JERRY R. NORTON and JAMES M. CLOEREN

PRECISION QUARTZ OSCILLATORS AND THEIR USE ABOARD SATELLITES

A space-qualified ultrastable quartz oscillator is an ideal instrument for use aboard a small satellite as the heart of its navigation and communication systems. Other applications, such as radio science experiments and altimetry, similarly require an ultrastable frequency source. The Applied Physics Laboratory has had a central role in introducing and improving ultrastable quartz oscillators for small satellites. Optimizing an oscillator design for a particular application entails balancing parameters such as frequency stability, environmental immunity, phase noise, aging rate, size, mass, and cost. The Laboratory's expertise in designing ultrastable oscillators is being applied to the development of an oscillator for the Pluto Flyby mission that will feature reduced size and weight without compromising performance.

INTRODUCTION

The Applied Physics Laboratory pioneered the use of precision quartz oscillators aboard small satellites in 1958, when development of the 50.8-kg Transit navigation satellite operating on 20 W began. Since navigational accuracy is directly related to oscillator frequency stability, the requirement for small, lightweight, low-power oscillators with excellent frequency stability was established at the outset, beginning a thirty-six-year tradition of state-of-the-art oscillator design. The oscillator for this early spacecraft had a frequency stability of 5×10^{-11} (100 s), consumed 1 W, weighed 1.18 kg, and had a volume of 1196 cm^3. The Laboratory's current spacecraft oscillator has a frequency stability of 7×10^{-14} (100 s), consumes 0.9 W, weighs 0.77 kg, and has a volume of 700.7 cm^3. This evolution represents a significant improvement in frequency stability (three orders of magnitude) and establishes APL as a leader in spacecraft ultrastable oscillator design. Since 1958, APL ultrastable oscillators have flown on many APL, NASA, DoD, and Jet Propulsion Laboratory spacecraft. These include DODGE, SAS, GEOS-C, NOVA, NAVPAC, GPSPAC, SEASAT, GEOSAT, Dual Precision Clock System, COBE, MARS Observer, and TOPEX/POSEIDON.

Quartz oscillators are used in satellites for a wide variety of applications. Among the more common of these are the following: (1) to provide an accurate clock for controlling events on the satellite as a function of time, (2) to time-tag data from experiments aboard the spacecraft, (3) to synchronize pseudorandom data in spread-spectrum communication systems, (4) to time-share or multiplex assigned channels among multiple users, (5) to encrypt data, and (6) to facilitate navigation. Both clock accuracy and frequency stability are essential for spacecraft navigation systems. A very stable frequency and phase are required for radar altimetry and high-resolution Doppler radar. Even greater phase stability is needed to conduct ionospheric studies and to perform radio science experiments, since they rely on detecting very small shifts in the phase of the stable carrier frequency.

Frequently, a spacecraft's quartz oscillator is mission critical; therefore, long-term, reliable operation of the oscillator is often as important as its frequency stability. With more than 375 APL-developed quartz oscillators placed in orbit over a thirty-six-year period, only one in-orbit failure has been reported. This event did not disrupt the mission because a redundant oscillator was switched into service. One APL program, the Navy Navigation Satellite System, 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 more than twenty-one years, as shown in Figure 1. This level of reliability allows system designers the option of nonredundant time and frequency systems for their spacecraft, which is a very important advantage for low-mass, low-cost satellite programs.

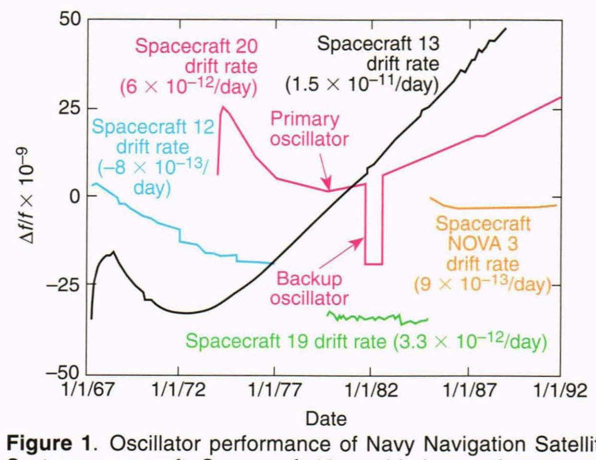

Figure 1. Oscillator performance of Navy Navigation Satellite System spacecraft. Spacecraft 13 provided more than twenty-one years of uninterrupted service. (f = frequency.)

QUARTZ RESONATORS

The quartz resonator, which is the most important component in any quartz oscillator, is a thin disk of quartz with electrodes plated on the two faces of the disk (see Fig. 2). The quartz used in resonator fabrication is a piezoelectric material that vibrates when stimulated electrically. The size of the quartz disk and the angle at which it is cut from the quartz crystal primarily determine the frequency of vibration or mechanical resonance of the device. Even with excellent oscillator circuits, performance cannot exceed the inherent quality or capability of the quartz resonator. Less than optimum electronic circuits, however, can seriously degrade resonator performance. The potential frequency stability has a wide variation from 1×10^{-6} to 5×10^{-14} (100 s). The resonator Q, or quality factor, is the best measure of possible resonator performance and may be expressed as follows:

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

Quartz resonators, as shown in Figure 3, are produced in many shapes, sizes, and operating frequencies and have many cost levels. For example, the resonator in a quartz watch is a relatively simple low-Q (about 30,000) device that is inexpensive (it costs less than $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 (more than $1000). A precision quartz resonator is capable of controlling frequency very precisely, but the operating environment must be very carefully controlled to realize the resonator's full potential.

QUARTZ OSCILLATORS

In simplest terms, a quartz oscillator is a quartz resonator supported by systems that keep it 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. 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.

The apparent simplicity of precision quartz oscillator design is deceiving. The balances and interrelationships among the various design disciplines—circuit, mechanical and thermal design, and design of environmental isolation systems—profoundly affect oscillator performance. Externally, a precision oscillator is a simple enclosure with few or sometimes no controls and usually only one connector. The number of internal electronic components and mechanical assemblies is relatively small; even so, an in-depth analysis reveals that ultrastable oscillators are quite complex. Figure 4 is a photograph of the components and subassemblies of an ultrastable oscillator.

SPECIFICATIONS AND DESIGN TRADE-OFFS

Specifications for a precision oscillator must include the following:

- Output frequency
- Short- and long-term frequency stability
- Phase noise
- Magnitude and spectral purity of the output signal
- Definitions of output frequency responses to environmental factors
  - Temperature
  - Acceleration
  - Magnetic fields
  - Vibration
  - Ionizing radiation
- Warm-up time

Mass, size, input power, and cost are also major considerations.

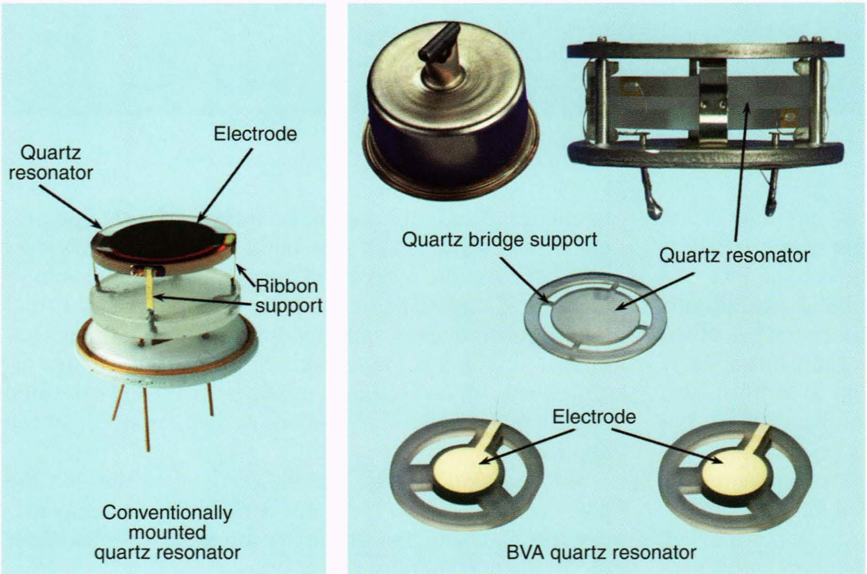

Figure 2. Conventionally mounted and BVA quartz resonators.

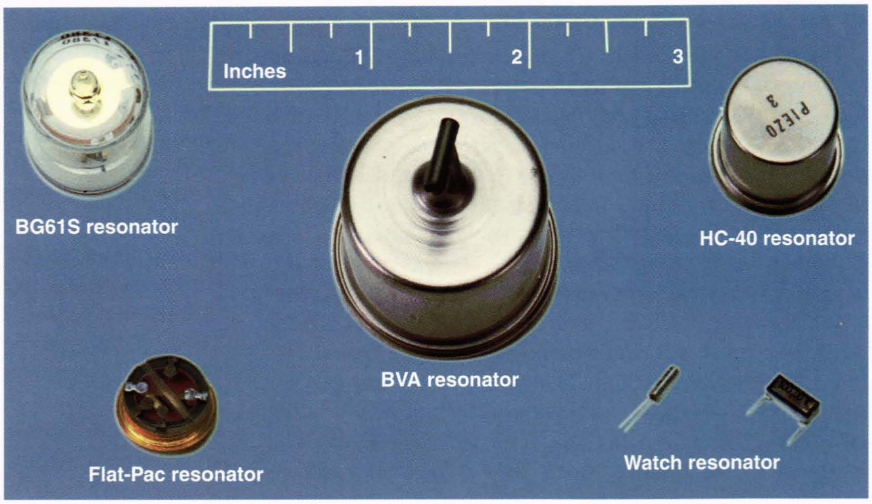

Figure 3. Typical quartz resonators.

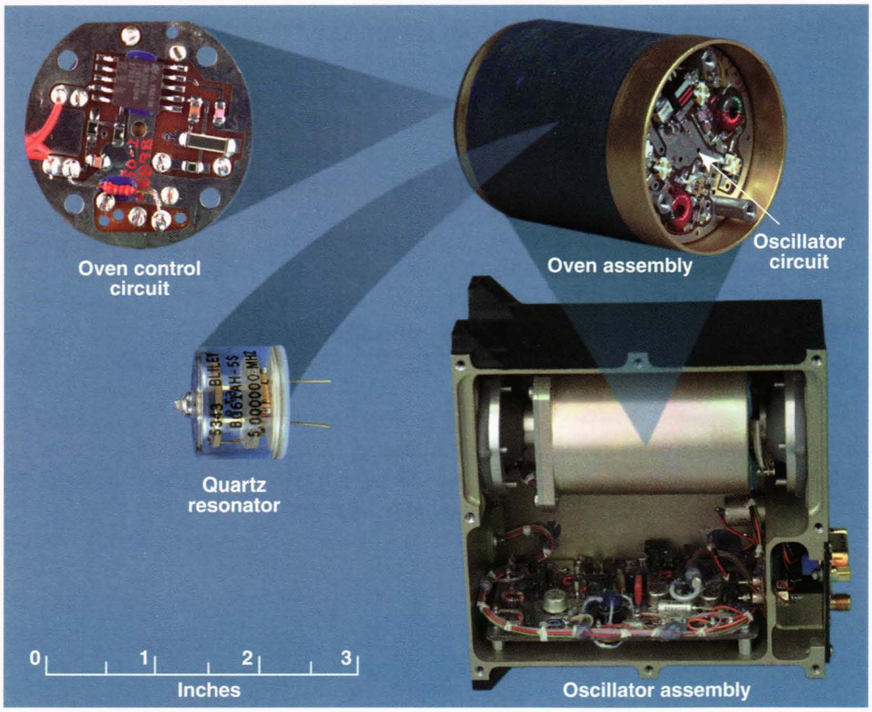

Figure 4. Ultrastable oscillator subassemblies.

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 1960s. Power consumption, mass, and size must also 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, frequency stability, accuracy, and responses to environmental effects will be sacrificed if the requirements are for a small, low-mass, low-power, low-cost oscillator. On the other hand, mass, power, and cost will increase if an oscillator must have excellent short- and long-term frequency stability, phase noise, and environmental immunity. Since trade-offs are limited, the requirements for an oscillator should be evaluated carefully, and its specifications should not exceed the needs of the application.

As stated previously, 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, all other factors being equal. A 5-MHz quartz resonator can have a Q exceeding 3.0 million and is the highest-Q quartz resonator commercially available. 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's output frequency must be multiplied into the gigahertz region, an oscillator operating at a higher frequency may be desirable. The phase noise floor of an oscillator can be reduced at the expense of oscillator aging rate.

The type of material used to fabricate a temperature-stabilized oven for a quartz oscillator influences oscillator performance and mass. Ovens for oscillators are frequently made of copper; however, if some degradation in frequency stability, radiation susceptibility, and output frequency versus temperature is acceptable, ovens can be made from aluminum or magnesium. The lighter materials provide a weight reduction of over 50%.

Other trade-offs can be made to reduce size, mass, and power consumption (usually at the expense of frequency stability, however). Trade-offs can also be made on cost-versus-performance and physical parameter bases.

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

1. Is a system more reliable with one oscillator made with the highest-reliability (S failure rate) components or redundant oscillators made with lower-reliability (R failure rate) components (where S denotes a failure rate of 0.001%/1000 h, and R signifies a failure rate of 0.01%/1000 h)?

2. Is oscillator redundancy a system requirement?

3. 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?

4. What acceptance testing is essential? Is an oscillator qualified to operate from −20° to +60°C really needed when the actual operating temperature is only 35° ± 10°C?

PRECISION QUARTZ OSCILLATOR FEATURES AND PERFORMANCE

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 changes in external parameters such as power supply noise, 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. Figure 5 is a functional block diagram of a typical precision oscillator. 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 (hydrothermally laboratory grown) quartz. If the oscillator is to be operated in a radiation environment, the quartz must also undergo radiation preconditioning and sweeping (a solid-state electrodiffusion process that "sweeps" impurities out of the quartz material) to reduce radiation sensitivity.

The oscillator circuit shown in Figure 5 is a modified Colpitts type with both alternating and direct current 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.

Temperature Control

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 quartz resonator is the most temperature-dependent of the frequency-determining components in the oscillator, but components in the oscillator and oven control circuit also have secondary effects on frequency stability. To achieve high frequency stability and signal purity, maintaining precise temperature control of all of these elements is essential. A single proportional-controlled oven therefore 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 0.001°C over the normal operating temperature environment.

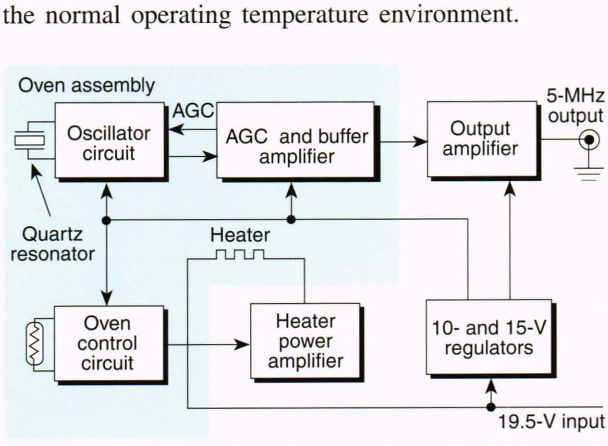

Figure 5. Functional block diagram of an ultrastable quartz oscillator. (AGC = automatic gain control.)

The primary thermal insulating system used in APL oscillators consists of alternate layers of porous glass paper 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 authors have developed the very rugged, low-mass titanium Dewar flask shown in Figure 6 for oscillator operation in atmospheric pressure applications. The flask is made without a pinch-off tube or other protrusions outside its cylindrical dimensions.

Vibration Isolation

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 2. 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 by the authors that provides superior isolation at frequencies above 100 Hz in any of the three orthogonal axes (see Fig. 7). The isolation system effectively isolates the resonator from the launch environment. Figure 8 is a photograph of this system. The resonator and oven assembly are suspended between two elastomeric vibration isolators made from a low-Q rubber 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 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 2. 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 incorporating such a resonator could eliminate the need for the elastomeric vibration isolators described earlier and greatly reduce the size, mass, and complexity of the oscillator.

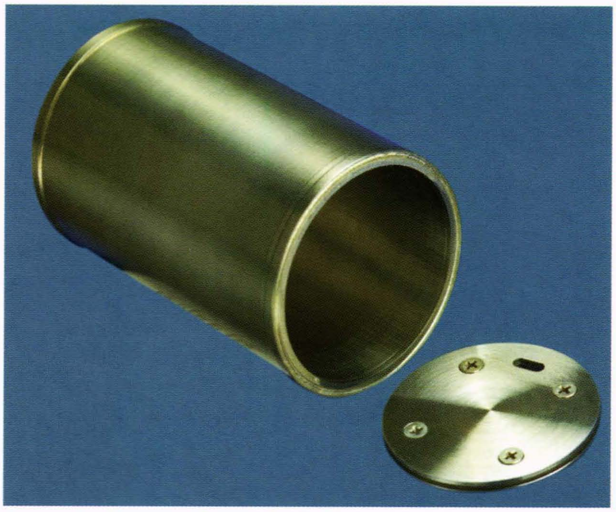

Figure 6. Titanium Dewar flask.

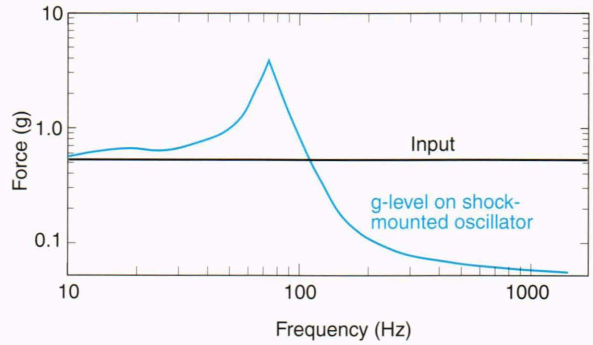

Figure 7. Attenuation characteristics of the vibration isolation system as a function of input excitation frequency.

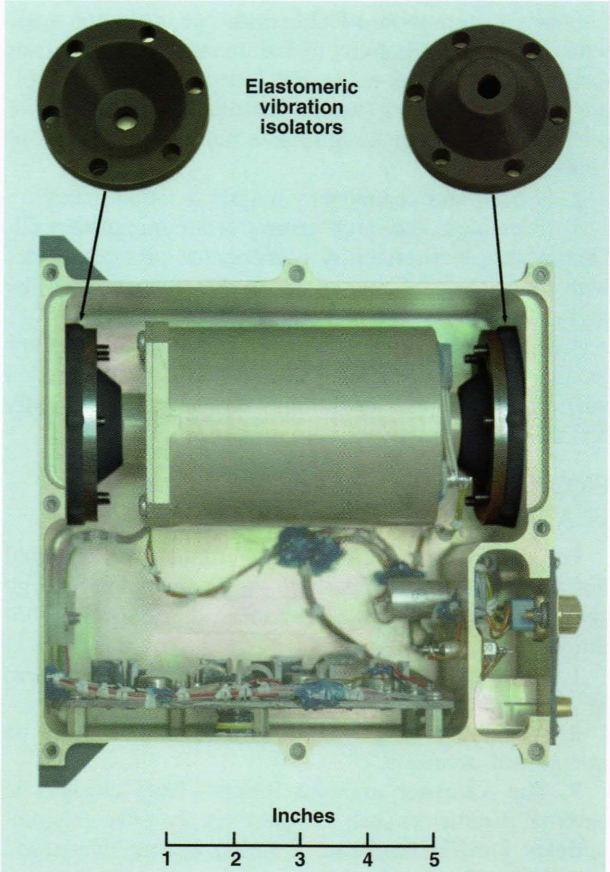

Figure 8. Ultrastable quartz oscillator showing vibration isolators.

The BVA resonator has other very desirable characteristics such as lower aging rates and less sensitivity to ionizing radiation and acceleration.[3,4]

Frequency Stability

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 9 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.[5] 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, more reliable, and less expensive for small satellite applications.

The aging rate and short-term frequency stability of APL quartz oscillators have steadily improved, as shown in Figure 10, to the point that what used to be secondary effects on oscillator performance, such as magnetic susceptibility and ionizing radiation, have become more obvious. These effects are present in low-performance oscillators but are masked by high aging rates and excess noise. In fact, radiation in some applications may become the largest, least predictable, and most difficult of the environmental stresses on frequency stability to control with design solutions.

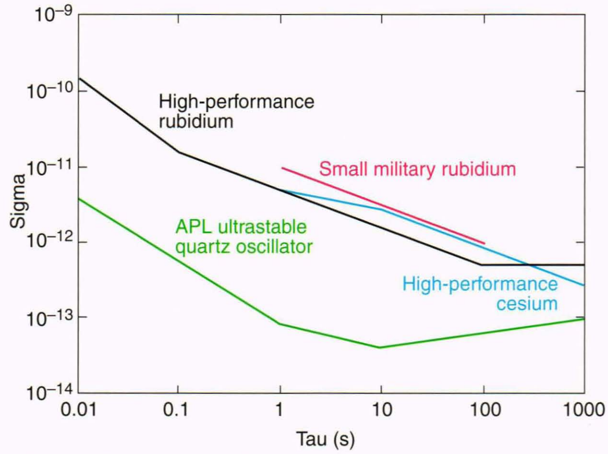

Figure 9. Allan variance of precision frequency standards. (sigma = Allan variance, tau = time interval.)

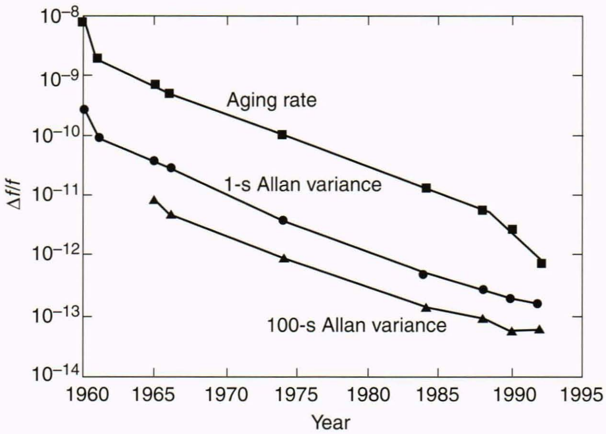

Figure 10. Frequency stability history of APL quartz oscillators. (f = frequency.)

Radiation Sensitivity and Other Performance Parameters

The Laboratory has conducted extensive studies on the effects of ionizing radiation on quartz resonators and oscillators,[6] since exposure to electrons, neutrons, gamma rays, and protons can influence the operating frequency of quartz oscillators. The magnitude and character of the frequency change depend on the radiation dose and dose rate.[7] Practically sized radiation shields effectively prevent charged electrons found in space from penetrating to the radiation sensitive oscillator components. Because neutrons typically are not found in orbit, protons are the major radiation threat to spacecraft oscillators. Radiation shields are very effective against protons with energy levels of less than 80 MeV and provide some protection from protons up to 120 MeV. As proton energy levels begin to exceed 120 MeV, increasingly thick and heavy shields, which have only limited effectiveness, are required. When a weight versus shielding effectiveness trade-off is evaluated, the equivalent to 5 g/cm^2 of aluminum is near optimum. Preconditioning quartz resonators by exposure to relatively high radiation doses (APL uses 20-krad[Si] from a cobalt 60 source) reduces their sensitivity to subsequent radiation exposures, as Figure 11 clearly shows. Fabricating resonators from swept cultured quartz further reduces their sensitivity to radiation exposure. Even after these radiation sensitivity reduction methods have been applied, oscillators may still have a radiation sensitivity of 1×10^{-10} to 2×10^{-10}/rad(Si). In some orbits, the radiation-induced frequency change will be the largest and least predictable of the environmental effects on the oscillator's output frequency.

As noted earlier, ambient operating temperature is another environmental stress that changes oscillator output frequency. The oscillator shown in Figure 12 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's unregulated power bus to eliminate the need for an additional regulated spacecraft bus supply specifically for the oscillator. The Laboratory has developed a high-efficiency (≈85%) isolated power converter especially for powering high-stability, low-noise oscillators. This converter is normally integrated

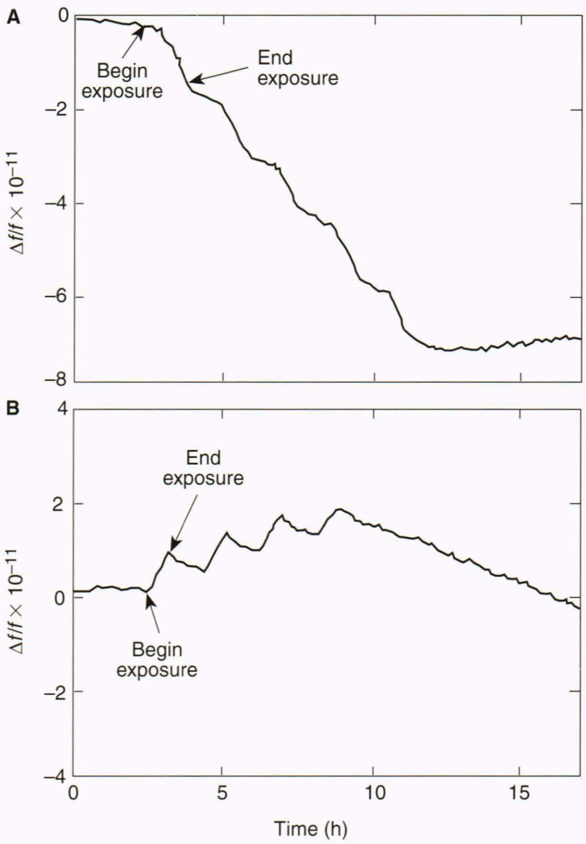

Figure 11. Frequency response of BVA-SC quartz resonator S/N23 to radiation. **A.** Before preconditioning with 20 krad(Si). **B.** After preconditioning. Exposure was 0.6 rad(Si) for 42 min at a dose rate of 0.014 rad(Si)/min for both. (f = frequency.)

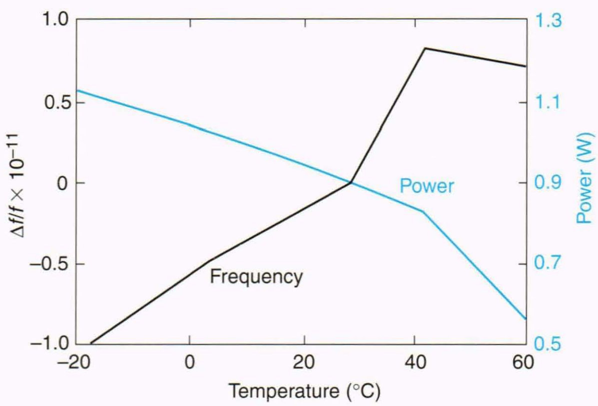

Figure 12. Oscillator performance in a vacuum versus temperature. (f = frequency.)

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 combination to provide multiple output frequencies from isolated output ports.

CURRENT OSCILLATOR RESEARCH AND DEVELOPMENT EFFORTS

Two ultrastable oscillator design efforts are under way at the Laboratory. One project is to develop an oscillator for use in a radio science experiment aboard the Cassini spacecraft. The other effort entails an extremely challenging oscillator design, which will have greatly reduced (≈50%) size and mass. This oscillator will be part of a radio science experiment on the Pluto Flyby mission. The estimated mass of the Pluto oscillator is 0.32 kg, and the volume is 353 cm^3. The design goal for this oscillator is to retain the excellent frequency stability and immunity to environmental effects that have been characteristic of APL-designed and built oscillators, even with the reduction of size and mass.

SUMMARY

The Laboratory's singular efforts in the introduction and improvement of ultrastable quartz crystal oscillators have fostered major advances in the technology as demonstrated by many successful spaceflight missions. Attentiveness to design optimization techniques has resulted in an enviable record of performance and reliability

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° to +60°C)	6.1×10^{-13}
Load	
(50Ω ± 10%)	2.0×10^{-12}
Supply voltage ±5%	1.0×10^{-12}
Acceleration	1.5×10^{-9}/g
Magnetic susceptibility	2.0×10^{-12} G
Output characteristics	
Power level	+7 dBm
Harmonic	−62 dBc
Spurious	−80 dBc
Weight (kg)	0.77
Power at 25°C (W)	0.9

Note: Tau = time interval, Sigma = Allan variance.

that has set the standards for the discipline. This excellence will continue to be embodied in oscillators for the Cassini spacecraft and Pluto Flyby mission.

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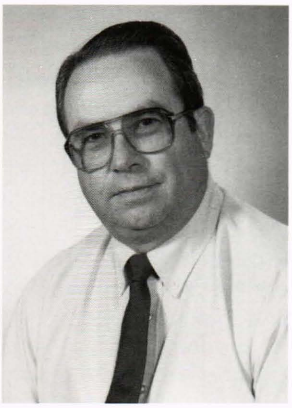
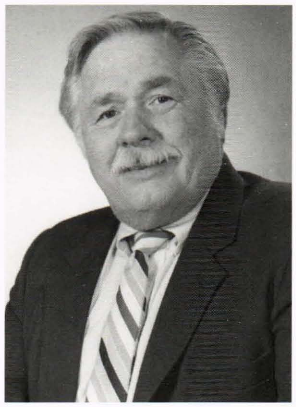
THE AUTHORS



JERRY R. NORTON has been a member of the Space Department since joining APL in 1961 and began his career as an RF design engineer for satellite navigation receivers, including the first portable battery-powered unit. Since 1974, he has been engaged in developing both atomic and quartz frequency standards. Mr. Norton was lead engineer for new ultrastable quartz oscillators for the NOVA spacecraft, the Dual Precision Clock System program, and the TOPEX spacecraft, which used a BVA quartz resonator for the first time in a space application. He has conducted extensive studies on the effects of radiation on quartz resonators and oscillators. Currently, he is designing an ultrastable oscillator half the size of the present oscillator for the Pluto Flyby mission. Mr. Norton received an A.A.S. degree in control systems from Capitol Radio Engineering Institute in 1960. He became a Senior Staff Engineer in 1979 and is a member of the Precise Time and Time Interval Advisory Board.



JAMES M. CLOEREN joined APL in 1982 as a Senior Staff Engineer in the Space Department. He has been active at the Laboratory in the design of ultrastable oscillators for the Dual Precision Clock System and for the COBE, EUVE, MARS Observer, POLAR BEAR, MSX, and Cassini spacecraft. He has also been the system engineer for the Dual Precision Clock System program and the TOPEX frequency reference unit. Mr. Cloeren has over thirty years of design experience in time and frequency as well as satellite navigation.