

An Introduction to Frequency Standards

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Invited Paper

Quartz oscillators, and rubidium, cesium, and hydrogen atomic frequency standards are described in terms of the physics of operation. Sources of frequency instability and inaccuracy are given. This review should serve as an introduction to the practical aspects of these high performance frequency standards, and guide the reader in selecting devices for particular applications.

INTRODUCTION

In this paper, the author will review the physical principles of the most widely used atomic frequency standards. For completeness, he will include a brief description of high performance quartz crystal standards. Advanced atomic ion frequency standards and laser cooling of neutral atoms are covered in other papers in this issue. The author's intention is to provide a basis for characterization of the more practical aspects of commercially available frequency standards, and to present a comparison of such standards which may be useful in selecting devices for various applications.

While the specifications given here are based upon manufacturer's published literature, users may find particular devices with performance better or worse than that described in this review. The specifications should be interpreted as a general indicator of the properties of various classes of devices. Emphasis of this discussion is on stability performance of precision frequency standards, but some discussion is also given of other physical characteristics and cost considerations.

Figure 1 shows the stabilities of various commercial and laboratory frequency standards. The ordinate axis is the Allan variance, and the abscissa is the time interval of a given frequency measurement. Any point on each graph may be approximately interpreted as the fractional frequency stability of that standard for a given measurement interval. The stability of a standard can generally be identified with physical processes which generate noise and limit signal size. For example, most of the standards in Fig. 1 have frequency stabilities which decrease as the square-

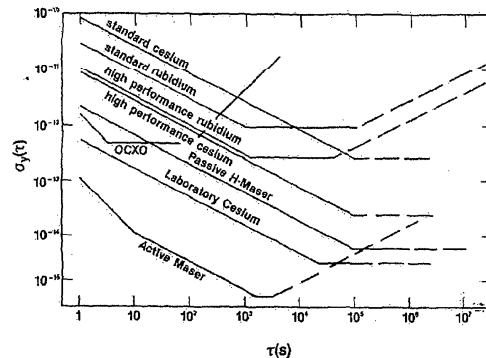


Fig. 1. Fractional frequency stability of several precision commercial and laboratory frequency standards.

root of the measurement interval for short intervals. This behavior occurs because the noise process is dominated by the statistics of counting quantum transitions, which varies as the square-root of the number of transitions. Details of both noise and signal processes for the various standards are given below.

In general, Fig. 1 illustrates that the short term ($\tau < 10$ s) frequency performance improves with device type in the order of rubidium, cesium, hydrogen maser, and quartz oscillator. The long term ($\tau > 100$ s) stability improves in the order of quartz oscillator, rubidium, cesium, and hydrogen maser. The frequency errors associated with laboratory cesium standards are bounded by the accuracy limits of the device and, therefore, the long-term instabilities of such instruments are independent of measurement interval.

Table 1 gives a summary of stability specifications for several types of crystal oscillators and commercial atomic frequency standards, as discussed in the text. Some values for resistor-capacitor oscillators (RCO) and inductor-capacitor oscillators (LCO) are included for comparison. Table 2 gives additional information on physical characteristics of precision frequency standards.

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Table 1 Commercial Device Performance¹

Device	Stability			Temperature Dependence	Lifetime	Comments
	@ 1 s	@ 1 day	@ 1 year			
RCO				1×10^{-3} (0°C to +50°C)		
LCO		2×10^{-4}	2×10^{-2}	3×10^{-3} (-40°C to +70°C)		10% tuning range
XO		1×10^{-10}	2×10^{-6}	$1 \times 10^{-7}/^{\circ}\text{C}$ to	3-20 years	1×10^{-6} tolerance possible
		to 2×10^{-7}	to 1×10^{-5}	$5 \times 10^{-6}/^{\circ}\text{C}$		
TCXO		1×10^{-9}	1×10^{-6}	1×10^{-7} to 2×10^{-6} (0° to +50°C)	>5 years	Lifetime often limited by tuning
DCXO	2×10^{-10}	1×10^{-9}	1×10^{-6}	5×10^{-8} (0° to +70°C)		
MCXO				2×10^{-8} (-55 to +85°C)		
VCO				1×10^{-4} to 1×10^{-6} (0°C to +50°C)		Tuning range 1×10^{-2} to 5×10^{-5}
OCXO	5×10^{-12}	5×10^{-10}	5×10^{-8}	$1 \times 10^{-10}/^{\circ}\text{C}$ to		Usually single oven,
		to 5×10^{-10}	to 1×10^{-6}	$1 \times 10^{-9}/^{\circ}\text{C}$		proportional control
OXCO	5×10^{-13}	$2 \times 10^{-11}/^{\circ}\text{C}$			10-20	Usually double oven
	to 5×10^{-11}	to $1 \times 10^{-10}/^{\circ}\text{C}$			years	Warm-up time of hours
STD	5×10^{-11}					
OCXO-SC	5×10^{-14}					
Rb	5×10^{-12}		Drift of parts	4×10^{-11} to 2×10^{-10}		
	to 3×10^{-11}	1×10^{-13}	in 10^{-10} / year	(0°C to +50°C)	>5 years	Warm-up time of minutes
Cs	5×10^{-12}	2×10^{-13}		5×10^{-12}	to 5 years	Accuracy of $\pm 4 \times 10^{-12}$ to $\pm 3 \times 10^{-11}$
	to 6×10^{-11}	to 3×10^{-14}	3×10^{-12}	(0°C to +50°C)		
H(Passive)	2×10^{-12}	1×10^{-14}	$< 1 \times 10^{-12}$	$5 \times 10^{-14}/^{\circ}\text{C}$		

¹Based upon manufacturers' published literature.

Table 2 Typical Physical Characteristics of Precision Frequency Standards

Device	Volume (cm ³)	Weight (kg)	Nominal Power (Watts)	Cost (K\$)
OCXO	36	.04	.45	
OCXO-STD	1×10^3	1	2 to 5	1.5 to 8.7
Rb	395 to 24,000	.55 to 15.4	10 to 35	4 to 38
Cs	4×10^4	20 to 30	30 to 100	25 to 46
H(Passive)	1×10^5	~ 35 kg	< 70	—

II. CRYSTAL OSCILLATORS

The equivalent circuit for a quartz crystal [1]-[3] is given in Fig. 2. The resonance frequencies of the crystal are determined by the values of L and C_1 , which in turn are dependent upon the physical characteristics of the crystal. The inductance L depends upon the mass of the crystal, and the capacitance C_1 is associated with its stiffness. C_0 is the shunt capacitance presented by the electrodes and crystal holder. The Q of the crystal is given by $\omega L/R$, where ω is the crystal frequency and R is a damping resistance associated with losses in the quartz and mounting arrangement. The losses in quartz are quite small, resulting in Q values of about 10^5 , and often Q values of more than 2×10^6 . This high Q is the source of the good short term stability of crystal oscillators (XO's). The crystal is placed in the feedback network of an amplifier; the circuit

oscillates at a frequency where the loop gain is equal to one and the phase shift around the loop is 0 or 360 deg. Because of the high Q of the quartz, the phase shift due to the crystal changes rapidly with frequency, resulting in a narrow frequency range for oscillation, and consequently good frequency stability. XO's are unexcelled for noise performance in the 1-100-MHz range, for times less than 1 s. Their low cost, a few dollars for the low stability oscillators used in digital circuitry, to a few thousand dollars for the finest high stability temperature controlled devices, make crystal oscillators particularly attractive for many applications. The main disadvantages of XO's are the temperature dependence ($\sim 1 \times 10^{-6}/^{\circ}\text{C}$) and the large aging rate (as big as $10^{-7}/\text{day}$). The latter problem can be alleviated by use of improved clean room techniques and careful attention to crystal mounts and housings, resulting

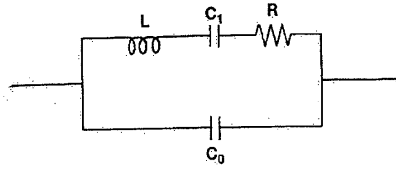


Fig. 2. Equivalent circuit of a quartz crystal.

in aging rates as small as 2×10^{-11} /day, and prices 2–3 orders of magnitude greater.

The other problem of temperature sensitivity is approached by temperature compensation or by temperature control. A temperature compensated crystal oscillator (TCXO) usually uses temperature dependent components external to the resonator in order to closely cancel the temperature related frequency shifts of the XO. This can result in an oscillator which holds frequency to 1×10^{-7} over a 50°C temperature range. The temperature dependence of a TCXO is usually quoted as a maximum change over a temperature range, instead of a coefficient, since the slope may vary considerably over the temperature range of interest.

A more stable device is the digitally compensated crystal oscillator (DCXO). Like the TCXO, the DCXO corrects the oscillator frequency for temperature dependent shifts, but instead of a simple varactor, for example, it uses a thermister to measure the temperature, and an *A* to *D* converter coupled with a look up table in order to determine the appropriate frequency correction. The advantage of this method is that not only is the compensation tighter (5×10^{-8} over 70°C), but the look up table can be written on EPROM, permitting the user to change the table as the oscillator ages.

Recently, a microcomputer compensated crystal oscillator (MCXO) has been proposed [4] and tested at the U.S. Army Electronics Technology and Devices Laboratory (LABCOM) [5]. This oscillator uses a dual mode oscillator, where the fundamental frequency of an SC cut quartz crystal is compared with the third harmonic frequency of the same crystal. These two frequencies shift differently with temperature, which thereby gives a measure of the effective temperature of the crystal. The frequency of the crystal is compensated by means of a microcomputer which applies a sixth-order polynomial fit to the temperature dependence. This method has the advantage that the temperature of the crystal is measured by the crystal itself, so that there is no time lag nor thermal gradient. Temperature dependent shifts of less than 2×10^{-8} over a temperature range of -55 – $+85^\circ\text{C}$ have been measured for the MCXO. It is believed that shifts as small as 1×10^{-9} are possible in the near future by refining this technique.

Still greater stability under temperature changes can be had by using one or more ovens about the crystal oscillator in order to control the temperature. Generally, two levels of sophistication exist commercially for oven-controlled crystal oscillators (OCXO's). The first level utilizes a single

proportional control oven and gives a temperature coefficient of $10^{-9}/^\circ\text{C}$ – $10^{-10}/^\circ\text{C}$. The second level of stability (and expense) often employs a double oven system. It can result in temperature coefficients as small as $1 \times 10^{-11}/^\circ\text{C}$.

Another recent improvement in the performance of high quality quartz crystal oscillators comes from the use of fifth-overtone SC cut resonators [6]. Measurements at NIST (National Institute of Science and Technology) indicate that stabilities of 6×10^{-14} are possible for this oscillator for times of 20 ms to several days, in a laboratory environment.

Even with the temperature control provided by its ovens, the OCXO suffers from frequency aging and instabilities due to environmental perturbations. An aging rate of 2×10^{-11} /day is exceptionally good in a commercial device. Frequency dependence upon acceleration is as large as $10^{-8}/g$ (and as small as $2 \times 10^{-10}/g$ for special cuts). This means then that turning a crystal oscillator over can produce 10^{-8} changes in frequency.

III. ATOMIC FREQUENCY STANDARDS

At some point, the need for long-term stability under changing environmental conditions requires one to abandon the low cost, small size, and low power consumption of crystal oscillators for the long-term stability performance of atomic frequency standards. Commercially available atomic frequency standards are passive devices [7]. That is, they extract information from an atomic resonance line by interrogating the resonance instead of using the atoms as a self-oscillating source. The notable exception to this comment is the active hydrogen maser, which derives an output signal from a microwave oscillation in an atomic hydrogen medium. Figure 3 is a diagram of the process employed in all passive atomic standards. Atoms are first prepared in a nonthermal distribution between two quantum mechanical energy states. This is represented by Fig. 4(b), where states *A* and *B* are two possible energy levels of the atom, usually the ground state hyperfine splitting in an alkali atom. For purposes of discussion, let us say that the atoms are prepared in state *B*, although the process can also work if the atoms are prepared in state *A*. The energy difference between the states is equal to $h\nu_0$, where *h* is Planck's constant, and ν_0 is the frequency of the electromagnetic radiation required to convert the atoms from state *A* to state *B* (or from state *B* to state *A*). In the commercial frequency standards ν_0 is usually several gigahertz. After state preparation, microwave radiation of frequency ν_0 is applied to the atoms in order to change some of the atoms back from state *B* to state *A* (see Fig. 3). This state change is detected by monitoring the number of atoms in state *A*. The detected signal is the maximum when the microwave frequency is tuned to the value which produces the maximum number of atomic state changes to state *A*. The standard's servo-electronics automatically adjusts the microwave frequency to this setting. Thus the stability and accuracy of the device are determined by intrinsic properties of the electronic and nuclear structure of the atom, not by bulk properties as is the case in the quartz oscillator.

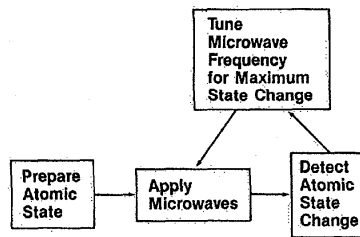


Fig. 3. Logical diagram of a passive atomic frequency standard

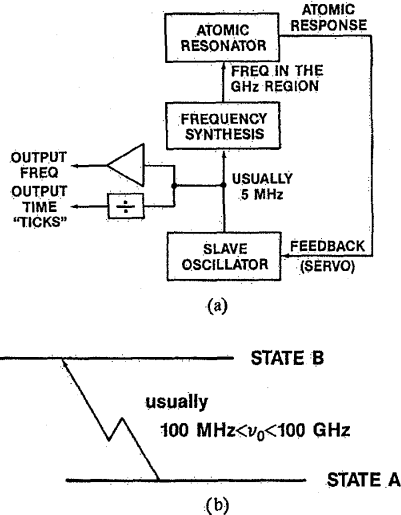


Fig. 4. (a) Block diagram of the electronics for a passive atomic frequency standard. (b) Energy levels of an atomic frequency standard.

Consequently, the frequency of an atomic standard is highly reproducible, varying only according to perturbations which affect the electronic states of the atom, as will be discussed below with each specific atomic standard.

A block diagram of the usual method of locking a useful reference frequency to the atomic resonance is shown in Fig. 4(a). The slave oscillator in this diagram is usually a 5- or 10-MHz quartz oscillator which has excellent short term stability (see Fig. 1). The microwave signal which interrogates the atoms is generated from this low frequency source by a combination of frequency multipliers and direct frequency synthesis, so that the ratio of the microwave frequency to the slave oscillator frequency is a known constant. Generally, the microwave frequency is modulated at an audio frequency, producing a concomitant modulation of the atomic signal. Phase sensitive detection of the atomic signal is used to adjust the quartz oscillator frequency to produce a maximum atomic response. The quartz oscillator output is used as the standard's output. In this way, the good short-term stability of the quartz oscillator is combined with the excellent long-term stability of the atomic resonance. Other approaches to the electronic servo are used, but they all have the same basic structure, locking a low frequency quartz oscillator to the atomic resonance, whether the

standard is a rubidium standard, a cesium beam standard, or a passive hydrogen maser.

In Fig. 1, for $\tau < 1000$ s, the atomic signal is directly proportional to the number of atoms which make the transition from state B to state A . The noise on the atomic signal is proportional to the square-root of the number of atoms which make the transition. Consequently, it follows [7] that the stability in this region is given by

$$\sigma_y(\tau) = k\tau^{-1/2}/Q(S/N)^{1/2} \quad (1)$$

where Q is the Q -factor of the atomic resonance (resonance frequency divided by atomic linewidth), S is the detected atomic signal power, N is the noise power per unit bandwidth, and k is a factor which depends upon the atomic lineshape and specific modulation method. Typical values for k lie between 0.1 and 0.5.

For both the OCXO and the active hydrogen maser, at times $\tau < 10$ s, the noise is limited by phase noise, which is independent of atomic signal. The fractional frequency instability is proportional to the uncertainty in the phase divided by the total number of cycles which have passed in the measurement interval. Therefore, $\sigma_y(\tau)$ is proportional to τ^{-1} in this region for these standards.

At much longer measurement intervals, environmental perturbations affect even atomic frequency standards (except for the laboratory primary standards, as explained above), and random walk of frequency takes over, producing the $\tau^{1/2}$ dependence shown in Fig. 1.

IV. RUBIDIUM STANDARDS

The atomic energy levels used in a rubidium vapor standard [8], [9] are shown in Fig. 5. In this figure the A and B states discussed above are the $F = 1$ and $F = 2$ hyperfine levels of the $^2S_{1/2}$ ground state of ^{87}Rb . The preparation of the atoms into state A is accomplished by a neat trick which relies upon a natural coincidence of optical resonance frequencies between ^{85}Rb and ^{87}Rb . The frequency of the ^{85}Rb optical transition from the $F = 3$ ground state to the $^2P_{1/2}$, $F = 2$ state is nearly the same as the transition frequency associated with the ^{87}Rb transition from $F = 2$ to the $^2P_{1/2}$, $F = 1$ state. Both transitions correspond to a wavelength of approximately 795 nm. This is shown explicitly in the laser absorption spectra of Fig. 6. The upper trace is the transmission of laser light by atoms in a vapor cell containing pure ^{87}Rb . The two dips are separated in laser frequency by the same amount as the A and B states, which is 6.834 GHz. The lower trace shows the transmission through a vapor cell which contains both ^{85}Rb and ^{87}Rb . The A and B states of ^{87}Rb are still evident, but the $F = 2$ and $F = 3$ ground states of ^{85}Rb are absorbing light as well. It is easy to see that the $F = 3$ absorption dip overlaps the $F = 2$ dip of ^{87}Rb .

Figure 7 illustrates how this coincidence is used to prepare the ^{87}Rb atoms in a preferred state. In this device light emitted from ^{87}Rb in a radio frequency discharge lamp passes through a filter cell containing ^{85}Rb . (In some designs the filter cell is incorporated within the absorption

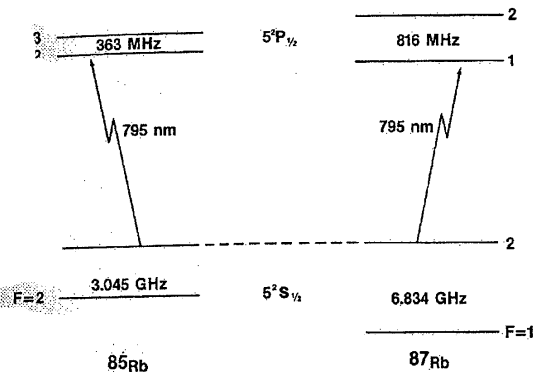


Fig. 5. Energy level diagram for a rubidium atomic standard.

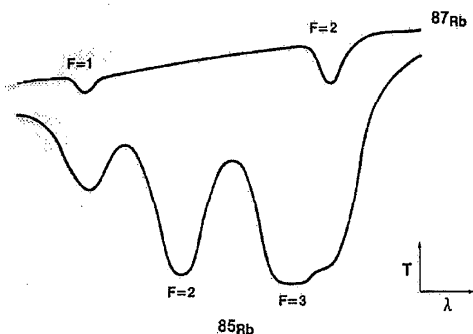


Fig. 6. Laser absorption spectra for two rubidium vapors. The upper trace is pure ^{87}Rb , and the lower trace is a mixture of both ^{87}Rb and ^{85}Rb .

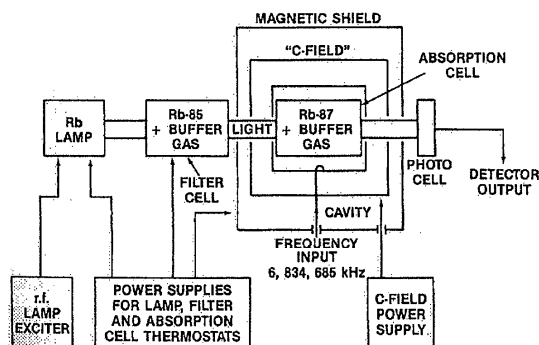


Fig. 7. Rubidium atomic standard diagram.

cell by using a mixture of both isotopes.) Due to the coincidence of atomic energy levels, the ^{85}Rb absorbs more light emitted by the ^{87}Rb atoms making the transition to the $F = 2$ ground state than light emitted in the transition to the $F = 1$ state. Consequently, the light which passes through the filter to the absorption cell is mainly light corresponding to the $F = 1$ excited state of ^{87}Rb . This light is absorbed by ^{87}Rb atoms, which quickly relax to the $F = 2$ and $F = 1$ ground states. Those atoms which return to the $F = 1$ state absorb more light, and the process is repeated until there

is a substantial imbalance in the populations of the $F = 2$ and $F = 1$ states. This process corresponds to the state preparation step of Fig. 3. The process, known as optical pumping, was first suggested by Kastler [10], and it is best analyzed with the density matrix formalism [11]. Such an analysis will not be presented here; however, the author will concentrate on the qualitative aspects of the optically pumped frequency standard.

When microwaves of the appropriate frequency are applied to the ^{87}Rb atoms, some of the atoms are converted back from the $F = 2$ to the $F = 1$ hyperfine level, which then provides still more atoms to absorb light from the lamp. A photocell is placed at the far side of the ^{87}Rb cell, where it can monitor the intensity of light which passes through the cell. At microwave resonance, the change in atomic state results in increased absorption of the light (the third step of Fig. 3). The electronics of Figure 4 can lock a quartz oscillator to this absorption dip. The dip is usually less than 1% of the total light intensity reaching the detector, with a width of 200–800 Hz, depending upon the buffer gases used, as well as the pump light intensity and microwave power. With a resonance frequency of about 6.834 GHz, this gives an atomic Q factor of about 10^7 , somewhat better than that of the very best quartz oscillators.

Since the resonance frequency of the rubidium standard is an intrinsic property of the ^{87}Rb atom, the device is relatively free of environmental perturbations. Frequency shifts must come from effects which alter the individual atoms, such as magnetic fields, or atomic collisions with the buffer gas. The magnetic field dependence of the resonance frequency of the rubidium microwave transition, for example, is given by

$$\nu_{\text{Rb}} = 6\,834\,682\,613. + 574 H^2 \quad (2)$$

where the frequency is in hertz, and the magnetic field is in oersted. Because of this field dependence, the standard must be shielded from changes in the earth's field, from power transformers, and other magnetic objects. The other atomic frequency standards have similar magnetic field dependence.

The buffer gas is used in the absorption cell in order to confine each rubidium atom within the microwave cavity to a region with dimensions much less than the microwave wavelength, thus meeting the Dicke criterion [12], [13], and ensuring that the microwave phase as seen by each atom is constant. In this case, there is no first-order Doppler shift. Additionally, the collisions with buffer gas atoms are relatively benign, as compared with ordinary wall collisions, and thus the ground state phase is preserved, resulting in narrow resonance features. Buffer gases such as He, N_2 , and Ne produce positive frequency shifts of the microwave resonance. Heavier atoms such as Ar, Kr, and Xe produce negative shifts. Both the negative and the positive shifts vary linearly in magnitude with the buffer gas pressure. Mixtures of gases can be chosen to produce shifts which are very nearly zero [14]. Nitrogen buffer gas will quench the rubidium excited state via nonradiative transitions, which allows the use of optically thick vapor

cells without the disadvantage of radiation trapping, which would limit the useful absorption signal.

Another source of frequency shift in the rubidium standard is light shift [15], which is also called the ac Stark shift. Light with frequency close to the optical transition frequency will change the ground state microwave separation. The effect is dispersive in the light frequency, and thus can be controlled to some extent by adjusting partial pressures of buffer gases in the RF discharge lamp or the filter cell. The design objective is to alter the light spectrum of the source to reach a condition which does not change with cell temperature.

Commercially available rubidium standards are quite successful in moderating these perturbations. Typical stabilities are about 1×10^{-11} /month. The change in frequency with temperature is about 4×10^{-11} over a 50°C temperature range. Other sources of frequency change are external magnetic fields (1×10^{-11} /gauss), power supply voltage change ($1 \times 10^{-11}/20$ percent voltage change), and atmospheric pressure change (1×10^{-13} /mbar). The device warms up quickly, to 2×10^{-10} in less than 10 min for some models. Rubidium standards are reliable, with MTBF of greater than 3 years, and they are small, compared with the size and weight of cesium standards. Power requirement can be less than 13 w, after warm up.

Since the useful microwave signal is represented by a small fraction of the total light which is transmitted through the rubidium absorption cell, the noise on that signal is greater than the quantum limit implied by (1). Instead, the noise is given by the statistical noise on the total transmitted light. The character of this noise is the same as the shot noise assumed for (1), however, and the short-term stability of rubidium standards follows a $\tau^{-1/2}$ power law. The Allan variance for rubidium standards can be less than $10^{-11}\tau^{-1/2}$ in the short term.

V. CESIUM STANDARDS

The Rb standard has frequency offsets due to buffer gas shifts of order 10^{-7} , making it difficult to ascribe an accuracy to this standard. For this reason, as well as to obtain better long-term stability, many applications will require the services of a cesium beam atomic standard [16], [17]. Instead of using optical pumping as in the rubidium standard, the cesium standard uses state selection magnets to deflect cesium atoms of different energy levels by different amounts. The force on a cesium atom in the i th energy state is given by

$$\vec{F}_i = -\vec{\mu}_i \cdot \vec{\nabla} \vec{B} \quad (3)$$

where $\vec{\mu}_i$ is the magnetic moment of the atom, and \vec{B} is the applied magnetic field. By passing a beam of cesium atoms through a strongly diverging magnetic field, atoms are deflected by an amount that depends upon their magnetic moments and, therefore, upon their quantum mechanical energy state. In this way, atoms of the ground state hyperfine level $F = 3$ (see Fig. 8) are physically separated from those of the level $F = 4$, which has a different

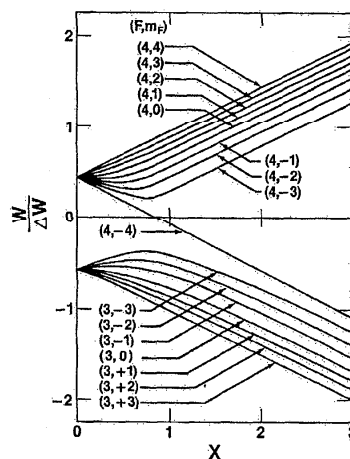


Fig. 8. Ground state energy levels of ^{133}Cs as a function of magnetic field X .

magnetic moment. These are the A and B levels of the earlier discussion. Interaction with microwaves at frequency 9.192 631 77 GHz changes some cesium atoms back from the $F = 3$ to the $F = 4$ level.

A second magnet enables the detection of atoms which have made the microwave state change by directing atoms which are in the $F = 4$ level toward a hot wire ionizer, where an electrical current is generated which is proportional to the number of atoms which make the microwave transition. The microwave frequency is stabilized by locking the quartz oscillator to the frequency which produces a maximum in this current. Figure 9 gives a schematic representation of a cesium beam standard, showing the cesium beam source, the two sets of selection magnets, the microwave cavity, and the hot wire detector.

The improved performance of the cesium standard over that of the rubidium standard stems from the fact that the cesium atoms pass through a high vacuum region, without the buffer gases which cause frequency shifts in the rubidium standard. This makes it easier to ascribe an accuracy to cesium clocks (about $\pm 4 \times 10^{-12}$). In fact, evaluation of the accuracy of laboratory cesium standards has been so successful that the duration of the second has been defined by international law in terms of the ground state hyperfine splitting of the cesium atom. For this reason, the frequency splitting of 9.192 631 77 GHz is an exact number. It is somewhat misleading to refer to a commercially produced cesium standard as a "primary" standard, however. While the second is defined in terms of the cesium resonance, the accuracy of a given cesium standard is still limited by environmental perturbations. The accuracy of a primary cesium standard at a national laboratory, such as NIST, is determined through an evaluation of the size of all known perturbations on the microwave resonance. The accuracy is valid only at the time of the evaluation.

Perturbations of the microwave resonance due to magnetic field changes are a consideration for cesium standards

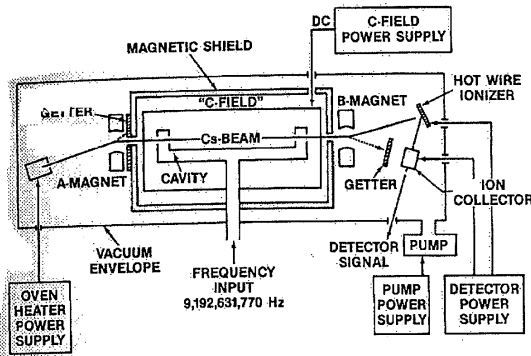


Fig. 9. Cesium atomic standard diagram.

as well as for rubidium standards. There are also other, more subtle effects [18]. Instead of confining the cesium atoms to a region whose dimensions are small compared with the microwave wavelength, cesium frequency standards use Ramsey's separated field method [16]. A microwave cavity is bent into a "U" shape, and the cesium beam passes through the two arms of the "U" (Fig. 9). The phase of the microwaves is chosen to be the same in the two regions which interact with the cesium atoms. The result is an interference effect which produces a narrower atomic resonance than would occur if the atoms had interacted with the microwaves for the entire time of flight. Certain systematic shifts, such as those related to magnetic field inhomogeneities, are also reduced in the separated field method. If the microwave phase is slightly different in the two ends of the cavity (due to losses in the waveguide, for example), then a residual first-order Doppler shift occurs. In a laboratory primary standard, such frequency shifts are evaluated by reversing the cesium beam direction through the microwave cavity. Another subtle shift is associated with the static magnetic field present in the standard (known as the "C-field"). As shown in Fig. 8, both the $F = 3$ and the $F = 4$ ground state hyperfine levels is composed of several magnetic sublevels, which are degenerate at zero applied field. The C-field is applied in the standard in order to separate these levels, and to define quantization axis for purposes of the microwave excitation. Microwave transitions are also possible among the magnetic sublevels, and transitions in the wings of these resonances can shift the clock frequency. This effect can affect the stability of commercially produced cesium standards [19].

These and other sources of frequency shifts are small compared with the shifts present in rubidium standards, and consequently the maximum frequency deviation over the life of the device is about $\pm 3 \times 10^{-12}$. Temperature dependent drifts are less than 5×10^{-12} over the complete operating temperature range of 0°C – 50°C . Magnetic field sensitivity is about 10^{-12} /gauss, and frequency shift upon flying to a 40 000-ft altitude is less than 2×10^{-12} . Warm up time is 20–30 min.

The linewidth of the microwave resonance is determined by the length of time atoms interact with the microwaves,

producing a linewidth of 600–1000 Hz in most commercial standards. This gives a microwave Q factor of about 10^7 . Noise is associated with the number of cesium atoms which make the microwave transition. That is, the uncertainty in the number of atoms N_a which make the transition is proportional to the square-root of N_a . Therefore, (1) applies to cesium standards, and in fact, predictions of short-term stability based on this expression agree well with measured values. Typical values of Allan variance for commercially produced cesium standards are about $3\text{--}5 \times 10^{-11} \tau^{-1/2}$ in a standard device, and less than $8 \times 10^{-12} \tau^{-1/2}$ in a high beam flux standard.

A number of researchers [20]–[24] have been working in improving the performance of cesium frequency standards through the use of optical pumping. Diode lasers can be used to prepare the quantum mechanical state of the cesium atoms, in the same manner as described above for rubidium. Additionally, lasers can be used to detect the final state of the atoms after they make a microwave transition. The advantages of the method are that no state selection magnets are used, larger numbers of atoms contribute to the signal, and the spatial symmetry of the optical pumping reduces certain frequency shifts.

VI. HYDROGEN MASERS

Hydrogen masers [25], [26] can be either passive or active. The essential difference is that in an active maser the atomic gain exceeds cavity losses, so that the maser oscillates. At short measurement intervals, the stability of the active maser improves as τ^{-1} , and the stability of the passive maser improves as $\tau^{-1/2}$. The stability of both active and passive masers surpasses that of commercially produced cesium standards. The downside, though, is that hydrogen masers are more expensive and appreciably larger than cesium standards.

Figure 10 gives the relevant energy levels of the hydrogen atom as a function of magnetic field. As in the cesium beam standard, the $F = 0$ and $F = 1$ states experience different forces in an inhomogeneous magnetic field, allowing atomic state selection by magnetic deflection. The optical transitions are not easily attained by present lasers, so no attempt is made to prepare hydrogen by optical pumping. Figure 11 represents the major components of the passive maser, showing the hydrogen source (where a beam of individual atoms must be formed by dissociating molecular hydrogen), the state selector magnet (which passes only the $F, m_F = 1, 1$ and $1, 0$ states), and the maser cavity (which doubles as a storage vessel for hydrogen atoms). The maser cavity is coated with Teflon, which does not greatly perturb the hydrogen atoms when they strike the wall. No buffer gas is used to confine the atoms. Instead, the physical dimensions of the containing vessel within the microwave cavity are less than the microwave wavelength, and thus satisfy the Dicke criterion.

In the passive maser a microwave signal at 1420 MHz is passed through the cavity in order to interrogate the energy states of the atom. This microwave signal is phase

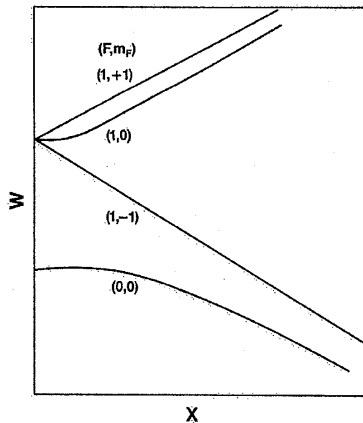


Fig. 10. Ground state energy levels of atomic hydrogen as a function of magnetic field X .

modulated at 12.3-Hz and 12.3-kHz rates. The hydrogen resonance, which is typically 0.5–1 Hz wide, produces a phase shift of the carrier frequency which is dispersive about atomic line center. The combination of phase shifted carrier plus the PM sidebands results in an AM signal at the modulation frequency which is proportional to the offset of the carrier from atomic line center. The maser electronics detect this AM, and tunes the baseband quartz oscillator to keep the microwave carrier centered on the atomic resonance. This signal is derived from the 12.3-Hz modulation. The 12.3-kHz modulation is used to tune the microwave cavity so that the center frequency of the cavity coincides with the atomic resonance. This tuning is required because a mistuning of the microwave cavity will pull the atomic resonance, producing a systematic shift in the maser's clock frequency.

Hydrogen atoms in the storage bulb (Fig. 11) are also perturbed by collisions with the walls (wall shift) and by collisions with other atoms (spin exchange). The fractional frequency offset due to wall shift is about 1×10^{-11} , and the spin exchange shift is about 2×10^{-13} . There is also a second order Doppler shift (time dilation) which depends upon the atomic velocity and, therefore, upon the maser temperature. This shift is about $3 \times 10^{-14}/^{\circ}\text{C}$. As in the rubidium and cesium standards, magnetic field perturbations is a concern as well. These perturbations and other smaller atomic effects limit the long term frequency stability of the passive maser to about 1×10^{-14} . The maximum change in fractional frequency over the life of the maser is expected to be less than 1×10^{-12} . The temperature coefficient is less than 5×10^{-15} , and the magnetic field sensitivity is better than 1×10^{-13} for an external field change of ± 1 gauss.

VII. CONCLUSION

Quartz crystal oscillators offer the best short-term stability for measurement intervals of less than a few hundred seconds. They are also the least expensive, smallest size,

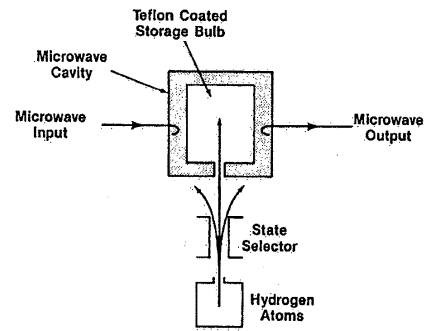


Fig. 11. Passive hydrogen maser diagram.

lowest weight, and lowest power consumption commercial frequency standards. However, the quartz oscillators have limited long-term performance because of their susceptibility to environmental effects, especially temperature, acceleration, and aging.

Improved performance for measurement intervals greater than several hundred seconds is obtained from rubidium frequency standards. These devices are the smallest and least expensive of the atomic frequency standards. However, they are generally limited in long-term stability to about 10^{-11} /month.

For more demanding applications, cesium atomic beam frequency standards can be used. These devices are very stable and accurate. They are often used as frequency references where accuracies of a few parts in 10^{12} are needed. Among the commonly used atomic frequency standards, cesium standards are the largest, highest power consumption, and most expensive instruments.

The best available short-term frequency stability is provided by the hydrogen maser. This device is also the largest, consumes the most power, and is the most expensive of all the atomic frequency standards.

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