Aging in OCXO and TCXO

Contents

1. Introduction

In specific applications or system structures, frequency stability is considered an essential parameter of the local clock. However, the long-term frequency deviation, called frequency aging, will affect the local clock. Even the most stable OCXO (oven controlled oscillator) products have aging characteristics increasing or decreasing the clock's frequency and thereby compromising system frequency stability. This white paper will introduce why SiTime MEMS (micro-electro-mechanical systems) products are better than traditional quartz products in aging performance and why SiTime can provide a more robust aging compensation solution. The discussion starts by describing the critical factors affecting the frequency deviation of both quartz-based and MEMS-based oscillators. Then a mathematical aging model is used to compare the predicted long-term aging performance of MEMS and quartz oscillators with actual aging measurement results. Finally, through an extrapolation of the mathematical aging model, long-term performance predictions are made.

2. Theory of Aging

Aging is defined as frequency change over time, and this effect must be considered during system design depending on the application. The International Radio Consultative Committee (CCIR) incorporates aging and drift into the military specifications for crystal oscillators, MIL-0-55310.[1] This paper provides information on aging behavior and focuses on the resonator structure of both quartz-based oscillators and MEMS-based oscillators.

2.1. Quartz Resonators

The piezoelectric effect is a physical phenomenon of energy transformation between mechanical energy and electrical energy in the material, and it is also the oscillation mechanism of quartz resonators. Quartz resonators include many materials, as shown in Figure 2.1.1. A metal film (Au or Ag) provides the electric field. Conductive epoxy glue fixes the structure and connects electrical signals. Lid and ceramic packages protect the device from the external environment. The quartz resonator performance can be optimized for various applications through different cut angles such as AT or SC cuts.

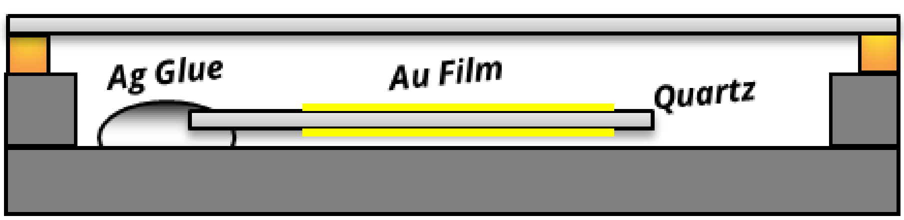

Figure 2.1.1: Quartz-based resonator structure

Aging has components that have a negative or positive change of frequency vs time slope as shown in the aging curve Figure 2.1.2.[2] There are two main reasons for aging. One reason is mass loading and the other is stress relief. The aging curve will approach A(t) if the performance is dominated by stress; the aging curve will approach B(t) if the performance is dominated by mass loading. In the first 10 days after power up, thermal and stress effects result in the change of frequency versus time having a positive slope.

However, as the proportion of the mass loading effect increases over time, the aging behavior becomes gradually monotonic and then transforms to a negative slope after 10 days. Finally, the aging rate keeps falling due to diminishing positive contributions from stress relief.

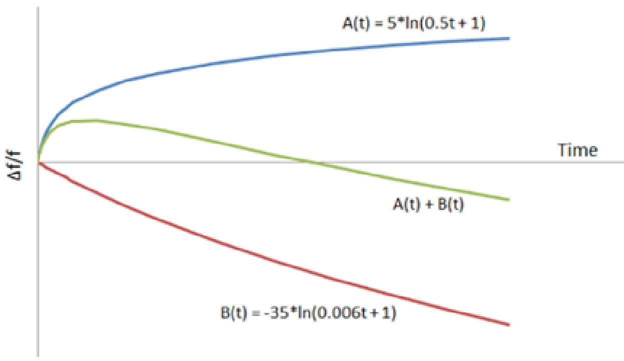

Figure 2.1.2: Typical aging behaviors

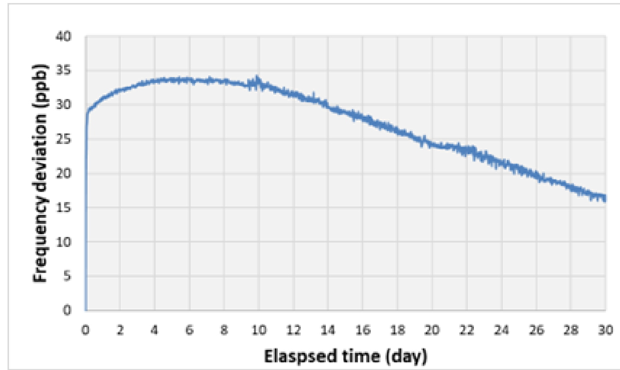

Figure 2.1.3: Quartz-based oscillator aging behaviors

During the manufacturing process of quartz resonators, potential residual stress conditions occur such as surface crack, polish abrasion during mechanical processing, and the bonding force between the quartz and the electrode film. In addition, due to the different thermal expansion coefficients of the materials, thermal stress will originate at the material interface after thermal processes, such as curing or reflow. Another risk is that the quartz resonator scrapes the Au film used for frequency trimming. Rough Au film surfaces produce a dangling bond which is another unstable element affecting frequency stability.

Another vulnerability of the materials used in the production of quartz resonators is the silicon glue (siloxane) that undergoes thermolysis into SiO_2, CO_2, and H_2O during the thermal process. The gas reacts with the dangling bond of the Au film to accumulate mass on the surface of the electrode film, causing the frequency to drop.

2.2. MEMS Resonators

Unlike quartz resonators, the oscillation mechanism of SiTime MEMS resonators is via electrostatic transduction. The MEMS design uses silicon material characteristics, and the geometry of the MEMS structure is used to create a resonant mode. In contrast to quartz resonators, the MEMS structure, shown in Figure 2.2.1, does not contain materials with outgassing properties. This ensures that the cavity, shown in Figure 2.2.2, remains clean and stable under long-term operation.

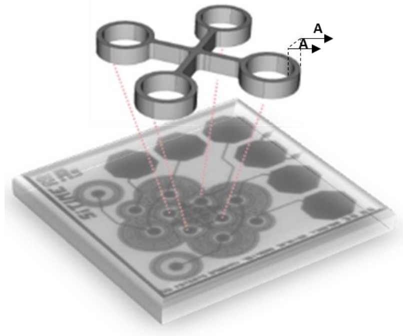

Figure 2.2.1: MEMS based resonator structure

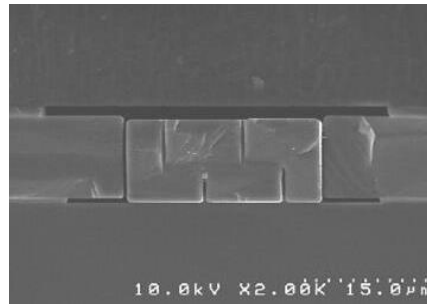

Figure 2.2-2: Cross Section from A-A side

MEMS resonators are manufactured using technology and materials deployed in semiconductor fabrication. In contrast to traditional quartz manufacturing, the MEMS manufacturing process does not include steps that can introduce potential contamination risks such as dicing saw or polish. All parameters related to the oscillation of MEMS structures are strictly controlled in the semiconductor factory. SiTime MEMS structures are made using SiTime's proprietary EpiSeal® process, which is key to forming stable resonators with extremely low aging. SiTime MEMS resonators are made of silicon. They are packaged in a wafer-scale silicon/polysilicon encapsulation under a high temperature (more than 1000 °C), creating a clean vacuum environment.[3] As the temperature of the MEMS cools to room temperature, an annealing process takes place. The internal residual stress is released by atoms migrating in the crystal lattice.

MEMS resonators have high reliability and stability. The aging effects due to MEMS are minimal through strict semiconductor process control, product structural design, and material properties. In contrast, quartz resonators use conventional low temperature packaging techniques (e.g., ceramic packages or wafer bonding) that leave volatile organics and water residues in the package, which generate the mass loading phenomenon causing frequency aging.

3. OCXO and Super-TCXO Aging Performance

OCXOs are commonly used in network infrastructure and high precision measuring equipment to provide a highly stable backup frequency source. In these applications, the OCXO—and in some cases, a TCXO—serves as a local backup clock in the event of a loss to a higher-accuracy external source like GPS. Holdover is the mode of operation when systems temporarily lose connection with the external reference signal and switch to a local source. The network holdover performance is impacted by the aging, temperature variation, and time deviation of the OCXO/TCXO. As required by the network structure or operators such as China Mobile, AT&T, and T-Mobile, holdover mode lasts from hours to days, making aging the dominant factor.

This section compares the aging performance of different Stratum 3E local clocks. Long-term aging measurement data from Elite X™ SiT5501 Super-TCXO (a SiTime MEMS temperature compensated oscillator that provides Stratum 3E precision), Emerald™ SiT5711 (a SiTime MEMS OCXO), and quartz-based OCXOs are examined.

3.1. Aging Performance Comparison between Quartz OCXO, MEMS OCXO and MEMS Super-TCXO

Compared to 4G infrastructure, the operating environments of 5G equipment are harsher. With the development of 5G technology, the application of OCXOs has been transferred from protected indoor environments to outdoor environments that require a wide operating temperature range. In addition, the network densification of 5G places pressure on the size of timing components. We separate quartz OCXOs into traditional DIP types and miniaturized surface mount types for more precise characteristic comparisons in different applications.

Power consumption in 5G applications is increasing, creating higher operating temperatures. This requires the internal oven temperature to increase when the ambient temperature rises. For example, if the ambient temperature increases to 95°C, the oven temperature must be set to 105°C or more based on the crystal temperature curve. But as discussed in the previous section, the high operating temperature will accelerate the outgassing phenomenon of quartz OCXOs and cause the frequency to initially drop and then progressively increase.

Figure 3.1.1 shows 30-day aging measurement data normalized to the first day for both MEMS and quartz. (In this plot, we compare a SiT5501 Super-TCXO with a miniaturized quartz OCXO.) Both the quartz OCXO and SiT5501 have positive aging trend at power on. However, the negative aging factor is gradually greater than the positive aging factor in the quartz OCXO during long operation. The final frequency deviation phenomenon takes on a negative slope and progressively increases in slope magnitude. Conversely, the SiT5501 quickly becomes very stable, and the offset is less than 20 ppb under 30 days of operation. In addition, the aging rate variability between the group of quartz OCXOs is significantly larger than the SiT5501 due to the limitations of the traditional quartz machining process. The large performance difference among the group of quartz OCXO devices is a contributor to potential failure. Generally, the aging rate specification will be defined after 30 days of operation.

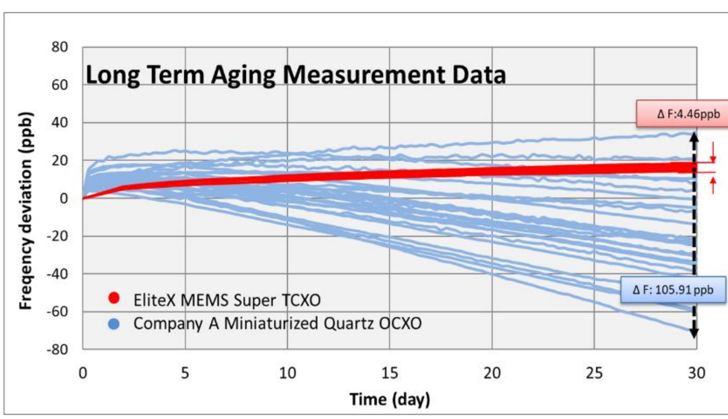

Figure 3.1.1: Long term frequency deviation of SiT5501 Super-TCXO (red) vs miniaturized quartz OCXO (blue)

This paper uses measurement data of day 30 and 31 to calculate the daily aging rate. As shown in Figure 3.1.2, the SiT5501 Super-TCXOs outperform miniaturized quartz OCXOs in terms of aging rate and standard deviation.

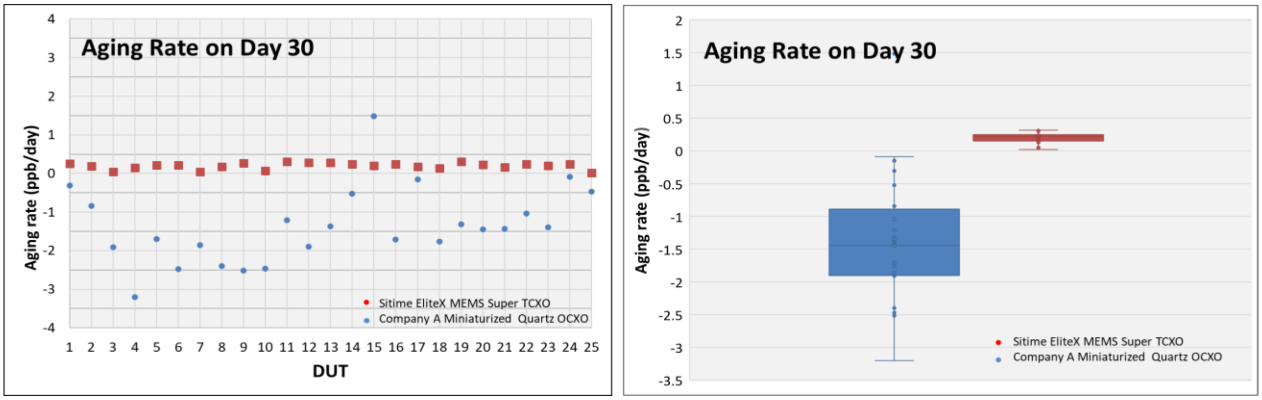

Figure 3.1.2: Aging rate comparison SiT5501 Super-TCXO (red) vs miniatured quartz OCXO (blue)

In addition to the SiT5501 Super-TCXO, which has a low profile and 7.0 mm x 5.0 mm footprint, the SiT5711 OCXO has a 9.0 mm x 7.0 mm footprint – 60% smaller than traditional DIP type OCXOs. SiT5711 OCXO can provide a stable signal source and great holdover characteristics under the steady state condition as shown in Fig. 3.1.3. SiT5711 aging behavior also has a high centralization and will deliver 4 hours of holdover at 1.5 µs. SiT5711 OCXOs are suitable for more precise applications such as DU, small cell, and edge server.

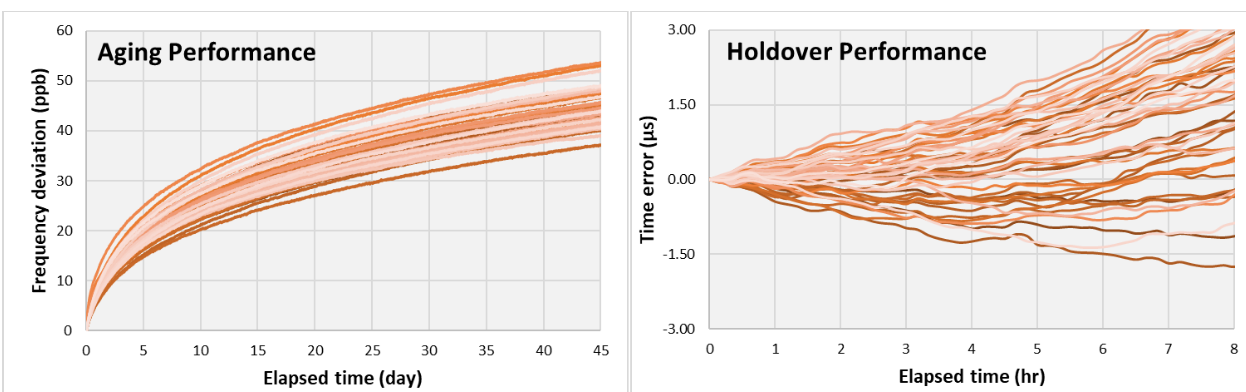

Figure 3.1.3: SiT5711 OCXO aging and holdover performance

3.2. SiTime MEMS Oscillator Actual Aging Raw Data vs. Prediction Result

Focusing on the long-term aging issue, in Figure 3.2.1 we use the SiT5501 Super-TCXO as the aging experimental subject, fit the aging process, predict the development trend, and compare the frequency output with the predicted result. We import the 7-day measurement data into the aging prediction model, predicting the 30-day results and compare it with the 30-day raw data. The results show that the measurement data (yellow solid line) correspond to the predicted data (green dotted line) with R^2 (coefficient of determination) greater than 99. Next, we used this model to predict a one-year aging phenomenon. The result is less than 60 ppb/year as shown in Figure 3.2.1.

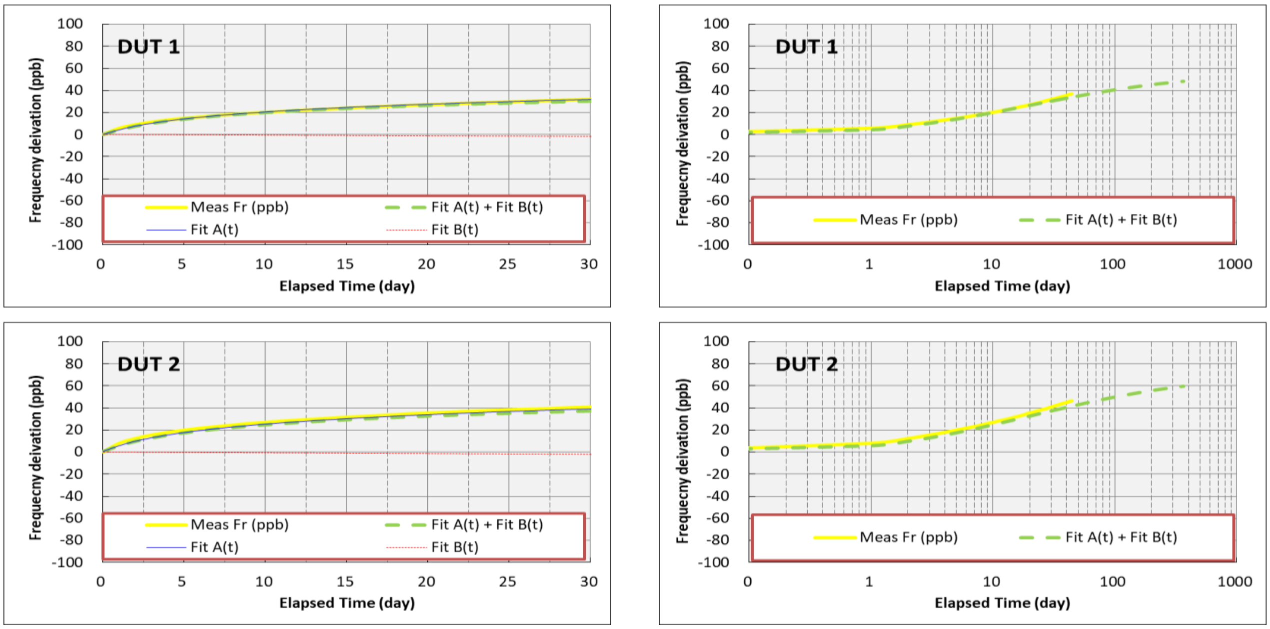

Figure 3.2.1: Aging performance of SiT5501 Super-TCXO with prediction result

With the expansion of 5G infrastructure, the requirements for local clocks are becoming more and more stringent. 5G requires precision clocks that can withstand harsh environmental conditions. MEMS timing products provide stable signals for a long time, and importantly, they maintain good performance at extremely high ambient temperatures as shown in Figure 3.2.2.

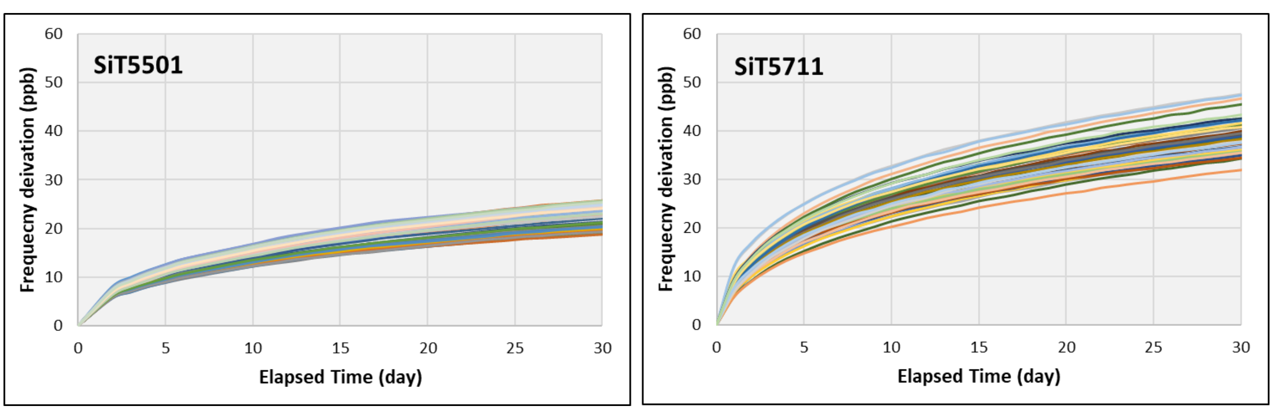

Figure 3.2.2: MEMS Super-TCXO (left) and OCXO (right) aging performance with high operating ambient temperature

4. Recommendations for Future Work

With the development of future 5G networks, high precision timing synchronization and holdover requirements become more challenging without SyncE function support (ITU-T G.8273.4). SiTime products are developed to have great aging performance and simultaneously be capable of being manufactured in mass production. The compensation method is based on the prediction model discussed in the previous chapter through a short training period to generate a product with good aging characteristics. In this case, we used a 10-hour training period (blue) after 24 hours of continuous operation. The aging slope is calculated with a linear curve fit during the training period (solid black line). A compensating curve is defined to cancel the aging slope as shown in the dotted brown line of Figure 4.1.

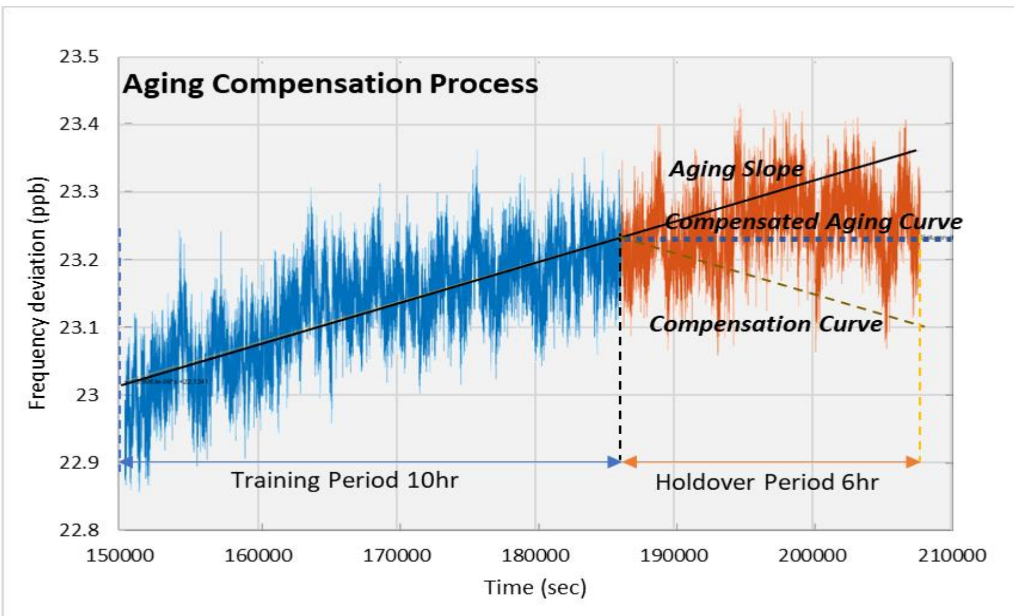

Figure 4.1: Training and prediction with aging compensation

Next, we compare the holdover characteristics of products with or without the aging compensation algorithm. We use 6 hours of holdover at ±1.5 µs time error to be the target specification. One hundred holdover tests were conducted on four DUTs at 100 evenly spaced points in time. Without aging compensation, only 52% of holdover results can meet the specification. With aging compensation, this number increases to 92%. Through the SiTime aging compensation algorithm, we successfully improve holdover characteristics by 40% as shown graphically in Figure 4.2.

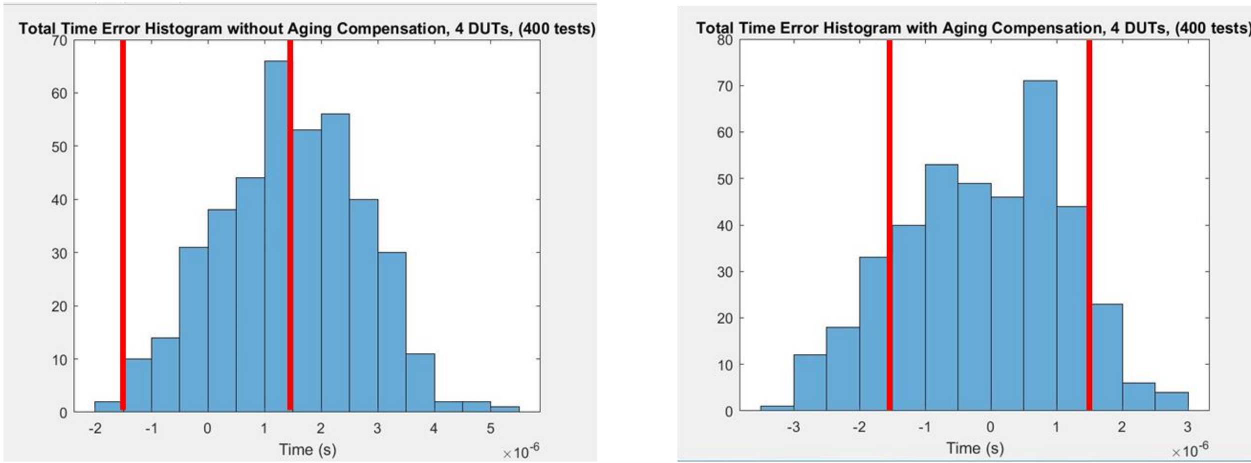

Figure 4.2: Total time error histogram before/after aging compensation

5. Conclusions

OCXO frequency aging characteristics are like leaves withering over time. It is an inevitable and irreversible process. This paper introduced MEMS and quartz OCXO aging performance, starting from the aging theory. Next, we moved to the actual aging data comparison and through the prediction model, discussed the long-term aging performance and the accuracy of the fitting result. Finally, we proposed an aging compensation algorithm to improve the aging characteristic.

The success of aging compensation lies in the accurate prediction model and stable frequency output. The variation of the MEMS resonator aging curve is very small. Unlike quartz resonators, SiTime MEMS resonators have no abnormal drift or jumping points that lead to increased time error. This MEMS resonator characteristic reduces curve-fitting complexity and minimizes overcompensation error. Using MEMS-based OCXOs allow the use of simple aging compensation methods to increase holdover time.

6. References

[1] MIL-0-55310

[2] “Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications – A Tutorial” Rev. 8.5.1.2, by John R. Vig, July 2001, AD-M001251.

[3] AN2001 SiTime MEMS First™ and EpiSeal® Process

Table 1: Revision History

Version	Release Date	Change Summary
1.0	4-Oct-20224-Oct-2022	Initial Release

SiTime Corporation, 5451 Patrick Henry Drive, Santa Clara, CA 95054, USA | **Phone:** +1-408-328-4400 | **Fax:** +1-408-328-4439