# SHM-S Board

## Strain Sensor Board

Datasheet and User's Guide

## Overview

Developed as part of the Illinois Structural Health Monitoring Project, the SHM-S sensor board is designed to use with the Imote2 smart sensor platform. This strain sensor board includes a wheatstone bridge, signal amplifier (up to 2500 times) and a terminal block to interface with external 350 ohm 3-wires strain gauge as well as any other DC-output analog sensor that needs signal amplification. The key feature of this sensor board is the precisely controllable wheatstone bridge circuit. In this sensor board, the strain signal is managed to fit the output range of the signal amplifier through accurately balancing the wheatstone bridge before signal amplification. To balance the bridge, digital potentiometers are used and controlled by software. This sensor board, which has no ADC, is designed to combined use with ISM400 board or SHM-DAQ board through the basic connectors. The conditioned signal is linked to the 4th channel of ISM400 or the 1st channel of SHM-DAQ board.

## Features

- Strain measurement using 350 ohm foil type 3-wires strain gauge
- Slide switches for selection of strain gauge input & DC-output analog sensor input
- Four selective gain factors: 500, 1000, 2000 and 2500 times
- Accurately controllable wheatstone bridge circuit
- Resistance variation compensation due to temperature change, strain gauge tolerance error and wire resistance
- Combined use with ISM400 or SHM-DAQ board
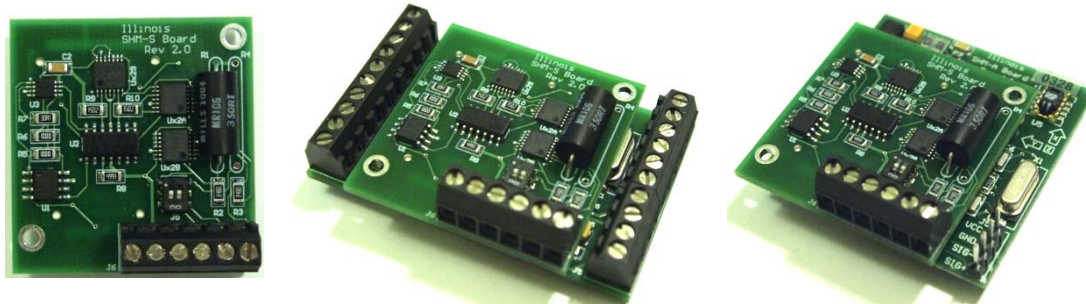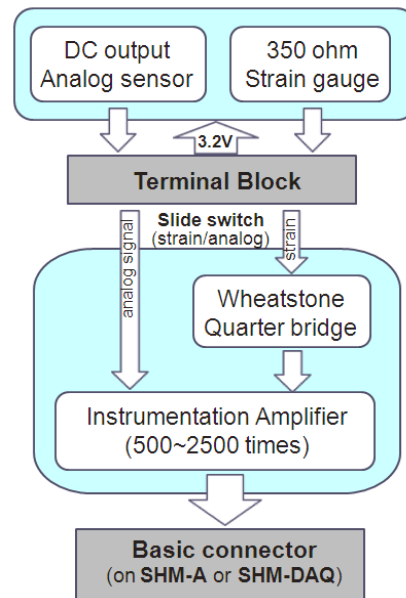- All features of ISM400 and SHM-DAQ board are retained





Figure 1. SHM-S board: top (left), with SHM-DAQ (middle), and with ISM400 (right).

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## 1.1    Block diagram



**Figure 2. SHM-S block diagram**

Note:  (1) Any DC voltage output analog sensor that needs signal amplification can be used. But the mean value of the signal should be closed to zero; otherwise the amplified signal output would be out of the amplifier's range. Some of strain gauge modules having a built-in bridge circuit, which provide DC voltage output, can be examples of this kind of analog sensor (e.g. BDI strain transducer ST350, Tokyo Sokki Strain Checker FGMH-1B).

(2) Two-channel digital potentiometer is connected parallel to the wheatstone bridge; which control the possible unbalance due to temperature change or strain gauge tolerance error. This balance control is done using `RemoteCommand` `SHMSAutoBalance` before sensing. More information is available at 4.1 Automatic Bridge Balancing.

(3) The digital potentiometers combined with Op Amp here are used to make three voltage dividers. Two voltage dividers are for controlling an analog switch for gain selection, the other one voltage divider is for providing a reference voltage to shift the amplifier output; to better fit the input range of the QF4A512 ADC, the amplified signal sometimes needs to be shifted little.

## 1.2   Pin descriptions

The SHM-S board connects to the SHM-A board or SHM-DAQ board via two connectors located on the bottom of the board.  In addition, the SHM-S board provides a terminal block on the top of the board to allow the external input from a typical 350 ohm strain gauge or a DC voltage-output analog sensor. Figure 3 gives the dimensions of the SHM-S sensor board, indicates the location of the connector on the bottom and the terminal block on the top of the board. The pin descriptions are given in Tables 1 and 2.
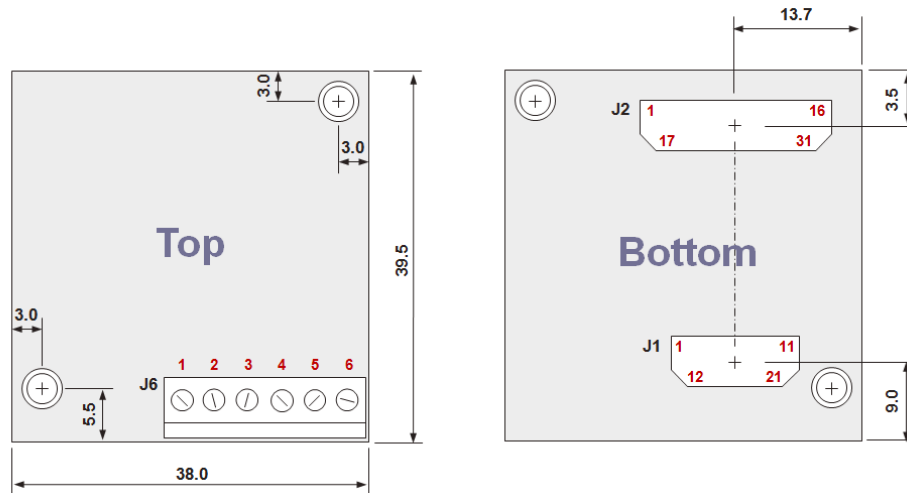


Figure 3. SHM-S dimensions (all dimensions in mm)

**Table 1. 31-pin connector (J4 on top of SHM-A/-DAQ and J2 on bottom of SHM-S) descriptions**

| Pins | SHM-A Functionality | SHM-DAQ Functionality | SHM-S Functionality |
|------|---------------------|------------------------|----------------------|
| 1 | none | none | none |
| 2 | none | none | none |
| 3 | SHT11 (Temp. and Hum.) data | Serial Data | none |
| 4 | SHT11 clock | Serial Clock | none |
| 5-8 | none | none | none |
| 9 | GND | GND | GND |
| 10 | none | SCLK – SPI Clock | none |
| 11 | none | SFRM – Chip Select | none |
| 12 | none | SPTxD – SPI Transmit Data | none |
| 13 | none | SPRxD – SPI Receive Data | none |
| 14 | TAOS2561 (Light) interrupt | GPIO | none |
| 15,16 | none | none | none |

| 17[1] | TAOS2561 clock | SCL – I2C Clock | MAX5479 (digital potentiometer) clock |
|---|---|---|---|
| 18[1] | TAOS2561 data | SDA – I2C Data | MAX5479 data |
| 19 | QF4A512 (ADC) SPI Clock | none | none |
| 20 | QF4A512 Chip Select | none | none |
| 21 | QF4A512 Serial Data Output | none | none |
| 22 | QF4A512 Serial Data Input | none | none |
| 23 | QF4A512 Data Ready Interrupt | GPIO | none |
| 24 | GND | GND | GND |
| 25 | none | none | none |
| 26 | none | none | none |
| 27 | none | Analog Input ch3 (negative) | none |
| 28 | none | Analog Input ch3 (positive) | none |
| 29 | none | Analog Input ch4 (negative) | none |
| 30 | none | Analog Input ch4 (positive) | none |
| 31 | QF4A512 Chip Reset | GPIO | none |

[1]I2C digital interface allows connecting multiple slave devices having different address.

**Table 2. 21-pin connector (J3 on top of SHM-A/-DAQ and J1 on bottom of SHM-S) descriptions**

| Pins | SHM-A Functionality | SHM-DAQ Functionality | SHM-S Functionality |
|---|---|---|---|
| 1 | none | 5V (regulated, 20mA limit) | none |
| 2 | none | none | none |
| 3 | GND | GND | GND |
| 4 | none | none | none |
| 5 | 5V supply | 5V supply | 5V supply |
| 6-7 | none | none | none |
| 8 | none | Analog Input ch2 (negative) | none |
| 9 | none | Analog Input ch2 (positive) | none |
| 10 | Analog input ch4 (negative): | Analog Input ch1 (negative) | GND |
| **11** | **Analog input ch4 (positive):** | **Analog Input ch1 (positive)[1]** | **Analog output (0-3.2V)** |
| 12 | 1.8V supply | 1.8V supply | 1.8V supply |

| 13 | 3.2V supply | 3.2V supply | 3.2V supply |
|----|-------------|-------------|-------------|
| 14 | none | none | none |
| 15 | Connected to VRTC (18) | none | none |
| 16 | None | none | none |
| 17 | GND | GND | GND |
| 18 | Connected to Alarm (15) | none | none |
| 19 | none | none | none |
| 20 | none | none | none |
| 21 | none | none | none |

[1]The signal from SHM-S board is feed to the 4th channel of QF4A512, when combined with SHM-A board; while connected to the 1st channel, when used with SHM-DAQ board.

**Table 3. Terminal block (J6 on top of SHM-S) pin descriptions**

| Pins | SHM-S Functionality |
|------|---------------------|
| 1 | GND |
| 2 | Strain gauge positive input[1] (red) or 3.2V supply |
| 3 | Strain gauge negative input1 [1] (white or black) |
| 4 | Strain gauge negative input2 [1] (white or black) |
| 5 | Analog input (positive)[2] |
| 6 | Analog input (negative)[2] |

[1]SHM-S is designed to use with **3-wires strain gauge**; which reduce the bridge unbalance effect due to the additional resistance of wire length. The positive wire (usually red color) should be connected to pin2, and the other two negative wires (usually white or black) should be connected to pin3 and pin4. If 2-wires strain gauge needs to be used, the pin3 and pin4 should be connected each other using dummy wire. In this case, the resistance increase of 2-wires strain gauge due to the wire length should be less than 2 ohms.

[2]Amplified output signal, Vout, should be in the output range (0~3.2V) of the MAX4194 amplifier. In other words, **$0 < V_{out} = (V1 - V2) \times Gain + V_{ref} < 3.2$**, where V1: positive analog input, V2: negative analog input, Gain: one of 500, 1000, 2000 and 2500 times, Vref: programmable reference voltage (0.5~2.5V)

# 2    Mechanical and electrical specifications

## 2.1    Mechanical characteristics

**Table 4. Strain measurement characteristics @ 500-times[1] Gain unless otherwise noted.**

| Input type | Parameter | Min | Typ. | Max. | Units |
|---|---|---|---|---|---|
| Strain gauge (connected to a bridge circuit) | Temperature Change[2] | | ±50 | | °C |
| | Strain measurement Range | ±1200[4] | ±1800[3] | | µ-strain |
| | Sensitivity | | | | LSB/µ-s |
| | Resolution[6] | | 0.3 | | µ-strain |
| | Adjustable resistance Range[5] | | ±2.5 | ±3.0 | Ohms |

[1]When other Gain factor (4 gain factors are available: 500, 1000, 2000 and 2500) is used, the Table 5 information is changed accordingly.
[2]Acceptable temperature change during sensing: 0°C at sensing start.
[3]No temperature change is assumed during sensing.
[4]Full range of temperature change is considered.
[5] The bridge unbalance at initial condition due to temperature change or strain gauge tolerance error can be adjustable in software before sensing starts (using `RemoteCommand SHMSAutoBalance`). But the entire resistance error should be in the range shown in Table 4.
[6] at 20Hz bandwidth.

## 2.2    Electrical characteristics

**Table 5.  Electrical characteristics @ 500-times[1] Gain unless otherwise noted.**

| Parameter | Min | Typ. | Max. | Units |
|---|---|---|---|---|
| Supply and Bridge exciting Voltage | 3.1 | 3.2 | 3.3 | V |
| Allowable voltage input Range[2] | -3.2 ~ 3.2 (@ $V_{ref}$ = 1.6 V) | | | mV |

[1]When other Gain factor (four gain factors are available: 500, 1000, 2000 and 2500) is used, the Table4 information is changed accordingly.
[2]When used with DC voltage output analog sensor, the signal input to the terminal block should be in the range shown in Table 5. Otherwise, the amplified signal would be range out of the MAX4194 amplifier. The input range can be changed accordingly as the Gain and offset voltage $V_{ref}$ change.

# 3    Slide switch for measurement type selection

SHM-S board is designed to interface with an external 350 strain gauge as well as DC voltage output analog sensor. Because a strain gauge changes its resistance as strain changes, to convert it to voltage signal, a bridge circuit is required, while an analog sensor gives out voltage signal, so it can be connected to the amplifier directly. To accommodate these two different types of devices, SHM-S board contains a slide switch as shown in Figure 4.
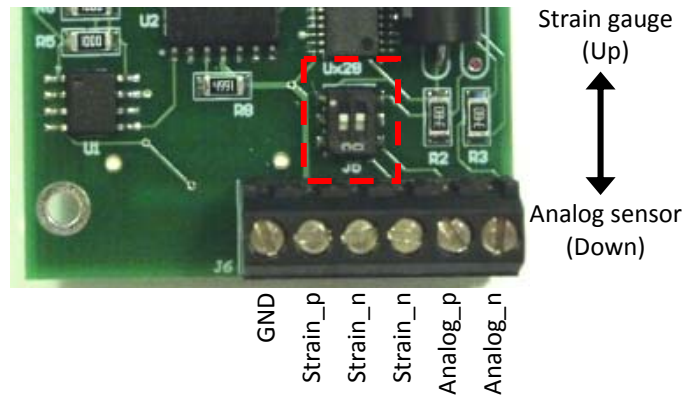


**Figure 4. Slide switch on top side**

- To connect a strain gauge, the actuator of the switch should be in the "Up" position, so that the signal is feed to the bridge circuit in SHM-S.
- To connect a DC voltage output analog sensor (including bridge built-in strain gauge module), the actuator of top switch should be in the "Down" position, so that the signal is feed to the amplifier directly not through the bridge circuit on SHM-S board.
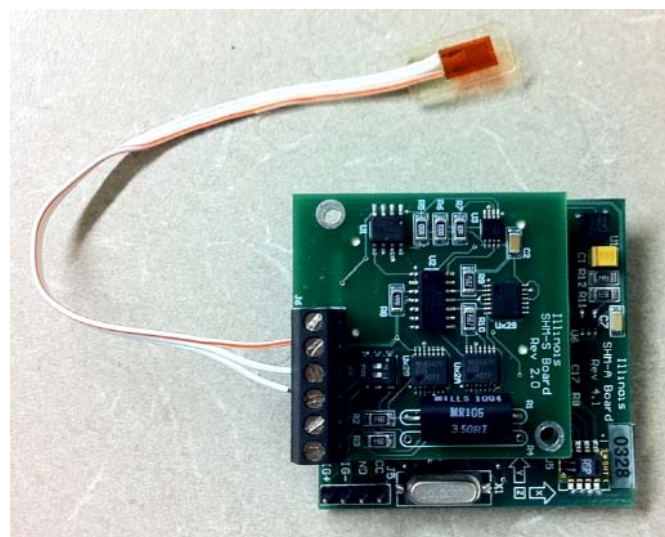


**Figure 5. Typical use with a 350 Ω foil type 3-wires strain gauge**

# 4    SHM-S board software setup for strain measurement

The strain signal from SHM-S board is feed to the ADC (QF4A512) on SHM-A board or SHM-DAQ board, so the basic sensing application like `RemoteSensing` of ISHMP Toolsuite is used to measure strain. It should be noted that the 4th channel measurement is the strain data when combined with SHM-A board, while the 1st channel data with SHM-DAQ board. To use SHM-S board, `DAUGHTERBOARD = SHM_S` should be specified in the *MakeFile* as shown in Figure 6.

```
COMPONENT = RemoteSensingC

# supported sensorboards: ITS400CA, ITS400CB, SHM_A, SHM_H, SHM_DAQ, SHM_S(only for daughterboard)
SENSORBOARD = SHM_A
DAUGHTERBOARD = SHM_S

# configuration parameters, uncomment only if changing default values
#UART_SPEED = UART_BAUD_921600
#SHMA_CUSTOM_FILTER_RATE = 1000
#RFPOWER = 31
#RFCHANNEL = 25
```

**Figure 6. Modification of *MakeFile* to use SHM-S board**

## 4.1    Automatic bridge balancing

Because very high gain factor is used for strain measurement, even little unbalance at the wheatstone bridge, it could cause the signal out of the range of the signal amplifier (MAX4194). SHM-S board contains the digital potentiometers that are connected parallel to the wheatstone bridge to compensate the possible unbalance. The digital potentiometers are controlled by `RemoteCommand SHMSAutoBalance` of ISHMP ToolSuite, so that the bridge unbalance can be automatically corrected before actual sensing start. Figure 6 shows the block diagram for `SHMSAutoBalance`.
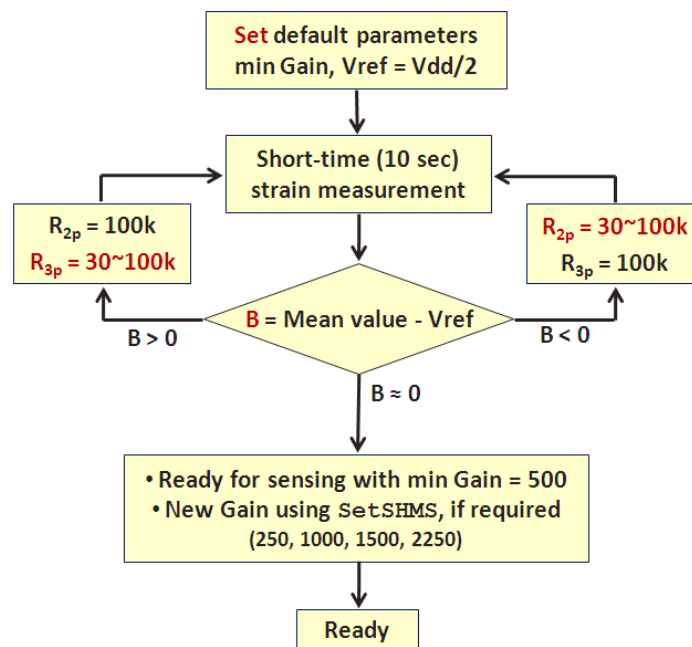


**Figure 7. Block diagram of `RemoteCommand SHMSAutoBalance`**

- First, it measures a short time of strain using default sensing parameters; 100Hz sampling rate, min Gain = 500, offset voltage $V_{ref}$ = $V_{dd}$/s = 1.5V
- Then, it compares the mean of the measured strain signal with the reference value $V_{ref}$.
- Based on the comparison, it changes the resistances of the potentiometers parallel connected to the bridge circuit to make the bridge balance.
- If the SHM-S board is calibrated (see Section 5), just one time iteration would be enough.
- It should be noted that the mean of the strain should not change that much over the balancing process and sensing period.

Figure 7 shows the example use of `RemoteCommand SHMSAutoBalance`. The usage is as follow,

- `RemoteCommand SHMSAutoBalance` <sensing time> <max # of iteration> [nodeID]



**Figure 8. Example use of `RemoteCommand SHMSAutoBalance`**

- In Figure 7, R2p and R3p represent the wiper locations, not resistance value, of the digital potentiometer. Because, 256 taps 10 kohm digital potentiometers are used in the SHM-S board, the wiper location, for example, G2p = 255 corresponds to 10 kohm×255/255 = 10 kohm.
- With default setting, the 1st time strain measurement shows the mean signal value is 0.192V.
- With the biased mean value (0.192V < Vref), it updates the resistance (wiper location) of Rp2; R2p: 255 → 130 corresponds to 10 kohm×130/255 = 5.1 kohm, while R3p remains default value of 255 (10 kohm).
- The 2nd sensing result with the updated potentiometers shows the mean signal is 1.527V, which is close to Vref.
- Then the SHM-S board is ready for sensing with Gain = 500 and Vref = 1.5V.

## 4.2   Manual setting of SHM-S board

If other gain factor (one of 1000, 2000 and 2500) or reference voltage (0.5 ~ 2.5V) is required, manual setting application for SHM-S board, `RemoteCommand SetSHMS`, can be used. The `RemoteCommand SetSHMS` control the gain factor and reference voltage as well as the resistance of Rp2 and Rp3. The usage is as follow,

- `RemoteCommand SetSHMS <R2p> <R3p> <Gain> <Vref> [nodeID]`
- Here, R2p and R3p could be the values obtained from `SHMSAutoBalance` to get same signal mean.
- Other R2p and R3p values will change the signal mean accordingly.

# 5   SHM-S board calibration

The diverse components and circuits on the way of the strain signal may have imperfection sources including tolerance error; accordingly, each SHM-S board also can show little different performance. To get better accurate performance, the calibration for each SHM-S board is required. It should be noted that the calibration, here, is to clarify the linear relationship between the amplified strain signal and the digitized ADC reading. In the algorithm of `SHMSAutoBalance`, a linear equation to convert ADC readings to the input voltage of the ADC is used. This calibration process is to find the better accurate equation. Simply, two different levels of amplified signals at pin 5 of the MAX4194 (U1) and corresponding ADC readings (output from `RemoteSensing`) provide information to build a linear equation.

- First, for a given strain signal or analog signal, measure the DC voltage at pin 5 of the MAX4194 amplifier (U1) using a voltage meter. For example, V1 = 1.30V
- Using `RemoteSensing`, take short time of data (e.g. 2000 data at 100Hz). Then the mean value of the output data, D1 = 11426
- For another different level of signal, find the two values. V2 = 0.699V and D2 = 6152
- Then the linear equation to convert an ADC reading to a voltage unit can be expressed in the format of V = a × D + b. In this example, V = 1/8775.38 × D − 0.002053
- Open a `AutoStrainM.nc` file (`shm/sensorboards/SHM_H/sensorboard.h`), and modify the linear equation (`mean1`) accordingly in `meanTask()`.
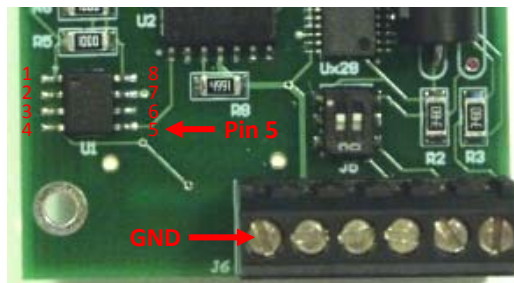


**Figure 9. Voltage reading location (pin5 - GND) for calibration**

```
task void meanTask()
{

        ChannelData *cd = sd->channels + readyChannels;
        uint32_t i;
        int32_t pk_neg, pk_pos, mean; // scaleft = 5660;

        // calculate the mean, max and min
        for (i = 200, mean = 0, pk_neg = INT_MAX, pk_pos = INT_MIN; i < cd->size; ++i) {
                mean += cd->data[i];
                pk_pos = cd->data[i] >= pk_pos ? cd->data[i] : pk_pos;
                pk_neg = cd->data[i] <= pk_neg ? cd->data[i] : pk_neg;
        }

        mean /= cd->size - 200;
        mean1 = (double) mean / 8775.38 - 0.002053;      // convert ADC reading to Voltage unit

        trace(DBG_USR1, "Channel %u mean = %d, mean1 = %.3f Volts\r\n", readyChannels, mean, mean1);

        if (readyChannels == 3) {
                afm.ch = readyChannels;
                afm.mean = mean1;
                afm.r2 = rr2;
                afm.r3 = rr3;
        }

        ++readyChannels;

        post checkTask();

}
```

**Figure 10. Conversion equation modification in AutoStrai nM. nc**

# 6    Software

The software required to operate the SHM-S board interfaced with the Imote2 is open-source and can be found at http://shm.cs.uiuc.edu/software.html.  This software includes drivers for the QF4A512 as well as a wide range of application software for acquiring data locally and remotely.

## 6.1    Driver and application software

The driver for the SHM-S sensor board is basically same as SHM-A or SHM-DAQ board driver. Because the strain data from the SHM-S board is feed to the QF4A512 (ADC) on SHM-A or SHM-DAQ board, it utilizes the driver as well as all other software for SHM-A or SHM-DAQ board. Only difference is, if SHM-S board is specified as DAUGHTERBOARD in *MakeFile*, it can use the special applications such like SHMSAutoBalance or SetSHMS for SHM-S board setting. Please see the associated documentation for further instructions on the use of the SHM-A board, SHM-DAQ board, and application software.

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