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Miniature Atomic Clock Holdover

White Paper

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Microsemi
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Abstract

This paper is intended to describe the time error performance of Microsemi's Miniature Atomic Clock (MAC) product line. It defines "holdover" and reviews a time error model used for prediction purposes. It contains information on MAC performance in a steady state and for aggressive temperature oscillations. It also provides design recommendations for more sophisticated timing solutions.

Background

Rubidium oscillators are used as primary and secondary frequency standards due to their excellent tilt/vibration, stability and re-trace performance. The MAC leverages the advantages of Rubidium into a low-power package small enough (2 x 2 x 0.7 inch) for a wide variety of applications. Evaluation of "time error" is necessary for a multitude of applications, and is relevant for designers of timing solutions.

Time Error during Holdover

Consider a local clock disciplined to some superior reference clock (GPS, for example). While disciplined, the local clock is continuously compared to its reference and steered to eliminate any phase or frequency difference. "Holdover" is what happens to the local clock when it is no longer disciplined. Some applications need to know the amount of frequency drift that occurs during holdover, referred to as "Allan deviation" over the short term and as "aging rate" over the long term. Other applications need to quantify the amount of phase drift that occurs during holdover, known as "time error". Said another way, time error denotes how far the rising edge of the clock pulse would drift when the clock is no longer disciplined to its reference.

In the below graphical representation (Figure 1), it is assumed that there is a local clock and a reference clock. At time t_h, communication between the two clocks is lost, and holdover begins. Time error, Δt, is measured as a function of the elapsed time.

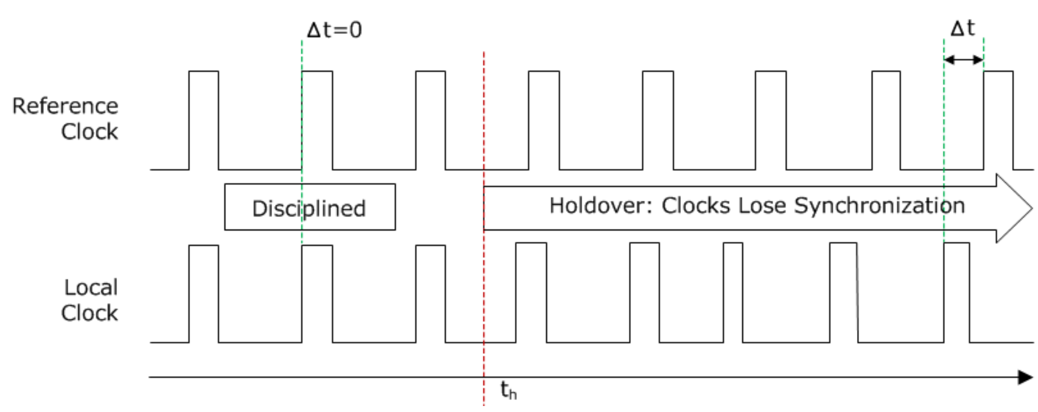

Figure 1 **• Local Clock Disciplined to a Superior Reference Clock**

Time Error Model

Time error is modeled mathematically in the following equation, and referenced in literature [1] and [2]. Understanding this model helps designers interpret the measured data.

$$E(t) = E_0 + \int_0^t y(t)dt + \varepsilon(t)$$

$$E(t) = E_0 + \left(y_0 t + \frac{1}{2}at^2\right) + \int_0^t y_e(t)dt + \tau\sigma(\tau)$$

EQ 1

where

E(t): Time error accumulation at time "t" after initial synchronization

E_0: Initial time error at t = 0

y(t): Fractional frequency of the clock at time t, approximated as

$y(t) = y_0 + at + y_e(t)$

y_0: Fractional frequency offset at t = 0

a: Clock aging rate

$y_e(t)$: Fractional frequency offset due to environmental effects (i.e., temperature)

$\varepsilon(t)$: Random fractional frequency fluctuations

$\varepsilon(t) = \tau\sigma(\tau)$

$\sigma(\tau)$: Allan deviation at sampling rate (τ)

For applications where holdover is important, it is likely that the clock has been disciplined and synchronized to a superior timing reference such as GPS. In this case, we assume that initial phase and frequency offset from the reference is zero ($E_0 = y_0 = 0$). This zero offset can be observed in the measured results shown later in this white paper.

Fixed Temperature Performance

Per EQ 1, short term stability (ADEV) of the clock comes in to play for short durations. For holdovers that last longer than a few days, aging becomes the dominant factor.

The following figure shows a plot of MAC SA35m measured at room-ambient conditions. It shows a maximum time error of 0.21 µs over three days of measurement. A lower performance, grade SA31m clock and an OCXO are overlaid as a reference.

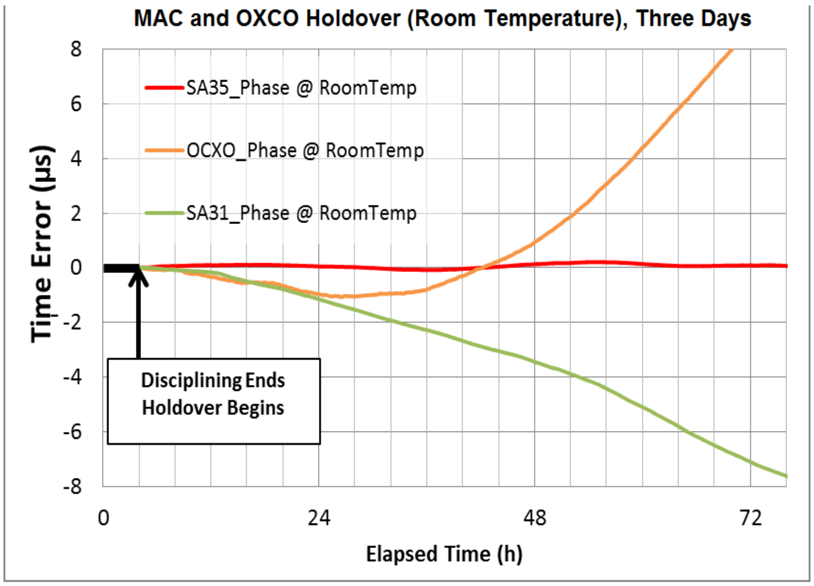

***Figure 2* • MAC and OCXO Holdover (Room Temperature), Three Days**

Note: For this plot, the typical laboratory temperature was 25°C ± 5°C.

Variable Temperature Performance

For applications where temperature is expected to vary significantly, the "tempco" of a clock is critical. This term quantifies the frequency drift of a clock over a specific temperature range, and is represented by the integral in EQ 1. The following figure shows the performance of three SA35m clocks when in holdover mode (starting at t = 4 h).

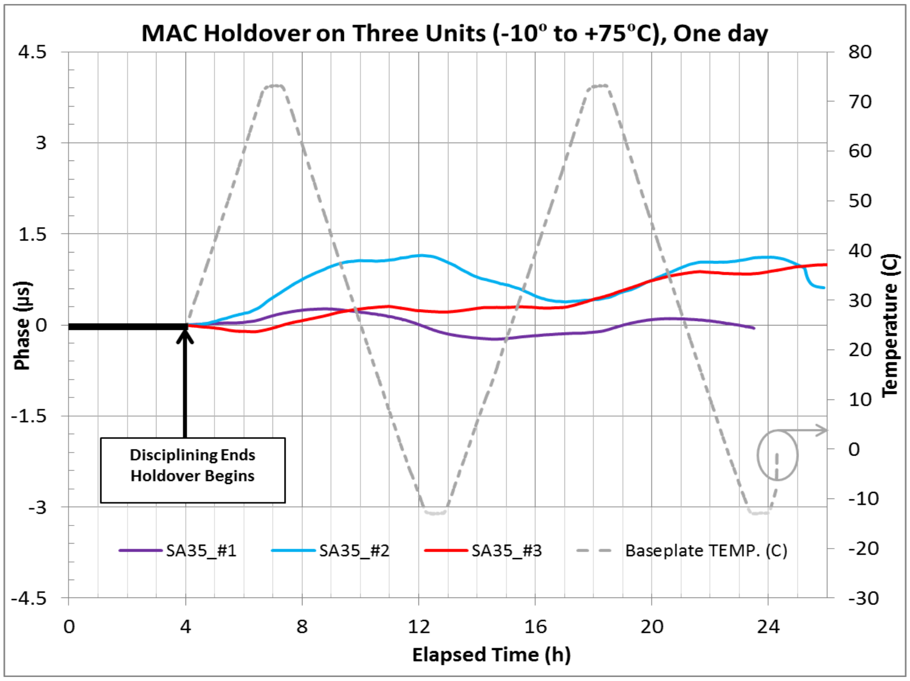

Figure 3 **• Holdover Performance when Temperature is Varied**

The temperature profile selected for this experiment had the following settings:

- Clocks disciplined at a temperature of 25°C before holdover initiation
- Ramp rate ~ 0.3°C per minute
- 40-minute dwell periods at the temperature extremes
- Baseplate temperature swing of -10 to +75°C

Under these conditions, the clocks had a peak-to-peak tempco of 1E-10 and a max time error < 1.15 µs. One of the units had an impressive time error of < 270 ns.

The median performer (SA35 #3) was selected to run over the same temperature profile, with an increased holdover duration of three days. The SA35m yielded 1 µs of time error after 24 hours in holdover mode. Overall, it averaged 1.27 µs of drift per day.

The following figure shows a typical OCXO overlaid upon the MAC phase drift for reference. The OCXO displayed a time error of 27 µs, showing a clear correlation between temperature and time error.

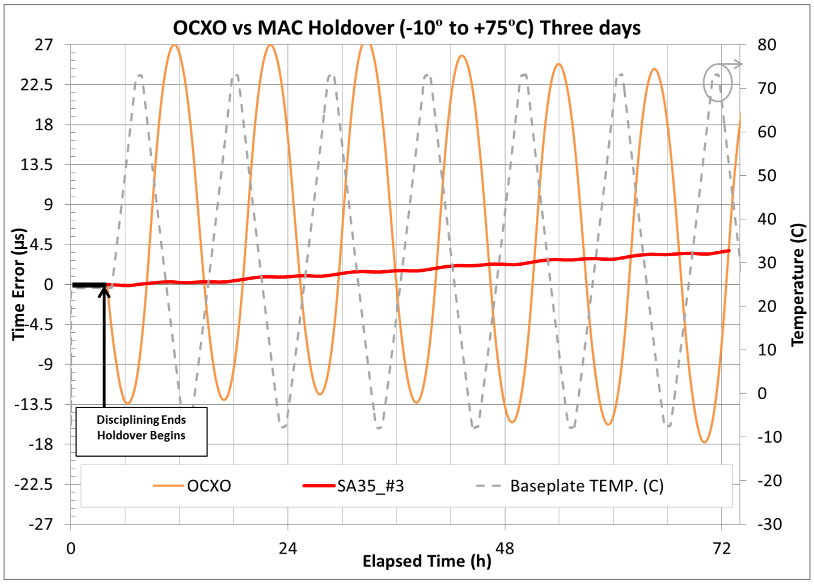

***Figure 4* • MAC and OCXO Time Error during Three Days of Holdover**

Large-batch Testing

At Microsemi, we have the means to test a larger sample size of MACs, albeit at the cost of less-than-ideal measurement conditions. In the large batch test environment, the chamber temperature as well as the internal MAC temperature is measured, as opposed to our original test where a thermocouple was fixed to the baseplate of each MAC. Also, the measurement resolution used in large-batch testing leads to noisier data, as seen in the sample chart shown below. These factors contribute negatively to the perceived performance.

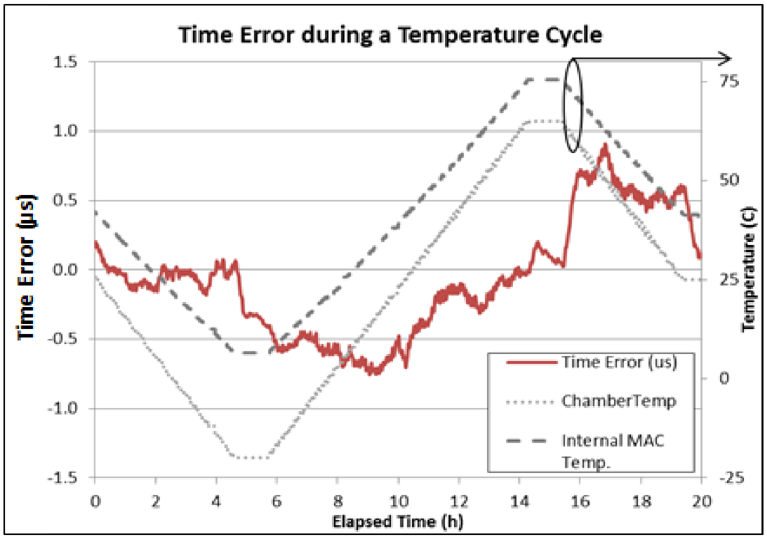

Figure 5 **• Sample of Large-batch Measurement Test on One Unit**

Even with non-ideal measurement conditions, we can draw some meaningful inferences based on the performance as a population. We looked at twenty samples of each performance-grade MAC out of a total of 2360 measurement samples (~ 3.5% of the population). With the temperature profile used in Figure 5, we could bin the time error measured during holdover as follows.

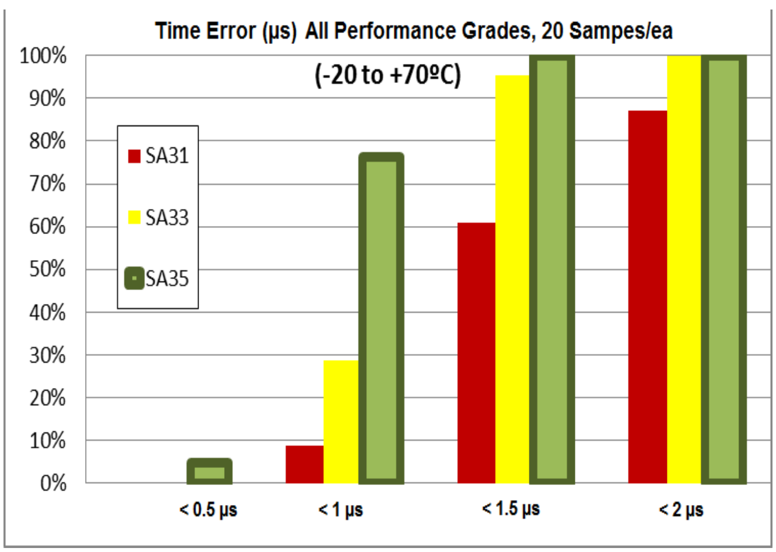

Figure 6 **• Percentage of Units with Time Error < 0.5, 1, 1.5 and 2 µs**

From this sample of units, it was observed that > 70% of SA35 MACs achieved < 1 µs of time error with the temperature profile used for large-batch testing. 89% of all MAC units exhibited < 1.5 µs of time error with this temperature profile.

Design Considerations

Due to the quadratic term "at^2" in EQ 1, an accumulating phase drift is noticed for the MAC, as shown in Figure 4. Designers of more sophisticated disciplined oscillators can leverage this equation by inserting an initial frequency offset "y_0" to compensate for the aging rate. Up to now, we had assumed $y_0 = 0$, zero frequency offset. If a certain amount of initial frequency offset is acceptable to the designer, they can achieve superior holdover performance out of their MAC.

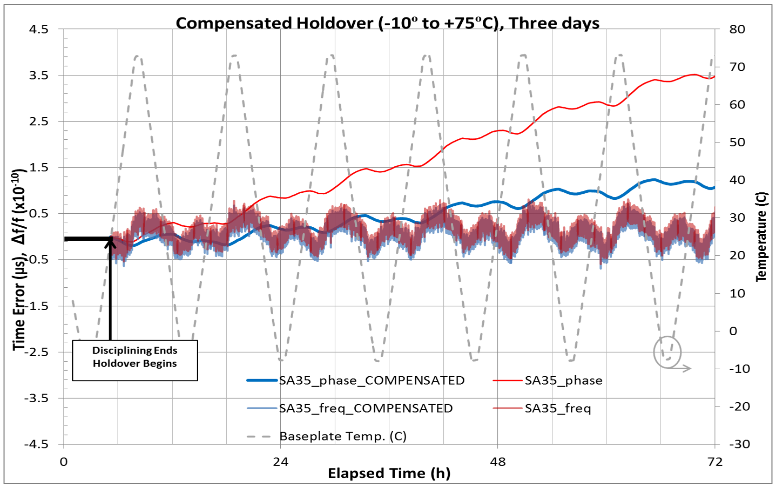

Figure 7 **• MAC Compensated for Aging Drift (Blue Trace)**

For instance, the above graph shows that an initial offset of y_0 = -1E-11 was added as a correction to the SA35m local clock at the beginning of holdover mode. The compensated clock (blue trace) enabled < 1.5 µs of total time error after three days of operation compared to 3.5 µs for the uncompensated clock (red trace).

Conclusion

In view of the quadratic effect of aging rate on time error, it is important to select clocks with good aging specifications. MAC units have shown very good holdover performance at room ambient conditions.

What really separates MAC from conventional OCXOs is its performance over aggressive temperature profiles. We noted a time error of < 1.15 µs after 20 hours of holdover and an average time error of 1.27 µs per day at the end of a three-day holdover. From the large-batch measurements, we observed that over 70% of SA35 MACs achieved < 1 µs of time error during a 20-hour holdover under a broad temperature profile.

References

1. John R. Vig, "Quartz Crystal Resonators and Oscillator for Frequency Control and Timing Applicatons, A Tutorial", FCS, 1996.
2. D.B.Sullivan, "Characterization of Clocks and Oscillators", NIST Technical Note 1337, 1990.

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