

# Stellaris® LM3S ADC Calibration

Sue Cozart Stellaris® Microcontrollers

### **ABSTRACT**

This application report describes a method for improving the absolute accuracy of the analog-to-digital converters (ADCs) found on Stellaris® LM3S microcontrollers. Due to inherent gain and offset errors, the absolute accuracy of the ADC is affected. The methods described in this application report can improve the absolute accuracy of the ADC results.

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### 1 ADC Error Definition

The following equation describes an ideal ADC with no error:

y = x \* mi

### where:

- x = input count, which is calculated as: input voltage \* 1023/ $V_{REF}$  (for a 10-bit ADC)
- x = input count, which is calculated as: input voltage \* 4095/ $V_{REF}$  (for a 12-bit ADC)
- y = output count
- mi = ideal gain = 1.0000
- V<sub>REF</sub> = ADC voltage reference expressed in volts

An actual ADC exhibits error as defined by Equation 1:

$$y = x * ma + b$$
 (1)

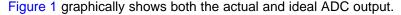
### where

- ma = actual gain (including error in the voltage reference)
- b = actual offset (relative to 0 input)

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ADC Error Definition www.ti.com



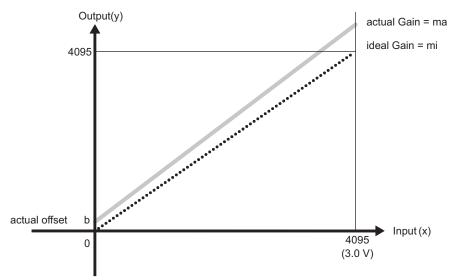


Figure 1. Graph of Actual and Ideal ADC Output

Stellaris LM3S microcontrollers belong to one of the following classes: Sandstorm, Fury, DustDevil, Tempest, and Firestorm. To find out which microcontrollers are in a particular class, see the following:

- Sandstorm—<a href="http://www.ti.com/sandstorm">http://www.ti.com/sandstorm</a>
- Fury—http://www.ti.com/fury
- DustDevil—http://www.ti.com/dustdevil
- Tempest—http://www.ti.com/tempest
- Firestorm—http://www.ti.com/firestorm

## 1.1 Stellaris Sandstorm-, Fury-, and DustDevil-Class Microcontrollers With 10-Bit ADC

Stellaris Sandstorm-, Fury-, and DustDevil-class microcontrollers with 10-bit ADC units have the following errors:

Gain Error : ±3 LSBOffset Error: +6 LSB

The ADC voltage reference can be configured to be one of two options:

- Internal 3.0 V reference with ±2.5% variation
- External voltage reference with unknown variation

For the purposes of this application report, the internal 3.0 V reference is used, however, the calculations could be easily modified for an external voltage reference.

Converting the gain error to a percentage is calculated as follows:

```
1 LSB = 3.0 V / 1024 V/count = 0.002930 ; gain error is \pm 0.008789 which is \pm 0.293\% of 3 V.
```

The internal reference error is ±2.5%. This reference error is combined with the gain error to determine the actual gain. Therefore, the values of ma and b are as follows:

- 0.97207< ma < 1.02793</li>
- 0 < b < 6



www.ti.com ADC Error Definition

# 1.2 Stellaris Tempest-Class Microcontrollers With 10-Bit ADC

Stellaris Tempest-class microcontrollers with 10-bit ADC units have the following errors:

Gain Error : ±30 LSBOffset Error: ±20 LSB

The ADC voltage reference can be configured to be one of two options:

- Internal 3.0 V reference
- External voltage reference

For the purposes of this application report, the internal 3.0 V reference is used, however, the calculations could be easily modified for an external voltage reference.

Converting the gain error to a percentage is calculated as follows:

```
1 LSB = 3.0 V / 1024 V/count = 0.000293 ; gain error is \pm 0.08789 which is \pm 2.93\% of 3 V.
```

Therefore, the values of ma and b are as follows:

- 0.97027< ma < 1.02793
- -20 < b < 20

## 1.3 Stellaris Firestorm-Class Microcontrollers With 12-Bit ADC

Stellaris Firestorm-class microcontrollers with 12-bit ADC units have the following errors:

- Gain Error: ±100 LSB
- Offset Error: ±40 LSB

The ADC voltage reference can be configured to be one of three options:

- Internal 3.0 V reference
- External 3.0 V reference
- External 1.0 V reference

For the purposes of this application report, the internal 3.0 V reference is used, however, the calculations could be easily modified for the other possible voltage references.

Converting the gain error to a percentage is calculated as follows:

```
1 LSB = 3.0 V / 4096 V/count = 0.0007324 ; gain error is \pm 0.07324 which is \pm 2.44\% of 3 V.
```

Therefore, the values of ma and b are as follows:

- 0.9756 < ma < 1.0244
- -40 < b < 40

## 1.4 Stellaris Firestorm-Class Microcontrollers Set to 10-Bit ADC Mode

Stellaris Firestorm-class microcontrollers using 10-bit ADC resolution have the following errors:

Gain Error : ±25 LSBOffset Error: ±10 LSB

The ADC voltage reference can be configured to be one of three options:

- Internal 3.0 V reference
- External 3.0 V reference
- External 1.0 V reference

For the purposes of this application report, the internal 3.0 V reference is used, however, the calculations could be easily modified for the other possible voltage references.



Error Impact www.ti.com

Converting the gain error to a percentage is calculated as follows:

```
1 LSB = 3.0 V / 1024 V/count = 0.000293 ; gain error is \pm 0.07324 which is \pm 2.44\% of 3 V.
```

Therefore, the values of ma and b are as follows:

- 0.9756 < ma < 1.0244</li>
- -10 < b < 10

# 2 Error Impact

ADC errors contribute to errors in the control system. Understanding these errors enables you to compensate in the design. The available input voltage range is affected by the ADC errors. Table 1 through Table 4 show how the ADC output range is affected by the actual gain and offset including the internal 3.0-V reference error as shown in the previous section.

Table 1. Worst-Case Scenarios for Linear Input Range for Sandstorm-, Fury-, and DustDevil-Class Microcontrollers With 10-Bit ADC

	Linear Input Range (V)	Linear Output Range (counts)	Effective Number of Bits	mV/Count Resolution
y = x * 1.00	0.0000 to 3.0000	0 to 1023	10.000	2.9326
y = x * 1.00 + 6	0.0000 to 2.9824	6 to 1023	9.990	2.9326
y = x * 1.02793 + 6	0.0000 to 2.9014	6 to 1023	9.990	9.990
y = x * 0.97207 +6	0.0000 to 3.0000	6 to 1000	9.957	3.0181
Safe Range	0.0000 to 2.8963	6 to 1000	9.957	2.9138

The last row in the table shows the safe parameters for device operation. As shown in Section 3, *Calibration*, it is possible to compensate for the offset and gain errors. After calibration, the effective number of bits of the ADC is only slightly reduced (9.956 bits). The mV/count is decreased from 2.9326 to 2.9167, which is approximately 0.5% decrease in resolution.

Table 2. Worst-Case Scenarios for Linear Input Range for Tempest-Class Microcontrollers With 10-Bit ADC

	Linear Input Range (V)	Linear Output Range (counts)	Effective Number of Bits	mV/Count Resolution
y = x * 1.00	0.0000 to 3.0000	0 to 1023	10.000	2.9326
y = x * 1.00 + 20	0.0000 to 2.9414	20 to 1023	9.970	2.9326
y = x * 1.00 – 20	0.0586 to 3.0000	0 to 1003	9.970	2.9326
y = x * 1.0293 + 20	0.0000 to 2.8577	20 to 1023	9.970	2.8492
y = x * 1.0293 – 20	0.0569 to 2.9716	0 to 1023	10.000	2.8492
y = x * 0.9707 +20	0.0000 to 3.0000	20 to 1013	9.956	3.0211
y = x * 0.9707 - 20	0.0604 to 3.0000	0 to 973	9.926	3.0211
Safe Range	0.0604 to 2.8577	20 to 973	9.896	2.9353

The last row in the table shows the safe parameters for device operation. As shown in Section 3, *Calibration*, it is possible to compensate for the offset and gain errors. After calibration, the effective number of bits of the ADC is only slightly reduced (9.896 bits). The mV/count is increased from 2.9326 to 2.9353, which is approximately 0.09% decrease in resolution.



www.ti.com Error Impact

Table 3. Worst-Case Scenarios for Linear Input Range for Firestorm-Class Microcontrollers With 12-Bit ADC

	Linear Input Range (V)	Linear Output Range (counts)	Effective Number of Bits	mV/Count Resolution
y = x * 1.00	0.0000 to 3.0000	0 to 4095	12.000	0.7326
y = x * 1.00 + 40	0.0000 to 2.9707	40 to 4095	11.985	0.7326
y = x * 1.00 - 40	0.0293 to 3.0000	0 to 4055	11.985	0.7326
y = x * 1.0244+ 40	0.0000 to 2.8999	40 to 4095	11.985	0.7151
y = x * 1.0244 - 40	0.0286 to 2.9571	0 to 4095	12.000	0.7151
y = x * 0.9756 +40	0.0000 to 3.0000	40 to 4035	11.964	0.7509
y = x * 0.9756 - 40	0.0300 to 3.0000	0 to 3955	11.949	0.7509
Safe Range	0.0300 to 2.8999	40 to 3955	11.935	0.7340

The last row in the table shows the safe parameters for device operation. As shown in Section 3, *Calibration*, it is possible to compensate for the offset and gain errors. After calibration, the effective number of bits of the ADC is only slightly reduced (11.935 bits). The mV/count is increased from 0.7326 to 0.7340, which is approximately 0.19% decrease in resolution.

Table 4. Worst-Case Scenarios for Linear Input Range for Firestorm-Class Microcontrollers Set to 10-Bit ADC Mode

	Linear Input Range (V)	Linear Output Range (counts)	Effective Number of Bits	mV/Count Resolution
y = x * 1.00	0.0000 to 3.0000	0 to 1023	10.000	2.9326
y = x * 1.00 + 10	0.0000 to 2.9707	10 to 1023	9.984	2.9326
y = x * 1.00 – 10	0.0293 to 3.0000	0 to 1013	9.984	2.9326
y = x * 1.0244 + 10	0.0000 to 2.8999	10 to 1023	9.984	2.8627
y = x * 1.0244 – 10	0.0286 to 2.9571	0 to 1023	10.000	2.9627
y = x * 0.9756 +10	0.0000 to 3.0000	10 to 1008	9.963	3.0061
y = x * 0.9756 - 10	0.0300 to 3.0000	0 to 988	9.948	3.0061
Safe Range	0.0300 to 2.8999	10 to 988	9.937	2.9345

The last row in the table shows the safe parameters for device operation. As shown in Section 3, *Calibration*, it is possible to compensate for the offset and gain errors. After calibration, the effective number of bits of the ADC is only slightly reduced (9.937 bits). The mV/count is increased from 2.9326 to 2.9345, which is approximately 0.06% decrease in resolution.



Calibration www.ti.com

### 3 Calibration

Calibration is performed by providing two known reference values to two ADC channels and calculating a calibration gain and offset to compensate for the input readings from the other channels. This approach is feasible because the channel-to-channel errors are small. The achievable accuracy using calibration is largely dependent on the accuracy of the known references provided to the ADC. The best possible accuracy achievable is limited by the channel-to-channel gain and offset errors of the ADC.

Figure 2 shows how the equations to measure the ADC actual gain and offset and calculations of the calibration gain and offset are derived.

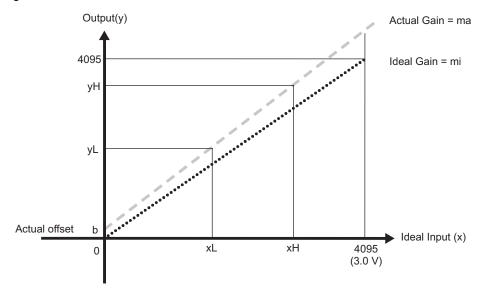


Figure 2. Graph of Equations to Measure Actual Gain and Offset

Returning to Equation 1:

$$y = x * ma + b$$

### where

- ma = actual gain (including error in the voltage reference)
- b = actual offset (relative to 0 input)

The actual gain can be described by Equation 2:

$$ma = (yH - yL) / (xH - xL)$$

$$(2)$$

#### where

- xL = Known reference low input, using a value within the safe range as discussed in Section 2
- xH = Known reference high input, using a value within the safe range as discussed in Section 2
- yL = Reference low ADC output
- yH = Reference high ADC output

The actual offset can be described by Equation 3:

$$b = yL - xL * ma$$
 (3)

using the above definitions.



www.ti.com Conclusion

The calibration equation (Equation 4) is derived by inverting the input and output of Equation 1 describing the ADC actual gain and offset and substituting terms:

$$x = y * CalGain - CalOffset$$

$$y = x * ma + b$$

$$x = (y-b) / ma$$

$$x = y / ma - b / ma$$

$$x = y * CalGain - CalOffset$$
(4)

#### where

- CalGain = 1 / ma
- CalOffset = b / ma

CalGain can be represented as shown in Equation 5 by substituting Equation 2:

$$CalGain = (xH - xL) / (yH - yL)$$
(5)

CalOffset can be represented as shown in Equation 6 by substituting Equation 3:

In summary, by using two known references (xL, yL) and (xH, yH), you can calculate the actual offset and gain error and calculate the calibration gain and offset using the following formulas:

- ADC actual equation: y = x \* ma + b
- ADC actual gain: ma = (yH yL) / (xH xL)
- ADC actual offset: b = yL xL \* ma
- ADC calibration equation: x = y \* CalGain CalOffset
- ADC calibration gain: CalGain = (xH xL) / (yH yL)
- ADC calibration offset: CalOffset = yL \* CalGain xL

The calibration process involves the following four basic steps:

- 1. Read the known reference values input channels (yL and yH).
- 2. Calculate the calibration gain (CalGain) using Equation 5.
- 3. Calculate the calibration offset (CalOffset) using Equation 6.
- 4. Cycle through all channels applying the calibration Equation 4.

### 4 Conclusion

By using software calibration, you can compensate for the inherent gain and offset errors in the Stellaris ADC modules, and improve the accuracy of the conversion results. This application report explains the effects of these errors and how to compensate for them.

### 5 References

The following related documents and software are available on the Stellaris web site at <a href="https://www.ti.com/stellaris">www.ti.com/stellaris</a>:

- Stellaris LM3S Microcontroller Data Sheet (individual device documents available through product selection tool).
- StellarisWare Driver Library User's Manual, publication SW-DRL-UG (literature number SPMU019).
- Stellaris Peripheral Driver Library. Available for download at www.ti.com/tool/sw-drl.

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