A HIGH PRECISION QUARTZ OSCILLATOR WITH PERFORMANCE COMPARABLE TO RUBIDIUM OSCILLATORS IN MANY RESPECTS

Manish Vaish
MTI-Milliren Technologies, Inc.
Two New Pasture Road
Newburyport, MA 01950

Abstract

An ultra-stable ovenized crystal oscillator (the 260 Series) has been designed and developed at MTI-Milliren Technologies, Inc. in order to provide an alternative to Rubidium oscillators. The oscillator has been developed for applications where it is critical to maintain comparable performance parameters of a Rubidium oscillator without the higher cost and inherent wear-out phenomena which may be a detriment to system design goals.

Introduction

Precision quartz crystal oscillators play a critical role in serving the needs for various types of applications ranging from satellite communications systems to telephone base stations and digital telephone networks. Each of these applications imposes stringent demands on frequency sources available today not only for performance but for lower costs as well.

A number of the most stringent performance requirements have been fulfilled, to a large extent, by Rubidium oscillators. However, there are some key areas that Rubidium oscillators have not been able to satisfy. These are: thermal stability, power consumption, reliability, useful life, size and cost. Quartz oscillators, on the other hand, typically do not exhibit these shortcomings. Two parameters where the quartz oscillator does not yet match the performance of a Rubidium oscillator, however, are aging and warm-up. For applications where a low aging rate is essential, a primary frequency standard such as a Cesium, Loran C or GPS may be utilized to discipline the quartz oscillator and compensate for this characteristic.

The 260 Series was developed utilizing SC cut quartz resonators in conjunction with double oven technology in order to provide performance characteristics comparable to Rubidium oscillators in many respects.

The key design goals in developing the 260 Series oscillator have been:

- Superior Thermal Stability
- Low Phase Noise
- Low Power Consumption
- Reduced Size
- Manufacturability and Consistency
- Low cost
- 20 year life

Design and Construction

A fundamental design goal of overall small size had to be achieved in order to minimize power for warm-up as well as during continuous operation. It would also support the goal of low part count, thereby reducing cost while leading to a design better suited for a large scale manufacturing environment.

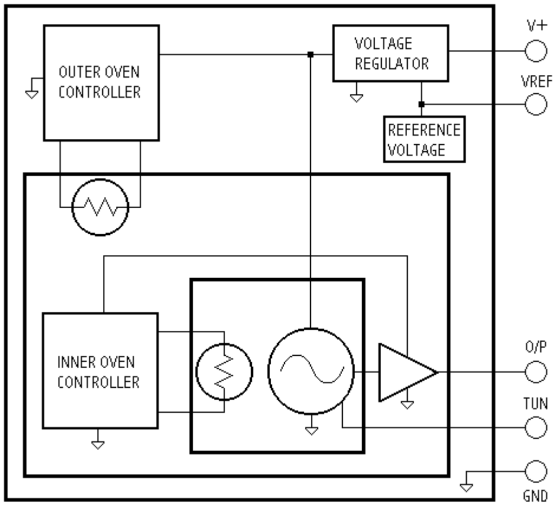

Figure 1: 260 Series Construction Block Diagram

To achieve the necessary thermal stability of < 2e-10/100°C and low phase noise, the 260 Series design utilizes an SC cut quartz crystal enclosed in a double oven. Figure 1 shows a block diagram of the construction of the oscillator. The quartz crystal and the sustaining circuit are located inside the inner oven. The inner oven assembly is then enclosed by a second, outer oven assembly. This provides a highly stable temperature controlled enclosure for the quartz crystal and the oscillator components resulting in exceptional thermal stability performance as well as low phase noise especially at frequencies below 1Hz from the carrier.

The inner oven control and output amplifier circuits are also enclosed by the outer oven assembly as shown by the block diagram in Figure 1. This provides better thermal stability by reducing the effects of temperature changes on the inner oven control and amplifier circuits.

A Comparison

Progress has been made in the development of the Rubidium oscillators over the last few years -- primarily with respect to size reduction. However, there still are certain shortcomings that are inherent in the performance of Rubidium oscillators. Examples of such shortcomings are the limited life of the Rubidium lamp, the total mass of the oscillator, thermal stability, phase noise and power consumption to name a few.

The 260 Series measures 50.8mm x 50.8mm x 38.1mm (0.098cm^3) and weighs 150g. This miniature package offers superior performance in the aforementioned areas in which the Rubidium oscillator falls short. As an example, the performance of a 10MHz (utilizing a 5MHz crystal which is then doubled) 260 Series oscillator for thermal stability is < 2e-10 over a temperature range of -30°C to +70°C, < -100dBc/Hz at 1Hz offset phase noise characteristic and < 5e-11/day aging rate at shipment. In comparison, the performance of a typical Rubidium clock for the same parameters is < 2e-10 over a temperature range of -10°C to +60°C, < -85dBc/Hz at 1 Hz offset and < 2e-12/day respectively. The aging rates of the 260 Series oscillators are measured and delivered at a rate of < 5e-11, but many 5MHz units currently achieve rates as low as 2 to 5e-12/day after 1 to 2 months of constant operation. Table 1 provides a comparison of the performance of the 260 Series oscillator utilizing a 10MHz SC cut quartz crystal against some of the performance results published by various manufacturers of Rubidium oscillators.

It can be seen from the data in Table 1 that the 260 Series oscillator performance is comparable, and in some cases, exceeds the performance of a Rubidium oscillator. This makes the 260 Series a viable candidate for replacement of Rubidium oscillators particularly in the areas of improved thermal stability and lower costs. For applications where trade-offs in oscillator aging rates cannot be made, the 260 Series may be used in conjunction with a primary frequency standard such as Loran C, T1 signal, GPS etc., to discipline the oscillator in order to improve the long term stability performance. The overall result can be a frequency reference with excellent short term stability of quartz combined with the long term stability of a primary Cesium standard. The quartz oscillator provides a filter function, allowing the relatively large jitter of the transmission medium to be removed to a large degree.

Test Methods and Results

To date oscillators of various frequencies between 4 and 20MHz have been manufactured. The frequencies of 5MHz and 10MHz comprise a statistically meaningful population. The test results discussed are for oscillators of these two frequencies.

During production, each oscillator is evaluated for performance characteristics of the following parameters: thermal stability, aging, phase noise, short term stability and supply voltage sensitivity. What follows is a detailed discussion of those parameters.

Thermal Stability

Temperature is typically the biggest source of instability in a quartz oscillator over periods of several weeks. The 260 Series oscillator utilizes a double oven configuration to largely attenuate large ambient temperature variations. The thermally sensitive sustaining oscillator circuit and quartz crystal are housed in the inner oven so that the effects of ambient temperature changes are minimized.

As an example, if the outer oven control circuit is able to attenuate ambient temperature changes by a factor of 100 and is then, followed by a similar inner oven gain, the temperature changes inside the inner oven would ideally be attenuated by a factor of 10,000 of the ambient temperature changes. Therefore, for an ambient temperature variation of 100°C, the temperature inside the inner oven in the example would only vary by 0.01°C. We can make some rough calculations to get a perspective on the expected thermal performance of an oscillator circuit and quartz crystal stabilized with the above mentioned oven control circuit.

Assuming the temperature of the oven can be set to within 0.1°C of the crystal turn-point, the temperature coefficient of a 5MHz SC cut crystal with an 86°C turn-point, can be approximated to be 8e-10/°C. The temperature coefficient of the components is estimated to be 1e-09/°C. Therefore, for a 0.01°C change in oven temperature (due to an ambient temperature change of 100°C), a thermal stability performance of 8e-12 + 1e-11 = 1.8e-11 may be expected from the oscillator.

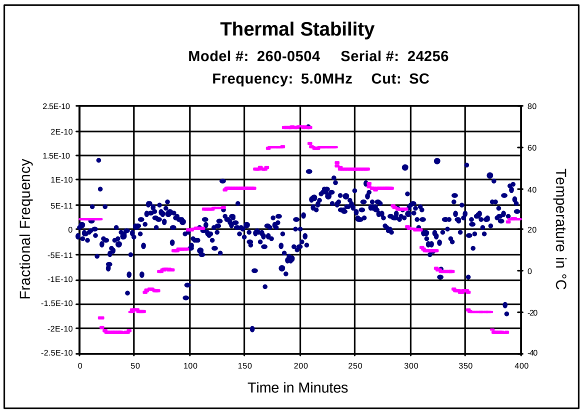

Figure 2: Thermal Stability of 5MHz Oscillator

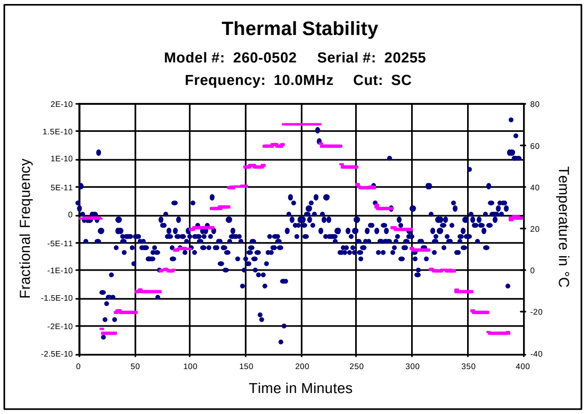

Figure 3: Thermal Stability of 10MHz Oscillator

The oscillator's performance over temperature is characterized by sweeping the ambient temperature from the minimum specified temperature to the maximum specified temperature in 10°C steps. The temperature is then swept back to the minimum specified as shown on the right axis of Figure 2 and Figure 3. The difference in frequency measured between the initial and final 25°C temperature points is used to cancel out any drift in the oscillator frequency by assuming a linear frequency drift over the test time period. Figure 2 and Figure 3 show the thermal stability performance of a 5MHz and 10MHz oscillator respectively.

Aging

Daily drift rates are determined for every oscillator prior to shipment. This is accomplished by powering the units on for extended periods ranging from 10 to 20 days. During this time, data is actively collected for each unit approximately every 2 hours. Each reading is an average of 10 frequency measurements with a 1 second gate time. The measured drift rate is determined by statistically fitting a straight line to all or part of the data set.

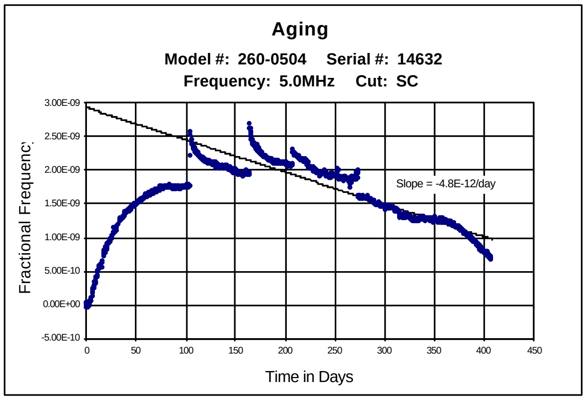

Figure 4: Aging Characteristic of 5MHz Oscillator

The aging result of a 5MHz oscillator over 408 days is shown in Figure 4. The aging rate of this oscillator is 4.8e-12 per day. For the 10MHz oscillator in Figure 5, the aging rate is 3.3e-11/day. The measurements shown in these two figures were not conducted over the same time period.

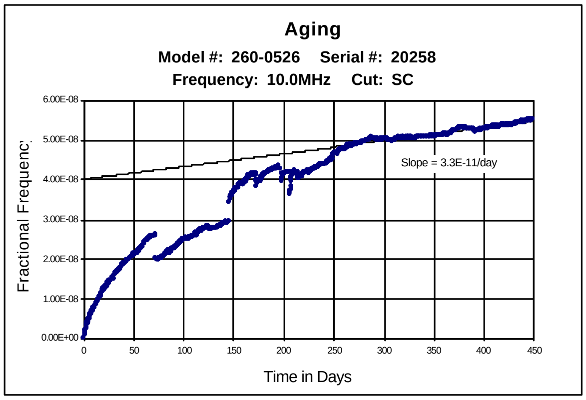

Figure 5: Aging Characteristic of 10MHz Oscillator

The jumps in the data presented in Figure 4 are due to extended periods of power failure. It is interesting to note that the initial retrace of this oscillator during the first two power interruptions is 8e-10, however, after about 60 days of continuous operation, the retrace value reduces to 2e-10.

In Figure 5, an unexplained frequency jump of 6e-9 occurs at day 70. The oscillator continues to age at the same rate while in this state for a period of 75 days. At this time, the frequency jumps back to the original aging curve. The cause of this offset in frequency is unknown. It is possible that the jump on each occasion may have been induced by a power interruption. The aging data presented represents real life situations concerning power interruptions and normal ambient fluctuations in room pressure, humidity and ±5°C of temperature. The units resided on the production floor and thus also experienced an ample dose of human activity all about.

Phase Noise

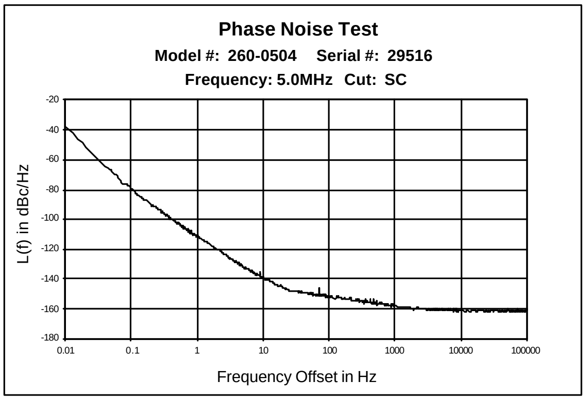

Figure 6: Phase Noise Results for 5MHz Oscillator

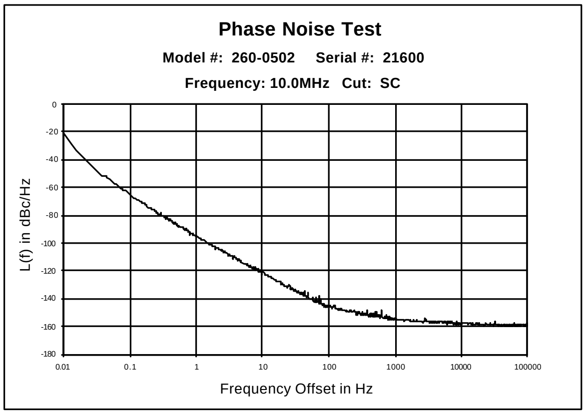

Figure 7: Phase Noise Results for 10MHz Oscillator

Phase noise measurements are made using two similar oscillators on a HP3048A test system. Figure 6 and Figure 7 show typical phase noise results for 5MHz and 10MHz oscillators respectively. The graphs shown do not account for equal sources and therefore, the actual performance of the individual units is as much as 3dB less than the results shown in the graphs.

Short Term Stability

Short term stability measurement results were derived from the phase noise measurements made using the HP3048A system. $\sigma_y(\tau)$ for 5MHz and 10MHz oscillator are shown in Figure 8 and Figure 9 respectively.

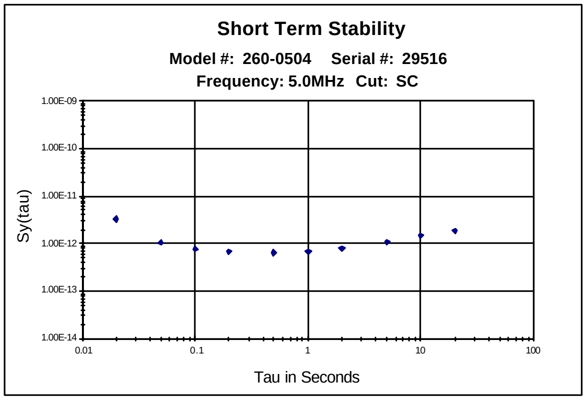

Figure 8: Short Term Stability of 5MHz Oscillator

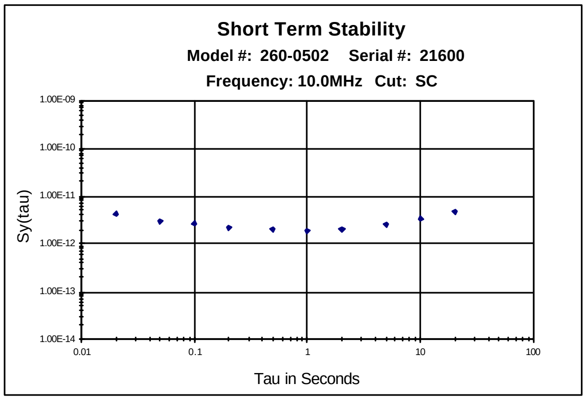

Figure 9: Short Term Stability of 10MHz Oscillator

Supply Voltage Sensitivity

Supply voltage sensitivity test is conducted on each oscillator by varying the supply voltage by ±5% from the nominal operating value. Frequency readings are then taken by averaging 10 samples with a

1 second gate interval. Figures 10 and 11 show the supply voltage sensitivity for a 5MHz and 10MHz oscillator respectively.

As can be seen from the graphs in Figure 10 and Figure 11, the 5MHz and 10MHz oscillators have a typical performance of < 2e-11 and 3e-11 respectively. The measurement resolution is limited to about 2e-11 and therefore the actual performance of the 5MHz oscillator has yet to be accurately measured.

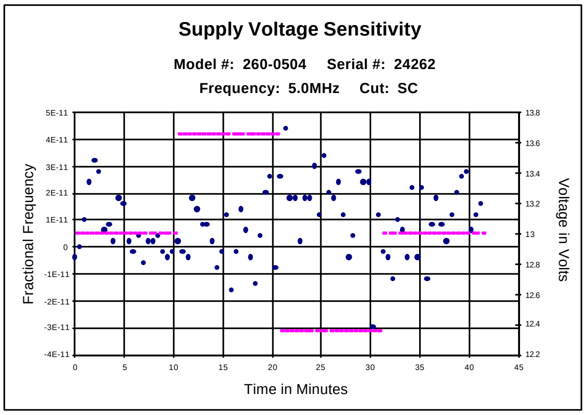

Figure 10: Supply Voltage Sensitivity for 5MHz Oscillator

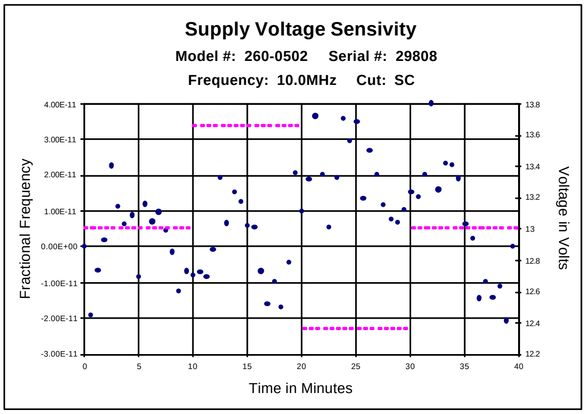

Figure 11: Supply Voltage Sensitivity for 10MHz Oscillator

Warm-up

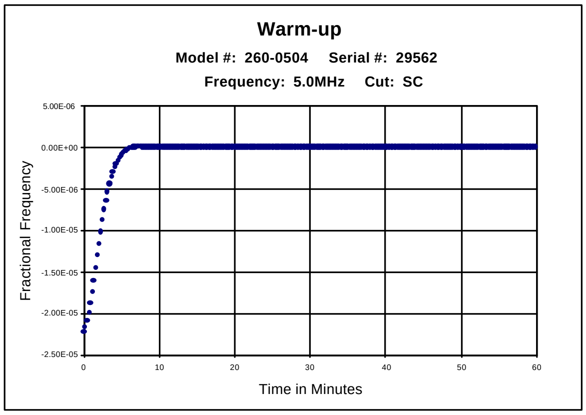

Figure 12: Warm-up of 5MHz Oscillator

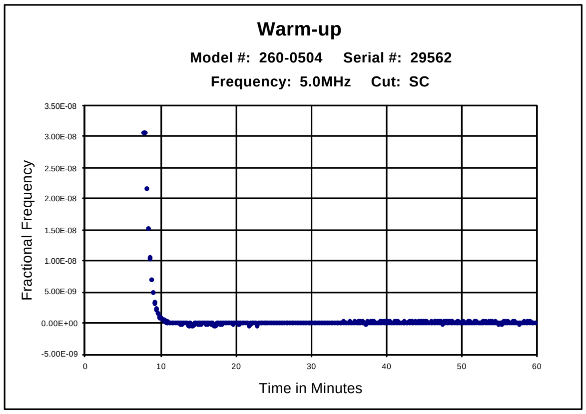

Figure 13: Warm-up of 5MHz Oscillator (Zoomed In)

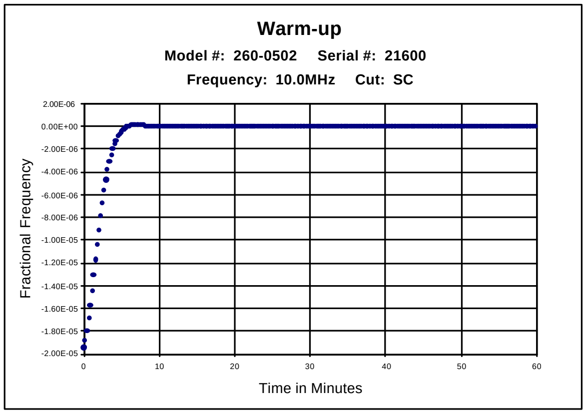

Figure 14: Warm-up of 10MHz Oscillator

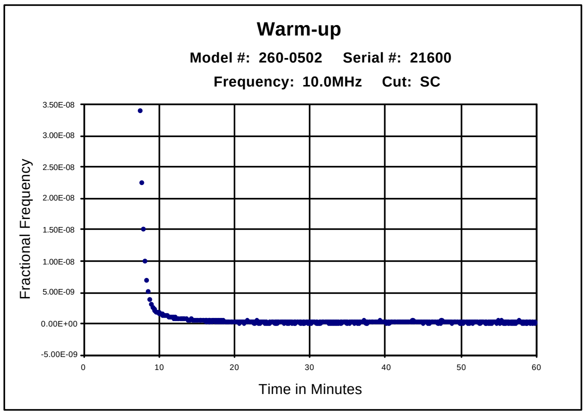

Figure 15: Warm-up of 10MHz Oscillator (Zoomed In)

The Warm-up test an important parameter for many applications and the data from this test is presented below.

Warm-up is conducted on the oscillators by powering the units off for a period of approximately 24 hours. The units are then powered on and frequency measurements are made with a 1 second gate interval. The test is run for 60 minutes which is 4 times the specified warm-up time. Warm-up df/f is referenced to the frequency at 60 minutes.

A statistical report of production test results for 28 units of MTI Model # 260-0504 (5MHz) and 36 units of 260-0502 (10MHz) is shown in Table 3.

System Design Considerations

Designing a system that utilizes a high precision oscillator requires careful consideration of the surrounding electronics. Two such examples are thermal design considerations and circuit track resistance. Neglecting these design issues tends to compromise the full performance of the oscillator.

260-0504 (5MHz) Statistical Analysis Number of Samples: 8				**260-0502 (10MHz) Statistical Analysis Number of Samples: 29**			
Parameter	**Specified**	**Average Value**	**Standard Deviation**	**Parameter**	**Specified**	**Average Value**	**Standard Deviation**
Thermal Stability	2.00E-10	1.80E-10	2.80E-11	**Thermal Stability**	2.00E-10	1.70E-10	3.80E-11
(-30°C to				**(-30°C to**			
Aging/Day	5.00E-11	4.60E-11	2.40E-11	**Aging/Day**	3.00E-10	1.90E-10	9.80E-11
Number of Days		23.8	11	**Number of Days**		13.2	13
Output Level	+9dBm ±2dB	8.36	0.56	**Output Level**	+9dBm ±2dB	8.13	0.64
Harmonics	-30dBc	-35.1	3.3	**Harmonics**	-30dBc	-37.3	5
Phase Noise @				**Phase Noise @**			
1Hz	-110dBc/Hz	-113.6	2.5	**1Hz**	-95dBc/Hz	-98.1	2.4
10Hz	-140dBc/Hz	-140.9	0.8	**10Hz**	-125dBc/Hz	-126.7	1.6
100Hz	-150dBc/Hz	-152.3	1.4	**100Hz**	-145dBc/Hz	-149.7	1.7
1KHz	-157dBc/Hz	-159.9	2.1	**1KHz**	-155dBc/Hz	-156.4	0.7
10KHz	-160dBc/Hz	-162.1	1.3	**10KHz**	-160dBc/Hz	-161.1	0.7
100KHz	-160dBc/Hz	-162.1	1.3	**100KHz**	-160dBc/Hz	-161.1	0.7
STS, 1sec.	1.00E-12	7.40E-13	1.80E-13	**STS, 1sec.**	7.00E-12	2.10E-12	6.20E-13
dF/dV [1]	2.00E-11	2.00E-11	7.00E-13	**dF/dV**	2.00E-10	5.70E-11	2.90E-11
Warm-Up Time [2]	15 Minutes	7.3	0.5	**Warm-Up Time** [3]	15 Minutes	8.6	0.4
Warm-Up dF/F [2]	2.00E-08	5.90E-10	3.60E-10	**Warm-Up dF/F** [3]	2.00E-08	1.00E-09	9.80E-10
Warm-Up Power	12W	11.9	0.3	**Warm-Up Power**	12W	11.9	0.4
Continuous Power	2.7W	2.5	0.2	**Continuous Power**	2.7W	2.3	0.2
Electrical Tuning				**Electrical Tuning**			
Min	5.00E-07	-6.00E-07	5.50E-08	**Min**	7.00E-07	-9.70E-07	1.10E-07
Max	1.00E-06	8.10E-07	6.50E-08	**Max**	2.00E-06	9.90E-07	1.10E-07
Tuning Linearity [1]	10%	6.0	0.9	**Tuning Linearity**	10%	6.4	0.9
Reference Voltage	5.9 - 6.5V	6.1	0.0	**Reference Voltage**	5.9 - 6.5V	6.1	0.1

[1] **Number of Samples: 7**

[2] **Number of Samples: 3**

[3] **Number of Samples: 2**

Table 3: Statistical Report of Production Test Result for 260-0504 and 260-0502

Thermal Design

To avoid compromising the thermal stability performance of any oven controlled crystal oscillator, it should not be placed in contact with large heat sinks such as against an equipment chassis (with exception to the intended mounting configuration) or in line with a ventilation fan. Excessive loss of heat from the oscillator may result in an operation environment which is different than the “as tested” environment. The outcome of which can result in correlation differences between the user’s configuration and the measured thermal stability at the time of manufacture.

Conversely, the oscillator must not be excessively insulated either. As an example, if the insulation around the oscillator was improved by a factor 3, then the heat generated by the internal circuits would cause the oscillator’s internal temperature to rise by a factor 3 as well. This has the undesired effect of reducing the upper ambient operating temperature.

Ground Loops

A more subtle design issue that also tends to compromise the overall performance of the oscillator is PCB track resistance from the power supply to the oscillator ground pin. Variations in ambient temperature, result in large changes in the oscillator supply current. As a result, there are fluctuations in the apparent ground voltage level at the oscillator ground pin with respect to the power supply ground pin. However, if the electrical tuning voltage input pin, which is referenced to the oscillator ground pin internally and draws negligible current, returns to the power supply directly, the result would be a voltage difference between the oscillator ground pin and its tuning input pin. The consequence of this is equivalent to applying a tuning voltage proportional to temperature to tune the oscillator.

Operating Frequency vs. Performance

Many of the operating characteristics of a quartz oscillator can be determined by the choice of the operating frequency. An underlying parameter which determines many of the oscillators’ specifications is the reactance vs. frequency slope or dX/dF value of the quartz crystal. This is approximated by the following equation:

$$\frac{dX}{df} = 4 \cdot p \cdot L_1$$

Where L_1 = motional inductance of the quartz crystal. This parameter is dependent on the crystal geometry and electrode size, and hence, the frequency of the quartz crystal.

An oscillator using a crystal with a small value for dX/dF is more susceptible to frequency changes since only a small change in circuit reactance is required to produce a frequency shift. For a 10MHz SC resonator, this value is approximately 18Ω/Hz compared to a dX/dF of 130Ω/Hz for a 5MHz resonator. This implies that a 5MHz oscillator is less prone to frequency changes due to external influences than a 10MHz oscillator by a factor of $130 \div 18 = 7.2$.

As an example, consider a 15μH inductor in the tuning circuit of an oscillator which changes by 1% over the life of the oscillator. The change in reactance of this inductor at 10MHz is:

$$dX = 15e\text{-}6 \cdot 0.01 \cdot 2 \cdot \pi \cdot 10e6 = 9.425\Omega$$
$$dF = 9.425 \div 18 = 0.524\text{Hz}$$

Similarly, for a 5MHz oscillator which has a 30μH (a non-standard value used to produce the same changes in reactance as above) that changes by 1% is 7.

$$dX = 30e\text{-}6 \cdot 0.01 \cdot 2 \cdot \pi \cdot 5e6 = 9.425\Omega$$
$$dF = 9.425 \div 130 = 0.073\text{Hz}$$

Any change in the oscillator circuit reactance as a result of temperature, humidity, aging of components etc., will be accompanied by a smaller change in frequency for oscillators operating at lower frequencies (larger dX/dF) than those at higher frequencies (smaller dX/dF).

It must also be noted that, by the same principle outlined above, the tuning range available for a 5MHz oscillator will be much smaller than for a 10MHz oscillator. However, this should not be of concern if the tuning range is used simply to discipline the oscillator since the tuning range available will be approximately proportional to the expected frequency shift over the life of the oscillator.

This is seen by the better performance of the 5MHz oscillator compared to that of the 10MHz oscillator for thermal stability, aging, phase noise, supply voltage sensitivity, etc.

Stability Budget

A stability budget serves as a useful tool in determining the overall stability requirement of the oscillator over the life of the system.

Parameter	Value	Squared	Linear
Thermal Stability	2e-10	X	2e-10
Aging (20 years)	2.0e-07	X	2.0e-07
Initial Setting	2e-08	4e-16	X
Retrace	5-09	2.5e-17	X
dF/dV	2-11	4e-22	X
dF/dL	2-11	4e-22	X
Sum	X	4.3e-16	2.0e-07
RSS	X	2.1e-08	X
Total (Linear+RSS)	2.2e-07	X	X

Table 2: Stability Budget

The use of stability budgets, in conjunction with a basic understanding of crystal frequency and the resulting performance trade-offs of the oscillator can be helpful in selecting the appropriate type oscillator for an application. Table 2 shows an example of such a budget over 20 years life using a 5MHz SC version of a 260 Series oscillator.

Future Developments

Future improvements to the 260 Series oscillators may include a version of the product where tuning is provided via a DDS. This has the benefit of removing temperature and aging contributions due to the tuning circuits.

Additionally, a study to fully understand the effects of humidity, pressure, thermal coefficients of gases inside the oscillator as well as thermal hysteresis is currently in progress.

Conclusion

From the performance data presented, it can be concluded that the 260 Series is indeed a viable candidate for use as an alternative to Rubidium, in which low cost, superior thermal stability and phase noise are key to system design goals.

The system designer needs to consider the consequences of thermal surroundings of the oscillator as well as the power supply and ground track resistance. The oscillator frequency must also be carefully examined for optimum performance. Lower frequencies result in better stability since the quartz is "stiffer" or has a larger dX/dF value.

References

[1] Y. Koyama, et al., *An Ultra-Miniature Rubidium Frequency Standard with Two-Cell Scheme*, Proceedings of the 1995 IEEE International Frequency Control Symposium, pp. 33-38.

[2] T. McClelland, et al., *Subminiature Rubidium Frequency Standard: Manufacturability and Performance Results from Production Units*, Proceedings of the 1995 IEEE International Frequency Control Symposium, pp. 39-52.

[3] C. Couplet, et al., *Miniature Rubidium Clocks for Space and Industrial Applications*, Proceedings of the 1995 IEEE International Frequency Control Symposium, pp. 53-59.

[4] M. Bloch, et al., *Subminiature Rubidium Frequency Standard for Commercial Applications*, Proceedings of the 1993 IEEE International Frequency Control Symposium, pp. 164-177.

[5] B. Parzen, Design of Crystal and Other Harmonic Oscillators, New York: Wiley, 1983.

[6] M. Vaish, et. al. *Precision Quartz Oscillator Tradeoffs*, Applied Microwave & Wireless, Summer 1994, pp. 89-97.

PARAMETER	**Rb MANUFACTURER #1**		**Rb MANUFACTURER #2**		**Rb MANUFACTURER #3**		**MTI (Quartz)**	
	Specification	Measured	Specification	Measured	Specification	Measured	Specification	Measured
Thermal Stability	±2e-10		±3e-10		4e-12	3e-12/°C	2e-10	1.8e-10
Minimum Temperature (°C)	-10		-5		0	0	-30	-30
Maximum Temperature (°C)	+60		+50		+40	+40	+70	+70
Aging								
Per Day				4e-12			3e-10	1.9e-10
Per Month	2e-11				4e-11	1e-11		
Phase Noise @								
1Hz (dBc/Hz)					-85	-90	-95	-98
10Hz (dBc/Hz)			-90	-115	-105	-110	-125	-127
100Hz (dBc/Hz)			-125		-125	-129	-145	-150
1KHz (dBc/Hz)			-145		-145	-148	-155	-156
10KHz (dBc/Hz)					-145	-148	-160	-161
100KHz (dBc/Hz)				-158			-160	-161
STS @								
1ms	5e-9							
10ms	5e-10							
100ms	7e-11							3e-12
1s	2e-11						7e-12	2e-12
10s	5e-12						1e-11	3e-12
100s	1e-12		3e-11	3e-12	1e-11	4e-12		
1000s	8e-13							
Magnetic Sensitivity	<4e-11/G				2e-11/G	1e-11/G		
Supply Voltage Sensitivity	<±1e-11						2e-10	5.7e-11
Supply Voltage Delta	±10%						±5%	±5%
Retrace	±3e-10/±3e-11				2e-11	1.2e-11	5e-9	
Off Time (Hr.)	24						24	
On Time (Min.)	10 / 30						120	
Warm-up Delta Frequency					5e-10	3e-10	2e-8	1e-9
Warm-up Time (Min.)					6		15	8.6
Warm-up Power (W)	22				15	14.5	12	11.9
Continuous Power (W)	8		6.5		8	7.5	2.7	2.5
Supply Voltage (V)	24				22 to 43	16 to 45	11 to 15	
Size (mm)	58 x 84 x 64		37 x 77 x 76				51 x 51 x 38	
Volume	312cc		182cc		1liter	1.2liter		98cc
Weight	677g				1kg	1.3kg		150g

Table 1. A Comparison of the Performance of the 260 Series (10MHz) Oscillator to Rubidium Oscillators Available from Three Other Manufacturers