Clock Technology

Stephen R. Cantor, The MITRE Corporation, 202 Burlington Rd. Bedford, MA, USA, 01730
Avinoam Stern, AccuBeat Ltd, 5 Ha'Marpeh St., Har-Hotzvim, Jerusalem, Israel 91184
Benny Levy, AccuBeat Ltd, 5 Ha'Marpeh St., Har-Hotzvim, Jerusalem, Israel 91184

BIOGRAPHIES

Stephen Cantor

Stephen Cantor received his BSEE degree from Tufts University, and his MSE degree from Johns Hopkins University. He completed all the work for a doctorate, except for a dissertation, at Johns Hopkins University. He held an Instructorship in the Department of Electrical Engineering at Johns Hopkins University, and an Instructorship in the Physical Sciences Department at Towson State College. He was a Member of the United States of America Delegation to the First Extraordinary Session of the Panel of Experts on Maritime Satellites of the Inter-Governmental Maritime Consultative Organization (IMCO) held in London, England. He was a Member of the United States of America Delegation to an Interim Meeting of the International Radio Consultative Committee (CCIR) held in Geneva Switzerland. He is an active member of the Technical Program Committee for the IEEE International Frequency Control Symposium. He is a Member of the Technical Staff at the MITRE Corporation, where he is responsible for the timing system portion of the terminal segment of a Satellite Communications System.

Avinoam Stern

Dr. Avinoam Stern received his B.Sc. degree (in Mathematics and Physics), his M.Sc. degree, and his Ph.D. degree from the Hebrew University, Jerusalem. His M.Sc. thesis was in Astrophysics, and his Ph.D. thesis was in Superconductivity. He was awarded a Chaim Weizmann Post Doctoral Scholarship, which he used at University of California-Santa Barbara for a Post Doctorate on the subject of the Free Electron Laser. Since 1986, he has been actively involved in the field of atomic clocks. He has worked at Frequency Electronics, Inc. (FEI) in New York; Time Frequency Ltd. (TFL) in Israel, where he was Vice-President for R&D; and, since 1994 has been serving as President of AccuBeat, Ltd., Israel, which manufactures rubidium oscillators and related instruments. He has published more than 20 papers, and holds several patents.

Benny Levy

Benny Levy received his Bachelor of Technology & Applied Sciences degree from Jerusalem College of Technology-Machon Lev in 1989, and his Practical Engineer degree from BTJ Institute-Jerusalem in 1980. Since 1980, he has been working on airborne integrated systems, including IFF, EW, radar systems, computer systems, and navigation systems. Since 1989, he has been involved in the field of accurate frequency and time systems. He has worked at Time Frequency Ltd. (TFL), Israel; and, since 1994, at AccuBeat Ltd, Israel, where he has been serving as the Vice-President. He has published several papers in the field of rubidium frequency standards, and he holds several patents. He developed a special method of accurate time transmission to airborne platforms.

ABSTRACT

This paper provides a description of the current technologies in the areas of quartz crystal oscillators (the basic uncompensated crystal oscillator (XO), the temperature compensated crystal oscillator (TCXO), the oven controlled crystal oscillator (OCXO), the microcomputer compensated crystal oscillator (MCXO)), and atomic frequency standards (cesium (Cs) beam frequency standard, rubidium (Rb) frequency standard, hydrogen maser frequency standard). A discussion of the Rb crystal oscillator is presented , as well as a discussion of GPS receivers as accurate frequency sources. The paper provides several examples of state-of-the-art oscillators, such as OCXOs, MCXOs, and Rb Frequency Standards. In particular, the paper describes a Rb Frequency Standard, manufactured by AccuBeat Ltd, which is the smallest known atomic oscillator (150 cc. in volume). That unit incorporates advanced techniques, whereby a microprocessor is embedded in a frequency lock loop; and, sophisticated software is used improve the frequency stability. Additionally, included in the paper is a description of emerging oscillator technologies which are currently under development. These new technologies include a miniature laser-pumped Cs cell atomic clock oscillator, a diode-laser-based low-power Rb frequency standard, and a Cs fountain. Finally, the paper provides information on major manufacturers of these devices.

1.0 INTRODUCTION

The purpose of this paper is to briefly review many of the common frequency sources that are being used for precision frequency and/or time control. The intention is to provide to the reader, who is not actively involved in this field, some insight into the principles of operation of several types of frequency sources (oscillators) and their levels of performance. A review of the current technology is provided along with a glance into future emerging technologies. It is to be emphasized that this review is not intended to be all inclusive. However, it is the hope of the authors that, within the limited framework of this paper, they will have covered the key technologies and issues. Additional and more comprehensive information can be found in some of the references cited at the end of the paper.

The various types of oscillators can be categorized into two groups: (1) Crystal Oscillators and (2) Atomic Frequency Standards. In the first group, the precise frequency is derived from a vibrating quartz crystal through the piezo-electric effect, which translates the mechanical vibration of a crystal into an electrical voltage at the resonant frequency. The vibration entity is a bulk of atoms, which are arranged in an array in a quartz ($Si0_2$) crystal.

In the second group, atomic frequency standards rely on individual free atoms (or ions) for precise frequency control.

1.1 Quartz Crystal Oscillators

Under the category of Quartz Crystal Oscillators are the Crystal Oscillator (XO), the Temperature Compensated Crystal Oscillator (TCXO), the Oven Controlled Crystal Oscillator (OCXO), and the Microcomputer Compensated Crystal Oscillator (MCXO).

1.2 Atomic Frequency Standards

Under the category of Atomic Frequency Standards are the Cesium-Beam Frequency Standard (Cs Std), the Rubidium Frequency Standard (Rb Std), and the Hydrogen Maser Frequency Standard.

1.3 Emerging Technologies

Under the category of Emerging Technologies, the authors describe the Ion Trap Frequency Standard, the Miniature Laser-Pumped Cesium Cell Atomic Clock Oscillator, the Diode-Laser-Based Low-Power Rubidium Frequency Standard, and the Cesium Fountain.

2.0 Influences on Oscillator Frequency

The following parameters have an influence on the frequency of an oscillator [1]:

- Time
  - Short term (noise)
  - Intermediate term (e.g., due to oven fluctuations)
  - Long term (aging)
- Temperature
  - Static frequency vs. temperature
  - Dynamic frequency vs. temperature (warmup, thermal shock)
  - Thermal history ("hysteresis", "retrace")
- Acceleration
  - Gravity (2g tipover)
  - Vibration
  - Acoustic noise
  - Shock
- Ionizing radiation
  - Steady state
  - Pulsed
  - Photons (X-rays, γ-rays)
  - Particles (neutrons, protons, electrons)
- Other
  - Power supply voltage
  - Atmospheric pressure (altitude)
  - Humidity
  - Magnetic field
  - Load impedance

Figure 1 is an idealized representation of the change in frequency versus time caused by several of the above disturbances.

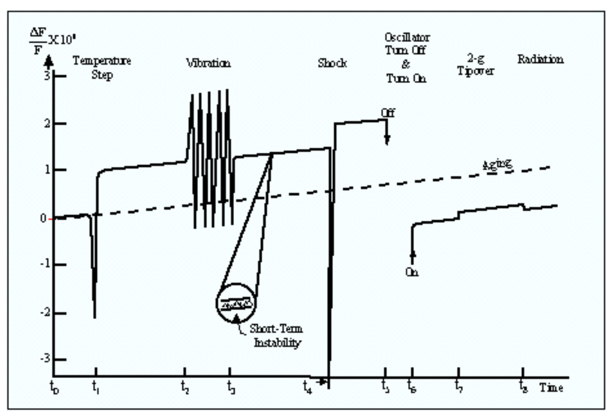

Fig. 1: Idealized Frequency-Time-Influence Behavior [1]

3.0 Crystal Oscillator Categories

An electronic oscillator is a device, which contains a resonance circuit (such as an LC circuit) connected in a loop with an amplifier-like circuit. The amplifier provides gain at the resonance frequency. Positive feedback is used to cause sustained oscillations to build up at the LC resonance frequency.
LC oscillators may attain stabilities of 0.01% (1×10^{-4}) over a reasonable period of time. For higher stabilities, the resonance circuit in the oscillator is replaced by a quartz crystal (i.e., a piece of $Si0_2$) which is usually cut and polished in the shape of a disk, deposited with electrodes, and held in a vacuum hermetic housing. Quartz is piezoelectric, meaning that a strain generates a voltage, and vice versa. Thus in a quartz crystal oscillator, the quartz can be modeled by a resonance RLC circuit, which is pre-tuned to some frequency. The quartz crystal's high Q (typically around 10^5 to 10^6) along with its good stability provide the crystal oscillator with stabilities between 100 parts per million (10^{-4}) to several parts per billion (10^{-9}).

Quartz crystals are categorized by their angle of cut relative to the crystal's atomic array. The most common cut for highly stable crystal oscillators is the AT-cut crystal. For higher grade crystal oscillators, the SC-cut is used.

The resonance frequency of quartz crystals is temperature dependent. Therefore, one attempts to compensate for changes in temperature by a variety of methods. The categorization of crystal oscillators is based upon the technique of compensating for the dependency of the crystal oscillator's frequency with temperature (f vs. T characteristic), and is as follows:

3.1 Crystal Oscillator (XO)

The basic crystal oscillator (XO) does <u>not</u> contain a means for compensating for the crystal's frequency dependency on temperature.

3.2 Temperature Compensated Crystal Oscillator (TCXO)

In the TCXO, the output signal from a temperature sensor (thermistor) is used to generate a correction voltage that is applied to a voltage-variable reactance (varactor) in the crystal oscillator's network. The reactance variations compensate for the crystal's frequency dependency on temperature. Analog TCXOs can provide about a 20 times improvement in the crystal's frequency dependency on temperature, i.e. they provide stabilities of 1 part per million (ppm) to 0.1 ppm (10^{-6} to 10^{-7}). One of the advantages of the TCXO is that it provides relatively high stability while consuming very low power (several milliwatts), which makes the TCXO very suitable for portable equipment (such as cellular phones).

3.3 Microcomputer Compensated Crystal Oscillator (MCXO)

An MCXO is a sophisticated version of a TCXO which provides better temperature stability and better aging characteristics, and still consumes low power. The MCXO incorporates two additional features which are not part of the conventional TCXO:

- The temperature of the crystal resonator is derived directly from the crystal itself by using a dual mode SC-cut crystal, which provides output signals at two frequencies: f_a and f_b. f_a is used for the output, and $\Delta f = (f_b - f_a)$ is used as a temperature indicator. In this way, one achieves a highly accurate indication of the temperature of the bulk crystal itself without the need for an external temperature measuring device.

- The frequency correction (compensation) is performed by synthesis of the output frequency by one of two methods. Either by: (1) <u>Pulse deletion</u> (which involves subtracting the required number of pulses from f_a to obtain the corrected output f_o); or by, (2) Use of a direct digital synthesizer (DDS) to generate a correction frequency df_a, which when added to f_a results in the compensated output frequency f_o. In this way, one avoids "pulling" the crystal's frequency and makes possible the use of a highly stable SC-cut crystal (which has a low pulling range compared with the less stable AT-cut crystal used in a conventional TCXO).

A simplified block diagram of an MCXO is shown in Figure 2. An MCXO achieves better temperature stability than a TCXO by a factor of 10 to 100 times. Stabilities of 10^{-8} to 10^{-9} have been achieved (compared to 10^{-6} to 10^{-7} for a TCXO). In addition, the use of an SC-cut crystal improves the aging to 10^{-7} to 10^{-8} per year.

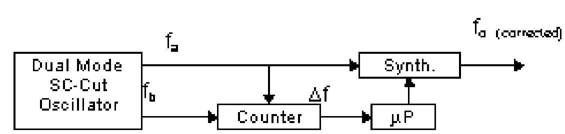

Figure 2: Simplified Block Diagram of an MCXO

3.4 Oven Controlled Crystal Oscillator (OCXO)

The OCXO is a crystal oscillator in which the crystal and other temperature sensitive components are in a stable oven, which is adjusted to the temperature where the crystal's f vs. T characteristic has zero slope. OCXOs can provide greater than a 1000 times improvement in the crystal's frequency dependency on temperature (i.e., they provide stabilities of 10^{-8} to 10^{-9} over the operating temperature range). Double-oven OCXOs provide even higher stabilities of 10^{-10} over the operating temperature range.

4.0 Atomic Frequency Standard

Atomic oscillators are based upon emission/absorption of electromagnetic (EM) radiation that occurs in individual free atoms. When an atomic system changes energy from an excited state to a lower energy state, a photon is emitted. The photon frequency ν is given by Planck's Law: $\nu = (E_2 - E_1)/h$, where E_2 and E_1 are the energies of the upper and lower states, respectively, and h is Planck's constant. An atomic frequency standard produces an output signal, the frequency of which is determined by this intrinsic frequency rather than some property of a bulk material (as in quartz oscillators). Atoms that are used are cesium, rubidium, and hydrogen, with transition frequencies of 9.2 GHz, 6.8 GHz, and 1.4 GHz, respectively. Lower output frequencies, typically 5 or 10 MHz, are realized by using either a frequency lock loop (FLL) or a phase lock loop (PLL) and several frequency divide circuits. The frequency of the crystal oscillator (around 5 MHz or 10 MHz) is multiplied, and either frequency locked or phase locked to the higher atomic frequencies.

The properties of isolated atoms in free space and at rest do not change with space and time. Under such conditions, the frequency of an ideal atomic frequency standard would not change with time or with changes in that environment. Unfortunately, in real atomic frequency standards: (1) the atoms are moving at thermal velocities in a random manner, (2) the atoms are not isolated, but experience collisions and electromagnetic fields; and, (3) some of the components needed for producing and observing the atomic transitions contribute to instabilities.

In an atomic frequency standard, as shown in Figure 3, a voltage controlled crystal oscillator (VCXO) is locked to the atomic resonator, which is a highly stable frequency reference generated from an atomic transition. Of the many atomic transitions available, the ones selected are from those which are least sensitive to environmental effects and which can be conveniently locked to the VCXO. The long term stability is determined by the atomic resonator. The short term stability is determined by the crystal oscillator.

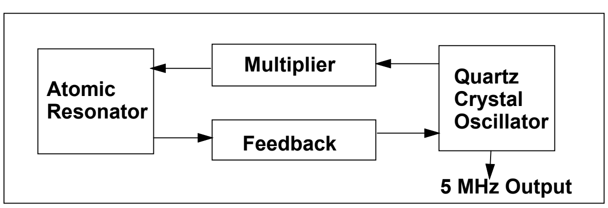

Figure 3: Block Diagram of an Atomic Freq. Std. [1]

A generalized atomic resonator is depicted in Figure 4. Suppose that A and B are two possible energy states of an atom, separated by $h\nu_0$. Then ν_0 is the frequency of the electromagnetic radiation required to convert the atoms from energy states A to B, or from B to A. ν_0 is in the microwave range for all currently manufactured atomic standards.

Under thermal equilibrium (above room temperature), the population in the two energy states is nearly equal. Therefore in a natural ensemble of atoms, during energy state transitions, about half the atoms absorb $h\nu_0$ and half emit $h\nu_0$; the net effect being zero. A nonthermal distribution is then prepared. That is, one of the states is "selected," either by optical excitation or by magnetic splitting of the atomic beam into two beams with the two states. Microwave energy is absorbed in the process of converting the selected atoms to the other energy state, e.g., from A to B. Thus, the applied microwave frequency (derived from the VCXO) can be "locked" to the frequency corresponding to the atomic transition.

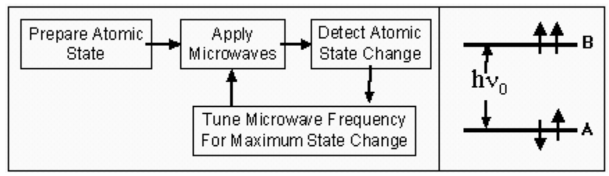

Figure 4: Generalized Atomic Resonator [1]

Magnetic shielding is used to reduce the effects of external magnetic fields (e.g., the earth's) by at least 100-fold.

The Heisenberg Uncertainty Principle limits the achievable accuracy: $\Delta E \Delta t \approx h$, and $E = h\nu$. Therefore, $\Delta\nu\Delta t \approx 1$. Thus, long observation times translate into small frequency uncertainties [1]. This means that the longer the time of interaction of the atoms with the electromagnetic radiation field, the sharper the transition and thus the more stable the frequency

Resonance linewidth (which is proportional to 1/Q) is inversely proportional to coherent observation time Δt. Δt is limited by: (1) when an atom enters and leaves the apparatus; and, (2) when the atom stops oscillating due to collisions with other atoms or with the container's walls (since collisions disturb the atom's electronic state).

Since atoms are in motion at various velocities, the resonance frequency is shifted due to the Doppler effect by an amount proportional to their velocity. Thus, the slower the atoms, the smaller the Doppler shift. Also, the velocity distribution of the atoms results in a "Doppler" broadening of the radiated spectrum. Since the velocity of the atoms in a gas are directly related to the gas temperature, the cooler the atoms the better the frequency stability.

Thus, in the quest to develop more stable frequency sources, one attempts to lengthen the interaction time, to isolate the atoms from external effects, and to cool the atoms as much as possible.

4.1 Cesium Frequency Standard

A general block diagram of the cesium frequency resonator (tube) is shown in Figure 5. This is a cesium beam apparatus, where a beam of cesium atoms is generated by an oven, then passes through a first state selector (A), then through a separated microwave cavity with two arms (a Ramsey Cavity), then through a second magnetic selector (B), and finally hits a detector.

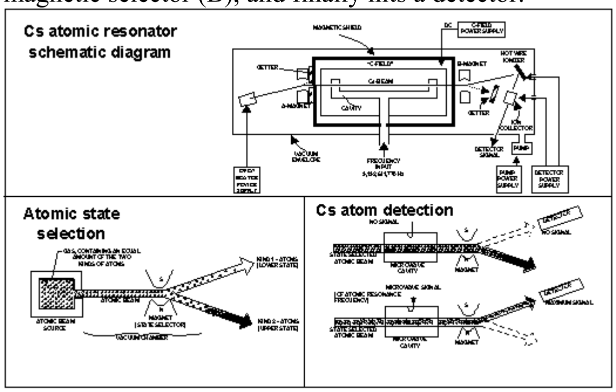

Fig. 5: Cs-Beam Freq. Std. General Block Diag. [1]

The atomic resonance frequency used is at 9,192,631,770 Hz (Note: The "second" is defined as 9,192,631,770 periods of that radiation). The temperature of the oven (the atomic beam source) is about 100°C, the pressure in the oven of the cesium gas is about 10^{-3} torr. The typical speed of the atoms in the beam is about 100 meters per second. The typical cavity length (between the two arms) in commercial cesium-beam frequency standards is 10 to 20 cm. The interaction time is about 1 to 2 milliseconds. The spectral linewidth is between 500 Hz and 1 KHz. The Q is about 10^7. For a laboratory standard, the length of the cavity is about 4 meters, and the Q is about 10^8.

The state selecting magnet A "selects" one of the two atomic levels. When the applied microwave frequency is equal to the Cs resonance frequency, it causes a state change. The second magnet B deflects the atoms (which have undergone the state change) to the detector. The peak fields of magnets A and B are about 10 Kgauss.

The atom detector is a ribbon or wire at a temperature of about 900°C. The cesium atoms are ionized, the ions are collected, the current is amplified, and fed back into the feedback network. When the frequency injected into the microwave cavity equals the cesium frequency, then one has a maximum ion current in the detector. Thus, the atomic transition frequency controls the microwave frequency, that is, the frequency of the crystal oscillator.

The Cs Frequency Standard is considered to be the primary standard for time and frequency. Cs standards provide very high accuracies of 10^{-12} to 10^{-14}.

4.2 Rubidium Frequency Standard

A general block diagram of a rubidium frequency resonator is shown in Figure 6.

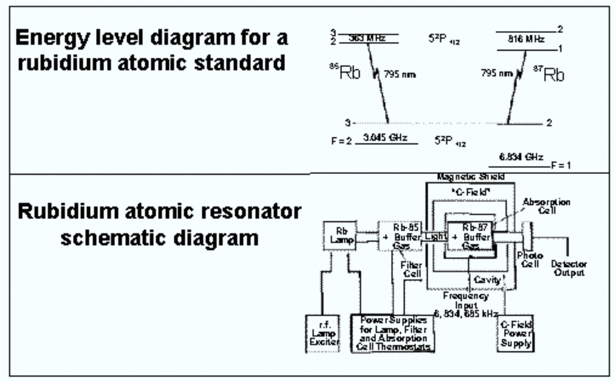

Fig. 6: Rb Frequency Std. General Block Diag. [1]

The atomic resonance frequency used is 6,834,682,608 Hz. The cell contains Rb gas at about 10^{-6} torr and an inert buffer gas at about 10 torr. The Rb atom's oscillation lifetime is limited by collisions to about 10^{-2} second. The linewidth is about 500 Hz. The Q is about 5 x 10^7. The buffer gas, a mixture of positive (e.g., N_2) and negative (e.g., Ar) pressure-shift gases, provides zero temperature coefficient at some temperature and confines the Rb atoms to a small region to reduce wall-collisions and first-order Doppler effects.

Optical pumping relies on the natural coincidence of optical resonance frequencies between ^{85}Rb and ^{87}Rb, both at a wavelength of 795 nanometers.

The RF excited ^{87}Rb lamp emits wavelengths corresponding to both the F=1 and F=2 transitions. The ^{85}Rb filter cell absorbs more of the F=2 transition light. Light which passes through the filter is absorbed by the ^{87}Rb F=1 state. Excited atoms relax to both the F=1 and F=2 states. However, the F=1 states are excited again. The F=2 state is overpopulated. The 6.8 GHz RF input signal converts the F=2 back to the F=1, which provides more atoms to absorb light. Microwave resonance causes increased light absorption, that is, a (< 1%) dip in the light detected by the photocell. Since the microwave frequency is locked to the photocell detection dip, the atomic transition frequency thus controls the microwave frequency, i.e., the frequency of the crystal oscillator.

The Rb Frequency Standard is considered to be a secondary standard, since it is less stable than a Cs Standard. It provides frequency stabilities of parts in

10^{-11} to 10^{-12} with respect to ambient temperature and with respect to time (aging). It is, however, much more compact (200 cc. to 400 cc.), consumes less power, and is less expensive compared to Cs and Hydrogen Maser Standards.

4.3 Hydrogen Maser Standard

A hydrogen maser is an atomic oscillator where hydrogen atoms are used as the oscillating media, with an atomic transition whose frequency is around 1420 MHz. As in the case of Cs and Rb, this transition is related to the hyperfine structure of the hydrogen atom and comes from the magnetic interaction between the nucleus spin and the electron. Figure 7 shows a schematic diagram of an active hydrogen maser.

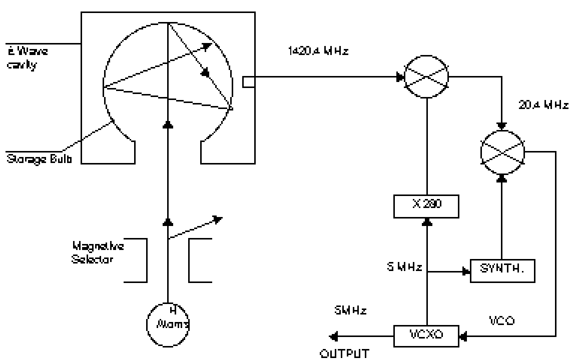

Figure 7: Active Hydrogen Maser Schematic

In a way, a hydrogen maser may be considered as an atomic beam apparatus, similar to the cesium-beam frequency standard, but with the following differences:

• In order to prolong the interaction time, and consequently narrow the linewidth and thereby increase the frequency stability, the following is done: After passing through a magnetic selector, the beam of hydrogen atoms is directed into a storage bulb where the atoms bounce back and forth. This prolongs the interaction time with the microwave field (to about 1 second), consequently narrowing the linewidth and thereby increasing the frequency stability.

• The storage bulb is located within a microwave cavity operating at the hydrogen frequency of 1420 MHz. The interaction of the hydrogen atoms with the microwave electromagnetic field <u>stimulates</u> transitions of the hydrogen atoms from their upper energy state to their lower energy state. This results in the <u>emission</u> of coherent radiation and the <u>amplification</u> of the microwave field in the cavity. Oscillations within the maser are self-sustained when the amount of energy thus generated is equal to the energy lost. This process is known as <u>M</u>icrowave <u>A</u>mplification by <u>S</u>timulated <u>E</u>mission of <u>R</u>adiation (hence the acronym MASER, similar to LASER, which is <u>L</u>ight <u>A</u>mplification by <u>S</u>imulated <u>E</u>mission of <u>R</u>adiation).

The hydrogen maser described above is an active device, in the sense that it provides output electromagnetic radiation at 1420 MHz. That radiation is used to phase lock a crystal oscillator at a lower frequency, such as 5 MHz, as shown on the right side of Figure 7. Hydrogen masers provide excellent stabilities, of the order of parts in 10^{-14} long term, and 10^{-15} medium term, which is better than all other commercial frequency standards. However, it is rather large and is very expensive.

5.0 THE RUBIDIUM-CRYSTAL OSCILLATOR (RbXO)

The RbXO provides the best of both worlds: The long term stability of a Rb standard and the low power requirement of a crystal oscillator [1]. An RbXO consists of: (1) A Rb reference, which is a miniature Rb frequency standard (RFS) that is modified to control an external crystal oscillator; and, (2) an OCXO which includes a digital tuning memory to hold the frequency control voltage while the Rb reference is off. Periodically, the system applies power to the RFS. After warm-up of the RFS (a few minutes), the interface circuits adjust the frequency of the OCXO to that of the RFS, and then shuts off the RFS. For manpack applications, the OCXO can be separated from the rest of the RbXO so that the manpack can operate with minimum size and weight, along with nearly the accuracy of the RFS for the duration of the mission. An MCXO can replace the OCXO for even lower power consumption. Occasionally, power is applied to the Rb Std for a few minutes. Upon warm-up of the Rb Std, the RbXO interface syntonizes the crystal oscillator and cuts off power to the Rb Std.

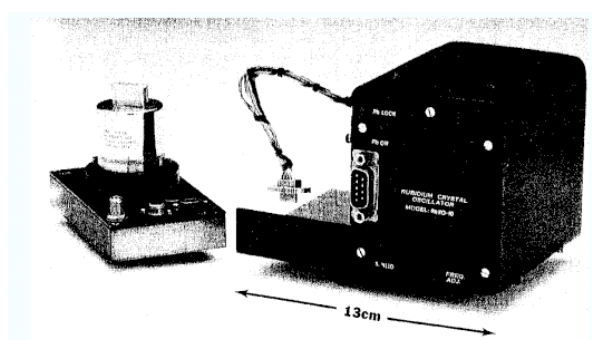

Figure 8: Rubidium Crystal Oscillator [1]

6.0 GPS RECEIVERS AS ACCURATE FREQUENCY SOURCES

A GPS receiver outputs four-dimensional data, which are comprised of location (position) and time. Part of the time signal is a 1 pulse per second (1 pps) signal that may be considered to be an accurate 1 Hz frequency source. The short term stability of the 1 pps is not very good due to its relatively high jitter. For example, a jitter of 100 nanoseconds translates into a short-term stability of 1 x 10^{-7} at an averaging time of 1 second, which is rather poor. However, in the long term, the stability of the 1 pps tracks the excellent stability of the GPS system (which is comprised of atomic clocks located aboard satellites and in ground stations). Thus, one may use a stable "local" oscillator, lock it via a phase lock loop (PLL) to the 1 pps signal coming from the GPS receiver, and then combine the local oscillator (which has good short term stability) with the excellent long term stability of the GPS receiver.

Sophisticated algorithms are being employed in the PLL to ensure that the local oscillator will continue to provide accurate frequency and time, even if GPS reception is lost. This is known as "the holdover mode."

By the integration of either a high performance OCXO or a Rb oscillator into their GPS receiver system, various manufacturers (such as Hewlett Packard, Datum, Odetics, True Time, Quartzlock) have been able to achieve stabilities of 1 x 10^{-12} both in the short term (hours), and in the long term (days, months).

7.0 STATE-OF-THE-ART OSCILLATORS

This section provides some examples of state-of-the-art oscillators.

7.1 Very Small, Digital Rubidium Frequency Standard: AccuBeat Model AR-40A/60A

AccuBeat produces Rubidium Frequency Standards (RFS), models AR-40A and the AR-60A. Both models are based upon the same core design. The AR-40A (shown in Figure 9), with dimensions of 77 x 57 x 35.6 mm is the smallest RFS available in the world today, and is intended for commercial applications. The AR-60A (77 x 77 x 39.6 mm) is designed to meet harsh environments, a wide temperature operating range, operation under shock, vibration, and moisture [4].

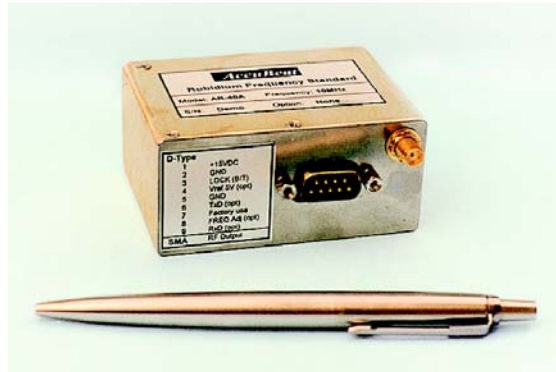

Figure 9: Rb Frequency Standard, Model AR-40A

The following is a summary of some of the key performance parameters of the AR-40A/AR-60A:

- Output Frequency: 10 MHz, sinewave
- Long Term Stability (Aging): 5 x 10^{-10}/yr.
- Phase Noise: -100 dBc/Hz @ 10 Hz
  -130 dBc/Hz @ 100 Hz
  -150 dBc/Hz @ 1 KHz
- Harmonics: -40 dBc
- Spurious: - 90 dBc, $\pm$ 1.5 MHz from carrier
- Warm-up: 5 minutes to 5 x 10^{-10}
- Supply: 15 Vdc/0.6A @ steady state
- Stability/Temp: $\pm$2 x 10^{-10}/(-20°C to +75°C) (AR-60A)
- Dimensions: 77 x 57 x 35.6 mm (AR-40A)
- Weight: 250 grams (AR-40A)
- Holdover Mode: When lock is lost due to an atomic resonator failure, the internal OCXO continues to provide an output frequency with the last saved frequency and with the good stability of the OCXO

In the conventional design of a RFS [2], one locks a crystal oscillator at 10 MHz to the rubidium hyperfine transition frequency at 6.8 GHz via a Frequency Lock Loop (FLL). The AR-40A/60A, however, utilize a more advanced scheme where a microprocessor and a direct digital synthesizer (DDS) are embedded in the FLL as shown in Figure 10, which makes the FLL into a digital loop.

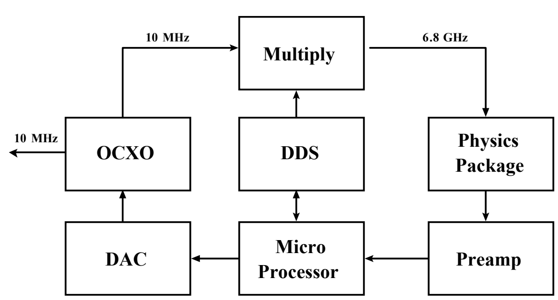

Figure 10: AR-60A FLL Approach

The scheme used for the software in the microprocessor (pending patent applications) transforms the RFS into a smart clock, improves the sensitivity to external disturbances, and allows for the holdover mode described above. The microprocessor also takes care of many functions, which in the conventional design requires many components.

7.2 High Stability MCXO

The Q-Tech Corporation has been developing microcomputer compensated crystal oscillators (MCXOs) for more than 10 years. Recently, they introduced their latest MCXO, Model QT2002, in a 1.5 x 1.5 x 0.5 inch (38 x 38 x 13 mm) package [5]. This new product features: (1) A stability of $\pm$ 1.5 x 10^{-8} over a temperature range of -55°C to + 85°C; (2) Aging of a few parts in 10^{-10} per day; and (3) A very low power consumption of 80 milliwatts.

7.3 Double Oven OCXO

The use of the double oven technique (of inserting one oven inside another) has been around for a number of years. Recently, several manufacturers, such as MTI, have been able to perfect this technique so as to produce a very small unit (51 x 51 x 38 mm) with a stability of 2 x 10^{-10} over a temperature range of -30°C to + 70°C, and an aging of a 5 x 10^{-11} per day.

7.5 High Operating Temperature Rubidium Oscillator

By employing a thermoelectric cooler to maintain the Rb absorption element at an acceptable temperature (at the high temperature end), Frequency Electronics Inc. (FEI) has been able to produce a Rb oscillator operating over a very wide temperature range of -54°C to + 95°C [6].

7.6 Rubidium Oscillator With Stability Of 10^{-14}

The addition of filtering to the pumping light of the Rb has enabled EG&G to build a Rb oscillator which exhibits a superb short term stability of better than 1 x 10^{-12} at 1 second, and 1 x 10^{-14} at a 1000 second averaging time [7]. This stability approaches the stability of a hydrogen maser and the best of the Cs beam standards.

8.0 OSCILLATOR COMPARISON

Table 1 provides a comparison of some of the oscillator types previously described

	Quartz Oscillators				Atomic Oscillators			
	TCXO	**MCXO**	**OCXO**	**Double Oven OCXO**	**Rubidium**	**RbXO**	**Cesium**	**H Maser**
Accuracy per Year	2 x 10^{-6}	5 x 10^{-6}	1 x 10^{-8}	1 x 10^{-8}	5 x 10^{-10}	7 x 10^{-10}	1-2 x10^{-11}	1 x10^{-12}
Aging/Year	5 x 10^{-12}	2 x 10^{-8}	5 x 10^{-10}	2 x 20^{-8}	2 x 10^{-10}	2 x 10^{-10}	0	1 x10^{-12}
Temp. Stab. (range, °C)	5 x 10^{-7} (-55/+85)	3 x 10^{-8} (-55/+85)	1 x 10^{-9} (-55/+85)	2 x 10^{-10} (-30/+70)	3 x 10^{-10} (-55/+68)	5 x 10^{-10} (-55/+85)	1-2 x 10^{-11} (-28/+65)	
Stability, $\sigma_y(\tau)$, τ **= 1s**	1 x 10^{-9}	3 x 10^{-10}	1 x 10^{-12}	1-2 x 10^{-12}	5 x 10^{-12}	5 x 10^{-12}	5 x 10^{-11}	1x10^{-12}-1x10^{-13}
Size (cm^3)	10	30	20-200	100	150-400	1000	6000	70000
Warmup Time (min)	0.1 (to 1x10^{-6})	0.1 (to 2x10^{-8})	4 (to 1x10^{-8})	8 (to 1x10^{-8})	3 (to 5x10^{-10})	3 (to 5x10^{-10})	20 (to 1x10^{-11})	10 hrs to lock
Power (W)	0.04	0.04	0.6	2-3	8-12	0.65	30	140
Price (~$)	10-100	1K	200-2K	500	1K-5K	<10K	30K-60K	60K-100K

Table 1: Oscillator Comparison [1]

9.0 EMERGING NEW TECHNOLOGIES

This section describes some new technologies which may provide higher stabilities.

9.1 Ion Trap Frequency Standard

One way to increase the interaction time of the atoms with the interrogation electromagnetic field is to use charged atoms (ions), and to store them for a very long time inside an electromagnetic trap. The trap either utilizes static magnetic and electric fields (Penning Trap) or the trap uses DC plus an RF electric field (Paul Trap) in order to confine the ions to a limited region of space.

An illustration of a typical Paul Trap is shown in Figure 11.

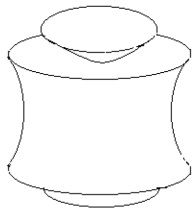

Figure 11: Paul Trap

Ions used in this method are Ba^+, Yb^+, and Hg^+. The method used to excite and detect the transition between the ion energy levels is an optical pumping scheme, which is similar to that used in a Rb frequency standard. For example, in a Hg^+ ion trap frequency standard, a $^{202}Hg^+$ lamp is used to pump $^{199}Hg^+$ ions in a Paul Trap. At the same time, 40 GHz microwave radiation, synthesized from a 5 MHz quartz oscillator, is used to excite transitions between lower levels. This process causes a change in the light absorption, as well as a change in the fluorescent light emitted by the ions. These changes are detected by a photo detector whose output is used to lock the quartz oscillator to the ion transition.

The main cause of instabilities in ion trap frequency standards originates from the Doppler shift due to the motion of the ions in the trap. Laser cooling techniques are used to slow down the ions and minimize the Doppler shift.

9.2 Miniature Optically (Laser) Pumped Cesium Standard

The miniature optically (laser) pumped Cs standard is a DARPA sponsored development with Northrop Grumman. The proper energy levels are populated by optically pumping with a diode laser, which provides superior utilization of the Cs atoms. The program goals are:

- An accuracy of 1×10^{-11} (about 100 times better than a rubidium standard)
  - Volume: 25 cm^3
  - Power required: 300 milliwatts (0°C to +50°C)
  - Operational temperature range: -50°C to +50°C

9.3 Diode-Laser-Based Low-Power Rubidium Frequency Standard

The diode-laser-based low-power Rb standard is a U.S. Army Communications-Electronics Command (CECOM) sponsored development with NIST. It uses Raman Scattering (scattering of diode laser light in a Rb vapor cell. In this technique, no microwave cavity is required and the photodiode produces an output frequency in the GHz range. This frequency is then divided and synthesized to obtain the output frequency of the device in the MHz range. Hence, no crystal oscillators are required. (Note: A Rb frequency standard normally contains both a Rb cell and a VCXO). This results in: (1) a Rb Std with potentially much lower acceleration sensitivity; and, (2) potentially a smaller size and lower power (1 watt) Rb Std. The program goals for the Raman Frequency Reference are:

- Size: 2.5 cm x 2.5 cm x 6 cm, using off-the-shelf components
- Volume: 25 cm^3
- Input power: 1 watt DC
- Initial temperature range: 0°C to +50°C

9.4 Atomic Fountain Standard

Shown in Figure 12 below is a picture of a water fountain, located in Lausanne, Switzerland. The principal of operation of the Cs fountain is analogous to that of a water fountain, as described in the following paragraphs:

In a Cs Standard, the atomic beam passes through two microwave regions defined by a Ramsey Cavity (Section 4.1). The linewidth is determined by the reciprocal of the time of flight between these two regions. In an Atomic Fountain Standard, the atoms are “thrown” upward against gravity while passing through a single microwave cavity region. Then, the atoms fall back down again and pass through the same cavity. The linewidth is proportional to the time it takes for the atoms to go up and come down. In order to construct a Fountain Standard, one needs to have very slowly moving atoms. To obtain those slowly moving atoms, one uses laser cooling. By irradiating a gas of atoms with lasers, it is possible to slow down the atoms which are moving in a direction opposite to that of the laser radiation, thus reducing the temperature of the gas (and hence the speed of the atoms).

Atomic Fountain Frequency standards have been built using both Cs atoms and Rb atoms. The following is a description of the operation of the Cs fountain built at the National Institute of Standards and Technology (NIST): Six laser diodes (3 pairs in the mutually perpendicular directions) are used. The Cs atoms are cooled to very, very low temperatures (°µK). The Cs atoms are “tossed up” by the beat frequency of one of the pairs of lasers in a 1 meter high cavity. The cooled atoms fall very slowly (0.5 to 1 second) due to gravity, which allows longer interaction times and hence greater accuracy. Note, the Cs atoms go up and down through the same opening in the cavity. The accuracy of the Cs fountains are projected to be 10 to 100 times better than that of the traditional Cs beam tube. An application of the Cs fountain is for use in the U.S. NIST-7 Primary Frequency Standard.

Figure 12: Fountain: Lausanne, Switzerland

10.0 MAJOR MANUFACTURERS

10.1 Crystal Oscillators (XO, TCXO, OCXO)

Some of the major manufactures for crystal oscillators (XO, TCXO, OCXO) are: Vectron (USA), Piezo Technology (USA), Hewlett-Packard (USA), FEI (USA), Raltron (USA), MTI (USA), Oak Frequency Control (USA), ISOTEMP, KVARZ Institute of Electronic Measurements (Russia), KVG (Germany), Tele Quartz (Germany), C-MAC (U.K.), CQE (France), CEPE (France), Tekelec (France), Oscilloquartz (Switzerland), Fordahl (Switzerland), Toyocom (Japan), Tech Time (Israel), and others.

10.2 Microcomputer Compensated Crystal Oscillators (MCXO)

Major manufactures of MCXOs include FEI, Q-Tech, and Rockwell/Cedar Rapids.

10.3 Cesium Beam Frequency Standard

Major manufactures of the Cs beam frequency standard include Datum-Frequency Time Systems (FTS), Hewlett-Packard, FEI, and the Russian Institute for Radionavigation and Time (RINT).

10.4 Rubidium Frequency Standard (RFS)

Major manufactures for the Rb frequency standard include EG&G, Datum-Efratom, Datum-Frequency Time Systems, FEI, AccuBeat (an Israeli company), and Tekelec Neuchatel time (a Swiss company).

10.5 Hydrogen Maser

Major manufactures of the hydrogen maser include Datum-Frequency Time Systems (the Sigma Tau division), Harvard Smithsonian Center for Astrophysics, and the KVARZ Institute of Electronic Measurements (a Russian company).

10.6 Rubidium Crystal Oscillator (RbXO)

Potential manufactures for the Rb crystal oscillator (RbXO), if a market develops for them, would be EG&G along with other companies.

10.7 Miniature Laser-Pumped Cesium Cell

A potential manufacturer for the miniature laser-pumped Cs cell is Northrop-Grumman.

10.8 Diode-Laser-Based Low-Power Rubidium Standard

The diode-laser-based low-power rubidium standard is currently under development by the National Institute of Standards and Technology (NIST). Potential manufacturers are unknown at this time.

10.9 Cesium Fountain

There are currently Cs fountain development programs being conducted by the USA (NIST), Canada, France, and China.. Potential manufacturers are unknown at this time.

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DISCLAIMER

The views and opinions expressed in this paper by Stephen R. Cantor are strictly his own, and do not reflect those of the MITRE Corporation.

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