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DEVELOPMENT OF PRECISION TIME AND FREQUENCY SYSTEMS AND DEVICES AT APL

APL's entry into research, development, testing, and fabrication of precision time and frequency devices was occasioned by its development of a high-quality, spaceborne oscillator for the Transit navigation satellite program. Later, this effort branched out into atomic frequency standards and other innovative frequency standards such as the superconducting cavity stability oscillator and trapped ion devices. As an auxiliary operation, APL maintains and operates a Time and Frequency Standards Laboratory containing in-house standard time and frequency devices that are tracked against other time standards that contribute data for the international calibration of the basic unit of time, the second.

INTRODUCTION

The importance of time and frequency is often unappreciated. Knowledge of accurate and precise time and frequency is vital to navigation, communications, geodesy, and gravitational studies, to name a few. In many cases, the limiting factor in these studies is the quality of their time and frequency information. We obtain time and frequency information from many types of devices, ranging from the centuries-old pendulum to today's atomic standards. The devices have become diverse in accuracy, precision, and operational and physical characteristics because of special requirements of the various applications.

Over the years, APL has been involved in the research and development of several types of time and frequency devices and their associated auxiliary equipment. This article describes some of the devices and outlines their applications.

CONCEPT OF STABILITY

The most important parameter in evaluating a time or frequency device[1] is its stability, which is a measure of how accurately it remains at a given frequency over a specified time interval. Stability is measured by counting the number of periods in a device's output signal over a specified time interval and relating the result to the nominal frequency. Stability is usually expressed as a fractional frequency difference; for example, if a device's frequency signal at 5 megahertz varied by 1 hertz over a measured time interval, its stability would be (1 hertz)/(5 megahertz), or 2 parts in 10^7.

The frequency stability of a device can be measured quite accurately; the noise floor on measurement systems developed at APL is parts in 10^{16}.[2] A common technique for measuring the stability of frequency devices, one that is used at APL, is known as the heterodyne frequency measurement method (outlined in Fig. 1). The technique requires a reference device that is offset in frequency and is of comparable or better stability than the one being tested. The two signals are mixed and filtered, and the resultant beat frequency (or time interval) is measured. The fractional frequency deviation is determined by dividing the measured value by the reference frequency. The stability of a fre-

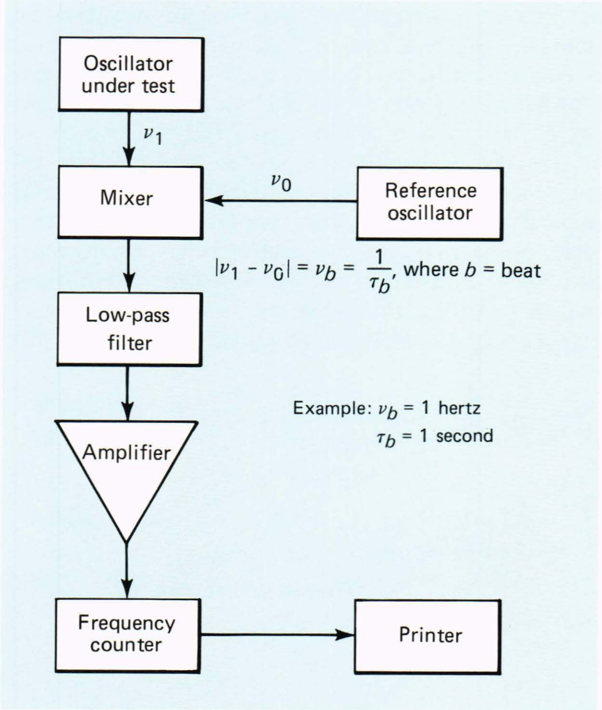


Figure 1—The heterodyne frequency measurement method used at APL as a frequency fluctuation measurement system. The difference frequency, $|\nu_1 - \nu_0|$, is measured with a frequency counter. A counter measuring the period (or multiple period) of the beat (difference) frequency could equally well be used.

quency device usually varies as a function of the measurement time interval; stability characteristics as a function of time are given for several frequency devices in Fig. 2.

The stability of a device is affected by factors other than measurement time. All frequency devices are based on some type of periodic physical phenomenon, whether it is the vibration of a quartz crystal or the resonant transition energy in an atom, and they can be influenced and perturbed by their environment. The perturbations, in turn, affect the device's stability. Different frequency devices are affected to different degrees by various environmental influences, primarily temperature, acceleration (gravity), vibration, radiation, and magnetic fields. Stability as a function of environmental factors is usually quoted as a performance characteristic separate from the type of stability shown in Fig. 2.

Aging or long-term drift, also a factor in a device's long-term performance, is usually caused by relaxation processes incorporated in the design and fabrication of the frequency device itself, but it is not necessarily inherent in the physical phenomenon on which it is based. Figure 2 shows the typical upward turn at the long time intervals associated with aging in all of the listed frequency devices except the trapped mercury ion. However, the latter's long-term stability is only projected at this point, as will be discussed later.

The frequency standards in Fig. 2 find practical applications in systems for timekeeping, propagation measurement, navigation, and communication by means of combinations of frequency multiplication, division, and mixing. The particular choice of frequency standard depends on the dominating characterization of the system application. The factors to be considered include size; cost; power consumption; frequency stability; frequency spectral purity; response to variations in such environmental conditions as temperature, magnetic fields, electric fields, ionizing radiation, and vibration; aging effects; and system reliability. In the following sections, the frequency devices on which APL is doing research (quartz oscillators, hydrogen masers, trapped-mercury-ion devices, and superconducting cavity stabilized oscillators) will be discussed in detail.

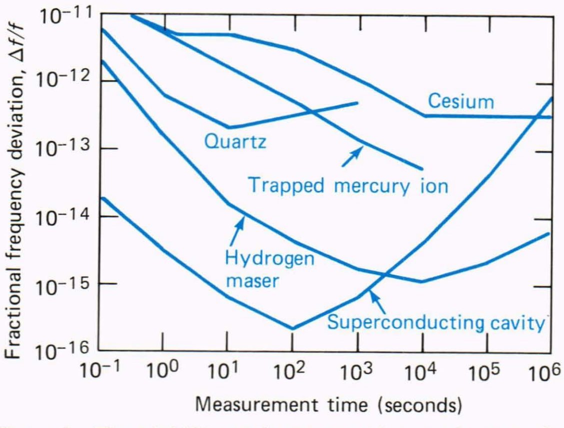


Figure 2—The stability performance of several types of precision frequency devices.

QUARTZ OSCILLATORS

APL's entry into the time and frequency field began with the development of the quartz oscillator for the Transit navigation satellite in 1959.[3,4] Transit's navigation system was based on precision measurement of the Doppler shift in the signal received on earth from a very stable satellite transmitter. The Doppler-shift phenomenon is used to calculate the dimensions of the propagation path between the earth receiver and the satellite transmitter as the craft passes overhead. The position of the satellite as a function of time is transmitted by a modulation of the satellite's signal. The position of the earth receiver is then derived from the satellite's position and the propagation path length.

Obviously, time and frequency play major roles in the system; the more accurately they are known, the more accurately the earth receiver's position can be determined. In the operational Transit system, receiver positions can be determined from within 0.2 nautical mile (the worst case) down to 0.015 nautical mile (approximately 40 meters) under optimal conditions. These navigation satellites therefore required very accurate on-board time and frequency standards.

Since APL designed the first oscillator in 1959, it has continued to research, design, develop, and fabricate oscillators for spaceflight applications. About 200 spaceflight-qualified oscillators have been built at APL since then. Spaceflight qualification requires very rigorous design and testing in order to provide adequate protection and reliability under harsh launch conditions and in view of the inaccessibility of space. APL-built oscillators are subjected to intense shock and vibration tests, extended thermal vacuum tests, and rigorous inspections at each step of fabrication. Table 1 lists some performance characteristics of the quartz oscillator. As Fig. 2 shows, the stability performance of the best bulk quartz oscillators is much poorer than that of the newer high-precision atomic frequency devices. Yet quartz oscillators are still used almost exclusively as the frequency device on satellites

Table 1—Typical performance of a quartz oscillator.

Short-term stability:	1 second	1×10^{-12}
	10 second	6×10^{-13}
	100 second	4×10^{-13}
Long-term aging		2×10^{-11}/day
Phase noise at 1 kilohertz: 155 decibels at 10 kilohertz from the carrier		
Frequency stability as a function of		
Temperature		$5 \times 10^{-12}/°\mathrm{C}$
Output short		3×10^{-11}
Radiation (low level)		1×10^{-10}/rads
Acceleration		1×10^{-9}/gravity
Power consumption		0.65 watt
Weight (single)		1.3 pounds

because of their small size, light weight, high reliability, and ruggedness.

A quartz crystal oscillator can be divided into two major components: the quartz resonator and the associated electronic circuit that keeps the resonator at optimal operating conditions. The components of one oscillator design and a partially assembled dual-oscillator book are shown in Figs. 3 and 4, respectively; Fig. 5 is a block diagram of the oscillator. The resonator, which is the physical source of the frequency signal, is a small piece of quartz that is cut and dimensioned so that it has a particular resonant vibration mode.

Resonator technology has improved significantly over the past 15 years. New techniques and designs for cutting the quartz material have resulted in resonators that are less sensitive to temperature variations. Advanced techniques for growing the synthetic quartz from which the resonator is cut have reduced impurities and structural defects, resulting in better performance characteristics, particularly long-term stability. New processing and cleaning procedures also have improved resonator performance. The primary research activity at APL has involved revising and redesigning the oscillator circuit to exploit the improved characteristics of resonators, new component technology, and new material and packaging techniques. The most important concept in this research is to maximize the oscillator's performance while qualifying it for spaceflight.

Another aspect of oscillator technology in which APL has recently become involved is low-dose-level radiation damage. Low-dose-level radiation is encountered in certain orbits during the satellite's passage through the Van Allen radiation belts. It can change the frequency of the resonator; however, the effect has not been well quantified for low dose levels. Preliminary experiments at APL indicate that low-level radiation effects depend in part on cleaning and fabrication processes during the production of the resonator.[5]

Figure 3—The components of an oscillator flask.

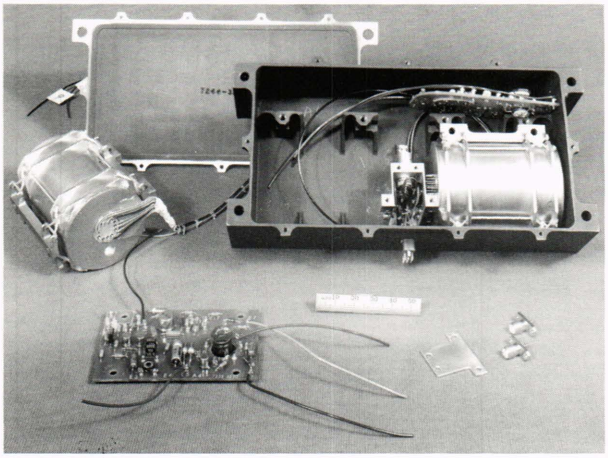


Figure 4—An oscillator flask in a partially assembled dual-oscillator book.

The resonators used in APL's spaceflight-qualified oscillators are classified as bulk quartz resonators because the frequency signal is derived from the resonance of the crystal itself. APL also has been developing applications of standing acoustical-wave devices, which consist of a 0.001-cubic-inch slab of quartz on which a grating of electrodes is deposited. Interdigital transducers are used to generate a standing acoustic wave just above the surface of the quartz block. The frequency of the standing wave can be adjusted by changing the spacing and number of gratings and the size of the quartz slab. The device acts as a resonator of fairly high stability but not as high as conventional bulk resonators. Typical stabilities for

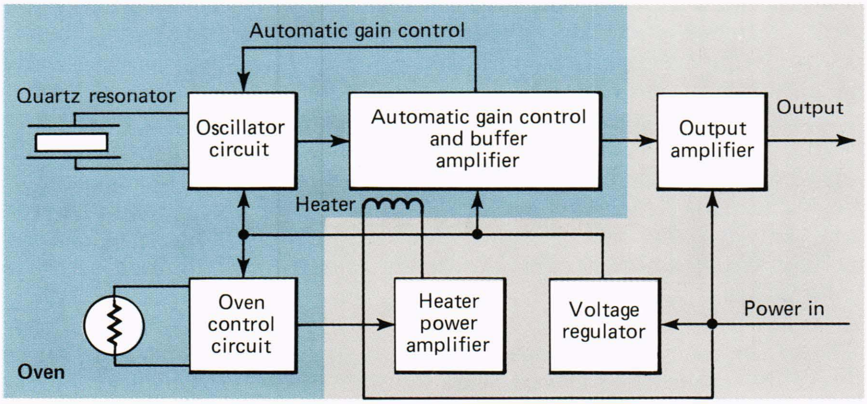


Figure 5—Functional block diagram of a quartz oscillator.

existing standing acoustical wave devices under ideal environmental conditions are parts in 10^{11} over 1 to 100 seconds. Although these devices are not of high precision, they have advantages (low cost, small size, high fundamental frequency output (up to 1 gigahertz), and good shock resistance) that make them attractive for certain applications. The higher-frequency output is an advantage for applications requiring frequencies much higher than 5 megahertz because multiplier chains do not need to be added to the system. (Conventional bulk resonators are usually cut for 5 megahertz and require multipliers to produce higher frequency outputs.) The low cost and small size are attractive for applications involving large quantities of the devices.

Applications to two programs are being investigated. The first is the Bird-Borne Program, sponsored by the Patuxent Wildlife Research Center of the Department of the Interior, for tracking migratory birds by satellite.[6] The program uses a standing acoustical wave device that will operate at 401 megahertz; since it is attached to the birds being tracked, its primary advantages are its small size and light weight. The second program is the Search and Rescue Satellite Aided Tracking Program of NASA (National Aeronautics and Space Administration), in which satellites would track distress signals emanating from almost anywhere on land or water. In that application, the device will operate at 406 megahertz and will supplement and potentially replace the existing 121.5 megahertz system. The higher frequency will provide better tracking than the present system does.[7]

HYDROGEN MASERS

In 1975, NASA asked APL to redesign its experimental hydrogen maser into a rugged model for the Crustal Dynamics Project. The redesign was to be accomplished without sacrificing performance. The Crustal Dynamics project encompasses several experiments in which the movement of the earth's tectonic plates is measured and tracked by means of very long baseline radio interferometry (Fig. 6). Very long baseline interferometry was originally developed by astronomers to study distant radio sources known as quasars. Signals from a quasar are recorded simultaneously by two (or more) antennas that are usually thousands of kilometers apart. The time of arrival of the signals is recorded at each antenna with a very accurate clock or frequency standard—the hydrogen maser. The difference in time of arrival of the signals at the antennas is used to determine the distance between the antennas, as well as the earth's rotational dynamics, by using cross correlation for detecting the fringe patterns between the two antennas. The "baseline" distances between any two antennas are measured routinely. With the present network, changes in baseline distances as small as 1 to 2 centimeters per year can be detected.

The hydrogen maser developed by APL is shown in Fig. 7; its stability characteristics are shown in Fig. 2. The original specification on frequency stability defined by the very long baseline interferometry network was 1 part in 10^{14} at 1000 seconds. The NASA research hydrogen maser developed at APL exceeds this requirement (Fig. 2) with a stability of 2 parts in 10^{15} at 1000 seconds.[8-11]

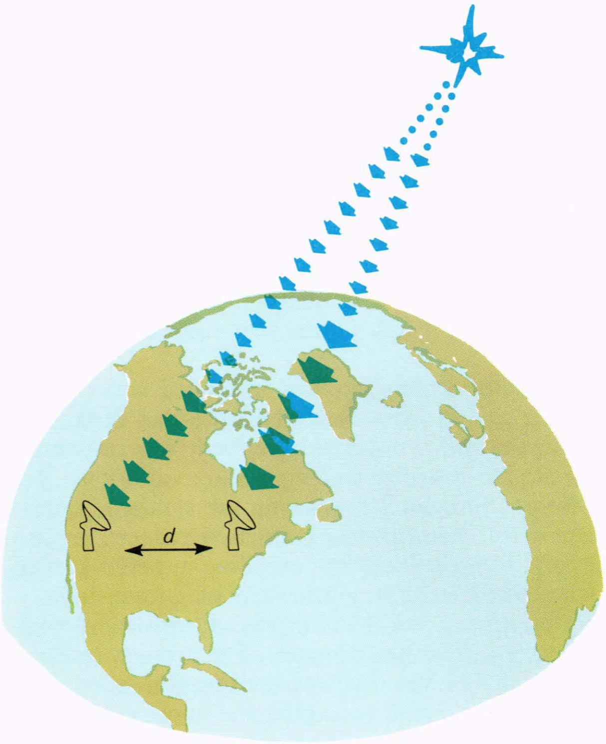


Figure 6—The principles of very long baseline interferometry. Two or more radio antennas receive signals from a distant radio source (pulsar), with time tags provided by a hydrogen maser.

The hydrogen maser is an atomic frequency standard based on a quantum transition of the hydrogen atom from an excited state to its ground state at a frequency of 1,420,405,751.68770 hertz. The maser can be divided operationally into two basic components: the physics package shown in Fig. 8 and the electronics system shown in Fig. 9. Gaseous hydrogen under low pressure enters a dissociator, where the molecule is broken down into hydrogen atoms by a radio frequency field of several watts at about 120 megahertz. The hydrogen atoms then flow through a collimator (a region of 0.002 × 0.020 inch parallel tubes), producing a beam of atoms. The hydrogen atoms in the beam can be in either of two excited states, each with different magnetic properties.

The beam of atoms then passes through a highly dispersive magnetic field region that removes the hydrogen atoms that are not in the proper excited state. The atoms that remain pass into a Teflon-coated storage bulb. In the storage bulb, they decay from their excited state to their ground state, giving up energy of 1,420,405,751 hertz. That transition stimulates oscillation within the surrounding metal cavity, which is resonant at the same frequency. A small portion of the cavity signal (about 10^{-14} watt) is coupled to a

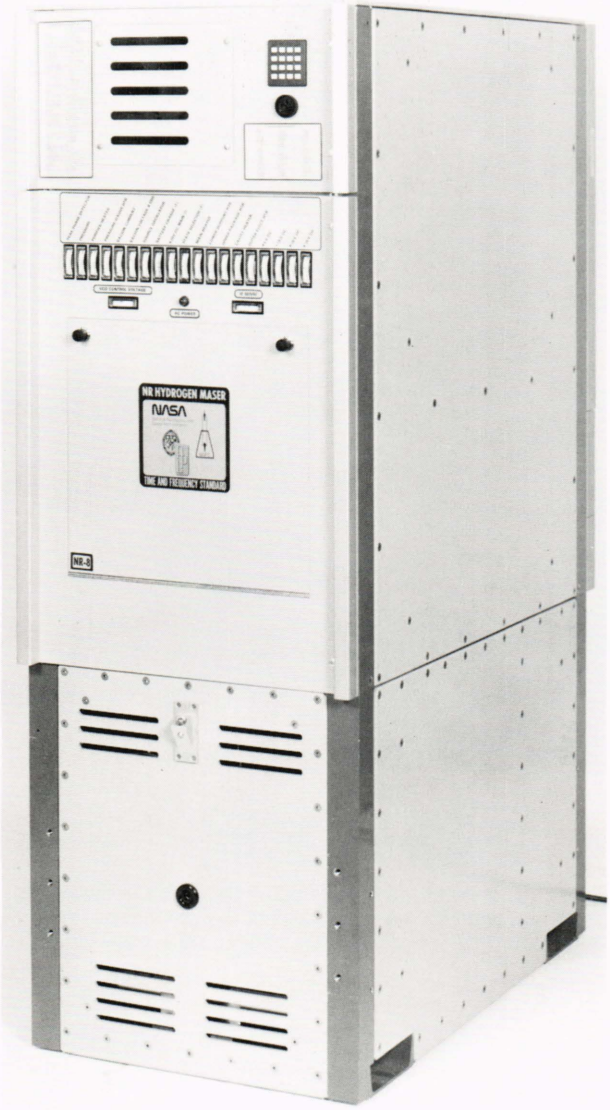


Figure 7—The NASA research hydrogen maser.

coaxial cable and is used to slave a quartz oscillator, which provides an output signal of 5 megahertz (at about 1/50 watt). The electronics system controls the environment and synchronizes the working 5 megahertz oscillator.

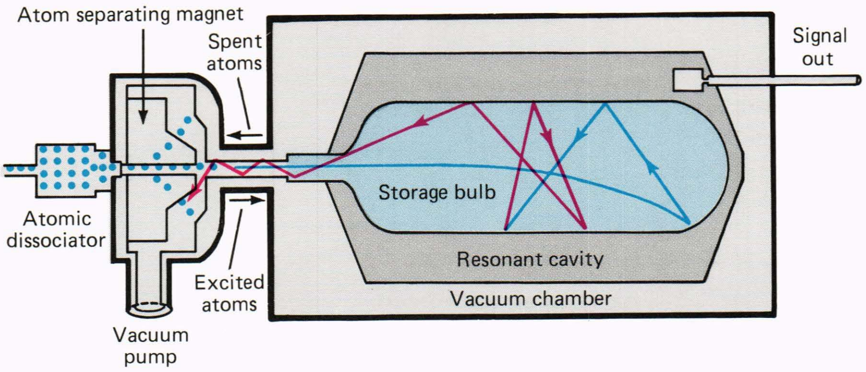
Several technical challenges had to be met to obtain a frequency stability performance of 2 parts in 10^{15} in the NASA research maser. An extremely stable temperature is required within the cavity to maintain the dimensional characteristics that control the cavity's resonant frequency. In the maser, the cavity temperature is maintained within 0.4×10^{-6}°C. Magnetic fields are shielded from the maser by a factor of 10^5. Buffer systems were developed to attenuate by a factor of 10^{12} reactive loads on the 5 megahertz output signals to ensure that disturbances of the internal control and slave circuits are kept to a minimum.

One of the most innovative features of the maser was the integration of a 64 channel microprocessor for monitoring and controlling operational parameters.[12] The microprocessor provides interfacing for an external terminal to request status information and to control operations. The interface can be performed locally or can be accessed at distant locations via a modem and telephone lines. The microprocessor also permits enhancement of the long-term stability of the maser. In the hydrogen maser, a factor in decreased stability over long periods is the gradual drifting of the frequency of its resonant cavity. (The mechanisms causing this frequency drift are not known in detail but probably involve mechanical and thermal changes or aging of the electronics.) An autotuner continuously and automatically tunes the cavity, allowing the maser to maintain its optimal stability of parts in 10^{15} over weeks and months (Fig. 2). This feature, in turn, provides great potential for the hydrogen maser as a clock. The sideband noise on the maser is low to allow the output signal to be multiplied to 100 gigahertz and still have less than 1 radian of phase noise.

The maser is also unique in that its output frequency (at 5 megahertz) can be adjusted over a range of 5 parts in 10^8 in steps of 1 part in 10^{16} by means of an APL-designed frequency synthesizer, without incurring phase jumps in the output signal or degrading the maser's inherent stability.

Its phase stability is another advantage of the hydrogen maser. The residual phase is less than 1 picosecond (i.e., the jitter of the signal). Figure 10 shows a typical phase comparison between two hydrogen masers and between a hydrogen maser and a commercial cesium frequency standard. The phase data and

Figure 8—The physics package of the NASA research hydrogen maser. The package consists of the electromechanical assemblies to provide dissociated hydrogen atoms, state selection, the quartz storage bulb, the resonant cavity, the aligning magnetic field, the thermal heaters and isolation, the magnetic isolation, and the vacuum system.



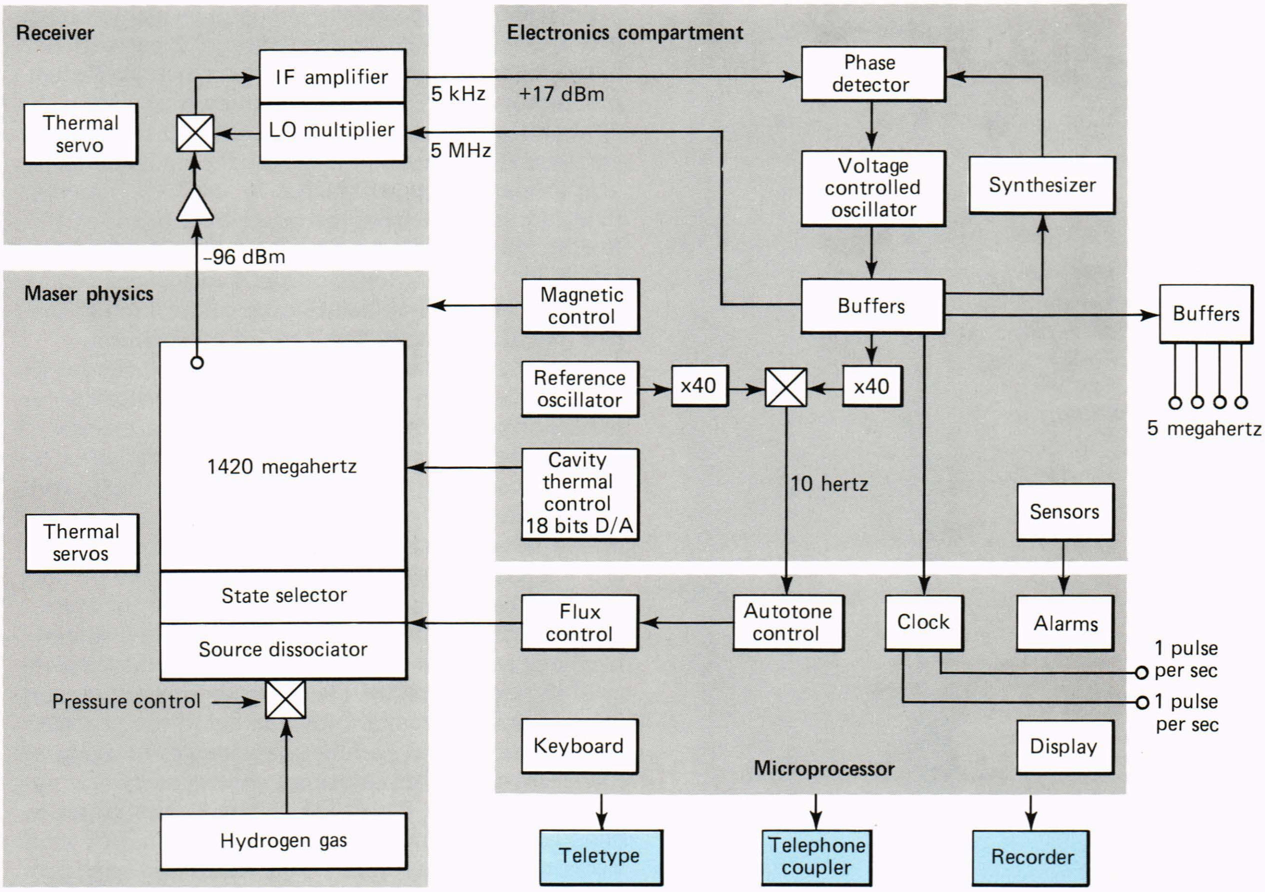


Figure 9—The electronics system of the NASA research hydrogen maser. The electronics system consists of the power supply, the phase-locked oscillator and receiver, the gas pressure controller, the magnetic field controller, the thermal controller, the output signal isolation system, the microprocessor system controller, the frequency synthesizer, and the autotuner system.

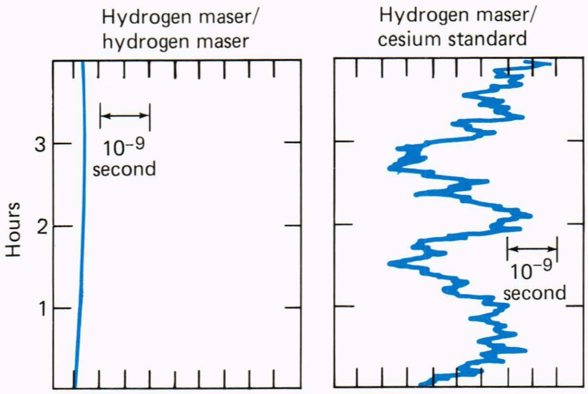


Figure 10—Comparison of measured phase differences as a function of time between two NASA research hydrogen masers and between a NASA research hydrogen maser and a Hewlett-Packard commercial cesium standard. The plots show the phase noise of the hydrogen maser and cesium standard.

the hydrogen maser of the cesium frequency standard are dominated by the poorer performance of the cesium standard, and its jitter is more than 1 nanosecond. A summary of typical environmental performance characteristics of the hydrogen maser is given in Table 2.

APL is investigating designs of small masers with possible spaceflight applications and designs for a maser absolute frequency standard at parts in 10^{14}. (Current absolute frequency standards are cesium clocks at parts in 10^{-13}.)

TRAPPED-MERCURY-ION DEVICE

The trapped-mercury-ion device is an atomic frequency standard based on transitions within the hyperfine levels of the mercury ion, $^{199}Hg^{+}$, at a frequency of 40,507,347,996.6 hertz. The device is still in the development stage, but it offers many attractive features. It is based on an electric field trap that can retain charged particles for long periods of time. The device

Table 2—Typical environmental performance characteristics of the NASA research maser.

Temperature coefficient	$2 \times 10^{-14}/°C$
Magnetic shielding factor	100,000
Magnetic susceptibility	$\leq 1 \times 10^{-14}$/gauss
Phase residual (1-second jitter)	<1 picosecond
Vibration/lift sensitivity	$<3 \times 10^{-14}$

is very stable and will not operate unless it is within 0.5 hertz of its output frequency (about 40 gigahertz). Its theoretical stability curve is shown in Fig. 2. Another feature is its small size. The trap itself is only about 2 × 5 inches, and it is lightweight. These factors, along with the device's projected superior stability, give it great potential as a spaceflight frequency standard. The goal in satellite technology for the 1990s is spacecraft autonomy, which will require an on-board frequency standard with stability of parts in 10^{14}. The trapped-mercury-ion device appears to have potential to fulfill this requirement.

The operation of the trapped-ion frequency standard is based on the quantum mechanics of the mercury ion. By isolating the quantum transition of the 199 isotope of mercury at the microwave frequency of 40.5 gigahertz, one can obtain signals to servo-control a crystal oscillator at 5 megahertz. The control signals are derived by using several of the quantum transitions in isotopes 199 and 202 of mercury, as shown in Fig. 11. The energy required to enhance the population of the ^{199}Hg ions at ground state to the proper excited state is derived in two steps. First, a microwave signal at 40.5 gigahertz raises the ion from $F = 0$ to $F = 1$ in the $^2S_{-1/2}$ ground state. Second, a ^{202}Hg ion lamp discharge at a wavelength of 194.2 nanometers raises the ion to the final excited state, $F = 0$, $^2P_{1/2}$. When ^{199}Hg ions decay from the $F = 0$, $^2P_{1/2}$ level to $F = 1$, $^2S_{1/2}$ level, fluorescent emission occurs that can be detected by a photon detector.

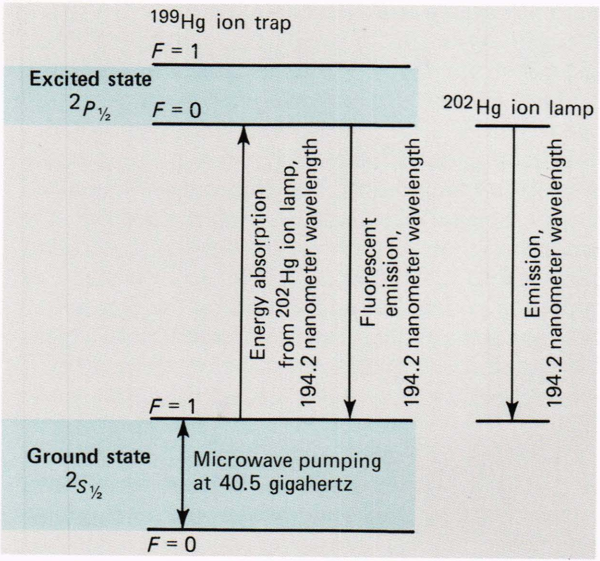


Figure 11—Energy levels of mercury 199 and 202 ions in the lamp and in the ion trap. Microwave pumping at 40.5 gigahertz is used to raise the mercury ions in the trap to the $F = 1$ hyperfine level of the ground state. The ions in that state can then absorb the energy from the mercury lamp. The ions then decay, giving off fluorescent emission with an extremely narrow linewidth.

Figure 12 is a schematic diagram of the trapped mercury-ion standard. ^{199}Hg atoms are ionized by means of a stream of electrons from an electron gun. This provides a charge on the atom that is used to hold

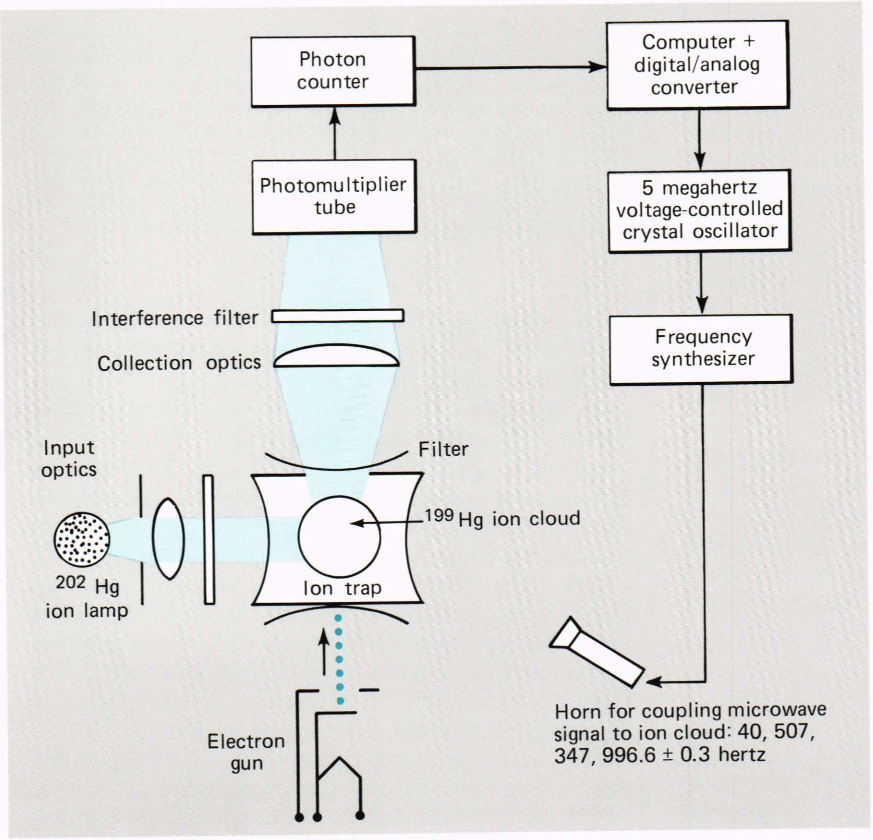


Figure 12—Schematic of the trapped-mercury-ion standard. The extremely narrow linewidth fluorescent emission from the mercury trap is detected by a photomultiplier tube that, in turn, is used to control a 5 megahertz oscillator. The oscillator provides a very stable output signal that is also used as the microwave pumping signal for the ion trap. This acts as a self check on the system because the signal can vary no more than ±0.3 hertz or the entire system will fail to operate.

the atoms isolated from the container walls in a specified region by means of an electric alternating field. Radiation from the ^{202}Hg lamp shines in from the left, 40.5 gigahertz microwave energy shines in orthogonally to the lamp radiation, and the photon detector (the photomultiplier tube) picks up fluorescence that is orthogonal to both the lamp radiation and the microwave signal directions. The microwave signal is synthesized from the 5 megahertz voltage-controlled oscillator and is modulated within ±0.3 hertz. The modulation is detected and sensed by the computer, which moves the oscillator so as to center the 40.5 gigahertz signal at the quantum transition frequency.

Two research groups have been active in the development of the trapped-ion device: a French group at the University of Paris (Sud) Centre d'Orsay and a U.S. group at Hewlett-Packard, both of which have produced working devices. However, the devices have operated continuously only over short time intervals, several weeks maximum, because of operational problems. APL, in conjunction with the Materials Science Department of The Johns Hopkins University, has recently become involved in a collaborative project with Hewlett-Packard concerning a possible contamination problem that limits the lifetime of the mercury lamp. The type of mercury lamp now being used becomes darkened within weeks or a few months of operation, requiring the entire device to be shut down for lamp replacement. Such a short lifetime is not acceptable for a time standard, and APL is now doing research on the problem.

SUPERCONDUCTING CAVITY STABILIZED OSCILLATOR

The superconducting cavity stabilized oscillator, shown in simplified form in Fig. 13, is a complex device that is based on the superconductivity of niobium at very low temperatures. It acts as a sharply tuned passive resonant circuit and is used as a frequency discriminator to provide a control signal to a Gunn oscillator. A 1-megahertz frequency modulation is imposed on the Gunn oscillator to scan the cavity resonance. By phase detecting the amplitude modulated signal reflected from the resonant cavity, a DC bias voltage is developed to control the Gunn oscillator frequency via a Varactor diode (whose capacity varies as function of bias voltage).

The oscillator, which is in the development stage (funded by NASA), offers potential as a very-high-stability device for short time intervals (Fig. 2). It would have applications in high-frequency requirements such as radar. Also, it is extremely sensitive to acceleration and may have potential use in gravity studies.

TIME AND FREQUENCY STANDARDS LABORATORY

Time and frequency have standards against which devices are compared. In reviewing Fig. 2 and referring to the section on measurement, it is logical that in some location(s) there should be an assembly of at least three[13] high-stability devices, operating continuously in constant environments, that could act as a standard against which other devices could be measured. There are several hierarchies within time and frequency standards laboratories, e.g., local, primary, and international. APL has a local Time and Frequency Standards Laboratory and is also part of the international time and frequency standard network.

The APL Time and Frequency Standards Laboratory has three commercial (Hewlett-Packard) cesium standards and two NASA research hydrogen masers (two more masers are being fabricated and tested). The devices are kept in constant operation in a temperature-controlled environment. Signals from the devices at 5 megahertz, 1 megahertz, 1 pulse per second, and IRIG-B (a time code signal) are distributed to various users throughout APL. The laboratory pro-

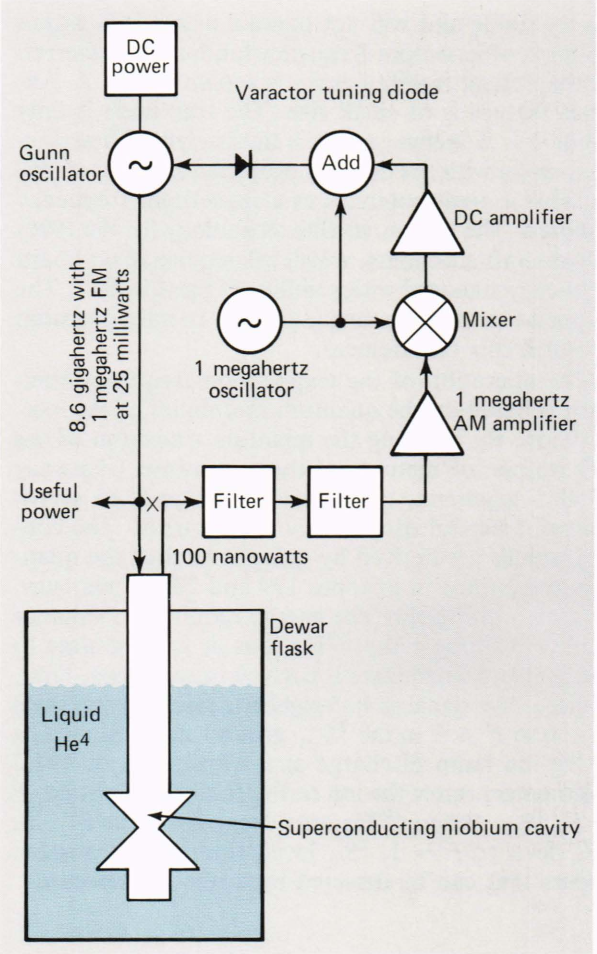


Figure 13—Simplified diagram of the superconducting cavity stabilized oscillator. A small signal is extracted from the niobium cavity, which is immersed in liquid helium at 1.4 kelvin. The signal is extremely stable because of the superconducting property of niobium. The signal is filtered, amplified, and mixed and then used to control a Gunn oscillator operating at 8.6 gigahertz. The Gunn oscillator provides the output signal for the device. That signal is used as the input signal to the cavity, thereby completing the loop.

vides signals with frequency stabilities down to 2 parts in 10^{15} at 1000 seconds (from the masers) and time stability of better than 1 nanosecond per day. Daily comparisons among all the frequency standards are made, and timing data are collected. In addition, a time transfer is performed each week during which APL standards are compared to the U.S. Naval Observatory's master clock via a portable cesium clock. This allows APL's standards to be compared to the U.S. Navy's standards. The link is also used to enter the performance of APL standards into the international standard determined by the Bureau Internationale de l'Heure in Paris. The Bureau uses the data from participating standards laboratories to form a large ensemble of clocks to derive Universal Time Coordinated, an international time scale, and to calibrate the definition of the second.[14] The performance of the APL cesium standards relative to Universal Time Coordinated as reported by the Bureau is shown in Fig. 14. The performance of one of the APL masers compared to Universal Time Coordinated is also shown, but those data were obtained by comparing the maser to one of the cesium clocks and extrapolating back to Universal Time Coordinated.

The world standard for time and frequency is based almost exclusively on cesium standards and, as such, is only accurate to parts in 10^{13}. Cesium was chosen as the standard because its fundamental frequency can be reproduced without reference to another frequency standard. Hydrogen masers have an operational effect (called the wall shift) that has not yet been quantified and does not allow the frequency to be reproduced with the same accuracy as that of the cesium clock. Studies are being carried out at APL on ways to operate its hydrogen masers as clocks.

One problem in establishing higher accuracy in international time standards lies in the area of transferring time from one facility to another with high enough resolution to take advantage of the stability of the frequency standards. Portable cesium clocks are usually only accurate to about 100 nanoseconds over international distances. Time transfers using the Global Positioning Satellite System are now being developed with accuracies as high as 10 to 30 nanoseconds. APL is fabricating receivers for use in satellite time-transfer techniques. As time transfers over large distances become more accurate, the international standards will be able to take advantage of higher stability devices.

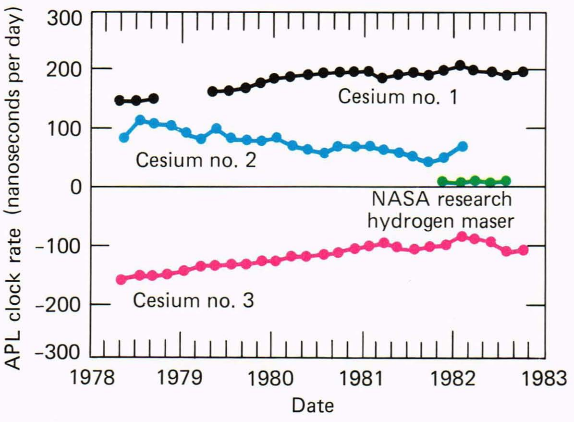


Figure 14—Rates of APL clocks relative to the Bureau Internationale de l'Heure world standard.

REFERENCES and NOTES

[1] There is a distinction to be made between time and frequency devices. Most timing devices, commonly referred to as clocks, are based on some type of periodic phenomenon such as that occurring in a frequency device. In a clock, the periodic phenomenon is tracked or counted, and the resulting timekeeping or clock accuracy depends on the stability of the periodic phenomenon. Therefore, timing devices are based on, and are special applications of, frequency devices.

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