VERY LONG TIME SCALE AGING PERFORMANCE RESULTS OF QUARTZ CRYSTAL OSCILLATORS

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ABSTRACT

Extended aging test results for time periods of up to 1900 days will be presented to provide an insight into the long-term drift characteristics of quartz crystal oscillators. The results will be discussed to show the effects of variations in environmental conditions and power on-off cycles.

1. INTRODUCTION

Very long time scale aging measurements have been made for several types of quartz crystal oscillators including AT and SC cut oven controlled crystal oscillators (OCXO) as well as temperature compensated crystal oscillators (TCXO.) Although every OCXO is aged in production, data is usually only collected for the period of time necessary to meet the aging rate specification. TCXOs are seldom aged at all due to the long test times required to determine the true aging performance. Studies on aging performance results for large groups of oscillators over extended periods of time are typically not available.

Many of the test results shown are of oscillators that are either overruns from production orders, units that did not meet a particular specification or exhibited abnormal behavior during the aging test measurement. It must be noted that the large number of data shown with frequency perturbations is not the norm and represents a small fraction of a percent of oscillators that do not show abnormalities. Nevertheless, data collected from these oscillators over extended periods of time exhibit interesting qualities that are worth noting. A number of oscillators were, in fact, intentionally left on the Aging System specifically to study the aging process and the data for these oscillators are also presented.

The data represents real world performance as it captures the cyclic variations in daily and seasonal changes as well as the effects of retrace due to power failures and scheduled systems maintenance. It is important to realize that the true aging performance of the quartz crystal oscillator is aliased by these factors.

2. METHOD

The data presented for each oscillator has been collected by averaging up to 20 samples of a 1 second gate interval approximately every 2 hours. Automated test measurements on all oscillators are made continuously via software control except when they are either loaded onto or unloaded from the Aging System each day. During this process, data collection is ceased for approximately 3 to 5 hours.

Interruptions may also be a result of routine maintenance work conducted on the Aging System or electrical power failures. In such cases, the oscillators may be powered off for several hours and data collection may be stopped for up to a few days.

All data presented have been reduced in size by removing every other data point due to limitations in the graphing software. The time scale has been normalized with the last data point taken on 15 February, 2000 representing day 0 on the x-axis labeled “Number of Days.” As a result, all data points taken prior to this date are represented by a negative number of days from the normalized date. This is to facilitate locating events that are common to the data set of more than one unit and, hence, isolating them from being the behavior of a single oscillator.

Stray points have been removed from the results shown to allow observation of data of interest. Stray data points occur primarily due to wear in the Aging System test fixture sockets and RF switches from excessive use. This results in erroneous frequency readings due to occasional intermittent contact along the RF signal path.

3. AGING

Aging is the change in frequency of the oscillator over time under constant environmental and system-level conditions. Aging in quartz crystal oscillators is caused by changes in either the quartz crystal itself or the remaining components in the oscillator assembly.

Aging in quartz crystals is the result of a combination of several factors. Some of these factors may include the diffusion of impurities and the outgassing of the quartz crystal, its holder, the glass or ceramic base and the adhesive used to mount the quartz. It may also include metal migration from the electrodes into the quartz surface. These events involve an exchange in the mass of the quartz crystal which causes a change in its frequency.

Other factors that also contribute to the aging of quartz crystals include stress relief of the crystal mounts and microscopic holder leaks. While gross leaks in holders are known to cause a downward shift in the frequency, the effects of microscopic leaks on long term aging performance is not well understood.

Frequency drift due to changes in component values over its life may either directly affect the oscillating loop or the steady state function of the sustaining circuits such as voltage regulation, oven control and signal output stages.

The magnitude of aging related to components within the oscillating loop or the surrounding circuits is dependent on the reactance slope of the quartz crystal at the operating frequency. To better understand the effect of component value drift within the oscillating loop on the aging performance, we need to consider the simplified impedance block diagram shown in Figure 1.

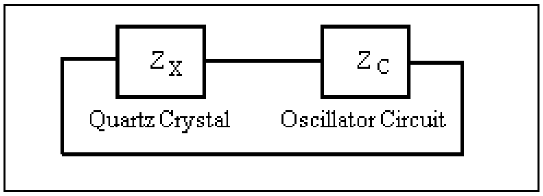

Figure 1

Under resonance,

$$Z_X = -Z_C \tag{1}$$

Where Z_X is the quartz crystal impedance and Z_C is the oscillator circuit impedance.

Since,

$$Z = R + jX \tag{2}$$

Substituting Equation (2) into (1) gives us,

$$R_X + jX_X = -R_C - jX_C \tag{3}$$

$$\Rightarrow \quad R_X = -R_C \tag{4}$$

$$\text{and} \quad X_X = -X_C \tag{5}$$

Equation (4) represents the condition for sustained oscillation at a given amplitude and is independent of frequency. Whereas, Equation (5) represents the frequency of oscillation. The slope of the Reactance vs. Frequency curve at the operating point, dX/df, is sometimes referred to as the "pullability" of the quartz crystal.

Some typical values of dX/df in Ω/Hz at series resonance for different crystal cuts and overtones are shown in Table 1.

Frequency	**AT Fund**	**AT 3rd**	**SC 3rd**
5 MHz	-	7.1	110
10 MHz	0.2	1.4	14.5

Table 1

The reactance of the circuit components is responsible for the frequency of the oscillating loop. Suppose that the reactance of all components other than the quartz crystal changes by ΔX_C after several years. For resonance to occur under the new conditions, Equation (5) must still be satisfied.

Therefore,

$$X_X + \Delta X_X = -X_C - \Delta X_C \tag{6}$$

$(X_X + \Delta X_X)$ represents a new operating point on the Reactance vs. Frequency curve of the quartz crystal and a corresponding frequency. The change in frequency is given by,

$$\Delta f = \Delta X_X / (dX/df) \tag{7}$$

Therefore, if a 10μH inductor drifts 1% over the course of its life, using Equation (7), a 5MHz SC Cut 3rd Overtone oscillator would drift 0.029 Hz or 5.7×10^{-09} fractional frequency. Compared to this, a 10 MHz SC Cut 3rd Overtone oscillator would drift 0.433 Hz or 4.3×10^{-08} and a 10 MHz AT Cut 3rd Overtone oscillator would drift 4.488 Hz or 4.5×10^{-08}. It is important to note that an oscillator capable of excessive tuning (or "pullability") is also prone to greater aging rates.

The magnitude of aging related to components in the oven control circuit of an OCXO is dependent on the temperature co-efficient of the quartz crystal. Table 2 shows approximate values of the temperature co-efficient, C, at the turn-point temperature of AT and SC Cut quartz crystals in °C^{-2}.

AT Cut	2×10^{-7}
SC Cut	2×10^{-8}

Table 2

The fractional frequency, Δff, deviation due to a ΔT oven temperature change is given by,

$$\Delta ff = C\Delta T^2 \tag{8}$$

Therefore, a 0.2 °C change in the oven temperature over the life of an AT Cut OCXO operating at the turn-point, will result in a 4×10^{-9} fractional frequency change. As it can be seen, the effects of component value drift in the oven control circuit will usually be overshadowed by drift within the oscillating loop.

The aging performance of quartz crystal oscillators is a complex phenomenon that is the cumulative effect of many factors, only a few of which have been mentioned. The effects of some of these factors may tend to cancel one another while others may dominate the aging performance. Furthermore, the effects of these factors may also decay at different rates causing them to dominate at different times during the aging process.

4. FIELD OPERATING CONDITIONS

Under normal operating conditions an oscillator may be subject to a number of environmental changes such as temperature, humidity and atmospheric pressure fluctuations, as well as changes in system-level parameters such as power on-off cycles, supply voltage and tuning voltage instabilities. To determine the aging performance, it is important to distinguish and isolate the effects of these factors on the frequency of the oscillator.

Evident in the data presented are the effects of warm-up, retrace and thermal stability. They are discussed below to differentiate these factors from the aging process, which is only possible with large data sets spanning several years.

4.1 Warm-up

Warm-up is the change in frequency that occurs when the quartz crystal and the components are raised in temperature due to the application of power. While this is obvious in OCXOs, it is also present to a smaller extent in TCXOs and VCXOs (voltage controlled crystal oscillators) as a result of heat dissipation from the circuit components. Warm-up in OCXOs, where it is most evident, is typically specified on the order of several minutes. The warm-up time is the time it takes for the frequency of the oscillator to reach within a specified frequency tolerance taken at a referenced time period of usually 1 hour from when the power is applied to the oscillator. However, it must be understood that warm-up does not cease after the specified warm-up time period and, therefore, must not be misinterpreted as aging. In fact, frequency changes due to the warm-up process may last up to several weeks. This is evident from the graph shown in Figure 8.

4.2 Retrace

Retrace is the shift in frequency observed by powering off the oscillator and then back on after some time. It is measured by taking the difference between the stabilized frequency, followed by a specified power off time period of usually 24 hours and the frequency measured after a power on time period of usually 1 to 2 hours conducted at a defined constant ambient temperature. Retrace is depicted in the graph in Figure 2 as a result of a power failure at –150 days and –47 days which lasted for approximately 2 to 4 hours.

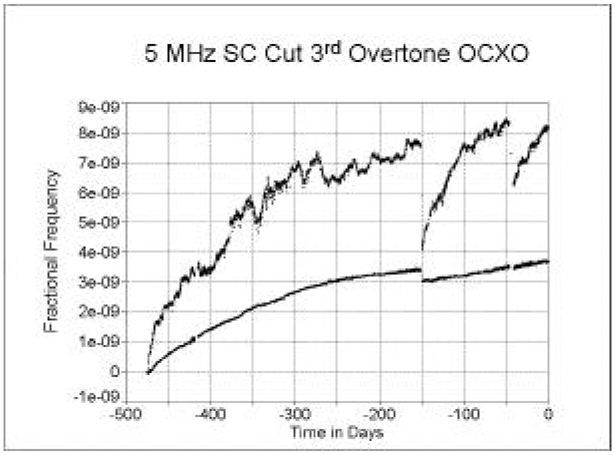

Figure 2

When operating for extended periods of time under static conditions, primarily temperature, the quartz crystal oscillator components tend to physically "anneal" themselves to that operating state. When the oscillator is powered off, the components begin the process of "annealing" themselves to the new state, the extent of which is dependent on the time period in this new state and the temperature difference between the two. When the oscillator is powered on again, the components physically change back to a state similar to right before when the power was turned off. However, they may not reach the exact state at which they originally existed resulting in retrace effects. Since, physical changes in a component causes a change in its electrical characteristics, this in turn will result in a frequency change. Components within the oscillating loop are the primary contributors to retrace and as with warm-up, OCXOs are much more susceptible to retrace due to the greater temperature difference between the power on and off states. In TCXOs, retrace is usually overshadowed by the larger temperature dependent variations and higher aging rates as seen in Figure 3.

Depending on the time period for which the oscillator was powered off and the type of product, it may take anywhere from a few hours to several weeks for the quartz crystal oscillator to recover from the effects of being powered off and return to its previous aging rate. In other instances, the oscillator may not exhibit the effects of retrace, for the same power failure event. In analyzing the data for this study, it was noted that the magnitude of retrace offset was typically proportional to the aging rate of that oscillator.

4.3 Thermal Stability

The effects of thermal stability can overshadow the true aging performance of an oscillator under normal operating conditions, especially when seasonal changes are considered. Quartz Crystal Oscillators with lower thermal stability such as TCXOs and VCXOs are much more susceptible to misinterpretation of the aging rate measurements than, say, precision double-oven OCXOs as seen in Figures 3 and 9.

5. AGING PERFORMANCE RESULTS

Aging test results for several types of oscillators is presented. Two recent power failures are prominently evident on almost all the data presented. A power failure on 30th December, 1999 at day –47 (not a Y2K related event!) lasted for approximately 3 to 4 hours. As a result, data collection was stopped for 4 days. Another power failure at day –150 lasted for nearly 2 hours. The entire Aging System was physically moved to the new manufacturing facility in an adjoining building in 1997. The resulting power interruption lasting over 6 hours is evident at day –837.

5.1 AT Cut Quartz Crystal Oscillator Results

Figure 3 depicts the aging performance of a 10 MHz AT Cut TCXO over 1799 days.

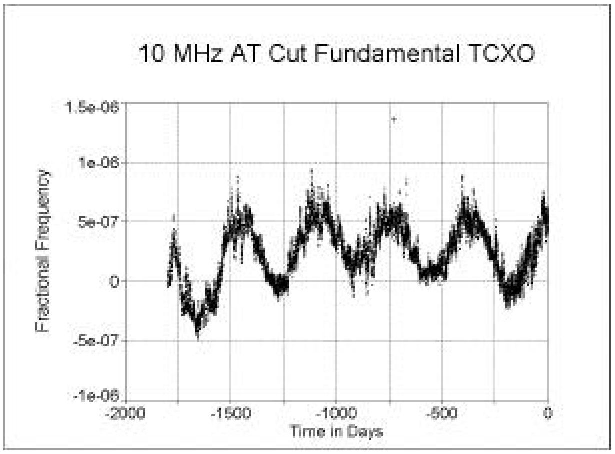

Figure 3

The daily variations in frequency due to temperature is clearly evident and expected. It is quite interesting to also note the cyclic behavior due to seasonal changes. It is important to realize that the yearly aging rate cannot be accurately determined by the first year of data collection alone, as the aging slopes during the transition from the Winter to Summer season and vice versa, are several magnitudes higher than the average yearly aging rate.

Similar aging performance was recorded for 3 other 10 MHz TCXOs over similar time periods and 2 TCXOs at 17.382812 MHz over 243 and 1119 days each.

In comparison, aging performance for 13 MHz Fundamental OCXOs are shown in Figure 4.

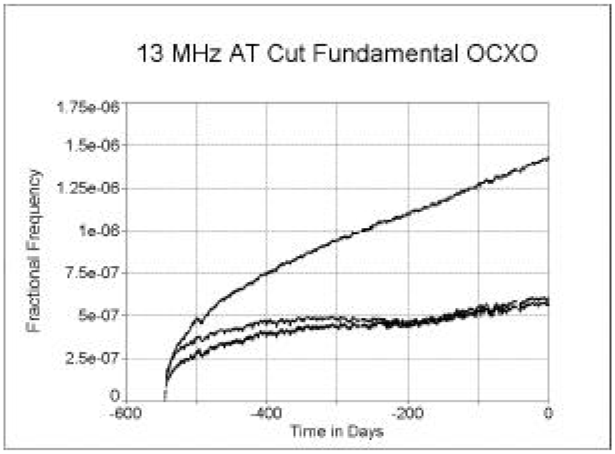

Figure 4

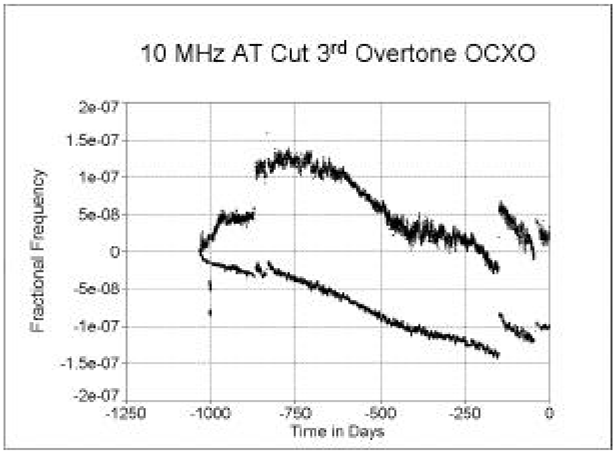

Figure 5

Aging results for 10 MHz 3rd Overtone quartz crystal oscillators are shown in Figure 5.

The aging performance of 2 OCXOs using 50 MHz 3rd Overtone quartz crystals are shown in Figure 6. The steps seen appear on both oscillators at exactly the same time period indicating some external perturbation.

100 MHz 3rd Overtone OCXO aging performance results are shown in Figure 7. Once again, the frequency shift occurs at exactly the same time period on both units with the exception of two frequency steps at –617 days and –433 days seen on one of the oscillators. The oscillators without the steps, is less prone to retrace from the power failures at –150 and –47 days.

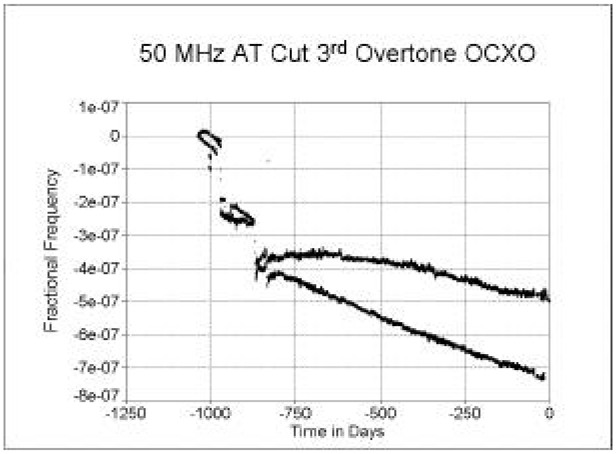

Figure 6

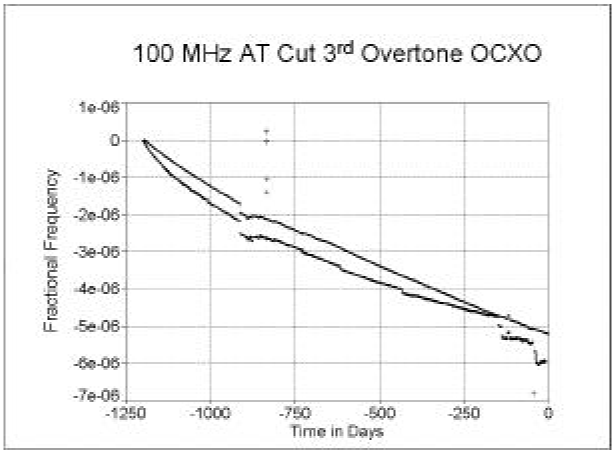

Figure 7

With the exception of the 100 MHz oscillators with much higher aging rates, the cyclic seasonal behavior can be noticed in each of the results presented.

5.2 SC Cut Quartz Crystal Oscillators Results

Aging results for 5 and 10 MHz SC Cut OCXOs are presented. Figure 8 shows a very correlated aging performance of 2 oscillators over a 1951 day time period. Seasonal cycles are also noticeable in these results.

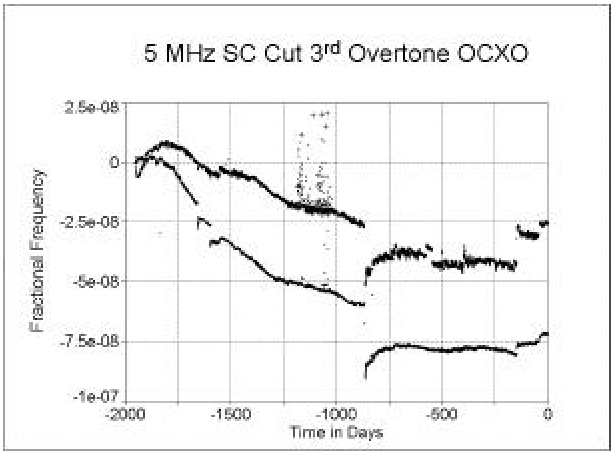

Figure 8

One oscillator exhibited a downward tail during the first few days of aging. Thereafter, it aged with a positive slope, followed by a steady negative slope with a diminishing rate. The gradual and smooth transition from either a positive to negative aging slope or vice versa which can occur over various time periods, is not an uncommon behavior that is perhaps more noticeable in oscillators with low aging rates.

Figure 9 shows additional performance results for 5 MHz 3rd Overtone OCXOs.

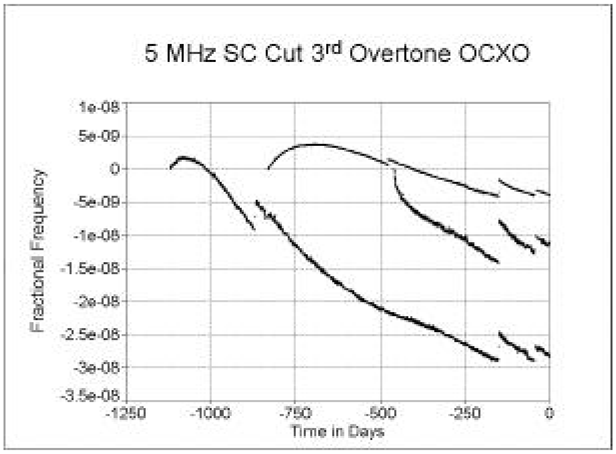

Figure 9

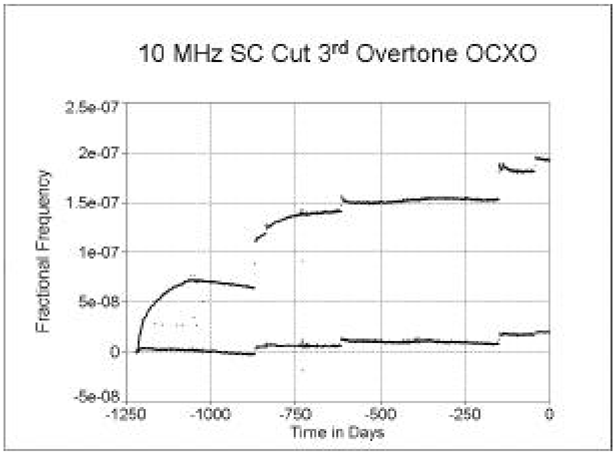

Figure 10

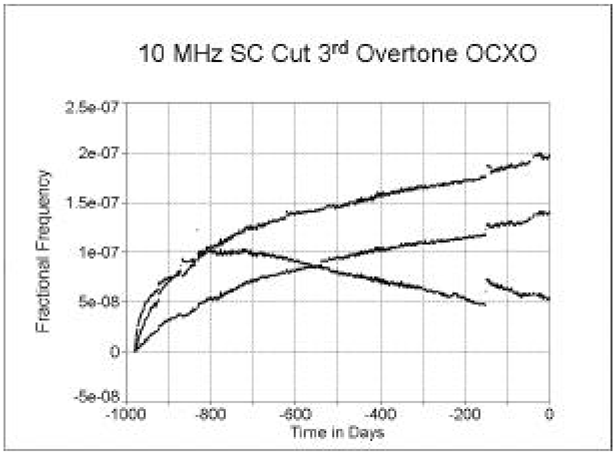

Figure 11

Aging results for 10 MHz 3rd Overtone OCXOs is shown in Figures 10 and 11. It is interesting to note that one of the oscillators exhibits two frequency states between which it jumps from –925 days to –872 days.

Figure 12 shows aging results for 10 MHz 5th Overtone OCXOs.

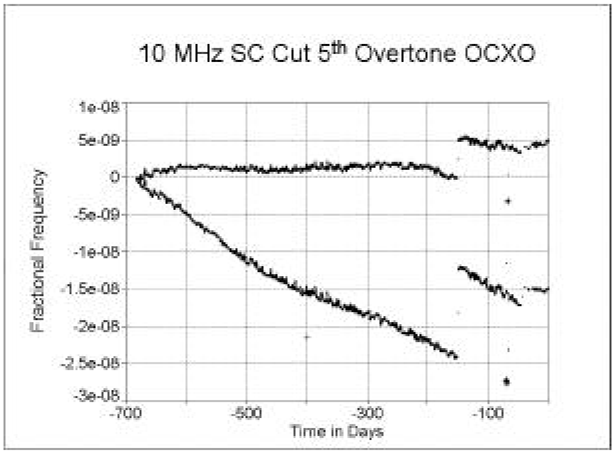

Figure 12

5.3 Experimental Results

An aging experiment was devised involving 32 OCXOs to study aging trends of 5 MHz SC Cut 3rd Overtone crystals.

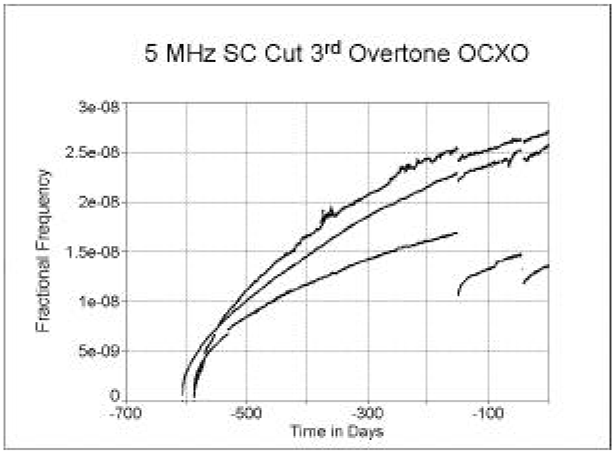

Figure 13

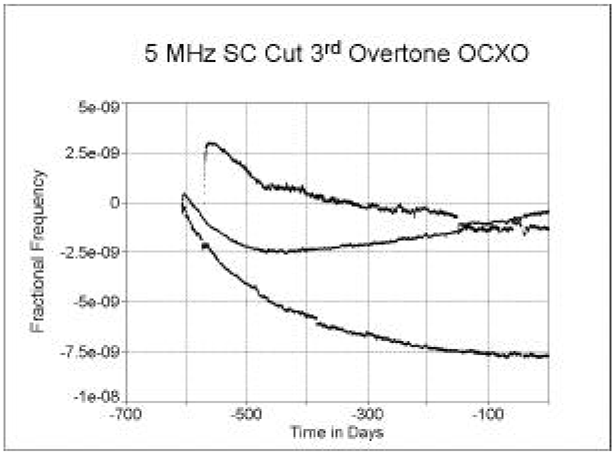

Figure 14

It was noticed that 13 oscillators exhibited a primarily positive aging slope while 19 oscillators exhibited a negative aging slope. Oscillators with positive aging slopes recorded an average of 1.5 x 10^{-08} total fractional frequency change over a period of approximately 600 days, or about 2.5 x 10^{-11}/day. Whereas, those with a negative slope recorded an average of 7.5 x 10^{-09} over the same period, or about 1.3 x 10^{-11}/day, a factor of 2 better. Representative results from the two groups are shown in Figures 13 and 14.

In analyzing the results of 226 oscillators for this study, the retrace effects for the 3 known power failures at day –837, –150 and –47 were recorded and are presented in Table 3 below.

Aging Slope Direction / Retrace Offset Direction	**# of Units**
Positive / Negative	25
Positive / Positive	29
Positive / Both	3
Positive / Negligible	5
Negative / Positive	93
Negative / Negative	24
Negative / Both	2
Negative / Negligible	6
Undetermined (Due to Data Quality)	39
Total	**226**

Table 3

It is interesting to note that, of the 171 oscillators with discernable retrace offset in one direction, 69% moved in the opposite direction to the aging slope.

5.4 Other Interesting Results

A 10 MHz AT Cut 3rd Overtone OCXO aging performance results due to a leak in the quartz crystal holder is shown in Figure 15.

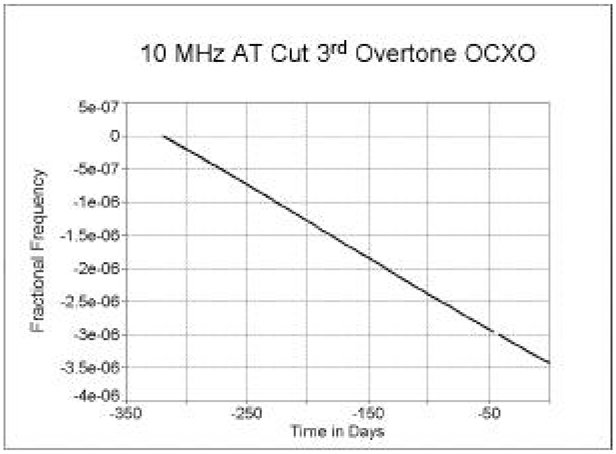

Figure 15

Figure 16 shows the result of a different 10 MHz AT 3rd Overtone OCXO with a precursor event occurring at day –254. This may be the result of the intersection of another oscillation mode aging at a different rate.

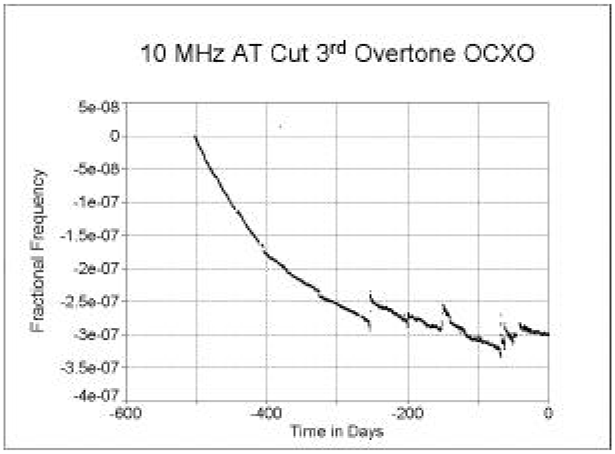

Figure 16

6. CONCLUSION

Aging is a complex process. The aging rate typically scales with the reactance slope of the quartz crystal, indicating some dependency on component performance.

It can sometimes be difficult to detect the aging performance of an oscillator without sufficient amount of data. Results heavily aliased by environmental effects can lead to misinterpretation for small data sets.

Retrace effects are common to all types of oscillators. However, the magnitude of retrace is somewhat independent of the type of oscillator.

For system level calculations, developing an error budget that includes all frequency dependent factors, primarily aging, is a good practice. This may be used to determine whether the application is able to tolerate the expected change in frequency of the quartz crystal oscillator over its life or if the available minimum tuning range is sufficient to offset this change.

7. REFERENCES

[1] J. Vig, Quartz Crystal Resonators and Oscillators For Frequency Control and Timing Applications A Tutorial, U.S. Army Communications - Electronics Command, January, 2000.