

Keysight Technologies

Calibration of Time Base Oscillators

White Paper

Introduction

Counting intervals has been going on since man's beginning. Early time measurements involved counting the number of days in terms of sunrises, sunsets, or moons. Later, the day was divided into smaller increments by using an hourglass, candles, sundial, etc. With the discovery of the pendulum, clocks were born. The accuracy of early clocks was around 1 part in 1000.

As more accurate clocks were produced, new uses of time measurement were explored. As new uses were discovered, the need for even more accurate clocks became apparent.

Atomic Accuracy

Current state-of-the-art atomic frequency standards have attained an accuracy of 1 part in 10^{13} (1 in 10 million, million) in the laboratory. The specified accuracy in commercially available atomic clocks has reached $\pm 1 \times 10^{-12}$. This unprecedented commercial accuracy is equivalent to a gain or loss of 1 second in a minimum of 400,000 years.

Definition of a Second

Frequency standards and clocks have no fundamental differences – they are based upon dual aspects of the same phenomenon. The basic unit of time, the second, is defined as “the duration of 9,192,631,770 periods of transition within the caesium atom.” Frequency is determined by counting the number of cycles over the period of a second. Therefore, the definition of a clock can be expressed as a device that counts the number of seconds occurring from an arbitrary starting time.

From this definition it appears that a clock needs three basic parts. First, a source of events to be counted. This source can be labeled a frequency standard, frequency source, or time interval standard. Second, a means of accumulating these events or oscillations. Third, a means of displaying the accumulation of time.

Errors in Accuracy

Accuracy in a timekeeping system is dependent on six major problem areas:

- Maintenance of accurate frequency
- Accurate time transfer
- Determination of radio propagation path delays
- Maximization of the frequency calibration interval
- Determination of the effects of noise in frequency generating equipment
- Determination of the effects of changing environmental conditions

Prior to analyzing the effects and impact of the above sources of error, it is necessary to determine the level of accuracy required and the tolerances essential for the individual application. Once the essential tolerances have been established, the sources of error can be analyzed to determine if they have impact on system operation. If, in fact, they affect the system operation, the appropriate steps can be taken to reduce that impact.

Types of Time Base Oscillators

There are five basic types of time base oscillators:

- XO - Room temperature crystal oscillator (sometimes referred to as RTXO)
- TCXO - Temperature compensated crystal oscillator
- OXO - Oven controlled crystal oscillator
- Rubidium
- Caesium

Each type of time base has its own characteristics. The room temperature model would be used in a portable counter. Usually, the better the time base, the longer it takes to verify it; the poorer the time base, the harder it is to adjust. Some timebase specifications would be impractical to completely verify, so operator judgment is required to identify which parameters have to be checked, when to adjust the time base, and when to predict final performance based upon rate of change of measured performance.

Time Base Aging

The physical properties of the quartz crystal exhibit a gradual change with time resulting in a gradual cumulative frequency drift called "aging." See Figure 1. The aging rate is dependent on the inherent quality of the crystals used, and goes on all the time. Aging is often specified in terms of frequency change-per-month since temperature and other effects would mask the small amount of aging for a shorter time period. Aging for air crystals is given in frequency change-per-month as it is not practical to accurately and correctly measure over any shorter averaging period. For a good RTXO, the aging rate is typically of the order of 3 parts in 10^7 per month. For a high quality oven controlled oscillator, the aging rate is typically 1.5 parts in 10^8 per month.

Aging rate specifies maximum frequency change with time. Any oscillator can be much better than specified but will never be worse than the indicated rate unless it is malfunctioning. You may have noticed that Keysight has two kinds of specifications – some oscillators are specified as having a daily aging rate, such as $< 3 \times 10^{-9}/\text{day}$, while others are specified as having a monthly aging rate, such as $< 3 \times 10^{-7}/\text{month}$. Keysight oscillators with a daily aging rate specification use ovens that sufficiently buffer the oscillator from the environment.

Time Base Aging (continued)

To determine crystal aging rate, one has to check the oscillator once a day when room temperature is at a constant value, plot these points for approximately a month, then draw a line through the points. The slope of the line is the aging rate of the crystal. By doing this you have created an "historical aging rate" of your unit. This is an important concept and each instrument should have its own history record. Table 1 summarizes the oscillator characteristics described above, utilizing typical specifications of well-designed oscillators having a 10 MHz nominal frequency.

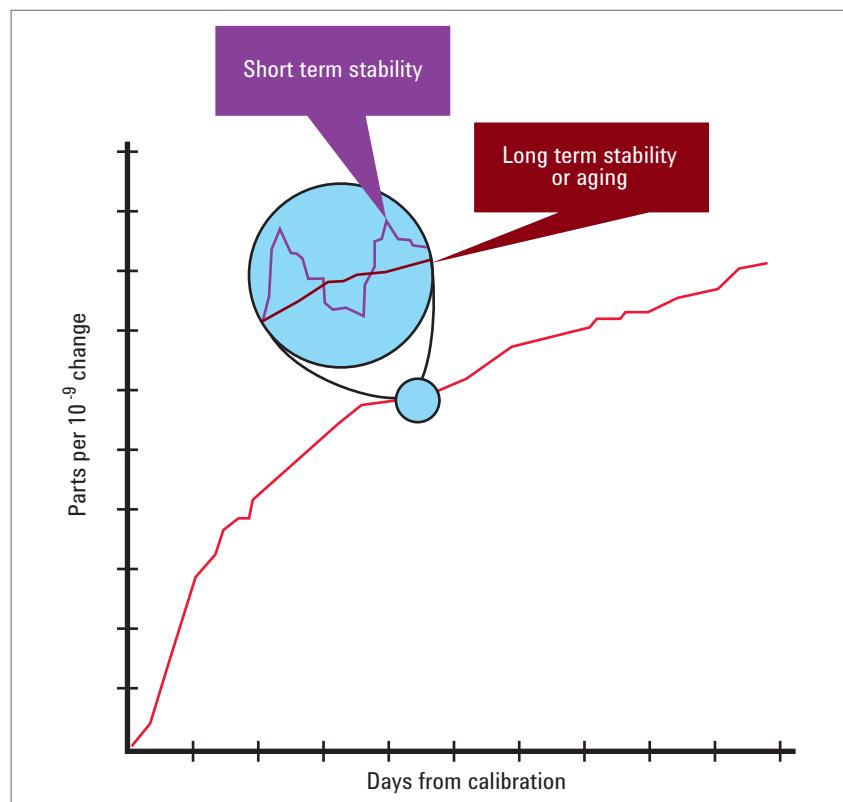


Figure 1. Effect of aging on frequency stability

Table 1. Typical specifications of the five types of oscillators

Type	Typical aging	Typical shift for 5 °C	Allowable offset	Typical warm-up	Allan variance (T = 1 s)
XO	3×10^{-7} per month	5×10^{-6}	60 Hz	30 minutes	1×10^{-9}
TCXO	1×10^{-7} per month	1×10^{-6}	13 Hz	3 hours	1×10^{-10}
OXO	5×10^{-10} per day	5×10^{-10}	150 MHz	3 days	5×10^{-12}
Rubidium	1×10^{-11} per month	5×10^{-12}	400 µHz	4 hours	7×10^{-12}
Caesium	None (primary std.)	3×10^{-12}	6 µHz	45 minutes (21.5 ns/hour)	1×10^{-11}

Time Base Warm Up

Under typical operating conditions, that is, when the instrument's power cord is left connected to the power source, there is no warm up because the time base is kept "warm" or in a "standby" mode. However, if the unit has been disconnected from the power source for 24 hours or more, the instrument should technically be warmed up for up to 30 days for it to meet guaranteed specifications. This may not be practical. Our experience has shown that approximately 85 percent of new units and 95 percent of older units will be within specifications after three days of warm up. Of course, this is due to the aging process slowing down over time. A typical problem you may encounter with some of the older units is that the time base has aged to a point where the mechanical adjustment can no longer compensate the frequency drift because the mechanical adjusting device has reached the physical limit of its travel. On other older units, drift may be almost non-existent.

The Question

Do you have to calibrate an oven time base even though the manual for the instrument being calibrated does not have a performance test for it? The answer is YES. The oven time base needs to have a drift test performed. The decision to remove offset depends upon the needs of the customer and the type of time base being calibrated. Calibration should always be checked after repair, after being shipped (shock can cause an offset of 1 part in 10^8 , and you don't know in which direction), or periodically to ensure that measurements made with these devices are within specifications ACCORDING TO THE USE OF THE INSTRUMENT. This is an important concept. Many users expect an oven time base to have a written specification to tell them exactly when the cumulative offset caused by aging has crossed some specification bound. These oscillators are just not specified in this manner. The use of the time base and the measurement needs of the user dictate how the time base is to be calibrated and supported.

On the other hand, crystal oscillator (clock) accuracy is seldom of consequence in practical time interval measurements. Most electronic counters have a quartz oscillator with an accuracy of 1 part in 10^6 (1 part per million) or better. As a result, the effect of oscillator stability does not affect a time interval measurement unless the display has 5 or 6 valid digits of information. While it is possible to measure long intervals with high resolution, most practical measurements today are the rise time of fast signals, propagation time through high-speed logic, or on narrow pulses. Resolving a 5 μs interval to 1 nanosecond entails only 4 digits of information - i.e., 5000 nanoseconds - so an oscillator as poor as 1 part in a million introduces only 1/200th as much error as ± 1 count for this measurement. For shorter intervals the oscillator error is proportionally less.

Time interval averaging increases the number of valid digits, but here again usually not to the extent that crystal accuracy is important. Short-term stability may become important when doing time-interval averaging on narrow pulses. The short-term stability specification is statistical in nature so is worse for short averaging times. Consider for example a short-term accuracy specification of 1×10^{-9} for a 1 second averaging time. This would be 1×10^{-3} for a 1 μs averaging time (5 nanoseconds for the example above) and would be greater for an oscillator with poorer short-term stability.

Aging rate is generally of consequence only in an application where the counter is used to make phase or time measurements to compare high precision frequency standards. In this application a counter is used to measure the time variations between once-per-second time ticks from the two different frequency standards. Each time-interval measurement may be as long as 1 second ($1 \times 10^6 \mu\text{s}$) on frequencies that are stable 5 parts in 10^{12} or better, so a stable crystal oscillator is needed.

Accuracy and Stability

Accuracy may be defined as the closeness of a measurement to the true value as fixed by a universally accepted standard. The measure of accuracy, however, is in terms of its complementary notion, that is, deviation from true value, or limit of error, so that high accuracy has a low deviation and low accuracy a high deviation. The plots shown in Figure 2 show successive measurements for four cases. The readings in case 2 are more spread out. This could be due to noise or the operator's inability to consistently read an analogue dial. The readings in case 3 are stable but offset from actual value. The important thing is that this offset is a systematic error that can be removed by calibration. The random errors of case 4 cannot be calibrated out.

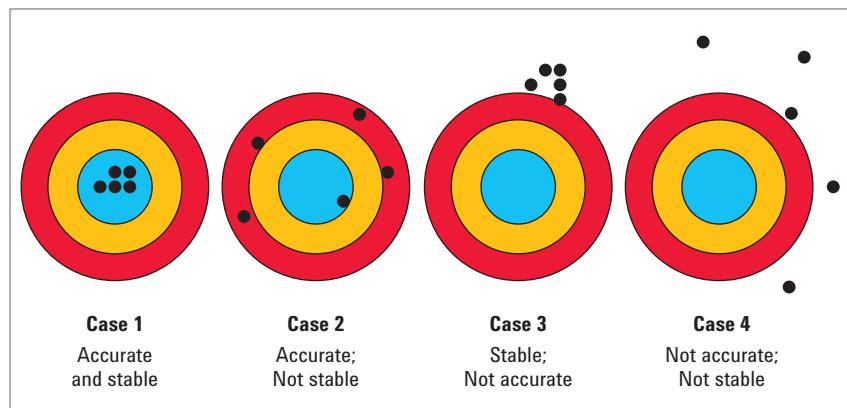


Figure 2. Pictorial representation of accuracy and stability

Frequency Calibration Interval

In theory, a time system based upon a quartz oscillator or a rubidium standard of known drift rate can be kept within prescribed limits of error with infrequent adjustments through a systematic approach.

With this systematic approach, the oscillator and clock are preset to offsets that will keep the time system operating within a selected accuracy for a long time despite the oscillator's drift. This drift (aging rate) must be known (measured) and must be nearly constant, so that a plot of the frequency over the adjustment interval (periods between calibration) can be approximated by a straight line.

What this means in simple terms is that the time base is adjustable, and if its drift rate is known, it can be set so that the drift remains within specifications for longer period of time, therefore extending the interval between calibrations.

One thing cannot be over-stressed; the limiting factor for almost all time bases is your ability to keep the temperature constant for the duration of the test. This is why the ability to make measurements and adjustments quickly is so important.

Once you have created a historical rate of drift (aging) for your particular instrument, you can calibrate it to an offset to take advantage of the known drift. For example, if you know that the timebase drifts from low to high at a certain rate, you can calibrate your unit at the low end of its specification so that it will drift from low through center and be at the high end of its specification at a prescribed point in time.

Recalibration Charts for Quartz Oscillators and Rubidium Standards

Figure 3 is useful for estimating the length in days of the recalibration cycle for an oscillator with a known drift rate, which will keep the time system based on that oscillator within prescribed error limits. A recalibration cycle is the time, in days, that can be allowed to pass between calibration adjustments. A shorter cycle (more frequency adjustments) is needed to keep a system accurate to $\pm 100 \mu\text{s}$ (total time excursion equals $200 \mu\text{s}$), rather than to 1 ms.

To use the charts, select the slant line marked for the aging, or drift rate of the oscillator in parts-per-day. Note the intersection of this line with the horizontal line corresponding to the permitted error excursion. This intersection, referred down to the horizontal axis, gives the recalibration cycle.

Example

A time system is to be maintained to within 10ms based on a quartz oscillator with a positive aging rate at $5 \times 10^{-10}/\text{day}$. Use Figure 3 to estimate the length of the recalibration cycle by locating the slant line marked $5 \times 10^{-10}/\text{day}$ (purple) and note its intersection with the horizontal line corresponding to a total time excursion of 0.020 seconds ($\pm 10 \text{ ms}$). The answer read from the chart is 60 days.

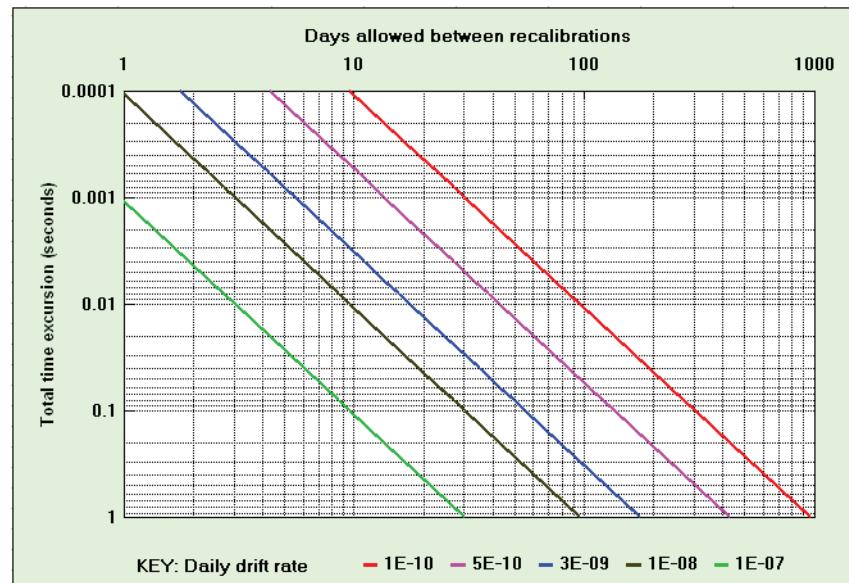


Figure 3. Recalibration chart for quartz oscillators

Temperature Effects

A very small temperature change can drastically affect the frequency of a time base. In some cases, $\frac{1}{2}$ °C temperature change can cause as much drift as 2 weeks of aging. Two points are worth remembering with respect to temperature effects. First, the change of frequency with temperature is usually not a linear function; furthermore, all crystals, even though the same kind, may have very different frequency temperature curves. Individual oscillator frequency-temperature curves must be made to determine a particular unit's actual performance. Second, the effects of temperature change can be reduced by providing a more constant ambient temperature (controlled room temperature) when better performance is required.

Line Voltage Change

Crystal oscillator frequency is also influenced by line voltage changes (often because the instrument's power dissipation increases, which causes the temperature inside of the instrument to rise). Good circuit design, proper buffering, and good mechanical design can reduce these effects. Operators needing better performance can use a line regulator to better control line voltage fluctuations.

Summary

Each time base ages differently. You should create a history file for each of your instruments and plot its drift. Determine how the unit is going to be used. If your measurements require extreme accuracy, the timebase will have to be calibrated more often. Either way, when you calibrate the timebase, adjust it to the extreme end of its specification and let it drift through center to the other end of its specification, maintaining calibration for the long period of time.

Keep your instruments plugged into the power source to maintain constant internal temperatures, and use a line regulator to buffer line voltage changes.

Above all, think about how you are using the instrument and what is reasonable to expect from it. *Do not try to use your counter to calibrate a caesium beam frequency standard!*

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