AN2604
Application note

STM32F101xx and STM32F103xx RTC calibration

Introduction

The real-time clock (RTC) precision is a requirement in most embedded applications, but due to external environment – temperature change, frequency variation of the crystal that clocks the RTC – the RTC precision may not be as accurate as expected.

The RTC embedded in the STM32F101xx and STM32F103xx comes with a digital clock calibration circuit suitable for manufacturing environments, that allows applications to compensate for crystal and temperature variations. This application note discusses the RTC calibration basics and explains how RTC calibration can be used to improve timekeeping accuracy.

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1 RTC calibration basics

1.1 Crystal accuracy

The term “quartz-accurate” has become a familiar phrase used to describe the accuracy of many time keeping functions. Quartz oscillators provide an accuracy far superior to that of other conventional oscillator designs, but they are not perfect. Quartz crystals are sensitive to temperature variations. *Figure 1* shows the relationship between accuracy (acc), temperature (T) and curvature (K) for a typical 32.768 kHz crystal. The curve follows the general formula given below:

$\mathrm{acc} = k \times (T - To)^2$, where:

- To = 25 °C ± 5 °C
- K = –0.040 ppm/°C^2

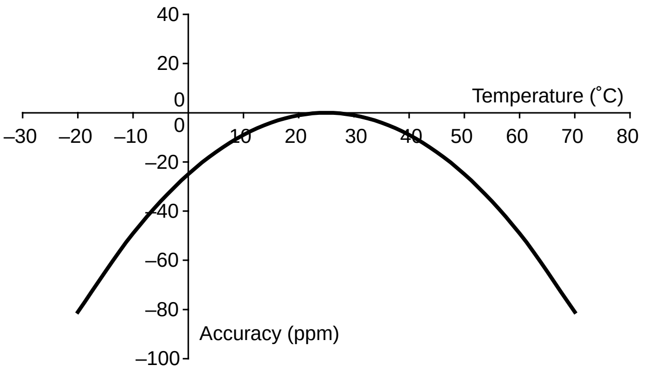
Note: The variable K is crystal-dependent, the value indicated here is for the crystal mounted on the STM3210B-EVAL board. Refer to the crystal manufacturer for more details on this parameter.

The clocks used in most applications require a high degree of accuracy, and there are several factors involved in achieving this accuracy. Typically most crystals are compensated for by adjusting the load capacitance of the oscillator. This method, though effective, has several disadvantages:

1. it requires external components (trim capacitors)
2. it can increase the oscillator current (a major factor in battery-supported applications)

Instead of this crude analog method, STM32F10xxx products use a digital calibration feature that gives the user software control over the calibration procedure, and make it user-friendly.

Figure 1. Typical crystal accuracy plotted against temperature



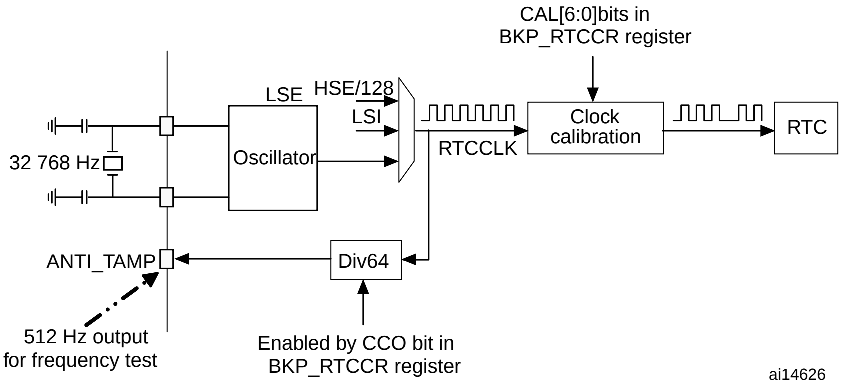
1.2 Methodology

The RTC of STM32F10xxx products is driven by a quartz crystal-controlled oscillator with a nominal frequency of 32.768 kHz. The crystal oscillator is one of the most accurate circuits to provide a fixed frequency. There are two causes of clock error:

1. temperature variation
2. crystal variation

As mentioned previously, most clock chips compensate for crystal frequency and temperature variations by using cumbersome trim capacitors. The STM32F10xxx design employs periodic counter corrections. The digital calibration circuit removes 0 to 127 cycles every 2^{20} clock cycles (see *Figure 2.*). The number of times the pulses are blanked depends upon the value that has been loaded into the seven least significant bits of the BKP’s RTC clock calibration register. Since the RTC clock calibration register is in the backup domain, the calibration value is not lost even if the device is powered off provided that a battery is connected to the V_{BAT} pin.

Figure 2. RTC calibration clock output



1. The clock output on the ANTI_TAMP pin is the RTC clock before calibration, so its value is not changed by the calibration.

Each calibration step has the effect of subtracting 1 oscillator cycle every 1 048 576 (2^{20}) actual oscillator cycles. That is, 0.954(1000000/2^{20}) ppm of adjustment per calibration step in the calibration register. As a result, the oscillator clock can be slowed down from 0 to 121 ppm.

Table 1 on page 7 shows how many ppm and seconds per month (30 days) each bit represents in real time.

Table 1. Calibration table: compensation values in ppm and seconds per month (30 days)

Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second	Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second
0	0	0	64	61	158
1	1	2	65	62	161
2	2	5	66	63	163
3	3	7	67	64	166
4	4	10	68	65	168
5	5	12	69	66	171
6	6	15	70	67	173
7	7	17	71	68	176
8	8	20	72	69	178
9	9	22	73	70	180
10	10	25	74	71	183
11	10	27	75	72	185
12	11	30	76	72	188
13	12	32	77	73	190
14	13	35	78	74	193
15	14	37	79	75	195
16	15	40	80	76	198
17	16	42	81	77	200
18	17	44	82	78	203
19	18	47	83	79	205
20	19	49	84	80	208
21	20	52	85	81	210
22	21	54	86	82	213
23	22	57	87	83	215
24	23	59	88	84	218
25	24	62	89	85	220
26	25	64	90	86	222
27	26	67	91	87	225
28	27	69	92	88	227
29	28	72	93	89	230
30	29	74	94	90	232

Table 1. Calibration table: compensation values in ppm and seconds per month (30 days) (continued)

Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second	Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second
31	30	77	95	91	235
32	31	79	96	92	237
33	31	82	97	93	240
34	32	84	98	93	242
35	33	87	99	94	245
36	34	89	100	95	247
37	35	91	101	96	250
38	36	94	102	97	252
39	37	96	103	98	255
40	38	99	104	99	257
41	39	101	105	100	260
42	40	104	106	101	262
43	41	106	107	102	264
44	42	109	108	103	267
45	43	111	109	104	269
46	44	114	110	105	272
47	45	116	111	106	274
48	46	119	112	107	277
49	47	121	113	108	279
50	48	124	114	109	282
51	49	126	115	110	284
52	50	129	116	111	287
53	51	131	117	112	289
54	51	133	118	113	292
55	52	136	119	113	294
56	53	138	120	114	297
57	54	141	121	115	299
58	55	143	122	116	302
59	56	146	123	117	304
60	57	148	124	118	307
61	58	151	125	119	309

Table 1. Calibration table: compensation values in ppm and seconds per month (30 days) (continued)

Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second	Calibration value	Value in ppm rounded to the nearest ppm	Value in seconds per month (30 days) rounded to the nearest second
62	59	153	126	120	311
63	60	156	127	121	314

As described above, the STM32F10xxx RTC clock calibration circuit subtracts cycles only from crystal clocks. And based on the fact that the RTC prescaler value is set by default to 32 768, faster crystal frequencies (> 32 768 Hz) can be calibrated whereas slower crystal frequencies (< 32 768 Hz) cannot be compensated for. So only crystal frequencies in the range [32 772, 32 768] can be calibrated.

Since the crystal frequency may vary about 32.768 kHz, a solution may be considered that consists in setting the RTC prescaler to 32 766 (instead of 32 768). The crystal frequency is thus compared to 32 766 instead of 32 768. In this way, a crystal frequency in the range [32 770, 32 766] can be compensated.

Throughout the rest of the document, the considered RTC prescaler value will be 32 766.

2 Calculating the needed amount of calibration

To establish how much calibration is required in a given application, a method specially suited to manufacturing environments is retained. It involves the use of the RTC clock output mode, which derives a 512 Hz signal from the clock divider chain as indicated in *Figure 2 on page 6*. This signal can be used to measure the accuracy of the crystal oscillator.

This method can be divided up into the following steps:

1. Enable the low speed external oscillator (LSE), select the LSE as the RTC clock source, then enable the RTC clock.
2. Enable the RTC clock output with a frequency divided by 64, on the ANTI_TAMP pin for crystal frequency measurement. This is achieved by setting the CCO bit in BKP_RTCCR.
3. Calculate the crystal frequency deviation in ppm. The deviation in ppm can be quickly calculated by dividing the measured deviation from 511.968 Hz by 511.968 and, by multiplying the result by 1 million. Find the nearest calibration value using *Table 1 on page 7*. This table is a direct look-up table for calibration values based upon variation values expressed in ppm.
4. Load the calibration value in the RTC calibration register to compensate for the crystal deviation.

Note: To set the RTC prescaler to 32 766, write 32 765 into the RTC prescaler load register.

For example, if the frequency measured during the test mode is 511.982 Hz, the delta is 0.014. By dividing by 511.968 and multiplying by 1 million, the result is 27.35 ppm. In this case, the nearest compensation value is 28. The inaccuracy will be reduced from 27.35 ppm (~71 seconds per month) to 0.65 ppm (~1.7 second per month).

Note: Since RTC calibration is based on removing clock cycles, it does not improve counting over short periods of time, it only improves counting over long periods. For example counting a 1/100 s using the RTC will be more accurate without calibration than with calibration. Since calibration cycle removal may or not occur during the considered time frame, the resulting value may change significantly. So depending on the application it may be better not to use calibration.

3 Calculating calibration over a temperature range

The calibration procedure described so far aims at calculating the correction for a specific temperature. This section provides a procedure for minimizing the frequency variation over a wider temperature range. This involves adjusting the frequency curve so that there is an equal amount of error above and below the zero (0) ppm point. *Figure 3 on page 11* shows how the frequency error can be minimized over a given temperature range.

The variables in the equation: $\mathrm{acc} = k \times (T - To)^2$ (see *Section 1.1 on page 5*) are the following:

acc = Accuracy, in ppm, of the frequency, at the turnover temperature
K = Curvature characteristic = –0.04 ppm/°C^2
To = Turnover temperature in degrees Celsius = 25 °C ± 5 °C
T = Working temperature in degrees Celsius

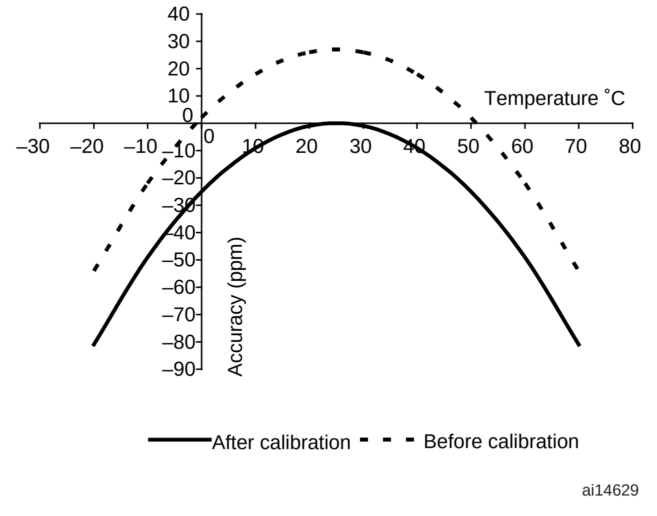
For example, if a device shows a deviation of +27 ppm at room temperature, but the operating temperature is 40 °C in the application, the equation may be used to calculate the required calibration value as follows:

$$\mathrm{acc} = 27\mathrm{ppm} + ((-0.04\mathrm{ppm}) / {}^{\circ}C^2) \times (40^{\circ}C - 25^{\circ}C)^2$$

$$\mathrm{acc} = 18\mathrm{ppm}$$

Since the accuracy deviation is 18 ppm, the nearest calibration value as indicated in *Table 1 on page 7*, is 19.

Figure 3. Crystal accuracy over a temperature range



4 Conclusion

The STM32F10xxx RTC digital clock calibration feature allows the user to adjust the clock accuracy during manufacturing (or later) at minimal cost. This feature also provides a method whereby “drift” (due to temperature variation) can be corrected and/or anticipated.

However, the method described in this application note is applicable only if the RTC prescaler is set to 32 766 (instead of 32 768).

5 Revision history

Table 2. Document revision history

Date	Revision	Changes
31-Aug-2007	1	Initial release.

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