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THE EFFECT OF TEMPERATURE VARIATION ON THE PERFORMANCE PARAMETERS OF MINIATURE ATOMIC CLOCKS WITH SIMILAR FREQUENCY STABILITY SPECIFICATION

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Abstract. The primary source of error that causes an increase in inaccuracy in determining the location of individual users in a communication network is the lack of synchronization of their time bases. Time synchronisation of the aeronautical communication network should be ensured to the greatest extent possible. Increasing the level of synchronisation would be possible by using a selected type of atomic clocks, which would be placed in the on-board equipment of UAV assets. The paper describes the possibilities of implementing available types of atomic clocks in the instrumentation of different categories of UAV assets. This paper compares the performance of miniature CSAC cesium atomic clocks with a high-performance OCXO quartz oscillator with similar frequency stability specifications and the effect of temperature on their performance parameters. The next section analyses how time, temperature, and initial frequency errors can affect the resulting frequency stability error of each oscillator

Keywords: UAV, CSAC, Stability

1. INTRODUCTION

Until recently, the use of atomic clocks was limited by their size and high cost. Nowadays, due to technological development, it is possible to use different variants of these devices according to the required parameters. From the point of view of the problem addressed, caesium, rubidium or quartz oscillators appear to be the most suitable ones, which meet the complex requirements of high reliability for frequency references in the aerospace, defence and aerospace markets. Their small size, low power consumption, fast heating capability, excellent stability, and spectral purity make these devices ideal for critical aerospace applications in harsh environments, whether in air, on the ground, or in space [4-5].

Depending on the chosen category of UAV vehicle, it would be possible to equip its technology base with a device capable of achieving short-term frequency stability values in the range of $<7.0E^{-12}$ - $1.0E^{-11}$ τ=100-1000 s and long-term frequency stability values in the range of $<5.0E^{-11}$ - $9.0E^{-10}$ (1 month) [6-7]. By implementing these available solutions, it would be possible to abstract from most of the errors that cause inaccuracies in the position measurements between users in the network. In the following section, the basic metrics related to the performance parameters of each oscillator are defined.

2. MONITORED PARAMETERS IN DETERMINING ATOMIC CLOCK PERFORMANCE.

It is important to understand the overall frequency stability of a Quartz (or other type) oscillator if the right oscillator is going to be selected for a specific application. Often specific questions referring to an oscillator's short term stability can be asked, mainly for one of two reasons: Firstly short term stabilities tend to point to effects and influences on oscillator performance that are hard to monitor and predict. Long term effects like an overall offset, aging or change under a steady temperature ramp can be monitored and corrected for. Some of the changes that are much harder to spot coming (e.g. a fan in the system switches on) happen in the short term [7].

The second reason has to do with over what time-scales you want to be able to be sure of an oscillator’s stability. For example if an oscillator is operating closed loop (e.g. it is in a phase locked loop and is ‘locked’ to another more stable reference) then longer term changes to the oscillator will be ‘tracked out’ by the loop response and will not have as much effect on the output signal as the reference will dominate. However shorter term changes to the oscillator will make it through the loop and show up at the output [7-8]. These are just two of the areas where discussions on oscillator short term stability are likely to focus To understand more about short term stability it is useful to look at frequency stability in general and to look at the different types of frequency stability that you might need to account for.

2.1 Definition of frequency stability

Stability refers to how well something can be re-produced. It does not say anything about how ‘right’ or ‘wrong’ the something is, just how consistent it is. So an oscillator with a large initial frequency offset from nominal can be just as stable as an oscillator that has no initial offset – the frequency stability will be determined by how the frequency offset (if any) changes. Frequency stability in general then points to how the frequency of an oscillator changes. Looking at an oscillator datasheet there is often a section that lists frequency stabilities (plural), showing that there are lots of ways that the frequency might change [5-6].

There is the stability over time (aging), stability over temperature and stability over supply or load changes, for example. In each case the effect of other influences is kept to a minimum, so that the stated aging for example is measured within a minimal temperature range . In all of these examples the end result is a frequency change over time. The distinction between long term stability, short term stability and noise comes from the time scales over which these changes occur [7-8].

Long term stability is usually measured over periods of a day or more; short term stability is usually measured over periods of perhaps 0.1 second to one day. Diurnal wander (frequency changes that happen on a daily basis), systematic frequency changes due to short term temperature changes (e.g. a fan blowing on the oscillator), vibration, supply line noise and unexpected events such as frequency jumps are some examples of unpredictable events that will influence an oscillator’s short term and also long term stability.

3. ATOMIC CLOCK (CSAC) PERFORMANCE DURING RAPID TEMPERATURE CHANGE

The chip-scale atomic clock (CSAC) is the world’s lowest-power, lowest-profile atomic clock. Its unique 1PPS input eases the design process by allowing an external reference to quickly calibrate the device. Thousands of units are deployed every year in a variety of applications, from seismic sensors on the bottom of the ocean to the space CSAC aboard low-earth-orbit satellites [1-2].

For mobile applications, frequency and timing stability in variable temperature environments is critical. Choosing the best oscillator for the job can be confusing when comparing product specifications from different manufacturers, or even different product lines within the same company. The reason is that commercial oscillators are not held to any standard test, so the temperature profile (temperature range, ramp rate, and number of cycles) used can vary from product to product. Atomic clocks and oscillators are generally considered to have superior temperature stability over their crystal-based counterparts [2]. This is mainly due to the sealed (Cesium or Rubidium) gas cell’s isolation from the outside environment. There are other factors that also contribute to an atomic oscillators’ temperature resistance, as discussed later.

This paper will compare CSAC performance to that of an OCXO with a similar stability-versus-temperature specification. The paper will also discuss how time, temperature, and initial frequency errors can effect holdover timing error. For the purposes of this paper, holdover means the period of time when an oscillator is allowed to free-run. The frequency and timing error that accumulates during holdover is relative to a perfect timing reference [3].

3.1 Effects on Timing Error: Elapsed Time

With a 9 x 10^{-10}/mo Hz/Hz typical aging rate, the CSAC has pretty good frequency drift (and corresponding time error). Its performance is similar to the best performing OCXOs. Time error can be calculated from published aging rates, as shown in the References section [2]. Taking the result of their derivation, the timing error accumulation over time is given as follows:

$$E(t)=E_0+\left(y_0 t+\frac{1}{2}at^2\right)+\int_0^t E_i(t)dt+\varepsilon(t) \tag{1}$$

Where:
E(t): Time error accumulation at time 't' after initial synchronization.
a: Clock frequency drift (or aging) rate.
E0: Initial time error at t = 0.
Ei (t): Fractional frequency offset due to environmental effects (such as temperature).
y0: Initial fractional frequency at t = 0.
ε(t): Error due to random fractional frequency fluctuations.

For simplification purposes, we have assumed zero initial phase or frequency offset and zero environmental perturbation, which reduces the equation to the following:

$$E(t)=\frac{1}{2}at^2 \tag{2}$$

The following graph and table show predicted time error over 72 hours of the CSAC, high-performance OCXOs, and Rubidium atomic oscillators. CSAC will accumulate ~1 µs in 24 hours, ~5 µs in 48 hours, and 8 µs to 12 µs in 72 hours. These calculations were made based on typical observed aging rates of 0.6 ppb/mo to 0.9 ppb/mo.

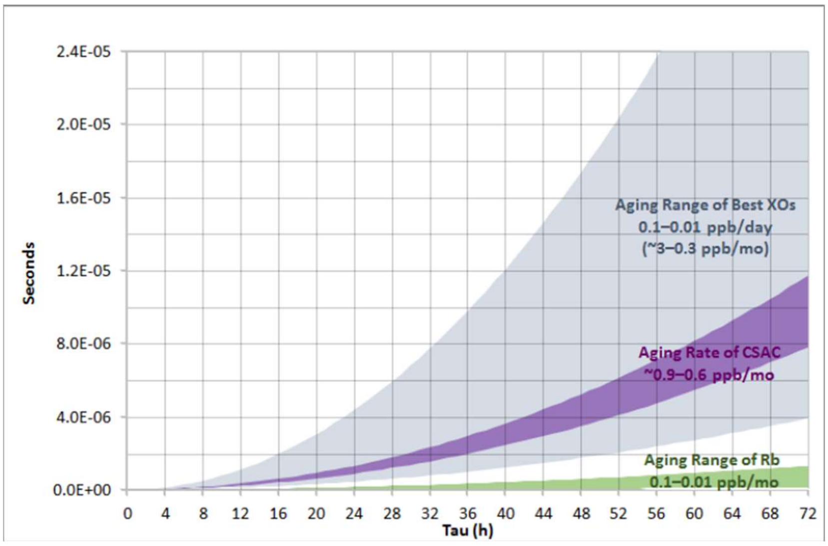

Figure 1 Time Error Derived from Aging Rates (at constant 25°C) [2].

Table 1 OSCILLATOR VS. TIME ERROR

Oscillator	24h	48h	72h
OCXO	0.3 µs to 4.5 µs	1.9 µs to 17 µs	4 µs to 28 µs
CSAC	0.5 µs to 1 µs	3.5 µs to 5 µs	8 µs to 12 µs
Rubidium	<0.2 µs	<0.5 µs	0.5 µs to 1.5 µs

4. EFFECTS ON TIMING ERROR: TEMPERATURE

The previous calculation is not practical for mobile applications where the oscillator is exposed to temperature variations. Timing error due to those effects cannot be calculated by simply looking at a data sheet temperature specification (commonly referred to as temperature coefficient). Ramp rate, dwell time, airflow, number of cycles, and other factors will all affect the outcome. The oscillator design and sample data must be considered to choose the best performer. The CSAC design, shown in Figure 2, is unique in that the physics (laser, resonance cell, and photodetector) is vacuumpackaged to eliminate convection/conduction effects, with an overall thermal resistance of 7000°C/W. Its tensioned, polyimide suspension further isolates the physics from outside vibration or thermal-induced mechanical stresses [1-3].

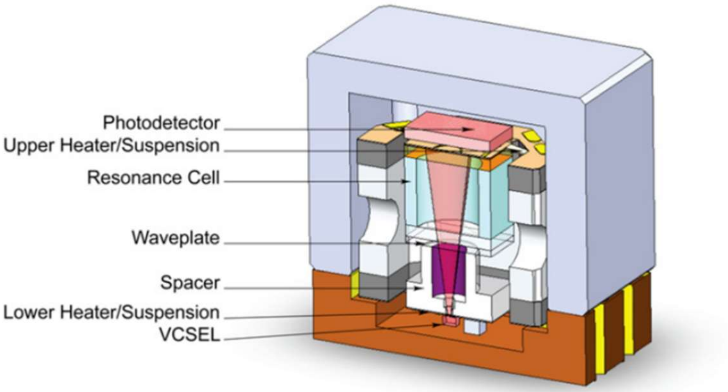

Figure 2 CSAC Physics Package [3].

Thanks to the design of the CSAC, the temperature ramp-rate of its environment has little impact on its frequency response. The following two graphs show an example of an aggressive temperature profile. The oscillators are soaked at a hot temperature (50°C) for over 1 hour before being rapidly cooled to –10°C in about 12 minutes (5°C/min). They are soaked at the cold temperature for 2 hours before they are rapidly returned to the hot temperature [2-3].

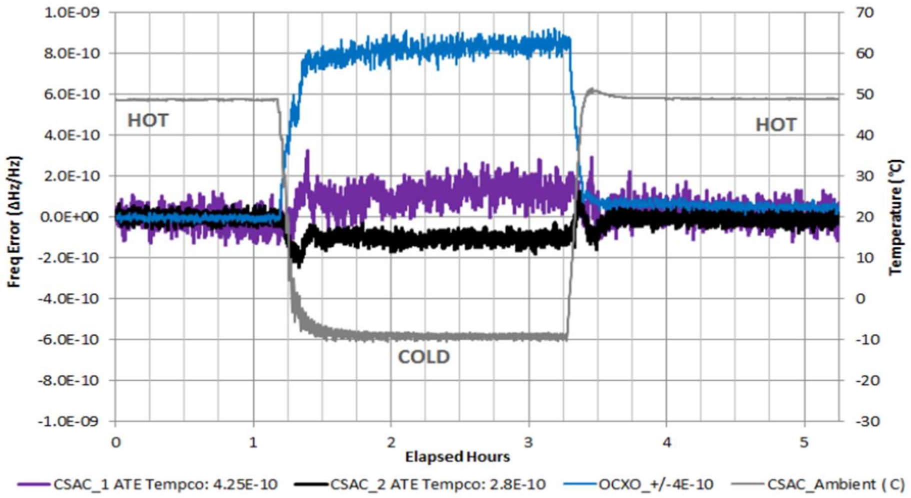

Figure 3 Frequency Response when Exposed to –10°C-to-50°C Temperature Profile [3].

Both CSACs, as shown by the purple and black traces, varied <±3 x 10–10 Hz/Hz. For comparison, an OCXO with similar specified temperature coefficient was subjected to the same test. Its frequency response was 3x to 4x worse.

Note: The CSAC temperature coefficient specification is ±5 x 10–10 from $^{-10}$°C to 70°C. OCXO is specified as ±4 x 10^{-10} from 0°C to 70°C. Measured factory temperature coefficient for CSAC_1 and CSAC_2 was 4.25 x 10^{-10} and 2.8 x 10^{-10}, respectively [2-4].

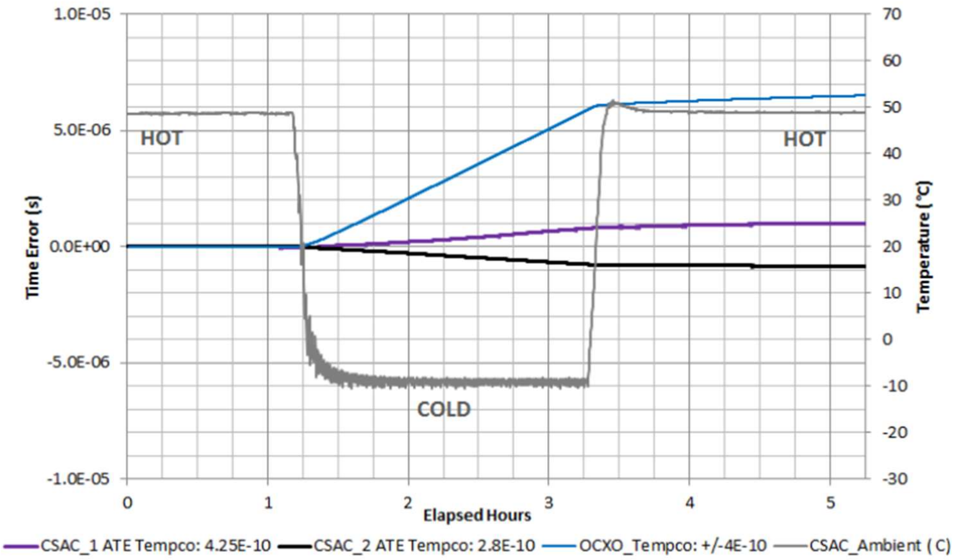

Figure 4 Phase Response when Exposed to –10°C-to-50°C Temperature Profil [2].

The following table lists the corresponding time error. At ~1 µs of time error, the CSACs are clearly superior when compared to a commercial OCXO, which accumulated 6.5 µs. A CSAC's thermal response approaches the performance of larger, more power-hungry Rubidium-based atomic oscillators.

Table 2 OSCILLATOR VS. TIME ERROR

Oscillator	2h	3h	5h
OCXO	2 µs	5 µs	6, 5 µs
CSAC 1	0.1 µs	0.7 µs	1.1 µs
CSAC 2	–0.2 µs	–0.8 µs	–0.9 µs

Note: Looking back at equation 1, we have demonstrated performance assuming zero initial phase and frequency offset. This time, however, the environmental effects are non-zero.

5. CONCLUSION

The paper points out certain limitations in terms of performance parameters of the compared types of oscillators and determines their sensitivity to external influences. It highlights the typical behaviour of oscillators under the influence of a radical change of the ambient temperature, which subsequently affects the initial frequency errors and, ultimately, their accuracy. Through the simulations performed, clear advantages of the CSAC device have been demonstrated, mainly due to the unique architecture of the components that are able to withstand external influences. These features make it superior to most commercial crystal oscillators and suitable for mobile applications in unstable temperature environments.

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