PRECISION QUARTZ OSCILLATORS AND THEIR USE IN SMALL SATELLITES

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Abstract

Space-qualified precision quartz oscillators are ideal instruments for use aboard small satellites as the heart of the spacecraft navigation system as well as for other applications such as radio science experiments, pseudorandom communications, and altimetry. This paper provides information on the history of precision quartz oscillator use aboard small satellites and discusses potential applications and design tradeoffs. The Johns Hopkins University Applied Physics Laboratory pioneered the use of precision quartz oscillators in small satellites in 1958. Current performance parameters of oscillators designed by the Applied Physics Laboratory will be presented along with mass and power considerations.

Introduction

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) pioneered the use of precision quartz oscillators aboard small satellites in 1958, when development of a 112-lb navigation satellite operating on 20 W began. Since navigation accuracy is directly related to oscillator frequency stability, the requirement for small, lightweight, low-power oscillators with excellent frequency stability was established, beginning a 34-year tradition that continues today. The oscillator for this early spacecraft had a frequency stability of 5×10^{-11} (100 s), used 1 W, weighed 2.6 lb, and had a volume of 73 in^3. Our current spacecraft oscillator has a frequency stability of 7×10^{-14} (100 s), consumes 0.9 W, weighs 1.7 lb, and has a volume of 44 in^3.

Quartz oscillators are used in satellites for a wide variety of applications, among the more obvious of which are to provide an accurate clock for controlling events on the satellite as a function of time, to time-tag data from experiments aboard the spacecraft, to synchronize pseudorandom data in spread spectrum communication systems, to time share or multiplex assigned channels between multiple users, and to encrypt data. Both clock accuracy and frequency stability are required in navigation systems to determine satellite position (navigation) or for Earth-based users to accomplish global navigation from transmitted satellite signals. A very stable frequency is required to control RF transmitters on the satellite, radar altimetry, and high-resolution Doppler radar as well as to conduct ionospheric studies and to perform radio science experiments by measuring the Doppler shift of a stable carrier frequency.

Frequently, the quartz oscillator is mission-critical to a spacecraft; therefore, long-term, reliable operation of the oscillator is often as important as frequency stability. More than 375 APL-developed quartz oscillators have been placed in orbit over a 34-year period. Only one in-orbit failure of an APL oscillator has occurred, and this failure did not result in mission failure, since a redundant oscillator was switched into service. One APL program, the Navy Navigation Satellite System (NNSS), has accumulated over one million hours of oscillator operation in orbit without a failure. One oscillator in this satellite constellation, Spacecraft 13, provided continuous service for over 21 years as shown in Figure 1. This level of reliability allows nonredundant operation, which is an important advantage for most light satellite programs.

Quartz Resonators

The quartz resonator is the most important component in any quartz oscillator. Excellent oscillator circuits cannot produce performance exceeding the inherent quality or capability of the quartz resonator. Less than optimum electronic circuits, however, can seriously degrade the potential performance of the resonator. Quartz resonators, as shown in Figure 2, are produced in many shapes, sizes, and operating frequencies and have many cost levels. The potential frequency stability also has a wide variation of from 1×10^{-6} to 5×10^{-14} (100 s). Resonator Q, or quality factor, is the best measure of the potential resonator performance. For example, the resonator in a quartz watch is a relatively simple low-Q (~30,000) device that is very inexpensive (< \$1.00). In contrast, a resonator for a high-precision oscillator is a complex, carefully processed, high-Q (> 3,000,000) device that is very expensive (> \$1000). A precision quartz resonator is capable of controlling frequency very precisely, but to realize the full potential of the resonator, its operating environment must be very carefully controlled.

What Is a Quartz Oscillator?

In simplest terms, a quartz oscillator is a quartz resonator supported by a variety of systems designed to keep the resonator operating within the parameters defined by the application. What support systems are required to keep the oscillator operating within specifications? For a quartz watch, a simple integrated circuit, a capacitor, and a battery are adequate. On the other hand, support systems for a resonator used in a high-precision, flight-qualified oscillator are much more complex and include temperature control, shock and vibration isolation, complex electronic circuitry, magnetic shielding, electromagnetic control, radiation shielding, and power conditioning.

Specifications and Design Trade-offs

Specifications for a precision oscillator must include output frequency, short- and long-term frequency stability, phase noise, magnitude and spectral purity of the output signal, definitions of output frequency response to environmental factors (temperature, acceleration, magnetic fields, vibration, ionizing radiation), and warm-up time. Mass, size, input power, and cost are also major considerations.

Evaluation of design trade-offs should begin by establishing the priority of each oscillator parameter. Excellent frequency stability has always been the driving factor in oscillator design at APL. Long-term, reliable operation is another important design goal, since the design life of the typical APL spacecraft was five years even in the early 1960's. Power consumption, mass, and size also must receive careful consideration because of the small overall size of the spacecraft and limited bus power.

Design trade-offs can optimize one or two parameters. If several parameters must be optimized simultaneously, however, one or more parameters may be compromised. For example, if the requirements are for a small, low-mass, low-power, low-cost oscillator, then frequency stability, accuracy, and response to environmental effects will be sacrificed. On the other hand, if an oscillator must have excellent short- and long-term frequency stability, phase noise, and environmental immunity, then mass, power, and cost will increase. Since trade-offs are limited, the requirements for an oscillator should be carefully evaluated and not overspecified.

As stated before, the one component that has the greatest influence on oscillator performance is the quartz resonator.[1] The higher the quartz resonator's Q, the better the frequency stability of the oscillator if all other factors are equal. The Q of a resonator may be expressed as follows:

$$Q = \frac{\text{Energy stored during a cycle}}{\text{Energy lost during a cycle.}}$$

The highest Q quartz resonator commercially available operates at 5 MHz and has a Q exceeding 3.0 million. If phase noise close to the carrier and low aging rate are the most important oscillator parameters, a 5-MHz resonator should be used. If the oscillator output frequency must be multiplied into the GHz region, an oscillator operating at a higher frequency may be desirable.

Ovens for the quartz oscillators are generally made of copper; however, if a small degradation in frequency stability and output frequency versus temperature is acceptable, ovens can be made from aluminum or magnesium, providing a weight reduction of over 50%. New alloys that are potentially attractive for oscillator ovens are becoming available. These alloys have many of the desirable characteristics of copper but have only half the weight of copper.

The phase noise floor can be reduced at the expense of oscillator aging rate. Other trade-offs can be made to reduce size, mass, and power consumption but usually at the expense of frequency stability. Trade-offs can also be made on cost versus performance and physical parameter bases.

The reliability level and its implementation should be carefully considered during design trade-off studies, since excessive requirements for component reliability and quality assurance provisions can easily double or triple the cost of an oscillator and have a heavy impact on delivery schedules. If a design must be executed using the highest reliability components, then the list of readily available components will be severely restricted. The following questions need to be addressed:

Is a system more reliable with one oscillator made with the highest reliability components or redundant oscillators made with lower reliability components (S failure rate of .001%/1000 h versus R failure rate of .01%/1000 h)?

Is oscillator redundancy a system requirement?

Does more thorough testing of a completed oscillator with lower reliability components produce a unit with higher reliability than an oscillator made with the highest reliability components and less testing?

What about acceptance testing? Is an oscillator qualified to operate from -20°C to +60°C really needed when the actual operating temperature is 35°C±10°C?

Again, the cost of a finished oscillator is directly related to the level of reliability and testing required. Reliability-related issues have a large influence on both oscillator and system design; therefore, trade-offs should be carefully balanced against mission requirements.

Precision Quartz Oscillator Features and Performance

In order for a precision oscillator to generate an output signal that has a low aging rate, high frequency stability, high spectral purity, and low phase noise, the following conditions must be met:

1. The quartz resonator must be kept excited (driven) at a very constant low power level.
2. The resonator's operating temperature must be maintained precisely.
3. The resonator must be isolated from varying external parameters such as power supply fluctuations, magnetic fields, ionizing radiation, vibration, external loads, and parametric changes in the electronic components.

The primary function of the electrical and mechanical subassemblies of a quartz oscillator is to provide a stable operating environment for the resonator. A functional block diagram of a typical precision oscillator is shown in Figure 3.

A 5-MHz, 3rd overtone, SC (stress compensated) cut quartz resonator is the frequency control element in the illustrated oscillator. The resonator is fabricated from premium Q cultured quartz. If the oscillator is to be operated in a radiation environment, the quartz, additionally, will undergo sweeping and radiation preconditioning to reduce radiation sensitivity.

The oscillator circuit shown in Figure 3 is a modified Colpitts type with both ac and dc negative feedback to reduce flicker noise and stabilize gain. The automatic gain control (AGC) circuit detects the level of the oscillator signal and adjusts the gain of the oscillator stage to maintain a constant resonator drive current. The AGC system also provides a large degree of isolation from changes in circuit parameters, input voltage, and temperature. The low-level signal from the oscillator is amplified by a low-noise, high-impedance buffer amplifier to increase the signal level and further isolate the sensitive oscillator stage from the environment. The output amplifier provides power gain, impedance matching, and load isolation for the oscillator signal.

A temperature-stabilized oven is used in high-stability oscillators to reduce the effects of ambient temperature changes on the frequency determining elements of the oscillator. The operating frequency of a quartz resonator and the performance of the oscillator and oven control circuit components, which has secondary effects on frequency stability, are temperature-dependent. To achieve high frequency stability and signal purity, it is essential to maintain precise temperature control of all of these elements. Therefore, a single proportional-controlled oven encloses the quartz resonator, the oscillator circuit, and part of the oven control circuit. The temperature of the oven is adjusted to the turning point of the resonator (~85°C) and is held within .001°C over the normal operating temperature environment.

The primary thermal insulating system used in APL oscillators consists of alternate layers of tissuglas separators and radiation-reflecting layers of aluminized Mylar sometimes referred to as space blanket. This system is an extremely good insulator at operating pressures less than 1×10^{-4} torr but is a very poor insulator at atmospheric pressure. Oscillators required to operate on Earth outside a vacuum chamber (a great help in ground testing and spacecraft integration) must incorporate a dewar flask in their design. The Applied Physics Laboratory has developed the very rugged, low-mass titanium dewar flask shown in Figure 4 for atmospheric pressure operation applications. The dewar flask is made without a pinch-off tube or other protrusions outside the cylindrical dimensions of the flask.

Conventional quartz resonators have a mechanical resonance associated with the system used to attach the quartz disk to the resonator enclosure. The thin support ribbons for the quartz disk are shown in Figure 5. The mechanical resonance frequency is in the 200- to 1000-Hz range and varies widely from unit to unit, depending on the attachment methods of the manufacturer. A resonator stimulated at its mechanical resonance frequency will be severely damaged or destroyed. To prevent damage, a vibration isolation system using elastomeric vibration isolators has been designed and provides superior isolation at frequencies above 100 Hz in any of the three orthogonal axes (see Figure 6). The isolation system effectively isolates the resonator from the launch environment. A photograph of the vibration isolation system is presented in Figure 7. The resonator and oven assembly are suspended between two elastomeric vibration isolators made from a low-Q RTV compound. These isolators are carefully processed to eliminate air bubbles during molding and are then baked in a vacuum to remove volatile components, thus reducing outgassing to acceptable levels.

A very different quartz resonator design, the BVA, eliminates or greatly reduces the mount mechanical resonance problem.[2] Quartz bridges are machined into the quartz during fabrication to create a mounting or suspension system for the active quartz disk as shown in Figure 5. The bridges are very short and stiff, thus moving the mechanical resonance above 2000 Hz. This system is capable of withstanding higher vibration levels, even at mechanical resonance, than the conventionally-mounted resonators. Preliminary vibration testing of the BVA resonator indicates that an oscillator design using a BVA resonator could eliminate the need for the elastomeric vibration isolators described earlier and greatly reduce the size, mass, and complexity of the oscillator. The BVA resonator has other very desirable characteristics such as lower aging rates and less sensitivity to ionizing radiation and acceleration.[3]

The Allan variance or short-term frequency stability (0.1 through 100 s) of quartz oscillators is superior to any other spacecraft frequency standard. Figure 8 presents the Allan variance achieved by an APL quartz oscillator compared with other frequency standards.

Oscillator aging rates of 2×10^{-12}/24 h have been measured during flight qualification tests. Oscillator aging rates usually improve after the oscillators are placed in orbit.[4] Aging rate data from in-orbit, APL-built oscillators are as low as 8×10^{-13}/24 h as shown in Figure 1. Aging rates of cesium atomic standards are superior to these rates, but quartz oscillator aging rates are comparable to those of rubidium atomic standards; moreover, quartz oscillators are much less complex and expensive for small satellite applications.

The aging rate and short-term frequency stability of APL quartz oscillators have steadily improveed, as shown in Figure 9, to the point that secondary effects on oscillator performance, such as ionizing radiation[5] and magnetic susceptibility, have become more obvious. Figure 10 graphically describes a typical response to radiation exposure for a quartz resonator. These effects are present in low-performance oscillators but are masked by high aging rates and excess noise.

Ambient operating temperature is another environmental effect that changes oscillator output frequency. The oscillator shown in Figure 11 has a temperature coefficient of 1.8×10^{-13}/°C between 0° and 30°C, which is the nominal operating range for many spacecraft.

The performance achieved by an APL ultrastable quartz oscillator is detailed in Table 1 for various parameters.

Power Supply and Frequency Distribution Unit

It is often desirable to operate a spacecraft oscillator directly from the spacecraft unregulated power bus to eliminate the need for an additional regulated spacecraft bus supply specifically for the oscillator. The Applied Physics Laboratory has developed a high-efficiency isolated power converter designed especially for powering high-stability, low-noise oscillators. This converter is normally integrated into the oscillator package and operates directly from the unregulated spacecraft bus. Use of this integrated power converter has the additional advantage of isolating the oscillator from the noise, electromagnetic interference, and power transients encountered from the typical spacecraft power bus.

Some applications require a frequency distribution unit to provide several coherent frequencies generated from the reference oscillator. Frequency multipliers and high-isolation buffer amplifiers (>70 dB between input and output) have been designed by APL for these applications. The multipliers and amplifiers are used in combinations to provide multiple output frequencies from isolated output ports.

Table 1. Performance of an APL Ultrastable Oscillator.

Parameter	Measured Data
Output frequency	5 MHz
Aging rate/24 h	4×10^{-12}
Allan variance	
Tau(s)	Sigma
0.1	8.1×10^{-13}
1	1.7×10^{-13}
10	8.9×10^{-14}
100	6.6×10^{-14}
1000	7.4×10^{-14}
Frequency offset (Hz)	
1	−121 dBc
10	−139 dBc
100	−147 dBc
1000	−150 dBc
10000	−152 dBc
Frequency as function of	
Temperature per °C (−20°C to +60°C)	6.1×10^{-13}
Load (50Ω ±10%)	2.0×10^{-12}
Voltage ±5%	1.0×10^{-12}
Acceleration	1.5×10^{-9}/g
Magnetic susceptibility	2×10^{-12} gauss
Output characteristics	
Power level	+7 dBm
Harmonic	−62 dBc
Spurious	−80 dBc
Weight (lb)	1.4 lb
Power at 25°C (W)	0.9 W

References

[1]J. R. Norton, "Ultrastable Quartz Oscillator for Spacecraft," in *Proc. 21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting,* pp. 509-518, Nov. 1989.

[2]R. J. Besson, "A New Electrodeless Resonator Design," in *Proc. 31st Annual Symposium on Frequency Control,* pp. 147-152, June 1977.

[3]J. R. Norton, "BVA-Type Quartz Oscillators for Spacecraft," in *Proc. 45th Annual Symposium on Frequency Control*, pp. 426-430, May 1991.

[4]L. J. Rueger, J. R. Norton, and P. T. Lasewicz, "Long-Term Performance of Precision Crystal Oscillators in a Near-Earth Orbital Environment," in *Proc. 1992 IEEE Frequency Control Symposium*, May 1992.

[5]J. R. Norton, J. M. Cloeren, and J. J. Suter, "Results from Gamma Ray and Proton Beam Radiation Testing on Quartz Resonators," *IEEE Transactions on Nuclear Science* NS-312, pp. 1230–1233, Dec. 1984.

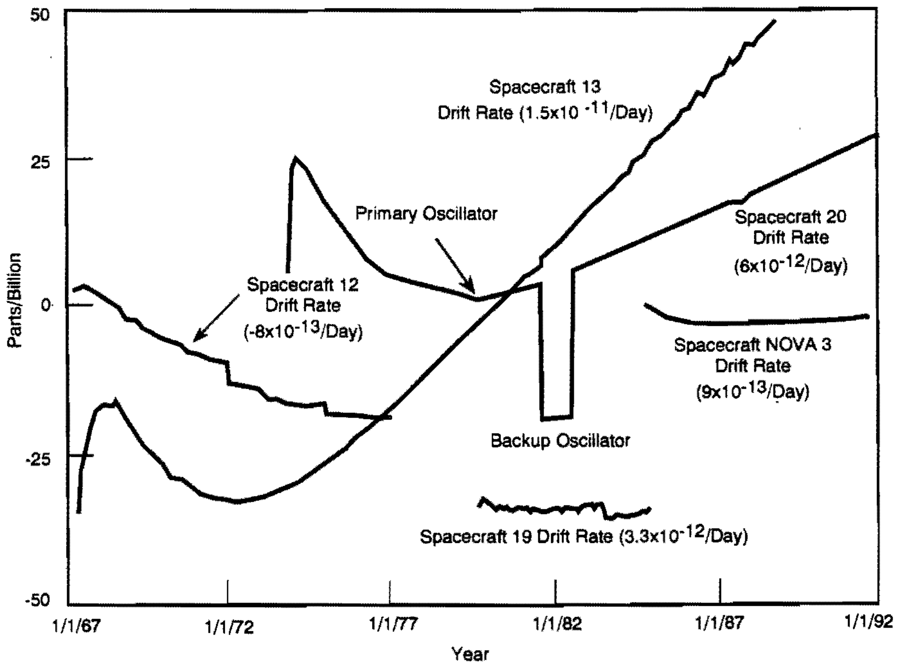

Figure 1. Oscillator Performance of NNSS Spacecraft.

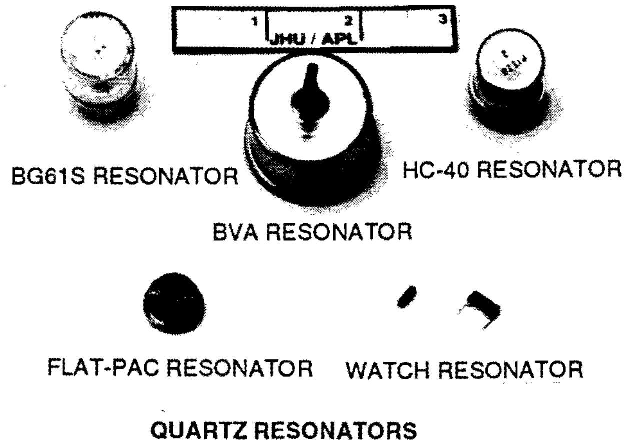

Figure 2. Typical Quartz Resonators.

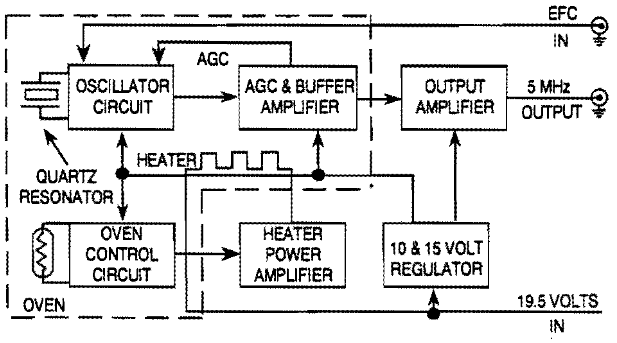

Figure 3. Ultrastable Quartz Oscillator Functional Block Diagram.

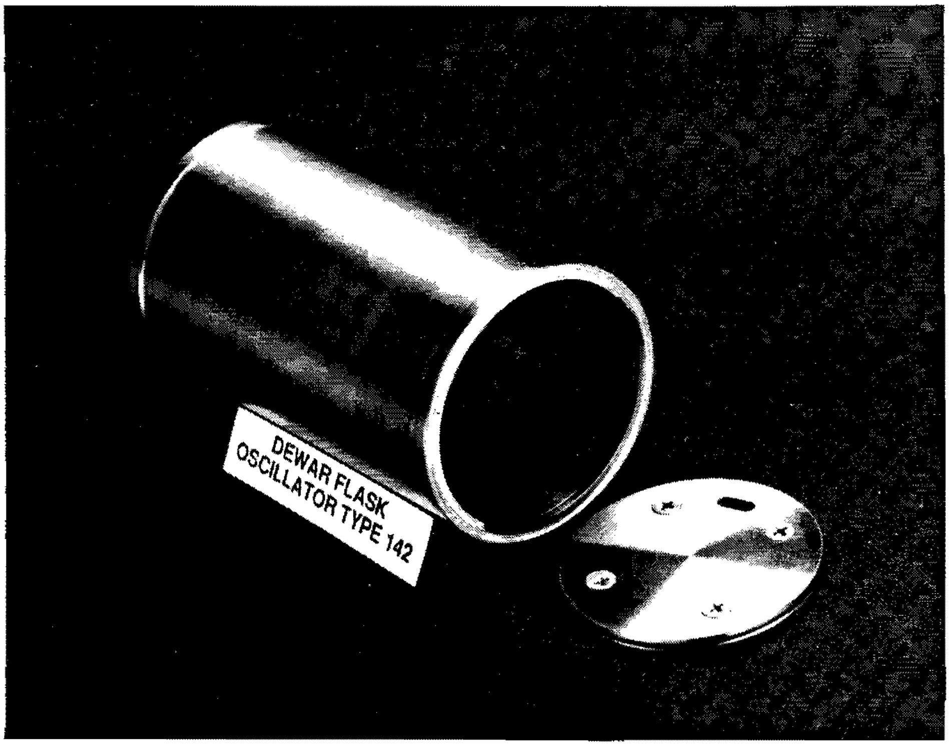

Figure 4. Titanium Dewar Flask.

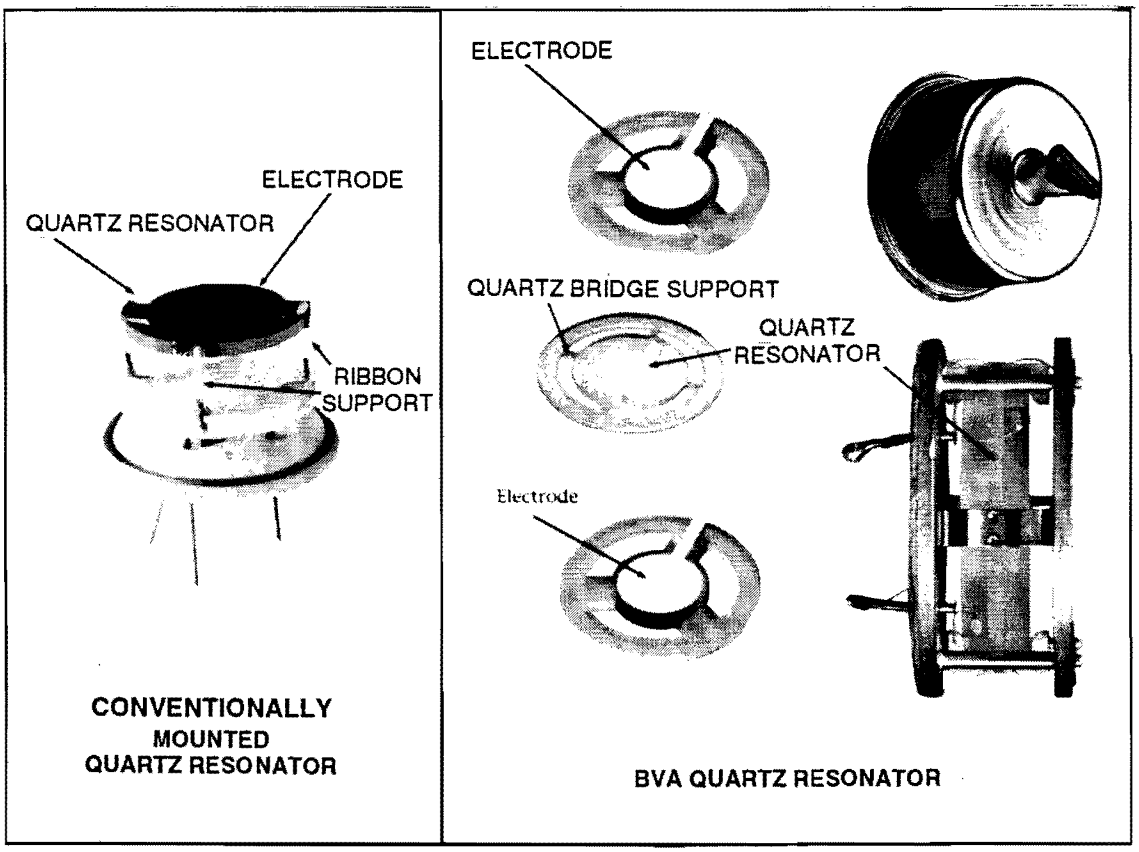

Figure 5. Conventionally-Mounted and BVA Quartz Resonators.

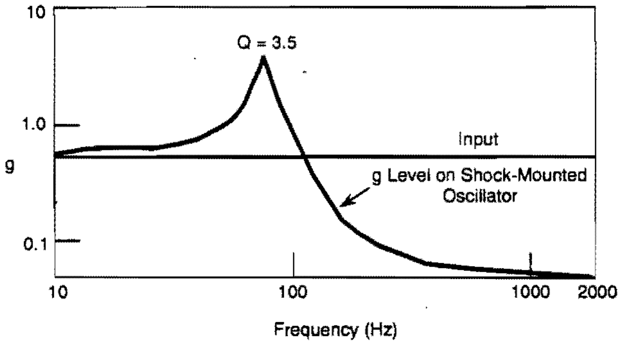

Figure 6. Attenuation Characteristics of the Vibration Isolation System as a Function of Input Excitation Frequency.

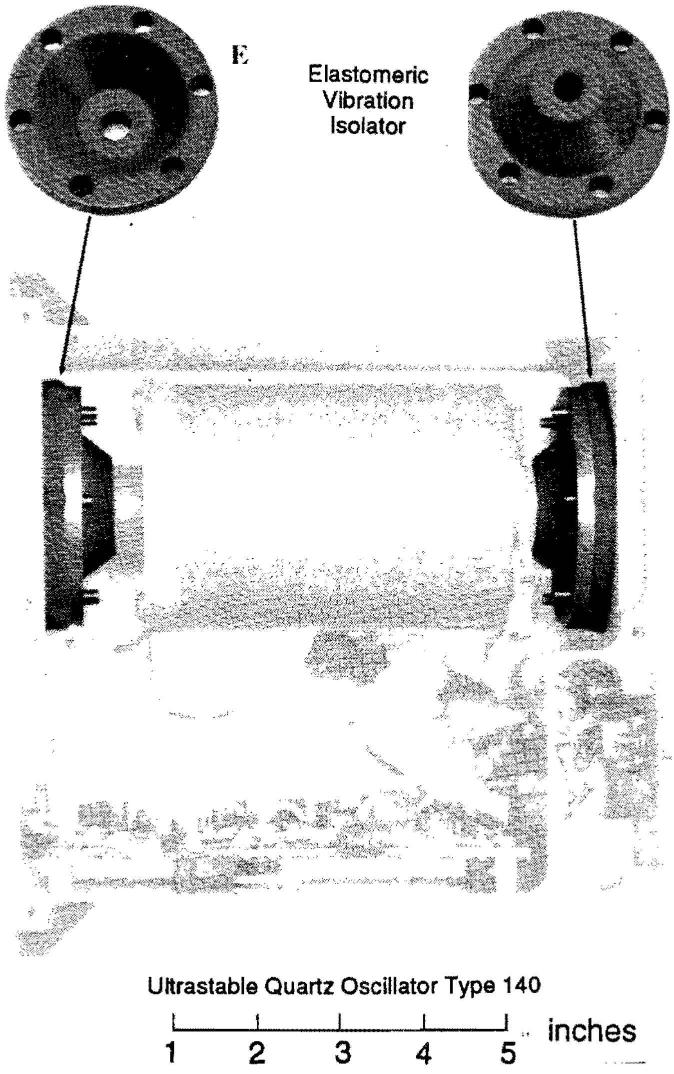

Figure 7. Ultrastable Quartz Oscillator Showing Vibration Isolators.

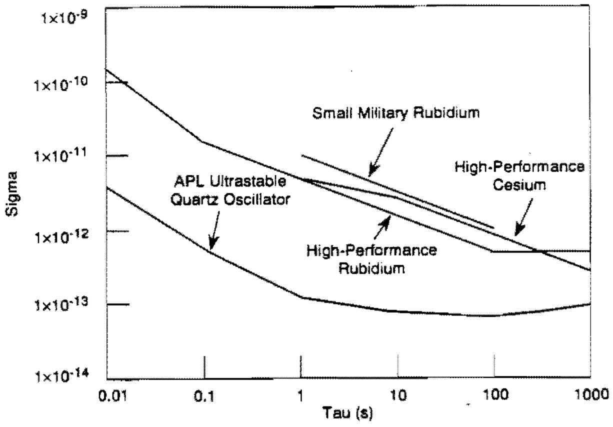

Figure 8. Allan Variance of Precision Frequency Standards.

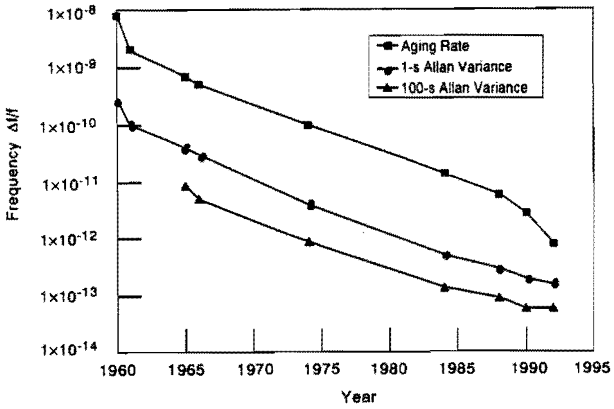

Figure 9. Frequency Stability History of APL Quartz Oscillators.

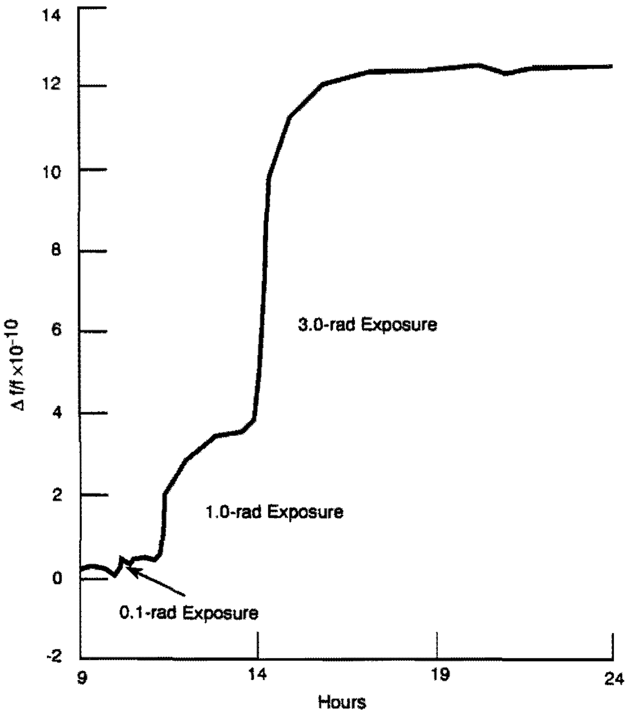

Figure 10. Frequency Response of Quartz Resonator SN33820 to Ionizing Radiation. Dose Rate = 0.1 rad (Si)/min.

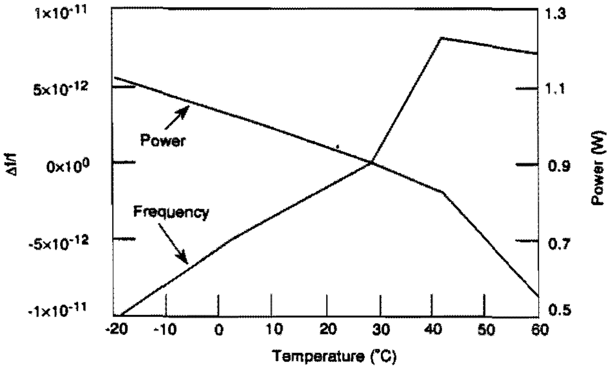

Figure 11. Oscillator Performance in a Vacuum Versus Temperature.