

Additive Improvement of the MSP430 14-Bit ADC Characteristic

Application Report

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ABSTRACT

This application report shows different simple methods to improve the accuracy of the 14-bit analog-to-digital converter of the MSP430 family. They all use only addition for the correction of the analog-to-digital converter characteristic. Different correction methods are explained—all without the need for multiplication—which makes them usable for real time systems like electronic electricity meters. The methods used differ in RAM and ROM allocation, reachable improvement, and complexity. The external hardware for the measurement of the analog-to-digital converter characteristic is also described. For all correction methods, proven, optimized software examples are given. The *References* section at the end of the report lists related application reports in the MSP430 14-bit ADC series.

1 Introduction

The application report *Architecture and Function of the MSP430 14-Bit ADC*[1] gives a detailed overview to the architecture and function of the 14-bit analog-to-digital converter (ADC) of the MSP430 family. The principle of the ADC is explained and software examples are given. Also included are the explanation of the function of all hardware registers contained in the ADC.

The application report *Application Basics for the MSP430 14-Bit ADC*[2] shows several applications of the 14-bit ADC of the MSP430 family. Proven software examples and basic circuitry are shown and explained.

Figure 1 shows the block diagram of the 14-bit analog-to-digital converter of the MSP430 family.

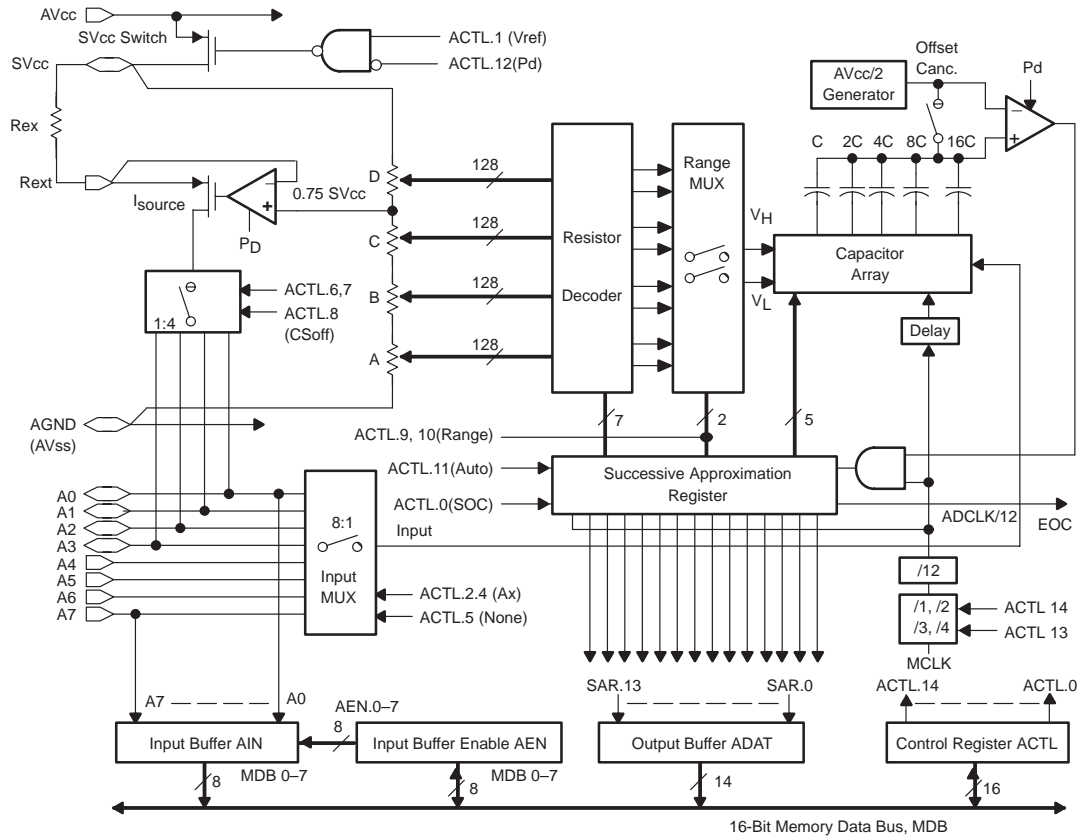


Figure 1. The Hardware of the 14-Bit Analog-to-Digital Converter

The methods for the improvement of the ADC described in the next sections are:

- Correction with the mean value of the full ADC range
- Correction with the mean values of the four ranges
- Correction with the centers of the four ranges
- Correction with multiple sections

Linear, quadratic, and cubic corrections are explained in *Linear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*[3] and nonlinear improvements are discussed in the *Nonlinear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*[4].

2 The External Calibration Hardware for the ADC

All of the methods of improvement discussed in this report need to know the actual errors of the ADC at different points of the four ADC ranges. See Figure 7 for an example of a noncorrected ADC characteristic.

2.1 Measurement Methods for the ADC Reference Samples

The characterization of the ADC for this report is made with three different methods:

- External digital-to-analog converter (DAC): an accurate DAC—controlled by the measured MSP430—produces precise analog output voltages that are measured with the 14-bit ADC. The difference of the two numbers is the absolute error of the ADC.
- External discrete, precise voltages: the MSP430 controls its input voltage via an external analog multiplexer. If only a few accurate input voltages are needed, then this method is best.
- External precision resistors: the MSP430 controls which resistor is measured. For systems that measure the resistance of sensors, this method is best.

Several other methods exist to measure the errors of different reference points for improvement of the ADC characteristic including:

- Measurement of a single ADC sample: fastest way, but not recommended due to statistical reasons.
- Multiple measurements of the same point and calculation of the mean value: e.g. 16 measurements.
- Multiple measurements of the errors around a given point and calculation of the mean value: e.g. 16 measurements ± 8 (or ± 32) around the center point of interest.
- External 16-bit DAC: measurement of all possible four points (xxx.00, xxx.01, xxx.10, xxx.11 for the 14-bit value xxx) and summing them up. This gives an additional 2 bits of resolution.
- Sophisticated statistical methods.
- Measurement of 12 samples for the same ADC point and rejection of the two extreme values. The remaining 10 samples are averaged.

These error measurement methods may be used for all of the given improvement methods in this report. However, they are not discussed with the description of the improvement methods. See also the *MSP430 Application Report*[5] section *Signal Averaging and Noise Cancellation* of Chapter 5.

This application report only uses simple measurement methods.

2.2 External Digital-to-Analog Converter

The external hardware connected to the MSP430-PC board (see Figure 3) is used to obtain the necessary information about the characteristic of the ADC. Its main part is a precise 14- or 16-bit digital-to-analog converter (DAC). Figure 2 shows the calibration process:

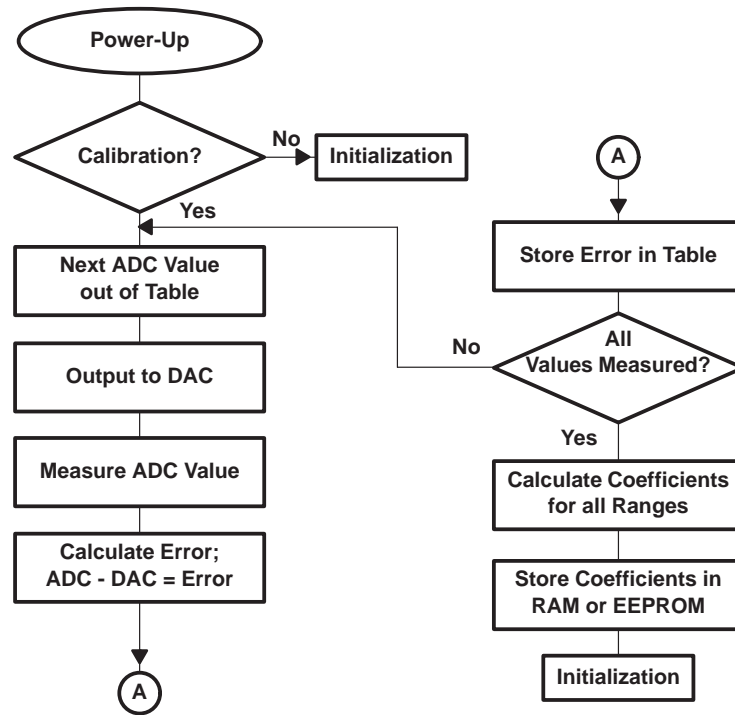


Figure 2. Flowchart 1: Calibration With an External Digital-to-Analog Converter

The measurement sequence for an ADC point is as follows (see also Figure 2):

- The MSP430 outputs via its select lines (parallel DAC) or via an output line (serial DAC) a 14- or 16-bit number. This number programs the DAC. The LCD is not damaged, due to the short duration of the signals (microseconds).
- The external DAC converts the digital number into a precise output voltage that corresponds to the input number.
- The MSP430 measures the output voltage of the DAC and compares the result with the number that was the output. The difference (measured ADC value – output DAC value) is the absolute error of the ADC at that given point.
- The measured errors are used for the calculation of the correction values. These are stored in the RAM or in an EEPROM and are used for the correction of the ADC characteristic. The format and the number of the stored correction values depend on the correction method used: 1 to 64 bytes for the examples given here.

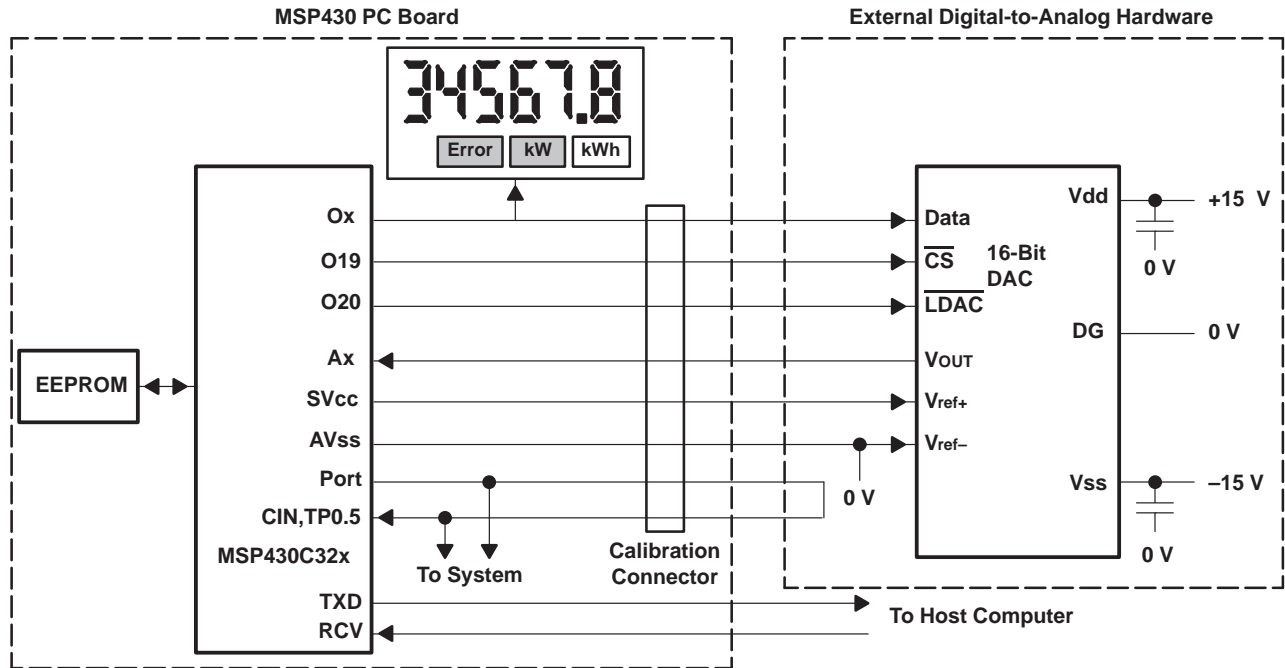


Figure 3. External, Serially Controlled DAC for ADC Measurement

The loop from Port to CIN that is closed by the external hardware indicates to the MSP430 during the initialization that the measurement of the ADC characteristic is active. Like the other DAC control lines, these two I/Os may be used for other system tasks when not in calibration mode.

It is also possible to use a parallel DAC for the calibration of the MSP430 ADC. The time needed for the measurement of the ADC characteristic is shorter than with a serial DAC, but the number of connections between the MSP430 board and the calibration unit are much higher than for a serially controlled DAC. Figure 4 shows this arrangement.

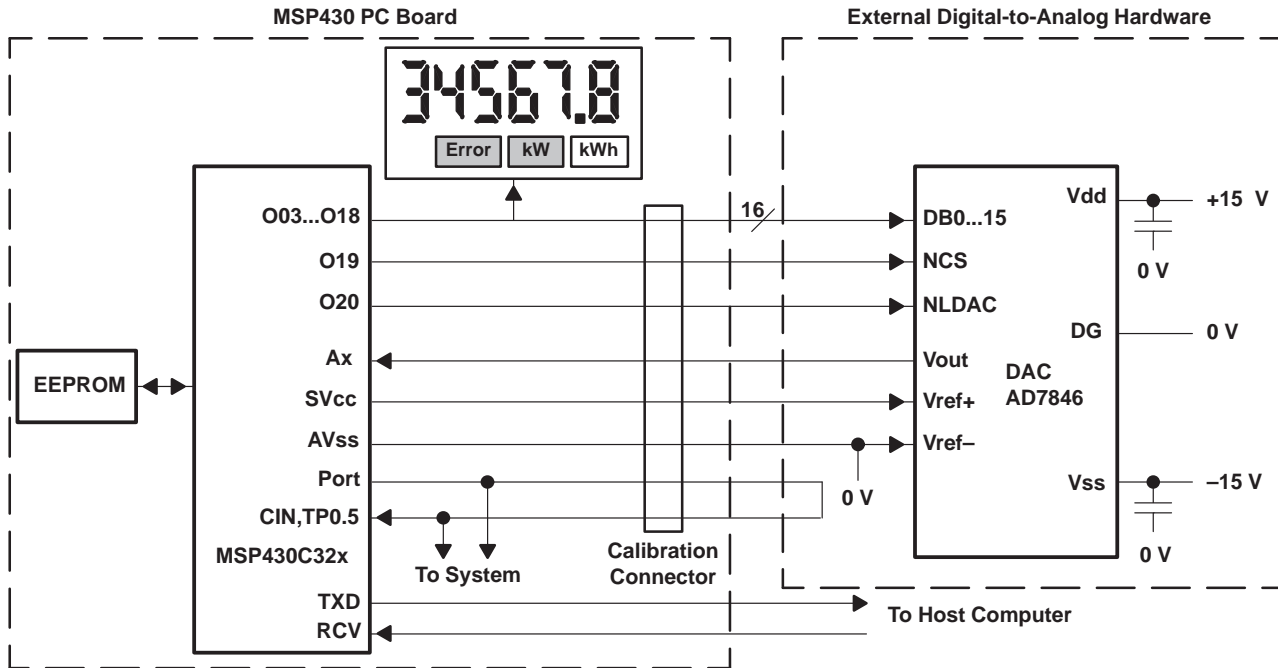


Figure 4. External, Parallel Controlled DAC for ADC Measurement

2.3 External Discrete, Precise Voltages

If only a few points of the ADC characteristic need to be known, then only a few discrete input voltages are necessary for the calibration process. These few points can be generated with a precise, external reference voltage or the supply voltage of the MSP430 and a resistor divider providing some defined output voltages. Figure 5 shows both possibilities.

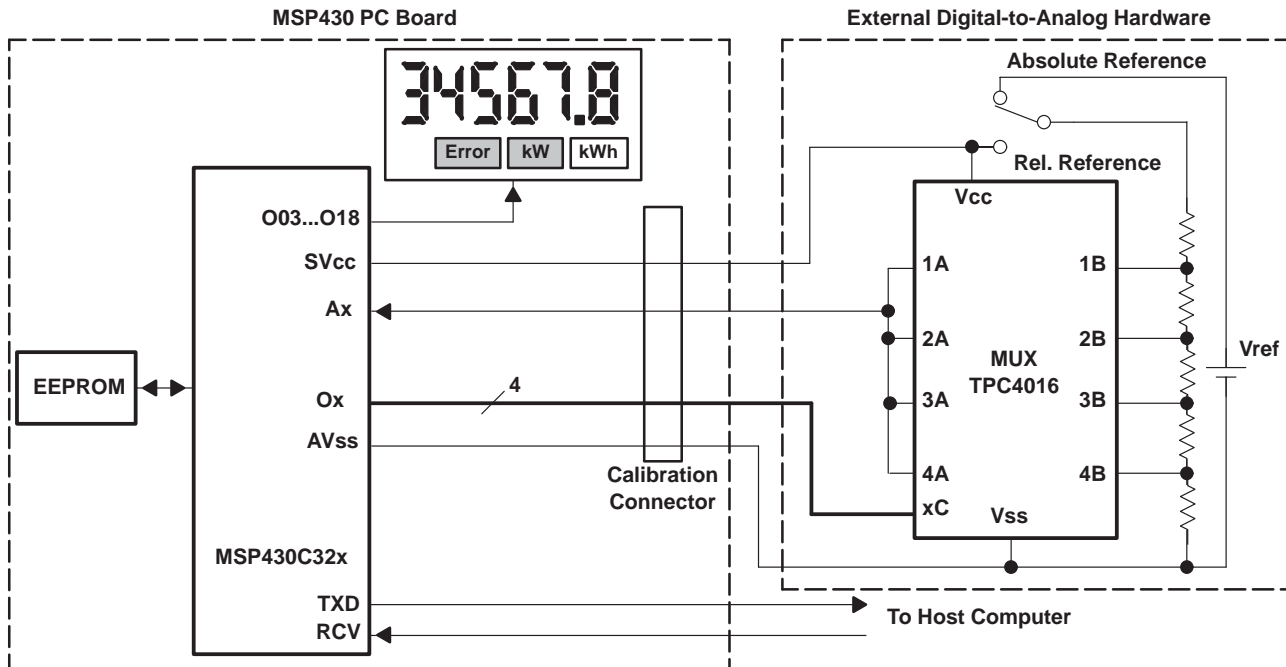


Figure 5. External, Precise Voltages for Calibration

2.4 External Discrete Precision Resistors

If the task for the MSP430 ADC is to precisely measure resistance—for example resistive sensors or platinum—and not external voltages, then this method should be considered. The external hardware is a multiplexer that connects precision resistors to one of the analog inputs of the MSP430. For external resistors with low resistance it may be necessary to use reed relays for this task due to the R_{Dson} resistance of the multiplexer paths. Figure 6 shows this solution for two external reference resistors: the current source outputs the current I_{cs} at the analog input A_x , the voltage drop at the selected external reference resistor is measured with the same analog input. The number of the external precision resistors may be adapted to the application needs.

This calibration method includes all onboard error sources such as R_{ext} and the ADC characteristic.

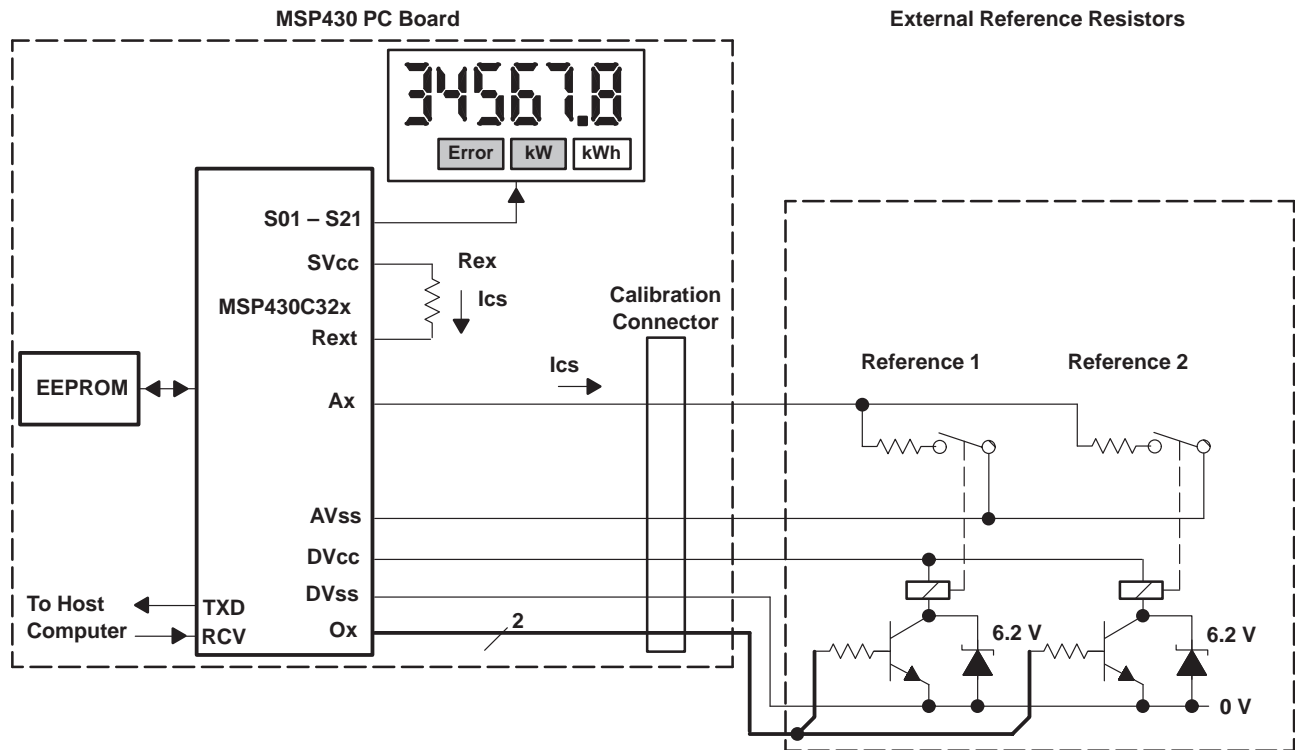


Figure 6. External Precision Resistors for Calibration

2.5 Storage of the Correction Data

The correction coefficients as calculated by the MSP430 or a host computer are stored in the RAM or in an external EEPROM:

- The RAM may be used if a battery is permanently connected to the MSP430 system.
- An EEPROM is necessary if the supply voltage of the MSP430 system can be interrupted e.g. due to the mains supply or a switch.

The format of the used 8-bit coefficients is given in *Nonlinear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*, SLAA050 [4]. If the accuracy that can be reached with these 8-bit numbers is insufficient, then 16-bit numbers—with doubled RAM space and calculation time—may be used. Also the MSP430 floating point package can be a solution in this case.

3 Different Improvement Methods

To allow a comparison between the different improvement methods, the mean value, the range, the standard deviation, and the variance of the corrected ADC characteristic are given. The nearer these values are to zero, the better the performance of the used improvement method.

The mathematical equations for the used statistical methods follow. They are applied to every fourth value of the 16383 corrected samples.

The mean value \bar{x} is calculated by summing all of the errors (e_i) of all corrected samples N_i and dividing this sum by the number of samples k . The mean value \bar{x} is:

$$\bar{x} = \frac{\sum_{i=1}^{i=k} e_i}{k}$$

The range R is the difference between the largest error e_{max} and the smallest error e_{min} (e.g. the most negative error value). The range R is defined as:

$$R = e_{max} - e_{min}$$

The standard deviation S is defined as:

$$S = \sqrt{\frac{\sum_{i=1}^{i=k} e_i^2 - \frac{\left(\sum_{i=1}^{i=k} e_i\right)^2}{k}}{k-1}} = \sqrt{V \times \frac{k}{k-1}}$$

The formula for the variance V is:

$$V = \frac{\sum_{i=1}^{i=k} e_i^2 - \frac{\left(\sum_{i=1}^{i=k} e_i\right)^2}{k}}{k} = \frac{\sum_{i=1}^{i=k} e_i^2 - \bar{x} \times \sum_{i=1}^{i=k} e_i}{k}$$

Where:

- k = Number of included ADC errors e_i
- e_i = ADC error at ADC step i , ranging from e_1 to e_k [Steps]
- i = Index for ADC errors

NOTE: Each measured ADC value needs to be corrected individually to get a correct result. If differences are measured (ΔN) then both values have to be corrected and then the subtraction executed. A correction of the difference ΔN alone leads to false results.

It is important to note the different scaling that is used for the y-axis of the graphs with the corrected ADC characteristic. They differ significantly, dependent on the amount of improvement.

The correction coefficients for all improvement methods are calculated in such a way that allows addition for the final correction of the measured ADC result. This saves execution time and program space.

All of the calculations used for the correction are made with a floating point package (like the MSP430 FPP4 software). If—as is necessary in real-time systems—an integer package is used, then small rounding errors will occur. In *Nonlinear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*[4] the software routines and their influence on the accuracy of the final result are explained.

The improvement methods and their results for this report are demonstrated with the characteristic of device 1 due to its worst characteristic compared to the other three devices shown in *Architecture and Function of the MSP430 14-Bit ADC Application Report*.[1]

The ADC samples used for the following improvement methods and calculations were measured the following way:

- Twelve samples with the same ADC input voltage—generated by a 16-bit DAC—were measured and stored.
- The maximum and the minimum value of these twelve samples were rejected (rejection of extremes).
- Out of the remaining ten samples the mean value was calculated and used afterwards.

The improvement methods are always shown for the full ADC range (ranges A, B, C, and D). If the current source is active, then only ranges A, B, and part of C can be used: the same improvement methods with the same formulas are valid but with less needed RAM or EEPROM space for the correction coefficients. Due to the importance of the current source for several applications, the statistical results are also shown for ranges A and B only.

The 14-bit oriented correction software is also usable if the 12-bit ADC mode is used: only the correction coefficients of the applied ADC range are used in this case.

The orientation of this application report to the ADC ranges (single or multiple corrections per range) is applicable, due to the visibly different slopes of the four ranges inside of an ADC characteristic. See the noncorrected ADC characteristics of device 1 (Figure 7) and devices 2 to 4 in [1] for examples.

3.1 The ADC Characteristic of Device 1 Without Correction

The noncorrected ADC characteristic of device 1 is shown in Figure 7. Its statistical values are given in the table below Figure 7.

The circle in Figure 7 indicates the irregularity located in range B. This irregularity is the reason why more sophisticated methods sometimes have worse results than simpler ones.

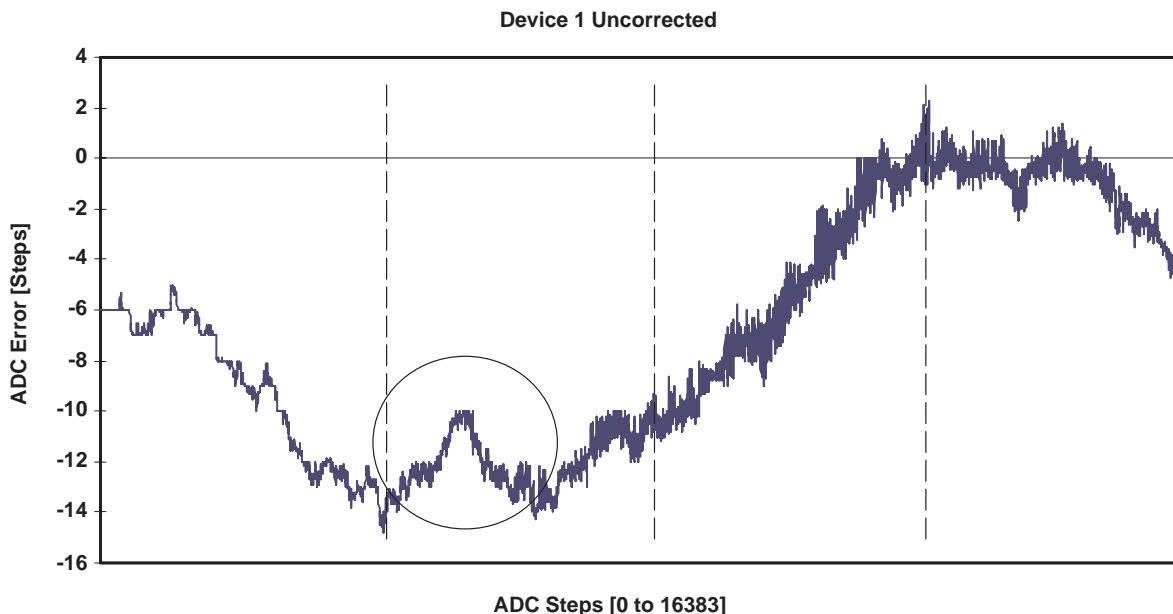


Figure 7. The Noncorrected Characteristic of Device 1

The statistical results of the original ADC characteristic of device 1 are:

	Full range	Ranges A and B only
Mean Value:	-6.95 Steps	-10.51 Steps
Range:	17.00 Steps	10.80 Steps
Standard Deviation:	4.74 Steps	2.61 Steps
Variance:	22.51 Steps	6.80 Steps

3.2 Correction Methods Using Addition Only

These four methods are the fastest because they omit the multiplication. The main disadvantages are the gaps between the ADC ranges e.g. from ADC step 4095 to 4096, and the amount of RAM used, but these methods not only show speed advantages but also the best results. The four methods explained below are best for real-time applications, where the 50 to 100 cycles that are necessary for a correction that uses multiplication cannot be spent: they are the fastest way possible for correction.

3.2.1 Correction With the Mean Value of the Full ADC Range

The ADC is measured at k equally spaced points. The errors of these k measurements are calculated and the mean value of these errors is stored and used for the correction of the ADC. The correction formula for each ADC sample N_i to get the corrected value N_{icorr} is:

$$N_{icorr} = N_i + \frac{\sum_{i=1}^{i=k} -e_i}{k}$$

Where:

N_{icorr}	= Corrected ADC sample	[Steps]
N_i	= Measured ADC sample (noncorrected)	[Steps]
k	= Number of included ADC errors e_i	
e_i	= ADC error i , ranging from e_1 to e_k	[Steps]

The principle is shown in Figure 8, the full ADC range is corrected with its mean value. As with all future principle figures in this report, the black straight line indicates the correction value, the scribbled black line indicates the noncorrected ADC characteristic, and the white line shows the corrected ADC characteristic. The small circles indicate the measured ADC points (the 128 circles of Figure 8 are not shown).

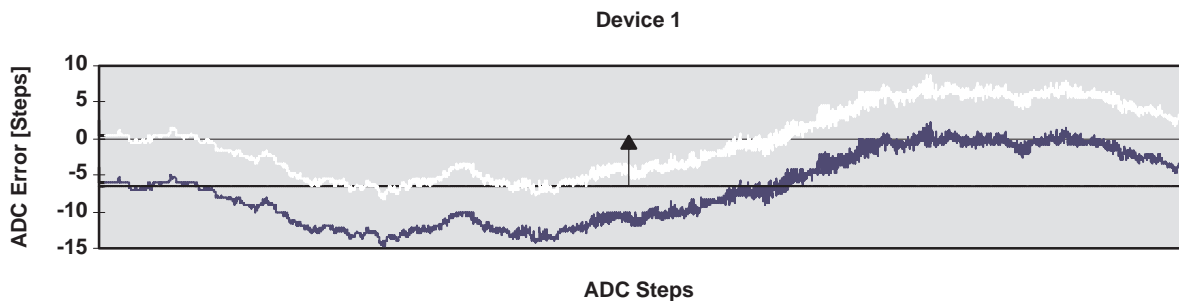


Figure 8. Principle of the Error Correction by the Mean Value of the Full Range

For $k = 128$ —which means 128 samples over the complete ADC range—the statistical results are:

	Full range	Ranges A and B only
Mean Value:	-0.44 Steps	0.15 Steps
Range:	17.10 Steps	10.80 Steps
Standard Deviation:	4.74 Steps	2.61 Steps
Variance:	22.51 Steps	6.80 Steps

Figure 9 shows the result in a graph. The corrected characteristic is displayed for the full range and for the ranges A and B only:

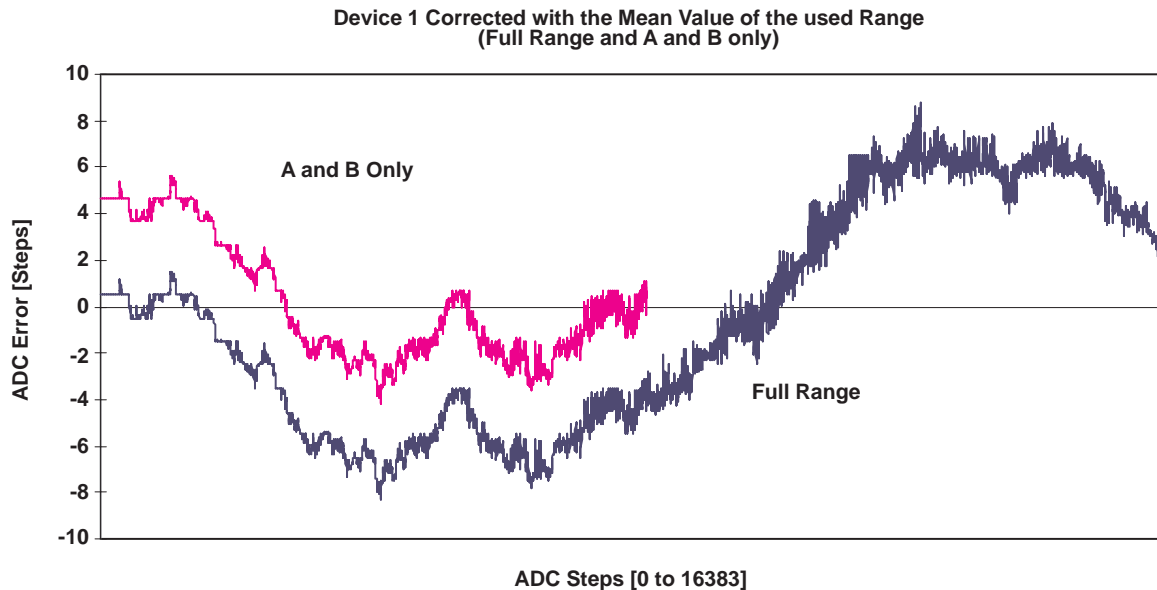


Figure 9. Error Correction With the Mean Value of the Used Range

- Advantages:**
- Only one addition is necessary
 - Very fast due to no missing multiplication or shifts
 - No gaps; the monotonicity of the ADC characteristic remains
 - Only one byte of RAM is needed for the correction coefficient

- Disadvantages:**
- Range, standard deviation and variance are not improved
 - Many calibration measurements are necessary

NOTE: Within the software examples, the format of the integer number is noted at the right margin. The meaning of the different notations is:

- 0.7 Zero integer bits, 7 fraction bits. Unsigned number
- ±4.3 Four integer bits, 3 fraction bits. Signed number
- 8.0 Eight integer bits, no fraction bits. Unsigned integer number
- ±7.0 Seven integer bits, no fraction bits. Signed integer number

The software part after each ADC measurement is as follows:

```

; Correction with the mean value of the full range. 7 cycles
;
MOV.B    TAB,R5        ; Correction for full range    ±7.0
SXT     R5             ; Sign extend byte to word    ±15.0
ADD     &ADAT,R5      ; Corrected ADC value in R5    14.0
...     ; Proceed with corrected ADC value
;
; The RAM byte TAB contains the correction for the full range:
; the negated mean value
;
.bss    TAB,1         ; Signed 8-bit number          ±7.0
    
```


EXAMPLE: The ADC is measured at nine points (rather than 128 to keep the example under control) and the calculated mean value is used for the correction of the full ADC range. The measured (k+1) errors (for device 1) are shown below. The numbers used for the correction are slightly shaded.

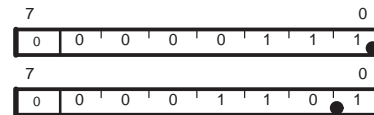
ADC Step	50	2048	4096	6144	8192	10240	12288	14336	16330
Error [Steps]	-6	-8	-13	-13	-10	-5	0	0	-3

$$\text{Correction: } \frac{\sum_{i=1}^{i=k} -ei}{k} = \frac{6 + 8 + 13 + 13 + 10 + 5 - 0 - 0 + 3}{9} = \frac{58}{9} = + 6.5$$

Corrected ADC sample: $N_{icorr} = Ni + 6.5$ Valid for the Full ADC range

Format: ± 7.0 $6.5/2^0 = 6.5 \approx 07h$

± 6.1 $6.5/2^{-1} = 13 = 0Dh$



3.2.2 Correction With the Mean Values of the Four Ranges

The ADC is measured at (4×k) equally spaced points. The mean value of the k errors per range is calculated and used individually for the correction of the four ranges A to D. The correction formula for each one of the four ranges is:

$$N_{icorr} = Ni + \frac{\sum_{i=1}^{i=k} -ei}{k}$$

The principle is shown in Figure 10, each range is corrected with its mean value (the eight used samples are drawn only in the range A):

Device 1 Corrected with the centers of the four ranges

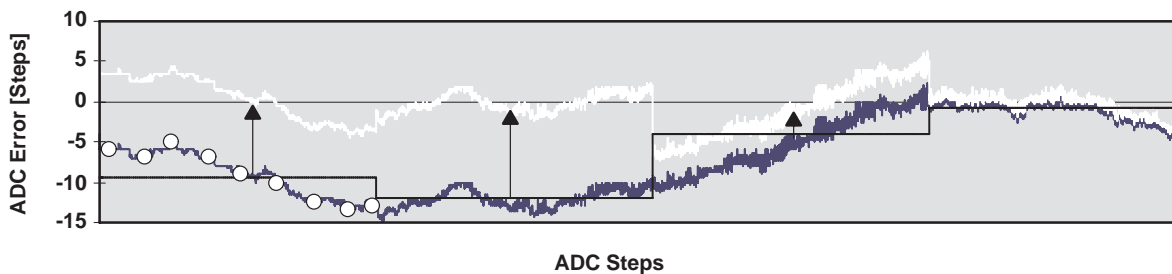


Figure 10. Principle of the Error Correction With the Mean Values of the Four Ranges

For k = 8 (8 samples per range) the statistical results are:

	Full range	Ranges A and B only
Mean Value:	-0.31 Steps	0.15 Steps
Range:	13.5 Steps	9.80 Steps
Standard Deviation:	2.49 Steps	2.10 Steps
Variance:	6.20 Steps	4.41 Steps

Figure 11 shows the graph for k = 8 (eight samples per range, 32 samples over the full ADC range):

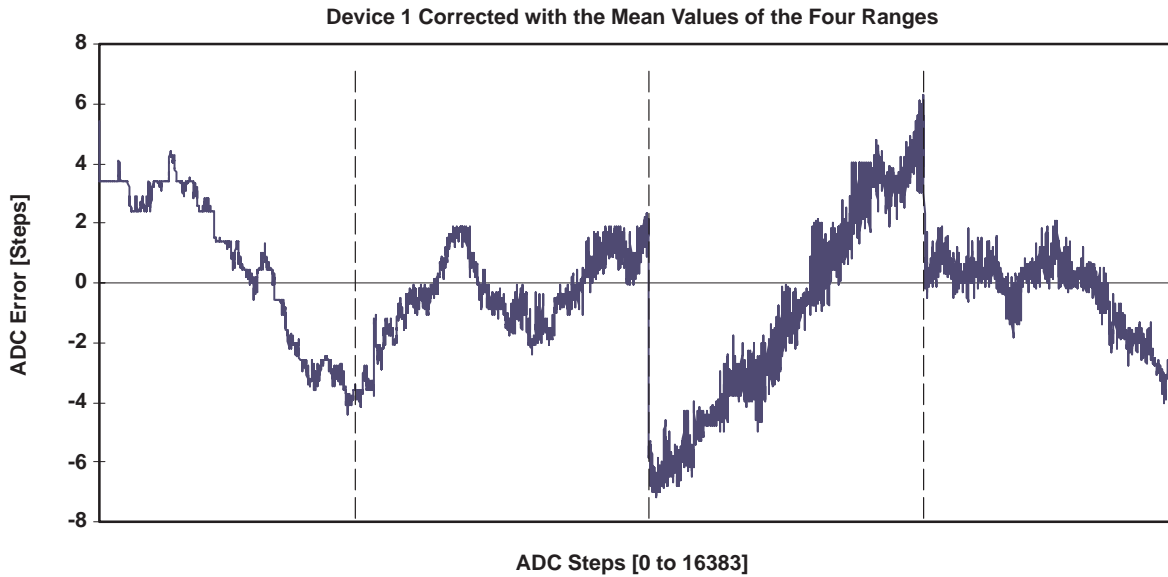


Figure 11. Error Correction With the Mean Values of the Four Ranges

Advantages: Only one addition is necessary for the correction
 Fast due to no multiplication
 Only four bytes are needed for the storage of the correction values

Disadvantages: Range, standard deviation and variance are only slightly improved
 Monotonicity is not preserved: gaps appear at the range borders.

The software part after each ADC measurement is as follows:

```

; Correction with the mean values of the four ranges. 16 cycles
; The four signed correction values are located in four RAM
; bytes starting at label TAB
;
MOV    &ADAT,R5        ; ADC result Ni to R5 (0...3FFFh)
MOV    R5,R6           ; Copy result for correction      14.0
SWPB   R6              ; Range bits of result to low byte
RRA.B  R6              ; Calc. byte address for corr.    5.0
RRA.B  R6              ; Shift two range bits to LSBs   4.0
RRA.B  R6              ;                               3.0
RRA.B  R6              ; Range bits now 0 to 3         2.0
MOV.B  TAB(R6),R6      ; Correction from table TAB     ±7.0
SXT    R6              ; Signed byte to signed word   ±15.0
ADD    R6,R5           ; Corrected result Nicorr in R5  14.0
...    ; Proceed with corrected Nicorr                14.0
;
; The four signed correction values are located in four RAM bytes
; starting at label TAB.
;
.bss   TAB,4          ; Signed 8-bit numbers            ±7.0
    
```

EXAMPLE: Range A of the ADC is measured at four points and the mean value is used for the correction of this ADC range. The corrections for the other three ranges (B, C and D) are calculated the same way. The measured errors for range A are shown below (for device 1):

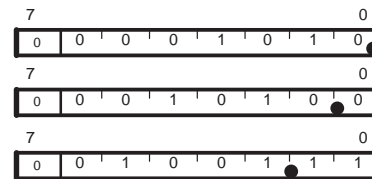
ADC Step	1024	2048	3072	4096
Error [Steps]	-6	-8	-12	-13

$$\text{Correction: } \frac{\sum_{i=1}^{i=k} -ei}{k} = \frac{6 + 8 + 12 + 13}{4} = \frac{39}{4} = + 9.75$$

Corrected ADC sample: $N_{icorr} = Ni + 9.75$

Valid for range A

Format: ± 7.0 $9.75/2^0 \approx 10 = 0Ah$
 ± 6.1 $9.75/2^{-1} = 19.5 \approx 14h$
 ± 5.2 $9.75/2^{-2} = 39 = 27h$



3.2.3 Correction With the Center Points of the Four Ranges

The ADC is measured at the four center points of the ranges A, B, C and D: the ADC steps 2048, 6144, 10240 and 14336. The four errors (ec) at these four center points are calculated and stored. To each measured ADC sample Ni the negated error ec of the pertaining range is added. The correction formula for each one of the four ranges is:

$$N_{icorr} = Ni + ec$$

Where:

ec = Negated error at the center of the actual ADC range [Steps]

The principle is shown in Figure 12, the four A/D ranges are corrected individually with the errors of their center points:

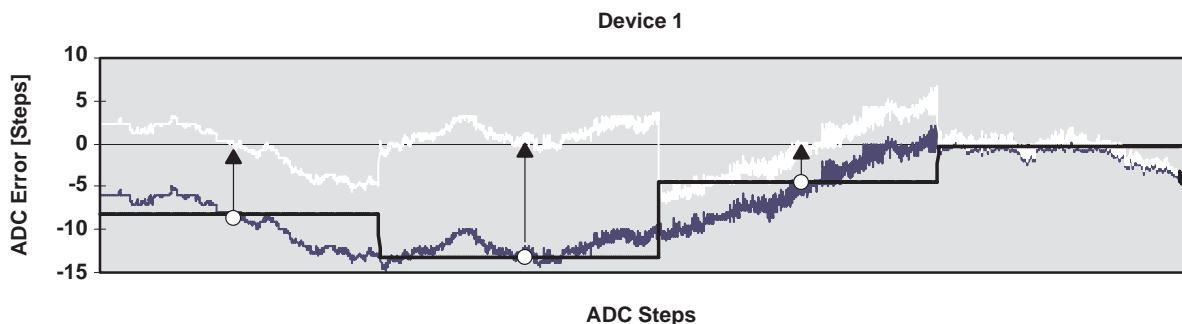


Figure 12. Principle of the Error Correction With the Centers of the Four Ranges

The statistical results of this simple kind of correction are:

	Full range	Ranges A and B only
Mean Value:	0.20 Steps	0.29 Steps
Range:	13.5 Steps	9.80 Steps
Standard Deviation:	2.56 Steps	2.27 Steps
Variance:	6.53 Steps	5.15 Steps

Figure 13 shows the resulting graph:

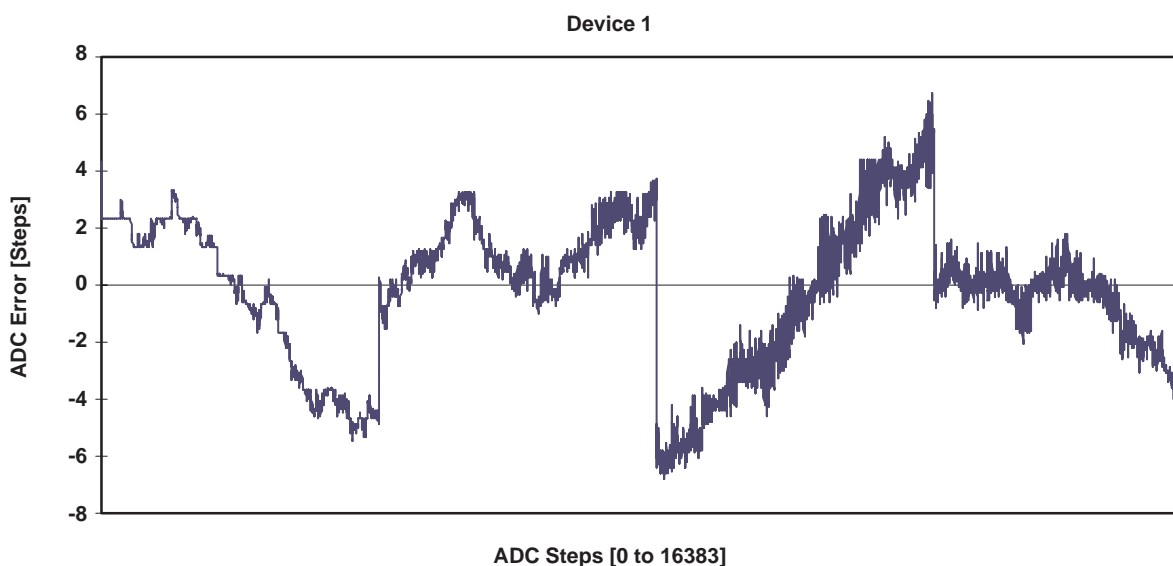


Figure 13. Correction With the Centers of the Four Ranges

- Advantages:** Only one addition is necessary for the correction
 Fast due to no multiplication
 Only four bytes are needed for the storage of the correction values
- Disadvantages:** The range, standard deviation and variance are only slightly improved
 Monotonicity is not preserved: gaps appear at the range borders.

The software part after each ADC measurement is the same one as shown for the correction with the mean values of the four ranges.

EXAMPLE: The center point of range C (10240 steps) of the ADC is measured and the result is used for the correction of this ADC range. The other three ranges are treated the same way. The measured errors of the centers of the four ADC ranges are shown below (for device 1):

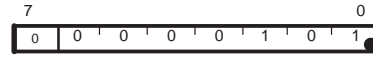
ADC Step	2048	6144	10240	14336
Error [Steps]	-6	-13	-5	0

Correction: $ec = -(-5) = 5$

Corrected ADC sample: $Ni_{corr} = Ni + 5$

Format: $\pm 7.0 \quad 5/2^0 = 5 = 05h$

Valid for range C



3.2.4 Correction With Multiple Sections

The ADC is measured at (p+1) equally spaced points of the full range of the ADC. This leads to p sections. The resulting errors (ek) are used to calculate the mean value for each section and the result (ekm) is stored. To each ADC sample Ni the appropriate negated error (ekm) is added. This method can be enhanced up to the measurement of all ADC points. The correction formula is:

$$Ni_{corr} = Ni + ekm \quad ekm = - \frac{ek + 1 + ek}{2}$$

Where:

- ekm = Mean value of the ADC errors at the borders of ADC section ek [Steps]
- k = Index for ADC sections (length $2^{14}/p$), ranging from 0 to p
- p = Number of sections ($1 \leq p < 2^{14}$)
- ek = ADC error at the ADC step $Ni = k \times 2^{14}/p$ [Steps]
- $ek+1$ = ADC error at the ADC step $Ni = (k + 1) \times 2^{14}/p$ [Steps]

The principle is shown in Figure 14. The full ADC range is divided into eight sections ($p = 8$). The nine measured ADC samples are indicated with circles.

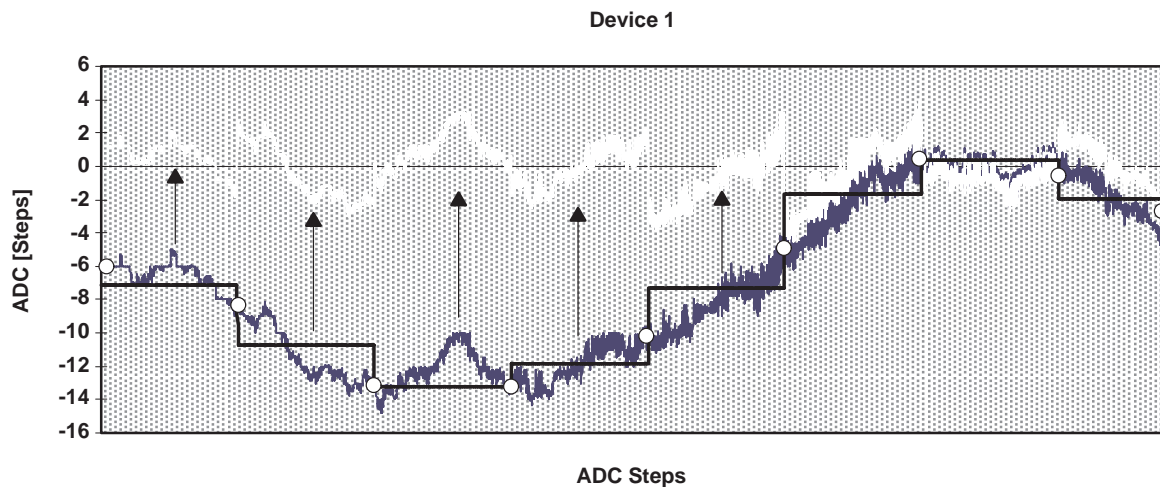


Figure 14. Principle of the Additive Correction With Multiple Sections (8 sections)

For $p = 8$ (section length is 2048 steps) the statistical results are:

	Full range	Ranges A and B only
Mean Value:	-0.14 Steps	0.22 Steps
Range:	8.40 Steps	6.30 Steps
Standard Deviation:	1.47 Steps	1.37 Steps
Variance:	2.16 Steps	1.89 Steps

Figure 15 shows the resulting graph for an additive correction with 8 sections ($p = 8$) over the full ADC range:

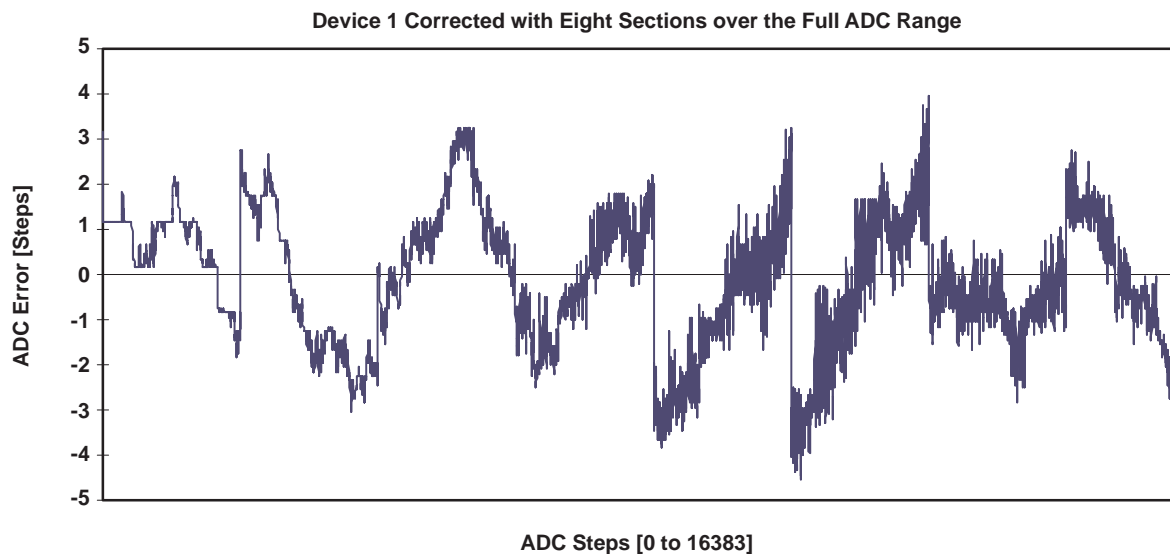


Figure 15. Additive Correction With 8 Sections Over the Full ADC Range

For $p = 16$ (section length is 1024 steps) the statistical results are:

	Full range	Ranges A and B only
Mean Value:	-0.29 Steps	0.05 Steps
Range:	6.40 Steps	4.85 Steps
Standard Deviation:	1.04 Steps	1.01 Steps
Variance:	1.08 Steps	1.02 Steps

Figure 16 shows the resulting graph for an additive correction with 16 sections ($p = 16$) over the full ADC range:

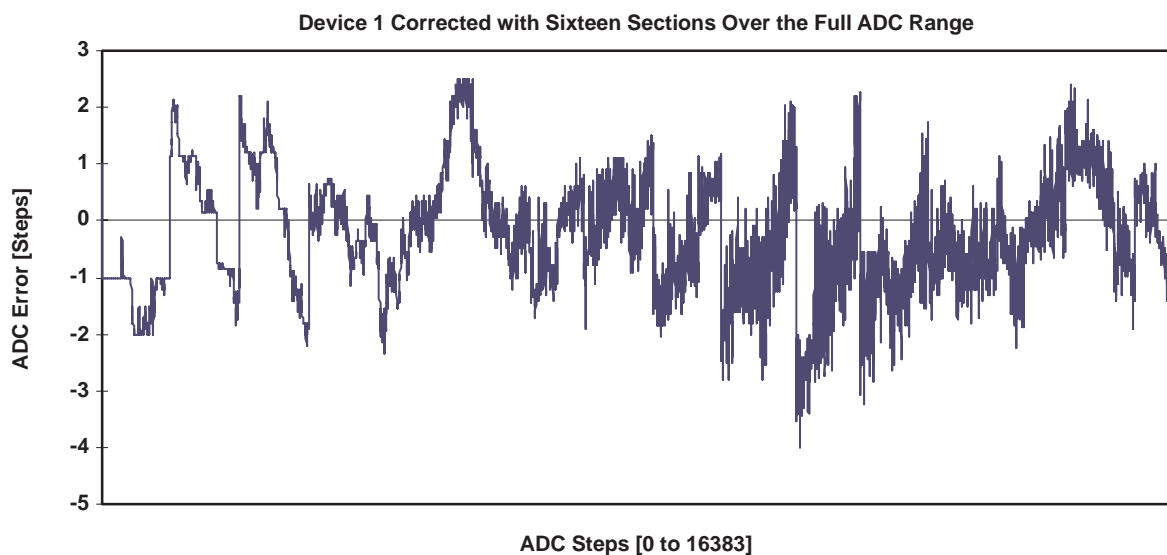


Figure 16. Additive Correction With 16 Sections Over the Full ADC Range

For $p = 32$ (section length is 512 steps) the statistical results are:

	Full range	Ranges A and B only
Mean Value:	-0.14 Steps	-0.05 Steps
Range:	5.20 Steps	3.65 Steps
Standard Deviation:	0.77 Steps	0.65 Steps
Variance:	0.59 Steps	0.42 Steps

Figure 17 shows the resulting graph for an additive correction with 32 sections ($p = 32$) over the full ADC range:

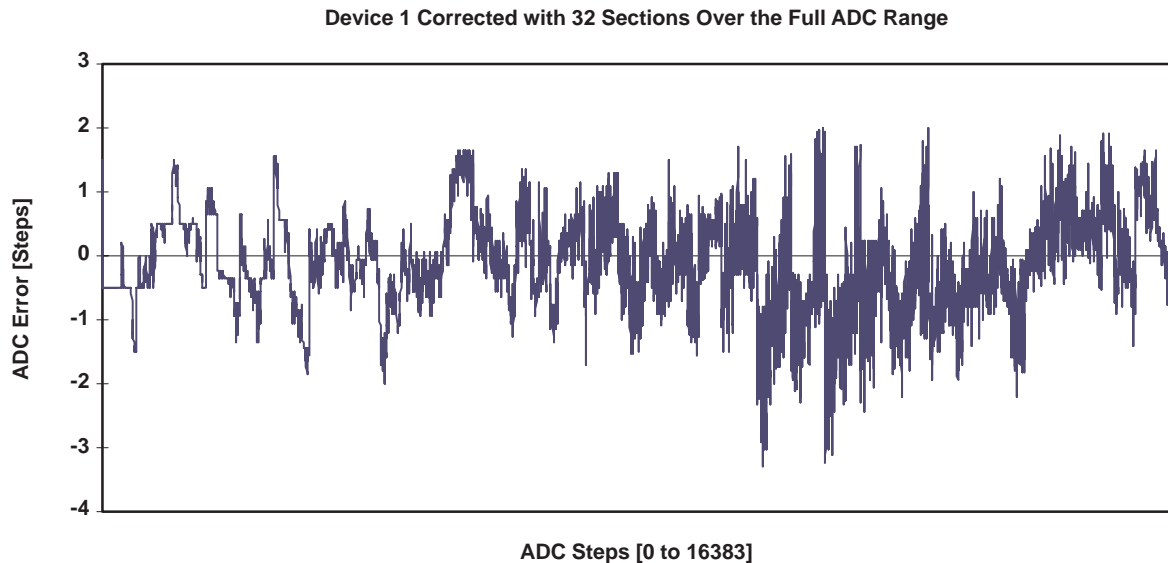


Figure 17. Additive Correction With 32 Sections Over the Full ADC Range

For $p = 64$ (section length is 256 steps) the statistical results are:

Mean Value:	-0.08 Steps	0.02 Steps
Range:	4.60 Steps	3.10 Steps
Standard Deviation:	0.64 Steps	0.53 Steps
Variance:	0.41 Steps	0.28 Steps

Figure 18 shows the resulting graph for an additive correction with 64 sections ($p = 64$) over the full ADC range. Note the scaling of Figure 18: only ± 3 steps!

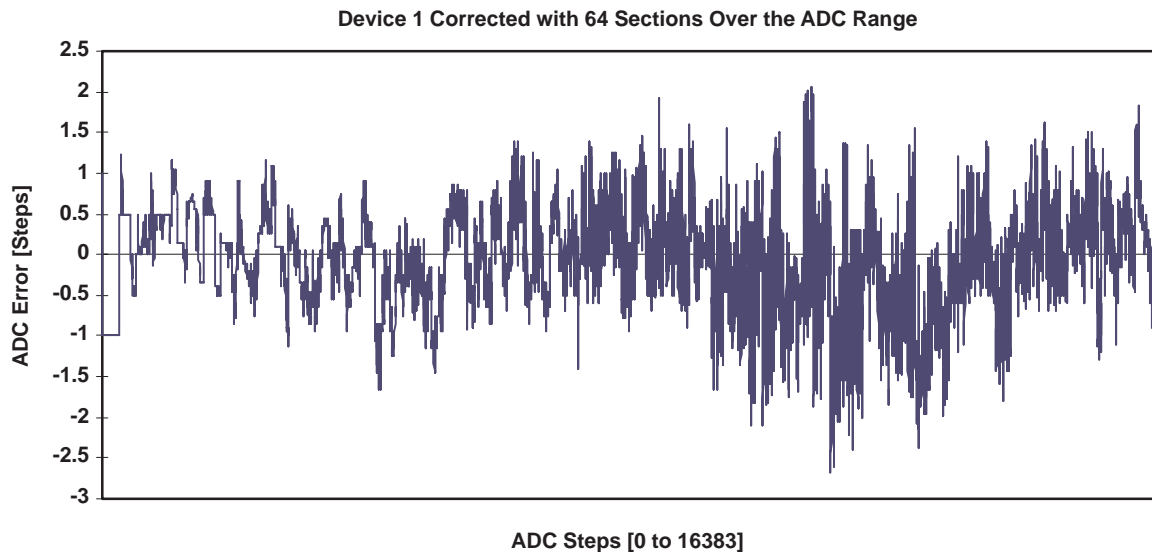


Figure 18. Additive Correction With 64 Sections Over the Full ADC Range

Advantages: Very good improvement with large section counts p
 Fast due to no multiplication
 The section count p is adaptable to specific applications.

Disadvantages: Relative large RAM storage is needed for a large section count p
 Gaps appear at the section borders: they get smaller with increasing p

The results for the additive correction with multiple sections are summarized below for section counts p ranging from 8 to 64. For comparison purposes, the results for $p = 4$ (the *center of ranges* method is used) are given as well.

	$p = 4$	$p = 8$	$p = 16$	$p = 32$	$p = 64$
Mean Value:	+0.2	-0.14	-0.29	-0.14	-0.08 Steps
Range:	13.5	8.40	6.40	5.20	4.60 Steps
Standard Deviation:	2.56	1.47	1.04	0.77	0.64 Steps
Variance:	6.53	2.16	1.08	0.59	0.41 Steps

The improvement of the statistical results with increasing section count p can be clearly seen. Figure 19 illustrates this.

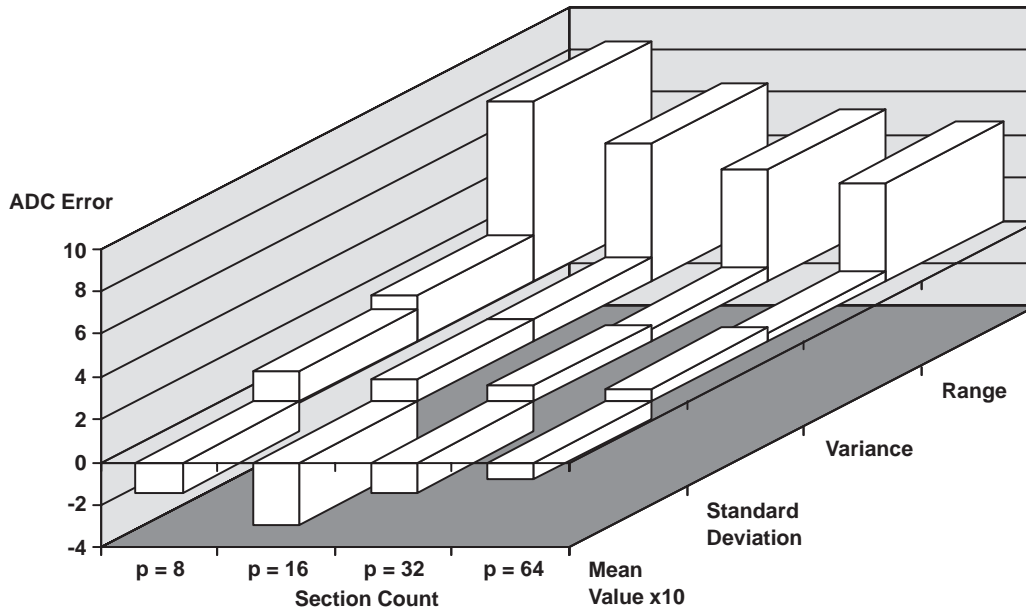


Figure 19. Improvement of the ADC Results With Increasing Section Count p

The software part after each ADC measurement follows. The addressing of the correction byte can be adapted easily also to 4, 8, 16, and 32 sections.

```

; Additive correction for 64 sections over the full ADC range.
; The 64 signed correction values are located in the RAM
; bytes starting at label TAB. 11 cycles
;
MOV    &ADAT,R5      ; ADC result Ni to R5 (0...3FFFh)
MOV    R5,R6         ; Copy Ni for correction      14.0
SWPB  R6             ; MSBs of result to low byte  6.0
MOV.B R6,R6         ; 00h...3Fh to R6 (0..63)    6.0
MOV.B TAB(R6),R6    ; Corr. eim from table TAB   ±4.0
SXT   R6            ; Extend sign of correction  ±4.0
ADD   R6,R5         ; Nicorr = Ni + eim         14.0
...
; Proceed with corrected Nicorr
;
; The 64 RAM bytes starting at label TAB contain the corrections
; eim for the 64 sections: each one for 256 ADC points.
; The bytes are loaded during initialization Signed 8-bit numbers
;
.bss  TAB,64        ; 0..255..511....16127..16383 ±4.0

```

EXAMPLE: The ADC is measured at nine points (8 sections) like shown in Figure 14. The measured errors for device 1 are shown below. The correction coefficient ekm of the 2nd section (2048 to 4095 ADC steps, upper half of range A) is calculated.

ADC Step	50	2048	4096	6144	8192	10240	12288	14336	16330
Error [Steps]	-6	-8	-13	-13	-10	-5	0	0	-3

$$\text{Correction: } e_{km} = -\frac{e_{k+1} + e_k}{2} = -\frac{-13 - 8}{2} = +10.5$$

Corrected ADC sample: $Ni_{corr} = Ni + 10.5$

Valid for the 2nd section

Format: ± 7.0 $10.5/2^0 = 10.5 \approx 0Bh$

± 6.1 $10.5/2^{-1} = 21 = 15h$



3.2.5 Summary of the Additive Corrections

Figure 20 gives an overview of all of the described additive correction methods. The results are given for different section counts p:

- N.C.: the noncorrected device 1
- p = 1: correction with the mean value of the full ADC range
- p = 2: correction with the mean values of ranges A/B and C/D
- p = 4: correction with the center values of the four Ranges
- p = 8...64: correction with 8 to 64 (multiple) sections over the full ADC range

As can be seen, the improvement increases significantly from the noncorrected device 1 to the additive correction with 64 sections.

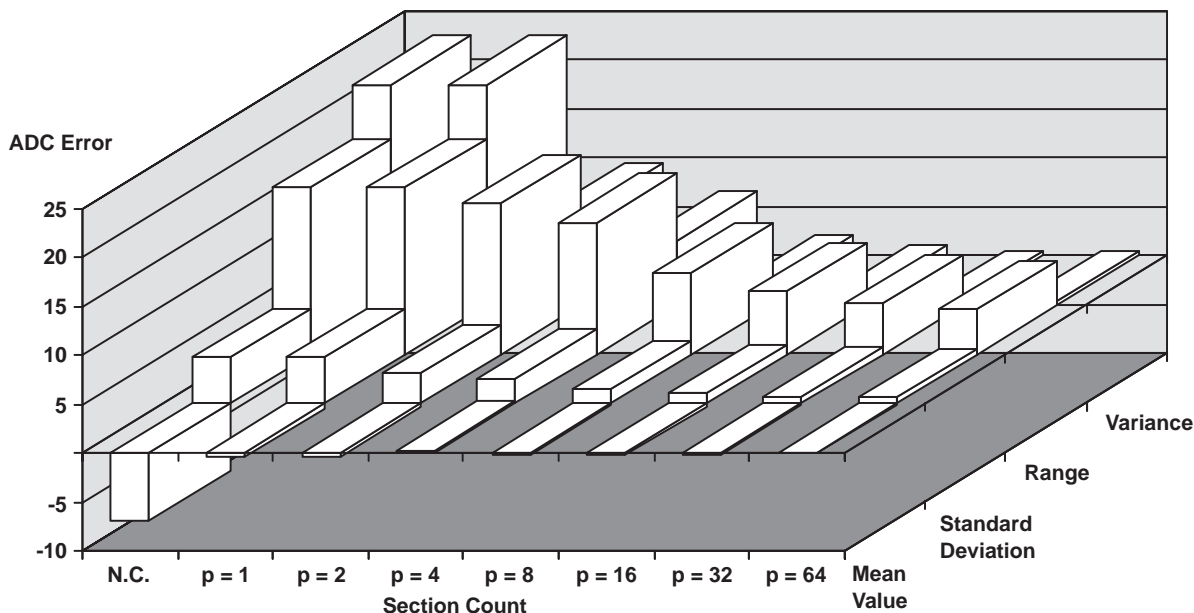


Figure 20. Overview of the Additive Correction Methods

3.3 Additional Information

The *Linear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*[3] shows linear methods for the correction of the 14-bit analog-to-digital converter of the MSP430. Different correction methods are explained: some with guaranteed monotonicity and some using linear regression. The methods discussed differ in RAM and ROM allocation, calculation speed, reachable improvement, and complexity.

4 References

1. *Architecture and Function of the MSP430 14-Bit ADC Application Report*, 1999, Literature #SLAA045
2. *Application Basics for the MSP430 14-Bit ADC Application Report*, 1999, Literature #SLAA046
3. *Linear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*, 1999, Literature #SLAA048
4. *Nonlinear Improvement of the MSP430 14-Bit ADC Characteristic Application Report*, 1999, Literature #SLAA050
5. *MSP430 Application Report*, 1998, Literature #SLAAE10C
6. Data Sheet MSP430C325, MSP430P323, 1997, Literature #SLASE06
7. *MSP430 Family Architecture Guide and Module Library*, 1996, Literature #SLAUE10B

Appendix A Definitions Used With the Application Examples

```
; HARDWARE DEFINITIONS

;
; ADAT      .equ  0118h ; ADC data register (12 or 14-bits)
; ACTL     .equ  0114h ; ADC control register: control bits
```

