APPLICATION NOTE

AT03155: Real-Time-Clock Calibration and Compensation

SAM3 / SAM4 Series

Scope

In most low-cost, low-power systems, the Real Time Clock (RTC) accuracy is inherited from a 32.768kHz crystal oscillator. It is commonly agreed that these oscillators have limited accuracy due to:

- Various manufacturing tolerances in the system: crystal, MCU, PCB, passive components
- Drifts that happen with temperature excursions or with aging of the system

To make very accurate RTCs, calibration and compensation mechanisms must be implemented. To adjust their RTC, Atmel® SAM3/4 series of microcontrollers offer a clock calibration feature that enables to make ppm-accurate RTCs at very low cost. In this application note, designers will find:

- A brief description of the various sources of inaccuracies in the RTC system
- A method to calibrate the RTC at room temperature on a production line
- A way to compensate for the temperature and ageing related drifts

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1. Inaccuracy Sources in the RTC System

1.1 Room Temperature Inaccuracies

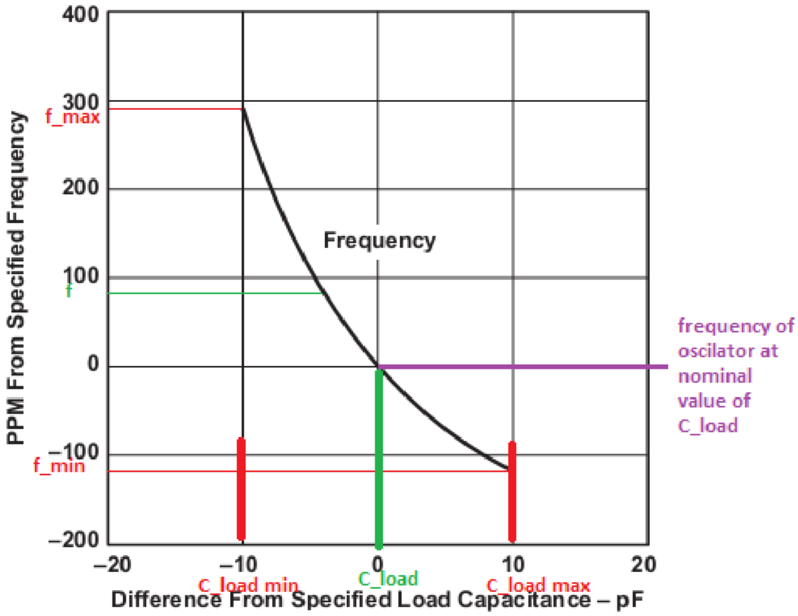
1.1.1 Crystal Manufacturing Tolerance

Most of the embedded systems are equipped with low-cost 32.768kHz watch crystals. When properly loaded, their frequency accuracy is in the ±20ppm range (i.e. ±10 min/year).

1.1.2 Crystal Capacitive Loading Mismatch

To operate a crystal oscillator circuit at the specified crystal frequency, the user must ensure that the crystal is loaded with the specified load capacitance C_L given by the crystal manufacturer. A mismatched load capacitance can contribute to an error up to almost 200ppm. A typical characteristic curve of Frequency vs. Load Capacitance is shown in Figure 1-1.

Figure 1-1. Frequency vs. Load Capacitance



It is important to remind that the effective load of a crystal mounted on a PCB is made of:

- The PCB parasitics
- The MCU parasitics (refer to the device datasheets in the oscillator section for further details)
- The mounted capacitors C_1 (between XIN32 and GND) and C_2 (between XOUT32 and GND)

The effective load capacitance can be calculated by the following formula:

$$C_L = (C_1 \cdot C_2) / (C_1 + C_2) + C_S$$

with C_S the equivalent capacitance between XIN and XOUT due to the PCB and the MCU parasitics. Usually, C_S is about 4 - 8pF.

Even if C_1 and C_2 values are generally optimized to fit the specified load capacitance of the crystal, this process has a limited effectiveness on a production line due to the manufacturing tolerances of the PCB, the MCU and the mounted capacitors themselves.

1.2 32.768kHz XTAL Oscillator Temperature Drift

Low-cost watch crystals have a parabolic frequency dependence over temperature (see Figure 1-2) for which the crystal manufacturers specify:

- A temperature coefficient (B) in “ppm/°C^2”
- A turnover temperature (T_0) in “°C”

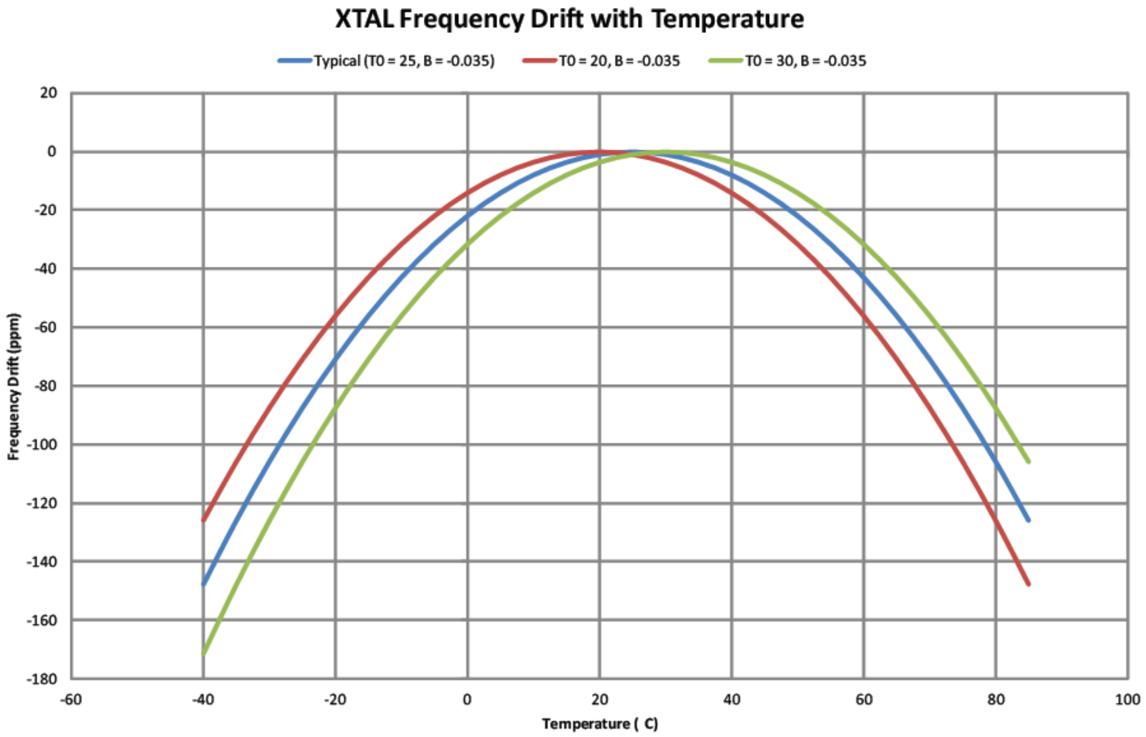
The temperature coefficient B is negative (meaning that the oscillator slows down at cold and hot temperatures) and has a tolerance (typically ±15%). The turnover temperature T_0 is generally 25°C and also has a tolerance (typically ±5°C). The frequency drift at temperature T is given by:

$$\Delta f / F_0 \text{ (ppm)} = B \bullet (T - T_0)^2$$

Example: As a numerical example, let’s assume B = -0.035ppm/°C^2 ±15%, T0 = 25°C ±5°C, and T = 85°C. This leads to a typical frequency drift:

$$\Delta f / F_0 = -126\text{ppm} \pm 40\text{ppm}$$

Figure 1-2. Crystal Drift with Temperature and Effect of the Turnover Temperature (T_0)



1.3 32.768kHz XTAL Oscillator Aging Drift

Most crystal manufacturers specify the aging of the crystal after one year operation. A typical value is ±3ppm for the first year. This specification means that the drift of the crystal is unpredictable in direction and happens mostly in the first year (which does not mean that the crystal aging ends up at this point).

The change in load capacitance over the years could also make a frequency drift but due to the composition of this load, this effect is negligible. The aging of PCB parasitics as well as the aging of the IC parasitics is almost non-existent. The aging of the mounted capacitor C_1 and C_2 of NP0 (C0G) type is less than ±0.1% for the whole life of the capacitor. This means less than 10fF for a 10pF capacitor, which translates into less than 0.1ppm of drift due to load change according to Figure 1-1.

2. RTC Correction in SAM3 and SAM4 MCUs

2.1 Clock Calibration Feature of the RTC Module

The Clock Calibration feature of the RTC module is a finite state machine that adjusts the 1Hz Real-Time-Clock automatically according to a requested (programmed) correction. The request is made in terms of “ppm” (e.g.: the user wants to accelerate the RTC by +100ppm) and the correction circuit translates this “ppm” request into period adjustments.

The RTC clock calibration circuit allows positive or negative correction in a range of 1.5ppm to 1950ppm. According to the range of correction applied, the residual error due to this single circuit is:

- Below 1ppm, for an initial 1Hz clock frequency error between 1.5ppm to 90ppm
- Below 2ppm, for an initial 1Hz clock frequency error between 90ppm to 130ppm
- Below 5ppm, for an initial 1Hz clock frequency error between 130ppm to 200ppm

To compensate for the crystal oscillator frequency errors, the calibration circuitry of RTC increases or decreases the 1Hz clock period slightly, depending on the sign of the correction. The amount of change of the 1Hz clock period is fixed to about 4ms, and the interval between two correction events is adjusted according to the programmed ppm value.

The RTC user interface provides three register fields to implement the auto correction. Table 2-1 gives the specific description of these fields.

Table 2-1. Register Parameters of RTC Correction

NEGPPM	Positive or negative correction based on ppm sign. To accelerate the Real-Time-Clock, the NEGPPM bit must be cleared
HIGHPPM	Lower or higher range of ppm correction, HIGHPPM must be set to ONE when the ppm absolute value is larger than 30
CORRECTIONS	The time interval between two correction events, the value is calculated by the following formula

If HIGHPPM = 0

$$\mathit{CORRECTION} = \mathit{ROUND}\ (3906 / (20 * \mathit{ABS}\ (ppm))) - 1$$

If HIGHPPM = 1

$$\mathit{CORRECTION} = \mathit{ROUND}\ (3906/ \mathit{ABS}\ (ppm)) - 1$$

The CORRECTION value has to be limited between 0 and 127.

For example, if the crystal has a -100ppm error, it means that the RTC has a 100µs deviation every second. Because the calibration circuit changes 4ms of a 1Hz clock period each time, about every 40s, the correction circuit will decrease 4ms of a 1Hz clock period to compensate the -100ppm error. In this case, NEGPPM is 0, HIGHPPM is 1 and the CORRECTION value is 38 by the given formula.

2.2 Frequency Measurement of the RTC and Room Temperature Correction

In this section low cost methods to measure the RTC error in a manufacturing environment are discussed. Once this error is measured, the application will apply the opposite correction to the RTC calibration function.

To make the frequency measurement, two embedded features of SAM3/4 MCUs are useful:

- The embedded waveform generator of the RTC module. In SAM3/4 MCU, this function allows to output the following internal clocks (sub-division of the 32.768kHz crystal oscillator): 1Hz, 32Hz, 64Hz, and 512Hz. This selection is made in the RTC Mode Register (RTC_MR) and the selected clock is output on the RTCOUT0 or RTCOUT1 pin.

- The Timer/Counter peripheral. In capture mode, this peripheral makes frequency measurement by counting the number of pulses on its TCLK input during one clock period of its TIOA input. Thanks to this peripheral, we can remove the need for an expensive frequency meter on the production line as long as a reference clock can be embedded in the production test setup.

As a clock reference source, several approaches can be considered. Here are two possible solutions:

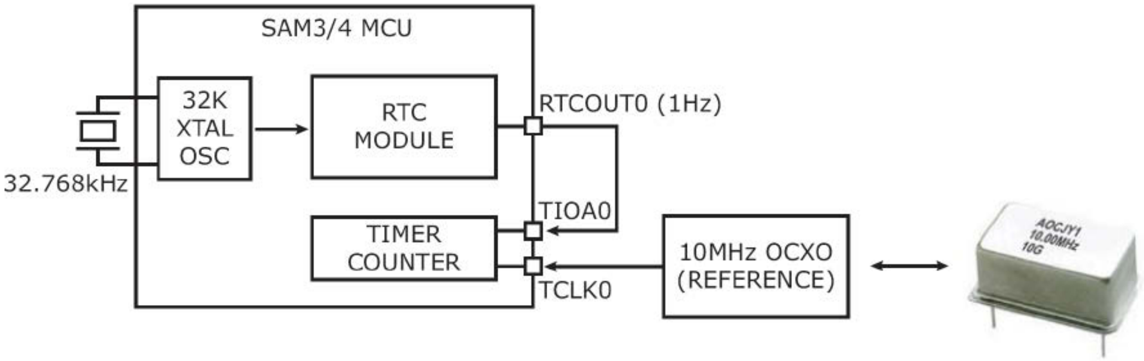
- Oven Controlled Crystal Oscillators (OCXO) are very stable oscillators. They come with an output frequency in the 1 to 100MHz range and their accuracy specification is in the sub-100ppb range for a cost in the $100 range. Their aging specification is generally a few ppms after ten years. For reference, users can look at the AOCJY1-10MHz reference from ABRACON Corporation. See Figure 2-1.
- To further improve the measurement accuracy and remove any aging drift from the reference clock, it is also possible to use the 1 Pulse per Second (1 PPS) output signal of a GPS disciplined clock generator. See Figure 2-2. As an example, users can look at the FTS250-010.0M clock generator module from Connor-Winfield.

Based on these timing references, two possible methods of period measurement are presented hereafter.

2.2.1 Direct Measurement using a 10MHz OCXO

In this method, the timer counter is configured in capture mode and the period of the RTC 1Hz signal gates the 10MHz OCXO (see Figure 2-1). The 1Hz period is then reported as counts of the 10MHz reference clock. The measurement resolution is 1 period of the reference clock, i.e. 100ns, which gives a measurement accuracy of ±50ns or ±50ppb. This resolution does not limit the measurement accuracy that is bounded to the OCXO accuracy (e.g. ±3ppm due to aging effect).

Figure 2-1. 1Hz RTC Measurement with a 10MHz OCXO

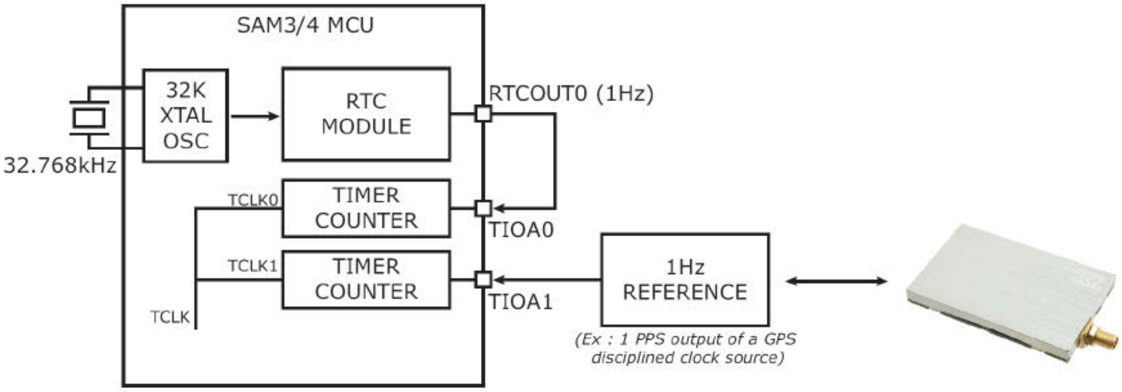


2.2.2 Indirect Measurement using a 1Hz Reference Signal

This method is described in Figure 2-2. For the sake of simplicity, two Timer Counter peripherals are shown but only one could be used.

In this method, the timer-counters configured in capture mode receive the same high-frequency clock TCLK. The first timer-counter measures the RTC 1Hz signal and the second one measures the 1Hz reference signal. The period of the RTC 1Hz signal is then obtained as the ratio of the two counters at the end of the measurement. The measurement resolution is 1 period of TCLK for both measurements giving a measurement accuracy of ±1 TCLK period. To reach ±1ppm accuracy here, the TCLK clock should have a frequency of at least 1MHz. This clock does not need to be accurate as its absolute value is cancelled thanks to the ratio measurement.

Figure 2-2. 1Hz RTC Measurement with a GPS Disciplined Clock Generator

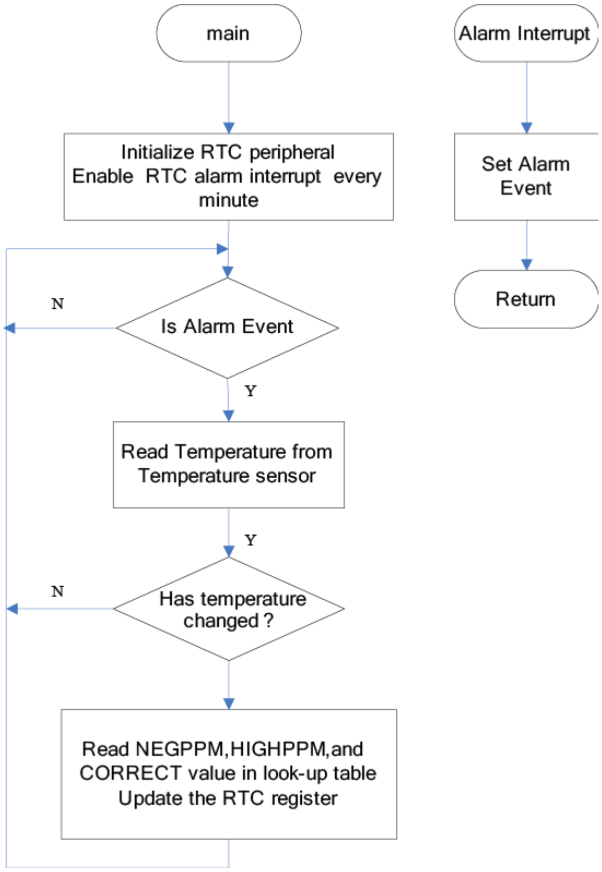


2.3 Crystal Temperature Drift Correction

2.3.1 Principle of Operation

As described in Section 1.2 on page 4, low-cost watch crystals have parabolic temperature dependence. By measuring the crystal temperature, and knowing its temperature dependence, it is possible to correct the RTC. Basically, the crystal temperature dependence is stored as a lookup table in the MCU flash and on a regular basis, e.g. every minute or so, the application makes a temperature measurement to know how much correction it should apply to the RTC calibration registers.

Figure 2-3. Software View of the RTC Temperature Correction



The measurement of the crystal temperature itself is not possible as it comes without a built-in temperature sensor. Anyway, under steady state conditions, we can assume that the crystal temperature follows the board temperature and to a greater extent the MCU temperature. It is then possible to use the on-die temperature sensor of the MCU to get the crystal's temperature. This assumption (crystal temperature = MCU temperature) is valid as long as the power dissipation of the MCU and that of other components on the board is kept very low. In particular, it is recommended that designers verify that:

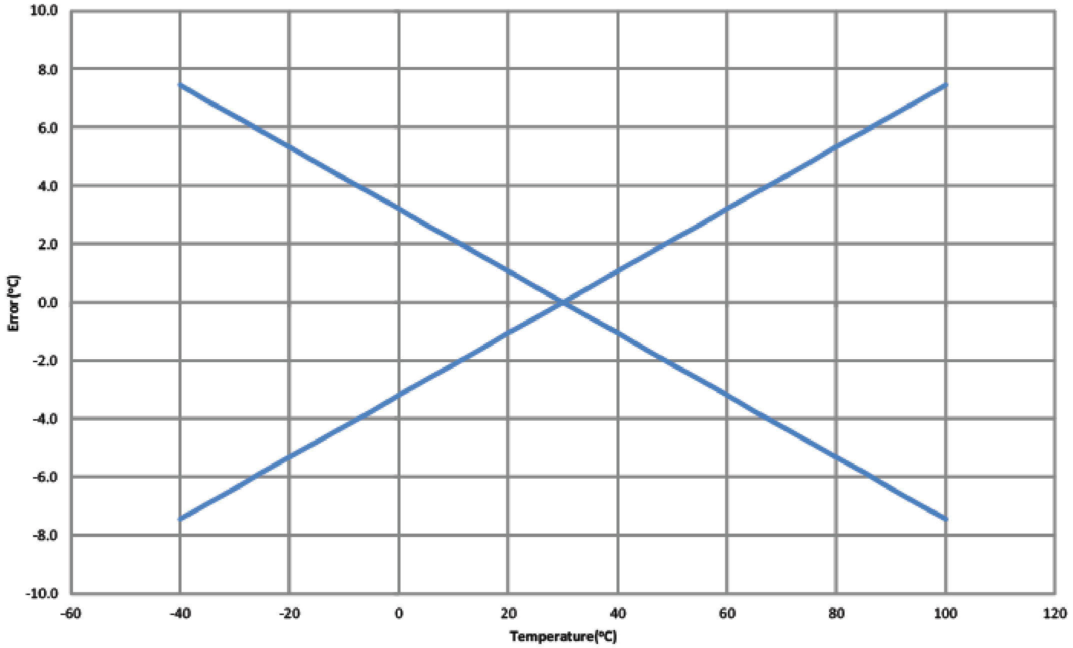
- On-board power parts like voltage regulators or power drivers don't create temperature gradients on the PCB and thus compromise the temperature equality between the MCU and the crystal
- The MCU activity is reduced to minimum to perform this temperature acquisition to avoid temperature rise in the MCU compared to the ambient temperature. If the MCU activity cannot be stopped then the die temperature rise may be characterized in order to get the crystal temperature by de-rating the die temperature.

2.3.2 Die Temperature Measurement with SAM3/4 Series

The Atmel Cortex®-M3/M4 based MCU Series provides an embedded temperature sensor, which is wired to one of the ADC channels. The temperature sensor provides an output voltage (V_T) that is proportional to absolute temperature (PTAT). At 27°C, V_T = 1.44V (±100mV) and its temperature slope is KTS = dV_T / dT = 4.7mV/°C (±0.5mV/°C).

- The offset error (±100mV) leads to ±20°C initial inaccuracy in the temperature reading (= ±100mV / 4.7mV/°C). This offset error needs to be removed during production by reading a reference thermometer at a single temperature point.
- The slope tolerance (±0.5mV/°C) induces temperature errors that increase with the distance between the measured temperature and the reference temperature used to remove offset errors. See Figure 2-4. Typically, 60 degrees away from the offset calibration point, the slope tolerance induces a ±6.4 degrees (= 60 x 0.5 / 4.7) of temperature reading inaccuracy. By adding a second temperature calibration point, the slope tolerance can be removed.

Figure 2-4. Temperature Reading Errors due to Slope Tolerance



In the SAM3/4 MCUs, the temperature sensor output is converted though a 10- or 12-bit ADC which has the following errors:

- An offset error. This one is removed when the offset correction of the whole acquisition chain is performed.
- A gain error. Generally, this error is in the order of less than ±1% which is of second order compared to the tolerance of the slope (±10%).
- An Integral Non-linearity Error. This error expressed in LSBs depends on the Voltage Reference used to feed the ADC. It adds to the total error in a random way and contributes to less than ±2 degrees. As a first example, on SAM4S, the INL is specified to be ±4LSB in 12-bit mode, which is ±3.2mV with a 3.3V reference. This leads to less than ±1°C of non-linearity error. As a second example, on SAM4C/CM, the INL specification is ±2LSB at 10-bit which leads to ±6.4mV with a 3.3V reference. This equates to ±1.4°C of non-linearity error.

2.3.3 Crystal Correction Look-up Table Example

In this section, an exemplary look-up table is provided to fill the calibration fields in the RTC user interface. The relative crystal error with temperature is expressed as:

$$E_{XTAL}(T) = E_{XTAL}(T_0) + B(T - T_0)^2$$

Where:

$E_{XTAL}(T)$:	Relative crystal error in ppm at temperature T
B:	Temperature coefficient in ppm/°C^2
T_0:	Turn-over temperature
$E_{XTAL}(T_0)$:	Relative Crystal error at temperature T_0

In Table 2-2 we assume B = -0.040ppm/°C^2, T_0 = 25°C and $E_{XTAL}(T_0)$ = +1ppm.

Table 2-2. RTC Calibration Registers vs. Temperature

Temperature	E_{XTAL} (T) [ppm]	NEGPPM	HIGHPPM	CORRECTION
-40	-168	0	1	22
-39	-163	0	1	23
-38	-158	0	1	24
-37	-153	0	1	25
-36	-148	0	1	25
-35	-143	0	1	26
-34	-138	0	1	27
-33	-134	0	1	28
-32	-129	0	1	29
-31	-124	0	1	31
-30	-120	0	1	32
-29	-116	0	1	33
-28	-111	0	1	34
-27	-107	0	1	36
-26	-103	0	1	37
-25	-99	0	1	38
-24	-95	0	1	40

Temperature	E_{XTAL} (T) [ppm]	NEGPPM	HIGHPPM	CORRECTION
-23	-91	0	1	42
-22	-87	0	1	44
-21	-84	0	1	45
-20	-80	0	1	48
-19	-76	0	1	50
-18	-73	0	1	53
-17	-70	0	1	55
-16	-66	0	1	58
-15	-63	0	1	61
-14	-60	0	1	64
-13	-57	0	1	68
-12	-54	0	1	71
-11	-51	0	1	76
-10	-48	0	1	80
-9	-45	0	1	86
-8	-43	0	1	90
-7	-40	0	1	97
-6	-37	0	1	105
-5	-35	0	1	111
-4	-33	0	1	117
-3	-30	0	0	6
-2	-28	0	0	6
-1	-26	0	0	7
0	-24	0	0	7
1	-22	0	0	8
2	-20	0	0	9
3	-18	0	0	10
4	-17	0	0	10
5	-15	0	0	12
6	-13	0	0	14
7	-12	0	0	15
8	-11	0	0	17
9	-9	0	0	21
10	-8	0	0	23
11	-7	0	0	27
12	-6	0	0	32
13	-5	0	0	38
14	-4	0	0	48
15	-3	0	0	64
16	-2	0	0	97

Temperature	E_{XTAL} (T) [ppm]	NEGPPM	HIGHPPM	CORRECTION
17	-2	0	0	97
18	-1	0	0	127
19	0	1	0	0
20	0	1	0	0
21	0	1	0	0
22	1	1	0	127
23	1	1	0	127
24	1	1	0	127
25	1	1	0	127
26	1	1	0	127
27	1	1	0	127
28	1	1	0	127
29	0	1	0	0
30	0	1	0	0
31	0	1	0	0
32	-1	0	0	127
33	-2	0	0	97
34	-2	0	0	97
35	-3	0	0	64
36	-4	0	0	48
37	-5	0	0	38
38	-6	0	0	32
39	-7	0	0	27
40	-8	0	0	23
41	-9	0	0	21
42	-11	0	0	17
43	-12	0	0	15
44	-13	0	0	14
45	-15	0	0	12
46	-17	0	0	10
47	-18	0	0	10
48	-20	0	0	9
49	-22	0	0	8
50	-24	0	0	7
51	-26	0	0	7
52	-28	0	0	6
53	-30	0	0	6
54	-33	0	1	117
55	-35	0	1	111
56	-37	0	1	105

Temperature	E_{XTAL} (T) [ppm]	NEGPPM	HIGHPPM	CORRECTION
57	-40	0	1	97
58	-43	0	1	90
59	-45	0	1	86
60	-48	0	1	80
61	-51	0	1	76
62	-54	0	1	71
63	-57	0	1	68
64	-60	0	1	64
65	-63	0	1	61
66	-66	0	1	58
67	-70	0	1	55
68	-73	0	1	53
69	-76	0	1	50
70	-80	0	1	48
71	-84	0	1	45
72	-87	0	1	44
73	-91	0	1	42
74	-95	0	1	40
75	-99	0	1	38
76	-103	0	1	37
77	-107	0	1	36
78	-111	0	1	34
79	-116	0	1	33
80	-120	0	1	32
81	-124	0	1	31
82	-129	0	1	29
83	-134	0	1	28
84	-138	0	1	27
85	-143	0	1	26

2.3.4 Expected RTC Accuracy after Calibration and Compensation

In the previous sections, a method to calibrate the initial errors of the RTC and a method to compensate its drift over temperature are presented. As shown in Section 2.2, the room temperature calibration can achieve an accuracy performance below 3ppm.

On the temperature compensation side, the resulting accuracy depends on the matching between the software correction applied and the actual amount of needed correction. Unfortunately, the software correction works with a set of typical parameters and ignores the real parameter set for the mounted couple (crystal + MCU). In particular:

- The temperature coefficient of the crystal (B) is compensated to its typical value (e.g.: -0.035ppm/K^2) but has a dispersion (e.g.: ±0.005ppm/K^2)

- The turnover temperature of the crystal (T_0) is also compensated to its typical value (e.g.: 25°C) with overlooking of its dispersion (e.g.: ±5°C)
- The slope of the temperature sensor (KTS = dV_T / dT) is coded to a typical value (e.g.: +4.7mV/K) but varies from part to part (e.g.: ±0.5mV/K)

To guarantee the final accuracy of the RTC system over temperature, an uncertainty calculation can be performed. The actual crystal characteristics lead to a temperature dependent frequency drift $dF_{XTAL}(T) / F_0$ (expressed in ppm) and described by:

$$\frac{dF_{XTAL}(T)}{F_0} = B_{XTAL} \bullet (T - T_{0XTAL})^2$$

In this equation, B_{XTAL} is the actual crystal temperature coefficient, and T_{0XTAL} is the actual turnover temperature of the crystal. T is the actual temperature.

The correction calculated by the software $dF_{XTAL}(T_{SOFT}) / F_0$ is based on the same formula but uses:

- The typical set of parameters B_{TYP} and T_{0TYP}
- The temperature as known by the software through the temperature sensor (T_{SOFT})

$$\frac{dF_{SOFT}(T_{SOFT})}{F_0} = B_{TYP} \bullet (T_{SOFT} - T_{0TYP})^2$$

The software temperature T_{SOFT} relates to the actual temperature T through the following formula:

$$T_{SOFT} = T \bullet \frac{KTS_{MCU}}{KTS_{TYP}}$$

With KTS_{MCU} the actual temperature sensor slope and KTS_{TYP} the typical slope defined in the MCU datasheet.

Finally, the compensation error at temperature T is:

$$\varepsilon(T) = dF_{XTAL}(T) - dF_{SOFT}(T)$$

Figure 2-5 gives a plot of the boundaries of this error over temperature when this equation set is entered in a spreadsheet application for 1000 Monte Carlo simulations. The following parameters are used:

$$B = -0.035\text{ppm/K}^2 \pm 0.005\text{ppm/K}^2,\ T_0 = 25°\text{C} \pm 5°\text{C, and KTS} = 4.7\text{mV/K} \pm 0.5\text{mV/K}$$

All parameters are assumed to follow a Gaussian distribution. The initial errors or room temperature errors are assumed perfectly calibrated.

Figure 2-5. Boundaries of the RTC Errors after Calibration and Compensation

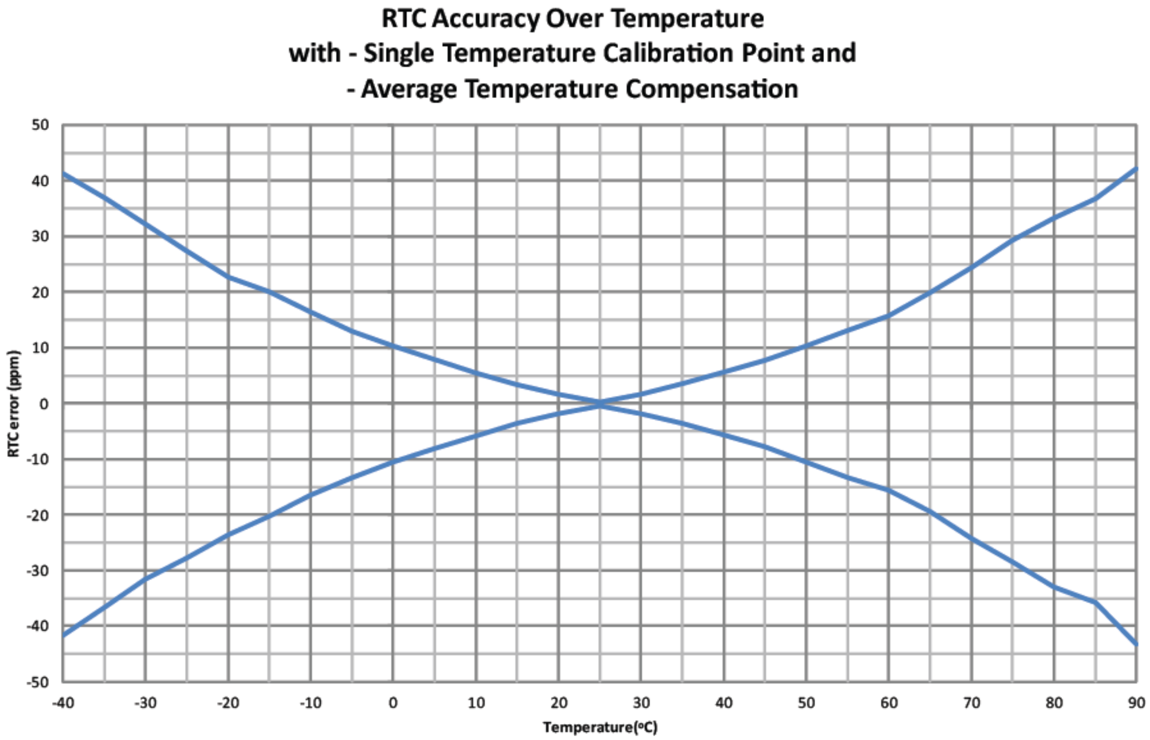


Figure 2-5 shows that the software compensation mechanism can achieve the following accuracy specifications over the respected temperature ranges:

- ±5ppm (±2.5 min/year) in the 15°C - 35°C range
- ±10ppm (±5 min/year) in the 5°C - 45°C range

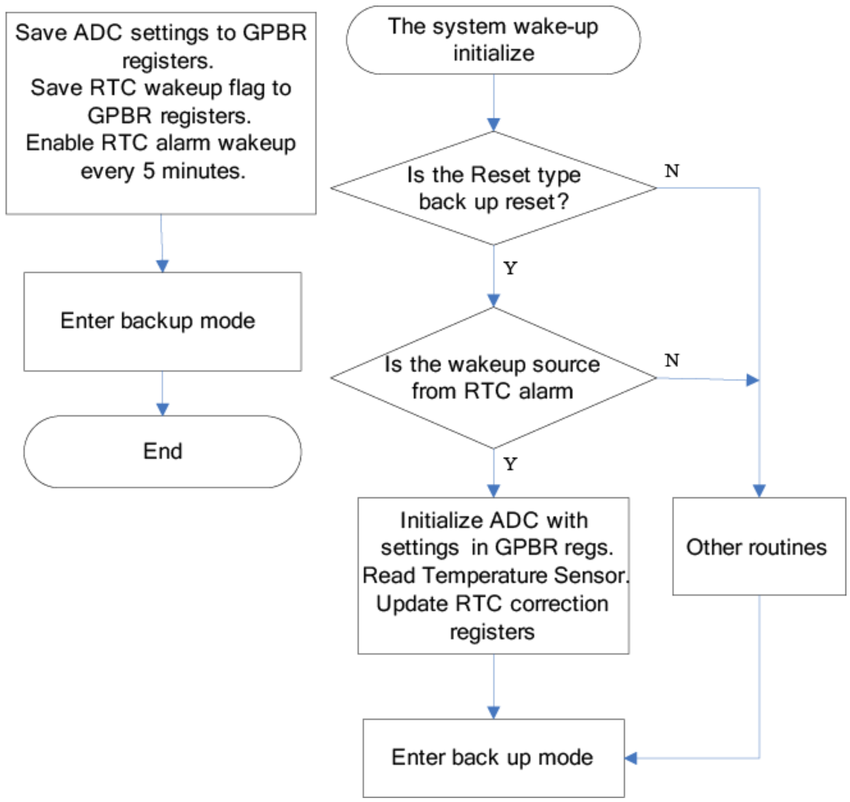
Further improvements of this software compensation method (e.g. on very critical applications) can be achieved by adding 1 or 2 calibration steps depending on the accuracy specification to fulfill.

2.3.5 Compensation in Backup Mode and Current Consumption

In low power backup mode, the RTC is still working to keep the time/date, and the temperature drift also needs to be compensated periodically (e.g. every five minutes). In this case, the power consumption to operate the software compensation is critical as the backup mode of the Atmel SAM3/4 MCUs typically consumes between 700nA (SAM4C/CM series) and 3µA (SAM3S series) to keep the RTC working.

Figure 2-6 shows the principle of the correction in backup mode. The RTC alarm is used to wake-up periodically (e.g. every five minutes) the core, which in return performs a temperature acquisition and calculates a new set of calibration parameters for the RTC.

Figure 2-6. Software Flow Chart for Crystal Error Compensation in Backup Mode



To estimate the energy consumption of such a periodic calibration, this method was coded on a SAM4E device. The experiment shows that the awaken phase lasts 8.8ms with an active current of 3mA@3.3 V and 25°C. As a result, the average power consumption is 88nA@3.3V at 25°C:

$$I_{AVG} = 3mA \cdot (8.8ms/300s) = 88nA$$

2.4 RTC Synchronization to the Network Time

For network enabled applications, it is possible and recommended to synchronize from time-to-time the local time (i.e. the MCU's RTC) to the network time. The Network Time Protocol (NTP) is a standard protocol for clock synchronization. The detailed implementation of NTP is beyond the scope of this application note. Further details are available at http://www.ntp.org.

Note: This method is the only way to ensure accuracy of the RTC over the years without re-calibrating the system.

3. Conclusion

While low cost watch crystals are the main stream in RTC applications, they require the RTC sub-system to be calibrated and compensated to yield an acceptable accuracy. This application note presents such techniques and the way they are implemented in the Atmel SAM3/4 MCU Series. With these techniques in place, users can expect ±10ppm accuracy in the 5°C - 45°C range.

4. Reference Documents

This application note applies to the following devices for which the datasheets can be downloaded at the indicated URLs.

Table 4-1. Reference Documents

Atmel series	URL of device overview page
SAM3S8/SD8	http://www.atmel.com/products/microcontrollers/arm/sam3s.aspx
SAM4N	http://www.atmel.com/products/microcontrollers/arm/sam4n.aspx
SAM4S	http://www.atmel.com/products/microcontrollers/arm/sam4s.aspx
SAM4E	http://www.atmel.com/products/microcontrollers/arm/sam4e.aspx
SAM4C/CM	http://www.atmel.com/devices/ATSAM4C16.aspx http://www.atmel.com/devices/ATSAM4CMP16.aspx
SAMG	http://www.atmel.com/products/microcontrollers/arm/sam-g.aspx

5. Revision History

Doc. Rev.	Date	Comments
42251A	03/2014	Initial document release

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