
ADC Gain and Offset Error Calibration on ARM® Cortex®-M0+ Based MCUs

Introduction

This technical brief provides a brief overview on gain and offset errors in ADC. It also describes a method to calibrate gain and offset errors in the SAM family microcontrollers (MCUs) that have a ARM® Cortex®-M0+ core. In SAM Cortex™-M0+ MCUs, the ADC gain and offset errors can be compensated through hardware, thereby reducing the application overhead of compensating these ADC errors.

Applicable MCUs

All SAM Cortex-M0+ MCUs, with the exception of the Sigma Delta ADC (SDADC) that is available in SAM C21 devices.

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1. Offset Error

ADC Offset error is defined as the deviation between the first ideal code transition and the first actual code transition. The first ideal code transition takes place at 0.5 LSB.

If the output code is greater than zero when the input voltage is less than 0.5 LSB, the ADC has a positive offset error. ADC has a negative offset error if the first output code transition occurs when the input voltage is greater than 0.5 LSB.

Both positive and negative offset errors limit the available range of the ADC. A large positive offset error causes the ADC to saturate before the input voltage reaches maximum. A large negative offset error results in zero ADC output code for small input voltages.

For additional information, refer to the [ADC Offset Error](#) page, which is available on the Microchip Developer Help site.

2. Gain Error

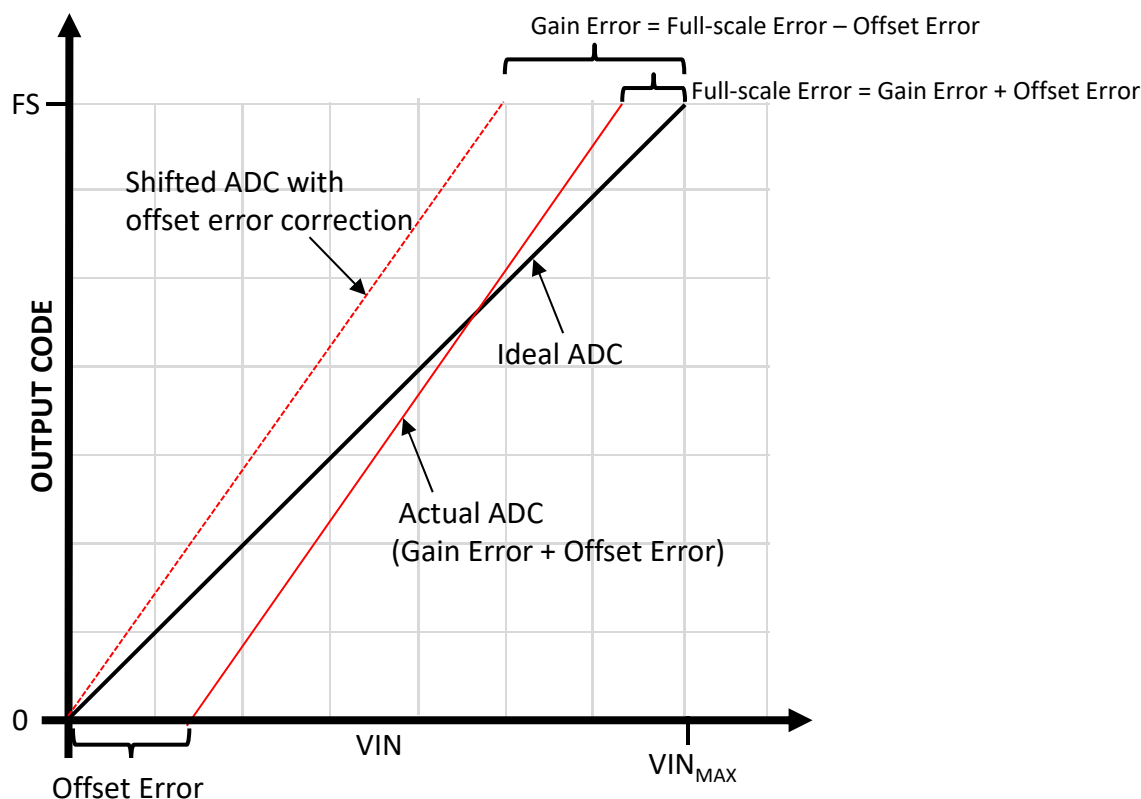
Gain error is defined as the deviation of the midpoint of the last step of the *ideal* ADC transfer from the midpoint of the last step of the *actual* ADC, after the offset error is compensated.

If the transfer function of the actual ADC results in ADC saturation before the input voltage reaches maximum, a positive gain error is produced. If the transfer function of the actual ADC is such that the ADC does not reach full-scale value when the input voltage is at maximum, a negative gain error is produced..

For additional information, refer to the [ADC Gain Error](#) page of the Microchip Developer Help site.

Gain error can also be represented as the full-scale error minus the offset error, as shown in the following graph.

Figure 2-1. Full-Scale Error, Gain Error, and Offset Error in ADC



3. Calibrating the Offset and Gain Errors Using a Two-Point Calibration Method

For a unipolar ADC, the input range is always positive and the output code ranges from zero to full-scale (or 0xFFF for a 12-bit ADC). However, a unipolar ADC can have both positive and negative offset errors. While it is possible to calculate (and calibrate) the positive offset error by applying zero volt input, it is not possible to calculate the negative offset error by applying zero volts to the ADC input. This is because in the case of a negative offset error, applying zero volt input will read 0x000, thereby giving a false impression that there is no offset error. Therefore, a two-point calibration method must be used and the two calibration points must be chosen such that one calibration point is slightly below 10% and the second calibration point is slightly above 90% of full-scale range.

Please note the SAM D21 MCU is used in this example.

In this example, the two calibration points are chosen at $V_1 = 0.15\text{V}$ and $V_2 = 1.55\text{V}$, which are at approximately 9% and 93% of the full-scale value of 1.65V (internal reference INTVCC1 is selected, which sets the ADC reference voltage to one-half VDDANA).

The ideal ADC output values at V_1 and V_2 are represented as C_{i1} and C_{i2} .

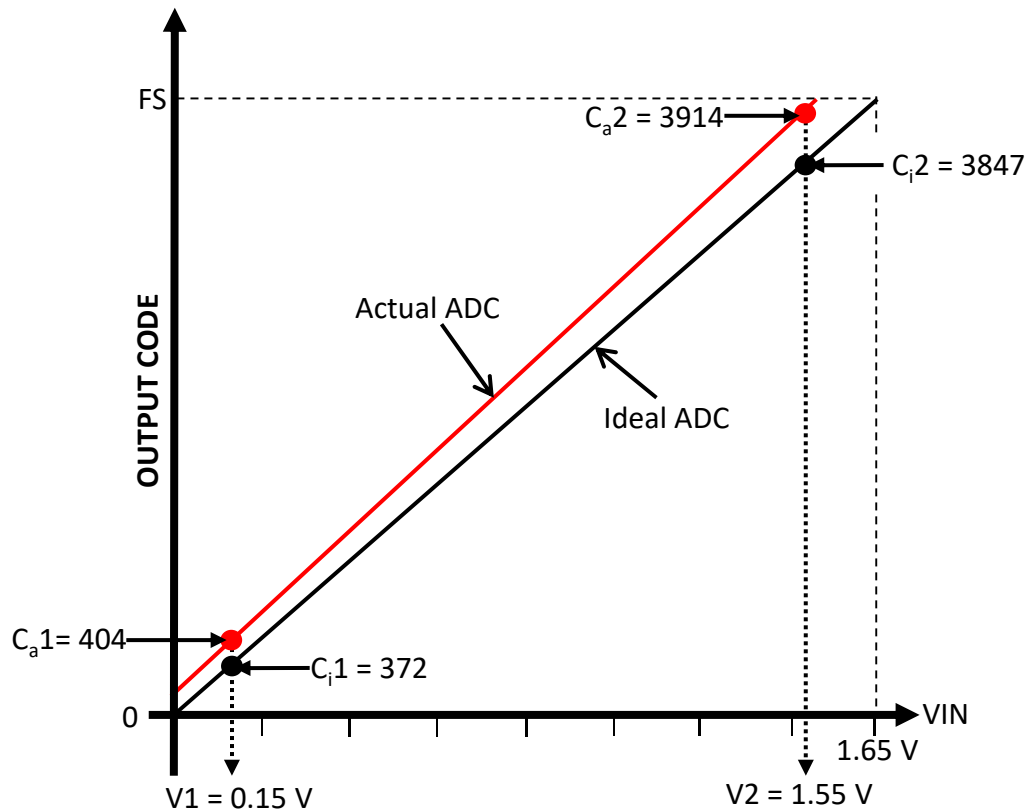
The actual ADC output values at V_1 and V_2 are represented as C_{a1} and C_{a2} .

Using an accurate voltage source, apply $V_1 = 0.15\text{V}$ and save the actual ADC output value as C_{a1} . The ideal ADC output voltage C_{i1} at $V_1 = 0.15\text{V}$ can be calculated as $(V_1 \times 4096)/1.65 \approx 372$.

Similarly, apply $V_2 = 1.55\text{V}$ and save the ADC output value as C_{a2} . The ideal ADC value C_{i2} can be calculated as $(V_2 \times 4096)/1.65 \approx 3847$.

The gain and offset error will be calculated using the equation of a straight line $y = mx + b$, where m is the slope of the line and b is the offset.

Figure 3-1. Two-Point Calibration Method



The gain error can be calculated as the slope of the actual ADC output divided by the slope of the ideal ADC output.

$$\begin{aligned}\text{Gain Error} &= (C_a2 - C_a1) / (C_i2 - C_i1) \\ &= (3914 - 404) / (3847 - 372) \\ &= 1.01\end{aligned}$$

Once the gain error is calculated, the offset error can be calculated as $b = y - m.x$

$$\text{Offset error} = C_a1 - (\text{Gain error} \times C_i1) = 404 - (1.01 \times 372) = 28$$

The gain and offset errors can be compensated by writing the calculated error values to the GAINCORR and OFFSETCORR registers.

The GAINCORR is a 12-bit register and the values can range from 1024 to 4095. The GAINCORR register must be programmed as:

$$\text{GAINCORR} = 2048 / \text{gain error}$$

The range of GAINCORR register is $0.5 \leq \text{GAINCORR} < 2$, where a gain error of 0.5 corresponds to a GAINCORR value of 4095 and a gain error of 2 corresponds to a GAINCORR value of 1024.

In the above example, $\text{GAINCORR} = 2048 / 1.01 = 2027$

The OFFSETCORR is also a 12-bit register and the value to be programmed is in two's complement format.

OFFSETCORR = offset error

In the above example, the OFFSETCORR register must be programmed as 28.

Once the GAINCORR and OFFSETCORR registers are programmed, the gain and offset correction can be enabled by setting the CTRLB.CORREN bit to 1.

Note: For SAM D21 MCUs the CORREN bit is part of CTRLB register. Refer to the specific device data sheet for register details on other ARM Cortex-M0+ based MCUs.

With the gain and offset correction is enabled, the compensated value will be calculated by the ADC as given below:

Result = (Conversion value – OFFSETCORR) x (GAINCORR/2048)

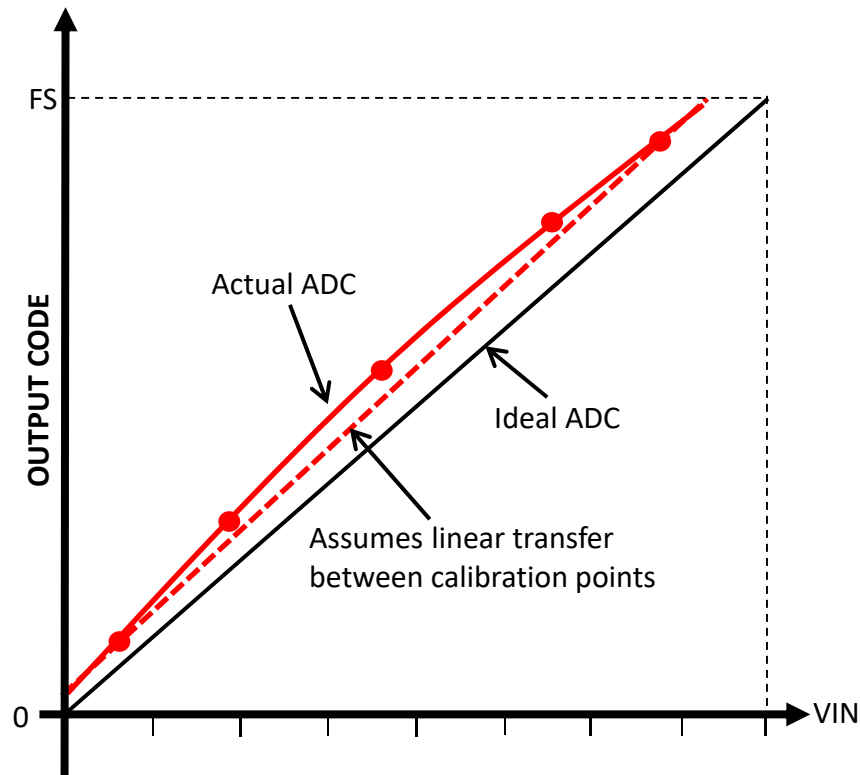
In the above example, the ADC will compensate for the gain and offset errors as:

$$C_{a1} = (404 - 28) \times (2027/2048) \approx 372 \text{ (which matches } C_{i1})$$

$$C_{a2} = (3914 - 28) \times (2027/2048) \approx 3846 \text{ (which is close to } C_{i2})$$

The above method of calibration assumes a straight line or a linear transfer function between the calibrated points. If the accuracy is needed over the entire range of ADC, multi-point calibration may be performed as shown in the following figure. The calibration values can be stored in a look-up table and the error can be compensated by the software at run-time. Of course, there is a trade-off between the number of calibration points, execution time and memory usage.

Figure 3-2. Software-Based Multi-point Calibration to Compensate for Non-linearities in the ADC Transfer Function



Other application considerations include selecting the calibration points to lie within the used ADC range. For example, if the sensor output varies from 0.75 V to 1.25 V, the calibration points must be chosen to remain within this range. Also, to improve the accuracy of the calibration values, the ADC samples may be averaged by enabling the averaging feature available in the ADC.

4. Relevant Resources

For additional information, refer to the following documents and web page:

- The [Understanding ADC Specifications](#) page on the Microchip Developer Help site
- Microchip application note: [AN693 - Understanding A/D Converter Performance Specifications](#)
- Microchip application note: [AT11481 - ADC Configurations with Examples](#)

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