# PROSPECTS FOR ADVANCES IN MICROWAVE
## ATOMIC FREQUENCY STANDARDS*

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## ABSTRACT

This paper will focus on conceptual and component develop-
ments which could have a major impact on the performance
of microwave atomic frequency standards.  Traditional
microwave standards based on rubidium, cesium and hydro-
gen have been greatly refined over the past decade, such
that the frequency stability of the current generation
of devices is generally limited by the basic concepts on
which they are based, as well as the performance of
various key subsystems.  Future advances in ultimate
frequency stability and environmental performance will
primarily come from new conceptual developments, and
only secondarily from improved ccomponents.  These new
advances will be explored in some detail and projections
for possible performance improvements made for microwave
frequency standards based on rubidium, cesium and hydrogen.
Brief mention of a new class of standards based on
stored ions will be made.

## INTRODUCTION

The next few years will, in my opinion, bring significant changes in atomic microwave frequency standards. Traditional standards based on rubidium, cesium and hydrogen have been greatly refined over the past decade, such that that the frequency stability of the current generation of devices is generally limited by those basic concepts on which they are based. In my opinion, future advances in frequency stability will principally come from changes in the concepts on which the standards are based, and only secondarily from more careful engineering of the old concepts.

In the following, I will point out what I consider the fundamental limitations in these standards and indicate the important conceptual and component advances which could have a major impact on future performance of these standards. In addition, brief mention is made of a very promising new class of microwave standards based on ion storage techniques.

## RUBIDIUM FREQUENCY STANDARDS

Fig. 1 shows a generalized block diagram of a rubidium gas cell frequency standard. Because of the small size, weight and cost, these standards are the most abundant of all atomic frequency standards. The short term stability is of order $5 \times 10^{-12}\tau^{-1}/_2$ limited by shot noise in the background optical signal with the rubidium hyperfine signal being about 0.5% of the total detected signal.[1] Long-term frequency stability is affected by many things; such as temperature of the buffer gas, density of the Rb, magnetic field gradients, microwave power variations, light spectrum changes, etc. The common contributor to most of these effects is the highly asymmetric hyperfine resonance caused by the presence

of the buffer gas, which essentially causes each interacting atom to sample a very small portion of the total cell volume. The buffer gas is primarily used to isolate the rubidium from the walls of the cell where it would normally relax, typically causing a frequency shift of order $\frac{\Delta \nu}{\nu} = 5 \times 10^{-7}$.[2] Typical linewidths are of order 300 Hz ($6.8 \times 10^9$), yielding a hyperfine line Q of $\cong 2 \times 10^7$. The very nature of the way the buffer gas acts causes a fundamental problem so that even excellent engineering is hard pressed to achieve frequency stabilities of better than $\cong 10^{-13}$ at several hours and provide a frequency reproducibility or retrace following several turn off/turn on cycles of $10^{-11}$. For example, 0.4dB change in microwave power caused a frequency change of order $10^{-11}$ for one Rb unit tested at NBS.[3]

Recent work initiated by Al Risley and Helmut Hellwig at NBS and carried out in collaboration with Jacques Vanier (University of Laval) and Hugh Robinson (Duke University),[4] demonstrates that parafin coated cells may provide a new way to make a rubidium gas cell standard with greatly improved characteristics. The parafin wall coating provides a means to contain the atoms with very small hyperfine relaxation and, very importantly, provides a means for the atoms to average all parameters over the entire bulb. Initial experiments yield a frequency shift of $\cong 10^{-8}$ for the wall coated cell and linewidth of less than 250 Hz. Linewidths of approximately 70 Hz are ultimately expected. Signal-to-noise is comparable to that of the buffer gas cell. Tests show, for example, that the coated cell has a factor of 100 less sensitivity to changes in microwave power than the buffer gas cell. Reductions in the sensitivity to magnetic field gradients and light intensity are also expected. As for cell lifetimes, Hugh Robinson has used one closed cell for 10 years with no measureable degradation in signal or signal-to-noise.[5]

The temperature coefficient of the wall shift is of order 1 - 2 Hz/K,[6] so that fractional instabilities due to this effect could be as low as $10^{-14}$ at a few hours and less than $10^{-13}$ per day. Aging of the wall shift has not yet been measured. I would also expect that the retrace of the coated cell could be made better than a buffer gas cell due to the factor of 10 smaller confinement frequency shift and spatial averaging. In the case of the buffer gas cell, many hours are required to reestablish the equilibrium between the gas phase and the absorbed gas on the surface of the cell after a change in temperature.

There is yet another large bias in rubidium gas cell standards due to the presence of pumping light interacting with the same energy level being probed by the microwave radiation. Absolute light shifts are of order $10^{-9}$.[2] The idealized pumping lamp profile of Rb$^{87}$, shown in Fig. 2, has a component which tends to depopulate the desired $F_2$ level. This unwanted light is filtered out by using Rb$^{85}$ as an absorber, but the filtering is not totally successful and it shifts the center of the optical spectrum, causing an output frequency shift of order $10^{-9}$. Also, the hyperfine signal is typically 0.5% of the total signal, instead of $\cong 10\%$ as would be expected from an ideal source.

Recent work by Tom English, et al. (Efratom, Inc.), has shown that the frequency shift from varying the light intensity by 30% can be reduced from $10^{-9}$ to $\leq 1 \times 10^{-11}$ by alternately applying pumping light and microwave radiation.[7] This technique was first suggested by M. Arditi.[8] English, et al., achieved a short-term stability of $\cong 2 \times 10^{-11}$ $\tau^{-1}/_2$ using a buffer gas cell.[7]

Many problems could well be solved by using a diode laser for pumping the Rb gas cell. The diode laser can be stabilized by

standard modulation techniques and can be tuned to pump only the $F_2$ levels, thereby increasing the hyperfine signal to $\cong 16\%$ of the total signal as compared to 0.5% in the standard design. This would:

1) improve S/N by $\cong 5$
2) reduce light shift to $<10^{-12}$
3) increase line Q by $\cong 2$
4) improve short-term stability to $\sim 10^{-12}\tau^{-1}/_2$.

Summary of projected performance for several variations of small rubidium standards is shown in Fig. 3. Performance could be improved considerably by increasing volume.

## CESIUM FREQUENCY STANDARDS

Fig. 4 shows a schematic of a cesium atomic resonator.[1] It has become increasingly apparent that present day cesium standards are fundamentally limited beyond $\cong 1$ day by the combination of phase variations of the microwave signal across the cavity end, the finite velocity of the atoms, and the spatial variation of velocity across the beam profile due to the dispersive nature of the A and B magnet state selectors.

The frequency offset due to the average phase shift is:

$$\Delta v = \frac{<\phi><v>}{L}$$

In my opinion, the major uncertainty and instability in the frequency is due to the fact that $<\phi^2>^{1/2}$ may be $100 <\phi>$.

The present state selection technique utilizing inhomogenic magnetic fields to spatially separate selected hyperfine states

causes a correlation between velocity and position within the microwave cavity window. This applies to dipole and quadruple-hexapole systems. As a consequence of this coupling between spatial position and velocity, any effect which can cause a variation in average velocity, state composition or spatial distribution will cause a frequency shift even if $\langle\phi\rangle = 0$.[9] Effects which can cause frequency shifts initially are variations in microwave power, C field, Majorana transitions occuring in the beam between the state selector and the microwave cavity, and even variations in the voltage on the mass analyzer before the ion collector. All of the above change the distribution of velocities contributing to the detected signal and shift the average frequency via the distributed cavity phase.

At present, there are no attractive ways to significantly lower beam velocity. Brute force attempts suffer from the low number of slow atoms due the Boltzmann Distribution, and significant laser cooling of neutral beams as proposed by Askin and also Hänsch and Schawlow [10,11] have yet to be demonstrated.

Reduction of the distributed cavity phase shift by reducing the diameter of the cavity window can be bought only at the price of lower beam intensity. Cooling the cavities to cryogenic temperatures could reduce this effect to near zero; however, the beam would have to be carefully masked in order to prevent Cs buildup within the cavity structure.

Recent work by Wineland, Jarvis, Hellwig and Garvey at NBS indicates that the effect of the average phase shift $\langle\phi\rangle$ can be reduced to zero by implementing a 2-frequency and 2-cavity system[12] as illustrated in Fig. 5. In such a system, the envelope of the Ramsey Resonance is detected so that the average $\langle\phi\rangle$ between two

ends is averaged to zero (see Fig 6). Since the frequency switching from $\nu_2$ to $\nu_2'$ is fast compared to changes in $<\phi>$, any perturbation which would change $<\phi>$ is greatly reduced. As a consequence, such a standard should be significantly more immune to frequency changes due to microwave power changes, fluctuations in oven temperature, position of oven/dectector, shock, vibration, etc.

In order to realize the full advantage of this technique, it is important that short-term stability be maintained of order $10^{-11}\tau^{-1/2}$ or better. To do this, it is necessary to open up the cavity window in order to have a wide velocity distribution so that the Ramsey envelope is narrow and to increase beam current. Under optimum conditions, it is estimated that $\sigma_y(\tau)$ of $10^{-11}\tau^{-1/2}$ can be achieved. The current NBS test bed demonstrates $\sim 10^{-10}\tau^{-1/2}$ for 4pA beam current $<v> \cong 130$ m/s, a 30% velocity width and a cavity length of 17 cm. Opening the cavity windows should substantially improve the performance.

Reduction of the velocity dispersion across the beam profile could also be accomplished with optical state selection. The laser diodes for pumping Cs at the proper wavelength exist and state selection has been demonstated.[13] Fig. 5 illustrates one possible configuration. The source is a single aperature to avoid brightness variations over the oven opening, such as can occur with multihole collimators. The straight through optics should help utilize the maximum number of slow atoms. By using an optical pumping scheme completely analogous to that used with Rb, the Cs beam can be predominately pumped into the $^2S_{1/2}$ F = 3 manifold. Len Cutler[14] has suggested a dual frequency optical pumping scheme by which all of the atoms could be pumped into the F = 3, $M_F$ = 0 sublevel; thus providing approximately a factor of 4 increase in signal-to-noise over standard design. With the absence

of the A Magnet, magnetic shielding of the resonance area is easier and Majorana transitions between the various sublevels could be completely eliminated. Beam detection could be obtained by conventional magnetic state selector/hot wire ionizer or by 2 step optical ionization. Both would offer near 100% efficiency and the ability to velocity select.

The net effect of the optical pumping scheme for state selection is to totally eliminate any correlation between spatial position within the beam and thereby within the cavity opening and velocity. Variations in microwave power, for example, will now cause a change in average velocity, but not average phase shift.

So the variation of frequency with average velocity, such as by changes in microwave power, should be reduced by a factor of 10 to 100 over present designs. In addition, the straight through geometry and the efficient state selection should permit a factor of 2 reduction in average velocity resulting in:

1) A factor of 4 reduction of second-order Doppler shifts $\cong \frac{1}{2} \frac{v^2}{c^2} \sim 1.5 \times 10^{-14}$.

2) $\sigma_y(\tau)$ improved by factor of 4 to 8  1s $< \tau < 10^4$s.

3) $<\phi>$ reduced by a factor of (2).

4) $\Delta<\phi>$ vs microwave power reduced by $\cong$ 20 to 200.

5) $\Delta\nu = \frac{<\phi><v>}{L}$ reduced a factor of approximately 2 over a magnetic state selection and should be extremely stable and measureable. The offset is not measurable with high accuracy with present magnetic state selection.

If the optical pumping scheme were coupled with the 2 frequency, 2 cavity technique, then the offset would also be made zero at the expense of decreased short-term frequency stability.

Fig. 7 shows a summary of projections for various configurations of commercial sized cesium frequency standards. Additonal improvements are possible with laboratory type cesium standards.

HYDROGEN FREQUENCY STANDARDS

A block design of a standard hydrogen maser·oscillator or active hydrogen maser is shown in Fig. 8.[1] This device is unique among the atomic standards being discussed now because it is an oscillator. By building up enough population in the excited hyperfine state, it can be made to oscillate. Frequency stability at a few hours is unexcelled and therefore such devices are used for the most exacting high frequency phase sensitivity receivers, such as VLBI and the JPL deep space tracking network (See for example references 15, 16 and Fig. 12). However, for long-term timekeeping application, active hydrogen devices are seldom used because the frequency drifts away due primarily to cavity pulling which causes a fractional shift of:

$$\frac{\Delta \nu}{\nu} \cong \frac{Q_C}{Q_H} \frac{(\nu_C - \nu_H)}{\nu_H}.$$

Assuming a hydrogen line $Q_H$ of $5 \times 10^8$ and a cavity $Q_C$ of $3 \times 10^4$ results in

$$\frac{\Delta \nu}{\nu} = 0.6 \times 10^{-4} \frac{\Delta \nu_C}{\nu_H}.$$

In order to achieve a stability of $10^{-15}$ in the output frequency the cavity frequency must be stable to $1.5 \times 10^{-11}$. Free running cavity stability of this order has never been demonstrated for

627

periods beyond a few hours. Long-term stability of active masers can be improved using automatic cavity tuning. One synchronously detects changes in output frequency with changes in beam flux and servos the cavity tuning to minimize output frequency changes. Stabilities of order a few times $10^{-14}$ have been reported.[17]

Recent work at National Bureau of Standards has produced a new concept for stabilizing the microwave cavity.[18,19,20] A simplified block diagram is shown in Fig. 9. A local probe oscillator is phase modulated at two different low frequencies $f_1$ and $f_2$ where $f_2$ is approximately the half-bandwidth of the hydrogen resonance and $f_1$ the half-bandwidth of the microwave cavity. The transmitted microwave signal is envelope detected and the resulting amplitude modulation processed in two separate synchronous dectectors referenced to $f_1$ and $f_2$ respectively. The error signal recovered from the $f_1$ synchronous dectector is used to electronically tune the cavity to the probe frequency and the error signal recovered from the $f_2$ synchronous detector is used to tune the probe frequency to the hydrogen hyperfine resonance frequency. This allows one to lock the cavity frequency to the hydrogen resonance with an attack time of a few seconds, thereby allowing rapid recovery from any induced cavity perturbation.

Fig. 10 shows the frequency stability realized with a conventional full-sized cavity as measured against NBS-6, one of our primary frequency standards and also the ensemble of 9 cesium standards, which generate UTC(NBS). The realized stability of $3 \times 10^{-15}$ at 4 days confirms that this NBS passive hydrogen maser scheme can be effectively used to control cavity induced frequency perturbations. For a more thorough discussion of the other possible perturbations see.[18,19,20] The above data was obtained with a hydrogen hyperfine line Q of $5 \times 10^8$. A new bulb configuration and better teflon

coating now yields a line Q of $5 \times 10^9$ with 10 times the previous signal-to-noise. Measured frequency stability at 1 s is better than $1 \times 10^{-13}$. Based on the above, one would expect a daily frequency variation of less than $1 \times 10^{-15}$ for this full-sized passive hydrogen maser cavity system.

This passive system concept also makes possible the use of a small dielectrically loaded microwave cavity. The new cavity system described in [19] was designed and assembled in colaboration with David Howe and S. Jarvis, Jr. at NBS. The hyperfine line Q with a storage volume of 1.1$\ell$ is $1.4 \times 10^9$ at low microwave drive and $1 \times 10^9$ at operating conditions. The observed frequency stability is $1 \times 10^{-12}\tau^{-1}/_2$ out to approximately 1 day. The small passive maser has been compared with UTC(NBS) for 54 days and its frequency drift was $1\pm1 \times 10^{-15}$/day.

Fig. 11 shows a comparison of frequency stability of hydrogen atomic standards. A line labeled H(Active) is the best reported in the literature.[21] The time-keeping ability of various atomic standards is shown in Figs. 12 and 13.[22] The data on the passive masers clearly shows that active cavity control can be used to greatly improve long-term frequency stability of hydrogen masers. Furthermore, this technique greatly simplifies the thermal vacuum design, thereby decreasing cost, weight and complexity.

STORED IONS

A new class of microwave frequency standards based on stored ions is presently under study. These devices appear to hold the possibility of achieving frequency stabilities of order $10^{-16}$ and absolute accuracy of order $10^{-15}$. These devices are explained by

D. J. Wineland in these proceedings, and are the only systems which <u>fundamentally</u> reduce both first and second-order Doppler effects to sub 10-$^{14}$ levels. For example, the cavity phase shifts encountered with Cs standards is a form of residual first-order Doppler shift.

The principles of ion storage based frequency standards are described elsewhere.[23] Basically, the ions are contained within an electromagnetic trap with dimensions of a few cm or less. Containment times are typically hours to days which, in principle, makes possible extremely large line Q's for hyperfine transitions, even at microwave frequencies. The ions can be cooled to sub-Kelvin temperatures using lasers tuned to the lower side of an allowed electric dipole transition. Each scattered photon carries off approximately 20 mk of energy if the laser is detuned by 500 MHz. Recent work[24] clearly shows that sub-Kelvin temperatures are easily achieveable in the case where appropriate lasers exist to pump the ions.

One proposed scheme for a stored ion standard has the following half cycle:

1)   state select ions using optical pumping,
2)   induce hyperfine transitions with probe tuned to the high frequency side of the hyperfine resonance and the laser off,
3)   optically pump ions to determine how many made the transition and to cool the ions.

In the next half cycle the same three steps are repeated; however, the probe frequency applied in step 2 is moved from the high frequency to the low frequency side of the hyperfine resonance.

The maximum frequency stability that can be realized for N ions having a hyperfine resonance frequecy $\nu_0$ is

$$\sigma(\tau) = \frac{2}{\tau_0 N} \frac{1}{\pi \nu_0} \tau^{-1/2}$$

where $\tau_0$ is the total cycle time or $2(\tau_1 + \tau_2 + \tau_3) = \tau_0$. Values for $\sigma_y$(1s) vary from $10^{-12}$ to $10^{-15}$ for some of the systems under consideration. At present, the most serious impediment to this effort is a lack of suitable lasers to overlap ions having attractive other properties for the application.

SUMMARY

In the above, I have presented what I feel to be the most serious perturbations to frequency stability of rubidium, cesium and hydrogen devices. Most of these are perturbations essentially due to the concepts on which the standards are based. I feel that there is great opportunity for substantial improvement in frequency stability in both laboratory and field settings and I have indicated how I think these improvements can be obtained.

ACKNOWLEDGEMENTS

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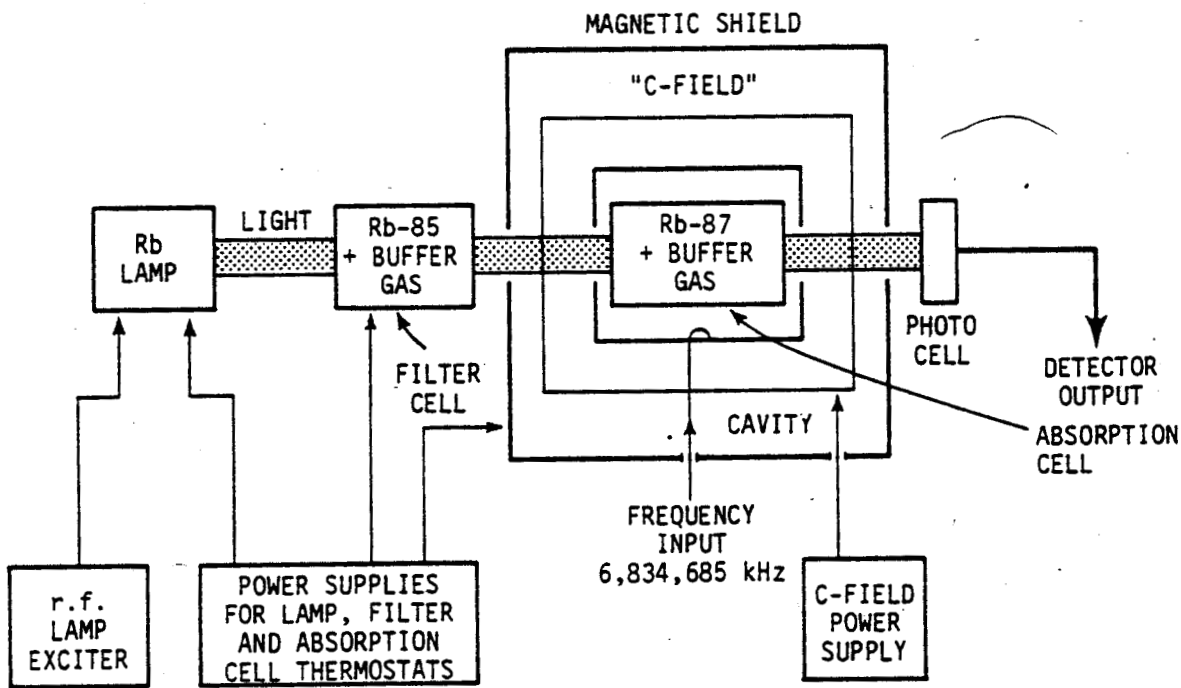
Figure 1. Simplified Diagram of a Typical Rubidium Atomic Resonator
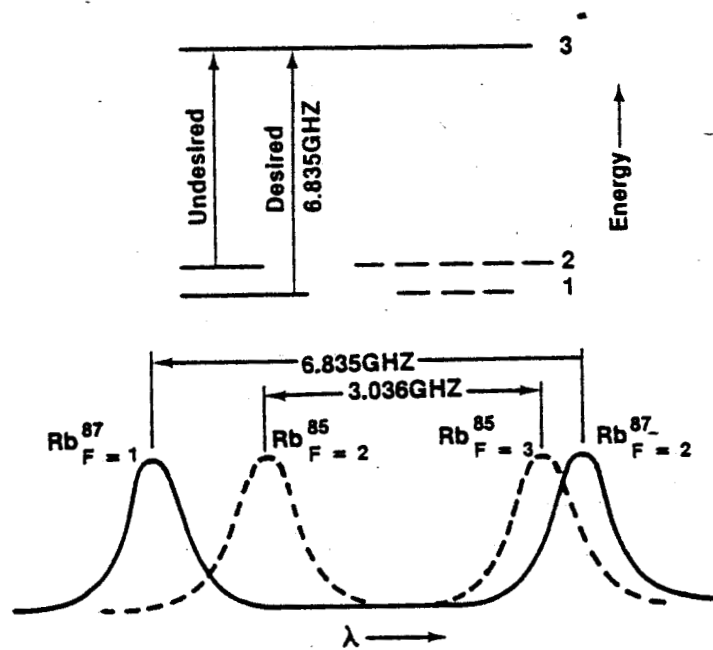


Figure 2. Levels of Interest for Optical Pumping of
Rubidium
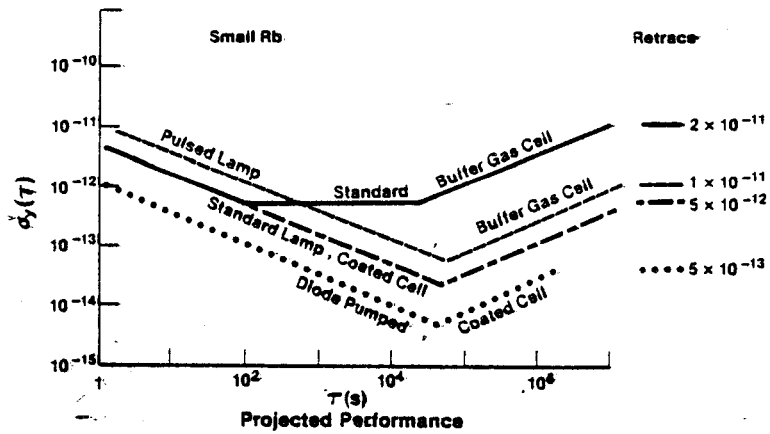
Figure 3. The Projected Performance of a Small Rubidium
Standards with Various Features are Shown. The Solid
Line is the Typically Achieved Performance of Small Rubid-
ium Devices. Selected Units have Performed Better Es-
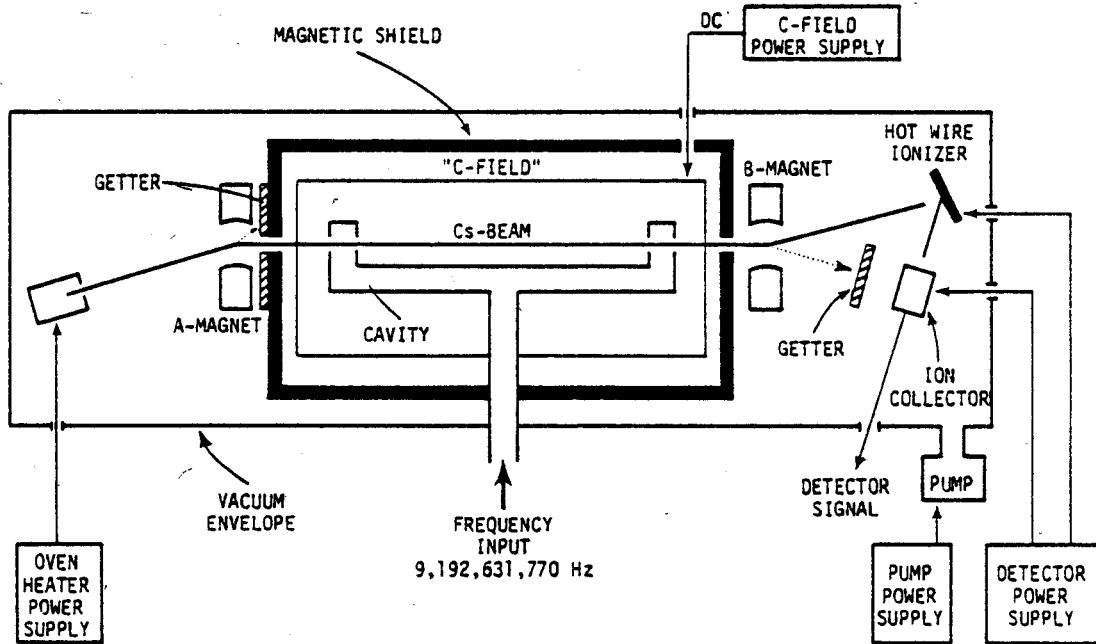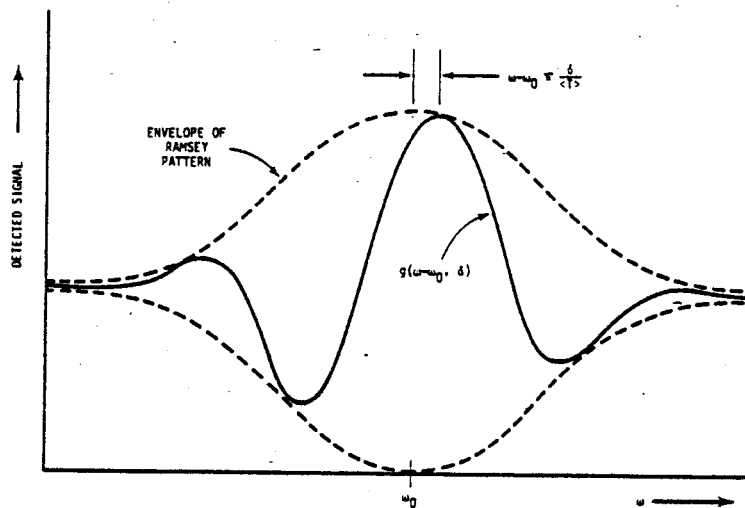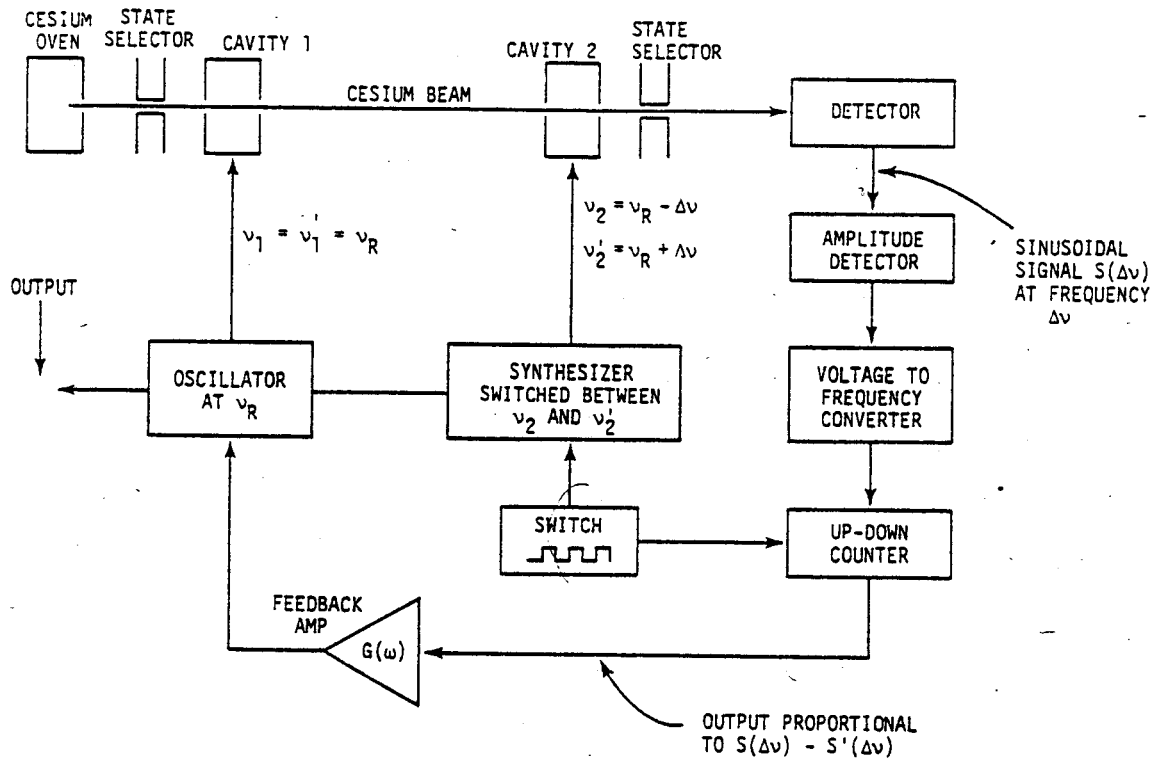pecially Under Environmental Control[1].



Figure 4. Simplified Diagram of a Cesium Beam Atomic Resonator

Figure 5.  Simplified Diagram of One Possible 2 Cavity-2 Frequency Configuration.[11]



Figure 6.  Ramsey Pattern for a Phase Shift Between the
Two Cavity Ends. Dotted Line Shows the Ramsey Envelope

a) typical performance
b) typical performance of high beam intensity tubes
——— Projected 2 Freq, 2 Cavity
——— Projected optical pumped 2 Feq 2 cavity
• • • • Projected optical pumped standard cavity

Figure 7. Projected Performance for Several Configurations
of Commercial Sized Cesium Frequency Standards. The
Solid Lines are Typically Realized Values for Commercial
Devices. Selected Units Perform Somewhat Better at $10^6$s
Especially Under Environmental Control.
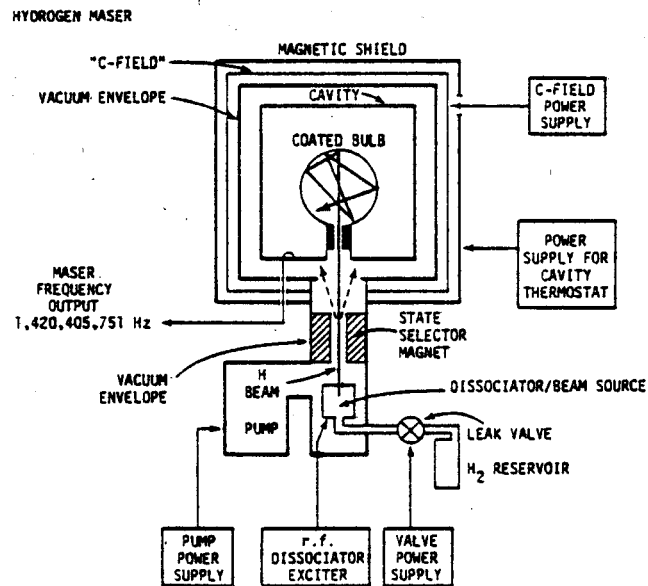


Figure 8. Simplified Diagram of an Active Hydrogen
Maser Oscillator.
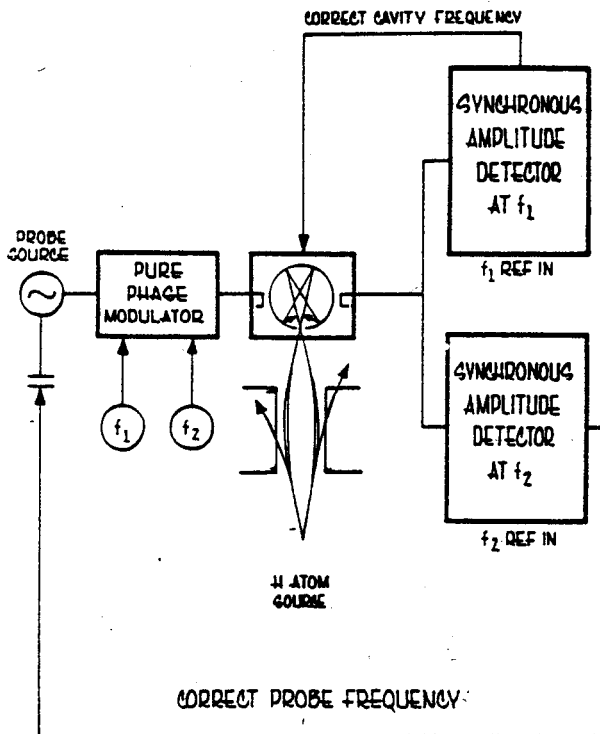
Figure 9. Simplified Diagram of One Possible
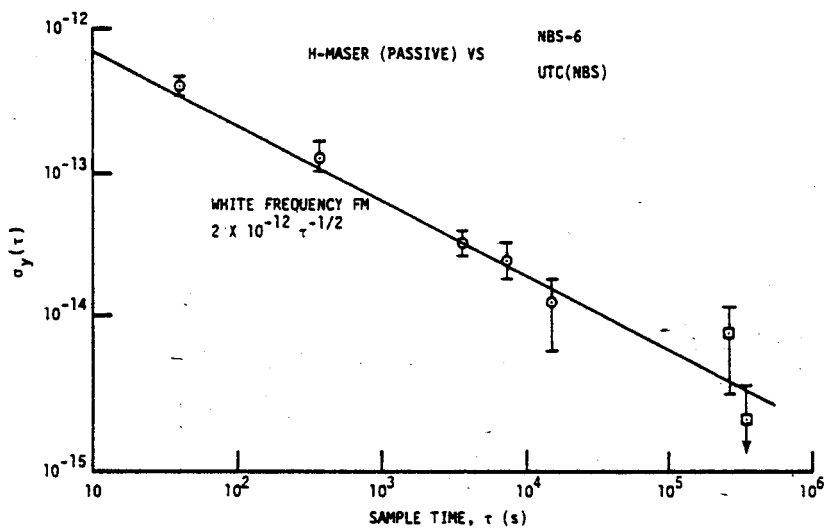Passive Hydrogen Maser Frequency Standard.



Figure 10. Joint Fractional Frequency Stability of Large Passive
Hydrogen Maser vs. Cesium Standards. The Last Point is 3
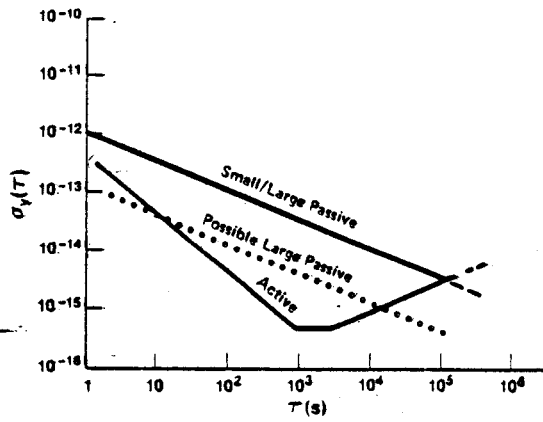Samples at 4 Days.

Figure 11.  Fractional Frequency Stability
of Hydrogen Masers.  Solid Lines are Meas-
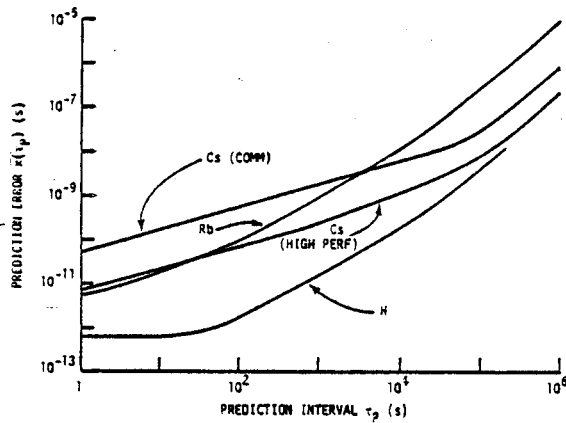ured While the Dotted Line is Projected
Performance.



Figure 12.  Minimum Time Prediction Error
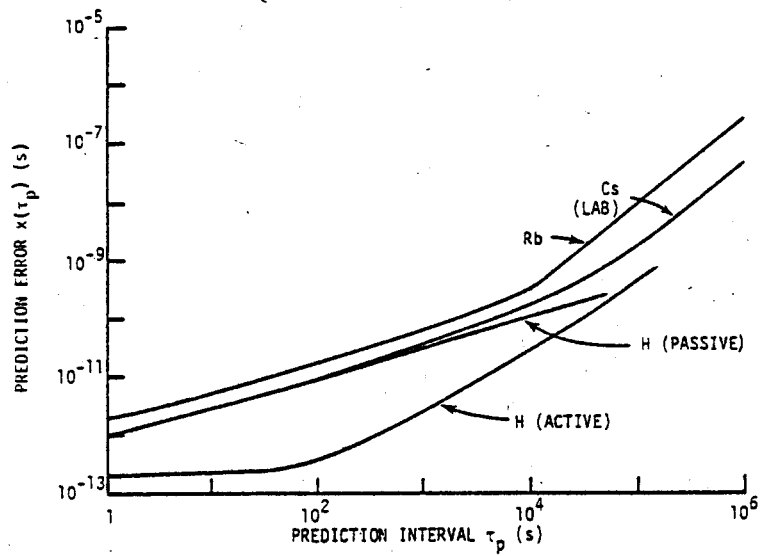for Several Atomic Standards Using "Normal"
Frequency Stability Performance.[21]

Figure 13. Minimum Time Prediction Error for Several
Atomic Standards Under Near Ideal Laboratory Condi-
tions.[21] Cs(Lab) Refers to Large Primary Cesium Stan-
dards, While H Passive Refers to the Data from the Original
Large Passive Performance.[17] Projected Large Passive
Performance is 5-10 Times Better.