an excellent choice for distributed telemetry applications in next-generation spacecraft. The strong immunity to single-event latch up and total ionizing dose, enable the device to be used in a variety of space and radiation environments.

### 2.3.2 ADC128S102QML-SP

The ADC128S102 device is a low-power, eight channel CMOS 12-bit analog-to-digital converter specified for conversion throughput rates of 50kSPS to 1MSPS. The converter is based on a successive approximation register architecture with an internal track-and-hold circuit. The device can be configured to accept up to eight input signals at inputs IN0 through IN7.

The output serial data is straight binary and is compatible with several standards, such as SPI, QSPI, MICROWIRE, and many common DSP serial interfaces.

The ADC128S102 can be operated with independent analog and digital supplies. The analog supply (VA) can range from 2.7V to 5.25V, and the digital supply (VD) can range from 2.7V to VA. Normal power consumption using a 3V or 5V supply is 2.3mW and 10.7mW, respectively. The power-down feature reduces the power consumption to 0.06μW using a 3V supply and 0.25μW using a 5V supply.

### 2.3.3 TLV1H103-SEP

The TLV1H103-SEP is a 325MHz, high-speed comparator with rail-to-rail inputs and a propagation delay of 2.5ns. The combination of fast response and wide operating voltage range make the comparator an excellent choice for narrow signal pulse detection and data and clock recovery applications in radar imaging and communications payload systems.

The push-pull (single-ended) outputs of the TLV1H103-SEP simplify and save cost on board-to-board wiring for I/O interfaces while reducing power consumption when compared to alternative high-speed differential output comparators. In addition, the TLV1H103-SEP offers the features such as adjustable hysteresis control and output latch capability. The comparator can directly interface most prevailing digital controllers and IO expanders in the downstream.

The TLV1H103-SEP uses a high-speed complementary BiCMOS process and is available in a 6-pin package.

### 2.3.4 TPS7H2211-SP

The TPS7H2211-SP is a single channel eFuse (integrated FET load switch with additional features) that provides reverse current protection, overvoltage protection, and a configurable rise time to minimize inrush current, soft start. The device contains P-channel MOSFETs that operate over an input voltage range of 4.5V to 14V and supports a maximum continuous current of 3.5A.

The switch is controlled by an on and off input (EN), which is capable of interfacing directly with low-voltage control signals. Overvoltage protection and soft start are programmable with few external components through the OVP and SS pins. The TPS7H2211-SP is available in a ceramic and plastic package with an exposed thermal pad allowing for improved thermal performance. A standard microcircuit drawing (SMD) is available for the QML 5962R1822001VXC. A vendor item drawing (VID) is available for the -SEP variant, V62/23609.

### 2.3.5 TPS7A4501-SP

The TPS7A4501-SP is a low-dropout (LDO) regulator optimized for fast-transient response. The 59621222402VHA can supply 750mA of output current with a dropout voltage of 300mV. The 5962R1222403VXC can supply 1.5A of output current with a dropout voltage of 320mV. Quiescent current is well controlled, and does not rise in dropout, as with many other regulators. In addition to fast to 20V transient response, the TPS7A4501-SP regulator has very-low output noise, which makes the device an excellent choice for sensitive RF supply applications.

### 2.3.6 INA901-SP

The INA901-SP is a voltage-output, current-sense amplifier that can sense drops across shunt resistors at common-mode voltages from  $-15\text{V}$  to  $65\text{V}$ , independent of the supply voltage. The INA901-SP operates from a single 2.7V to 16V supply, drawing  $700\mu\text{A}$  (typical) of supply current.

The gain of the INA901-SP is  $20\text{V/V}$ . The 130kHz bandwidth simplifies use in current-control loops. The pinouts readily enable filtering.

The device is specified over the extended operating temperature range of  $-55^\circ\text{C}$  to  $125^\circ\text{C}$  and is offered in an 8-pin CFP package.

### 2.3.7 INA1H94-SP

The INA1H94-SP is a radiation-hardened precision unity-gain difference amplifier with a very high input common-mode voltage range. The device is a single, monolithic device that consists of a precision op amp and an integrated thin-film resistor network. The INA1H94-SP can accurately measure small differential voltages in the presence of common-mode signals up to  $\pm 150\text{V}$ .

In many applications, where galvanic isolation is not required, the INA1H94-SP can replace isolation amplifiers. This ability can eliminate costly isolated input side power supplies and the associated ripple, noise, and quiescent current. The excellent 0.0005% typical nonlinearity and 500kHz bandwidth of the INA1H94-SP make the device an excellent choice over those of conventional isolation amplifiers.

### 2.3.8 LMP7704-SP

The LMP7704-SP is a precision amplifier with low input bias, low offset voltage, 2.5MHz gain bandwidth product, and a wide supply voltage. The device is radiation hardened and operates in the military temperature range of  $-55^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$ .

The high DC precision of this amplifier, specifically the low offset voltage of  $\pm 60\mu\text{V}$  and ultra-low input bias of  $\pm 500\text{fA}$ , make this device an excellent choice for interfacing with precision sensors with high output impedances. This amplifier can be configured for transducer, bridge, strain gauge, and transimpedance amplification.

### 2.3.9 TMP9R00-SP

The TMP9R00-SP device is a radiation-hardened, multi-zone, high-accuracy, low-power temperature sensor using a two-wire, SMBus or I<sup>2</sup>C compatible interface. Up to eight remote and one local temperature zones can be monitored simultaneously, aggregating the temperature measurements in a system reducing design complexity. Typical use cases are monitoring temperature of different high power devices, such as MCUs, GPUs, ADCs, DACs and FPGAs. Advanced features such as series-resistance cancellation, programmable ideality factor, temperature offset correction, and temperature limits are included to provide a robust thermal monitoring design.

Each remote channel and the local channel have two independently programmable thresholds that trigger when the corresponding temperature exceeds the limit. A programmable hysteresis setting is available to avoid toggling around the threshold.

The TMP9R00-SP device provides high accuracy ( $\pm 1.5^{\circ}\text{C}$ ) and high resolution ( $0.0625^{\circ}\text{C}$ ) measurement capabilities. The device supports low voltage rails (1.7V to 2.0V), common two-wire interfaces (1.7V to 3.6V), and an operating temperature range from  $-55^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  and a remote junction temperature range from  $-55^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ .

### 2.3.10 LM117QML-SP

The LM117QML-SP 3-terminal positive voltage linear regulator is capable of supplying either 0.5A or 1.5A over a 1.2V to 37V output range. The device is simple to use and requires only two external resistors to set the output voltage.

The regulator is *floating* and sees only the input to output differential voltage, thus enabling supplies of several hundred volts to be regulated as long as the maximum input-to-output differential is not exceeded.

The flight-proven LM117QML-SP offers full overload protection such as current limit, thermal overload protection, and safe area protection. The device is exceptionally versatile and can also be used as an adjustable switching regulator, a programmable output regulator, a precision current regulator, and more.

### 2.3.11 LM4050QML-SP

The LM4050QML precision voltage reference is available in a 10-lead ceramic CLGA package. The design of the LM4050QML eliminates the need for an external stabilizing capacitor while providing stability at  $25^{\circ}\text{C}$  with a capacitive load, thus making the LM4050QML easy to use. The LM4050-2.5QML has a  $60\mu\text{A}$  minimum and 15mA maximum operating current. The LM4050-5.0QML has a  $74\mu\text{A}$  minimum and 15mA maximum operating current.

## 3 Hardware, Software, Testing Requirements, and Test Results

### 3.1 Hardware Requirements

Five pieces of hardware are required for this reference design:

1. 12V power supply: An external 12V power supply is required and is connected through the TIDA-010931 reference design, *Batt\_Out* power connector
2. TIDA-010931: Space battery management system reference design board
3. MSP430 Programmer and debugger: A JTAG debug probe for programming
4. USB-to-TTL Serial Cable: Used for SCI communication between the BMS GUI and TIDA-010931
5. Eight-cell battery pack or battery simulator

### 3.2 Software Requirements

Three pieces of software are required: Code Composer Studio™ integrated development environment (IDE), BMS firmware, and the BMS GUI.

The Code Composer Studio™ IDE supports TI's MCU and embedded processor portfolios. The software is needed to program the MSP430FR5969-SP. The flow begins with initializing the GPIO, PWM, SPI, SCI, and ADC, followed by an infinity loop controlled by the GUI. The program first waits to receive a GUI command. Based on the command received, the program does the work and gets back to the beginning of the loop for the next GUI command.

After loading the firmware into MSP430FR5969-SP, the TIDA-010931 is connected to the computer through a USB-to-TTL serial cable. This cable allows a serial communications interface (SCI) between the MATLAB® GUI and TIDA-010931. The GUI then displays each battery cell voltage and current based on feedback from the MCU. [Figure 3-1](#) shows the GUI screen.

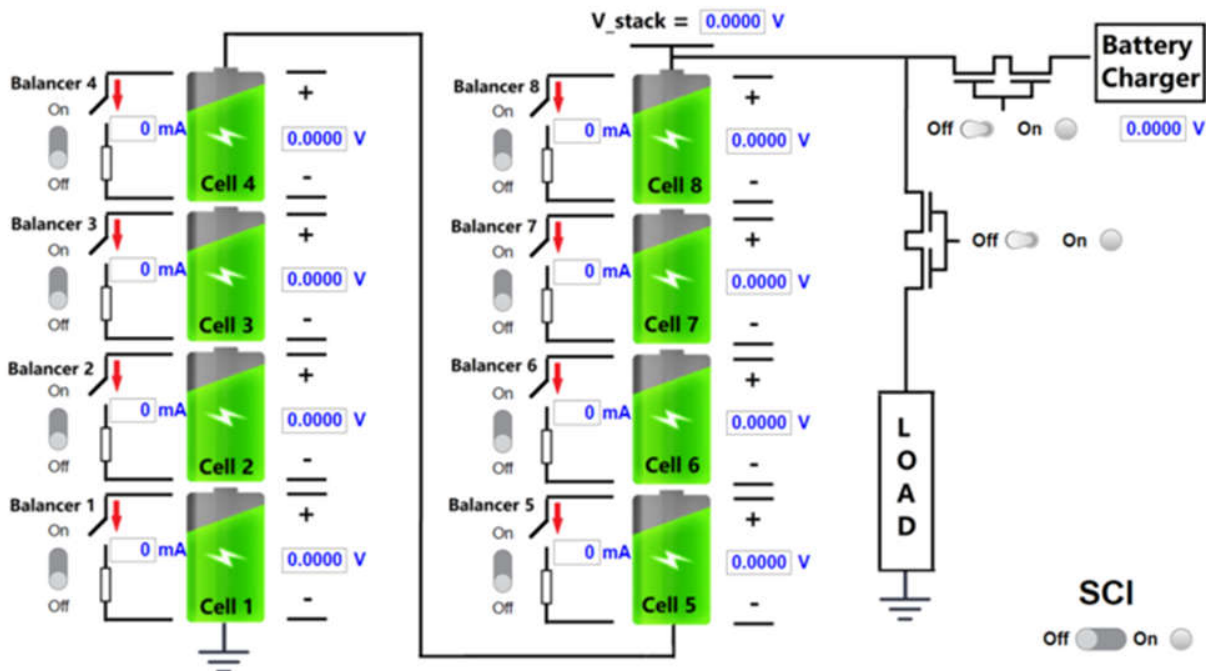


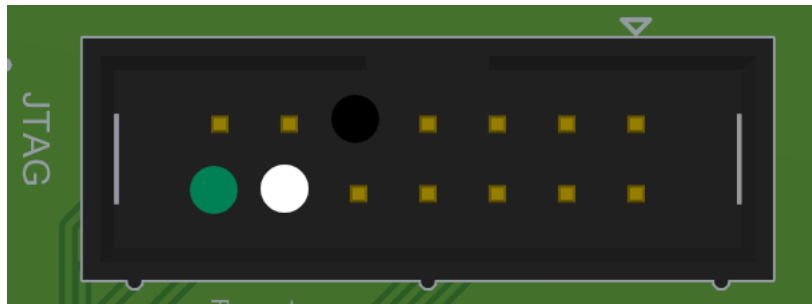
Figure 3-1. TIDA-010931 GUI

### 3.3 Test Setup

The TIDA-010931 is an easy to use reference design with the provided firmware and GUI. To set up the BMS, follow the steps below:

1. Prepare all the required hardware and software
2. Supply 12V to TIDA-010931. There are two options:
  - a. Power the BMS with the output from the batteries and select the *12V\_LDO* pin on the *Supply Sel* jumper
  - b. Use a 12V DC voltage supply and select the *12V\_Supply* pin on the *Supply Sel* jumper
3. Connect the MSP430 debug probe to the TIDA-010931 JTAG header
4. Program the MSP430 MCU using Code Composer Studio
5. Connect the JTAG header and USB-to-TTL serial cable to PC
  - The TTL serial cable has four connectors that are red, green, white, and black. Only the green, white, and black connectors are attached to the JTAG as [Figure 3-2](#) shows
6. Install and run the BMS MATLAB GUI
7. In the GUI, enter the SCI COM number and click the *Connect* button. Once connected, a green light appears, the GUI is ready to control the TIDA-010931
8. Calibrate the GUI by measuring the output from the *5VCC* pin and updating the value on the GUI. Calibrate the *2.5Vref* by location J5 on the reference board and clicking the *cal* button on the GUI.

Only the black, green, and white connectors are connected as [Figure 3-2](#) shows. The red connector can remain disconnected.



**Figure 3-2. TTL Serial Cable to JTAG Connection**

### 3.4 Test Results

Figure 3-3 illustrates the battery cell monitoring error after offset calibration. Error is less than  $\pm 1\text{mV}$  for battery voltages ranging from 3.0V to 4.2V.

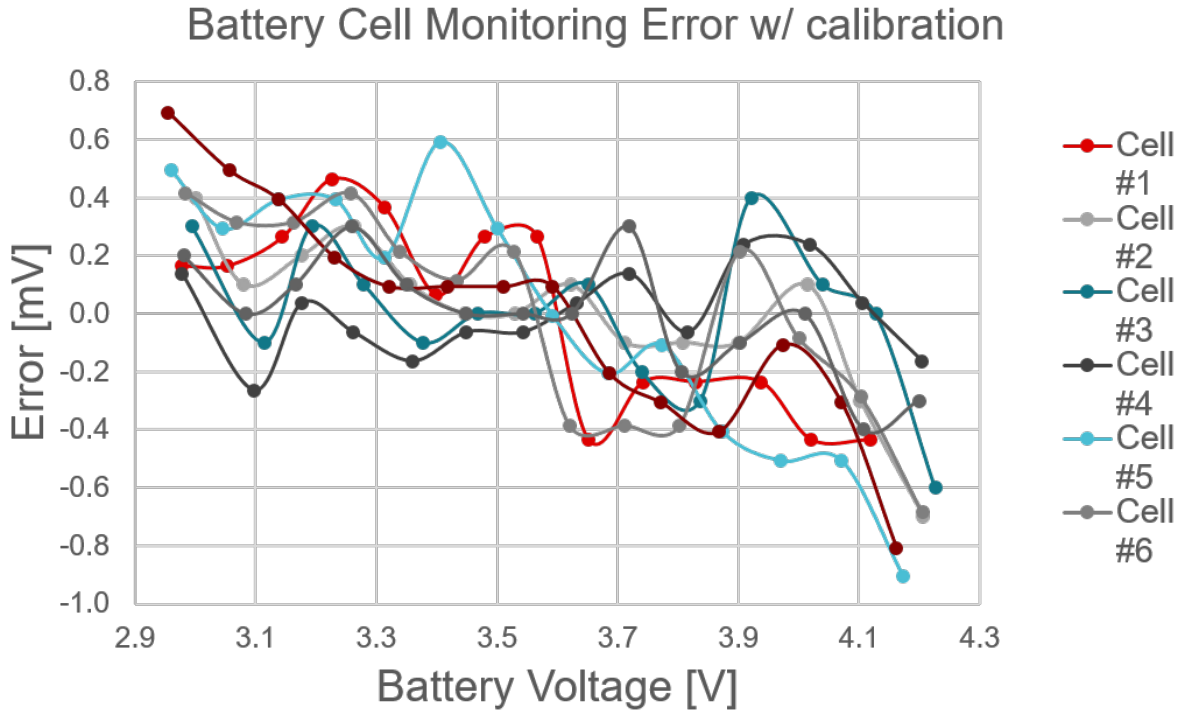


Figure 3-3. Battery Cell Monitoring Error

Figure 3-4 shows the short-circuit protection with power turned off within a  $4.56\mu\text{s}$  delay.

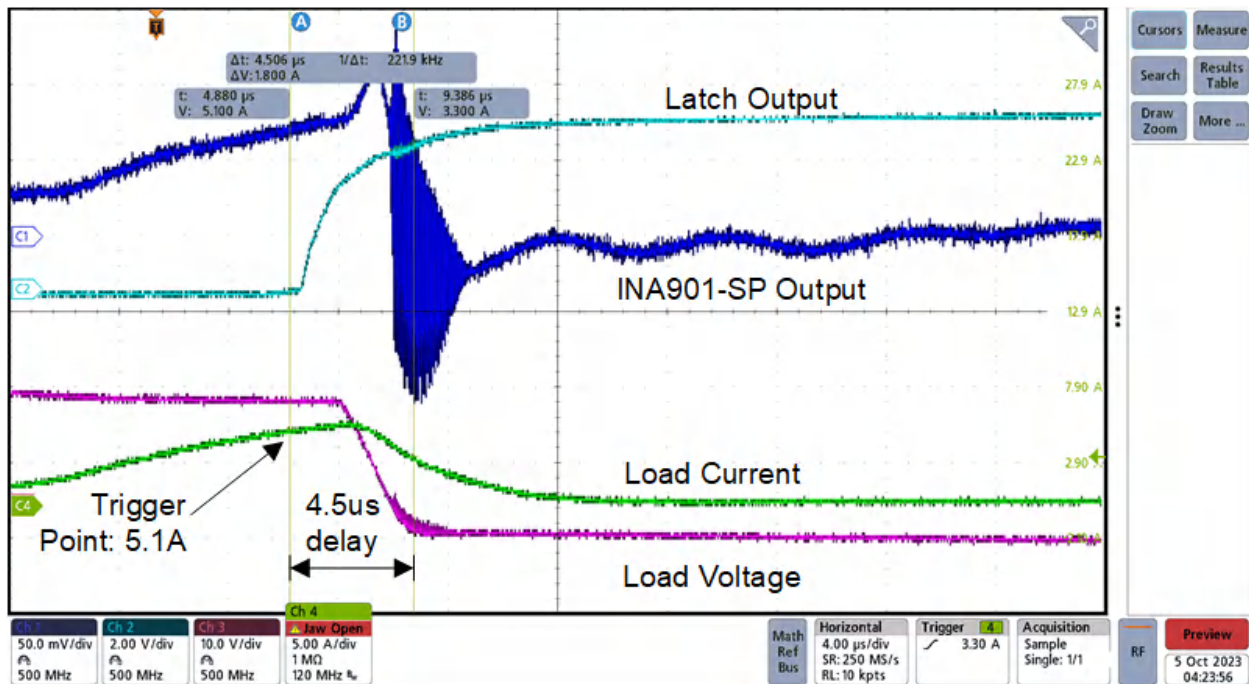


Figure 3-4. Short-Circuit Protection



## 4 Design and Documentation Support

### 4.1 Design Files

#### 4.1.1 Schematics

To download the schematics, see the design files at [TIDA-010931](#).

#### 4.1.2 BOM

To download the bill of materials (BOM), see the design files at [TIDA-010931](#).

### 4.2 Tools and Software

#### Tools

<a href="#">MSP430 Debugger</a>	Debugger for firmware programming
<a href="#">USB-to-TTL Cable</a>	Reference design to GUI connection cable

#### Software

##### BMS GUI

### 4.3 Documentation Support

1. Texas Instruments, [MSP430FR5969-SP Radiation Hardened Mixed-Signal Microcontroller Data Sheet](#)
2. Texas Instruments, [ADC128S102QML-SP Radiation Hardened 8-Channel, 50 kSPS to 1 MSPS, 12-Bit A/D Converter Data Sheet](#)
3. Texas Instruments, [TLV1H103-SEP Radiation Tolerant High-Speed Comparator with 2.5ns Propagation Delay Data Sheet](#)
4. Texas Instruments, [TPS7H2211-SP and TPS7H2211-SEP Radiation-Hardness-Assured \(RHA\) 14V, 3.5A eFuse Data Sheet](#)
5. Texas Instruments, [TPS7A4501-SP Low-Dropout Voltage Regulator Data Sheet](#)
6. Texas Instruments, [INA901-SP Radiation Hardened, -15-V to 65-V Common Mode, Unidirectional Current-Shunt Monitor Data Sheet](#)
7. Texas Instruments, [INA1H94-SP Radiation-Hardened, High Common-Mode Voltage Difference Amplifier Data Sheet](#)
8. Texas Instruments, [LMP7704-SP Radiation Hardness Assured \(RHA\), Precision, Low Input Bias, RRIO, Wide Supply Range Amplifier Data Sheet](#)
9. Texas Instruments, [TMP9R00-SP 9-Channel \(8-Remote and 1-Local\), High-Accuracy Temperature Sensor Data Sheet](#)
10. Texas Instruments, [LM117QML-SP RHA 4.25-V to 41.25-V 3-Terminal Adjustable Regulator Data Sheet](#)
11. Texas Instruments, [LM4050QML Precision Micropower Shunt Voltage Reference Data Sheet](#)

### 4.4 Support Resources

[TI E2E™ support forums](#) are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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## 5 About the Author

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