SOME CAUSES AND CURES OF FREQUENCY INSTABILITIES (DRIFT & NOISE) IN CESIUM BEAM FREQUENCY STANDARDS

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SUMMARY

Frequency drift of the order of several parts in 10^{13} per year is often observed in commercial cesium beam frequency standards, and on some occasions significant changes in the white noise frequency modulation level is also observed. Recently at the National Bureau of Standards some standards with these types of problems have been analyzed and their velocity distributions measured. A comparison of the changes in drift and noise performance with measurements of the velocity distribution leads to some interesting interpretations:

Changes in focusing voltage at or in the vicinity of the detector may cause the finite surface area of the detector to act like a velocity selector; i.e., the detection efficiency of cesium atoms mapped across the surface of the detector changes with time as a result of changing electric fields which focus the cesium ion-beam. Changes in the microwave power cause changes in the most probable cesium atom velocity, which transduce via the Ramsey cavity phase shift into frequency changes.

The magnitude of the cavity phase shifts in a cavity was inferred by reversing the current through the C-field inducing mixing of the m_F states.

I. INTRODUCTION

A basic limitation in keeping accurate time with a cesium beam atomic clock results from its long-term frequency instabilities. It is the purpose of this work to investigate in a non-destructive way some of the causes of these instabilities and, in some cases, propose some possible improvements.

II. BACKGROUND

There are several possible causes of frequency instabilities and drifts in cesium beam frequency standards. Specifically some of these are: microwave spectrum impurities and asymmetry; distortion of the modulation frequency; excess noise at the modulation frequency; ac and dc instabilities in the servo demodulator circuitry; servo loop gain degradation; frequency drift in the quartz crystal oscillator locked to the cesium resonance causing frequency drift in the cesium standard's output due to too low a loop gain; drift and instabilities in the magnetic field in the C-field drift region; gradual changes in the cesium beam optics; pulling by neighboring field dependent lines; etc. Basically, the performance of the electronics is dependent on the beam tube's characteristics.

It has been shown that one of the main limitations to the accuracy of a cesium beam primary frequency standard is the cavity phase shift associated with the Ramsey microwave excitation region as seen by the cesium beam [1,2]. At this point we will develop a model which indicates that this is also one of the main limitations to the long-term stability in cesium beam frequency standards. From Ramsey [3] we have the transition probability near the Ramsey resonance for cesium atoms with a velocity, v, as follows:

$$P_{p,q} = \sin^2 2b\tau \cos^2 1/2(\omega_o - \omega - \phi/T)T, \quad (1)$$

where b is proportional to the square-root of the microwave power in the cavity, τ is the time the atoms spend in each end of the Ramsey cavity, ω_o is the natural resonance frequency of the cesium atoms, ω is the microwave interrogation frequency, ϕ is the cavity phase shift between the cavity ends, and T is the flight time of the cesium atoms between the cavity ends (of course v = L/T where L is the distance between the cavity ends). Now from eq. (1) it is clear that the center of the resonance will be shifted from ω_o by an amount ϕ/T causing a frequency shift in the standard of that amount due to the cavity phase shift. In most commercial cesium tubes, the "average" T is of the order of 1 ms, so in order to have a frequency shift of less than 1 part in 10^{12} requires ϕ to be less than 60 microradians or a synchronization of the microwave fields at the cavity ends to less than about 1 femto second (10^{-15} s). Furthermore, the amount of microwave power ($\propto b^2$) present in the cavity determines the most probable velocity of atoms to undergo a transition; hence, for typical non-zero kinds of cavity phase shifts encountered, the resulting frequency shift may be highly dependent on the microwave power.

A further complication arises because of geometrical imperfections and finite conductivity associated with the ends of the Ramsey cavity. This causes the cavity phase shift not to be single valued for a given cavity but to have a value dependent upon where the cesium beam transverses the cavity opening. In other words, the phase shift, ϕ, is a function of the coordinates across the cavity opening, which has been called the "distributed cavity phase shift" effect [4,5]. The distributed cavity phase variations may be of the same order as the basic phase difference. Frequency shifts result which are a function of the beam trajectory location which itself depends on other parameters, such as microwave power.

In practice, of course, there is a velocity distribution, $\rho(v)$, which convolves with the transition probability to give the typical kinds of Ramsey spectra observed. Knowing the velocity distribution and changes in it may lead to insights into beam trajectories, trajectory changes and effects these changes might have on the performance of a cesium clock.

III. EXPERIMENTAL RESULTS

A. Analysis of an older commercial cesium beam standard with significant frequency drift

Figure 1 shows measured frequency changes of a particular commercial cesium standard over more than 900 days [6]. One notes a positive frequency drift over the first 100+ days and then a negative drift of about -2×10^{-12}/year over the remainder of the data. One notes also a significant increase in the white noise FM level toward the end of the plot in Figure 1. For a white noise FM process the spectral density is given by $S_y(f) = h_o$ where y is the fractional frequency, f is the Fourier frequency, and h_o is the noise level. In this case one may write $\sigma_y(\tau) = \sqrt{h_o/2}$, where τ is the sample time in seconds for the two-sample sigma. The values of $\sqrt{h_o/2}$ went from 1.2×10^{-11} to 2.6×10^{-11} to 8×10^{-11} for 1975, mid-1976 and for 11 November 1976, respectively. The velocity distribution of this particular cesium tube was measured 6 December 1976 and is shown in Figure 2 as curve a. A modification was made per the manufacturer's recommendation to the circuit associated with the cesium detector. The velocity distribution was again measured on 14 December 1976 as is plotted as curve b in Figure 2. Note that the maximum velocity moved higher by about 10 m/s. Appropriately compensating for the magnetic field correction and measuring the frequency before and after the modification showed a frequency increase of 2.8×10^{-12} and $\sqrt{h_o/2}$ went to 7×10^{-12} (an order of magnitude improvement). The drift was measured over about a month and was observed to be back positive at about the rate of $+8 \times 10^{-13}$/year. One will note that the frequency also returned to about its same value as at the beginning of the life of the tube.

The low velocity secondary hump seen in curve b of Figure 2 is also characteristic of this type of tube at the beginning of its life [5]. It seems probable in this case that gradual changes in the characteristics of the detector (the only parameter changed in the modification) cause a preferrential detection of different velocities of atoms, which in turn may cause a frequency drift via the cavity phase shift. We cannot offer a more detailed explanation of the actual physical changes (probably in the detector) beyond these phenomenological statements. Much more work in this area is required.

B. Analysis of a new standard

Figure 3 is a plot of the average daily frequency of the first 2 months of the life of a new cesium standard. It appears to be drifting positively at a rate of about 1×10^{-12}/year. Following this data a velocity distribution, $\rho(v)$, was taken on 17 March 1977 and is shown in Figure 4. From the $\rho(v)$ curve, one can generate [7]: the corresponding Ramsey spectrum as shown in Figure 5; the beam current intensity, I_B, at the detector as a function of microwave power as shown in Figure 6 (curve g_o), for which the frequency shift is:

$$\nu_b = +\frac{\phi v_p}{2\pi L} \qquad (2)$$

where v_p is an appropriate average velocity.

The typical operating point for the microwave power is with I_B set to a maximum, called "optimum power". Clearly, at this point the v_p curve has a significant non-zero slope; i.e. if the microwave power changes, then v_p will change, and if there is a cavity phase difference or a distributed cavity phase shift then the frequency will change.

This particular standard has a temperature coefficient of about -1×10^{-13}/°C in an operating environment of 20°C to 30°C. It was believed that a main cause of this was due to microwave power changes as a function of temperature; i.e., one could see a noticeable change in the beam current monitor voltage as a function of temperature as shown in Figure 7. A similar temperature coefficient was obtained by applying localized heating at the harmonic generator which generates the microwave signal. No attempt was made to apply localized heating at the frequency multiplier which starts at 5 MHz.

Now, in the case of a mono velocity beam with the appropriate (optimum) microwave power this velocity is the same as v_p. From Eq. (1), one calculates that the offset frequency of the first side lobe is simply:

$$\nu_1 - \nu = \frac{v_p}{L} . \tag{3}$$

This equation will be somewhat modified when Eq. (1) is convolved with a velocity distribution, but we can verify that the offset frequency of the side lobe is strongly and nearly linearly dependent on v_p over the power range of interest. Also, this dependence is, by far, the predominate determinant of the frequency separation of the side lobe from the main peak. Since v_p depends on microwave power, so will ν_1. Figure 8 is a plot of the frequency dependence of the first upper Ramsey side lobe as a function of temperature as measured at the harmonic generator.

Using the v_p curve in Figure 6 allows one to estimate the change in microwave power per degree assuming Eq. (2) is nominally valid. Doing so indicates that in this particular standard the microwave power changes about -0.1 dB/°C.

The fractional frequency shift of the cesium tube (main frequency peak) is given as a function of ϕ and v_p in Eq. (2). If the cavity phase shift ϕ is of the order of $\phi \approx .1$ m rad [1,2], then for a tube with $L \approx 17$ cm a velocity change of 1 m/s (about 1%) causes $\delta\nu_B/\nu \approx 10^{-14}$. From Figure 6, 1 m/s change is caused by a power change of approximately $P = .6$ dB at optimum power. In other words, flicker noise of the microwave power in the amount of .6 dB would limit the standards' performance to a flicker floor of 10^{-14}. Furthermore, smaller values of L (shorter tubes) would lead to worse performance according to Eq. (2), as well as steeper slopes of the $v_p(b)$ curve (Fig. 5), for constant ϕ and v_p. A steeper $v_p(b)$ curve is related to broader velocity distribution (v) and a narrow velocity distribution results in relatively smaller dependence of v_p on b (at optimum power).

Data from many tubes bear out this assertion; i.e., the shorter the tube and the broader $\rho(v)$, the worse the flicker floor in $\sigma_y(\tau)$ [8]. Therefore, with conventional tube design, the long-term stability can be fundamentally improved by going to relatively long tubes and narrow velocity distributions while keeping the "scale" factor, (cavity phase difference and distributed cavity phase shift) as small as possible via careful fabrication and the use of small beam openings in the cavity.

Other mechanisms which can transduce microwave power changes to frequency shifts include pulling by neighboring field dependent lines and microwave impurities or assymetry. We report on a net effect; studies of other mechanisms are under way.

Based on the measurements reported here, a novel power control could be built by constructing a servo to keep the first Ramsey side lobe at a constant frequency offset by controlling the microwave power. This may significantly improve the long-term stability of such a cesium clock. For a stability performance equivalent to 10^{-15}, v_p must be controlled to about 0.01%; this may be accomplished by sensing and maintaining the frequency separation of the side lobe from the main peak to the same precision; This means to about 0.01 Hz or 1×10^{-11}. This is quite feasible and would lead to response time of such a servo of about 10s.

We reversed the magnetic field of a commercial cesium beam tube which resulted in a frequency shift of the order of 1×10^{-11}. It is unlikely that this effect is attributable to a discrepancy between $\bar{H}^2$ (measured) and H^2 (seen by the atoms).

Consider, however, the following condition present in most commercial tubes (see Figure 9):

(A) The region between the state selecting magnet and the shielded C-field region is characterized by a rapid change in magnetic field strength of over five orders of magnitude. Magnetic trimmers are installed to assure a smooth transition without abrupt changes and reversal of magnetic field components. This condition is optimized for the given magnetic shielding and C-field conditions. Reversal of the C-field leads to a destruction of this condition and thus to mixing of the m_F-states via Majorana transitions.

(B) All presently used cavity structures in cesium beam tubes not only have a small cavity phase difference between the two interrogation regions of the Ramsey cavity, but also a variation of the phase across the beam opening in the cavity. This latter effect, the distributed cavity phase shift, causes a frequency shift which depends on the location of the atomic trajectories with respect to the beam tube axis [6,7]. The magnitude of this effect, which limits the accuracy of primary standards, was determined to be as large as several parts in 10^{13} for NBS-6 [2] and is estimated to be of the order of 10^{-12} to 10^{-11} for commercial tubes.

From (A) and (B) above, we construct the following explanation for the frequency shift under C-field reversal: In the original C-field direction, negligible state-mixing takes place and the interrogated trajectories of the C-field region are those of the originally selected $m_F = 0$ state. In the reversed field configuration, mixing produces some $m_F = 0$ states in all trajectories. Since the m_F states have different [fig. 9] magnetic moments, the trajectories are different, leading via the distributed cavity phase shift and a possible change in the effective velocity distribution to a frequency change.

To summarize, because of the presence of the (distributed) cavity phase shift, the frequency of the cesium beam tube depends on the degree of mixing of m_F states in the region between state selector and C-field and is bounded by the magnitude of the distributed cavity phase shift. In order to avoid additional uncertainties in the evaluation of primary standards via beam reversal, the degree of m_F state mixing must be made identical for both transition regions on either side of the C-field region. This can be done by the techniques used in NBS-6 and many commercial tubes, i.e. by the use of trimmers, or by assuring complete mixing via properly designed magnetic field discontinuities in the transition region or via use of low frequency fields coupling the m_F-states. The former approach is sensitive to external fields; it also leads to a "correct" C-field polarity versus a "wrong" one [9]. Both approaches warrant further investigation to determine their full impact.

IV. CONCLUSIONS

It now seems clear that significant improvements are still possible in cesium beam frequency standards. The microwave cavity phase shift appears to be the transducer of many of the inaccuracies and long-term instabilities in such a standard. One needs to either reduce that shift or provide better control of those elements which transduce via this shift to cause inaccuracies and long-term instabilities. As an example a method is proposed in this paper of improving the control of the microwave power by one or two orders of magnitude which may yield parts in 10^{15} stability. Better cesium atom detectors, which are not cross section dependent with changes in the associated parameters, could significantly improve the long-term performance.

Magnetic field related frequency shifts can occur not only via changes in the C-field but via m_F-state mixing between state selector and C-field. However, a minor redesign could control this effect.

V. ACKNOWLEDGEMENTS

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[9] In NBS-6 as well as in NBS-5 all measurements reported in the past were done with the "correct" C-field polarity, i.e., preservation of the $m_F = 0$ state was assured by properly aligned trimmers for both beam directions. We believed until now that the trimmers helped only to improve the signal strength.

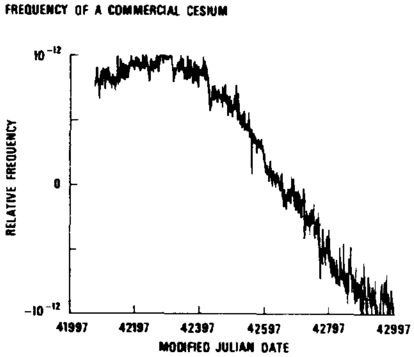

FIGURE 1 A plot of the relative frequency of a commercial cesium beam frequency standard with respect to the USNO frequency reference. The frequencies are one day averages and the plot is of about 900 days starting about the beginning of 1974. (Taken from ref. [4])

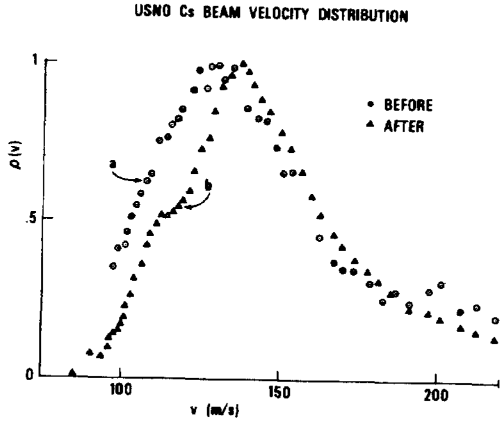

FIGURE 2 Curve a is a plot of the velocity distribution of the commercial cesium beam frequency standard. This distribution was measured (6 Dec. 76) after the data were taken at USNO (plotted in Fig. 1) and before modifying the detector. Curve b is a velocity distribution measured (14 Dec. 76) after the manufacturer's recommended modification to the cesium detection system.

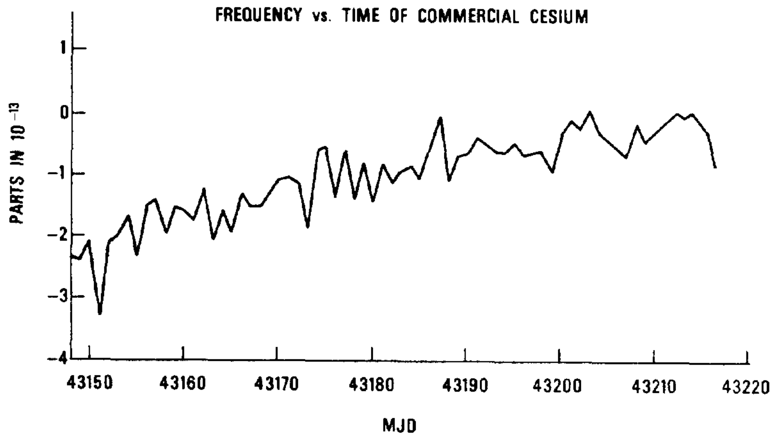

FIGURE 3 A plot of the frequency of a newly received commercial cesium beam frequency standard relative to an NBS frequency reference. Each point is a one day average, starting 5 Jan. 1977.

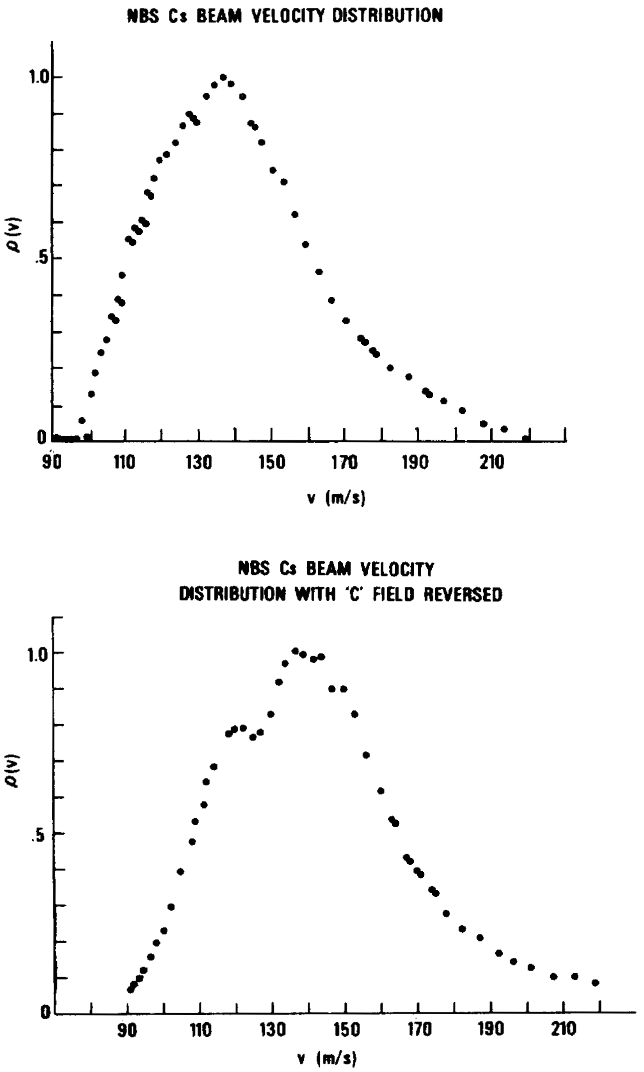

FIGURE 4 A velocity distribution measured (15 Mar 77) on the standard of Fig. 3.

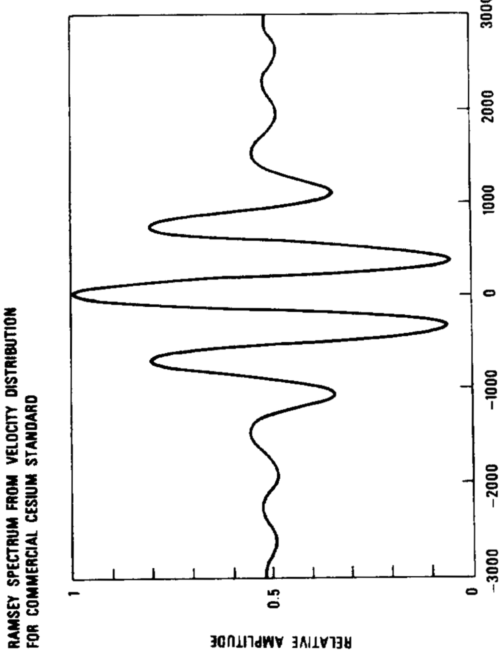

FIGURE 5 The Ramsey spectrum for a commercial cesium beam frequency standard as derived from the velocity distribution shown in Figure 4.

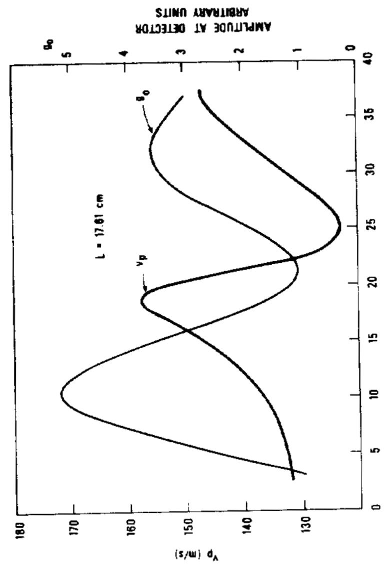

FIGURE 6 (a) The g_o curve is proportional to the beam current at the cesium beam detector (scale on right) as derived from the velocity distribution shown in Figure 4, as it depends on microwave power ($\propto b^2$);

(b) The v_p curve (ordinate scale on the left) is transition velocity as a function of microwave power as derived from the d(v) curve in Figure 4. Both curves are for the same commercial cesium beam frequency standard.

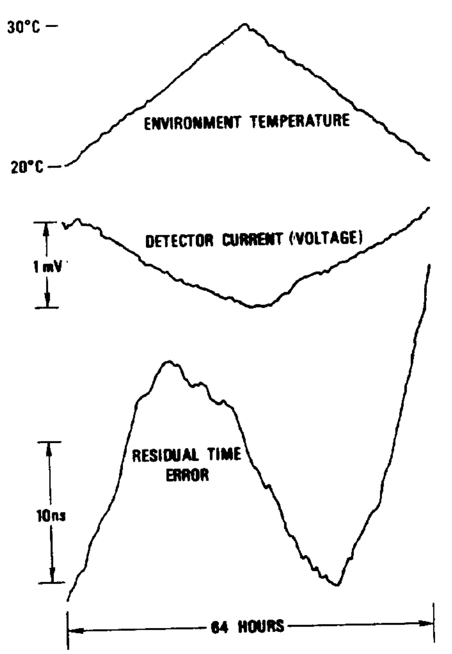

FIGURE 7. A plot of the changes in the residual time error and in the monitor voltage of the beam detector current as a function of the environmental temperature for the same commercial cesium beam frequency standard of Figures 3 and 4.

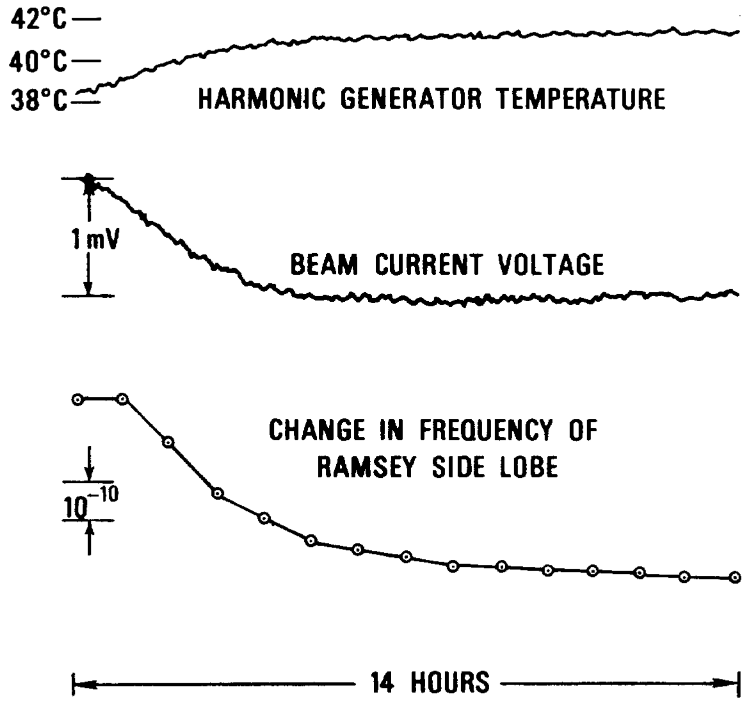

FIGURE 8 A plot of the dependence of the temperature at the harmonic generator (microwave source for the Ramsey cavity), of the monitor voltage of the beam detector current, and of the frequency of the upper first side lobe of the Ramsey spectrum as a function of environmental temperature of the same commercial cesium beam frequency standard of Figures 3 and 4. The environmental temperature was moved from about 23°C to about 27.5°C and left at the latter temperature for the last several hours of the experiment. The large dependence of the frequency of the Ramsey side lobe is obvious and was simple to measure; i.e., a frequency measurement was made every hour with an averaging time of 11 seconds.

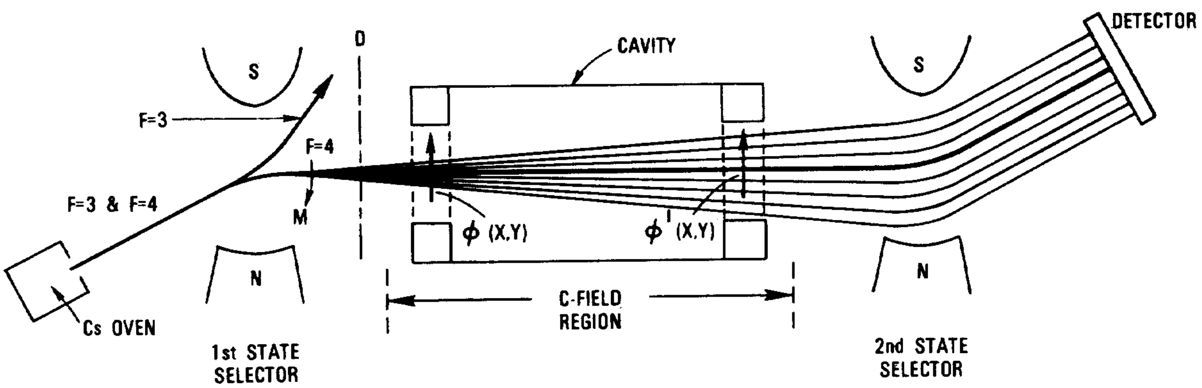

FIGURE 9 Frequency shifts due to distributed cavity phase shifts, $\delta(x,y)$ and $\delta'(x,y)$ in conjunction with m-state mixing.

D depicts an assumed magnetic field discontinuity causing more or less complete mixing of the m-states.

For illustration purposes, only one of several possible beam optics configurations is depicted.