AN14999

RTC Timekeeping Accuracy

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Document information

Information	Content
Keywords	AN14999, RTC, crystal, accuracy, timekeeping, drift, aging, compensation, temperature, real time clock
Abstract	This document explores the various factors affecting the accuracy of a Real Time Clock (RTC), and how to mitigate each error type. It further highlights the types of RTC's that NXP offers, and introduces a new category of RTC IC with temperature compensation.

1 Introduction

A Real-Time Clock (RTC) is an electronic device that tracks current time. RTCs are commonly used in computers and servers, but find use in many different embedded applications where independent timekeeping is essential.

An essential feature that goes with reliable timekeeping is its accuracy. It is not acceptable to have a timekeeping system that drifts by several seconds or minutes every day.

This application note explores the various factors that affect the timekeeping accuracy of an RTC, and how to mitigate each of them in embedded system design.

It also shows the three categories of RTCs that NXP offers, and how each category addresses the topic of timekeeping accuracy.

2 Calculation of error in ppm

At the heart of every RTC circuit is a resonator that produces the timely oscillations to generate a stable clock – it is usually a 32,768 Hz quartz crystal.

This means that the ideal resonant frequency is 32,768 Hz.

Any deviation from this ideal value is expressed in parts per million (ppm) using the formula below.

$$\text{Error in ppm} = \frac{(\text{ActualFrequency} - 32{,}768) \times 10^6}{32{,}768} \tag{1}$$

3 Sources of error and mitigation

Most of the inaccuracies with timekeeping come from the crystal’s natural behavior. The RTC and its associated electrical circuit contribute minimally to the error. These sources of error are discussed in detail as follows.

Several environmental factors such as humidity, vibration, and pressure can influence RTC accuracy. However, the primary source of deviation as temperature changes is the inherent temperature-dependent behavior of quartz crystals. Various techniques have been developed to improve the timekeeping accuracy of RTCs that use 32.768 kHz crystals.

3.1 Crystal errors

This section provides details on crystal frequency errors, including temperature response, tolerance at 25 °C, and aging drift.

3.1.1 Crystal response to temperature

All 32,768 Hz tuning fork crystals have a parabolic response to ambient temperature. A typical (ideal) crystal response to temperature is shown in Figure 1. The response can be modeled using a temperature coefficient of -0.035 ppm/°C^2, and assuming the crystal is calibrated to 0 ppm at 25 °C.

Even for an ideal crystal, the error gets worse the more we move away from 25 °C. The Table 1 shows the crystal error at a few temperature points and how it impacts timekeeping if it goes uncorrected.

This is the largest contribution to timekeeping errors in any RTC system.

In practice, a crystal response is never **ideal**. There is a min-max limit defined for the parabolic coefficient, which must be described inside the crystal’s data sheet. So, a crystal can exhibit a slightly worse error than what is represented by the ideal curve.

Table 1. Temperature effects on crystal accuracy and timekeeping

Temperature	Crystal error (ppm)	Timekeeping drift in one day	Timekeeping drift in 30 days	Timekeeping drift in one year
-40 °C	-147	12.7 s	381 s (6.35 min)	77 min (1.28 hr)
+85 °C	-126	10.8 s	326 s (5.44 min)	66 min (1.1 hr)
+125 °C	-350	30.2 s	907 s (15.12 min)	183 min (3.06 hr)

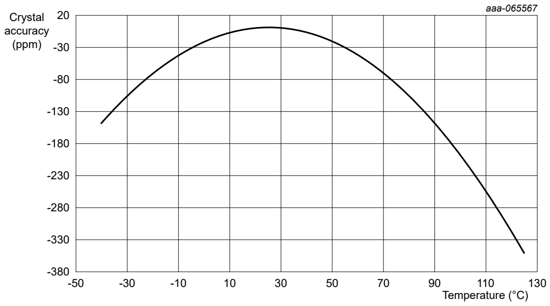

Figure 1. Typical crystal response to temperature

Mitigation:

To compensate for the crystal’s drift across temperature, the RTC must know two things:

1. The ambient temperature
2. The crystal’s exact error at that ambient temperature

RTC modules with temperature compensation make this possible by integrating a temperature sensor in the die, as well as integrating a specific crystal within the package. The crystal’s behavior is recorded and stored in the die, and the RTC records ambient temperature and applies the required compensation in real time. See Figure 2 for more details.

RTC ICs (where the crystal is connected externally) typically cannot perform such temperature compensation. There is one exception, and this is explained in Section 4.2 of this document – RTC IC with temperature compensation.

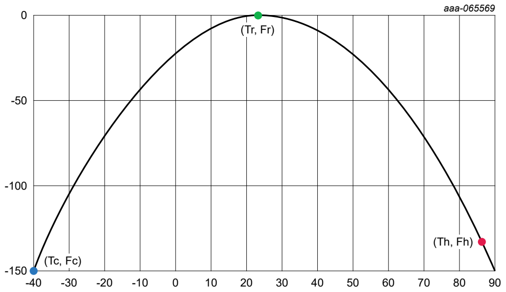

Figure 2. RTC module accuracy calibration

From Figure 2, the die temperature (TX in °C) and the uncompensated clock accuracy (Fx in ppm) are measured in at least three temperatures: (Tc, Fc), (Tr, Fr), (Th, Fh).

A polynomial equation is calculated based on the measured data:

$$y = A \times x^2 + B \times x + C \tag{2}$$

Where y is the accuracy and x is the temperature.

The polynomial coefficients (A, B, C) are programmed into the RTC’s OTP memory during production.

3.1.2 Crystal tolerance at 25 °C

A tuning-fork crystal is typically cut so that its frequency-versus-temperature characteristic follows a parabolic curve centered at approximately 25 °C. As a result, a tuning-fork crystal oscillator operates very close to its nominal frequency at room temperature, but its frequency drifts lower as the temperature increases or decreases from this midpoint.

In the Section 3.1.1 describing the ideal crystal response, it was assumed that the crystal was perfectly calibrated to 0 ppm at 25 °C. In reality, this is rarely the case. Every crystal has a frequency tolerance often in the range of ±20 ppm at 25 °C (based on commercial 32.768 kHz crystals).

This tolerance can be understood as a fixed offset applied to the ideal parabolic frequency-temperature curve. For example:

- If a crystal has a +20 ppm tolerance, its entire frequency-vs-temperature curve shifts upward by 20 ppm.
- If a crystal has a -50 ppm tolerance, its entire curve shifts downward by 50 ppm.

In other words, the tolerance does not change the *shape* of the temperature response; it simply adds a constant offset to the ideal parabolic curve. This offset directly impacts timekeeping accuracy, especially when combined with temperature-dependent drift.

Mitigation:

RTCs typically contain an aging offset register that allows for a fixed compensation to be applied to the internal clock driving the time counters.

This fixed compensation can be viewed as a dc offset applied on the crystal temperature response (Figure 2), and consequently can be used to correct the crystal tolerance at 25 °C.

3.1.3 Crystal aging drift

Similar to the Section 3.1.2, quartz crystal has an aging specification described inside the crystal's data sheet. It refers to the frequency drift experienced by the crystal after continuous operation for at least one year.

Similar to the tolerance specification, aging is also specified at 25 °C. However, unlike the tolerance specification, the value cannot be directly translated as a fixed offset across the temperature range. Aging drift can be different at different temperatures.

The absolute value of this aging drift is small compared to the other two crystal errors.

Mitigation:

The aging offset register can also be used to counteract any additional errors caused by aging drift.

3.2 RTC and circuit errors

This section provides details on RTC and circuit errors arising from load capacitance and supply voltage variations.

3.2.1 Load Capacitance (C_L)

Quartz crystals are always specified with a load capacitance (C_L). The same crystal is often available in different C_L flavors (typically from 6 pF to 12.5 pF).

C_L is a measure of the ideal load that the crystal should see to resonate at the typical 32,768 Hz frequency. In other words, if the load capacitance of the circuit matches the C_L spec of the crystal exactly, it oscillates at 32,768 Hz.

If the theC$_L$ of the circuit is higher than the C$_L$ spec of the crystal, the crystal oscillates slower than expected (negative ppm). If the C$_L$ of the circuit is lower than the C$_L$ spec of the crystal, it oscillates faster than expected (positive ppm).

Figure 3 shows this effect. For example, if the crystal C$_L$ is 12.5 pF, but only a 7 pF circuit load is presented to this crystal, it leads to a ~+60 ppm error.

Total C$_L$ of the circuit includes capacitance of the RTC pins, parasitic caps from the Printed-Circuit Board (PCB), package, and internal silicon.

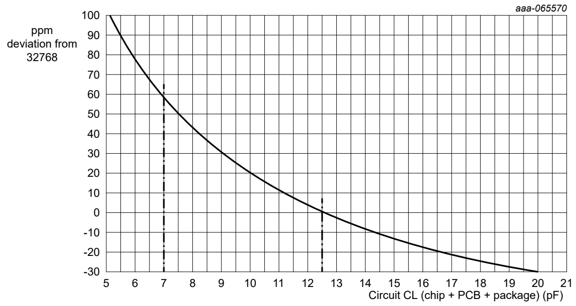

Figure 3. Load capacitance spec vs frequency dependency example

Mitigation:

The best way to mitigate this error is to ensure the total load presented to the crystal terminals is as close to its C$_L$ spec as possible.

Some RTCs integrate the load capacitance, and it can have a 10 % part to part variation. In such cases, the aging offset register can be used to compensate for this error digitally.

3.2.2 RTC supply voltage

Changes in the RTCs supply voltage directly impact the internal oscillator performance, therefore slightly affecting the oscillation frequency. This error is small (~1 ppm/V), as shown in Table 2.

This error can only be considered if the RTCs supply voltage changes over time (for example, when using a supercapacitor as a backup battery). Even then, it can be ignored in comparison to all the other errors discussed above.

Table 2. Load capacitance (C$_L$) specification

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$\Delta f/\Delta V$	Frequency variation with voltage	On pin CLKOUT	-	±1		ppm/V

4 NXP RTC offerings

Any RTC system consists of two components:

1. An electro-mechanical resonator (like quartz crystal) that provides the oscillations at a resonant frequency (32,768 Hz).
2. An IC with two main blocks: The analog oscillator circuit, which drives the resonator, and digital circuitry that counts the date/time and provides additional features like alarm, timer, etc.

NXP's RTC portfolio can be broadly divided into three categories. Each of these RTC types offers different ways of dealing with all the error sources discussed in the Section 3.2.

4.1 RTC IC

An RTC IC is an IC that provides the oscillator and timekeeping circuit within. It must be connected to a compatible quartz crystal externally on the PCB.

If the RTC IC has an aging offset register, most of the smaller error sources can be corrected.

But the large error source (crystal temperature coefficient) cannot be corrected in an RTC IC.

Some popular RTC ICs from NXP are PCF85053A, PCA85073A, PCF85263A, PCF85363A.

4.2 RTC IC with temperature compensation

It is a new category of RTC. NXP has introduced the first RTCs of this kind – PCF8525 and PCA8525 **(available only with the HVSON10 package option)**.

These are essentially RTC ICs with the addition of the temperature compensation engine. Temperature compensation is typically done in RTC modules where the crystal data is unique. In RTC ICs, the crystal is external and its exact behavior is not known. So, these RTC ICs compensate for a typical crystal temperature coefficient (-0.035 ppm/°C^2). Doing so accounts for the major part of the error, and dramatically improves RTC timekeeping accuracy compared to regular RTC ICs.

4.3 RTC Module with temperature compensation

RTC modules with temperature compensation are the most accurate and complete RTC solutions available. They integrate both parts of the RTC system inside the same package: crystal and die.

Since the RTC is manufactured with the exact crystal, the crystal behavior can be known to a high accuracy. This means RTC modules are able to offer the highest level of accuracy compared to any other category of RTC.

The popular RTC modules from NXP are PCF2131 and PCA2131.

5 Revision history

Table 3 summarizes the revisions to this document.

Table 3. Revision history

Document ID	Release date	Description
AN14999 v.1.0	19 May 2026	Initial public release

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