AMX8X5 Family Autocalibration

1. Introduction

The Ambiq AMX8X5 includes the capability of using the internal RC Oscillator for all timing functions. For increased accuracy at a small power penalty, the RC Oscillator may be periodically calibrated to the external Crystal (XT) Oscillator which is turned on only during this calibration. The overall process is referred to as Autocalibration and under most conditions produces a clock with long term accuracy essentially indistinguishable from the XT Oscillator alone, as shown in the RC/Acal bubble in Figure 1. This document describes the procedures for configuring Autocalibration and presents analyses of the expected clock accuracy and power dissipation.

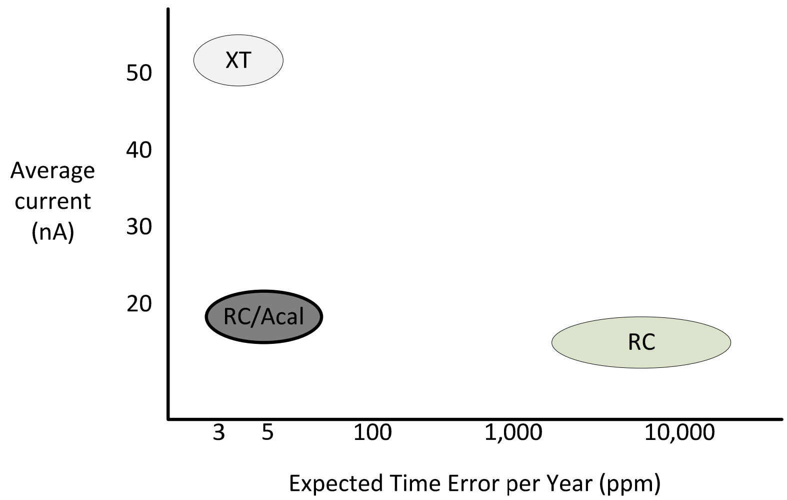

Figure 1 – Basic Mode Comparison

2. Basic Autocalibration Operation

The AMX8X5 includes a very powerful, patented automatic calibration feature that allows the RC Oscillator to be automatically calibrated to the XT Oscillator. The XT Oscillator typically has much better stability than the RC Oscillator, but the RC Oscillator requires significantly less power. Autocalibration enables some system configurations to achieve accuracy and stability similar to that of the XT Oscillator while drawing current similar to that of the RC Oscillator. Autocalibration functions in two primary modes: XT Autocalibration Mode and RC Autocalibration Mode.

2.1 Autocalibration Operation

The Autocalibration operation counts the number of calibrated XT clock cycles within a specific period as defined by the RC Oscillator and loads new values into the Calibration RC Upper and RC Lower registers which will then adjust the RC Oscillator output to match the XT frequency. In most cases Autocalibration is configured by the host controller over the serial interface when the AMX8X5 is initialized.

2.2 Autocalibration Frequency and Control

The Autocalibration function is controlled by the ACAL field in the Oscillator Control register as shown in Table 1. If ACAL is 00, no Autocalibration occurs. If ACAL is 10 or 11, Autocalibration occurs every 1024 or 512 seconds. In RC Autocalibration Mode, an Autocalibration operation results in the XT Oscillator being enabled for roughly 32 seconds. The 512 second Autocalibration cycles have the XT Oscillator enabled approximately 6% of the time, while 1024 second Autocalibration cycles have the XT Oscillator enabled approximately 3% of the time.

Table 1 – Autocalibration Modes

ACAL Value	Calibration Mode
00	No Autocalibration
01	RESERVED
10	Autocalibrate every 1024 seconds (~17 minutes)
11	Autocalibrate every 512 seconds (~9 minutes)

If ACAL is 00 and is then written with a different value, an Autocalibration cycle is immediately executed. This allows Autocalibration to be completely controlled by software. As an example, software could choose to execute an Autocalibration cycle every 2 hours by keeping ACAL at 00, getting a two hour interrupt using the alarm function, generating an Autocalibration cycle by writing ACAL to 10 or 11, and then returning ACAL to 00.

2.3 XT Autocalibration Mode

XT Autocalibration Mode is used when the XT Oscillator is normally active, but the system is configured to switch to the RC Oscillator on a failure or a switchover to battery power. XT Autocalibration continually calibrates the RC Oscillator to the XT Oscillator so that the RC Oscillator is accurate whenever a switch occurs. To configure XT Autocalibration Mode, the OSEL register bit is set to 0 and ACAL is set to 10 or 11. The AMX8X5 has the ability to automatically switch over to the VBAT supply whenever the VCC supply voltage drops out or is too low. To enable automatic switchover of the oscillators, the AOS bit is set. When the VCC voltage drops out or is too low, the system will switch to using VBAT, the clocks will begin using the RC Oscillator, autocalibration will be disabled and the XT Oscillator will be disabled to reduce power requirements. Because the RC Oscillator has been continuously calibrated to the XT Oscillator, it will be very accurate when the switch occurs. When VCC is again above the threshold, the system will switch back to use the XT Oscillator and restart autocalibration. It is possible to gain or lose up to one second during a switchover between the oscillators.

2.4 RC Autocalibration Mode

RC Autocalibration Mode is used when the RC Oscillator is always used as the clock but it is desired to maintain the frequency of the RC Oscillator as close to the XT Oscillator as possible. To configure RC Autocalibration Mode, the OSEL register bit is set to 1 and ACAL is set to 10 or 11. Periodically the XT Oscillator is turned on and the RC Oscillator is calibrated to the XT Oscillator. This allows the system to operate most of the time with the XT Oscillator off but maintain high accuracy for the RC Oscillator.

3. Accuracy Errors in RC Autocalibration Mode

RC Autocalibration Mode is typically the most useful mode, because it allows a dramatic reduction in the power used by the AMX8X5 while maintaining the accuracy of the internal clock. The RC is always used as the internal clock so that no time errors occur as can be seen with XT Autocalibration Mode and automatic switchover. RC Autocalibration Mode is the only applicable mode in systems where there is only a single battery supply, which is very common. Because the RC Oscillator is fundamentally less stable with temperature than the XT Oscillator, many applications cannot use the RC Oscillator alone as the timing clock. RC Autocalibration improves the accuracy of the RC Oscillator by continuously adjusting it to match the XT Oscillator.

Autocalibration maintains the RC Oscillator at a frequency very close to the XT Oscillator, but there are obviously small errors which can occur on each cycle. However, as temperature and the raw RC Oscillator frequency vary, errors typically cancel each other out and produce very low accumulated error. Figure 2 shows a time sequence with varying frequency. The heavy shaded line shows the variation of the raw RC Oscillator, and the vertical dashed lines indicate the boundaries of Autocalibration Periods (ACPs, either 512 or 1024 seconds). The RC Oscillator is calibrated within a small number of PPM at the beginning of each ACP to the XT Oscillator, so the calibrated RC frequency is the sawtooth function in the center of the figure, with the accumulated error in each ACP shown by the shaded triangles.

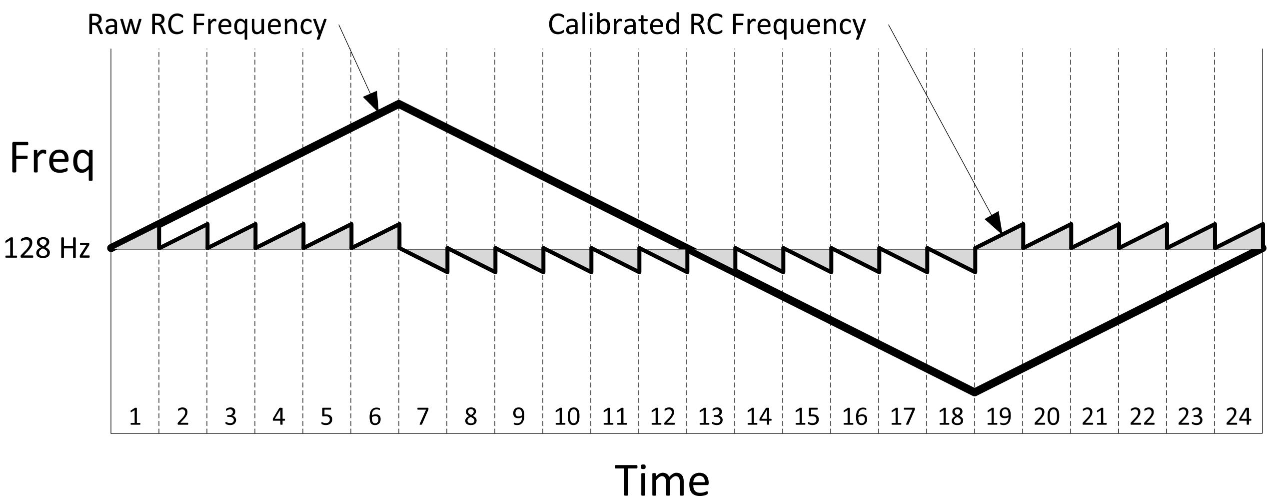

Figure 2 – Autocalibration Error Cancellation

Although some error is accumulated in each ACP, it can be seen that the positive errors which occur when the frequency is rising are cancelled by the negative errors when the frequency is falling. Over any significant period of time, the net accumulated error is almost completely determined by the frequency difference between the beginning and end of the period and the rate of change of the frequency with time.

Since the frequencies of both the RC and the XT Oscillators are functions of temperature, and temperature changes are easy to understand and quantify, accumulated error is measured as a function of the temperature profile. The behavior of RC Autocalibration has been modeled by varying the temperature in a random way and simulating the desired period, which in the cases below is one year. The temperature rises or falls at a random rate between twice the average rate specified and the negative of that value, and is limited to the specified maximum and minimum temperatures. One thousand simulations were executed, and the specified error is the worst case result of all iterations. Figure 3 shows the maximum accumulated time error relative to the XT Oscillator as a function of the maximum temperature range and the average temperature change rate over a one year period, in ppm (1 ppm = 31 seconds in a year), with an Autocalibration Period of 512 seconds. Note that even the lowest average change rate of 0.025 equates to one degree C every 40 minutes, which is still quite fast when averaged over an entire year. At this change rate, the error over the full temperature range is less than 3 ppm.

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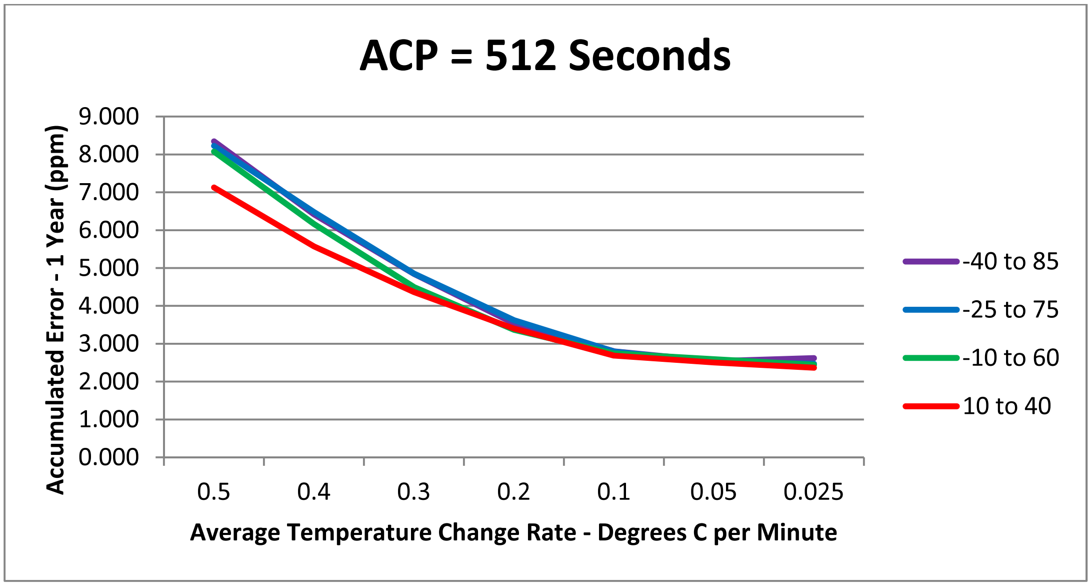

Figure 3 – Autocalibration Error, ACP = 512 Seconds

Figure 4 shows the results when the ACP is 1024 seconds. At high temperature change rates, this setting produces roughly 3 times the error of the 512 second case, but the errors for low change rates are still negligible.

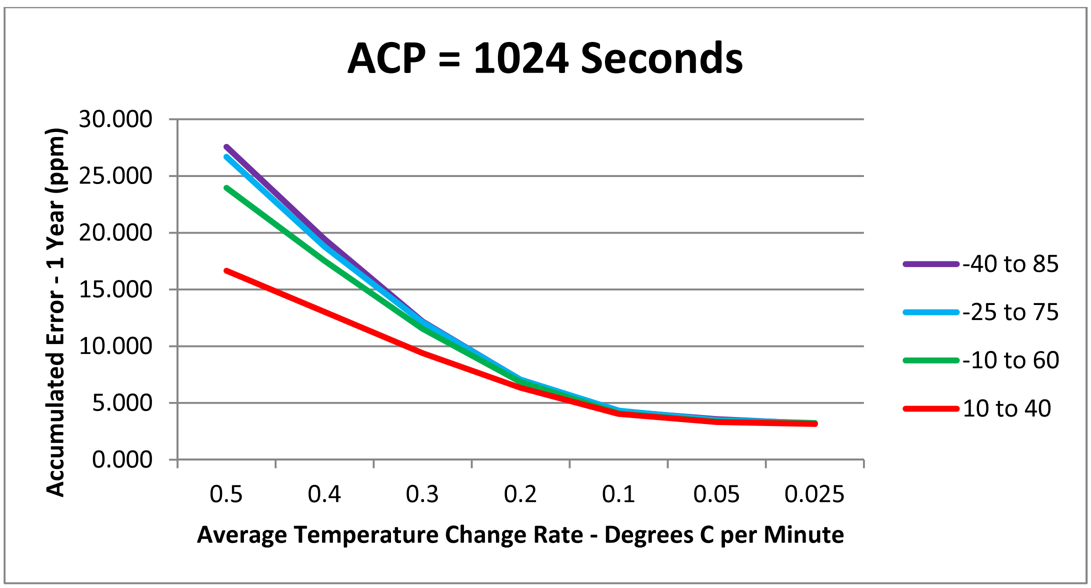

Figure 4 – Autocalibration Error, ACP = 1024 Seconds

The deviations in both of the cases above for relatively low temperature change rates are less than the error introduced by the XT Oscillator itself. The frequency error due to ambient temperature changes for a typical 32.768 kHz tuning fork crystal is shown in Figure 5 below.

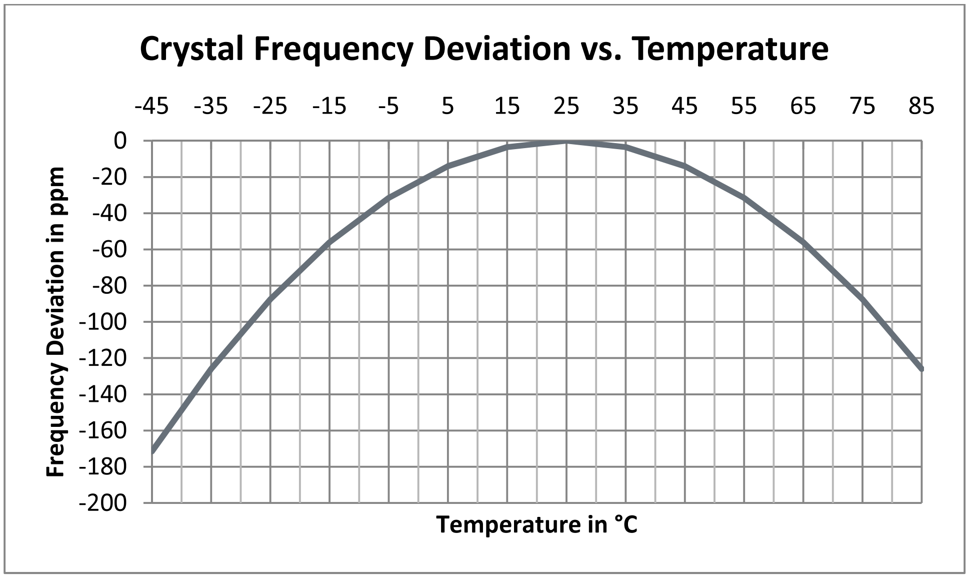

Figure 5 – Typical Tuning Fork Crystal Frequency Deviation

Figure 6 shows the raw XT error, which is more strongly a function of the maximum temperature range than the calibrated RC error. The XT error is a similar function of the temperature change rate but is more influenced by the maximum temperature variation. Errors in the XT Oscillator are larger when the temperature is further away from the nominal 25˚C, and therefore it is expected that the accumulated error will be greater if the temperature range is larger.

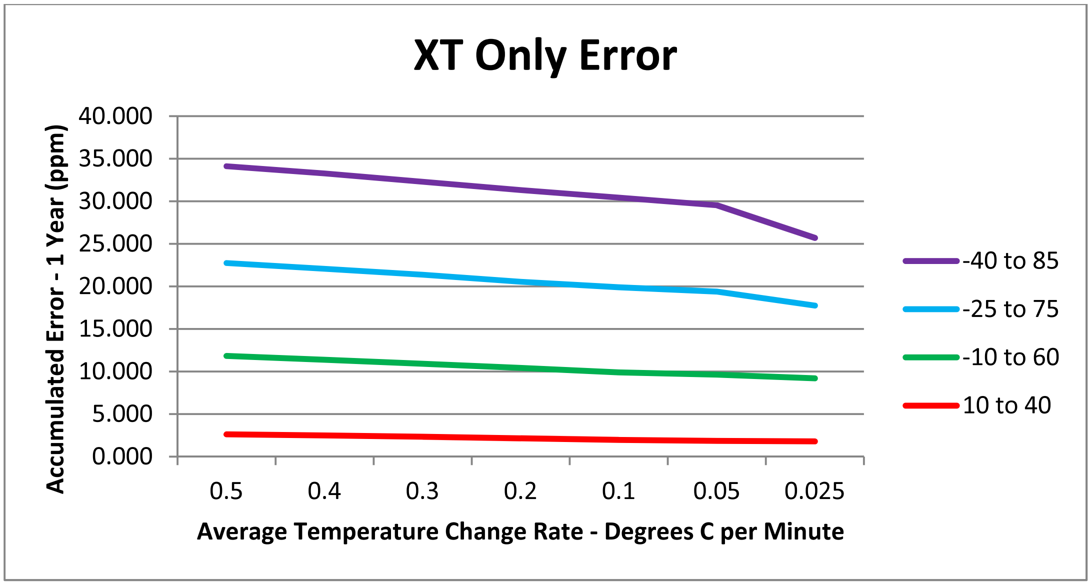

Figure 6 – Raw Error, XT Oscillator

4. A Real World Example

Even if the temperature occasionally reaches the extremes of the allowable range and changes relatively quickly, in most real applications the temperature is reasonably stable. A proposed “real world” temperature profile assumes that for 30 days per year the temperature has a maximum range of -25 to 75˚C and an average change rate of 1 degree C every 5 minutes. For the remainder of the year, the maximum temperature range is 10 to 40˚C with a maximum change rate of 1 degree C every 40 minutes. Using this profile, the accumulated errors over the year (including the XT error in the calibrated RC cases) are shown in Table 2. As can be seen, with an ACP of 512 the clock accuracy using Autocalibration is quite close to the error achieved by the XT alone. Extending to an ACP of 1024 adds a small incremental error.

Table 2 – Real World Accumulated Errors

	Accumulated Error (ppm)
XT Only	3.3
Cal RC, ACP = 512	6.1
Cal RC, ACP = 1024	8.4

5. Power Analysis

The power comparisons between the various cases are quite straightforward. During an Autocalibration, the XT Oscillator is powered up for 50 seconds. Therefore if the AMX8X5 draws 55 nA when the XT Oscillator is running and 14 nA when the XT Oscillator is off, the average current for each ACP case is shown in Table 3. Even the shortest ACP results in a savings of more than 60% of the current.

Table 3 – Autocalibration Current

	Average Current (nA)
XT Only	55
Cal RC, ACP = 512	19
Cal RC, ACP = 1024	17

6. Disadvantages Relative to the XT Oscillator

6.1 Maximum Output Clock Frequency

The primary disadvantage of using the autocalibrated RC Oscillator is that the highest output clock frequency which can be generated is 128 Hz (i.e., the frequency of the RC Oscillator). In applications where a higher frequency clock is required, the XT Oscillator must be used. If such a clock is required only occasionally, the AMX8X5 may be temporarily placed in XT Mode by setting the OSEL bit to 0, and then returned to RC Mode by setting OSEL back to 1 when the high frequency clock is no longer required. The AMX8X5 will continue to autocalibrate the RC Oscillator while the XT Oscillator is selected, but the calendar counters may gain or lose up to 1 second on each of the oscillator switchovers.

6.2 Large/Rapid Temperature Fluctuations

The XT Oscillator may also be preferable to Autocalibration when there are frequent, rapid and large temperature changes. In such a situation, the XT Oscillator may provide a measurable improvement in accuracy, although at a significant power penalty relative to using Autocalibration.

6.3 Short Term Jitter

A third disadvantage of using the RC Oscillator is that it displays higher internal jitter relative to the XT oscillator. This jitter is caused by pulse addition or subtraction of the Autocalibration process as well as the inherent thermal noise jitter of the RC Oscillator itself. This jitter may introduce significant frequency errors over short time periods. In both cases the mean of the jitter is zero, and Table 4 shows the standard deviation of the clock period for several short time periods including both jitter and temperature effects. A typical worst case metric is 4 standard deviations, which covers approximately 99.99% of all cases.

Table 4 – Short Term Standard Deviation

Time Interval	Std. Dev. (PPM)	Std. Dev. (ms)
0.5 hours	90.9	164.8
1 hour	45.5	163.7
2 hours	32.3	231.8
4 hours	22.5	324.8
1 day	9.3	801.1
2 days	6.5	1114.2
3 days	5.3	1383.7
1 week	3.5	2139.4

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Document Revision History

Rev #	Description
0.01	Initial version
0.02	Add short term jitter analysis
0.03	Added tuning fork crystal frequency deviation curve. Changed document part number.

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