

ADVANCED TECHNOLOGY OSCILLATOR FOR THE PLUTO FLYBY MISSION

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Abstract

A small, low-mass ultrastable oscillator with excellent frequency stability (1×10^{-13} at 100 s) is required for the radio science experiment on the proposed Pluto Fast Flyby mission. A high premium is placed on mass, size, and power for the Pluto spacecraft. The primary task of this exploratory design was to reduce by 50% the mass and size of a flight-proven ultrastable oscillator design without seriously degrading the oscillator's frequency stability or immunity to environmental stress—a very challenging design problem. The mass of key components of an oscillator fabricated to test new design ideas was reduced by over 78%. A series of tests, including vibration testing to the expected Pluto mission levels, met or exceeded our expectations. Based on the results of the vibration tests, a vibration isolation system will not be used for the Pluto oscillator. The knowledge and data obtained from this advanced technology feasibility study provides a solid basis to develop a small, ultrastable quartz oscillator.

Introduction

An oscillator with a very stable output frequency is required for the radio science experiment aboard the Pluto Flyby mission. The science objective of this experiment is to measure the pressure and temperature structure in the lower atmosphere of Pluto. Change in the radio propagation path length as the signal passes through Pluto's atmosphere must be measured to an accuracy of $\approx 100 \mu\text{m}$ to determine pressure and temperature of the atmosphere. A very stable reference oscillator is required because the accuracy of path length measurements is directly related to frequency stability. Minimizing mass, size, and input power are equally important because every kilogram added to the Pluto spacecraft increases cost by about \$250,000 and adds one week to the flight time.¹ The primary objectives for this exploratory design were to demonstrate that a quartz oscillator with greatly reduced mass and size could be realized while retaining excellent frequency stability and immunity to environmental effects. Two tasks were critical to realizing this goal: 1) reduce the mass and size of the oscillator resonator oven assembly; and 2) demonstrate that the oscillator could survive the launch environment without a vibration isolation system. The Applied Physics Laboratory (APL) has a rich heritage of building small, highly reliable oscillators with excellent frequency stability; even so, to reduce the mass and size of an oscillator by 50% and retain high performance is an extremely challenging design problem.

Our experience has shown that the quartz resonator dominates oscillator frequency stability in a well-designed oscillator.² The tactical BVA resonator was chosen for the Pluto design because it has demonstrated the capability of providing very good frequency stability, and its mechanical resonance is ≈ 2000 Hz, the upper limit of the Pluto vibration specification.³ The resonator is a 10-MHz, 3rd-overtone, stress-compensated (SC) cut device housed in an HC-40 enclosure.

Resonator Oven Design

The resonator oven and its design are the most critical mechanical assembly in terms of oscillator performance. The resonator oven assembly, which includes the oven housing, the quartz resonator, an oven controller circuit board, and an oscillator printed circuit board, establishes the minimum mass and size of the entire oscillator. The sizes of the mechanical enclosures, supporting assemblies, and the insulating system are directly related to the size of the oven. The mass of the oscillator is likewise directly related to the size for a given material. The power required to maintain the oven at a given temperature is a function of surface area, which is again related to size. Ideal oscillator ovens should be fabricated from a material that has infinite thermal conductivity and thermal capacity. Unfortunately, materials that approach these characteristics are typically very dense. Therefore, a compromise must be made between mass and thermal properties. An aluminum alloy was selected for the Pluto resonator oven because it has relatively high thermal conductivity and relatively low mass. The size of the Pluto oven is smaller than the oven used in the present APL oscillator. The internal structure of the oven was also modified to reduce its mass. The design changes implemented for the Pluto oven reduced its mass to 28.6 g (78% less than the present oscillator oven housing). The frequency vs. temperature performance of the Pluto oscillator is excellent, with little or no degradation resulting from the oven design changes. The results from oscillator short-term frequency stability tests are not as well defined. Short-term stability two to three times better than the Pluto oscillator has been measured in similar APL oscillators using tactical BVA resonators. The higher stability most likely results from the quartz resonator and not the oven design. Detailed oscillator performance data are presented in a later section of this paper.

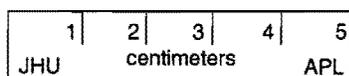
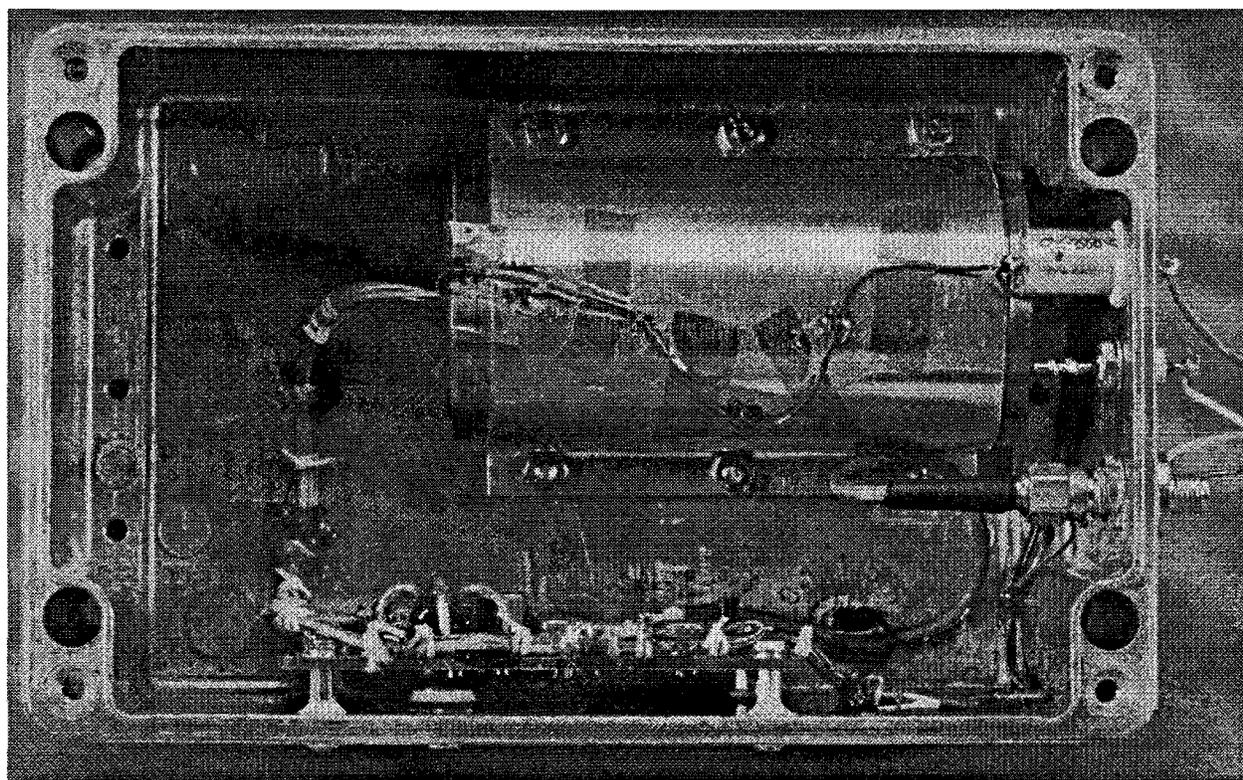
Magnesium has a density 33% less than aluminum and would produce a comparable mass reduction, but its thermal conductivity is 65% less than that of aluminum. With a

conflict between these parameters the overall effect on the performance of an oscillator using a magnesium oven is not clear, but additional tests using a magnesium oven should be pursued in view of the extremely critical mass requirement for the Pluto spacecraft. If performance of a magnesium oven is not satisfactory, a composite oven should be investigated. A composite oven could also provide ionizing radiation shielding. Radiation effects on quartz oscillators are discussed later in this paper.

Oscillator Chassis Design and Vibration Testing

The oscillator housing is the second largest contributor to total oscillator mass. Again, minimizing size is the key to reducing mass. All previous APL oscillators required vibration isolation systems to prevent damage to the quartz resonator during launch. These isolation systems increase the mass of the housing in two ways: 1) space inside the housing must be provided to allow movement of the housing around the isolated resonator oven assembly; and 2) the housing must have thick, heavy internal structures and exterior walls to provide stiff, rigid supports for the vibration isolation system.

A tactical BVA quartz resonator that has been under development for several years has become commercially available.⁴ Its specifications indicate it should survive the Pluto launch environment. A test oscillator with all components hard mounted to the basic structure was built and a series of tests was conducted in the APL Vibration Facility. The oscillator tested is shown in Fig. 1. The critical vibration-sensitive internal assemblies of the test oscillator, including the resonator, were similar to those that would be used for a flight oscillator. These assemblies are located inside the cylinder on the top side of the chassis. The rest of the test oscillator was assembled for convenience and low cost, bearing little resemblance to a flight oscillator. The oscillator was tested in two axes to the vibration levels expected during the Pluto launch, which are relatively high, as shown in Fig. 2. The vibration tests were conducted in the x and y axes, oriented relative to the quartz resonator as shown by the inset in Fig. 2. The oscillator was powered and operated during the vibration tests. The 10-MHz output signal from the oscillator, which was monitored throughout the vibration test, was not interrupted. The oscillator was not damaged by the vibration tests and performance was not degraded following the test.



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Fig. 1. The ultrastable test oscillator with tactical BVA quartz resonator. All components were hard mounted to the basic structure for the series of tests conducted in the APL Vibration Facility.

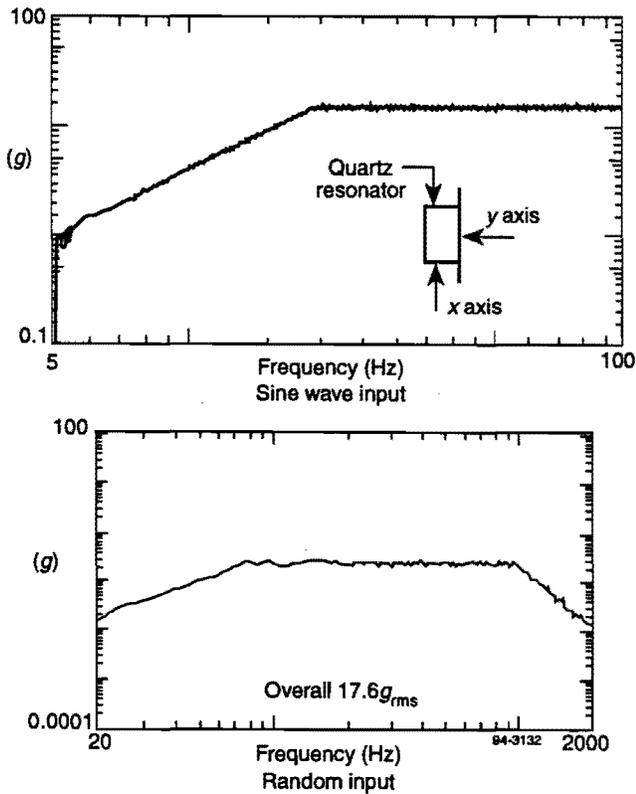


Fig. 2. The levels of vibration expected during the Pluto launch. Inset: the vibration test orientation of the x and y axes relative to the quartz resonator.

Based on the results of this vibration test, a vibration isolation system will not be used for the Pluto oscillator. Eliminating the vibration isolator will greatly reduce the size and mass of the oscillator housing. Minimizing wall thickness in keeping with structural integrity also reduces mass. The estimated mass of a Pluto flight-qualified oscillator is only 320 g and its volume is 353 cm³.

Frequency Stability and Phase Noise Performance

To measure the change in the radio propagation path length to $\approx 100 \mu\text{m}$, the onboard portion of the radio science instrument can be thought of as primarily a phase-measuring device with the capability of a measurement accuracy of approximately 0.01 rad. This corresponds to a frequency stability requirement of 1.8×10^{-13} for the onboard oscillator.⁵ The design goal for this oscillator was 1×10^{-13} for a 100-s measurement period.

Short-term frequency stability is a measure of short-term frequency changes and generally has a measurement period of 1000 s or less. The Allan variance is the industry standard for measuring short-term frequency stability. Allan variance data for the Pluto oscillator are shown in Fig. 3. The measured Allan variance for the Pluto test oscillator was only 4.8×10^{-13} . Another set of data, also presented in Fig. 3, has an Allan variance of 1.3×10^{-13} . These data are from

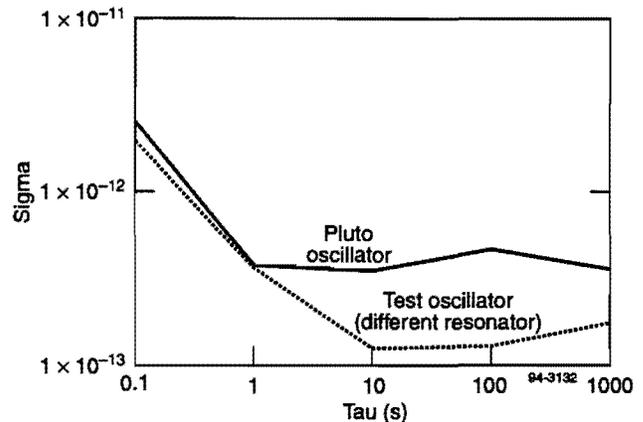


Fig. 3. Allan variance data for the 10-MHz BVA ultrastable oscillator compared with data from a similar test oscillator with a different resonator.

a similar test oscillator with a different resonator. While the number of tactical BVA resonators evaluated at APL has been limited, more than 35% of the units tested had an Allan variance of $< 2 \times 10^{-13}$. Resonator selection will be required to achieve an Allan variance of 1 to 2×10^{-13} , but this goal is achievable. Resonator selection was not possible for the Pluto test oscillator because of limited time.

Phase noise (\mathcal{L}_f) data are presented in Table 1. The goals for this design were achieved for all offset frequencies except 1 Hz. Phase noise performance for the Pluto oscillator is very good; however, resonator selection will also benefit phase noise performance. Oscillator circuit optimization has the potential to improve both the Allan variance and the phase noise performance. Neither the Allan variance nor the phase noise data presented assume equal noise sources.

Long-term frequency stability, or aging rate, is the measured oscillator output frequency change over a 24-h period. The 24-h aging rate for the Pluto oscillator was -3×10^{-12} , which is very good for a quartz oscillator and approaches the stability of small atomic rubidium frequency standards.⁶ Frequency retrace and the time required to establish an aging rate can be important parameters in some applications. The output frequency as a function of time for the Pluto test oscillator is presented in Fig. 4. The oscillator was operated in air at atmospheric pressure for the first 11 days. Changes to the oscillator were being made and various tests were being conducted, so the aging rate was not well established. On day 11 the oscillator was moved to a vacuum chamber and evacuation initiated. A rapid frequency increase of $\approx 9 \times 10^{-10}$ occurred during the first day. During the next 20 days frequency decreased and established an aging rate of $-3 \times 10^{-12}/24 \text{ h}$. On day 46 the oscillator was turned off for 2 days; then power was turned back on. A frequency change or retrace to the frequency prior to turnoff was $\approx -2 \times 10^{-10}$. An aging rate of $-3 \times 10^{-12}/24 \text{ h}$ was re-established within 2 to 3 days after the oscillator was

Table 1. Performance data on the Pluto Flyby mission oscillator.

Performance parameter	Goals for Pluto oscillator	Measured data from Pluto development oscillator
Aging rate/24 h	2.0×10^{-11}	-3.00×10^{-12}
<i>Allan variance, Tau (s)</i>		
0.1	1.0×10^{-12}	2.54×10^{-12}
1	3.0×12^{-13}	3.82×10^{-13}
10	1.0×13^{-13}	3.59×10^{-13}
100	1.0×13^{-13}	4.80×10^{-13}
1000	2.0×13^{-13}	3.67×10^{-13}
<i>Phase noise</i>		
Frequency offset (Hz)		
0.1	—	-88 dBc
1	-120 dBc	-116 dBc
10	-135 dBc	-140 dBc
100	-145 dBc	-150 dBc
1000	-150 dBc	-153 dBc
10000	-150 dBc	-155 dBc
<i>Frequency as function of—</i>		
Temperature per °C (20° to 40°C)	1.0×10^{-12}	-2.00×10^{-13}
Load (50 Ω ±10%)	2.00×10^{-12}	2.00×10^{-12}
Input voltage	1.00×10^{-12}	1.00×10^{-12}
Radiation	1.0×10^{-10} rad*	N.T.**
Magnetic susceptibility	$2 \times 10^{-12}/G$	2×10^{-12} to 2×10^{-11} *
Acceleration	$1.5 \times 10^{-9}/g$	$1.00 \times 10^{-10}/g$
Vibration	5-2000 Hz	Survived*
<i>Output characteristics</i>		
Power level	0 dBm	+7.4 dBm
Harmonic	-50 dBc	-52 dBc
Spurious	-60 dBc	-86 dBc
Power at 25°C (W)	0.8*	0.77*
Mass (g)	320 (est.)	—
Size (cm)	$9.65 \times 6.86 \times 5.33$ (est.)	—

*See text.

**N.T.-Not Tested

restarted. Both the retrace frequency offset and the time required to reestablish an aging rate can be important to missions such as Pluto, where power is a premium quantity. If Mission Operations decides not to keep the power to the oscillator on during the cruise time to Pluto, then having some knowledge of how frequency stabilizes as a function of time after turn-on becomes very important.

Table 1 also shows data on the performance and on other parameters of the Pluto oscillator.

Environmental Effects on Frequency Stability

Temperature

Changes in the ambient temperature and environment in which the oscillator is operating will cause frequency

changes. Oscillator design and operating temperature range are related to oscillator power consumption. Output frequency and input power consumption for the Pluto oscillator are presented in Fig. 5. Data for three configurations are presented. The amount of insulation or the thermal resistance the insulation provides directly affects oscillator performance. Configuration 1 had about half the insulation normally used in APL oscillators so that the oscillator subassemblies could be hard mounted for vibration testing. Input voltage for this test was 19.5 V. Configuration 2 had the quantity of insulation normally used in APL oscillators, and the input voltage was 19.5 V. This configuration has only one data point at 28°C. Configuration 3 is the same as configuration 2 except the input voltage was reduced to 17 V. These data provide insight to the tradeoffs that can be made in the design of the oscillator and how they relate to operating conditions, specified temperature range, and input power.

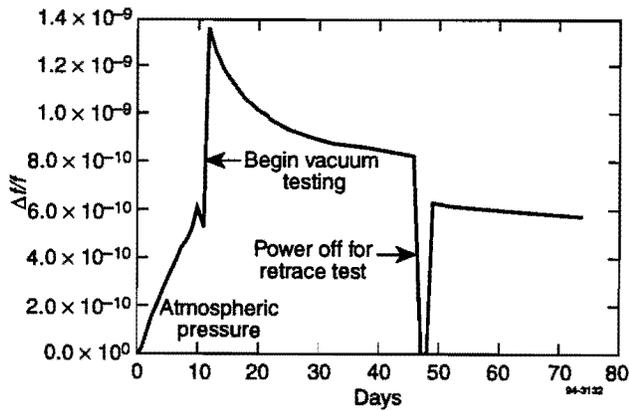


Fig. 4. Output frequency as a function of time, showing aging rate and frequency retrace.

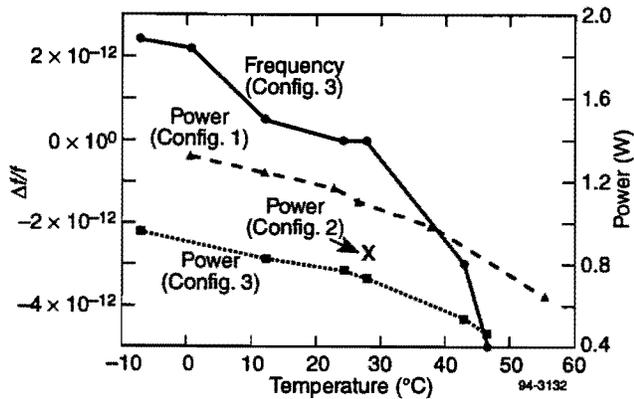


Fig. 5. Output frequency and input power consumption as a function of temperature for three configurations of the Pluto oscillator.

The quartz resonator must be operated precisely at its turning point temperature, which is $\approx 85^{\circ}\text{C}$. The thermal control circuitry requires a temperature differential between the ambient temperature and the set turning point temperature to maintain control of the turning point temperature. The magnitude of the temperature differential depends on several design parameters, but the primary ones are the quantity of insulation surrounding the resonator oven and the required upper operating temperature. Input power requirements are different for the three configurations, as clearly shown in Fig. 5. Configuration 2 requires 24% less power than configuration 1, and configuration 3 requires 33% less than configuration 1. Recall the only difference between configuration 1 and 2 is the quantity of insulation. To maintain a given oven temperature at a given ambient temperature requires a constant input power to the oven; additional power is dissipated in the control circuits and in the transistor controlling current to the oven heater. If the input voltage is reduced, the oven power remains constant, but the power dissipated in the control transistor decreases. This explains the power difference between configuration 2 and configuration 3. Another

method of changing the power balance between the oven and the control transistor is to change the resistance of the heater.

High ambient operating temperature is limited by and directly related to the quantity of insulation. Beyond this limit, control of the oven temperature is not maintained. The high-temperature limit for configuration 3 was $\approx 49^{\circ}\text{C}$, compared with $\approx 62^{\circ}\text{C}$ for configuration 1. Again, the quantity of insulation is the primary cause for the difference. As the above data indicate, design tradeoff options frequently conflict with each other, so intelligent compromises must be made which include realistic oscillator specifications that do not exceed the real science requirements.

The dynamics of the thermal time constant are heavily influenced by the quantity of insulation, as shown in Fig. 6. The longer time constant achieved with more insulation (configuration 3) will delay or sometimes prevent the full magnitude of short-term ambient temperature changes from reaching the resonator oven. If the magnitude of the change in ambient temperature is large, the rate of change inside the insulation layers at the oven will be slower, allowing the control circuits to respond more accurately and thereby minimizing oven temperature change.

The Pluto oscillator has a very low temperature coefficient of $-2 \times 10^{-13}/^{\circ}\text{C}$ between 20 and 40°C . The frequency change as a function of temperature from -10 to $+55^{\circ}\text{C}$ is shown in Fig. 5. These data are for the oscillator in configuration 3. Even small, rapid temperature changes can have a detrimental effect on oscillator output frequency. Therefore, in addition to the static temperature test in which a large step in ambient temperature was made and the oscillator output frequency change measured after stabilization, a dynamic temperature test was also conducted. The test temperature was changed in 10°C increments at ≈ 30 -min intervals. With an oscillator thermal time constant of 3 to 4 h, the temperature control circuits and output frequency did not have enough time to stabilize before the test temperature was reversed. This simulates a real world condition that often occurs in spacecraft, particularly small spacecraft, as they pass in and out of sunlight. The results of this test are shown in Fig. 7. The peak-to-peak frequency change is $\approx 3 \times 10^{-12}$.

Acceleration

A quartz oscillator's output frequency is sensitive to position changes in the gravitational field and to acceleration forces. Usually this sensitivity is not a problem after the spacecraft is placed in orbit, but if thrusting maneuvers are conducted by the spacecraft, acceleration sensitivity may be a design consideration. BVA resonators are generally less sensitive to acceleration than conventionally mounted resonators.³ The Pluto oscillator was tested by rotating the oscillator around both axes while observing the change in output frequency. This is called a 2-g tip-over test. A maximum

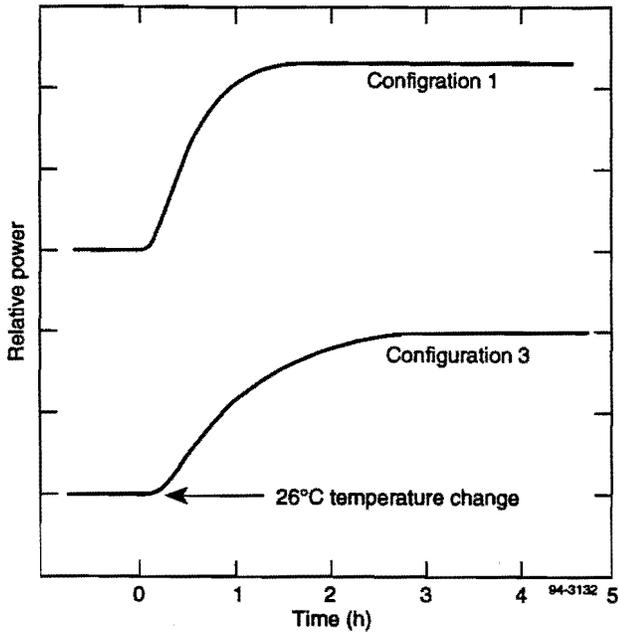


Fig. 6. Influence of insulation quantity on the dynamics of the thermal time constant.

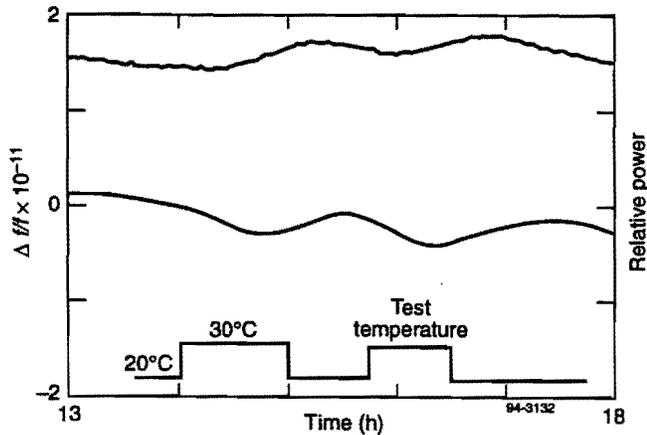


Fig. 7. Results of the dynamic temperature test simulating the conditions of a small spacecraft passing in and out of sunlight (oscillator configuration 3).

frequency change measured for the Pluto oscillator was $1 \times 10^{-10}/g$. The g sensitivity is not linear and is different for each axis. In applications with known directional acceleration forces, the oscillator could be oriented in the plane with the minimum acceleration sensitivity.

Magnetic Sensitivity

Both the oscillator circuits and the tactical BVA resonator are sensitive to magnetic field changes. The largest magnetically induced frequency change measured for the Pluto oscillator was 2×10^{-11} for a 1-G change measured

in a DC field. Again, the magnetic sensitivity of the oscillator is not symmetrical and depends on polarity. The tactical BVA resonator is less sensitive ($\approx 2.7 \times 10^{-12}/G$) than the oscillator circuits.³ A low-mass magnetic shield is routinely incorporated in the oscillator if magnetic field in the spacecraft varies. This shield reduces the magnetic sensitivity to $\approx 1 \times 10^{-12}/G$.

Radiation

Interest in the effects of ionizing radiation on quartz resonators and oscillators has been intense at APL since the late 1960s.⁷ With improvements in oscillator performance and reductions in sensitivity to other environmental stresses, the radiation-induced frequency change is the largest and least predictable environmental effect in many orbits. The radiation environment for the Pluto mission has not been well defined; therefore, radiation tests, which are time consuming and expensive, were not conducted on the Pluto oscillator. The configuration of the Pluto oscillator as designed has little radiation shielding. If radiation shielding becomes necessary to meet mission frequency stability requirements, mass of the oscillator will increase, because effective shielding materials are usually heavy. BVA-type resonators are generally less sensitive to radiation than conventionally mounted resonators. Radiation tests on tactical BVA resonators have been conducted with a spread of 2×10^{-10} to $2 \times 10^{-11}/\text{rad}(\text{Si})$ for a 0.6-rad exposure.⁸

Future Development

The major thrust of this experimental design was to prove the feasibility of reducing the mechanical elements of our ultrastable oscillator design, thereby reducing its mass and size. Little effort was devoted to electronic circuits, either in terms of improving performance or reducing their size. Existing circuits and printed circuit boards were utilized with minimal or no modifications. Circuit optimization is needed to improve performance, reduce power requirements, and reduce physical size. Further exploration of resonator oven materials and insulating systems could yield additional mass and size reductions. The overall power budget will be explored, including input voltage, voltage regulation, and the optimum balance between heater resistance and the control transistor.

Conclusion

The knowledge and data gained from this advanced technology feasibility study provide a solid basis to develop a small, ultrastable quartz oscillator to support the Pluto Fast Flyby mission. The effort to reduce mass and size met or exceeded our expectations. We firmly believe we can meet the design goals for mass and size, environmentally induced frequency changes, and power requirements. The design goals for frequency stability are more difficult, but with

circuit optimization and resonator selection these goals are believed to be within reach. Funding limitations prevented exploration of aspects of the oscillator design that are important but would be of little interest if the primary objective to reduce mass and size could not be achieved. By addressing the tasks listed above a small, low-mass oscillator with outstanding performance can be developed.

Acknowledgment

This work was supported with a contract from Stanford University. The author is grateful to many colleagues, especially J. M. Cloeren and R. J. Besson, for valuable discussions and contributions to this exploratory development oscillator.

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Biography of Jerry R. Norton

Jerry R. Norton is a Senior Staff Engineer at The Johns Hopkins University Applied Physics Laboratory. He began his career in 1961 as an RF design engineer for satellite navigation receivers, including the first portable, battery-powered unit. Since 1974 he has been engaged in development of both atomic and quartz frequency standards. This work includes development of a low-noise receiver and frequency synthesizer for a hydrogen maser frequency standard. Mr. Norton was the lead engineer for a series of new ultrastable quartz oscillators developed for use in spacecraft including Topex/Poseidon, which used a BVA quartz resonator for the first time in space. He has conducted extensive studies on the radiation effects on quartz resonators and oscillators. Currently, he is designing an ultrastable oscillator half the size of the present oscillator for the Pluto Fast Flyby mission. Mr. Norton is a member of the Precision Time and Time Interval Advisory Board.