Building Robust Aerospace and Defense Products with Ruggedized Endura MEMS Oscillators

Ruggedized platforms often operate in the most hostile environments. Aerospace and defense systems can be exposed to extreme temperatures or large magnitude shock and vibration events. Reliable operation under such harsh conditions couldn't be more important, and in some circumstances could make the difference between mission success or mission failure.

State-of-the-art MEMS timing technology has come of age. Because MEMS-based timing products now exceed the performance of traditional quartz oscillators in many performance categories, it is ideally suited to meet the challenges of aerospace and defense.

The Evolution of MEMS Oscillator Technology

Quartz-based oscillators have served the electronics industry for over 70 years in applications that require frequency accuracy. But because of certain intrinsic weaknesses in quartz oscillator technology, compounded with the economy of scale associated with the silicon manufacturing infrastructure, all-silicon MEMS timing solutions are replacing quartz oscillators across a broad spectrum of emerging applications.

In 2006, the first MEMS-based oscillator was released and it demonstrated superior performance in areas such as shock, vibration, and the absence of sudden frequency jumps at certain temperatures (activity dips and micro jumps). Since the initial release of MEMS oscillators, the technology has advanced by orders of magnitude, improving temperature compensation and the performance of the phase lock loop (PLL), to deliver significantly lower (better) jitter and phase noise.

Today's MEMS oscillators, such as SiTime Endura™ products, are the result of years of technology innovation and improvement. The latest MEMS timing technology delivers low-noise/low-jitter clocks with unmatched resilience to environmental stresses including shock, vibration, airflow and fast temperature transients. This enables higher reliability and higher performance products across a range of aerospace and defense applications.

MEMS Reliability

In MEMS resonator design, the designer has control over the lateral shape of the resonator and thus control over resonant modes. MEMS are designed from the ground up to be free of spurious mode crossings with the fundamental mode, and are therefore free of resonator-induced activity dips. The MEMS structure is comprised of a single mechanical structure of pure, single-crystal silicon. The tensile strength is 7 GPa, which is about 14 times higher than Titanium at 330 to 500 MPa.

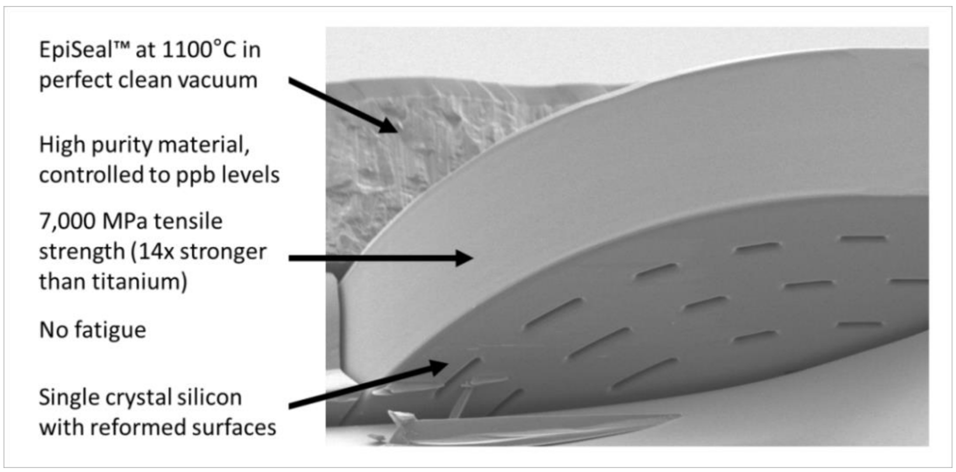


Figure 1. Scanning Electron Microscope (SEM) View of MEMS Resonator

Reliability is an important consideration for any design and is especially vital for equipment that must dependably operate under harsh environmental conditions. Figure 1 shows a SEM cross section view of a MEMS resonator. During MEMS manufacturing, an EpiSeal™ process is used to clean the resonator and to hermetically seal it in a vacuum. This process, which eliminates aging mechanisms, is the basis for the very high quality and reliability of MEMS oscillators.

The quality of SiTime's MEMS oscillators is <1 DPPM, which is significantly better than the typical failure rate of quartz oscillators. Figure 2 illustrates the reliability of MEMS oscillators, measured in mean time between failures (MTBF), as compared to quartz. The MTBF rate of SiTime oscillators is 1.14 billion hours, about 30x better than quartz suppliers.

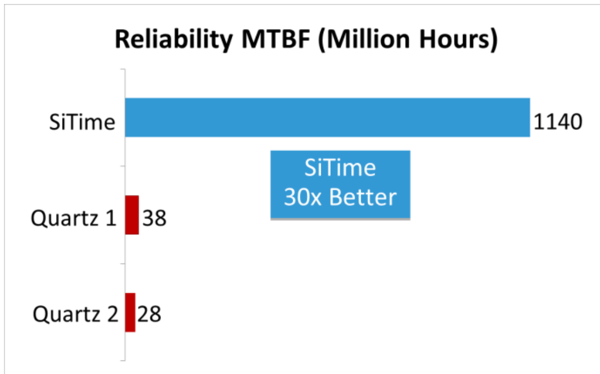


Figure 2. SiTime MEMS Oscillator MTBF vs. Quartz Suppliers

MEMS Aging

Low aging rate is the other benefit of the construction of MEMS in an ultra-clean wafer fab using the hermetic EpiSeal process. Contaminants are controlled to a very low parts-per-billion level and the 1100°C process step anneals the silicon crystal and serves as a stress relaxation process. The epitaxial seal is applied at the wafer level, which seals the enclosure in high vacuum with essentially very low or no impurities. The resulting ultra-clean resonator cavity and stress relaxation virtually eliminates resonator aging mechanisms. Any aging mechanisms are related to package related aging effects over time or CMOS IC aging, which age at a very low rate.

By contrast, Quartz oscillators are usually packaged in an open-cavity ceramic package, and the IC and quartz resonator are each bonded to the package substrate with a different type of adhesive. Moreover, each quartz device is individually trimmed using either ablation of deposition of metal onto the quartz resonator to trim the output frequency to the desired specification. The adhesives and metal trimming can be a source of contamination that can age the quartz through mass loading and reduce long-term reliability. Figure 3 shows the construction of a typical quartz oscillator.

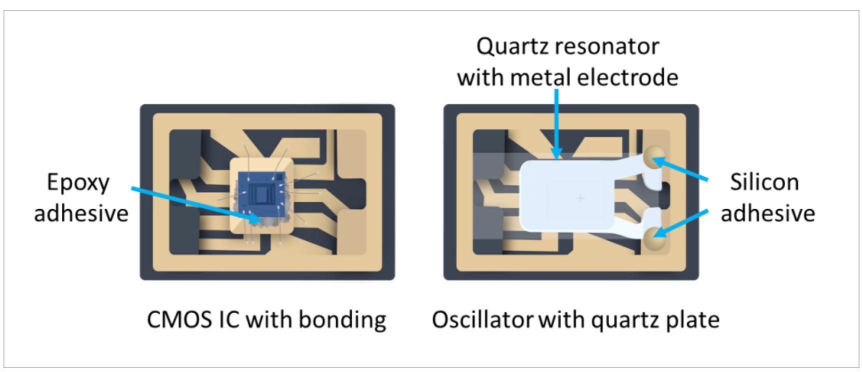


Figure 3. Typical Quartz Oscillator Construction

Lower aging is the net result of the MEMS oscillator construction. As shown in Figure 5, the typical 20-year aging specification for Endura Super-TCXO is ±540 ppb vs. ±3,000 ppb (±3 ppm) for quartz.

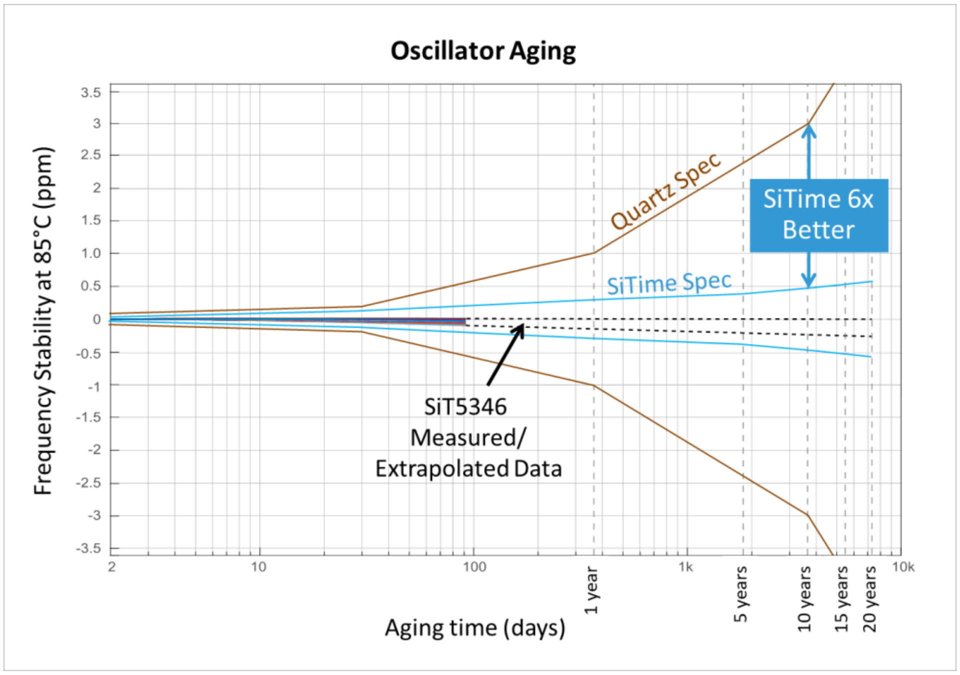


Figure 4. Endura MEMS Super-TCXO (92 devices) Aging vs. Typical Quartz Aging Specification

Vibration Performance

MEMS-based oscillators are much more resistant to shock and vibration, in part because MEMS resonators have approximately 1,000 to 3,000 times lower mass than quartz resonators. This means a given acceleration imposed on a MEMS structure, such as from shock or vibration, will result in much lower force than its quartz equivalent and will therefore induce a much lower frequency shift. Figure 5 shows the construction and size of a MEMS resonator compared to a quartz resonator.

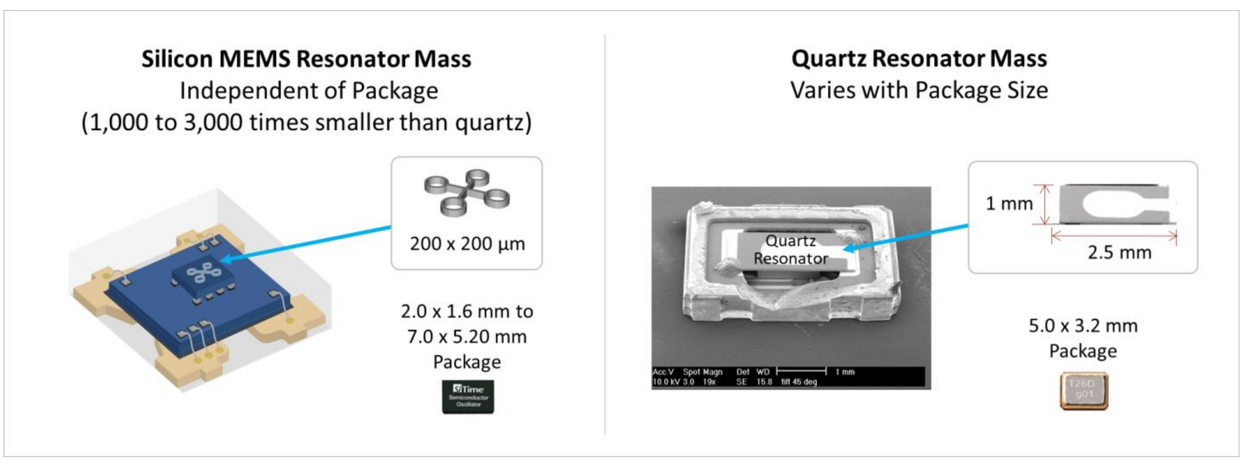
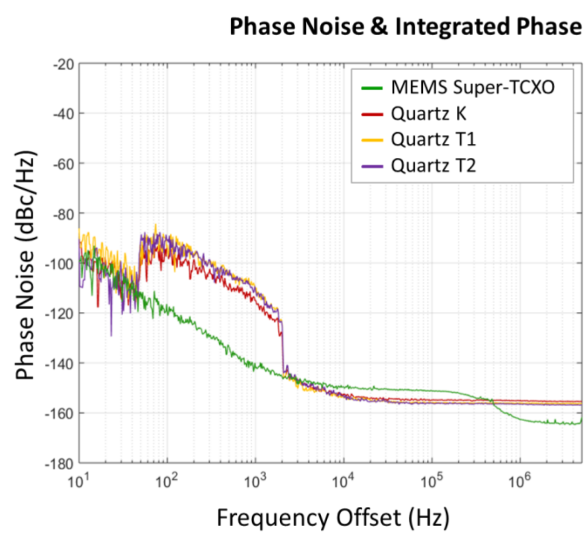


Figure 5. Comparison of MEMS and Quartz Oscillator Structures

A benefit of the MEMS structure is illustrated in Figure 6, which shows phase noise of a SiTime Endura MEMS Super-TCXO shown by the green curve compared to quartz TCXOs. The random vibration magnitude was 7.5*g* root mean square (rms) over a frequency band of 10 Hz to 2 kHz. The MEMS Super-TXCO had about 20 dB lower phase noise in this vibration frequency band. Integrating the phase noise over the vibration frequency band from 10 Hz to 2 kHz demonstrates the integrated phase jitter (IPJ) of the MEMS oscillator is increased by a factor of 1.2 times, while the quartz TCXOs increased IPJ by as much as 10 times. Maintaining good phase noise performance in the presence of vibration stress is very important to systems such as moving vehicles, aircraft, and any system deployed near vibrating machinery.



DUT	IPJ, 10 Hz – 10 kHz		
	Base-line	Vibration on	Ratio increase
	ps RMS		X
MEMS	0.53	0.63	1.2x
Quartz K	0.54	2.42	4.5x
Quartz T1	0.58	3.93	6.8x
Quartz T2	0.44	4.43	10.1x

Figure 6. Phase Noise in the Presence of Random Vibration, 20 MHz Output Frequency

Another measure of vibration sensitivity is the frequency shift per *g* of sinusoidal acceleration applied. The most common unit of measurement is part per billion (ppb) frequency shift per *g* of acceleration, or ppb/*g*. Figure 7 shows the total acceleration sensitivity gamma vector (over 3 axes) of 30 Endura Super-TCXO SiT5346 units over vibration frequencies from 15 Hz to 2 kHz. The maximum observed value of only 5.77 parts-per-trillion/*g* is the lowest (best) vibration sensitivity in the industry.

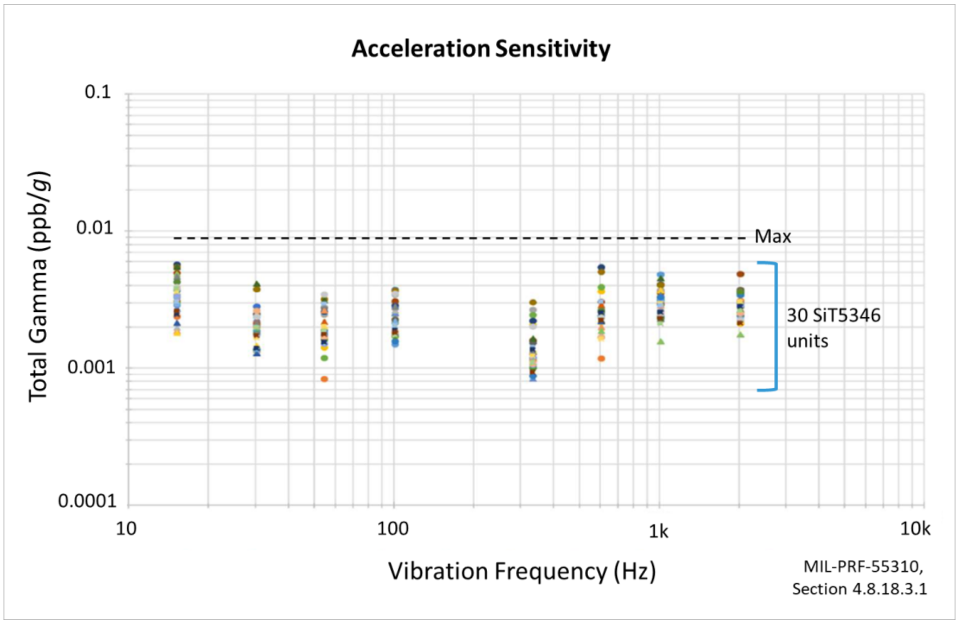


Figure 7. ppb/*g* Vibration Sensitivity Gamma, 15 Hz to 2 kHz Vibration Frequency

Another important parameter for certain applications such as munitions is shock resistance, and that is yet another area where MEMS technology excels over quartz technology. SiTime Endura products are shock tested up to 30,000*g* which is significantly higher than most quartz products. The below graphic shows qualification report excerpts for a typical quartz device and for SiTime Endura MEMS oscillators. The quartz oscillator was qualified up to 1500*g* and the SiTime Endura MEMS oscillators are qualified to 30,000*g*. To better understand this level of shock resistance, 155-mm gun projectiles experience typical peak set back acceleration of 15,500*g* over a 9-msec pulse duration[1]. Typical desired system design margins are 1.5 times which implies 155-mm gun projectile components should be certified for up to 23,250*g*. Endura oscillator 30,000*g* qualification exceeds this margin.

[1]Burd, Jeff, *High-G Ruggedization Methods for Gun Projectile Electronics*, Proceedings of the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1999), Nashville, TN, September 1999, pp. 1133-1142.

SiTime

Excerpt from SiTime Oscillator Qualification Report

Type of Stress	Ref Standard	Test Condition
Vibration	MIL-STD-883 Method 2007	70g peak 20-2000 Hz, X,Y,Z axis
Mechanical Shock	MIL-STD-883 Method 2002	30,000g peak, duration 0.2 ms, 5 shocks, six axis
Constant Acceleration	MIL-STD-883	30,000g, Y1 axis

Excerpt from "Well-Known" Quartz Oscillator Qualification Report

Vibration	JESD22-B103	20g peak 10-2Khz, 1.52mm, 20 minutes/sweep, 3 axis	6 sweep /axis
Mechanical Shock	JESD22-B104	1500g peak, 0.5ms pulse, 6 axis	5 pulse/axis

DualMEMS Oscillator Technology

Vibration resistance and reliability have been intrinsic advantages of MEMS oscillators since the early generations were developed. Recent advances in technology, notably a novel dual MEMS-based architecture employed in Endura MEMS oscillator families from SiTime[2], yield additional benefits such as resilience to fast temperature ramps and low phase noise. Before quantifying these benefits, it will be instructive to provide a brief overview of the DualMEMS™ technology and architecture to explain how these advantages are achieved.

Figure 8 shows a block diagram of the DualMEMS oscillator architecture. Starting at the left of the block diagram are the resonator and temperature sensor that comprise the two MEMS. One resonator is used as a temperature sensor, exploiting its relatively steep but linear -7 ppm/C° frequency vs. temperature slope. This resonator is the TempSense (TS) resonator. The other resonator, which provides a reference clock to the downstream phase lock loop (PLL) is designed to have a relatively flat frequency vs. temperature slope and is the TempFlat™ (TF) resonator. The ratio of frequencies between the TF and TS resonators provides an extremely accurate reading of the resonator temperature with 30-µK resolution. Another key feature is the tight thermal coupling between the TF and TS resonators, which is due to their small 100-micron separation and their fabrication on the same die substrate. This construction results in virtually no thermal gradient between the TF and TS resonators. Simulations have shown only 52 milliKelvin (m°K) temperature offset between the TF and TS resonators under heat flux.

[2]SiTime's DualMEMS architecture and TurboCompensation™ technology is employed in Endura Super-TCXOs, Endura DE-XOs (differential-ended oscillators), Endura DCXOs (digitally-controlled oscillators), and Endura VCXOs (voltage-controlled oscillators).

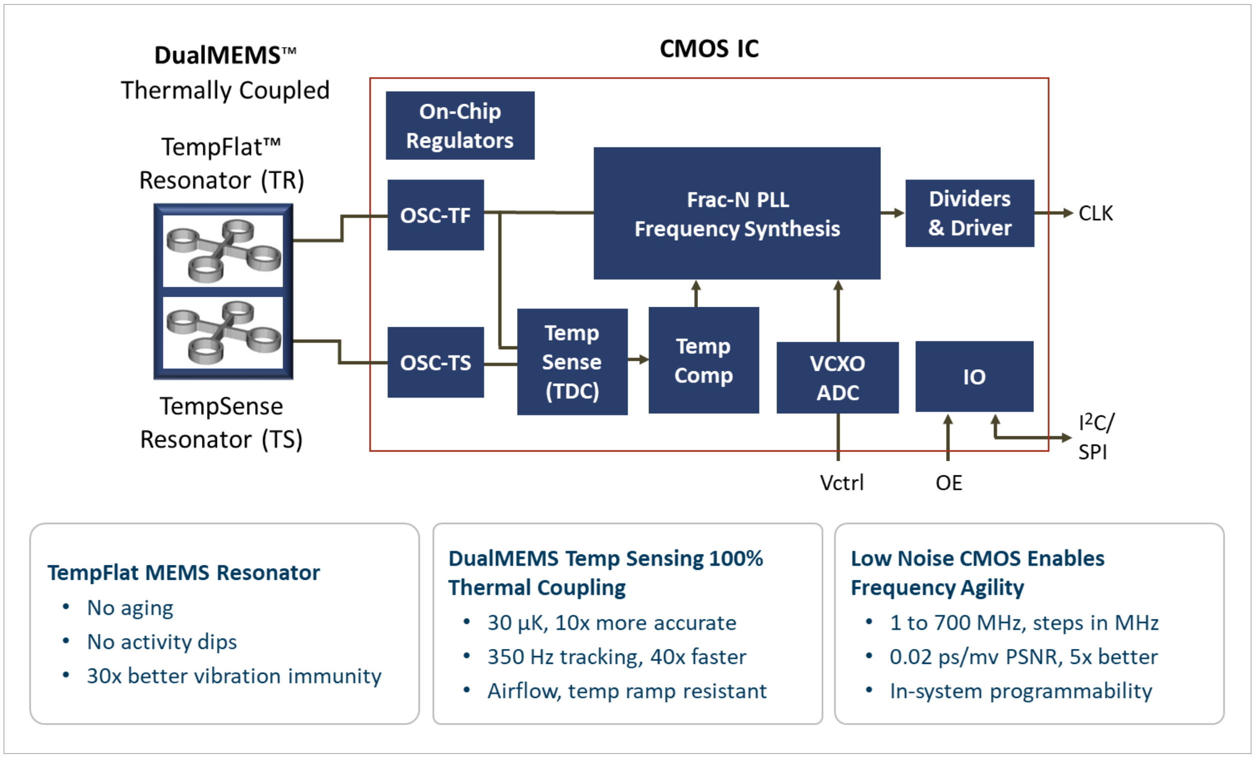


Figure 8. Endura DualMEMS Block Diagram and Benefits

By contrast, the temperature sensor in quartz TCXOs is integrated in the IC that sits below the quartz resonator on the substrate of the ceramic package as shown in Figure 9 below. The spatial separation between the temperature sensor and the resonator in the quartz oscillator construction results in a substantial thermal gradient between the two elements, and introduces significant frequency error when subjected to fast thermal transients. Response to fast thermal transients between quartz and MEMS will be quantified later in this paper.

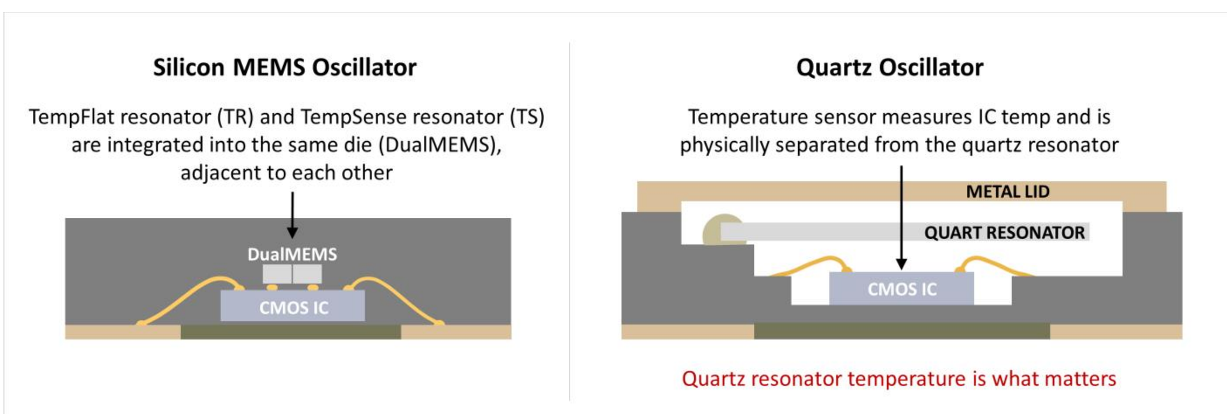


Figure 9. DualMEMS Oscillator vs. Quartz Oscillator Construction (Cross Section)

A key element of the temperature compensation architecture is the temperature to digital converter (TDC). As shown in Figure 10, this circuit block generates an output frequency which is proportional to the ratio between the frequencies generated by the TF resonator and the TS resonator. The TDC has a 30 microKelvin (µ°K) temperature resolution and bandwidth up to 350 Hz. These features enable excellent close-to-carrier phase noise performance and Allan deviation (ADEV) performance.

The high bandwidth of the TDC combined with the tight thermal coupling between the TF and TS resonators result in minimal frequency error when the TCXO is subjected to fast temperature transients.

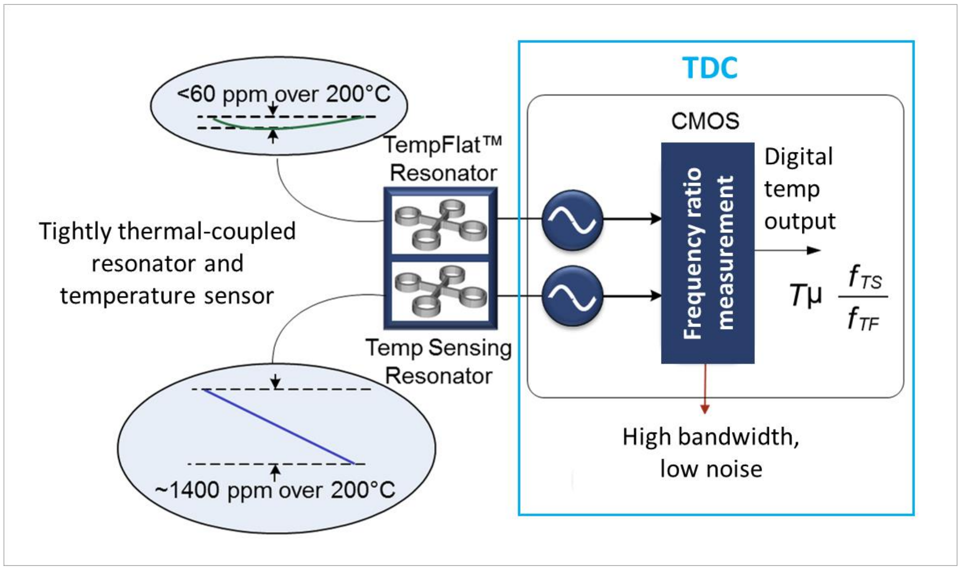


Figure 10. Temperature to Digital Converter (TDC)

Frequency Response to Fast Thermal Transients

Figure 11 is a video screen capture that demonstrates the benefit of the DualMEMS architecture during fast thermal transients. This screen shot is captured when a heat gun is simultaneously applied to two devices: a DualMEMS Super-TCXO and a ±50 ppb carrier-grade TCXO from a leading quartz vendor. In response to the heat gun stimulus, the quartz TCXO deviates up to 650 ppb peak-to peak (-450 ppb to +200 ppb) from nominal temperature, exceeding its datasheet specification by a factor of up to 9. The frequency change of the DualMEMS Super-TCXO is barely noticeable, about 3 ppb maximum, and is well below its specification limit of 100 ppb. Resilience to rapid temperature transients is very important for the performance and quality of service in communications infrastructure equipment during rapidly changing environmental conditions. Note the Endura Super-TCXOs are based on the DualMEMS architecture of SiTime's Elite Platform™ and will have comparable performance to Elite Super-TCXOs. Watch the full video demonstration for comparative responses to additional stresses including air flow, supply voltage, and small shock stresses.

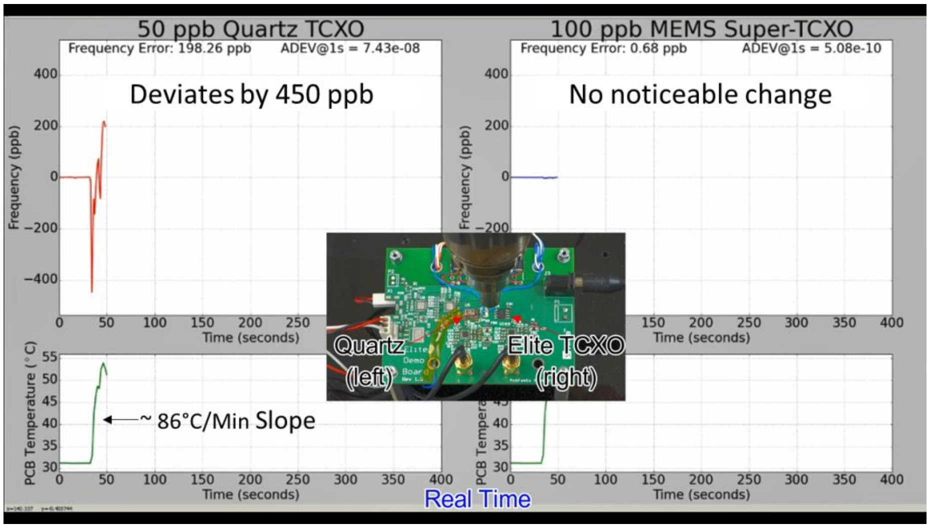


Figure 11. Screenshot of ±50 ppb Carrier-grade Quartz TCXO vs. a MEMS Super-TCXO under Fast Temperature Ramp

Airflow

Airflow is another system stressor that can cause changes in frequency and is a potential stress factor for outdoor equipment. Airflow can result in die temperature changes due to the change in heat flow out of the oscillator. Rapid, turbulent airflow can have an even more pronounced effect on heat flow from the oscillator to the environment, and in extreme cases, can cause vibration effects. Figure 12 plots Allan deviation in the presence of airflow using averaging times from 1 second to 1,000 seconds. As shown, MEMS Super-TCXOs demonstrate up to 38 times better ADEV performance than a quartz TCXO using averaging times between 1 second and 10 seconds.

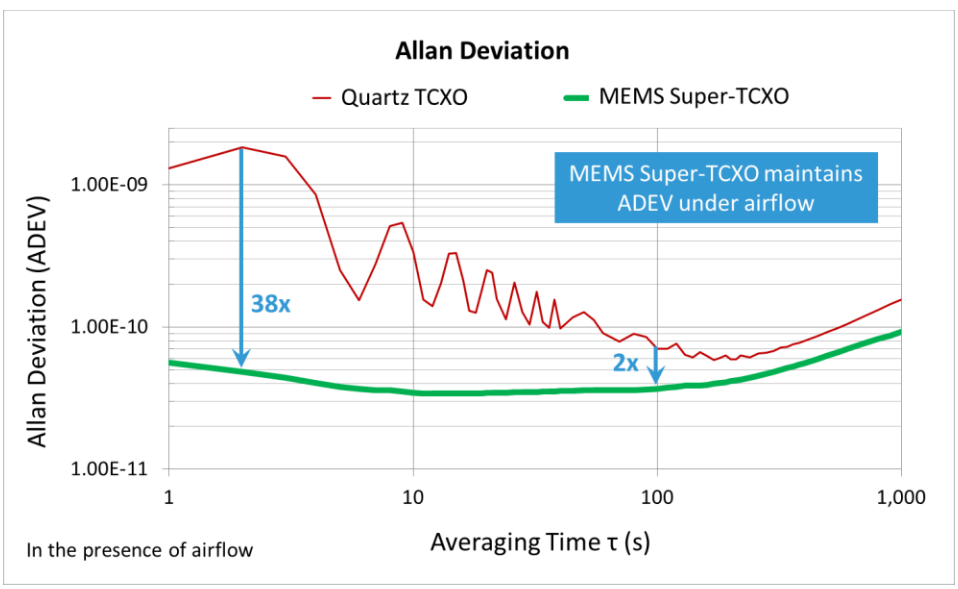


Figure 12. MEMS Super-TCXO and Quartz TCXO Allan Deviation in the Presence of Airflow

Allan deviation is a time domain measure of frequency stability. The main advantage of ADEV over standard deviation is that it converges for most noise types, therefore, it is widely used for characterizing frequency stability of precision oscillators such as TCXOs. Good ADEV performance is particularly important for satellite communications and precision GNSS applications and Endura Super-TCXOs excel at this key performance metric.

Power Supply Noise Rejection

Besides external environmental stresses such as vibration, ambient temperature changes, and airflow changes, internal system stresses are often present. For example, power supply noise can result from crosstalk from nearby data lines and switching regulators. It is very important for the oscillator to maintain good phase noise and jitter performance in the presence of noise on the power supply pin in order to maintain good system performance. Power supply noise rejection (PSNR) is a measure of the resilience of the oscillator to power supply noise and is the ratio of jitter observed at the output in picoseconds divided by the amplitude of injected sinusoidal deterministic jitter on the supply pin in millivolts. Normally, sinusoidal jitter is injected onto the supply pin with 50 mV amplitude. Figure 13 shows the peak-to-peak jitter of a the MEMS SiT9346 differential oscillator (DE-XO) oscillator as compared to quartz oscillators from six different suppliers across the noise frequency range of 20 kHz to 40 MHz.

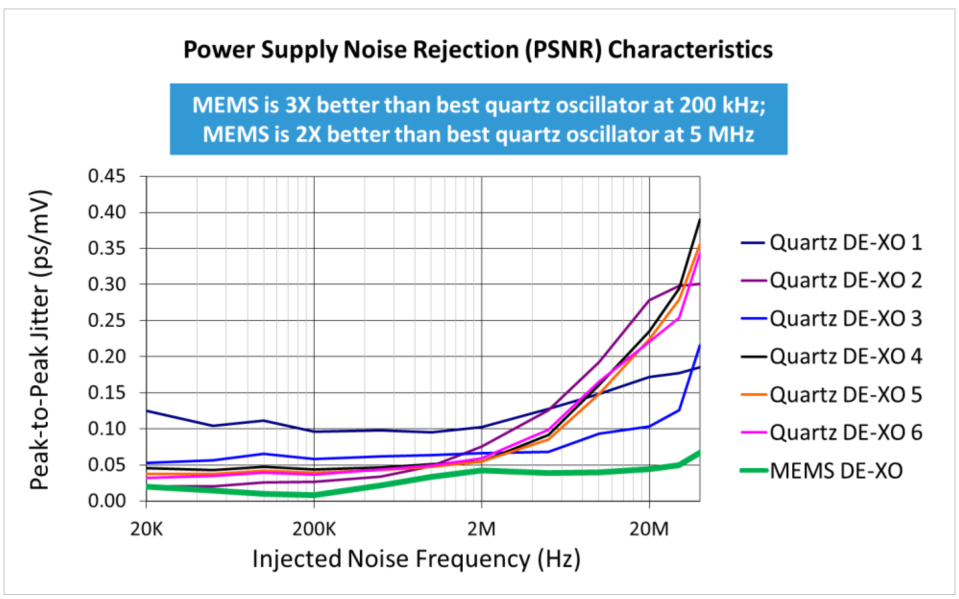


Figure 13. Power Supply Noise Rejection of MEMS DE-XO vs. Quartz Oscillators

As shown in the plot, the MEMS oscillator excels in PSNR. The low jitter demonstrated in the MEMS device is due to its multiple on-chip low-dropout regulators (LDOs) which isolate critical components such as the VCO, MEMS oscillator, etc.

Addressing the Timing Challenges of Aerospace and Defense Applications

MEMS oscillator technology has improved significantly over the past decade. Improvements encompass key elements that comprise a high performance oscillator: resonator, temperature compensation circuitry, PLL, and on-chip voltage regulators to filter noise. Building on the intrinsic advantages of shock and vibration resistance, state-of-the-art MEMS timing technology also delivers best-in-class dynamic performance (resilience to system and environmental stresses), making it an ideal choice to address the challenges associated with equipment deployed in rugged environments. Table 1 below summarizes the latest SiTime Endura MEMS technology compared to quartz oscillators.

Performance Parameter	SiTime Endura Oscillator	Typical Quartz Oscillator	Endura Improvement
Maximum Shock Acceleration	30,000*g*	1,500*g*	**20x**
Sinusoidal Vibration	70*g*	20*g*	**3.5x**
TCXO Frequency Deviation, fast thermal transient	3 ppb	650 ppb	**200x**
Power Supply Noise Rejection (PSNR) @ 200 kHz	0.01 ps/mV	0.06 ps/mV	**6x**
IPJ Increase under Vibration	1.2x	10.1x	**8.3x**
TCXO ADEV under Airflow at τ= 4 sec	4.5E-11	1.7E-9	**38x**
Mean Time Between Failure (MTBF) Million Hours	1,140	38	**30x**
20-Year Aging	±540 ppb	±3,000 ppb	**~ 6x**

Table 1. Summary of Endura MEMS Oscillator Benefits vs. Quartz Oscillators

Additional investment and innovation in MEMS timing technology will continue through the foreseeable future, aimed at improving phase noise and frequency stability and making MEMS-based timing the de-facto solution of choice for the next several decades.

Appendix A: Endura MEMS Oscillators

Device Type	Device	Frequency (MHz)	Temp. Range (°C)	Stability (ppm)	Output Type	Package Size (mm)
Super-TCXOs	SiT5146, SiT5147	1 to 220	-40 to 10 -40 to 105 0 to 70	±0.5 to ±2.5 ±0.1 to ±0.25 ±0.05	LVCMOS, Clipped Sine Wave	5.0 x 3.2
	SiT5346, SiT5347					
	SiT5348, SiT5349					
Differential Oscillators	SiT9346, SiT9347	1 to 725	-20 to 70 -40 to 85 -40 to 95 -40 to 105	±10 to ± 50	LVPECL LVDS HCSL	3.2 x 2.5 5.0 x 3.2 7.0 x 5.2
Single Ended Oscillators	SiT8944, SiT8945	1 to 137	-40 to 85 -40 to 105 -40 to 125 -55 to 125	±20 to ±50	LVCMOS	2.0 x 1.6 2.5 x 2.0 3.2 x 2.5 5.0 x 3.2 7.0 x 5.0
	SiT2044, SiT2045					SOT23-5
Spread Spectrum Oscillators	SiT9045	1 to 150	-40 to 85 -40 to 105 -40 to 125 -55 to 125	±50	LVCMOS	2.0 x 1.6 2.5 x 2.0 3.2 x 2.5
VCXOs	SiT3342, SiT3343	1 to 725	-20 to 70 -40 to 85 -40 to 95 -40 to 105	±15 to ±50	LVPECL LVDS HCSL	3.2 x 2.5 5.0 x 3.2 7.0 x 5.2
DCXOs	SiT3541, SiT3542	1 to 725	-20 to 70 -40 to 85	±10 to ±50	LVPECL LVDS HCSL	5.0 x 3.2

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