Application Report
SPMA034C–July 2011–Revised November 2012

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.

Contents

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_{REF} = ADC voltage reference expressed in volts

An actual ADC exhibits error as defined by Equation 1:

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

where

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

Stellaris is a registered trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

Figure 1 graphically shows both the actual and ideal ADC output.

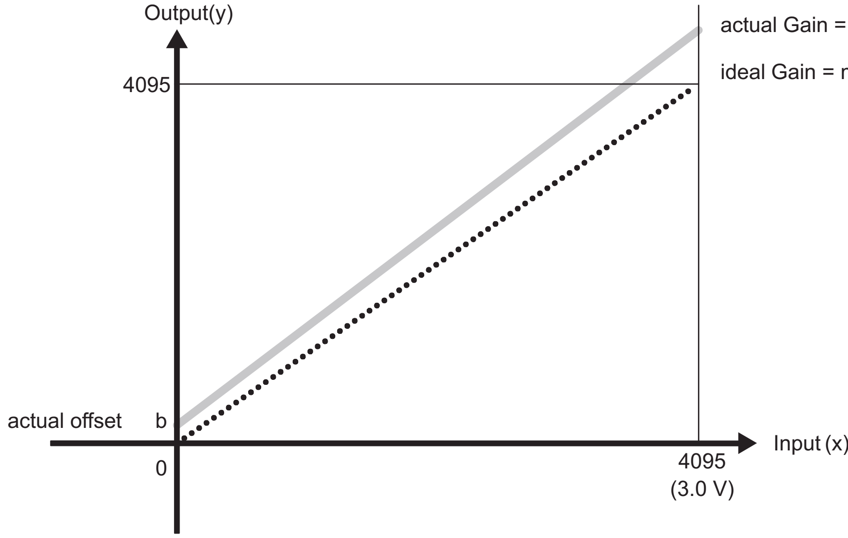

Figure 1. Graph of Actual and Ideal ADC Output

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—http://www.ti.com/sandstorm
- 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 LSB
- Offset 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 ±0.008789 which is ±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
- 0 < b < 6

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 LSB
- Offset 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 ±0.08789 which is ±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 ±0.07324 which is ±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 LSB
- Offset 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.

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

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

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

- 0.9756 < ma < 1.0244
- –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.

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.

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.

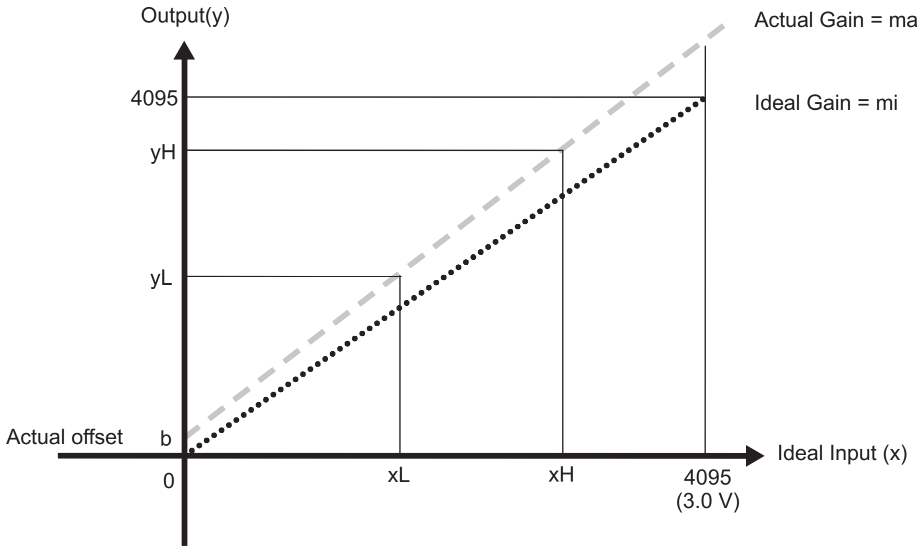

Figure 2. Graph of Equations to Measure Actual Gain and Offset

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.

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:

$$x = y * CalGain – CalOffset \tag{4}$$

```
y = x * ma + b
x = (y-b) / ma
x = y / ma - b / ma
x = y * CalGain - CalOffset
```

where

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

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

$$CalGain = (xH – xL) / (yH – yL) \tag{5}$$

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

$$CalOffset = (yL – xL * ma)/ma \tag{6}$$

```
CalOffset = (yL - xL * ma)/ma
CalOffset = yL / ma - xL
CalOffset = yL * CalGain - xL
```

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 www.ti.com/stellaris:

- 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.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components which meet ISO/TS16949 requirements, mainly for automotive use. Components which have not been so designated are neither designed nor intended for automotive use; and TI will not be responsible for any failure of such components to meet such requirements.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265