Mass-Produced Quartz Oscillators as Low-Cost Replacement of Passive Rubidium Vapor Frequency Standards

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Abstract - **High precision oscillators that are capable of effectively operating over large temperature ranges and extreme temperature transients as well as providing excellent aging and holdover are continuously sought by industry. The wireless telecommunications industry, in its constant quest to minimize the cost of base stations, has reduced the usage of GPS in applications such as UMTS. Consequently, it requires oscillators with reliable and proven aging, where the oscillator free-runs and maintains an accuracy of better than 40 ppb for a minimum of ten years. Other applications require oscillators that must exhibit excellent temperature coefficients. For CDMA applications that oscillator is expected to provide better than 10 microseconds time-error over a 24 hour period (holdover). In wireline applications oscillator stability and holdover capability is paramount for Building Integrated Timing Supply (BITS) clocks, Timing Signal Generators (TSG) and Synchronization Supply Units (SSU). Similarly, applications exist in the Aviation, Navigation, Instrumentation, Military and other markets. In the past these industries had only two choices: rubidium atomic standards, or limited quantities of virtually non-reproducible precision crystal oscillators. In this paper we present a class of extremely precise, yet reproducible oscillators, developed by Frequency Electronics, Inc. These oscillators are identified as the FE-405A Series, and are capable of providing any frequency from 1 pps to 100 MHz with an aging characteristic of better than 20 ppb/10 years, accumulated time error of less than 10 microseconds in 24 hours and with temperature coefficient of < 1 x 10^{-10} over the temperature range of -40°C to +75°C. These devices are currently being mass-produced using standard manufacturing techniques at approximately one-third the cost and one-fifth the power dissipation of rubidium vapor frequency standards. Quartz oscillators with internal MEMS acceleration compensation are also discussed. These oscillators provide as much as 30 dB reduction in vibration sidebands for vibration from DC to 2 KHz.**

I. INTRODUCTION

Precision ovenized-crystal oscillators (OCXO) are typically defined as those oscillators with frequency stability of better than 1x 10^{-10} over a wide range of environmental conditions. These conditions include operating temperature, humidity, supply voltage variations, repeatability, frequency settability, and frequency drift over long periods of time. As shown in the table, stability in the range of 1×10^{-10} was previously achieved only with Rubidium and other Atomic Standards. There has been a long-recognized need for a precision oscillator with stability better than 1 x 10^{-10} over a wide range of environmental conditions that can be manufactured in large quantities and at a low cost. The FE-405A family of OCXO offered by Frequency Electronics, Inc. (FEI) fulfills this need.

Oscillator Type	**Frequency Stability** (–40°C to +75°C, and high slew rates)
Crystal Oscillator (XO)	1×10^{-4} to 1×10^{-5}
Temperature Compensated Crystal Oscillators (TCXO)	1×10^{-6}
Microcomputer Compensated Crystal Oscillators (MCXO)	1×10^{-7} to 2×10^{-8}
Oven Controlled Crystal Oscillators (OCXO)	1×10^{-8} to 3×10^{-10}
FE-405A Series High-Precision Double Oven Crystal Oscillator (OCXO)	**1×10^{-10}**
Rubidium Atomic Frequency Standards (Rb) (–10°C to +70°C)	3×10^{-10} to 7×10^{-11}
Cesium Atomic Standard (Cs) (0°C to +50°C)	1×10^{-11} to 1×10^{-12}

II. QUARTZ CRYSTAL STANDARD

FEI designs and manufactures cesium and rubidium frequency standards (Rb) as well as precision crystal oscillators, and has developed a quartz oscillator that approaches the stability of Rb devices, but at a third of the atomic frequency source's price, and at one fifth the power dissipation. The FE-405A is a family of OCXO with a stability better than 1 x 10^{-10} over a wide range of environmental conditions that do not require an accurate crystal frequency, nor a precision crystal cutting angle for precise operating

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temperature characteristics, nor the use of reactive components for tuning and setting the desired output frequency.

By removing all the previously required costly key elements and time-consuming production and alignment hours, FEI has achieved precise OCXO that are reproducible, easy to manufacture, low-cost, and affordable. The resulting OCXO performance is very close to the performance of a Rubidium Atomic Frequency Standard, and it has been dubbed the “Poor Man’s Rubidium.” Various patents have been awarded to FEI. The resulting device is truly a Quartz Crystal Standard with the outstanding features summarized below.

- Producible in large quantities
- Excellent temperature stability < 1×10^{-10} per 50°C
- Low aging: typically < 1×10^{-11} / day; < 20×10^{-9}/10 year
- Near-Rubidium stability at 1/3 the cost and 1/5 the power dissipation
- Any frequency from 1 pps to 100 MHz
- Analog or digital frequency control with better than 1% linearity
- Standard frequency: 10 MHz and 15 MHz

III. PACKAGES

The oscillators are available in various packages. FE-205A packaging style is shown in Fig. 1, and the FE-405A and FE-505A packages are shown in Fig. 2. The FE-205A is housed in a package measuring 2x2x1.5 in. (51x51x38 mm). The FE-405A is housed in a package measuring 3x3x1.44 in. (76x76x37 mm). The FE-505A package dimensions are 2.98x2.80x0.89 in. (76x71x23 mm).

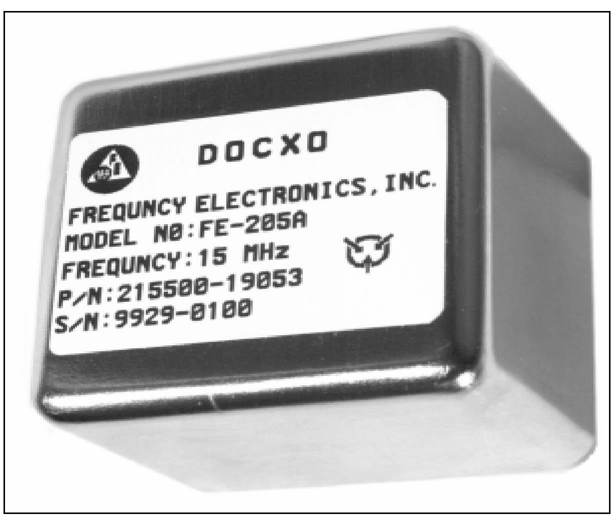

Figure 1. FE-205A

Figure 2. FE-405A and FE-505A

The enclosures chosen for the FE-405A and FE-505A are representative of existing Rb device packages, and are intended to easily substitute for Rb devices in legacy circuits as well as in new designs.

IV. DESIGN

The FE-405A series of OCXO’s consists of a unique design that incorporates a proprietary double-oven structure as well as an innovative implementation of a direct digital synthesizer (DDS). The DDS digitally adjusts the crystal oscillator’s frequency with a resolution of 2×10^{-14} and achieves device outputs that range from 1 pps to 100 MHz. The double-oven stabilizes the temperature of a stress-compensated-cut (SC-cut) crystal that is operated in fifth-overtone mode. The system block diagram is shown in Fig. 3.

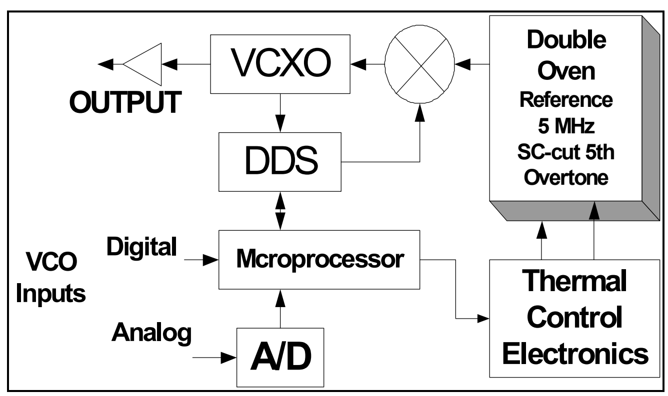

Figure 3. System Block Diagram

The major characteristics of the design are as follows:

- SC-cut 5^{th} overtone resonator with good aging and excellent short-term stability.
- Thermal control electronics with inner oven stability of $\pm 1 \times 10^{-3}$ °C over a change in ambient temperature of 100°C.

- Stability of internal reference clock electronic circuit is better than $3x10^{-11}$ over ambient temperature of -40°C to + 75°C and with a supply voltage tolerance of ± 5%.
- High-resolution DDS ≈ $2x10^{-14}$
- Microprocessor controlled.
- Less than $1x10^{-12}$ with load variation of ±10%.

V. PERFORMANCE

Actual measured performance for 15 MHz and 10 MHz devices are presented in the following plots. Oscillators typically experience overshoots and undershoots when subject to temperature changes. However the FE-205A, FE-405A and FE-505A overcome these disadvantages and result in very stable performance even as the temperature changes at an extremely high rate. Figs. 4 and 5 demonstrate the superb performance of a 15 MHz oscillator. Fig. 6 demonstrates the performance of the device when tested over a wider range of ambient temperatures.

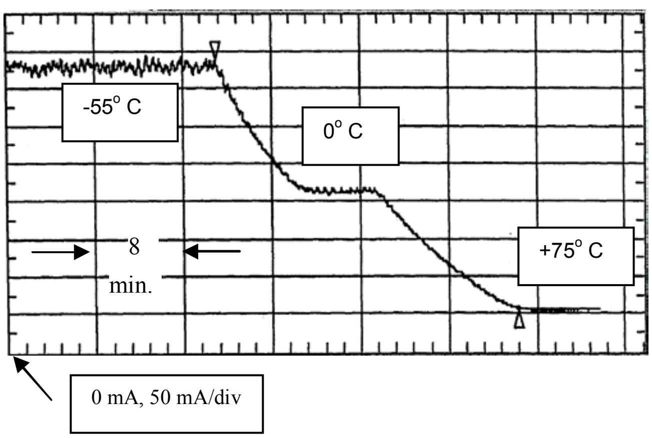

Figure 4. Oven Current vs. Time and Temperature of a 15 MHz OCXO

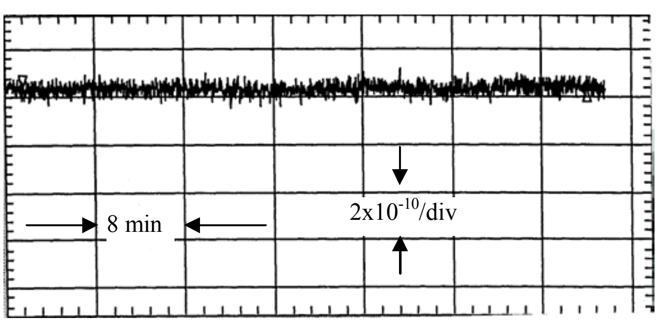

Figure 5. Frequency vs. Temperature for the Temperatures and Time Period shown in Figure 4 above

The OCXO was cooled to –55°C and within a period of 56 minutes the temperature was raised to +75°C. Fig. 5 shows the frequency stability resulting from the changes demonstrated in Fig. 4.

The plot in Fig. 6 below demonstrates the excellent frequency stability as a function of fast-varying temperature. In this case the unit is cycled from –40°C to +75°C and then to +25°C room temperature all within the short period of approximately 105 minutes.

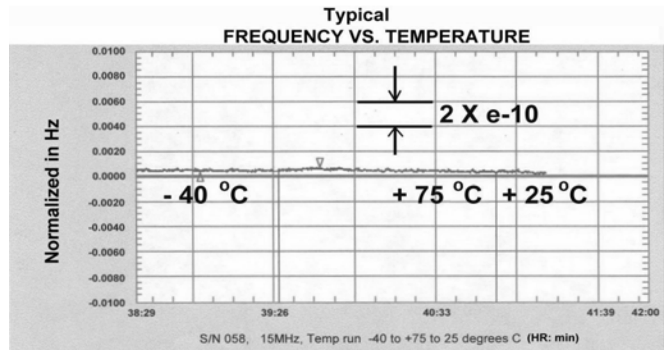

Figure 6. Frequency Stability of 15 MHz Oscillator over a Range of Temperature Variations

The statistical data presented in Fig. 7 indicates that the frequency stability over the temperature range of –40°C to +75°C is typically < $5x10^{-13}$/°C.

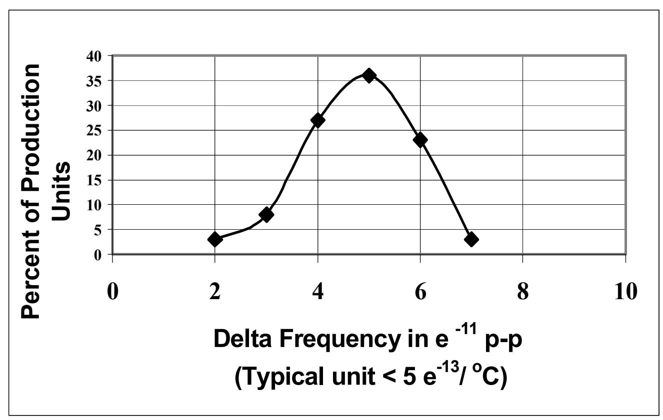

Figure 7. Frequency Stability vs. Ambient Temperature (–40°C to +75°C)

Fig. 8 shows a typical warm up time of a 10 MHz device. Approximately 20 minutes is required to achieve a specified frequency. The retrace performance of a 15 MHz oscillator is shown in Fig. 9. The device is shut off for 24 hours and the frequency stabilizes within 30 minutes after turn-on to $1x10^{-10}$ of the previous frequency.

The short-term stability is better than Rb atomic standards with $\sigma_y(\tau) = 2x10^{-12}/\tau$ for $\tau \leq 1$ second and $\sigma_y(\tau) = 1x10^{-12}$ for $\tau = 100$ seconds.

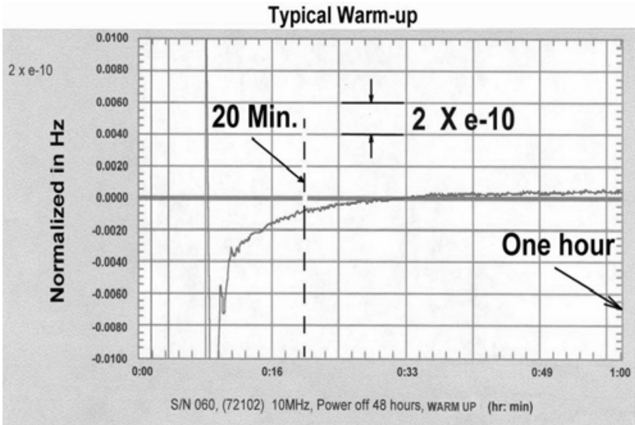

Figure 8. Typical Warm-Up of a 10 MHz Device

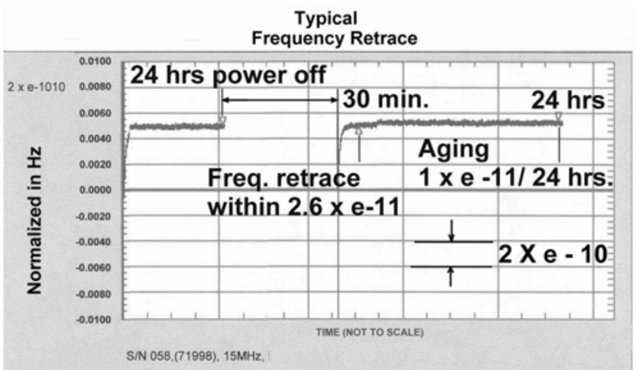

Figure 9. Typical Frequency Retrace of 15 MHz Oscillator

Long term frequency aging (or drift) performance for the FE-405A series of oscillators is outstanding. This is due to the unique design in which the long term stability is determined by the 5 MHz, fifth overtone, SC cut quartz crystal resonator. The low frequency and high overtone of this design result in a relatively massive quartz resonator (≈0.080" thick x 0.590" diameter), which exhibits less frequency change due to mass transfer (typically one of the dominant frequency aging mechanisms).

Furthermore, because this resonator need not be tuned to a precise frequency in a secondary plating process (calibration is provided by the digital synthesizer), it achieves better long term stability than other calibrated resonators of the same design.

Frequency aging measurements made over an extended period of approximately one year are shown in Figure 10. In Figure 11, the data from Figure 10 are used to predict the frequency aging over a 10 year time period. This is done by fitting the data to a function of the form:

$$\text{Freq} = a \, \text{Log}(b\,t + 1),$$

Where a and b are constants, and t is the elapsed time. It is well known that quartz oscillators typically exhibit frequency aging consistent with this functional dependence. For reference, the frequency aging data over an 8 year period, for a similar design 5 MHz oscillator used in a satellite application, are shown on the same scale. These actual data demonstrate that the predictions for the FE-405A series oscillators are indeed reasonable.

The statistical data shown in Fig. 12 indicate that the typical aging for the device at the factory is $< 5\text{x}10^{-11}$ / day. As seen in Figures 10 and 11, this initial aging decreases with time, and is typically $< 1\text{x}10^{-11}$ / day within one month of continuous operation. The long term aging is typically $< 20\text{x}10^{-9}$ /10 year.

The phase noise meets the requirements for wireless and wireline applications as shown in Fig. 13.

VI. LOW G SENSITIVITY QUARTZ OSCILLATORS

FEI has also developed quartz oscillators in which the inherent resonator sensitivity to acceleration is effectively reduced. This is accomplished using MEMS accelerometers to measure and compensate for externally applied accelerations or vibration. With this approach, effective g-sensitivities of $<2 \text{ X } 10^{-12}$ /g have been achieved. The basic performance with this approach is as follows:

- Acceleration sensitivities better than 2E-12/g
- Improvements of greater than 30dB for vibration sidebands
- Optimized compensation from DC to 200 Hz
- Broadband compensation from DC to 2 KHz is possible
- Economies in manufacturability
- Small package < 5in3

Figure 14 shows the improvement in phase noise during vibration for an oscillator employing this technology.

VII. CONCLUSION

Performance results for the FE-405A ultra-stable quartz oscillators have been presented. This series of products continues FEI's trend toward high-precision quartz oscillators that perform similarly to Rubidium devices, but at one-third the cost. These products are capable of operating in extreme temperature environments (-55 C to +95 C) and are applicable for cellular base stations, stratum clocks, GPS timing systems, test equipment, aviation systems, instrumentation and military electronics.

Performance results for quartz oscillators with MEMS g-compensation have also been presented.

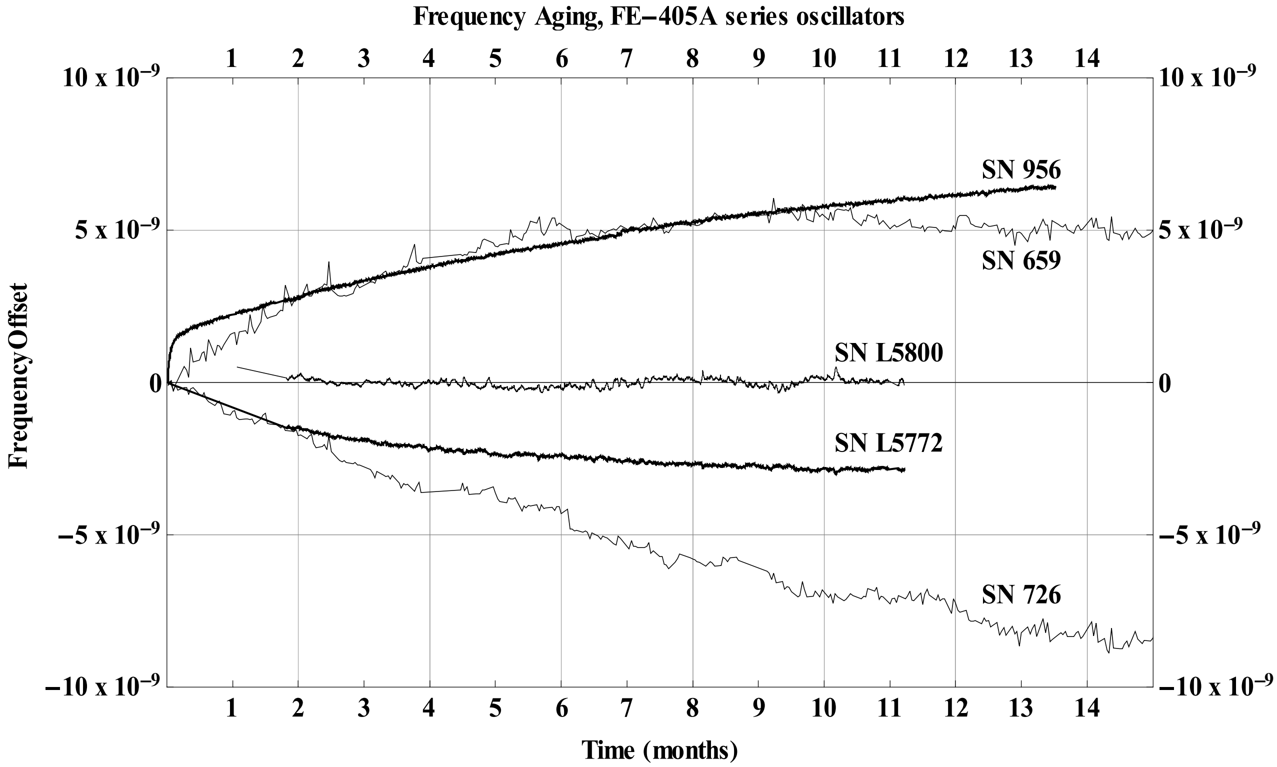

Figure 10: Frequency aging measurements of FE-405A series oscillators

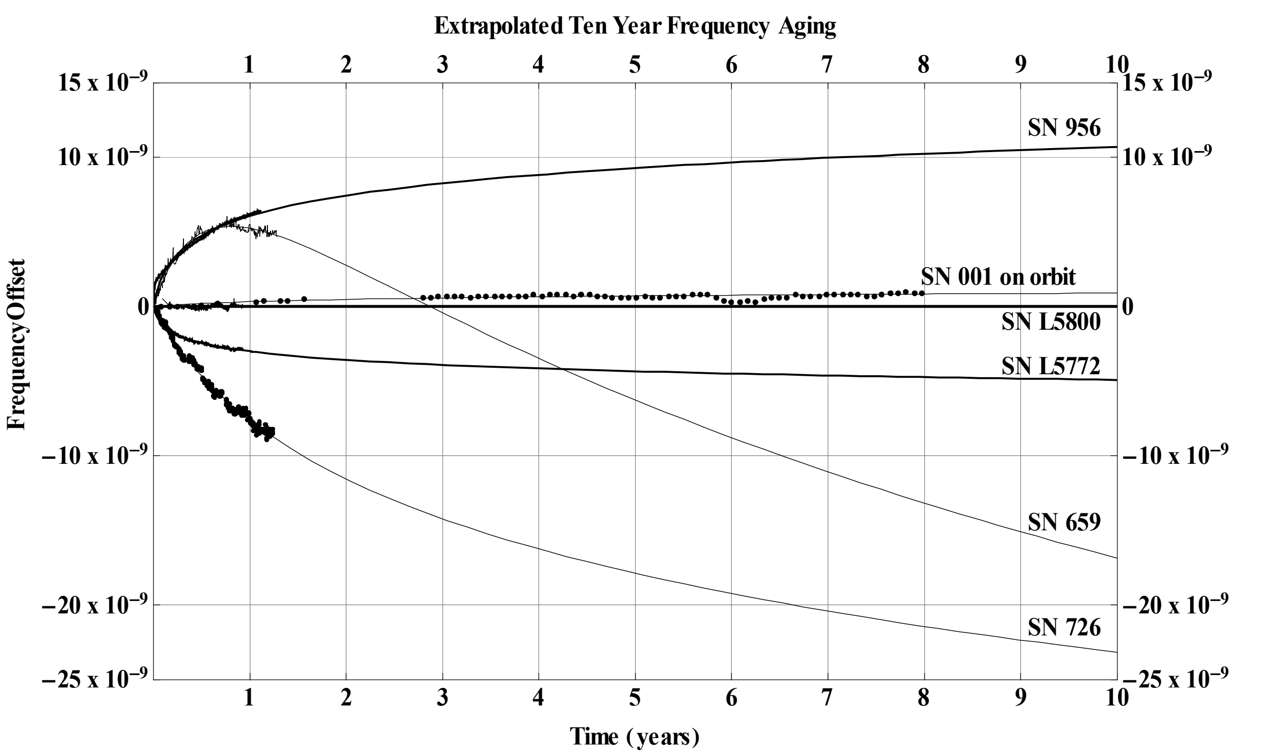

Figure 11: Extrapolation of the measurements from Figure 10 over a 10 year period. Also shown is the 8 year aging data for a 5 MHz oscillator (same quartz resonator as used in the FE-405A series oscillators) flown on a communications satellite. This actual 8 year measurement record demonstrates the reasonableness of the extrapolations.

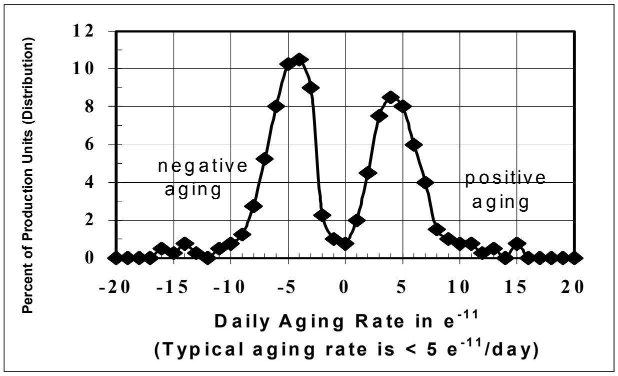

Figure 12. Frequency Aging

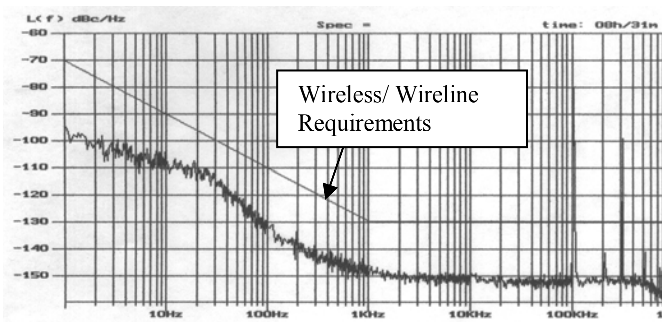

Figure 13. Phase Noise of 10 MHz Oscillator

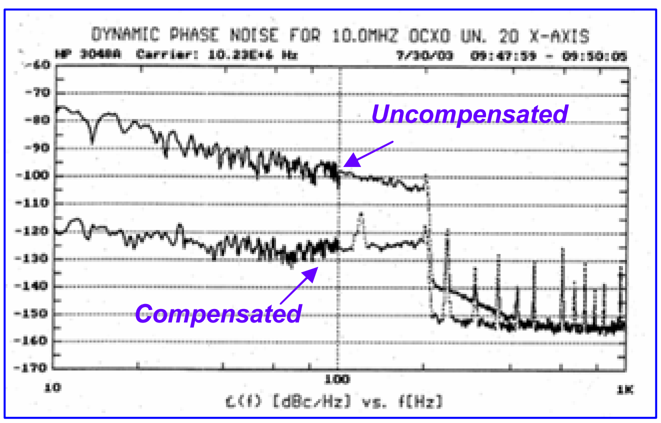

Figure 14. Phase noise under vibration showing improvement achieved using newly developed compensation technology. The vibration environment for these measurements is random vibration of 0.08 g^2/Hz from 10 to 200 Hz (4 g RMS total).

VIII. SUMMARY SPECIFICATIONS

Frequency: 10 MHz Standard (Option for any other frequency 1pps to 100 MHz)

RF Output: 10dBm ± 2dB into 50-ohm load

Frequency Stability:
Temperature (-40°C to +75°C): < 1×10^{-10}
(including frequency over- or undershoot at any fast or slow temperature slew rate)
Supply Voltage: < ± 2×10^{-11} (+15VDC ±5% or +5VDC ±5%)

Aging: per day: < 1×10^{-10} (typ. < 1×10^{-11})
per 10 yrs: < 50×10^{-9}

Short Term Frequency Stability (Allan Standard Deviation):
τ = 1 second 1×10^{-11}
τ = 10 second 2×10^{-12}
τ = 100 second 1×10^{-12}

Retrace: 1×10^{-10} in 1 hr. after 24 hours power off, 5×10^{-10} in 20 min. after 24 hours power off

G-Sensitivity: 2×10^{-9} per G, any axis

Digital Frequency Adjustment: Standard
Digital control via TTL serial port interface.
Adjustment resolution: LSB ≈ 1.7×10^{-14}
Adjustment range:
± 20Hz for 15MHz output
± 9.5Hz for 10MHz output

Power:
Supply Voltage:

Standard : +15VDC ±5% (1 amp max), +5VDC ±5% (200ma)
Option: single 15V input
Warm-up: 15W max.
Steady State: 3.5W max at 25°C

Please consult FEI for further details.