The following section contains OFC Application Notes

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Oven Controlled Crystal Oscillators

What Is an OCXO?

An Oven Controlled Crystal Oscillator typically consists of a precision quartz crystal, an oven block, a temperature sensor, a heating element, oven circuitry, oscillator circuitry and insulating material. The crystal and other temperature sensitive circuit elements are placed in the oven block where the temperature sensor, heating element, oven circuitry and insulation function to maintain a stable temperature. By keeping the crystal at a constant temperature, great improvements in oscillator performance can be realized over other forms of crystal compensation.

OCXOs usually use AT- or SC-cut crystals, though IT, BT and other crystal cuts are used for specific applications.

When to Use an OCXO

While an Oven Controlled Crystal Oscillator offers a number of advantages over uncompensated oscillators and Temperature Compensated Crystal Oscillators (TCXOs), they have some disadvantages as well. Listed below are some of the most important advantages and disadvantages of OCXOs. Typical OCXO values are given below; other performance levels are possible.

Advantages of an OCXO

- *Improved Frequency-Temperature Stability*

  +0.1 to +0.001 parts per million (ppm) frequency deviation over temperature

- *Improved Aging*

  0.002 ppm to 0.0005 ppm per day frequency deviation

  0.5 ppm to 0.03 ppm per year frequency deviation

- *Improved Phase Noise*

  -100 dB to -130 dB at 10 Hz from the resonant frequency

  -155 dB to -165 dB noise floor

- *Decreased Acceleration (G) Sensitivity*

  As good as $2x10^{-10}$/G

- *Lack of Frequency and Phase Discontinuities*

- *Stability During Thermal Transients*

  Extremes from -55 °C to 85 °C

Disadvantages of an OCXO

- *Higher Power Consumption*

  1 to 3 Watts steady state

  5 to 20 Watts warm up

- *Warm-Up Time*

  3 to 10 minutes warm up

- *Increased Size*

  Height from 0.4″ to 2.5″

  Length and Width from 1″ to 3″

- *Increased Weight*

- *Higher Cost*

  $100 to $1000

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Specifying an OCXO for Minimum Cost

OFC offers a line of standard OCXO products in order to meet customers' technical needs with reduced cost and lead times. When a standard product does not meet a customer's specific application, the customer can take steps to minimize the costs of a non-standard product. (Refer to "OCXO Specification Guide with Cost Saver Tips" application note.)

AT vs. SC Cuts

SC cut crystals, while providing improved performance over the AT cut, are more difficult to manufacture and will cost more. If SC cut performance is not needed, then an AT crystal should be specified.

Excessive Temperature Range and Stability

Over-specifying the temperature range or stability of an OCXO will drive costs up due to the need for increased testing.

High Ambient Temperature – Especially for SC Cut Resonators

An OCXO's oven temperature is usually set such that the oscillator functions at the upper turning point of the crystal's frequency vs. temperature curve. Furthermore, to function well, an OCXO's oven temperature must be at least 5 to 7 degrees above the highest ambient operating temperature. Higher oven temperatures demand tighter crystal angle tolerance, thus increasing cost. For SC cut crystal oscillators, a maximum ambient temperature of 60 °C or less gives the lowest cost oscillator. A 70 °C maximum ambient temperature is also quite acceptable but with a somewhat increased cost. If the maximum ambient temperature exceeds 75 °C, the crystal can be very expensive.

Phase Noise Requirements

Requirements for low phase noise will generally drive costs up. Designing an oscillator with a very low phase noise floor is difficult, while low close-in phase noise can only be achieved by specifying more expensive crystals. Also, very low phase noise oscillators require time-consuming tests to verify that they are within the desired parameters.

Size

Fixed dimension requirements can drive costs up, especially for low volume OCXOs. This cost can be mitigated by speaking with an OFC design engineer, or applications engineer, early in the product development cycle in order to establish the required physical space for the needed oscillator.

Choosing oscillator dimensions for which seamless enclosures exist significantly reduces both cost and, in some cases, leadtime. Non-standard enclosures are manufactured from folded sheet metal. Custom progressive die sets must be ordered before seamless enclosures can be used.

Lead Time Drivers for Ovenized Oscillators

Crystal Lead Time

The primary factor driving most OCXO characteristics (frequency, aging, EFC, close in phase noise, etc.) is the quartz crystal itself. Because of this fact, crystals are generally custom manufactured for a customer's application. Depending on the frequency and difficulty of the requirements, lead times for crystals can be as high as 8 to 12 weeks.

Testing and Aging

Temperature testing and aging can also be important drivers for OCXO lead times. Very tight temperature stability specifications require more rigorous testing, while tight aging specs will often require increased time on active burn-in before the OCXO meets its specifications.

OCXO Trade Off Summary

Size

Minimizing the OCXO package size will have several effects.

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Included among these effects are:

- Frequency vs. Temperature Stability will Degrade
- Power Consumption will Increase

Power

Increasing power will decrease warm up time (to a point, but limited by the crystal thermal line constant)

Crystal Cut

The advantages of SC-cut crystals include:

- Thermal Transient Compensated (faster warm up)
- Static and Dynamic Frequency vs. Temperature allow Higher Stability
- Better Frequency vs. Temperature Repeatability (no hysteresis)
- Far Fewer Activity Dips
- Lower Drive Level Sensitivity
- Planar Stress Compensated, lower delta f due to edge forces and bending
- Lower Sensitivity to Radiation
- Higher Capacitance Ratio, less delta f for oscillator reactance changes
- Higher Q for fundamental mode resonators of similar geometry
- Less Sensitive to Plate Geometry, wider contours possible

The disadvantages of SC-cut crystals include:

- More Difficult to Manufacture (more expensive)
- B-mode Is Excited in the SC-cut, must have circuitry to trap this mode
- Limited Pull Range for Electronic Frequency Control

Ovenized Oscillator Parameters

Frequency-Temperature Stability

Frequency-temperature stability measures how much an oscillator's frequency changes as the ambient operating temperature changes. This value is usually stated as plus-or-minus (±) some number of parts per million (ppm) over a temperature range. That is to say that as the temperature changes from some starting temperature (usually 25°C), the oscillator frequency may drift up or down XXX parts per million. For a 10 MHz oscillator, ±0.01 parts per million would equate to a frequency variation of ±0.1 Hz over the operating temperature range. Additionally, frequency-temperature stability may sometimes be stated as ± XXX ppm per °C.

One way to improve frequency-temperature stability of an OCXO is to increase the amount of insulation in the oscillator, though this means increasing its size as well.

Good thermal design and good oven control circuitry will also improve frequency-temperature stability. Also, the temperature stability of an OCXO will degrade as the operating temperature range increases, especially towards high temperatures.

Warm-Up Time and Power

Warm-up time is the amount of time it takes for an OCXO to go from turn-on to within a specified limit of its nominal (or final) frequency. Warm-up power is the power used during the warm-up period.

Warm-up time is affected by the ambient temperature, the amount of power being supplied, the thermal mass of the oven block and the crystal thermal time constant (how long it takes for heat to travel through the leads to the crystal). Increasing power will reduce warm-up time until the thermal time constant of the crystal (and other components) is reached.

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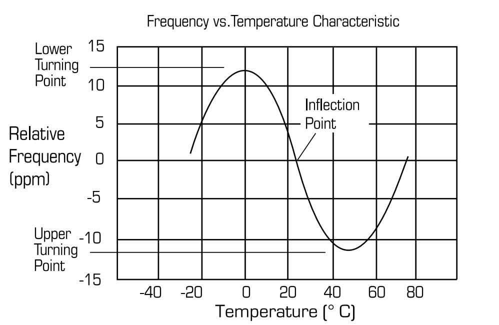
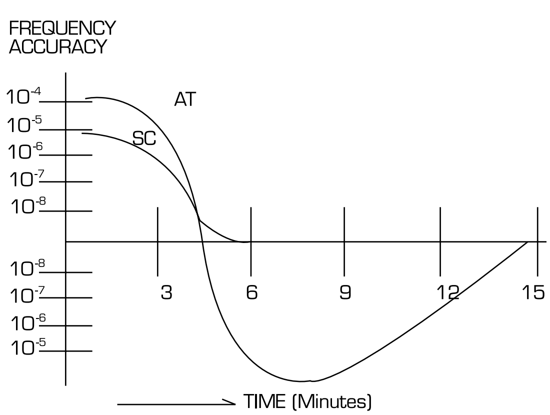
Warm-up time will be affected by the kind of crystal used in the oscillator. SC cut crystals warm up faster than AT cuts since AT cuts have larger thermal time constants and are more sensitive to thermal stresses.

Because crystal resonators are sealed in evacuated enclosures for best aging, heat is conducted into the crystal primarily through the leads. During warm-up, the portion of the resonator mass in contact with the leads is significantly warmer than the surrounding quartz, thus establishing a thermal gradient. Thermal expansion creates mechanical stress which in turn creates a frequency shift, especially in non stress-compensated resonators. SC-cut (stress-compensated) resonators are nearly immune to this effect.

In the graph, the frequency transient in the AT cut curve results from thermally induced mechanical stress.



Inflection Temperatures are ~26° C for AT-cuts, ~96° C for SC-cuts.



Hysteresis

Changes in the frequency of an oscillator at a given temperature that are dependent on the prior temperature history of the oscillator are known as hysteresis. As a result of hysteresis, an OCXO will not warm up to exactly the same frequency each time it is turned on.

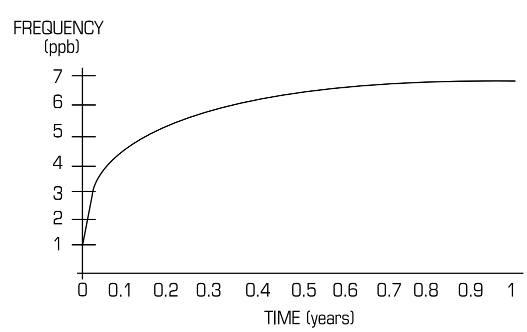
Aging is the frequency drift of a crystal oscillator (at constant temperature) over time. Aging is caused by stress changes in the resonator and its mounting structure, and to mass transfer mechanisms associated with contamination. Well-designed mounting structures and carefill process control in crystal manufacturing can help characterize and minimize aging (see “Aging and Retrace in Oven Controlled Crystal Oscillators”).

OCXO aging is usually measured in parts per billion (ppb) per day and fractions of parts per million (ppm) per year. As the figure shows, aging is non-linear and is often described by a logarithmic curve. While a crystal’s daily aging rate is known at the time of shipment, it can be difficult to fully characterize its long-term aging. Therefore, different manufacturers will often extrapolate the same daily aging rate into different yearly rates.

OCXOs are normally “aged” at the factory until their daily aging rates have reached a specified level. The OFC group employs an automatic test system that measures an oscillator’s aging rate at a constant temperature. Units are shipped when their daily aging rates reach a specified level and their characteristic aging curves begin to flatten out.

Typical Aging Curve for AT & SC-Cut Crystals

$F(t) = A[\ln(Bt + 1)] + fo$



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In order to reduce the time an OCXO must remain on aging, crystals can be stored at an elevated temperature before being installed.

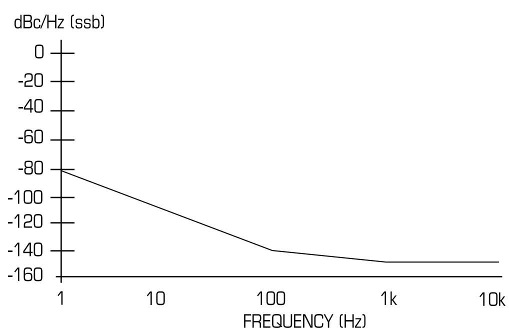
Electronic Frequency Control (EFC)

OCXOs with an electronic frequency control option can have their frequencies adjusted by varying a control voltage. EFC is usually used to compensate the oscillator for long term aging, but can also be used for phase locking or, in some cases, modulation. An OCXO without an EFC option will generally have a built in trim potentiometer for the same purpose. The amount of frequency change possible for a given crystal is called its pull range and is usually specified in ppm/Volt. SC-cut crystals have a more limited pull range than AT-cuts. The degree of linearity required between the control voltage change and the oscillator frequency change is often specified by customer requirements, with highly linear EFC requirements increasing the cost.

Phase Noise

Undesired frequencies near the oscillator set frequency are referred to as phase noise. Close in phase noise is due mostly to crystal characteristics while an oscillator's phase noise floor (generally 10 KHz from the carrier and up) is due mostly to circuit design.

TYPICAL PHASE NOISE PLOT
10 MHz OCXO using 3rd Overtone AT



Logic Output Option

A logic output option is available on many OCXOs, though such an option will generally cause some degradation in phase noise. OFC supplies OCXOs with logic outputs that can drive TTL, ACMOS, HCMOS and CMOS.

OCXO Specification Guideline and Cost Saver Tips

This document is intended for use by Component Engineers, Design Engineers, Systems Engineers, technical writers and those involved in creating source control documents for the procurement of Oven Controlled Crystal Oscillators (OCXO). Oak Frequency Control Group has a well-defined methodology for the development of high performance, low cost OCXOs. Using the following guidelines will improve performance, decrease costs and lessen development time for OCXOs.

Mechanical Considerations

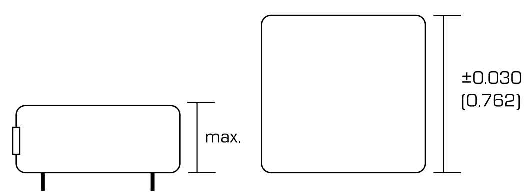
Enclosures

OFC utilizes a preferred parts lists that includes a selection of commonly used enclosures. As a result, a stock is maintained thus facilitating prompt delivery of the finished enclosure from our machine shop. Standard sizes in inches (mm) include:

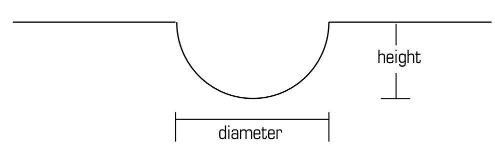
- .82″ (20.8) x .52″ (13.2) x .40″ (10.2)
- 1.0″ (25.4) x 1.0″ (25.4) x 0.5″ (12.6)
- 1.4″ (38.0) x 1.0″ (25.4) x 0.53″ (13.5)
- 1.5″ (38.1) x 1.5″ (38.1) x various heights
- 2″ (50.8) x 2″ (50.8) x var. heights
- 3″ (76.2) x 2″ (50.8) x var. heights
- 2.8″ (71.1) x 2.4″ (70) x var. heights

The preferred height range is one to two inches (25.4 to 50.8). A higher cost will be incurred for heights less than one inch (25.4). Tolerances on the length and width of the enclosures should be specified no tighter than ± 0.030 inches (±0.762). The height is best specified as a maximum. A strong relationship exists between enclosure height and performance. As the enclosure height decreases, power consumption increases and frequency stability decreases. If it is not possible to use one of the standard sizes listed above, consult a tool and die catalog (such as those from Hudson, CFW or JJ Orly) for previously "tooled" sizes. These manufacturers usually charge for tooling of new designs not listed in their catalog.

Cold rolled steel with a hot solder dipped finish is the preferred case material and plating for enclosures. Experience has shown that internal electronics, when enclosed in steel, are less susceptible to nearby electromagnetic fields than when brass enclosures are used.



When it is critical to have the oscillator raised off of the PC board for cleaning purposes or to prevent electrical contact, small standoffs or "dimples" can be formed on the enclosure's surface. Use these guidelines when specifying standoff dimensions:



0.02″ (0.508) height at 0.062″ (1.57) diameter
0.03″ (0.762) height at 0.100″ (2.54) diameter
0.05″ (1.27) height at 0.150″ (3.81) diameter

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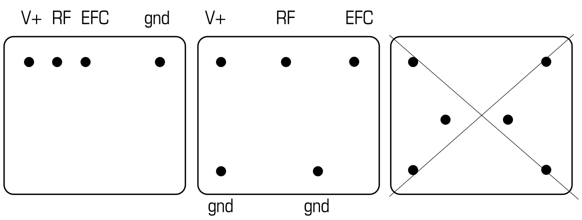
I/0 Terminals

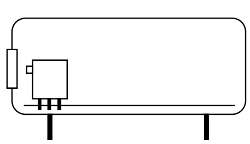
For enclosures that are 1.5″ (38.1) square or less, input/output terminals should be in-line or arranged such that non-ground pins are grouped to one side as illustrated below. Otherwise, keep terminals away from the center. To avoid interference with the enclosure's radius, space the terminal centers 0.25 inches (6.35) from the edge.



Specify either 0.020″ (0.508), 0.030″ (0.762) or 0.040″ (1.02) diameter terminals for I/O connections and a minimum length of 0.25 inches (6.35).

Frequency Adjust

OFC suggests the use of electronic frequency control (EFC) whenever possible. However, if mechanical frequency adjustment is required and the enclosure's height is 2 inches (50.8) or less, locate it such that the adjustment screw will be at the side. Allow a designated window for placement of the access hole (as opposed to a precise location). Ideally the exact positioning of the access will be determined by OFC. The enclosure height must be at least 0.6″ (15.24) for mechanical adjustment to be utilized.



Seal

The majority of OFC's enclosures are solder sealed. Solder sealing is adequate to ensure compliance with gross leak requirements such as MIL-STD-202, method 112, test condition D. Indicate whether the unit will be subjected to immersion cleaning, and if so, specify that a gross leak test be performed. Solder sealed enclosures cannot reliably meet fine leak requirements such as MIL-STD-202, method 112, test condition C.

Weight

The typical weight for various sizes of OCXOs are:

1.0″ (25.4) x 1.0″ (25.4) x 0.5″ (12.7)	12 grams
1.5″ x (38.1) 1.5″ (38.1) X 0.5″ (12.7)	33 grams
2″ (50.8) x 2″ (50.8) x 0.85″ (21.59)	67 grams
3″ (76.2) x 2″ (50.8) x 1.25″ (31.75)	130 grams
2″ (50.8) x 2″ (50.8) x 3.25″ (82.55)	177 grams

Shock/Vibration

Typically, a commercial grade OCXO will meet the requirements of MIL-STD 202, method 201 {0.06″ (1.524) peak to peak amplitude change in a frequency range of 10 Hz to 55 Hz}. If the unit will be subjected to high random or sinusoidal vibration levels, consider the use of hold down brackets on two sides of the enclosure. The mechanical strength of glass feed-thru terminals should not be the sole means of securing the unit when a vibration level higher than 20 g's is expected.

Labels

OFC uses a computer controlled label generator that prints oscillator model number,

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serial number, date code and customer requested markings on polyester labels. These labels stay legible after being subjected to the ordinary environmental tests found in MIL-STD-202.

Electrical Considerations

Keep in mind that certain performance parameters are mutually exclusive, that is, there are trade-offs to be made. For example, extremely tight aging precludes having high EFC sensitivity – high EFC sensitivity precludes having very low "close-in" phase noise.

Frequency Adjustment

An oscillator can be designed to allow for frequency adjustment by mechanical or electrical means. In most cases where frequency adjustment is required, it is most cost effective to design-in an Electronic Frequency Control (EFC) line. Usually the end user will connect the EFC to a DAC output, to a potentiometer or in a phase locked loop.

A number of parameters must be specified for the EFC line:

- *Input Voltage Range*

  The preferred range is 0 to 10 volts, inclusive.

- *Total Pulling Range*

  The range should be large enough to allow for the return to the nominal frequency over the lifetime of the OCXO plus an additional amount for safety margin. Excessive pulling range usually results in lower short term, long term and frequency-temperature stability. High stability OCXOs that require an SC cut crystal will typically have ± 1 ppm range while precision AT cut OCXOs can be pulled up to ± 10 ppm.

- *Slope*

  This refers to the direction of the frequency change with a change in the input voltage. A positive slope means that the frequency will increase while the input voltage increases and vice versa. A monotonic response (no slope reversals) is always verified.

- *Linearity*

  Linearity is a means of comparing the frequency - voltage response to a straight line. OFC computes linearity as specified in MIL-O-55310.

$$\text{linearity} = \frac{F_{max} \cdot 100}{D_T} \%$$

  where F_{max} is the largest frequency deviation between the raw data and a best straight line fit and D_T is the total frequency deviation

  A low cost linearity requirement is 20% or greater. Linearity requirements of less than 10% are verified in production resulting in increased labor costs.

- *Input Impedance*

  The input impedance is largely resistive and typically is optimum at 10K ohms minimum.

- *Modulation Bandwidth*

  The bandwidth can extend from DC to about 10KHz. Phase noise degradation due to noise on the EFC line can be reduced by specifying the bandwidth as less than 100 Hz.

- Reference Voltage

  Probably the best source of a "clean" voltage supply for the EFC line is from the oscillator's internal regulator.

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The load that the reference voltage line connects to must not demand more than 1 mA of current.

The stability of the signal applied to the EFC line must be considered as it will directly influence the stability of the oscillator's output. For instance, if the input voltage exhibits a linear temperature coefficient with changing ambient temperature then the output frequency will drift correspondingly.

If mechanical adjustment is necessary, specify mechanical adjust resolution as no finer than | total trim ÷ 100.

Input Voltage and Current

Designs are possible using voltage magnitudes between 4.75 volts and 30 volts. *The desirable voltage is one that falls within the range of +5 volts to +15 volts with a tolerance of ±5%.*

In general, combining the oven and oscillator supply into one input will yield the lowest parts count oscillator design. Not only does a single supply reduce the I/O terminal count, but also reduces the need for internal regulators and filtering. One exception is if the output is TTL or CMOS (5 V_{pp} output). In this case, it is beneficial to have a well regulated +5 volt supply available for the oscillator output stage.

The supply ripple (or noise on the supply line) will affect the frequency stability by degrading Allan variance and phase noise. Both the frequency range and magnitude of the noise spectrum should be specified. These numbers along with the frequency stability requirements will dictate the amount of internal regulation and filtering required. *To keep filtering costs down, specify ripple levels as less than 10 mV_{p-p} amplitude over a frequency range of 60 Hz to 100 KHz.*

Maximum input power (cold current) occurs during the warm-up period when the oven mass is attaining operating temperature. The cold current level has a direct impact on warm-up performance. A quick warm-up time requires either high cold current, an SC cut crystal, a small oven mass or a combination of the three. *The normal range for maximum input power is 5 watts to 20 watts with 6 watts being typical*. Keep in mind that the turn-on power must be greater than the steady state power usage anticipated at the lowest operating ambient temperature.

Once the oven mass has reached operating temperature, the input current will be an almost linear function of ambient temperature. Lower temperatures will require a higher input current and vice versa. Typical steady state oven input power specifications for various enclosure sizes in still air at room temperature are:

1.5"(38.1) x 1.5"(38.1) x 0.5"(12.7) high	1.4 watts
2.0"(50.8) x 2.0"(50.8) x 1.0"(25.4) high	1.2 watts
2.0"(50.8) x 2.0"(50.8) x 3.0"(76.2) high	1.0 watts

Initial Frequency Tolerance

Initial frequency tolerance is the allowable range of frequency that the oscillator will output at the time of receipt at incoming test. An oscillator will exhibit frequency aging and recovery when not under power. Because there is a time lag between final test and installation into the customer's system, the oscillator will not be at the exact frequency it was set to at final test. *The initial frequency tolerance should be specified as no tighter than ±0.05 ppm of nominal frequency and a reasonable time limit for this window to be met should be based on the aging requirement*. For example, an aging rate of 0.25 ppm per year would hold ±0.05 ppm frequency tolerance for about 2 months.

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Frequency – Temperature Stability

Specify a peak to peak error over temperature or reference a temperature that is roughly in the middle of the range. For example:

0.02 ppm from -20°C to +70°C, or
± 0.01 ppm from -20°C to +70°C referenced to +25°C.

The first example is somewhat less costly than the second. More difficult and costly would be:

< ± 0.01 ppm from -50°C to +40°C referenced to +25°C.

Warm-Up

When specifying warm-up there must be a reference time and frequency, for example, "Within 15 minutes after application of power the oscillator frequency shall be within ± 0.01 ppm of the frequency measured at 1 hour."

Unless specified otherwise, the ambient temperature at which warm-up is to be tested is assumed to be +25°C, ± 5°C, with the supply voltage(s) at nominal.

Acceleration Sensitivity (g-sensitivity)

Two widely used techniques to measure g-sensitivity are the 2g tipover test and measurement of vibration induced sidebands on a spectrum analyzer. Both methods will yield the same results except when vibrating at a frequency where either the crystal structure or enclosure is in resonance, when thermal convection currents are significant or when the crystal is stressed into non-linear performance at very high g-levels.

State which axis is of concern when specifying g-sensitivity requirements for the oscillator.

The amount of frequency change during a 2g tipover test depends on the orientation of the crystal. In three dimensional space, there is one axis that will exhibit the most sensitivity and one axis with virtually no sensitivity. If one of the oscillator's axes can tolerate only small changes in frequency due to vibration, an optimum orientation for the crystal can be determined. However, costs rise dramatically as a result of the time required to characterize the crystal's g-sensitivity vector.

The formula used for computing sidebands expected from a phase noise measurement is:

$$L(f) = 20 \log \left[\frac{\bar{\Gamma} \cdot \bar{A} \cdot f_o}{2 \cdot f_v} \right]$$

where: Γ is the g-sensitivity vector
f_v is the vibration frequency
f_o is the crystal frequency
A is the g-level for sinusoidal vibration or $\sqrt{2 \cdot PSD}$ for random vibration where PSD is the power spectral density in g^2/Hz.

For 3rd overtone crystals close to 10 MHz, typical 2-axis g-sensitivity vector magnitudes are 2 x 10^{-9} or better.

Short Term Stability

Time domain short term stability is usually computed using the Allan variance (AVAR). Better AVAR performance at medium and long observation times requires higher quality (and higher cost) crystals. AVAR can be determined by accumulating zero dead time frequency data and using the following formula:

$$\sigma_y^2(\tau) \approx \sqrt{\frac{\sum_{k=1}^{N-1} (f_{k+1} - f_k)^2}{2(N-1)}}$$

where N is the sample size.

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The following limits on a standard 10 MHz OCXO require testing on a less costly sample basis.

tau	AVAR
0.01 seconds	1×10^{-10}
.1 seconds	5×10^{-11}
1 seconds	1×10^{-11}

AVAR is degraded by vibration and the performance can be predicted with the help of the following formula:

$$\sigma_y^2 = \frac{\vec{\Gamma} \cdot \vec{A}}{\pi f_v \tau} \sin^2(\pi f_v \tau)$$

where A is the g-level.

Phase Noise

Phase noise is a measure of the frequency stability in the frequency domain. It is typically specified as single sideband noise with units of dBc/Hz.

The following static limits for a typical 10 MHz OCX0 require testing on a less costly sample basis.

Frequency Offset	AT Performance	SC Performance
1Hz	-75 dBc/Hz	-85 dBc/Hz
10	-105	- 115
100	-130	-135
1 KHz	-140	-145
≥ 10	-150	-150

Undefined points outside the stated range are assumed to be of no importance and the specification limit between points is determined by joining successive points with a straight line.

Phase noise during vibration will be drastically degraded at the vibration frequency(s). (See the formula presented in the section covering g-sensitivity.

Aging

The most cost effective method of specifying aging is to choose the longest term condition.

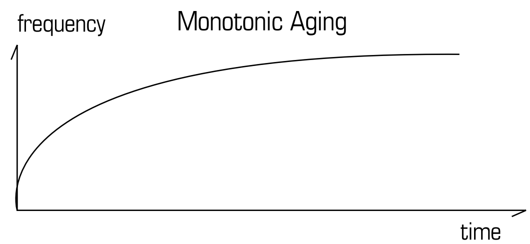
Instead of specifying multiple aging conditions, ie., /day, /week, /year, specify the long term rate only. For example, "The aging rate shall not exceed 0.05 ppm for a period of one year." Monotonic frequency data will be curve-fitted to either a logarithmic equation or a linear equation.

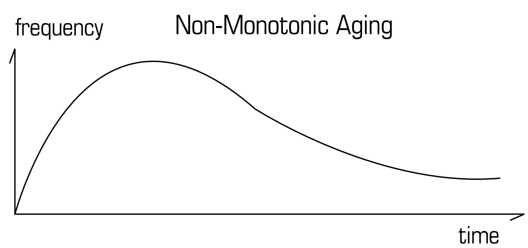
The logarithmic equation as defined in MIL-PRF-55310 is:

$$\text{Frequency}(t) = A \cdot \ln(Bt + 1) + f_o$$

where A & B are constants and f_o is the initial frequency.

This equation has proved not to be valid for non-monotonic aging curves.





Typical aging performance for various frequencies are:

± 0.5 ppm per year for a 10 MHz AT cut
± 0.1 ppm per year for a 10 MHz SC cut
± 0.05 ppm per year for a 5 MHz SC cut
± 1 ppm per year for a 100 MHz AT cut

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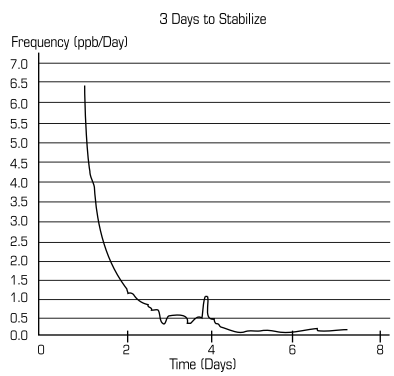
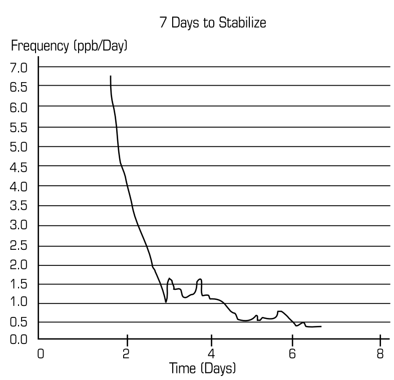
Restabilization

Consider a situation where an oscillator has been on power for two weeks and has attained an aging rate of 5×10^{-10} per day. Power is removed for 5 minutes and then reapplied. The aging rate will return to normal within a few hours. However, if the power is reapplied after 1 week of being unpowered, it may take anywhere from 2 days to 7 days for the aging rate to return to 5×10^{-10}.

If it is necessary to specify the stabilization time, state that the required aging rate shall be met within 1 week if the off time is greater than 24 hours.



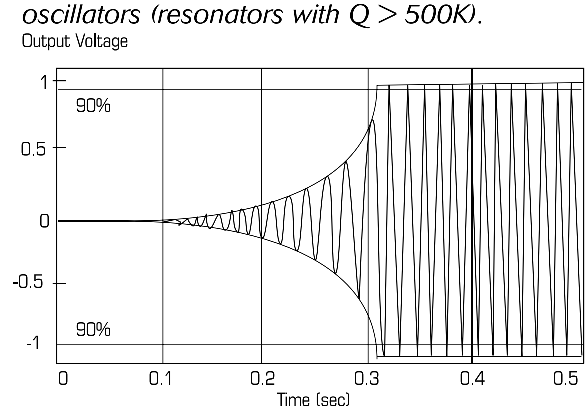


Tight aging specifications increase oscillator delivery time due to the extended burn-in period required at the oscillator and/or crystal level.

Start-Up Time

Start-up time is defined as the amount of time required for the RF output to reach 90% of the final amplitude after application of power. In general, start-up time increases with increasing oscillator stability.

Start-up time should be specified as 0.5 seconds (or higher) maximum for high stability oscillators (resonators with Q > 500K).



Frequency – Load Stability

Changes in the load impedance induce slight variations in the thermal pattern on the oven mass resulting in frequency changes.

Typical performance will be:

± 0.001 ppm per gate for TTL or CMOS loads
± 0.001 ppm for a ± 5% change from 50 ohms

Frequency – Supply Voltage Stability

Frequency changes due to variations in the supply voltage (also known as pushing) are more pronounced in the AT cut OCXO and wide-pull OCXO. The typical performance after steady state is reached will be:

± 0.001 ppm per 1% change in supply for AT cut OCXOs
± 0.0001 ppm per 1% change in supply for SC cut OCXOs

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Built In Test (BIT)

A BIT line can be included to monitor the status of the output signal or the oven controller. The simplest output signal BIT will toggle to the fault condition if the signal level drops below a certain voltage. More elaborate and costly would be a BIT that monitored both minimum and maximum output level. The least costly oven controller BIT simply indicates whether the OCXO is still warming up (cold current) or is drawing steady state current. Since thermal equilibrium does not occur until several minutes after the oven current "cuts back", the frequency will continue to drift. The BIT transition can indicate only that the frequency is close to nominal and is continuing towards steady state. The typical frequency error for various types of crystals when BIT transition occurs is:

± 1 ppm for SC cut oscillators
± 2 ppm for AT cut oscillators

B-Mode

The B-mode frequency is an unwanted mode of oscillation and is present in doubly rotated crystals (SC, IT, etc.). It is "trapped out" in the oscillator and will not appear after steady state conditions exist in the oscillator. However, since the B-mode response is stronger than the desired mode, the B-mode may exist for several tens of milliseconds. This frequency will be about 10% higher than the desired frequency.

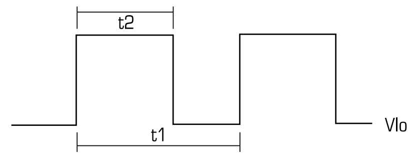
To reduce costs, do not prohibit B-mode from existing at initial start up.

It is possible to hand tune oscillators so that no B-mode is visible at start-up on a spectrum analyzer. However, this process is very costly, so normally a fixed capacitor is installed during assembly and subsequent testing reveals any problems.

Output Characteristics

The duty cycle of logic outputs should be specified no tighter than 50% ±5%. *A requirement of 50% ±10% is preferable as no production alignment at set up is necessary*.

Duty Cycle = t2 ÷ t1 * 100



Typical sinewave output levels are in the range of -3 dBm to +13 dBm and the typical load is 50Ω resistive. A tolerance of at least ±3 dB will lower costs as no production alignment at set-up is necessary.

Use the following formulae to convert oscilloscope readings into dBm:

$$dBm = 10\log\left[\frac{V^2_{peak}}{2\cdot R_{load}}\cdot 1000\right]$$

$$dBm = 10\log\left[\frac{V^2_{p\text{-}p}}{8\cdot R_{load}}\cdot 1000\right]$$

$$dBm = 10\log\left[\frac{V^2_{rms}}{R_{load}}\cdot 1000\right]$$

Harmonics and Subharmonics

Harmonics of a sinewave output can be cost effectively suppressed at a typical value of -25 dBc.

Certain combinations of frequency, aging rate and phase noise require frequency multiplication to obtain the benefits of lower crystal frequencies. Subharmonics that do not exceed -20 dBc can be achieved easily. Tighter demands require individual adjustment of tuned circuits in the oscillator to properly suppress the subharmonics.

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Spurious Responses

Spurious responses should be specified as "no greater than -70 dBc" due to the difficulty of viewing smaller levels on the spectrum analyzer.

In addition to the level, specify the range of frequencies that should be examined, eg., "within 100 KHz of the nominal frequency."

Spurious signals higher than -100 dBc are usually caused by untrapped B-mode in SC cut oscillators, LC tank free-running oscillations, RC free-running oscillations in the oven controller, UHF parasitics and external sources such as supply line ripple and mechanical vibration.

MTBF (Mean Time Before Failure)

The MTBF for a "ground fixed" OCXO using MIL-STD-217, Rev. F (Notice 1, Appendix A) is typically 200,000 hours. Appendix A is the parts count reliability prediction. As stated in the handbook, ground fixed is "moderately controlled environments such as installation in permanent racks with adequate cooling air and possible installation in unheated buildings; includes permanent installation of air traffic control radar and communications facilities."

The MTBF for a "ground benign" OCXO using MIL-STD-217, Rev. F (Notice 1, Appendix A) is typically 400,000 hours. As stated in the handbook, ground benign is "Nonmobile, temperature and humidity controlled environments readily accessible to maintenance; includes laboratory instruments and test equipment, medical electronic equipment, business and scientific computer complexes, and missiles and support equipment in ground silos."

Other Cost Saving Ideas

- Include the following statement at the beginning of the specification: *"All specifications apply for an ambient temperature of +25°C, ±5°C and nominal power supply voltage(s) unless otherwise specified."*
- Do not specify the crystal cut, ie., AT, SC, etc. This is best determined during the design phase of the oscillator.
- Do not specify conditions that necessitate the use of thermal fuses.
- If high reliability parts are required, allow the use of screened plastic encapsulated semiconductors.
- Do not specify that test data be sent with the oscillator, especially if phase noise and aging results are requested. At OFC, test data are routinely stored either in a computer database or in a hardcopy filing system at no additional cost.
- Always keep safety margins to reasonable levels. This is especially important for phase noise, g-sensitivity, aging and frequency-temperature stability.
- Completely specify parameters which will affect system performance. Redesigning the oscillator in order to meet undocumented requirements is time consuming and costly. On the other hand, do not include unnecessary parameters since this could lead to a more costly design.

Author: Mike F. Wacker
Senior Design Engineer

Aging and Retrace in Oven Controlled Crystal Oscillators

Quartz crystal oscillators are widely used as frequency and time standards in a variety of electronic systems. While quartz crystal oscillators are well suited to the task, best performance in demanding applications, as is true for any precision device, requires in-depth understanding of device idiosyncrasies.

Aging is the long term frequency drift of an oscillator. Though carefull design and manufacturing minimize aging at the time of shipment, aging continues for the life of the oscillator and is affected by the circumstances and duration of power-off storage. This paper highlights the physical processes responsible for aging and explains why, after being in power-off storage, a re-stabilization period is highly recommended prior to oscillator frequency adjustment.

Aging has two basic causes. First, the frequency of a quartz crystal resonator is strongly affected by electrode mass. Contamination of the electrode or the surface of the quartz blank increases resonator mass and thereby lowers the resonant frequency. Water vapor is a prime culprit of this type of contamination, though oxygen and hydrocarbons cause problems as well. Outgassing of the conductive adhesive used to mount the resonator in its enclosure is also a factor. Crystalline quartz and metallic electrodes are both porous at sub-microscopic scales with a huge number of small cavities that harbor contaminants. Contamination is always present at some level, but production processes such as ozone cleaning, high temperature vacuum bake, and the use of hard vacuum can minimize contamination effects to almost negligible levels.

Contamination would be much less of a problem if the contaminants would remain in place. Unfortunately, contamination on a new crystal, especially one installed in an ovenized oscillator operating at an elevated temperature, moves under the influence of evaporation, adsorption, condensation, and mechanical acceleration. As a result, a new oscillator ages quickly until contaminate movement stabilizes.

Mechanical stress is the second cause of oscillator aging. A crystal is an orderly lattice of atoms whose shape, along with the atomic spacing, determines the physical properties of the crystal such as dielectric constant and elasticity. Many of these properties affect resonant frequency. Mechanical stress deforms the atomic lattice, slightly changing the atomic spacing which in turn slightly alters the physical properties of the crystal. If the crystal lattice being stressed happens to be a quartz crystal resonator, the result is a slight change in the resonant frequency. For this reason, AT-cut resonators exposed to mechanical stress shift frequency. Doubly-rotated crystals such as IT- or SC-cuts are partially stress compensated and are affected less by stress. Therefore, re-stabilization times are less for doubly rotated cuts, but these resonators are much more difficult to manufacture and are more expensive than common AT-cut resonators.

Stress in quartz crystal resonators has many sources; mounting stress from the spring action of the mounting clips, contraction of conductive adhesive as it sets, residual stress from the cutting and grinding operation during manufacturing and differential thermal expansion and contraction. The last factor is particularly interesting in ovenized oscillators because the crystal is heated from room temperature to about 80°C every time power is applied, and because the coefficient of thermal expansion in crystalline quartz is different in each axis.

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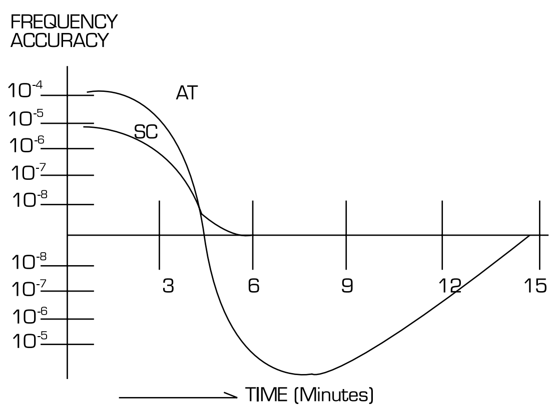
Because quartz conducts heat poorly, thermal gradients are steep and dissipate slowly. Ovenized AT-cut resonators undergo a strong, stress-induced frequency transient during warm-up, when the edge of the resonator, in contact with the mounting clip, is significantly warmer than the center. This transient is visible in the figure as the sharp frequency undershoot occurring at four to five minutes after turn-on. Residual stresses are at a maximum in a new oscillator just after turn-on, slowly relaxing during the first few days of operation until an equilibrium condition is reached.



Frequency shifts coming from contaminant re-distribution and stress relaxation amount to as much as a few parts per billion per day for a new oscillator. Standard practice at Oak Frequency Control Group is to burn in, or age, new oscillators while continuously monitoring frequency until daily aging rates stabilize. The amount of time needed depends upon the oscillator frequency and crystal cut along with the specified aging rate. Typical aging durations vary from less than a week to several weeks.

What happens when a new "well-aged" oscillator is turned off? Ovenized oscillators re-acquire mechanical stress as they cool down, the amount of stress being a function of the difference between the oven temperature and the ambient temperature. This stress eventually dissipates, although the rate of stress relaxation is much reduced at lower temperatures.

When the oscillator is turned off, contaminants begin to move again towards a new equilibrium condition. As before, the rate of re-distribution is much less at lower temperatures. If the power off time is brief, and the storage temperature is modest, the oscillator will return to an aging rate close to that measured at the time of shipment after a brief warm up period. The actual frequency is close – but not identical – due to hysteresis and because aging continues during power-off periods, although not necessarily at the same rate.

An extended power-off interval, or (according to some references on the subject) exposure to temperature extremes during the power-off interval allows a greater degree of stress relaxation and contaminant re-distribution. Some of the aging stabilization acquired during the original production burn-in is lost in this case. Therefore, when power is reapplied, a much longer re-stabilization period is needed to reach the previous aging rate. The re-stabilization period varies. Re-stabilization for a third overtone AT-cut ovenized oscillator after 24 hours represents very good performance for a non-stress compensated crystal. The presence of even a small amount of crystal contamination would significantly extend the re-stabilization period.

What does all this mean in practice? First, an ovenized oscillator should be continuously powered if at all possible. If power interruptions are unavoidable, be aware that the oscillator will take some time beyond normal warm-up to return to the prior aging rate and, because of aging and hysteresis, is unlikely to return to exactly the same frequency. Hysteresis for AT-cut resonators is unlikely to be much better than a few parts in 10^{-8}. Frequency adjustment during the re-stabilization period is not a good idea. With its extensive experience designing precision ovenized oscillators, OFC is able to assist in determining an appropriate re-stabilization period, especially if the power-offperiod exceeds a few days and a longer re-stabilization period is necessary.

Electrical Frequency Control in Crystal Oscillators

The output frequency of a crystal oscillator is adjustable by a certain amount. Electrical frequency control (EFC) requires an external circuit to adjust the frequency. The external circuit is either a DAC or a voltage divider made with a potentiometer (pot) or fixed resistors. An external voltage source provided by the customer or an internal reference voltage provided by OFC supplies power for this circuit.

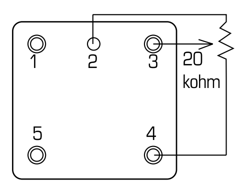
To operate the EFC with a voltage divider, one end goes to supply, the other to ground, and the middle to the EFC pin. The voltage at the middle is in the center of the tuning range. This voltage level is the offset. By varying the voltage, the frequency will change. With a positive slope unit, the frequency will increase with increasing voltage and decrease with decreasing voltage. With a negative slope unit, the frequency will decrease with increasing voltage and increase with decreasing voltage.

Using a DAC is essentially the same as using a voltage divider. If an internal reference voltage is present, it can supply power to the DAC. The analog output connects to the EFC pin, with digital input varying the voltage to operate the EFC.

For example, on the Model 4853, an internal reference voltage on Pin 4 supplies a stable voltage over temperature for the pot or DAC. Pin 3 is for the input voltage that operates the EFC. The offset voltage for nominal frequency is set at approximately 2V.

By increasing the voltage on Pin 3 by 2 volts (the swing voltage), the frequency will increase by roughly 8 ppm. By decreasing the voltage on Pin 3 by 2 volts, the frequency will decrease by roughly 8 ppm.

The figure below shows the basic set-up for EFC using a voltage divider made with a potentiometer for the Model 4853.



PIN CONNECTIONS
1 - RF Output
2 - GND
3 - EFC
4 - Output Reference Voltage (+4V)
5 - Supply Voltage

Model 4853 – Typical EFC Configuration

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OAK Frequency Control Group

Frequency Stability Characterization in The Time Domain

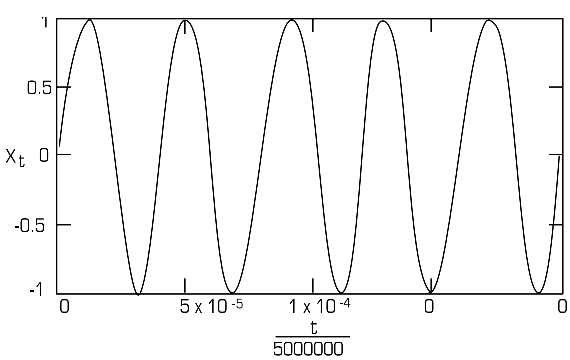
Noise Types

Many factors degrade the frequency stability of a crystal controlled oscillator. *Time, environmental conditions and deterministic/ non-deterministic noise will inevitably reduce the accuracy of an oscillator*. To some degree, contributions from all three categories exist during a stability measurement. If one were to consider the primary (desired) frequency polluted with phase modulation, the oscillator's output as a function of time could be represented as:

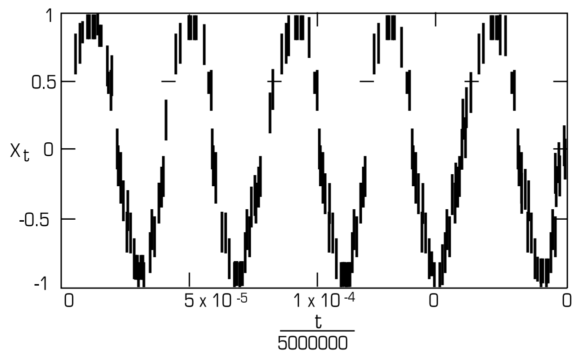
$$v(t) = A\left[\sin\left(2\pi\upsilon t + \phi(t)\right)\right] \text{ eqn. 1}$$

where A is the magnitude scaling factor
(which could be time varying)
υ is the frequency in Hz and ϕ is the modulated noise

The ideal situation occurs when the f term in equation 1 is zero. A noise free time domain signal in this situation would appear as follows:



With ϕ containing a white phase noise component, the signal becomes visibly degraded.



The non-deterministic (stochastic) noise types that are characterized in crystal oscillators include:

Random Walk Frequency
Flicker Frequency
White Frequency (random walk phase)
Flicker Phase
White Phase

As will be discussed further into this paper, each noise type has a unique character and can be identified by various measurement and calculation techniques. What follows is a short description of the noise sources. However, the source of each type of noise is not always clear cut.

- *Random Walk*

  Environmental factors such as mechanical shock, vibration and temperature fluctuations which cause random shifts in frequency

- *Flicker Frequency*

  Resonator noise and/or active component noise

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- *White Frequency*

  Often found when an XO is locked to a Ce or Rb standard

- *Flicker Phase*

  Noisy components

- *White Phase*

  Broadband noise from amplifier stages and components

Allan Variance

The frequency stability of most crystal controlled oscillators cannot be gauged using the classical definition of standard deviation. An oscillator's output contains many noise components that cause the classical standard deviation to give erroneously large answers since these components cannot be averaged. David Allan proposed a variant of the standard deviation formula that basically acts as a filter to many noise components. This new formula has become widely used and accepted and is known as the Allan variance (AVAR).

The exact expression for AVAR is the infinite set:

$$\sigma_y{}^2(\tau) = \frac{1}{2}\left[(\Delta y)^2\right] \quad \text{eqn. 2}$$

where Δy is the difference of two adjacent slopes (frequency)

Figure 1 illustrates the concept of the averaged frequency Δy.

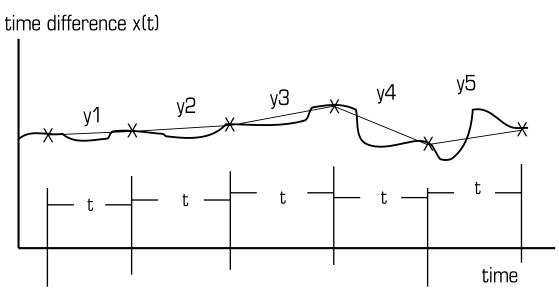

Figure 1

Allan variance can also be expressed in terms of phase measurements:

$$\sigma_y{}^2(\tau) = \frac{1}{2\tau^2}\left[(\Delta^2 x)^2\right] \quad \text{eqn. 3}$$

where Δ is the second finite difference operator and x is a phase measurement

An infinitely long data set is not practical, so as an approximation AVAR can be represented by:

$$\sigma_y{}^2(\tau) \approx \frac{1}{2\,(N-2)\,\tau^2}\sum_{i=1}^{N-2}\left(x_{i+2} - 2x_{i+1} + x_i\right)^2 \quad \text{eqn. 4}$$

where τ is the sample time, N is the number of samples, and x_n is time data

The approximation that is used most often (HP5372A, MIL-0-55310B, etc.) to calculate AVAR from a sample of averaged frequencies is:

$$\sigma_y{}^2(\tau) \approx \frac{1}{f_o}\sqrt{\frac{\sum_{i=1}^{N-1}\left(f_{k+1} - f_k\right)^2}{2\,(N-1)}} \quad \text{eqn. 5}$$

where f is the frequency data and N is the number of samples

The various noise components and how they can be identified on an AVAR plot are shown in figure 2. Note that white PM and flicker PM are not distinguishable. Be aware that deterministic noise processes will influence the curve as well. For instance if the unit has significant linear frequency drift, the slope of the noise curve at long taus will be greater than $t^{0.5}$.

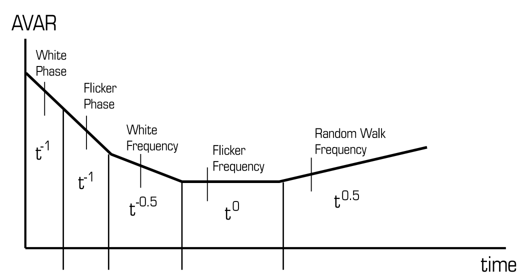

Figure 2

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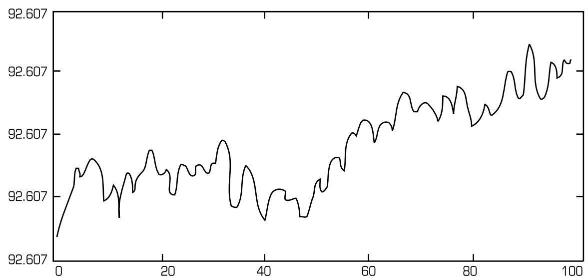
AVAR Example 1

100 consecutive frequency measurements were sampled at 1 second zero dead time. A plot of these data:



Using the AVAR formula:

$$\text{avar:} = \frac{1}{10000000} \cdot \sqrt{\left[\frac{\sum_i \left[x_{(i+1)} - x_i\right]^2}{2 \cdot (N-1)}\right]}$$

avar = 2.437373×10^{-12}

Using the classical standard deviation:

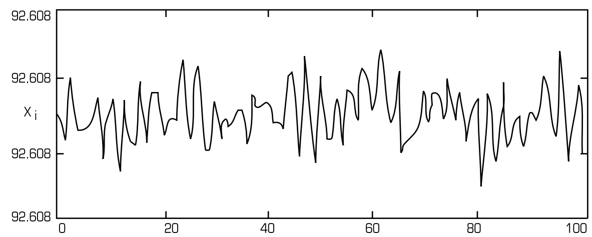
$$\text{stddev:} = \frac{\sqrt{\frac{1}{N-1} \cdot \sum_i (x_i - \text{mean}(x))^2}}{10000000}$$

stddev = 7.815191×10^{-12}

When non-white noise is present, the classical standard deviation formula will give a larger answer than the AVAR formula since divergence occurs.

AVAR Example 2

100 consecutive frequency measurements were sampled at 0.01 second zero dead time. Using the AVAR formula:



$$\text{avar:} = \frac{1}{10000000} \cdot \sqrt{\left[\frac{\sum_i \left[x_{(i+1)} - x_i\right]^2}{2 \cdot (N-1)}\right]}$$

avar = 2.289493×10^{-11}

Using the classical standard deviation:

$$\text{stddev:} = \frac{\sqrt{\frac{1}{N-1} \cdot \sum_i (x_i - \text{mean}(x))^2}}{10000000}$$

stddev = 1.915353×10^{-11}

At this observation time, the data are more white resulting in higher agreement between AVAR and classical standard deviation.

Effects of Frequency Drift on AVAR

It is important to note that drift due to aging or warm-up will inflate AVAR results. The oscillator must be allowed to stabilize completely after application of power. One method of dealing with a "fast" aging oscillator is to assume a linear slope between the starting and ending frequencies and remove the slope component from the data. The influence frequency drift has on AVAR is illustrated in the following example set.

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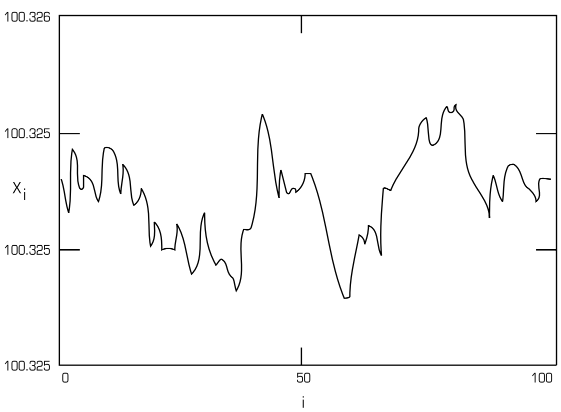
Calculations are performed on a data set consisting of 100 readings taken with zero dead time at $\tau = 1$ second from two 10 MHz oscillators separated by 100 Hz.

No Drift:

$i := 0..(N - 2)$

$$avar := \frac{1}{10000000} \cdot \sqrt{\left[\frac{\sum_i \left[x_{(i+1)} - x_i\right]^2}{2 \cdot (N-1)}\right]}$$

$avar = 3.578 \times 10^{-12}$



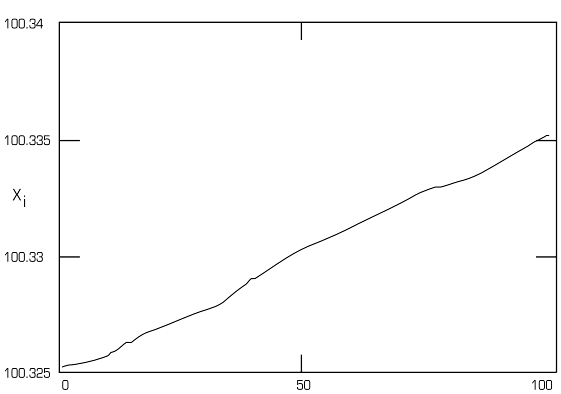
0.00001 ppm/second Drift:

$x_i := x_i + i \cdot 10^{-11} \cdot 10^7$

$i := 0..(N - 2)$

$$avar := \frac{1}{10000000} \cdot \sqrt{\left[\frac{\sum_i \left[x_{(i+1)} - x_i\right]^2}{2 \cdot (N-1)}\right]}$$

$avar = 7.924 \times 10^{-12}$



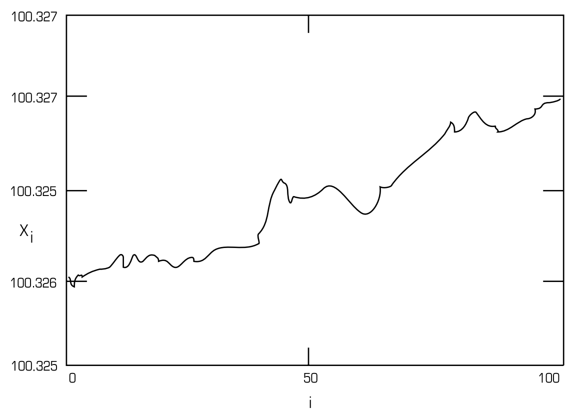
0.000001 ppm/second Drift:

$x_i := x_i + i \cdot 10^{-12} \cdot 10^7$

$i := 0..(N - 2)$

$$avar := \frac{1}{10000000} \cdot \sqrt{\left[\frac{\sum_i \left[x_{(i+1)} - x_i\right]^2}{2 \cdot (N-1)}\right]}$$

$avar = 3.647 \times 10^{-12}$



From this, one can conclude that drift becomes significant when the rate of change is higher than the static AVAR.

Effects of Vibration on AVAR

Vibration modulated sidebands will appear on a phase noise plot or spectrum analyzer during the measurement of a quartz crystal resonator undergoing vibration. Likewise, degradation is expected under the same conditions when making an AVAR measurement. The absolute best performance that will be obtained during sinusoidal vibration can be predicted with equation 6.

$$\sigma_y{}^2(\tau) = \frac{\vec{\Gamma} \cdot \vec{A}}{\pi f_v \tau} \sin^2(\pi f_v \tau) \qquad \text{eqn. 6}$$

where Γ is the resonator g-sensitivity
A is the acceleration level in g's
f_v is the vibration level
τ is the sampling interval

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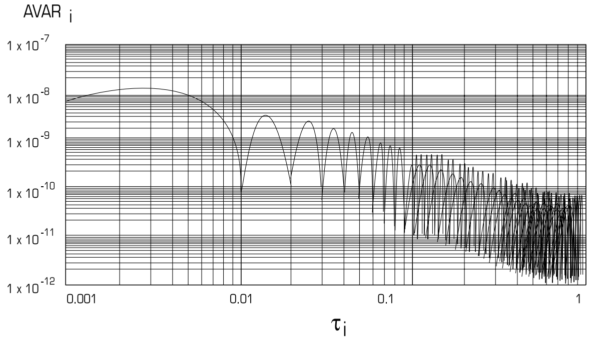
An example of AVAR during vibration:

Given that an oscillator with static root AVAR of $10^{-12}/\tau$ is subjected to a vibration frequency of 100 Hz at 10 g's and that the resonator g-sensitivity is 2×10^{-9}/g, the resulting AVAR will be:



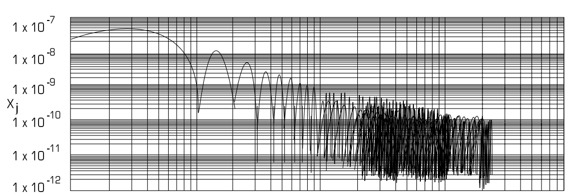
Notice that peaks occur when $\tau = (2n+1)/(2f_v)$ and valleys occur when $\tau = (n+1)/f_v$ for n = 0, 1, 2 ....

Effects of Voltage Supply Ripple on AVAR

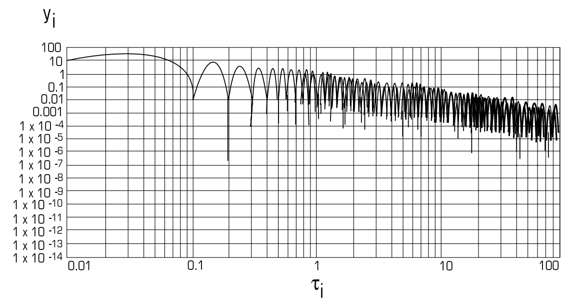
Modulating an oscillator's EFC or supply voltage with a sinusoidal signal will degrade AVAR at observation times that are dependent on the frequency of the polluting signal. The formula to predict this is:

$$\sigma(y) = \frac{X_{pp}}{\tau} \cdot SIN^2(š \cdot \partial_m \cdot \tau) \quad \text{eqn. 7}$$

Example: An OCXO was modulated on the EFC line by a 10 Hz signal and 8000 samples at tau = 0.01 seconds were taken.



Compare this with the theoretical result using equation 7 assuming static AVAR performance to be $10^{-12} \div \tau$:



Frequency → Time Domain Translation

Frequency domain measurements can be translated into time domain equivalents. Thus, Allan variance can be computed from the power spectral density as follows.

$$\langle \sigma_y^2(N,T,\tau) \rangle = \frac{N}{N-1} \int_0^\infty S_y(f)\, \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} \left\{ 1 - \frac{\sin^2(\pi r f N \tau)}{N^2 \sin^2(\pi r f \tau)} \right\} df$$

where $r = T/\tau$; N = 2 for 2 sample Allan variance

This equation can be simplified to:

$$\sigma_y^2(\tau) = \frac{2}{(\pi V_0 \tau)^2} \int_0^\infty S_\Phi(f) \sin^4(\pi f \tau) df \quad \text{eqn. 9}$$

Be aware that translations from time domain to frequency domain cannot be readily accomplished.

Noise components on a frequency domain plot.

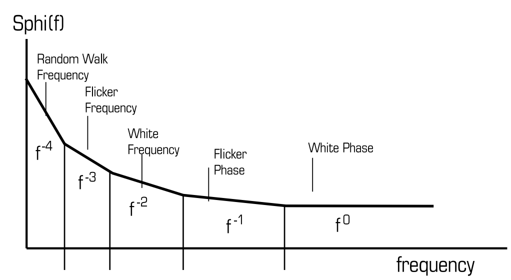


Figure 3

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Additional AVAR Information

- *A minimum of 3 readings is required to compute AVAR for a given tau.*
- *The IF frequency must be higher than 1/τ.*
- *The degree of uncertainty of an AVAR measurement is inversely proportional to the square root of the number of samples:*

$$\text{Uncertainty (rms)} = \frac{1}{\sqrt{N}} \cdot 100\% \qquad \text{eqn. 10}$$

- *Fractional frequency stability such as AVAR is not affected by multiplication or division as long as the electronics used is noise free. This contrasts to frequency domain measurements such as single side band phase noise in which improvement or degradation follows 20log(N) where N is the multiplication or division factor.*
- *Allan variance and the standard variance will yield the same results if only white PM is present on the signal. Standard variance diverges in the presence of random walk noise.*
- *If measurements are made with no interruption for data transfer between readings, then one can boast of "zero dead time". As a consequence, if the measured tau is 1 second then AVAR can be calculated for integer multiples of 1 second, ie., 2s, 3s, 4s, ..., until the number of 1 second samples divided by the integer multiple becomes less than 3.*

  For example, suppose 1000 readings at 1 second gate time have been taken on the HP5372A modulation domain analyzer. This machine is a zero dead time data accumulator with a maximum sampling period of 8 seconds. If we needed to know AVAR for τ = 10 seconds, this is the procedure:

  Average the first 10 frequency readings. Then average the next 10 frequency readings and the next and the next until 100 averages have been obtained. Each of the 100 samples represents τ averaged over 10 seconds. Using equation 5 will yield AVAR for 10 second sampling.

  It is important to remember that this procedure is valid only when the test method yields zero dead time.

Modified Allan Variance

As stated earlier, the Allan variance filter cannot distinguish between white PM and flicker PM. Synchronization networks require frequency standards which have good time or phase stability. White PM and flicker PM levels are an important indicator of time/phase stability. Therefore, another algorithm is necessary to distinguish the various noise components. Modified Allan variance (MVAR) will discern white PM and flicker PM.

MVAR is defined as:

$$\text{mod}\,\sigma_y^{2}(\tau) \approx \frac{1}{2\tau^2}\left\{(\Delta^2\bar{x})^2\right\} \qquad \text{eqn. 11}$$

where Δ is the second finite difference operator and
x bar is the phase average

It is not greatly different from ordinary Allan variance. An approximation for MVAR using a finite set of measurements is:

$$\text{mod}\,\sigma_y^{2}(\tau) \approx \frac{1}{2\tau^2 n^2(N-3n+1)}\sum_{j=1}^{N-3n+1}\left[\sum_{i=j}^{N+j-1}\left(x_{i+2n}-2x_{i+n}+x_i\right)\right]^2$$

where x are time error measurements
N is the number of time error measurements spaced by τ_o
$\tau = n\tau_o$ where τ_o is the minimum data spacing of the sample eqn. 12

Equation 12 is illustrated in figure 4.

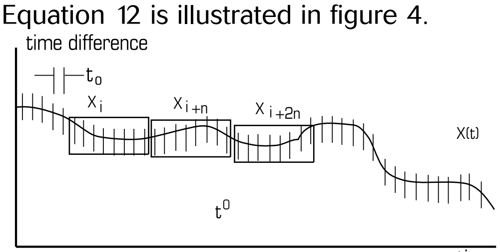

Figure 4

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The contrast between white phase and flicker phase becomes apparent:

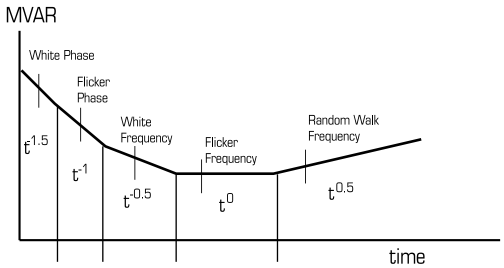

Figure 5

Time Variance and Time Deviation

Since switching networks depend on clocks with very good time or phase accuracy, a measure of stability is needed for this domain. MVAR can distinguish between white PM and flicker PM, however it is calculated from frequency measurements. We need the functionality of MVAR in the time domain and when the translation is made we end up with TVAR.

TVAR is accurately described by the following expresion:

$$\sigma_x^2(\tau) = \frac{1}{6}\left[(\Delta^2 \bar{x})^2\right] \quad \text{eqn. 13}$$

Note the close similarity to modified Allan variance.

For a finite set of data TVAR can be solved using:

$$\sigma_x^2(\tau) \approx \frac{1}{6n^2(N-3n+1)} \sum_{i=0}^{N-3n}\left[\sum_{j=0}^{n-1} x_{i+2n+j} - 2x_{i+n+j} + x_{i+j}\right]^2$$

where x are time error measurements
N is the number of time error measurements spaced by τ_o
$\tau = n\tau_o$ where τ_o is the minimum data spacing of the sample eqn. 14

Time deviation (TDEV) is simply the square root of the time variance.

TDEV:

$$\sigma_x(\tau) = \sqrt{TVAR} \quad \text{eqn. 15}$$

The relationship between modified Allan variance and TVAR is:

$$\sigma_x(\tau) = MVAR \cdot \frac{\tau}{\sqrt{3}} \quad \text{eqn. 16}$$

Measurement Pitfalls

Minimize the following when performing measurements for frequency stability:

- *TIME*
  Aging
- *ENVIRONMENTAL CONDITIONS*
  Temperature fluctuations
  Gravitational field variations
  Electromagnetic field variations
  Ambient pressure changes
  Physical pressure changes
  Vibration/shock
- *NOISE*
  Power supply noise
  Mixer/amplifier trigger noise
  Mixer IF bandwidth
  Ground loops

Author: Mike F. Wacker
Senior Design Engineer

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Quartz Frequency Control Devices For Wireless Base Stations

Introduction

Today's steadily increasing market for wireless communications has brought on a number of new types of component needs and associated solutions. In the area of frequency control devices, a multitude of new needs are being addressed. Quartz crystal controlled oscillators are being deployed to serve many functions in wireless land based systems; as broadcast references, as data recovery and transmission clocks into and out of the public switched network, for system timing and control functions, as GPS filters, and a host of other ways.

Focus

In this paper the focus will be on OCXOs (Oven Controlled Crystal Oscillators), these being the most stringently and thoroughly specified oscillators in the system, and the frequency references for the broadcast stability and timing of many wireless systems today.

Circuit theory and overall performance aspects of various OCXOs are reviewed with their usage and capabilities explained, and suggestions how to specify them to get the most from these critical devices. The concepts and usage considerations discussed here can be expanded to any type of crystal controlled oscillator.

System Review

Wireless voice and data systems have become a necessity for effective business and personal communications. Cellular phone, paging, and PCS networks are rapidly expanding. Systems of importance today are reviewed in Table 1 below. The wide range of technologies requires a multiplicity of quartz oscillators for system operation. Four categories are, in general, prevalent: clocks, TCXOs, VCXOs and OCXOs. For all, the important questions are the same: what is the frequency stability and accuracy under various operating conditions, and what modulation characteristics (if any) are compatible with my system?

System Oscillator Usage

Most cellular phone and paging systems have similar requirements for frequency accuracy of broadcast. A number of schemes are used to guarantee that such accuracy is maintained. These range from use of master atomic clock frequency references to GPS satellite receiver controlled systems to those with a simple TCXO providing the needed reference. Figure 1 shows a typical block diagram for the land transmitter portion of a CDMA cellular system. In this example, broadcast occurs via an 800-900 MHz VCO which is locked to an OCXO

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Table 1 System Specifications for Wireless Communications Networks

	CELLULAR				PAGING	PCS	IN–FLIGHT
	GSM	NADC	PDC	CDMA			
Frequency Range	890-960 MHz	824-894 MHz	890-1513 MHz	824-894 MHz	900 MHz	800 to 2200 MHz	1500 MHz
Data Structure	TDMA	TDMA	TDMA	CDMA	TDMA Simulcast	TDMA	TDMA/ FDMA
Modulation	GMSK	DQPSK	DQPSK	QPSK	Various	Various	Various
Typical Frequency Accuracy	±50 PPB	±100 to ±300 PPB	±50 PPB	±50 PPB	±50 PPB	±1 PPB	±100 to 300 PPB

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for long term frequency control and modulated with data or voice for information transmission.

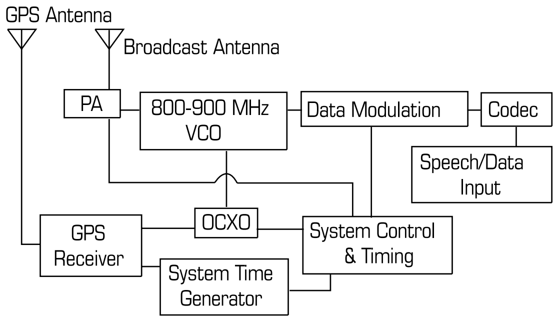
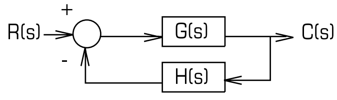


Figure 1
CDMA Fixed Land Transmitter Block Diagram

In US implementations of CDMA cellular, a GPS satellite receiver generated signal is used as the master timing element which controls the precise timing of timeslots being broadcast. Here, the OCXO is also being controlled by the received GPS signal which allows for monitoring and potential correction of the OCXO frequency.

Oscillating Loop Fundamentals

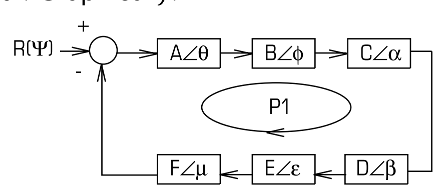
All feedback oscillators can be represented as basic servo systems operating under a condition where instability occurs. At this point, the system equations break down and an oscillation takes place at a limit cycle, the amplitude of which is limited by the non-linearities of the system. Figure 2 illustrates a block diagram of a feedback system. Manipulation of the transfer functions G(s) and H(s) can allow representation of just about any closed loop system, including an oscillator.



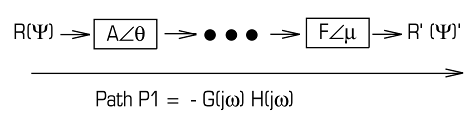
$$T(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)\,H(s)}$$

Figure 2
General Feedback System Diagram

The transfer function T(s) has zero factors in the numerator and pole factors in the denominator. Of importance are the pole factors, for the eigenvalues of these factors provide the frequencies at which oscillations may occur. The general function T(s), is seen to have a denominator of I+G(s)H(s). Assuming G(s) and H(s) are frequency dependent functions, it is seen that at the frequency where G(s)H(s) = -1, the function becomes infinite and oscillations occur. Difficulties now occur since the system now is at a singularity that is not described by the pre existing transfer function T(s) and limited knowledge is obtained by this closed loop analysis other than an estimate of the frequency of oscillation. If we let the Laplace variables decay to the steady state, we can open the loop and utilize a simple open loop method for oscillator design and analysis. Figure 3 plots the transfer function T(jw) as G(jw)H(jw) takes on a range of values. Clearly, we observe regions of negative feedback, regions of positive feedback and a region of oscillation. In the steady state, G(jw) and H(jw) are made up of some group of elements each having an overall net gain and phase shift characteristic. Since the product must equal -1 for oscillations to occur, we can open the loop and solve for conditions where this occurs. At this point, we have determined if, and at what frequency, oscillations will occur. Graphically:



Here, G(jw) and H(jw) are arbitrary transfer functions of magnitude and phase angle. We can break the loop and get the following:



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Energy at the input comes out the end of the opened loop modified by the transfer functions. For oscillatory feedback to occur when the loop is closed, the overall open loop transfer function, Pl, must have a magnitude greater than or equal to 1 (gain) and a phase angle of zero degrees (or an integer multiple of 360 degrees). This is referred to as the Barkhausen Criteria for oscillation.

Phase Slope and Stability Implications

For stable, accurate oscillators, control of the phase angle is critical and essentially determines the stability of the oscillator.

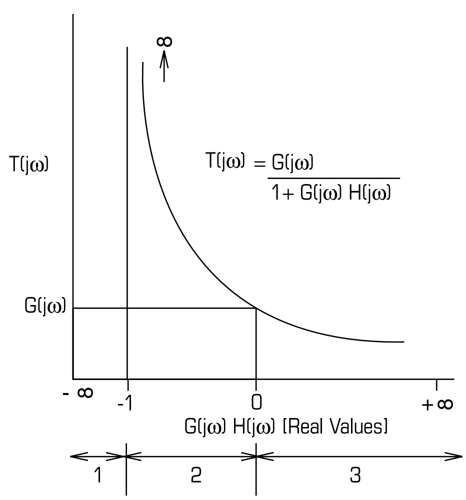

Figure 3
Closed Loop Gain vs. G(jω) H(jω)

Gain in appropriate and controllable amounts is generally obtainable and is usually of lesser concern. Observing Figure 4, we have a simplified schematic diagram of an ovenized oscillator circuit. The Gain-Phase plot for this configuration is shown in Figure 5 when the loop is opened. We see that gain greater than 1 exists over a range of frequencies and that a zero phase crossing exists in this same range. This satisfies Barkhausen's Criteria and predicts oscillations to occur. The key factors for frequency stability of this oscillator is the slope of the phase plot as it crosses zero and our ability to keep the phase zero point from shifting in frequency due to external variables and operating conditions.

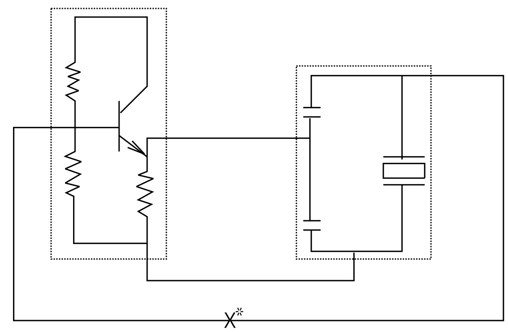

Figure 4
OCXO Oscillator Circuit

The high stability of an OCXO is directly attributable to the steepness of the phase slope and the accuracy to which it is maintained. Since the frequency of oscillation occurs where the phase function crosses zero, all the components of the oscillator loop affect the frequency of oscillation. Therefore, part of a designer's concern is that all components are stable in impedance. A shift in transistor junction capacitance or an inductor will cause an undesirable change in the operating frequency. To combat this, resonators with very high slope reactance vs. frequency functions within their bandwidths are utilized in OCXOs. This forces the loop phase slope to cross zero phase with a very high slope. Therefore, component instabilities or drifts which cause a change in loop phase will cause very small changes in frequency because the resonator supplies a new value of impedance for loop zero phase at only a very slightly shifted frequency. For this reason, low frequency third and fifth overtone AT and SC cut crystal resonators are almost always used for best stability. Figure 6 illustrates the desirability of the steep phase slope in an oscillator.

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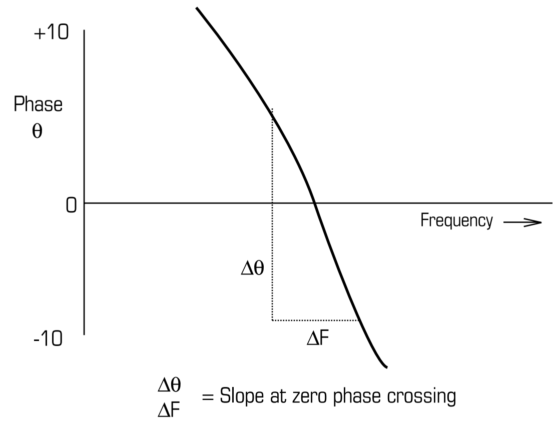
With its high reactance slope (dX/dF), the resonator overwhelmingly controls the oscillator's frequency. The other phase shift contributing components can only modestly affect the frequency. With a third overtone 5 MHz SC cut resonator, a 50% change in a capacitor value in the circuit may only cause a few parts in 10^7 change in frequency. However, stabilities in the 10^{-10} or 10^{-9} arena are typically sought in precision OCXOs, and a 10^{-7} shift may be disastrous. The stiff resonator is seen to 'correct' for phase variations in the loop, thereby reducing the effect of drift, snaps and temperature coefficients of the other components in the loop and frequency stability is maintained.



Steep loop phase-frequency slope attributable to stiff resonator allows for a small ΔF for a given Δθ in oscillator loop phase caused by a shift in an oscillator component value.

Figure 6
Oscillator Loop Phase Slope

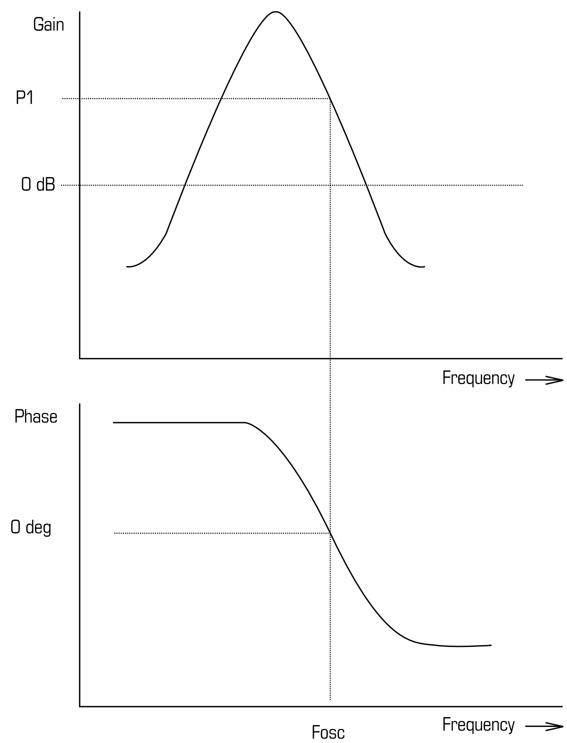


Figure 5
Open Loop GainÐPhase Plot

Stability of Phase Zero Crossing

We have seen how the slope at zero phase is important for frequency stability. The second main factor is how much the position of this curve moves with respect to frequency for various operating conditions. In other words, how constant the point is at which zero phase occurs. Referring to Figure 7 we see the effect in question.

The operating frequency of the oscillator can change due to a translation in frequency of the entire phase curve. This is usually a resonator effect. The temperature coefficient of the resonator will dictate that the resonant frequency of the resonator moves as a function of temperature with the phase curve shape remaining essentially unchanged. Another such effect occurs when the resonator 'ages', or drifts, in frequency with time due to physical changes in the resonator itself. Again, low frequency overtone, and therefore physically large, resonators are chosen to minimize the occurrence of aging.

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The overwhelming effect, however, in terms of frequency change, is the TC.

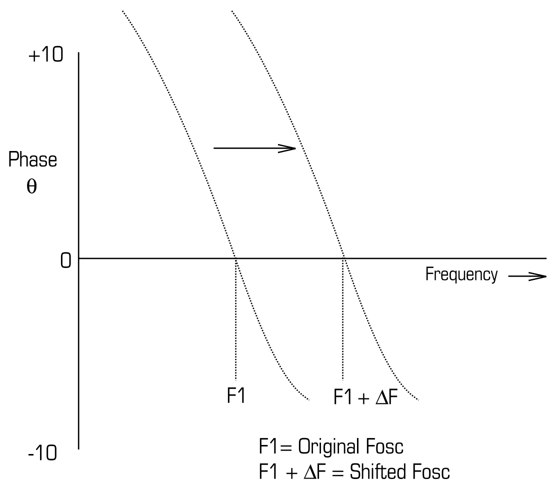

Figure 7
Effects of Resonator Frequency Shift

In practical situations, the TC of a resonator can only be modestly controlled. Therefore the need for a well designed thermally controlled oven is paramount.

OCXO Design Considerations

From the previous discussions, we see that three main areas of design performance are the characteristics of a highly stable OCXO. They are:

1. A high precision quartz resonator. Usually a third overtone AT or SC cut crystal. This provides for a high slope of phase vs. frequency at the frequency of oscillation, thereby minimizing the effect on frequency of instabilities in the impedance (and therefore phase shift) of the other circuit elements. The resonator is the chief controller of the long term aging of the oscillator's frequency. Its sharp phase slope minimizes the effect of other component aging. Precision processing of the crystal makes for very slow aging of the resonator's intrinsic frequency.

2. An electrically stable circuit design which resists changes in loop phase due to voltage variations or changes in load and has well controlled component TCs and component aging.

3. An extremely stable oven section which isolates the crystal and oscillator circuit components from ambient temperature changes which affect frequency.

These three tenets of design are key to achieving OCXO performance needed in today's wireless applications.

Transmit & Timing Control Applications

From the previous section, we find that the main reason to include an OCXO in a wireless transmitter is for broadcast center frequency control or time of broadcast control. Care must be taken such that the oscillator provides the system with a frequency reference that does not drift out of needed limits. Various factors of instability must all be allotted for or periodically corrected out of the system.

OCXO → $F(t) = A\cos(vt + \phi)$

The OCXO is charged with producing a frequency output F(t). Unfortunately, A, v, and f turn out to be functions of time, voltage, environmental stresses, etc., which provide for instability and inaccuracy of the output frequency. Usually, in transmitters, it is the aging, or long term drift, of frequency that is of most concern. Other effects can be designed down to a point where they are not a problem. The methodology of correction of this error is a task of the system designer and numerous ways are practiced. Figure 8 capsules several implementations in practice today. Type 8a is a free running OCXO with no provision to correct the frequency. While this may provide a very good reference (holding perhaps tens of parts per billion per year), unless the required system accuracy is fairly loose, the long term drift will probably cause unacceptable frequency error after several years in service.

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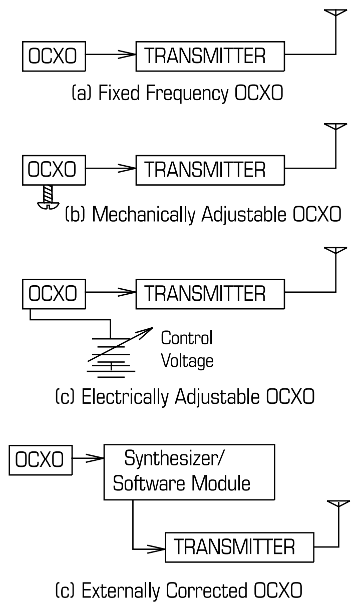

Figure 8
Frequency Correction Methods

Type 8b is correctable via a mechanical adjustment port. Periodic adjustment will allow for the frequency to always be within tolerance and give long system life. This method is manual, however, and may be unreliable due to the inherent human element. Type 8c uses Electronic Frequency Control (EFC) and is the preferred method from an oscillator design standpoint because troublesome mechanical trimmers are not used. This not only eliminates an undesirable part, but preserves design freedom since the OCXO assembly no longer has to be designed to position an externally accessible trimmer in a prescribed location. This method is compatible with software-based control of the oscillator frequency. Type 8d is an implementation where the OCXO drives a module which can synthesize the correct frequency from an oscillator that may have some error. The oscillator is non-adjustable and may drift out of system tolerance limits. The external correction is applied as needed via information from periodic measurements of the systems output against a known reference frequency. A common method of obtaining an accurate frequency reference is the use of GPS satellite signals. Figure 9 shows a configuration where an OCXO or Rubidium oscillator is locked to a GPS signal.

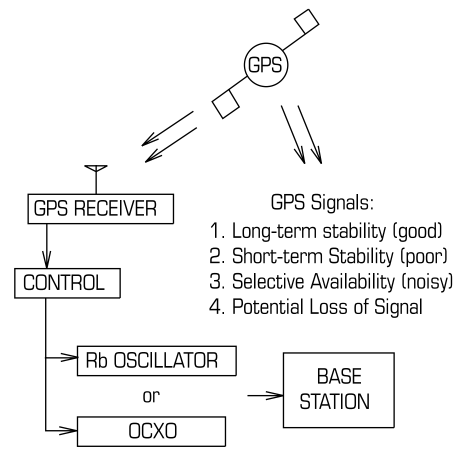

Figure 9
OCXO Locked to GPS Signal

This provides essentially perfect long term accuracy of frequency and overcomes the poor short term stability of the GPS signals. The OCXO acts as a filter to the GPS signal, and is called on to maintain accuracy if the GPS signal is unavailable, and remains a necessary component of the system.

Electronic Frequency Control

The Electronic Frequency Control port is a critical interface between the oscillator and host system. Specification of characteristics is very important. As a minimum, the following should be specified:

1. Voltage range of adjustment
2. Deviation range of frequency
3. Polarity
4. Rate of adjustment or bandwidth
5. Temperature coefficient of control circuit
6. Ripple or noise present on control line
7. Curve fit of transfer function (optional)

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System designers should take steps to minimize the noise on the control line as this will directly frequency modulate the oscillator and create sidebands.

The temperature coefficient of the supply voltage and control circuit must be kept low. If not, the TCs from the EFC control line voltage will increase the drift of frequency vs. temperature beyond what the OCXO inherently produces. The frequency deviation range should be no more than is needed to pull the oscillator back to nominal frequency under all operating life conditions. Excessive deviation range will compromise the oscillator overall stability. The system should be designed to tolerate 10-15% linearity error in the EFC transfer function.

Since many systems rely on DACs to drive the EFC control port, opportunities exist to make use of mathematical fit approximations of EFC curves. Figure 10 illustrates how an EFC transfer function may look.

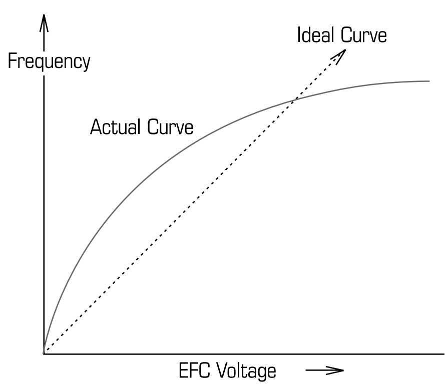
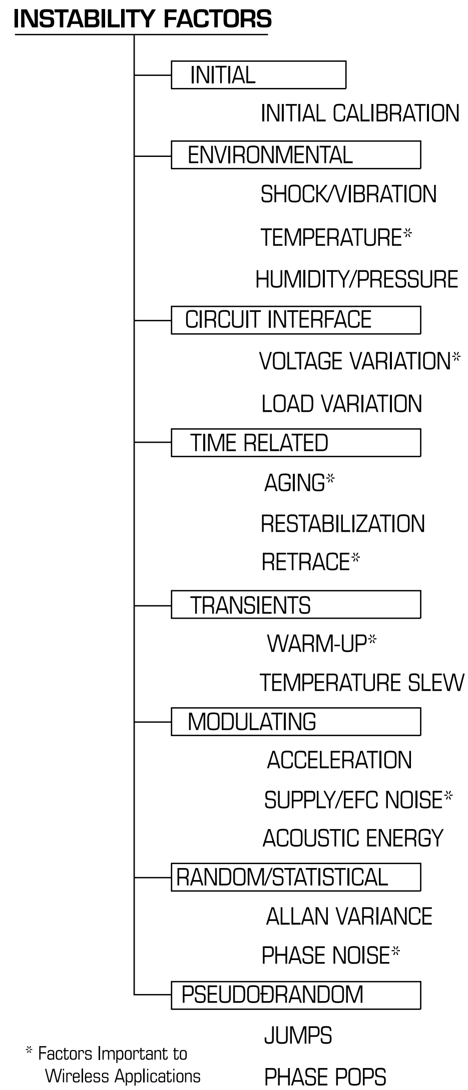


Figure 10
EFC Transfer Function Example

Here we note that a deviation from an ideal straight line is the norm. Typically some number is calculated to describe the linearity of the curve or departure from ideal. This is of limited value in that it is a single number and does not provide any information specific to any point on the curve. Instead of this concept, we can curve fit the function and provide accurate information at all points on the curve. The curve fit data is presented as coefficients to a known equation which allows the user to make precise adjustments to the oscillator frequency via software control. The broadcast can be monitored remotely and correction instructions can be sent back and made based on a knowledge of the current EFC voltage setting and the curve equation. Frequency corrections to within a few parts per billion accuracy are achievable by this method.

Figure 11
OFC "Oak Tree" of Instability Factors for OCXOs



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Overall Oscillator Stability Considerations

The successful use of an oscillator requires that appropriate specifications are established via an understanding of performance trade-offs. As discussed earlier, the three tenets of design are the key to premium performance. The oscillator designer must distribute 'design costs' among the tenets for the best design solution. Since a host of factors will affect the stability of an oscillator, it is best to think in terms of an 'overall stability' need required by the system for proper operation and then budget this among the various factors for the best cost/performance resultant oscillator. From work done specifying numerous wireless OCXOs at OAK Frequency Control, a tree of instability factors has been developed to guide the development of OCXO specifications. This is shown in Figure 11, noting the factors of most critical performance to the wireless OCXO user. From an overall system frequency accuracy need, a Stability Budget allocation should be made for the optimum design solution. Borrowing from Table 1, we have typical system frequency accuracy needs:

GSM	PDC	D-AMPS	PAGING
±50 ppb	±50 ppb	±250 ppb	±50–1OO ppb

These are clear-cut limits of frequency tolerance needs for broadcast or timing of system operation. Using, for example, the GSM requirement of ±50 parts per billion overall frequency tolerance, a potential stability budget might look like this:

Instability Factors	1 Year Calibration Cycle	3 Year Calibration Cycle
Temperature: (-30° to +65°C)	±4 ppb	±2 ppb
Voltage (± 5%):	±5 ppb	±2 ppb
Load (± 10%):	±1 ppb	±1 ppb
Retrace/ Restabilization:	±10 ppb	±5 ppb
Aging: (1 or 3 years)	±25 ppb	±35 ppb
Environmental: (Shock/Vib/Hum)	±5 ppb	±5 ppb
Max. Error over Calibration Period:	±50 ppb	±50 ppb

In this example, budgets are developed to accommodate l year or 3 year calibration periods. The oscillator total allowable error has to be weighed against the system ability to re-calibrate the OCXO, thereby periodically removing the accumulated error due to aging. Frequent re-calibration eases aging requirement (and cost) for the OCXO. Conversely, the better aging that is supplied, the longer the calibration period may be. For state-of-the-art aging performance and longest calibration cycles, Oak Frequency Control produces custom precision SC cut (Stress Compensated) crystals for use as the OCXO resonator. Best performance is had with low frequency (i.e. 4 to 10 MHz) third overtone SC resonators. These OFC OCXOs can supply needed tolerance frequencies for the tightest wireless network stabilities without frequency corrections applied for periods of 5 years or more. The state-of-the-art for overall stability of a production volume OCXO would be represented in the OFC Model 4834 which can achieve stability budgets as per the following:

OFC Base Station Standard - Model 4834

Temperature (-30 to +70°C):	<2 ppb
Load Variation(50 ±10%):	<1 ppb
Voltage Variation (+12V ± 5%):	<1 ppb
Shock/Vibration (Bellcore Specs)	<2 ppb
Retrace (30 days offtime)	<5 ppb
Aging (1 Year operation)	<10 ppb
Worst Case Frequency Error:	^{2}20 ppb/l Yr
	^{2}50 ppb/5 Yr

It should be realized that for most precision resonators, the aging rate decreases with time. Therefore, the five year aging rate can be specified as less than a linear extrapolation of the aging offset encountered in the first year. Aging predictions and methods of compliance testing are complex undertakings. At OFC, ongoing tests take place to establish long term performance capabilities of product. A number of test and extrapolation methods have been developed for production testing and for long term qualification verification.

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Suffice to say, however, a picture gives the best image of the displacement of frequency due to aging. Figure 12 shows typical aging plots for OCXOs produced at OFC.

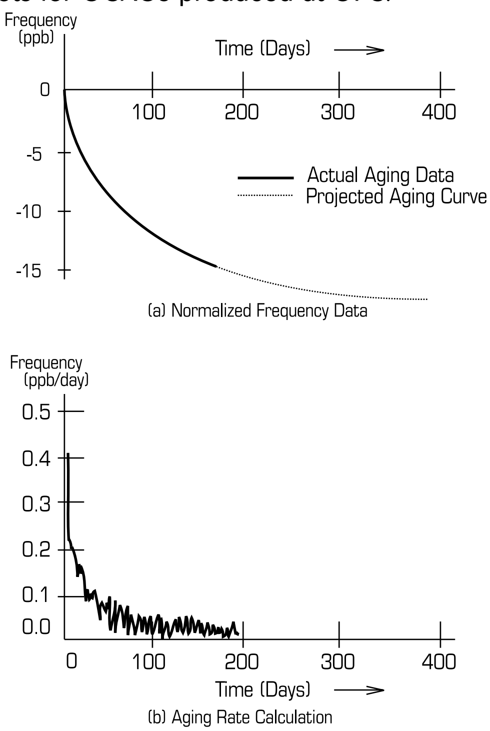

Figure 12
Long Term Aging Performance of
OFC Model 4834 OCXO

Data has been taken on a custom automated measurement system which calculates rate of change of frequency and mathematically curve fits data for projection of long term performance. The proprietary curve fitting solutions developed have been verified to be good models for predicting future performance of the OCXO aging.

It should be kept in mind that the stability budget examples as presented so far only represent worst case analysis results. The maximum frequency errors would only be reached if all factors added up in the same direction simultaneously.

In general, aging should only be assumed to be progressive and always at its worst case value. The other instability factors change with external inputs (i.e. voltage, temperature, etc.) and will randomly be at various values within their range of influence. The performance at any given time is equal to the sum of the instantaneous values of the 'vectors' of all the instability factors. Therefore, everyday system performance is typically better than worst case stability numbers give. Figure 13 illustrates the various vectors coming into play. Stability can be seen to be typically much better than the "Worst Case Scenario".

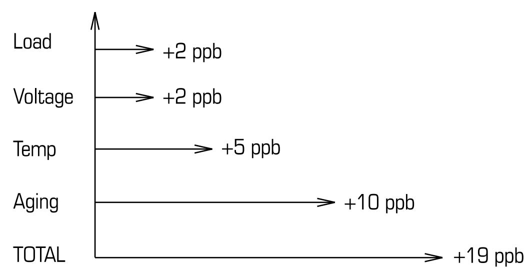

Figure 13 (a)
Vectors Summed at Maximum Value

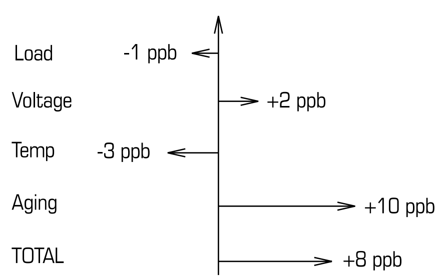

Figure 13 (b)
Vectors Summed at Instantaneous Value

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OAK Frequency Control Group

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Conclusion

Wireless systems are well served by precision Ovenized Oscillators for precise frequency control. System designers can use the principles reviewed here for understanding, specifying and obtaining the best performance cost benefits from OCXO products. The general methods of specification and analysis described here can be extended to all types of quartz oscillator products such as TCXOs and VCXOs.

Author: Dan Nehring
Precision Oscillator Engineering Manager

References

1. *Sentz, Bartkowiak; Feedback Amplifiers and Oscillators; Holt, Rinehart & Winston, 1968.*

2. *Varall, Belcher; Data Over Radio; Quantum Publishing, 1992.*

3. *Dorf; Modern Control Svstems; Addison Wesley, 1974.*

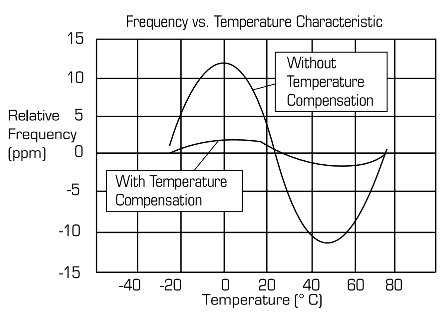
4. *Boucher, The Cellular Radio Handbook; QuantumPublishing, 1992.*

5. *Hewlett-Packard Company; Digital Communication System Basics; Hewlett-Packard (Spokane Div.), 1992.*

Temperature Compensated Crystal Oscillators

What Is a TCXO?

A TCXO (Temperature Compensated Crystal Oscillator) typically consists of a precision quartz crystal, a temperature compensation network, an oscillator circuit and a variety of buffer and/or output stages determined by the output requirement. The temperature compensation network is used to sense the ambient temperature and “pull” the crystal frequency in a manner that reduces the ‘frequency vs. temperature’ effect of the quartz crystal. Because each crystal has a temperature characteristic that is as unique as a fingerprint, OFC uses a computer generated temperature compensation network that is tailor made for each individual crystal. The form and configuration of the temperature compensation network will vary greatly depending on requirements such as input voltage, temperature range and temperature stability



When to Use a TCXO

A TCXO is generally required when overall stability needs fall between those of a clock oscillator on the low end and an ovenized oscillator on the high end. Also, the long term aging effects of a TCXO are better than those of most clock oscillators.

Advantages of a TCXO

- *Tighter Frequency vs Temperature Stability than a Clock Oscillator*

  ±0.2 ppm to ±5 ppm typically

- *Improved Aging with respect to a Clock Oscillator*

  Typically ±1 ppm per year, ±5 ppm for 10 years

- *Lower Power Consumption than an OCXO*

  Typically 10 to 50 milliwatts on a ±5 VDC TCXO and up to 150 milliwatts depending on input voltages and output requirements

- *Smaller Package Volume than an OCXO*

  Typically from 0.125 cubic inches to 2 cubic inches

Disadvantages of a TCXO

- *Limited Maximum Frequency vs. Temperature Stability*

  Quartz crystal hysteresis, perturbations, and lack of thermal control, limit how well a particular crystal can be compensated. In most cases the best practical limit is about 0.2 PPM over a 0 °C to +50 °C temperature range, but better stabilities can be achieved under special conditions.

- *Higher Cost than a Clock Oscillator*
- *Larger Package Size than a Clock Oscillator*

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Specifying a TCXO

The family of standard TCXOs found in this catalog offer the lowest price and shortest lead times. Quite often, however, special customer requirements, from simple modifications of a standard catalog model's specification to custom designs from customer source control drawings, are required. At OFC, we have broad experience manufacturing custom TCXOs for applications ranging from low cost models for the telecommunications industry to high-precision, high-reliability models for military and space.

Frequency Stability

When specifying a custom TCXO, keep in mind that the tighter the frequency stability with respect to temperature and aging rate, the higher the cost. This cost is driven primarily by oscillator testing requirements and the quartz crystal cost. Tight frequency vs. temperature requirements demand crystal resonators with low frequency perturbations and low hysteresis characteristics. While crystal resonators are designed to minimize these parameters, there is a manufacturing yield (quantity of acceptable crystals from a manufacturing lot) which directly contributes to cost. Also, as the temperature stability is made tighter, more test time is required to manufacture the part and to guarantee performance. A two-tier specification should be considered to help reduce this cost.

Input Voltage

Most TCXOs are designed to operate at +12 VDC, +5 VDC or a combination of both. Custom TCXOs can be designed to operate at other positive or negative input voltages as the situation requires. In cases where an ECL output is required, a -5.2 VDC supply is usually needed.

RF Output

A TCXO can be manufactured with various types of outputs: sine wave, clipped sine wave, TTL, HCMOS and ECL. Be sure to specify the desired output type, signal requirements and the load that the oscillator will be driving.

Typical RF Output Specifications include:

1. Sine wave: +5 dBm minimum into 50 ohms, Harmonics -25 dBc

2. TTL: Logic '0'; 0.4V max., Logic '1'; 2.4V min., Pulse Width; 40% to 60% @ l.5V level, Rise & Fall Time; 20 nsec 0.8V to 2.0V level, Load; 10 TTL loads

3. HCMOS: Logic '0'; 0.5V max., Logic '1'; 4.0V min., Pulse Width; 40% to 60% @ 50% level, Rise & Fall Time; 5 nsec 10% to 90% level, Load; 10 HCMOS loads

4. ECL: Logic '0'; -1.8V typ., Logic '1'; -0.8V typ, Pulse Width 40% to 60% @ 50% level, Rise & Fall Time; 5 nsec max. 10% to 90% level, Load; 1 10K ECL gate

Frequency Adjustment

The primary purpose for a frequency adjustment is to re-adjust the oscillator to its center frequency to compensate for aging. This adjustment can be provided in the following ways:

1. A mechanical adjustment within the oscillator accessible via a hole in the enclosure or a removable seal screw.

2. An electrical adjustment via a lead in the enclosure for either a remotely located potentiometer or a voltage. An oscillator using this technique is called a Temperature Compensated Voltage Controlled Crystal Oscillator or "TCVCXO".

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3. A combination of both mechanical and electrical adjustment.

Special Considerations

Phase Noise

TCXOs can be designed to minimize their phase noise characteristics. Depending on the actual requirement, this will directly affect cost. Close-in phase noise (typically < 300 Hz offset from the center frequency) is directly affected by the crystal resonator. Generally, lower frequency crystals or overtone crystals are best for close-in noise. Also, crystals can be subjected to special processing which will minimize their phase noise characteristics. Phase noise > 300 Hz is controlled primarily by the associated oscillator and output circuitry.

In some cases, the customer may not be as concerned with phase noise in a l Hz bandwidth at specific offset frequencies, but is more concerned with the total overall integrated noise. Noise referenced in this manner can be specified as Radians, Degrees RMS, picoseconds or Residual FM.

OFC has the capability of performing phase noise testing, but does not recommend that this be performed on a 100% basis in manufacturing due to the lengthy test time involved and associated cost. However, testing can be performed as needed.

Vibration and Shock

While most TCXOs will withstand a certain amount of shock and vibration, typically 100 g shock and 5 to 10 g sine vibration up to 500 Hz, there are cases where the oscillator will be used in environments of considerably higher sinusoidal or random vibration and shock levels. TCXOs can be designed for these higher levels by employing special internal assembly techniques and using special crystal holders. These requirements need to be identified as early in the program as possible to avoid costly design changes later.

Acceleration Sensitivity

Acceleration Sensitivity (also known as G-sensitivity) is defined as the frequency shift caused by subjecting a quartz crystal to a constant acceleration. This acceleration is most commonly in the form of sinusoidal or random vibration. As the oscillator is vibrated, the quartz crystal vibrates and generates FM sidebands on the RF output that are the same frequency as the vibration frequency. The amplitude of the sidebands are a direct result of the crystal's acceleration sensitivity. The higher the sensitivity, the higher the sideband's amplitude. Since the vibrating frequency range is generally ≤ 2000 Hz, these sidebands can be much higher in amplitude than the oscillator phase noise.

Therefore, in certain situations it may be necessary to specify a 'phase noise during vibration' specification.

OFC has developed TCXOs with low acceleration sensitivity crystals to minimize these effects. We will work with you to develop a specification to meet your requirements.

Because there are numerous cost/performance tradeoffs with respect to package size, temperature stability, aging, input voltage, etc., OFC recommends that you contact one of our engineers to discuss your requirements — if possible at the initial design stage of your project. By knowing your application and requirements, OFC can help you develop the right combination of specifications to provide the best overall price/performance tradeoffs.

Author: Harry Wilson
Precision Oscillator Design Engineer

Voltage Controlled Crystal Oscillators

The term "VCXO" refers to a Voltage Controlled Crystal Oscillator. A VCXO is a crystal controlled oscillator where the frequency changes in direct proportion to the application of a control voltage. Another term for this phenomena is Frequency Modulation, or FM. Frequency Modulation is achieved by impressing a voltage on a modulator, which causes the frequency to move or deviate from its nominal frequency. This control, or modulating voltage, can be a DC voltage, a sine wave, a square wave or a complex wave such as music. In all VCXOs manufactured at OFC, the type of modulator employed is a varactor diode. The varactor diode is a semiconductor device that is designed to act as a variable capacitor when a voltage is applied to it. When used in series with a crystal, as shown in Figure 1, changing the control voltage causes the diode capacitance to change. This change in capacitance causes the total crystal load capacitance to change and subsequently causes a change in crystal frequency. This change in frequency is known as deviation and is described graphically in Figure 2.

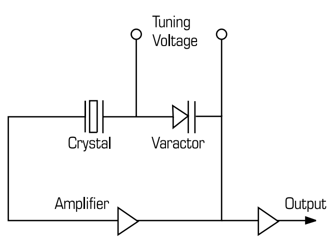


Figure 1

The graph in Figure 2 shows an "ideal" response to the control voltage input. In reality, the increase in frequency will not be as linear as shown in Figure 2. A more typical response is shown in Figure 3. The measure of a VCXO's deviation performance is known as linearity. Linearity measures how well the change in frequency tracks the change in control voltage.

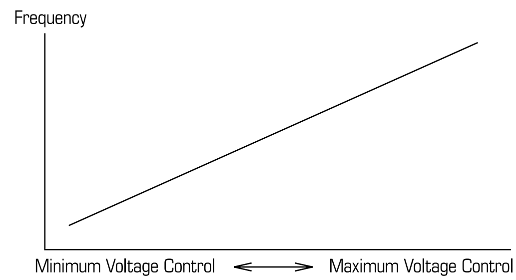


Figure 2

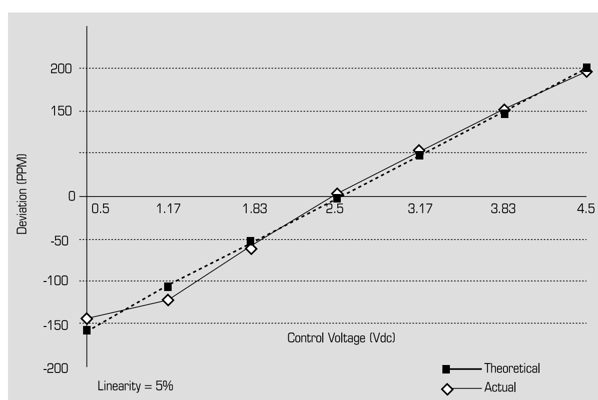
If the frequency would change by exactly the same number of Hertz (or ppm) each time the voltage is increased by a given amount, the VCXO would have perfect linearity.

Linearity is measured in % and is typically determined by comparing the actual frequency deviation with a theoretical straight line. The linearity is computed as a ratio of the worst case departure from the straight line to the total deviation of the VCXO, as shown below.

$$\% \text{ Linearity} = F_{max} \times 100/D_t$$

Where F_{max} = Max. frequency diviation from straight line, and D_t = total deviation.

TYPICAL FREQUENCY VS. CONTROL VOLTAGE @ +25°C



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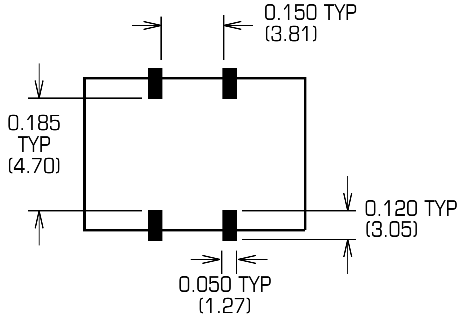
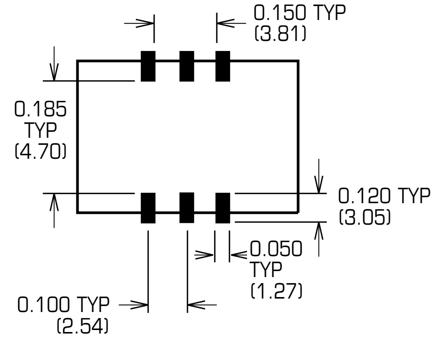
SURFACE MOUNT VCXO: SOLDER & REFLOW DATA

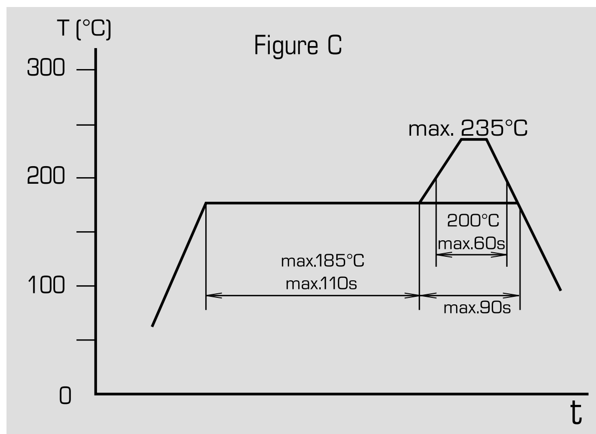


Recommended Solder Pad Layout
Models 044, 344, 046 and 346.



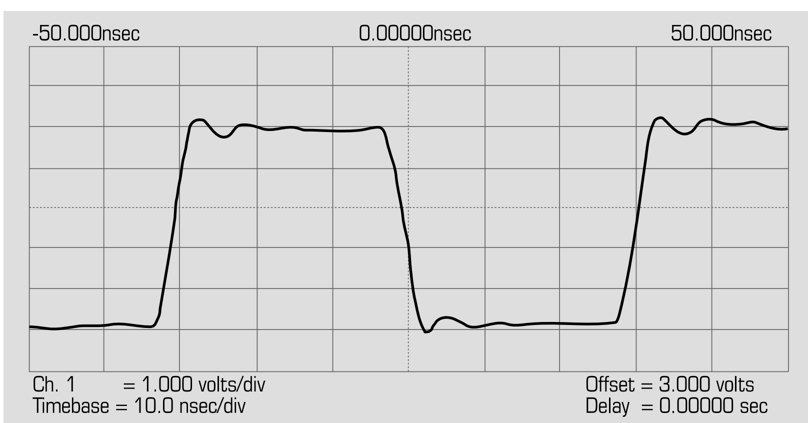
Recommended Solder Pad Layout
Models 047, 347, 049 and 349.

RESISTANCE TO SOLDERING HEAT
Components will withstand IR-soldering with temperature profile according to Fig. C.



TAPE & REEL
In accordance with EIA spec 481 dash 1, 2, 3.

TYPICAL VCXO WAVEFORM @ 16.384 MHz



EMI
Passes EN55022 Class B per paragraph 6, Table 4.

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Definitions and Typical Limits

Control Voltage

The minimum, nominal and maximum voltages to be applied to the control voltage input. The nominal control voltage is the voltage that sets the oscillator to nominal frequency.

Example: +0.5 Volts to +4.5 Volts, +2.5 Volts ±0.5 Volts for nominal frequency.

Frequency Deviation

The change in frequency, measured in Hz or ppm, which results from varying the control voltage from nominal to the minimum or maximum voltage.

Example: ±100 ppm minimum from nominal frequency for a +0.5 to +4.5 Volt change in control voltage.

Deviation Sensitivity

The slope of the "Voltage vs Frequency" curve which is expressed in ppm/Volt or Hz/Volt.

Example: 50 ppm/V

Modulation Rate

The audio frequency in Hz or kHz at which the demodulated deviation decreases or rolls off to one half the deviation of a DC voltage of equivalent amplitude.

Example: 10 kHz

Deviation Slope Polarity

The slope of the "Voltage vs Frequency" curve can be either positive or negative. An increase in frequency caused by an increase in control voltage is a "positive slope." A decrease in frequency caused by an increase in control voltage is a "negative slope."

Deviation Linearity

Linearity is a function of how well the frequency changes in proportion to control voltage changes. Linearity is usually determined by computing a "best straight line" through a set of frequency vs voltage data points and is specified as a percentage error with respect to the total deviation.

Example: Linearity $<$ 10%

Others

Other typical oscillator requirements may also be specified for VCXO's. Limits for frequency stability, aging, output waveform, temperature range, supply voltage and supply current should be determined for individual application requirements. Refer to specific OFC data sheets or contact the factory to choose from available options.

Authors:
Harry Wilson, *Precision Oscillator Design Engineer*
Dan Fry, *Hybrid Oscillator Design Engineer*

SMOCXO – OFC's Surface Mount OCXO

Oven controlled crystal oscillators (OCXOs) have traditionally been thru-hole devices due to size, weight, and performance concerns. In 1996, Oak Frequency Control Group (OFC) revolutionized the crystal based frequency control product market by introducing a family of surface mount OCXOs.

SMOCXO™ (AT-cut crystal) and SMOCXO-SC™ (SC-cut crystal) are reflow process compatible oscillators and are designed for numerous applications including PCS base stations, cellular base stations, wireless communications, wired communications, and test equipment.

OFC's goal was to develop a product that possesses, or improves upon, all of the performance characteristics of OCXOs in our current product line, while adding the essential surface mount feature. Numerous design, component, and process engineers expressed a need for such a product as, in many cases, the OCXO is the only thru-hole component on their board. Installing OCXOs by hand adds time, money, and labor quality issues to the manufacturing process.

Using 0402 chip component technology and a very low mass oven design, size and weight have been reduced to allow SMOCXO positioning by a standard pick and place machine. The internal construction also allows the SMOCXO to be processed through a typical reflow profile. Electrical performance was optimized by designing OCXO circuitry using miniature, high performance AT- and SC-cut crystals developed by OFC.

The resistance weld package was designed by OFC and offers several advantages over traditional solder seal packages. The benefits include reflowability, enhanced thermal characteristics, and ease of packaging.

SMOCXO possesses excellent moisture protection and is hermetically sealed to 1 x 10^{-8} ATM cc/sec. The header is steel with nickel finish; the cover is nickel. These materials protect the unit from corrosion and provide EMI shielding.

The construction techniques used in Oak Frequency Control Group's SMOCXO family are identical to those used in our standard thru-hole OCXOs. Large quantities of these OCXOs have been shipped to leading electronics OEMs worldwide. OFC's new surface mount OCXOs meet the needs of today's design, component, and process engineers.

Combining surface mountability, reflow compatibility, and compact size, SMOCXO and SMOCXO-SC are quickly becoming preferred components for precision OCXO applications.

Note: *For SMOCXO™ and SMOCXO-SC™ Electrical Specifications, please refer to Pages 8 and 9 of the Data Book.*

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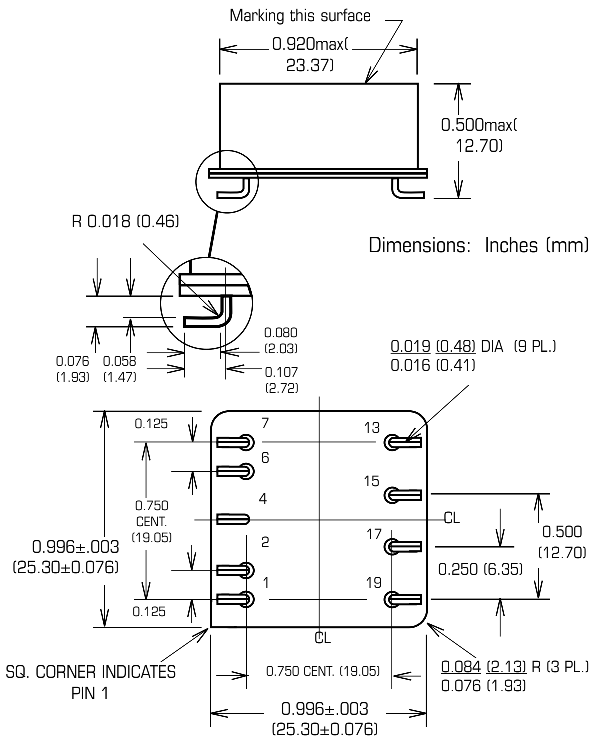
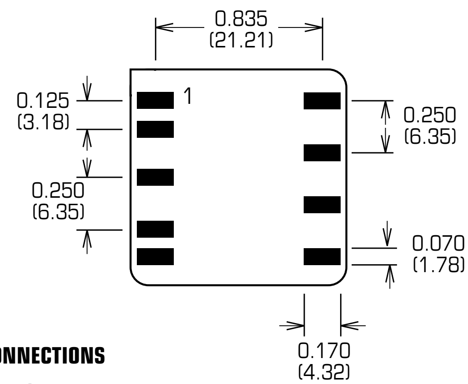
CONFIGURATION & REFLOW DATA



RECOMMENDED SOLDER PAD LAYOUT

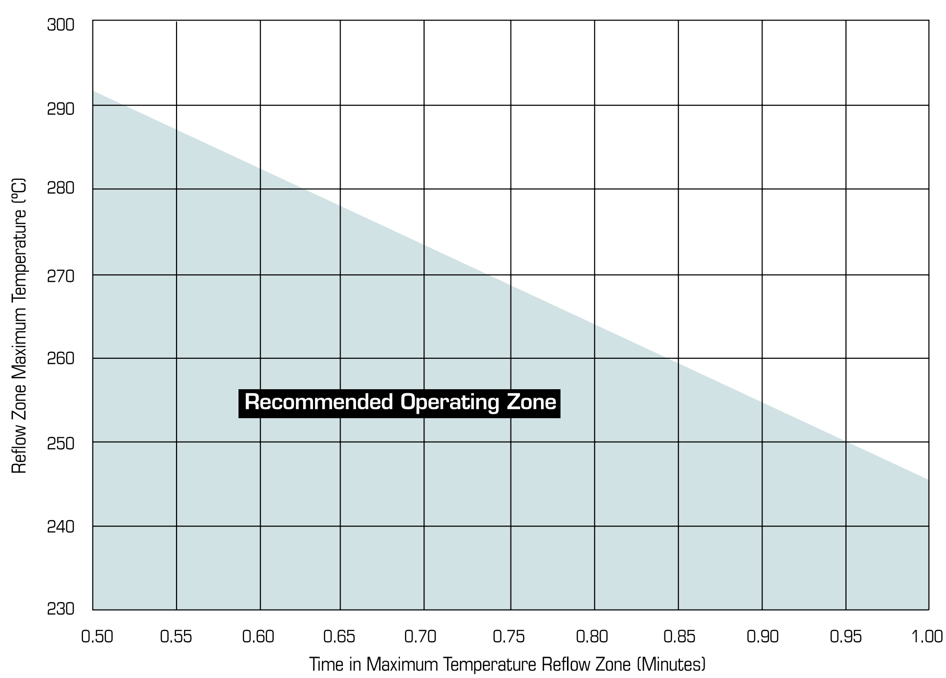


PIN CONNECTIONS

1 – RF Output
2 – N/C
4 – GND/Case
6 – N/C
7 – EFC
13 – Ref. Volt. Output
15 – N/C
17 – N/C
19 – +5V Supply

WEIGHT: 12g max.
COPLANARITY: 0.003" max. (0.0762mm)

MAXIMUM REFLOW TEMPERATURE VS. TIME



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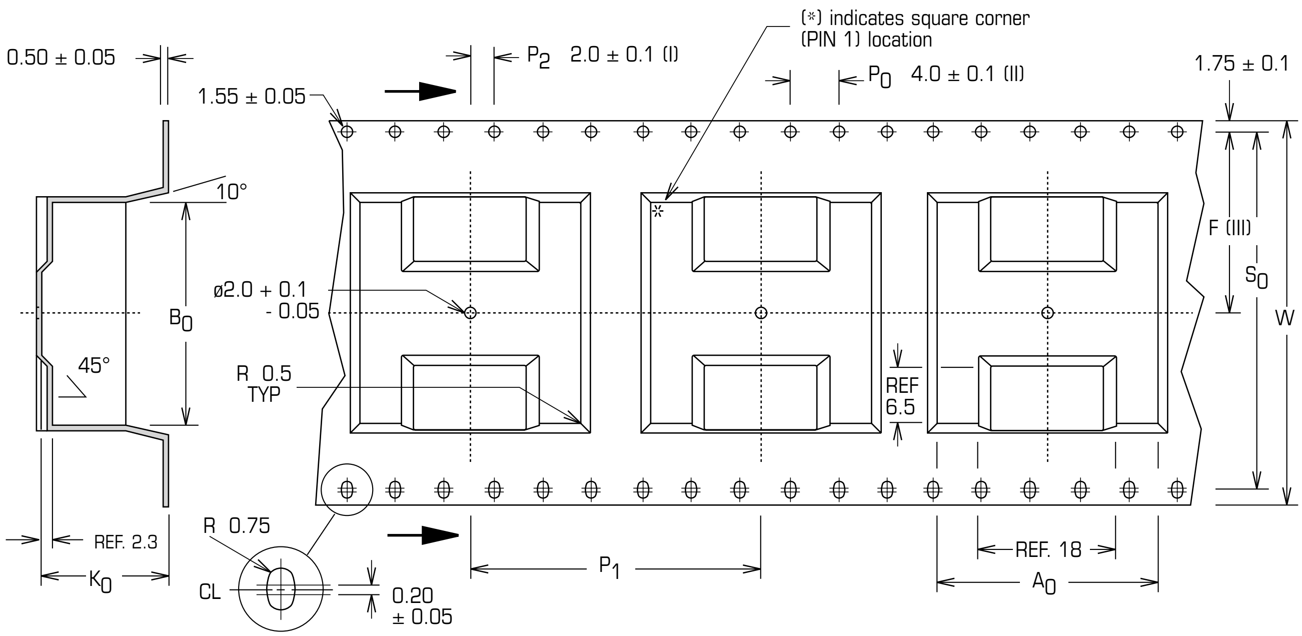
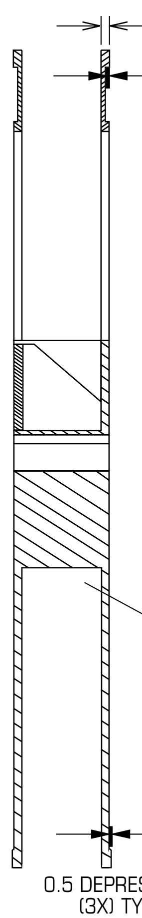
TAPE & REEL SPECIFICATIONS



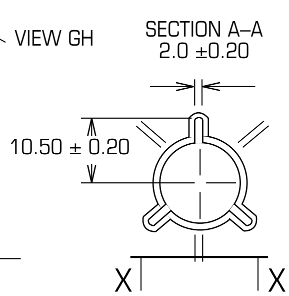
A_0	25.70 ± 0.1
B_0	25.70 ± 0.1
K_0	13.00 ± 0.1
P	20.20 ± 0.1
P_1	32.00 ± 0.1
S_0	40.40 ± 0.1
W	44.00 ± 0.3

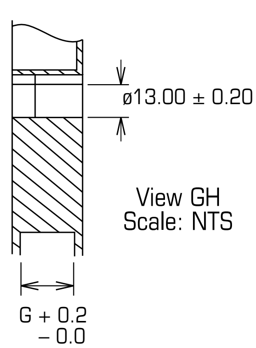
(I) Measured from centerline of sprocket hole to centerline of pocket.
(II) Cumulative tolerance of 10 sprocket holes is ±0.20.
(III) Measured from centerline of sprocket hole to centerline of pocket.
(IV) Other material is available.

ALL DIMENSIONS IN MILLIMETERS UNLESS OTHERWISE STATED.



TAPE WIDTH	G SPECIFIED
44.0	44.6





RECOMMENDATIONS FOR TAPE & REEL

1. Deep pocket feeders available from major pick and place equipment manufacturers. Call factory for details.
2. 150 units per 4" reel; 100 units per 7" reel.
3. SMOCXO™ can also be shipped in JEDEC tray packaging (36 per tray).

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