AN1155

Run-Time Calibration of Watch Crystals

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INTRODUCTION

For watch and timekeeping applications, 32.768 kHz crystals with an accuracy close to 20 ppm are common, but 20 ppm translates to a ±0.65536 Hz frequency deviation, or a whopping 51.8 seconds error per month. This error only accounts for variation in crystal properties. Other significant sources include temperature, aging, component selection and layout.

In this application note, we discuss errors associated with low-cost watch crystals used in Real-Time Clock and Calendar (RTCC) applications and methods to overcome these errors. We also discuss a unique built-in calibration feature in Microchip Technology's Real-Time Clock and Calendar circuits, which minimizes these errors during run time.

SOURCES OF CRYSTAL ERROR

Cross cut (X-Cut) crystals are the most common type of crystal used in (RTCC) circuits. These crystals are inexpensive, readily available and reasonably accurate.

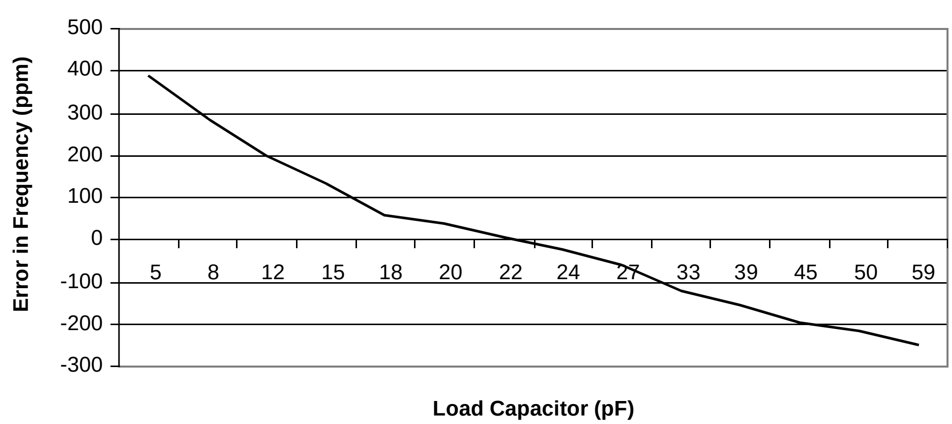
The following are the most common factors leading to oscillator errors in crystal sources:

- Mechanical Vibration
- Load Capacitor
- Temperature
- Age

Mechanical vibration should be avoided to minimize crystal errors. If possible, we need to move all vibration sources away from the crystal. Potential vibration sources include buzzers, speakers, motors and so on.

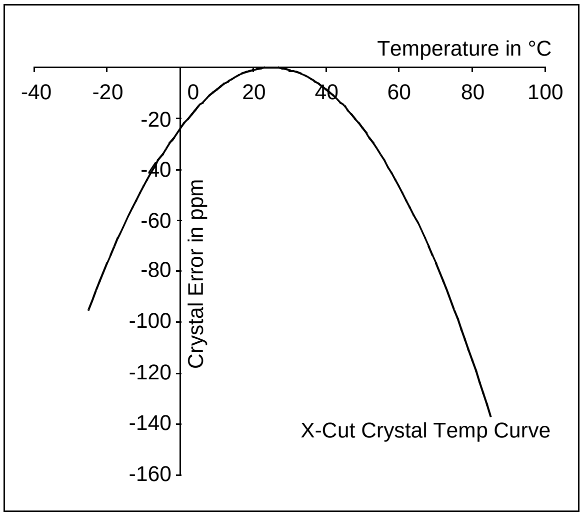
For resonance at the correct frequency, the crystal should be loaded with its specified load capacitance, which is the value of capacitance used in conjunction with the crystal unit. Load capacitance is a parameter specified by the crystal manufacturer; typically expressed in pF. A mismatched load capacitor can contribute to an error of up to almost 400 ppm, as shown in Figure 1. It is important to consider capacitor value due to parasitic capacitance of the PCB traces and other crystal leads. Determining an optimal capacitor value is beyond the scope of this application note, but additional information is available in *AN826, "Crystal Oscillator Basics and Crystal Selection for rfPIC™ and PICmicro® Devices"*, *AN849, "Basic PICmicro® Oscillator Design"*, *AN943, "Practical PICmicro® Oscillator Analysis and Design"* and *AN949, "Making Your Oscillator Work"* on Microchip Technology's web site (www.microchip.com).

FIGURE 1: CRYSTAL ERROR vs. LOAD CAPACITOR (FOR A CRYSTAL MATCHED FOR 22 pF)



Temperature affects crystal frequency and contributes significantly to crystal errors. Many crystals are designed to center the inflection in error near the room temperature. Figure 2 shows a typical 32.768 kHz X-Cut crystal error vs. temperature. From this figure, we can see that a typical crystal error doubles in as little as 20°C (degree Celsius) variation.

FIGURE 2: CRYSTAL ERROR vs. TEMPERATURE



All components' characteristics change with their age. Although it is commonly overlooked, its effect can significantly contribute as much as 50 ppm to crystal errors.

The error due to temperature and aging presents a significant challenge to a system designer. Even though a high-quality crystal with properly matched capacitors may be used, along with the best layout practices, they do not account for temperature or aging. This is due to the fact that these factors are unknown during the design process, and hence, must be taken care of during its run-time execution.

Timing errors, due to aging or temperature variations, are typically very slow in nature and will not abruptly change the crystal frequency. By characterizing their effects, time could be adjusted in the software. This can, however, complicate the RTCC routines since large counters are needed to apply these adjustments at the correct time.

To counter the drift caused by the above sources, Microchip Technology's PIC24F RTCC has an automatic calibration feature. It features a software writable register, capable of compensating for up to 260 ppm crystal error, which is sufficient to counter typical crystal error due to mismatched load capacitor, change in temperature, etc., without adding a significant software overhead during run time. This is a unique feature since most off-the-shelf RTCC solutions do not support run-time calibration.

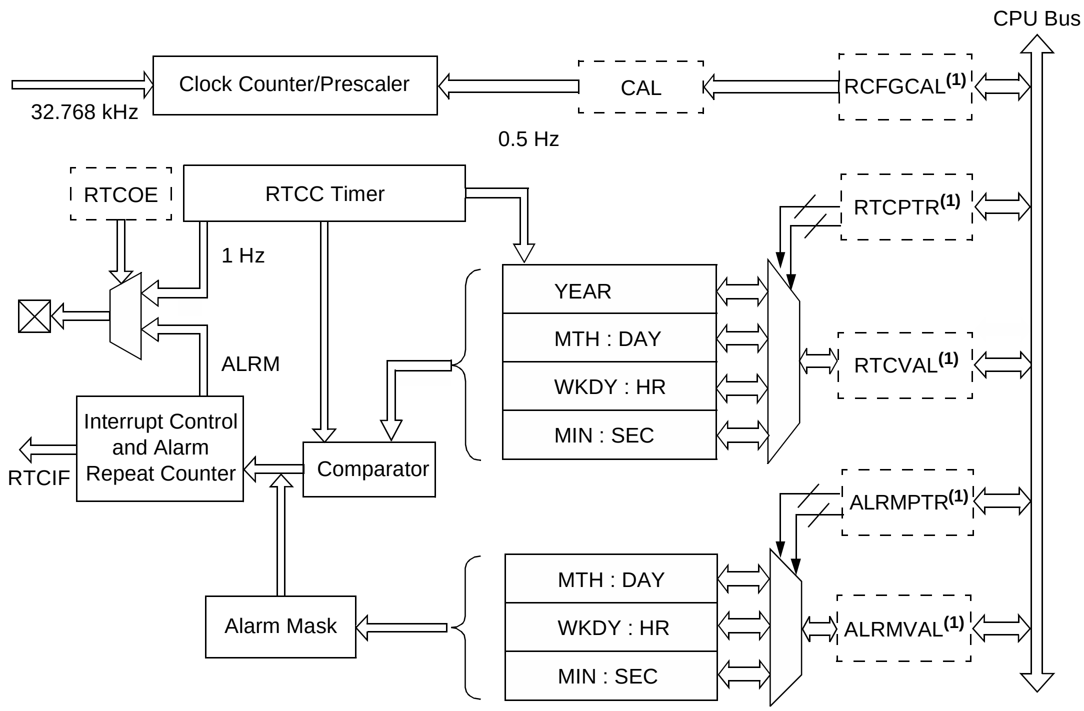
The RTCC block diagram in Figure 3 depicts the various features of PIC24F RTCC peripheral.

The RTCC module is comprised of the following features:

- Hardware Real-Time Clock and Calendar
- Year 2000 to 2099 with Leap Year Correction
- Provides Time – Hours, Minutes and Seconds using 24-Hour Format
- Provides Calendar – Weekday, Date, Month and Year
- Optimized for a Long-Term Battery Operation
- Provides Configurable Alarm
- Alarm Configurable for Half a Second, 1 Second, 10 Seconds, 1 Minute, 10 Minutes, 1 Hour, 1 Day, 1 Week or 1 Month
  - Alarm repeat with decrementing counter
  - Alarm with indefinite repeat – chime
- Provides Seconds Pulse Output on an Output Port if Configured
- Provides Interrupt to the CPU on Every Alarm Event
- User Calibration for the 32.768 kHz Clock Crystal Frequency with a Periodic Auto-Adjust
  - Calibration within ±2.59 seconds and up to ±11.23 minutes error per month
  - Calibrates up to 260 ppm of crystal error

Note:	Refer to the specific device data sheet for complete features.

FIGURE 3: BLOCK DIAGRAM OF MICROCHIP RTCC



Note 1: These are Special Function Registers which can be accessed by the CPU.

Calculating Crystal Calibration Constant for PIC24F RTCC

To minimize timing errors, Microchip has introduced a novel idea of modifying the RTCC counter value automatically, based on error value loaded in the calibration register, RCFGCAL. The value of the register is made to auto-adjust the crystal errors every minute without software overhead.

To determine the correct calibration value, find the number of error clock pulses per minute and store this value in the lower half of the RCFGCAL register. This is stored in an 8-bit signed value format. The peripheral multiplies this value by four and will either add or subtract this from the RTCC timer, once in every minute.

Use Equation 1 to calculate the correction calibration value from the crystal error (ppm) rate.

In Equation 1, the Error Clocks/Min is a signed value, so the value of RCFGCAL is added when positive and subtracted when negative.

EQUATION 1: CALCULATING CRYSTAL ERROR RATE TO RCFGCAL VALUE

$$\text{Error Clocks/Min} = (\text{Ideal Frequency} - \text{Actual Frequency}) \times 60/4$$

Note: The value is multiplied by 60 to get error clocks for minute and divided by 4 as a resolution of each count in the calibration register is 2^2.

Methods to Determine Calibration Value for Crystal Error

To calibrate the Real-Time Clock counter, the first step is to determine the error associated with the oscillator. This can be done in various ways; this document focuses on two types of error estimation and calibration methods.

METHOD 1 – LOOK-UP TABLE-BASED APPROACH

As discussed earlier, temperature and load capacitors are major contributors for oscillator error. It can be assumed that the error contributed by the load capacitor is constant and the error from temperature is variable. With this assumption, we can generate a look-up table for temperature vs. crystal error. The RCFGCAL value can be then updated at a fixed interval or whenever there is a change in temperature.

Figure 4 and Figure 5 show the typical flowchart to implement software using look-up table-based crystal calibration.

GENERATING LOOK-UP TABLE FROM TC CURVE

Consider the TC curve for X-Cut watch crystals as shown in Figure 2, which is generated by Equation 2.

Example 1A, Example 1B and Example 2 show how to compute the calibration value and **Appendix A: “Look-up Table”** lists out the complete look-up table for temperatures from -25°C to 85°C, considering a load capacitor mismatch of 10 ppm.

Note:	Please refer to **Appendix A: “Look-up Table”** for a typical look-up table for 32.768 kHz X-Cut watch crystal.

EQUATION 2: TEMPERATURE vs. CRYSTAL ERROR

$$\Delta f/f_0 \text{ (ppm)} = -0.038(T - T_0)^2 \pm 10$$

Where T_o = 20°C and T is the Ambient Temperature

EQUATION 3: TOTAL CRYSTAL ERROR

RCFGCAL = -((Total Crystal Error in ppm/1000000) x (Clocks per Minute in 32.768 kHz)/4)

EXAMPLE 1A: TO CALCULATE RCFGCAL VALUE FOR -30 ppm CRYSTAL ERROR

If the crystal has -30 ppm error at 40°C and 10 ppm error due to the load capacitor mismatch, the calibration value will be:

RCFGCAL Value = -(((-30 + 10)/1000000) x 1966080/4)
= 9.8304
= 10
= 0x0A

EXAMPLE 1B: TO CALCULATE RCFGCAL VALUE FOR -80 ppm CRYSTAL ERROR

If the crystal has -80 ppm error at -50°C and 10 ppm error due to the load capacitor mismatch, the calibration value will be:

RCFGCAL Value = -(((-80 + 10)/1000000) x 1966080/4)
= 34.4064
= 34
= 0x22

EXAMPLE 2: TO CALCULATE RFGCAL VALUE FOR +80 ppm CRYSTAL ERROR

If the crystal has -20 ppm error, and the error due to load capacitor mismatch is +100 ppm, then the total error of the clock source will be 80 ppm (-20 + 100); then the calibration value will be:

RCFGCAL Value = -((80/1000000) x 1966080/4)
= -39.3216
= -39
= 0xD9

FIGURE 4: SAMPLE APPLICATION FLOWCHART FOR LOOK-UP TABLE-BASED CRYSTAL CALIBRATION

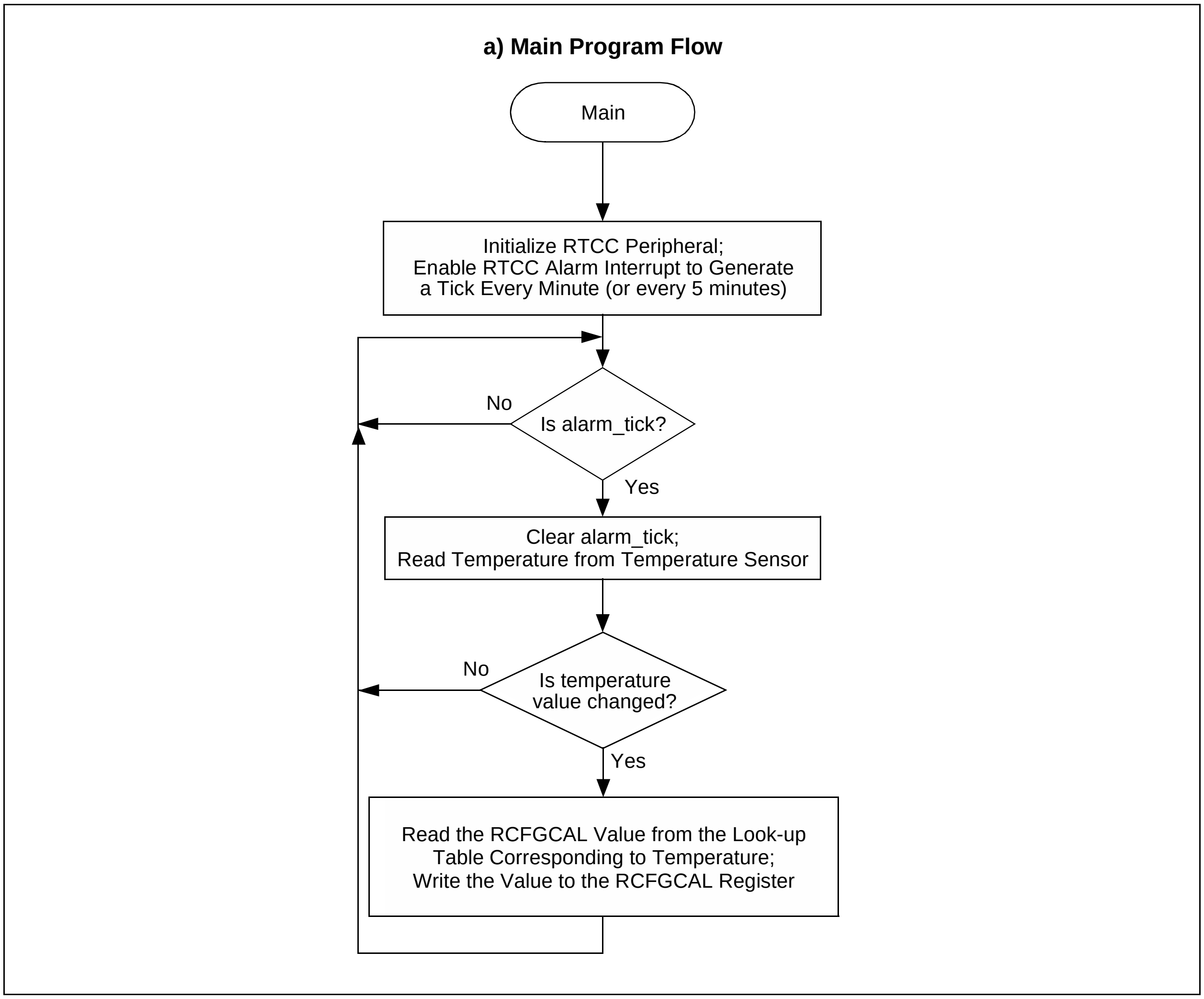
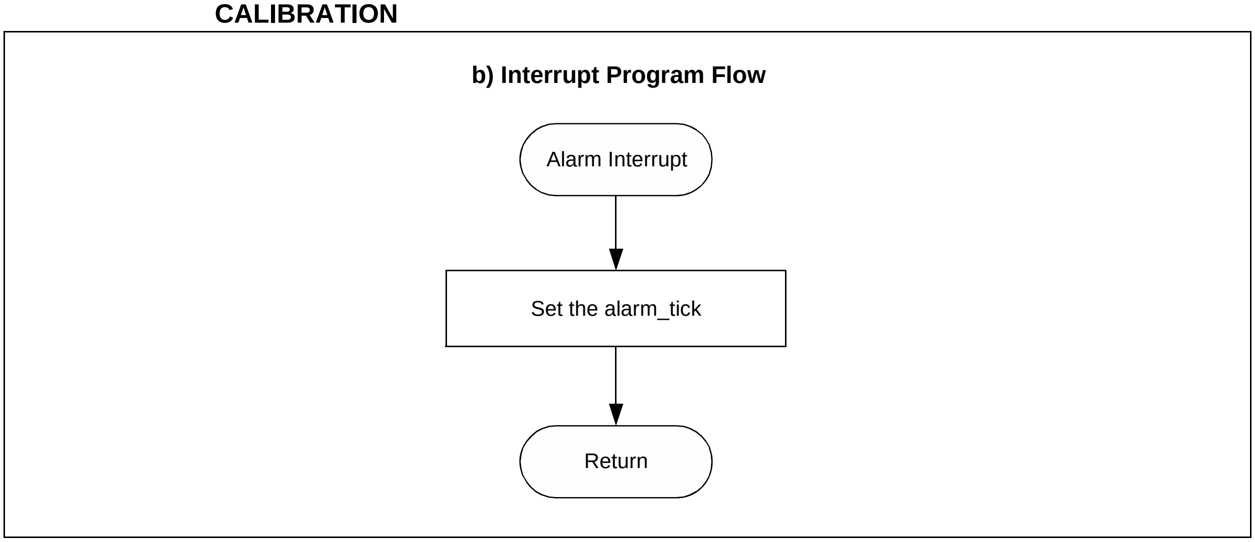


FIGURE 5: SAMPLE APPLICATION FLOWCHART FOR LOOK-UP TABLE-BASED CRYSTAL CALIBRATION



METHOD 2 – REFERENCE SYSTEM CLOCK-BASED APPROACH

Method 1 uses a precomputed table give in **Appendix A: "Look-up Table"**. This table doesn't consider factors like aging, part-to-part variations or environmental changes.

Most of the high-frequency crystals in embedded systems are AT-Cut crystals, which have better accuracy (0.1 ppm to 4 ppm) and less temperature drift as compared to X-Cut crystals. Effects/errors can be minimized by comparing the RTCC value with a timer value based on these high-frequency crystals, Equation 4 describes the error in one second for both clock sources.

EQUATION 4: ERROR IN ONE SECOND

$$\text{Error in 1 Second} = \text{Error Clocks per Second} \times \text{Clock Period}$$

EXAMPLE 3: CALCULATING ERROR IN TIME DUE TO 20 ppm AND 1 ppm ERROR IN CRYSTAL

Calculating the error/second for 32.768 kHz and 8.00 MHz crystal for one second having 20 ppm and 1 ppm error, respectively:

Error in 1 second for 32.768 kHz crystal with 20 ppm is = (20x32768/1000,000) x 1/32768
= 0.00002 Seconds

Error in 1 second for 8.00 MHz crystal with 1 ppm is = (1x8000000/1000,000) x 1/8000000
= 0.000001 Seconds

From the above calculation, it is evident that by comparing a low-frequency crystal oscillator with a high-frequency stable system oscillator, a software routine could improve the lower frequency crystal's accuracy. Steps involved in calibrating the crystal using this method are given below:

1. Select system frequency as a multiple of RTCC timer frequency. This simplifies the calculations and reduces the error due to asynchronous operation of timers.
2. Configure an available timer to use the system clock as a clock source and select a prescaler for an overflow of approximately 2 seconds.
3. Initialize the RTCC.
4. Enable RTCC interrupt for every second.
5. In the first interrupt, clear the timer count.
6. In subsequent interrupts, clear the RTCC interrupt and read the timer value.
7. Calculate crystal frequency error using the following formula:
   Error Counts = 32768 – Timer Counts Accumulated Over a Second
8. Convert frequency error to calibration value using the following formula:
   Calibration Value = Error Counts/4
9. Compute average calibration value for 1 minute. Load the computed average calibration value to the RCFGCAL register every minute.
10. Repeat steps 5 to 10, as needed, to compensate for system temperature variation, typically between 1 to 5 minutes.

By this method, we can overcome all the limitations of method 1; however, this requires a highly stable and accurate system clock and a timer.

EQUATION 5: COMPUTING THE CALIBRATION VALUE

Let us assume that the frequency of the main oscillator is 16.777 MHz and the timer prescaler is 256:

$$F_{TMR} = \frac{F_{CY}}{\text{Prescaler Value}}$$

$$= \frac{F_{OSC}/2}{\text{Prescaler Value}}$$

$$= \frac{16.777/2}{\text{Prescaler Value}}$$

$$= \frac{8.388608}{256}$$

$$F_{TMR} = 32.768 \text{ kHz}$$

With this configuration, the timer should have 32,768 counts for every second. If the crystal has 0 ppm error, any variation in the counts will result in error counts.

Error Counts = 32768 – Timer Counts

RFGCAL Value = Error Counts/4

Figure 6 and Figure 7 depict the typical flowcharts to implement software using the reference system clock-based crystal calibration method.

FIGURE 6: SAMPLE APPLICATION FLOWCHART FOR REFERENCE SYSTEM CLOCK-BASED CRYSTAL CALIBRATION

a) Main Program Flow

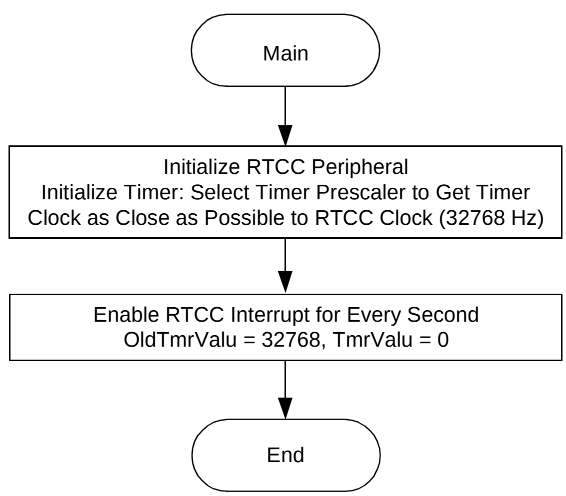
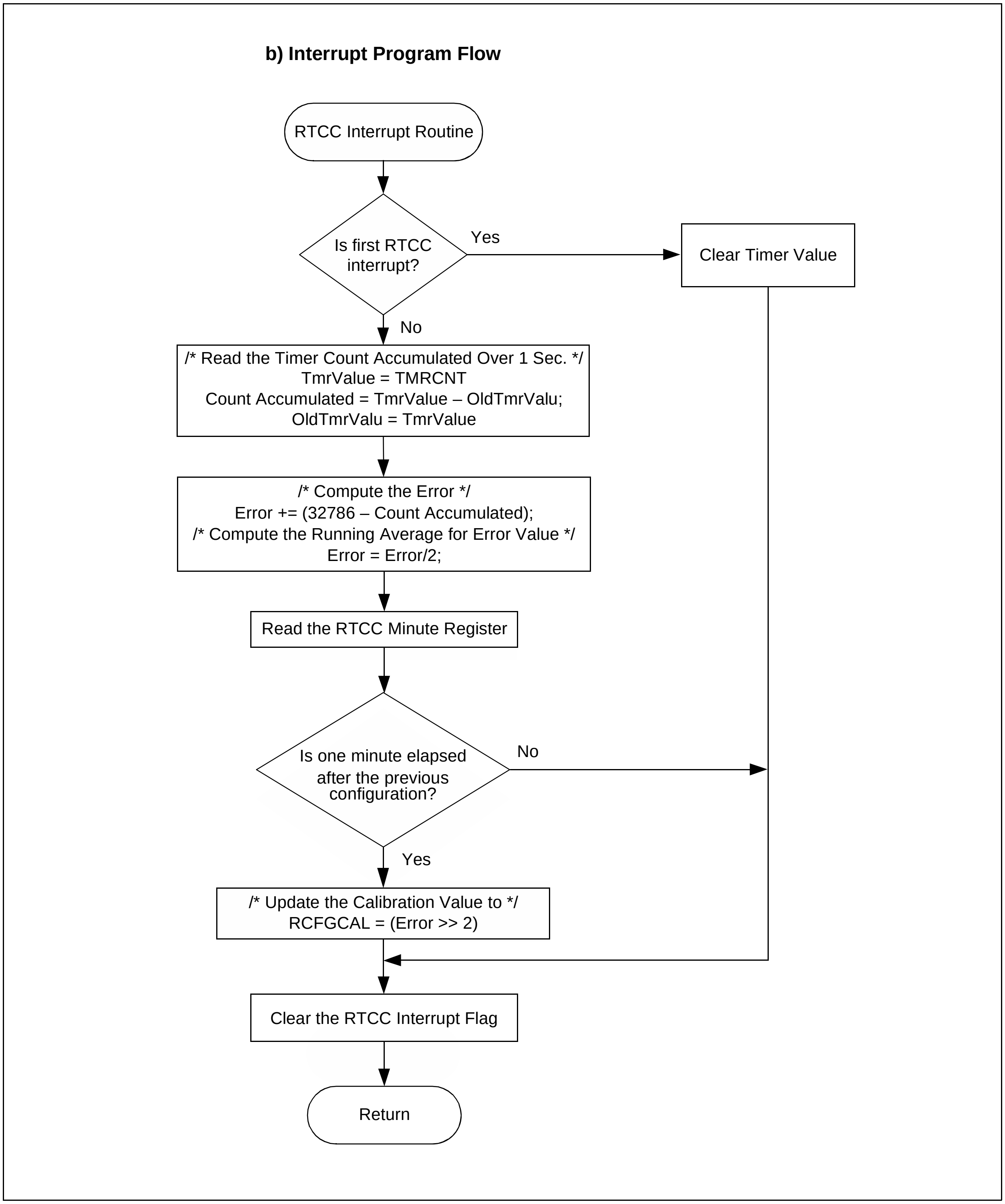


FIGURE 7: SAMPLE APPLICATION FLOWCHART FOR REFERENCE SYSTEM CLOCK-BASED CRYSTAL CALIBRATION



CONCLUSION

Designing a Real-Time Clock and Calender with inexpensive watch crystals is a challenge without run-time error calibration. Now, Microchip provides an easy and inexpensive solution to address this issue. Using Microchip's RTCC you can implement Real-Time Clocks within ±2.59 seconds error/month.

REFERENCES

- Microchip's *"PIC24FJ128GA010 Family Data Sheet"* (DS39747)
- Norman Bijano's *"Choosing the Right Crystal for Your Oscillator"*, EDN, Feb., 1998 pp 66-70

APPENDIX A: LOOK-UP TABLE

TABLE A-1: TEMPERATURE vs. CALIBRATION VALUE LOOK-UP TABLE FOR 32.768 kHz X-CUT WATCH CRYSTAL

Temperature (in °C)	X-Cut Crystal Characteristic Curve $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2$	X-Cut Crystal Characteristic Curve with 10 ppm Load Capacitor Mismatch $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2 \pm 10$	Cal Value = -((Total Crystal Error in ppm/1000000) x (Clocks per Minute in 32.768 kHz)/4)	RCFGCAL Value Rounded Off to the Nearest Integer
-25	-95	-85	41.78	42
-24	-91.238	-81.238	39.93	40
-23	-87.552	-77.552	38.12	38
-22	-83.942	-73.942	36.34	36
-21	-80.408	-70.408	34.61	35
-20	-76.95	-66.95	32.91	33
-19	-73.568	-63.568	31.24	31
-18	-70.262	-60.262	29.62	30
-17	-67.032	-57.032	28.03	28
-16	-63.878	-53.878	26.48	26
-15	-60.8	-50.8	24.97	25
-14	-57.798	-47.798	23.49	23
-13	-54.872	-44.872	22.06	22
-12	-52.022	-42.022	20.65	21
-11	-49.248	-39.248	19.29	19
-10	-46.55	-36.55	17.97	18
-9	-43.928	-33.928	16.68	17
-8	-41.382	-31.382	15.42	15
-7	-38.912	-28.912	14.21	14
-6	-36.518	-26.518	13.03	13
-5	-34.2	-24.2	11.89	12
-4	-31.958	-21.958	10.79	11
-3	-29.792	-19.792	9.73	10
-2	-27.702	-17.702	8.7	9
-1	-25.688	-15.688	7.71	8
0	-23.75	-13.75	6.76	7
1	-21.888	-11.888	5.84	6
2	-20.102	-10.102	4.97	5
3	-18.392	-8.392	4.12	4
4	-16.758	-6.758	3.32	3
5	-15.2	-5.2	2.56	3
6	-13.718	-3.718	1.83	2
7	-12.312	-2.312	1.14	1
8	-10.982	-0.982	0.48	0
9	-9.728	0.272	-0.13	0
10	-8.55	1.45	-0.71	-1
11	-7.448	2.552	-1.25	-1
12	-6.422	3.578	-1.76	-2
13	-5.472	4.528	-2.23	-2
14	-4.598	5.402	-2.66	-3
15	-3.8	6.2	-3.05	-3
16	-3.078	6.922	-3.4	-3

TABLE A-1: TEMPERATURE vs. CALIBRATION VALUE LOOK-UP TABLE FOR 32.768 kHz X-CUT WATCH CRYSTAL (CONTINUED)

Temperature (in °C)	X-Cut Crystal Characteristic Curve $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2$	X-Cut Crystal Characteristic Curve with 10 ppm Load Capacitor Mismatch $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2 \pm 10$	Cal Value = -((Total Crystal Error in ppm/1000000) x (Clocks per Minute in 32.768 kHz)/4)	RCFGCAL Value Rounded Off to the Nearest Integer
17	-2.432	7.568	-3.72	-4
18	-1.862	8.138	-4	-4
19	-1.368	8.632	-4.24	-4
20	-0.95	9.05	-4.45	-4
21	-0.608	9.392	-4.62	-5
22	-0.342	9.658	-4.75	-5
23	-0.152	9.848	-4.84	-5
24	-0.038	9.962	-4.9	-5
25	0	10	-4.92	-5
26	-0.038	9.962	-4.9	-5
27	-0.152	9.848	-4.84	-5
28	-0.342	9.658	-4.75	-5
29	-0.608	9.392	-4.62	-5
30	-0.95	9.05	-4.45	-4
31	-1.368	8.632	-4.24	-4
32	-1.862	8.138	-4	-4
33	-2.432	7.568	-3.72	-4
34	-3.078	6.922	-3.4	-3
35	-3.8	6.2	-3.05	-3
36	-4.598	5.402	-2.66	-3
37	-5.472	4.528	-2.23	-2
38	-6.422	3.578	-1.76	-2
39	-7.448	2.552	-1.25	-1
40	-8.55	1.45	-0.71	-1
41	-9.728	0.272	-0.13	0
42	-10.982	-0.982	0.48	0
43	-12.312	-2.312	1.14	1
44	-13.718	-3.718	1.83	2
45	-15.2	-5.2	2.56	3
46	-16.758	-6.758	3.32	3
47	-18.392	-8.392	4.12	4
48	-20.102	-10.102	4.97	5
49	-21.888	-11.888	5.84	6
50	-23.75	-13.75	6.76	7
51	-25.688	-15.688	7.71	8
52	-27.702	-17.702	8.7	9
53	-29.792	-19.792	9.73	10
54	-31.958	-21.958	10.79	11
55	-34.2	-24.2	11.89	12
56	-36.518	-26.518	13.03	13
57	-38.912	-28.912	14.21	14
58	-41.382	-31.382	15.42	15
59	-43.928	-33.928	16.68	17
60	-46.55	-36.55	17.97	18
61	-49.248	-39.248	19.29	19

TABLE A-1: TEMPERATURE vs. CALIBRATION VALUE LOOK-UP TABLE FOR 32.768 kHz X-CUT WATCH CRYSTAL (CONTINUED)

Temperature (in °C)	X-Cut Crystal Characteristic Curve $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2$	X-Cut Crystal Characteristic Curve with 10 ppm Load Capacitor Mismatch $\Delta f/f_0$ (ppm) = $-0.038(T - T_0)^2 \pm 10$	Cal Value = -((Total Crystal Error in ppm/1000000) x (Clocks per Minute in 32.768 kHz)/4)	RCFGCAL Value Rounded Off to the Nearest Integer
62	-52.022	-42.022	20.65	21
63	-54.872	-44.872	22.06	22
64	-57.798	-47.798	23.49	23
65	-60.8	-50.8	24.97	25
66	-63.878	-53.878	26.48	26
67	-67.032	-57.032	28.03	28
68	-70.262	-60.262	29.62	30
69	-73.568	-63.568	31.24	31
70	-76.95	-66.95	32.91	33
71	-80.408	-70.408	34.61	35
72	-83.942	-73.942	36.34	36
73	-87.552	-77.552	38.12	38
74	-91.238	-81.238	39.93	40
75	-95	-85	41.78	42
76	-98.838	-88.838	43.67	44
77	-102.752	-92.752	45.59	46
78	-106.742	-96.742	47.55	48
79	-110.808	-100.808	49.55	50
80	-114.95	-104.95	51.59	52
81	-119.168	-109.168	53.66	54
82	-123.462	-113.462	55.77	56
83	-127.832	-117.832	57.92	58
84	-132.278	-122.278	60.1	60
85	-136.8	-126.8	62.32	62

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