"G"- COMPENSATED, MINIATURE, HIGH-PERFORMANCE QUARTZ CRYSTAL OSCILLATORS

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Abstract

Sophisticated military radars and sensors mounted on high dynamic platforms such as helicopters, unmanned air vehicles, and missiles, all have one thing in common—one or more Quartz Crystal Oscillators generating precision frequency and time signals for these systems. Of all the components, the oscillator is the most sensitive to severe dynamics and, as a result, will degrade the performance of the entire platform. This paper describes the new quartz crystal oscillator "g"- compensation technology that significantly reduces the dynamic effects on the oscillator, bringing the system to near quiescent-state performance, while in the mobile (dynamic) state. To increase the utility of this component for both platforms and portable applications, it must also be small and have low power consumption.

THE PROBLEM

Sophisticated military electronic systems aboard helicopters, unmanned air vehicles, and missiles must provide superior performance while subjected to severe environmental conditions. The greatest impact comes from dynamic environments—those that induce degradations while the military platform is in motion accomplishing its intended mission. Of these mobile disturbances, vibration, acceleration, and shock have the greatest influence on performance. In light of this fact, a chasm exists between the performance of such systems in the quiescent (stationary) state and the performance while dynamic (mobile). The technology described herein closes this gap—providing performance near theoretical quiescent limits while the platform is in the operational, dynamic state.

THE CONSEQUENCES

Systems most troubled with such environmental conditions are radars and sensors mounted on helicopters; sensors mounted on unmanned air vehicles and missiles; emitter detection and signal analysis systems on airborne platforms; GPS-aided navigation, guidance, and targeting systems; and broadband, high-data-rate communication systems on dynamic hosts. The performance of these systems can be directly linked to the *threat-to-life* risk level of our military personnel that operate them. For example, degraded helicopter radar performance may relegate the system to detect only larger, faster-moving objects and miss the enemy combatant on foot. For systems detecting and analyzing enemy emitters, degraded performance will compromise the detection stand-off range. Harsh dynamics that degrade weapons guidance and targeting could mean nothing short of life or death for our troops.

THE SOLUTION

What do all these aforementioned systems have in common?—Quartz Crystal Oscillators and Rubidium Vapor Atomic Oscillators—the heart of these systems and the culprit of degradation from harsh environments. These internally mounted components generate the precision frequency and time signals crucial to systems performance. Quartz crystal oscillators, whether stand-alone or part of traditional rubidium oscillators, are sensitive to acceleration forces, vibration, and shocks. These cause the oscillator stability and accuracy to degrade and in turn degrade the systems performance. The "g" (acceleration)-compensated quartz oscillator technology makes significant inroads toward defeating degradations from dynamic environments.

THE SYSTEM

Almost all electronic modules and systems, whether commercial or military, have oscillators with the appropriate precision levels to accomplish the intended function. As the sophistication level of an electronic system increases, so does the need for the precision level of its internal oscillator. Dynamic systems most sensitive to the performance of its internal oscillator in terms of its oscillation accuracy [1] over time and the stability [2] of its oscillations are:

- *Radars and sensors mounted on helicopters* – here, the problem lies in the severe low and medium frequency vibration environment, typical of large-rotor aircrafts. The precision oscillators contained in a radar system integrate these mechanical vibrations (oscillations) with their own electronically generated oscillations, resulting in undesired frequency and time domain noise. This noise then translates to the systems level, relegating the radar to lower precision imaging and false target detection.

- *Sensors mounted on unmanned air vehicles and missiles* – the power plants of UAVs are generally composed of large propellers, piston or turbine driven, as well as jet engines. Due to the need for target "loitering" at very low speeds, vehicle vibration levels in the low- and medium-frequency range can be as severe as those of helicopters. Like radars, this will affect sensor precision and may also impact communications with the control center.

- *Emitter detection and signal analysis systems on airborne platforms* – whether on helicopters, UAVs, or reconnaissance aircraft, these systems degrade very rapidly in severe and even moderate dynamic environments. The result is loss of detection range (the vehicle must be closer to the emitter to make an

[1] *Accuracy* as related to an oscillator refers to the precision to which its "output frequency" is held over the long term with respect to the international standard (UTC). This also applies to its "time accuracy" capability, since time is the reciprocal of frequency.

[2] *Stability* as related to an oscillator refers to its ability to maintain precise oscillations over the short term. Although an oscillator can be accurate over the long term, the oscillations during that time period can be unstable. This relates to both the time domain error associated with each oscillation and the frequency domain noise – in other words, how many unwanted frequencies are generated and how strong they are with respect to the desired frequency. Frequency domain noise is also called Phase Noise.

accurate identification) and a slower signal analysis process (the time it takes for positive identification of the threat).

- *GPS-aided navigation, guidance, and targeting systems* – launch environments and high dynamic flight operations subject onboard oscillators to not only severe vibration environments, but also shock and other in-flight pyrotechnic events. Depending on the sophistication level of the navigation aiding through gyros and/or GPS, accuracy can be degraded.

- *Broadband, high-data-rate communication systems on dynamic hosts* – low-noise frequency sources play a major role in data rate, since these sources are multiplied to very high carrier frequencies. Platform dynamics degrade the signal-to-noise ratio, which in turn increases the BER (bit error rate), forcing the system to decrease its data rate to maintain the desired BER.

Needless to say, the precision oscillator is the Achilles Heel and defines the system performance specifications. The proposed compensation technology is a breakthrough, providing significant system's performance improvements under dynamic conditions.

THE APPLICATION

Since the technology described herein is most applicable to high-tech platforms in dynamic environments, we will begin with the most difficult ones—"loiter" aircraft and helicopter-mounted radar systems. For these, we will discuss the application of the "g"-compensated quartz technology in a 10 GHz X-Band Doppler radar operating in both quiescent and dynamic states. One of the processes of radar imaging involves the detection of the Doppler Frequency generated by a moving object. Figure 1 shows the Doppler frequency as related to objects moving toward the radar vs. the radar carrier frequency.[3] To detect an enemy combatant on foot moving about 4 km/hour, a 10 GHz Doppler radar system must detect a certain signal energy level relating to approximately 70 Hz deviation from the radar carrier frequency.

THE STATIONARY PLATFORM

The signal energy level needed to detect a 4 km/hr object relates to a phase noise performance of the radar's 10 GHz frequency source of about 70 dBc at ~70 Hz from the carrier, as shown in Figure 2. This is achieved by a good 10 GHz DRO-quartz oscillator combination[4], which performs with a ~10 to 20 dBc margin to detect our example target while the platform is at rest. To meet the ~70 dBc at ~70 Hz

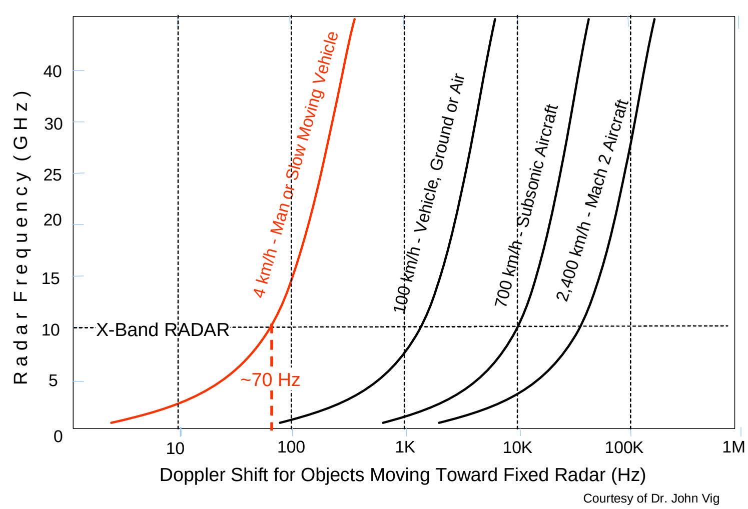


Figure -1, Doppler Shifts of Moving Objects vs. Radar Frequency[3]

[3] Courtesy of Dr. John Vig; from a tutorial – Quartz Crystal Resonators and Oscillators: *J.Vig@ IEEE.org*, January 2001.

[4] *DRO,* Dielectric Resonator Oscillator; SAW, Surface Acoustic Wave oscillator; and BAW, Bulk Acoustic Wave oscillators are best suited for high frequency usage. For example, combining a quartz oscillator with a DRO provides excellent low phase noise performance out to several GHz from the carrier frequency. The quartz provides good close-in phase noise performance (1 to 10 KHz) and DROs, SAWs, and BAWs, good performance 10 KHz and beyond.

from the 10 GHz carrier, the quartz oscillator must perform better than -130 dBc at ~70 Hz from its carrier frequency of 10 MHz.

This oscillator performance is needed, because the phase noise will degrade ~60 dB through the multiplication process per the expression: 20 Log (N); where N is multiplication factor. 10 MHz to 10 GHz is a (N) of 1000; the Log of 1000 is 3, times 20, yielding a 60 dB noise increase. Quartz oscillator performance of less than -120 dBc will make detection difficult, unless the radar moves closer to the object, theobject moves faster, or in some way becomes larger. This can be seen in Figure 3. Here, the -130 dBc performance relates to a 2σ detection probability, while the -125 dBc performance realizes only a 1σ detection probability.

The Dynamic Platform

Now, let's fly the radar and subject it to "loiter" aircraft and helicopter flight dynamics and vibration levels. The mechanical and acoustically generated environments for such platforms are shown in Figure 4. As expected, the vibration energy integrates with the unwanted oscillator-generated noise signals, raising the overall frequency domain noise floor.

The oscillator performance in the quiescent state vs. the dynamic state is mostly affected by the "g" sensitivity of the quartz crystal resonator, the heart of the quartz oscillator. This parameter is formulated by RSS [Root Sum Square; i.e., $\Gamma = (x^2 + y^2 + z^2)^{1/2}$] of the "g" sensitivity of each of the quartz crystal axes (X, Y, and Z) and is referred to as " Γ " (Gamma). Figure 5 shows the typical phase noise performance of 10 MHz quartz oscillators with four improving Γ specs in a loiter aircraft vibration environment (Figure 4).

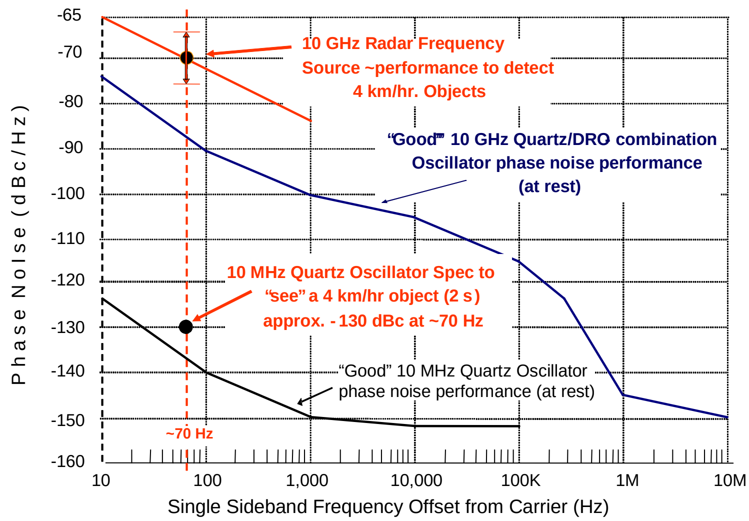


Figure-2, Oscillator Phase Noise Performance for 4 km/hr. Object Detection

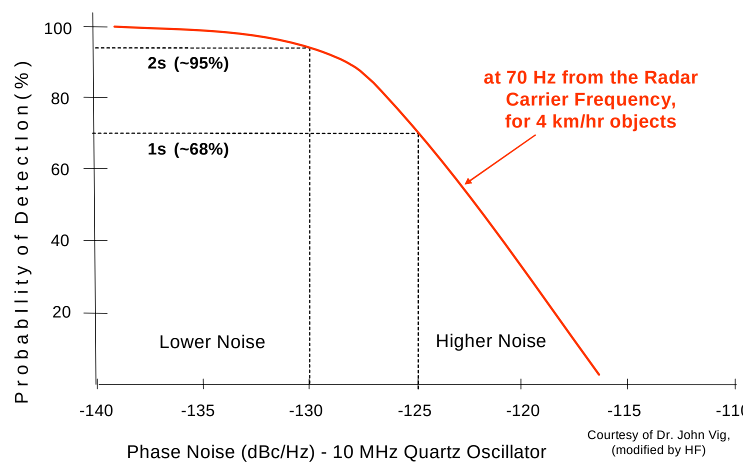


Figure-3, Radar - Probability of Detection [3]

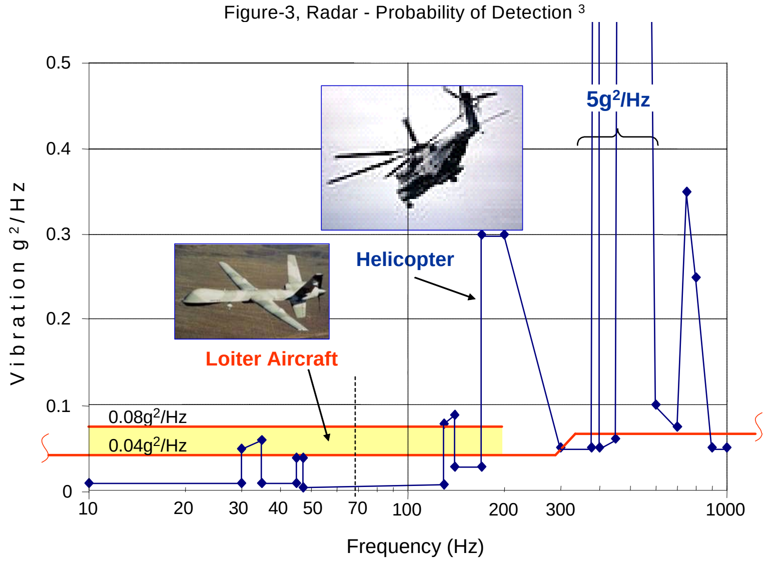


Figure-4, Typical Helicopter and Loiter Aircraft Random Vibration

The Γ of ~1E-9/g is a traditional good quartz resonator; a Γ of ~5E-10/g is a very expensive, well designed and produced state-of-the-art resonator; a Γ of ~2E-11 is an extremely good oscillator, produced by only one known manufacturer at present; and a Γ of ~2E-12/g is not presently achievable in a cost-effective manner. As seen in Figure 5, the 4 km/hr detection spec requires a quartz resonator Γ of better than 2E-11/g. Considering all the platform dynamics that may come into play, a 5E-12/g spec is most likely needed. To achieve this, the "g"-compensation technology will be required for frequencies less than ~200 Hz from the carrier. To shield the oscillator from vibrations greater than 200 Hz, a shock mount must be used.

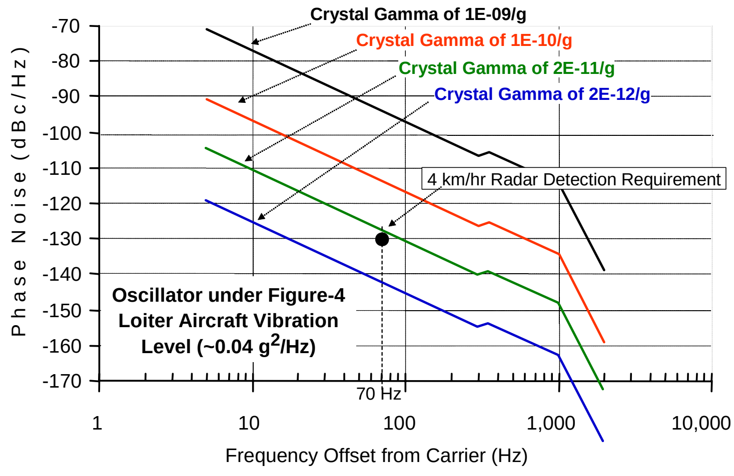


Figure-5, Phase Noise Performance vs. 10 MHz Oscillator "g" Sensitivity (Gamma) (Loiter Aircraft Random Vibration Environment)

This is also the case for the oscillator performance in a helicopter vibration environment shown in Figure 6. The traditional quartz resonator with a Γ of ~1E-9/g will not do the job in the dynamic environment, nor will a very high-tech uncompensated quartz resonator of ~5E-11/g. As in the case of the loiter aircraft environment, a Γ of ~5E-12 will be needed to meet the 4 km/hr requirement. The quartz oscillator compensation technology must bring the dynamic phase noise performance to better than the -130 dBc level at 70 Hz. Frequencies other than 70 Hz will not be as important in our example.

Figure-7 shows the expected performance of the same oscillator in the helicopter environment with compensation to a Γ of ~5E-12/g. For each decade of Γ reduction, there is a corresponding phase noise reduction of about 20 dBc.

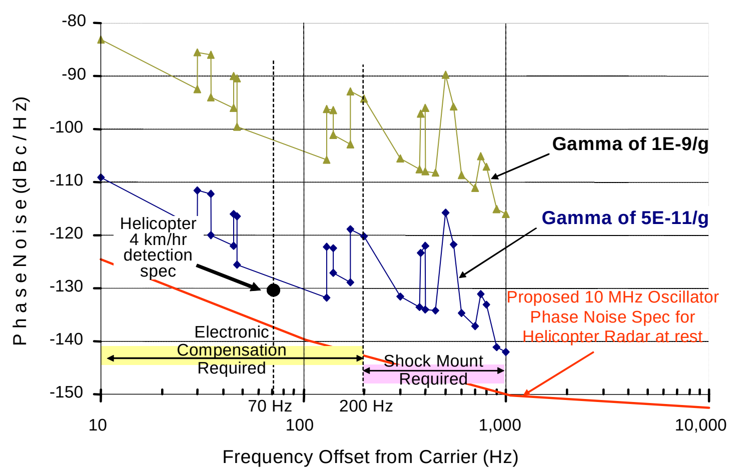


Figure-6, Phase Noise Performance vs. 10 MHz Oscillator "g" Sensitivity (Gamma) (Helicopter Random Vibration Environment)

THE TECHNOLOGY

The application of the FEI "g"-compensation technology is well on its way, providing performance improvement for a host of critical military platforms fielded in high dynamic environments. The technology is based on a breakthrough in two main areas: (a) new methods of quartz resonator design and manufacturing, which provides for less cross-coupling between the 3 axes (in other words, each axis is more independent of the other, making compensation more effective); and (b) new sensing devices that can easily be mounted and aligned in each resonator axes. Figure 8 represents a functional diagram of the "g"-compensation scheme.

As shown in item (A) of Figure 8, each specially produced quartz resonator with low cross-talk and low g-sensitivity will have a 3-axes response, defining its Gamma (Γ). The resonator is then packaged in the traditional quartz crystal oscillator form-factor and enclosure (B), which in this case, includes the compensation electronics. As linear and oscillatory accelerations are applied (C), the quartz oscillator responds (D), and so do the sensing devices (E). Compensation circuitry adjusts amplitudes and 180° phase relationships of the signals (F), resulting in less crystal "g"-sensitivity through electronic compensation (G).

Figure 9 represents a sample of the hardware presently being delivered. As can be seen, compensated quartz crystal oscillators are both stand-alone as well as being part of a more sophisticated master clock module. In this example, the GPS receiver provides the time and frequency synchronization of the rubidium oscillator, which provides the hold-over performance. It in turn disciplines a "g"-compensated quartz crystal oscillator, providing the system with excellent phase noise performance while in a severe vibration environment.

The Performance Data

The following represents actual test data for aircraft environments, but in this case, 0.08g^2/Hz for a total of ~4g RMS, 10 to 200 Hz (the higher level for loiter aircrafts shown in Figure 4). In actual applications, careful analysis of the platform's dynamics will provide important information on crystal oscillator mounting, so that the most sensitive oscillator axis is mounted in the least active vibration axis of the platform. Figures 10, 11, and 12 show oscillator performance—uncompensated and compensated; after ~200 Hz, a shock mount (vibration isolator)

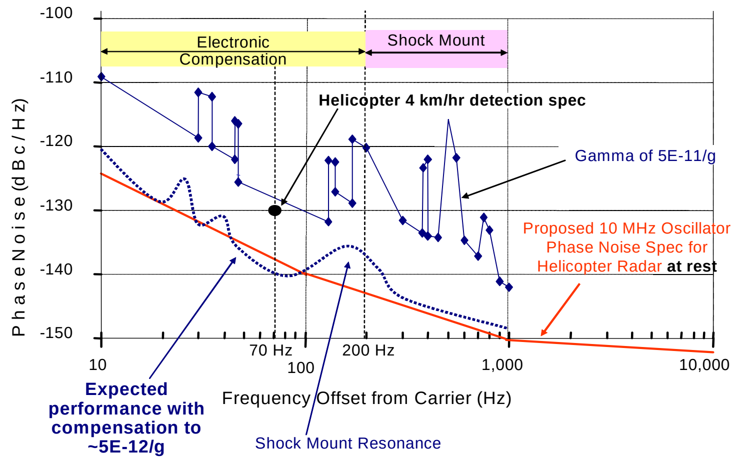


Figure-7, Expected Phase Noise of 10 MHz Oscillator "g" Sensitivity of ~5E-12/g (Helicopter Random Vibration Environment)

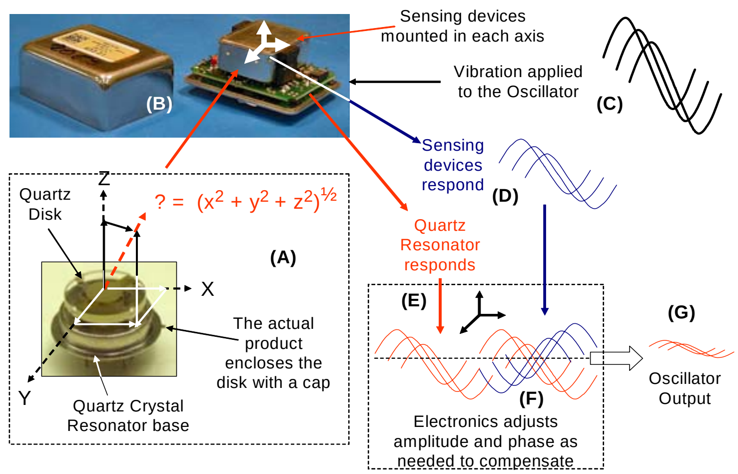


Figure-8, Functional Description of the g-Compensation Technology for Phase Noise

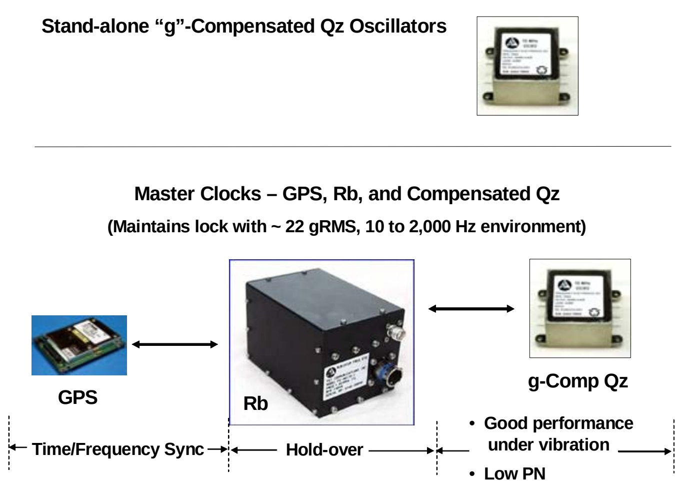


Figure-9, "g"-Compensated Quartz Oscillators and Master Clocks being fielded provides the improvement.

Note that the X and Y axes (Figures 10 & 11) meet the 4 km/hr detection criteria. However, the Z-axis, Figure 12, needs further improvement to meet the 4 km/hr detection criteria. This may require additional fine tuning in the compensation electronics or it may be as simple as changing the Z-axis mounting alignment with respect to the dynamics of the platform.

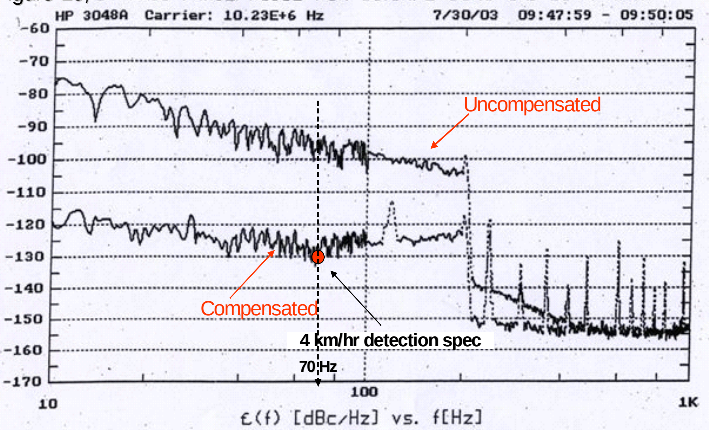
SPECIFICATION GOALS

To improve the performance of the applicable systems and to achieve the highest level of compensation, the specification goals for the oscillator are as follows:

"g"-Sensitivity (the primary focus of this report): The goal is to achieve a compensated frequency "g"-sensitivity performance of better than **$2\cdot10^{-12}$/g**, from 10 Hz to 2,000 Hz. Compensation to $1\cdot10^{-11}$/g is presently being produced. At the uncompensated quartz resonator level, the best-in-class performance is ~$2\cdot10^{-10}$/g. A traditional, well performing uncompensated quartz oscillator exhibits a "g"-sensitivity of about $1\cdot10^{-9}$/g.

Power Consumption: **100 mW**; presently being produced is a "g"-compensated quartz oscillator at 1.5 watts.

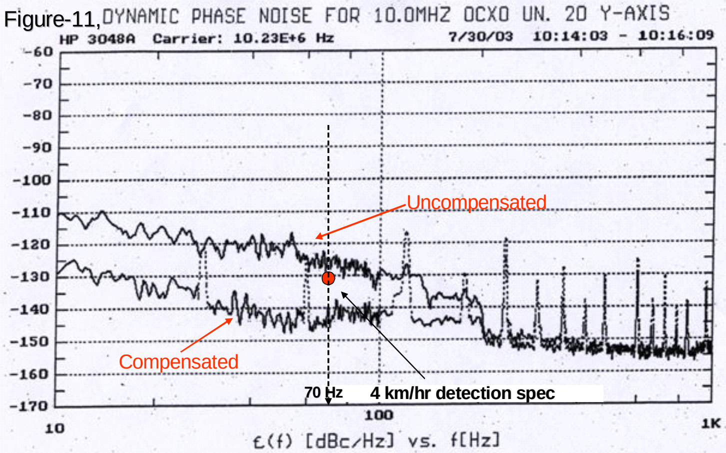
Figure-10, DYNAMIC PHASE NOISE FOR 10.0MHZ OCXO UN. 20 X-AXIS



Vibration Profile: 4g RMS total, Random; 0.08g²/Hz, 10 to 200 Hz

	Approximate Sensitivity per g (G)		
	10 Hz	50 Hz	100 Hz
Uncompensated	1.1 E-9	7.9 E-10	8.9 E-10
Compensated	6.3 E-12	2.2 E-11	4.0 E-11

Figure-11, DYNAMIC PHASE NOISE FOR 10.0MHZ OCXO UN. 20 Y-AXIS



Vibration Profile: 4g RMS total, Random; 0.08g2/Hz, 10 to 200 Hz

	Approximate Sensitivity per g (G)		
	10 Hz	50 Hz	100 Hz
Uncompensated	2.2 E-11	2.8 E-11	2.2 E-11
Compensated	2.8 E-12	2.5 E-12	5.0 E-12

Volume: **8 cm³**; a reduction from standard units, usually having a volume of at least 40 cm³ or more.

Short Term Stability: **$1\cdot10^{-13}$** @ 1 to 100 seconds Allan variance; presently in production is $1\cdot10^{-12}$.

Aging: **$1\cdot10^{-8}$ over 10 years**; presently in production is $1\cdot10^{-10}$ per day.

Temperature Coefficient: **± $2\cdot10^{-11}$** for the total range of -40C to +85C; presently in production is ± $1\cdot10^{-10}$ over the range.

CONCLUSION

The technology presented in this report is tried and proven and ready for application in platforms that need "beyond" state-of-the-art oscillator performance in dynamic environments. The technology has been proven effective for vibration frequencies of 10 to ~200 Hz, after which shock mounts are the practical solution for both volume and performance to isolate the oscillator up to 2000 Hz. The technology is well on its way to essentially achieve steady-state oscillator performance while in mobile-induced environments. With future improvements in acceleration sensing devices, quartz resonator design, and "g"-compensation design, effective compensation can be extended to 2000 Hz, eliminating shock mounts altogether.

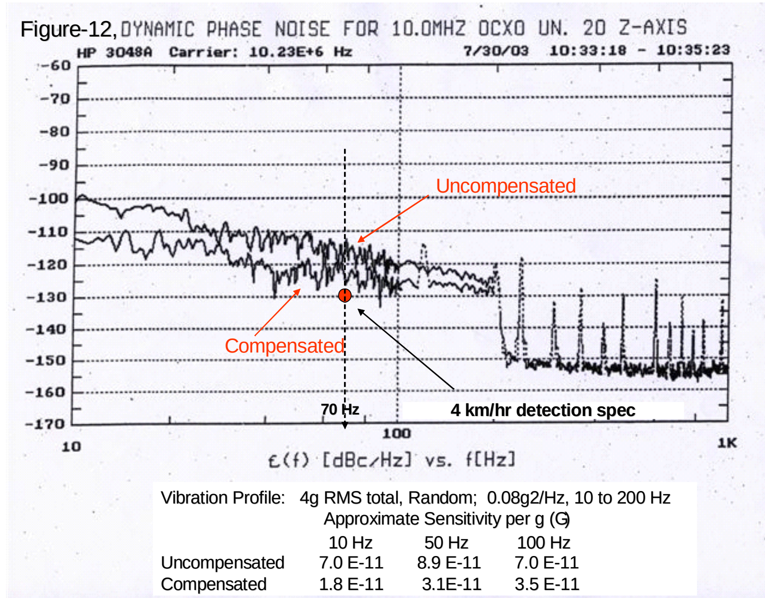


Figure-12, DYNAMIC PHASE NOISE FOR 10.0MHZ OCXO UN. 20 Z-AXIS

Vibration Profile: 4g RMS total, Random; 0.08g2/Hz, 10 to 200 Hz

Approximate Sensitivity per g (G)

	10 Hz	50 Hz	100 Hz
Uncompensated	7.0 E-11	8.9 E-11	7.0 E-11
Compensated	1.8 E-11	3.1E-11	3.5 E-11

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Frequency Electronics, Inc. (FEI) designs, develops, and manufactures high precision timing, frequency control/generation, and synchronization products for ground, seaborne, airborne, and space applications. The product line consists of both components and systems-level hardware, typically rack-mounted in standard 19-inch wide consoles or in form-factors needed by the application. Functionally, the product makeup is comprised of precision Quartz Crystal Oscillators, Rubidium Vapor Atomic Oscillators, Cesium Beam Atomic Oscillators, Passive Hydrogen Maser Oscillators, high-frequency DRO/SAW oscillator modules, and the associated frequency/time control, RF-frequency chain, and distribution electronics. The market segments served by these products include all aspects of commercial, government, and military telecom and computer networks, as well as operational platforms such as satellite payloads, missiles, unmanned and piloted aircraft, and GPS navigation and augmentation systems.

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