# A NEW METHOD TO ELIMINATE CAVITY PHASE SHIFT IN CESIUM BEAM STANDARDS

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## Abstract

In our presently known laboratory and commercial cesium standards, the so-called Ramsey cavity is employed. The envelope of the associated Ramsey pattern is determined by the distribution of atomic velocities in the atomic beam. The wider the velocity distribution, the narrower will be the half-width of the envelope of the Ramsey pattern. The envelope of this Ramsey pattern is invariant against cavity phase shift. In other words, the center of the envelope - in contrast to the center of the main peak of the resonance - does not shift from cesium atomic resonance frequency when the cavity phase shift is varied.

Therefore, it is suggested that the systematic frequency shift due to an rf phase difference between the two interaction regions of a normal Ramsey cavity can be eliminated by using simultaneously two different frequencies around the cesium resonance applied to two separated interaction regions which are not part of the same cavity. To the atom this is equivalent to a time-varying cavity phase shift between the two interaction regions. A modulation of the frequencies $\nu_1$ and $\nu_2$ applied to cavities 1 and 2 will produce signals symmetrically spaced around true line center of the cesium resonance. This technique is briefly described and the advantages are noted.

An improvement in the achievable accuracy with laboratory type primary frequency standards appears possible. Commercially produced small beam tubes may realize accuracies presently achieved only with the much larger and more expensive laboratory units. In addition, long-term stability and clock performance should be enhanced significantly in both laboratory and commercial versions of this new technique. An experimental program aimed at realizing these advantages is presently under way.

## INTRODUCTION

Atomic clocks of many configurations have been studied, used, and commercially produced. The most used and important example is the cesium beam atomic frequency standard or clock. Devices of this type form the basis for today's time services as well as for precision navigation and communication systems. They are also used as the primary standard for the unit of time. In addition to a number of laboratory built cesium beam clocks, a large number of commercial cesium atomic clocks is in existence in the world.

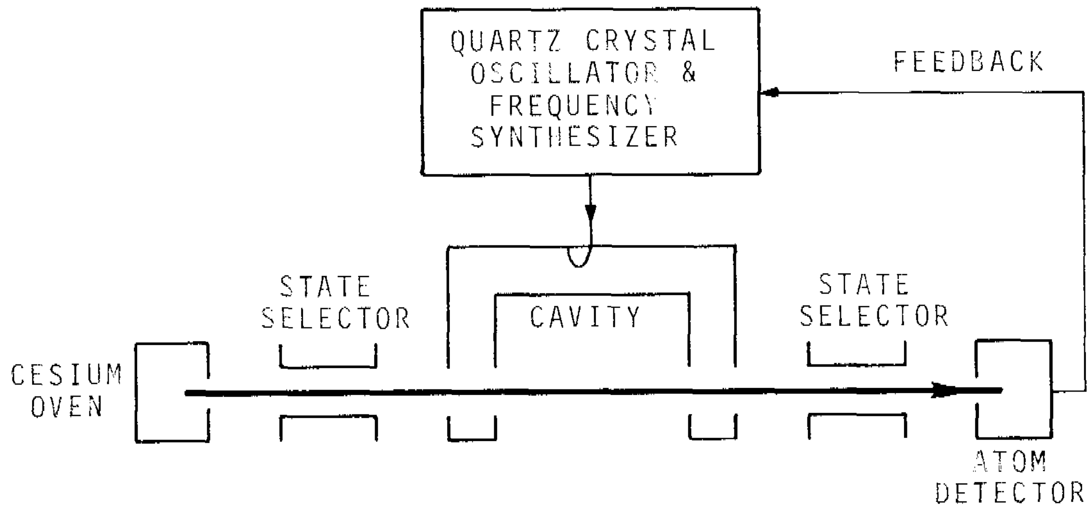


Figure 1. Schematic of a cesium beam frequency standard.

The basic configuration of a cesium standard is shown in Fig. 1. An oscillator (usually a crystal oscillator) is controlled via a servo loop by the cesium atomic resonator or beam tube. In order to lock the oscillator to the atomic resonance, the resonance has to be interrogated in order to produce an electronic signal at the detector which indicates how large the frequency offset from the atomic line center is and on which side of line center the frequency offset is located [1].

The properties of the microwave cavity to a high degree determine the performance of this device as a frequency standard or clock in terms of accuracy and long-term frequency stability. During the approximately twenty-five years of development of cesium beam devices, different cavity configurations and different modulation schemes have been tried. Most notably, cavities of the Ramsey type are being employed, i.e., two regions of interaction, spatially separated but part of the same microwave cavity as shown in Fig. 1 [2]. The modulation schemes for line-center lock which have been employed are generally of the frequency and phase modulation type, and sinewave or squarewave modulation has been used.

## CAVITY PHASE SHIFT

The properties of the cavity affect the apparent frequency of the cesium resonance, i.e., the interaction of the cavity with the resonating cesium atoms may cause an apparent shift of the resonance frequency from the true resonant frequency of the atom. Cavity phase shift is caused by a non-uniform phase in the microwave cavity, either an end-to-end phase difference or a distribution of phases along and across the atomic beam trajectories in the cavity [3]. This cavity phase shift currently limits the absolute accuracy of the primary cesium standards to about $1 \times 10^{-13}$ and the accuracy of commercial units to about $7 \times 10^{-12}$. There is also evidence that a time-varying cavity phase shift causes long-term frequency changes and instabilities (over the period of months to years) in such devices, limiting their usefulness as clocks in time generation.

In an atomic cesium standard using a Ramsey cavity there exists time dispersion between the two pulses (e.g., atomic beam with velocity spread which uses the separated oscillatory field technique) and one can observe the envelope of the resonance spectrum $g(\omega-\omega_o, \delta)$ (Ramsey pattern) as shown in Fig. 2. This envelope (dashed curve in Fig. 2) is symmetric

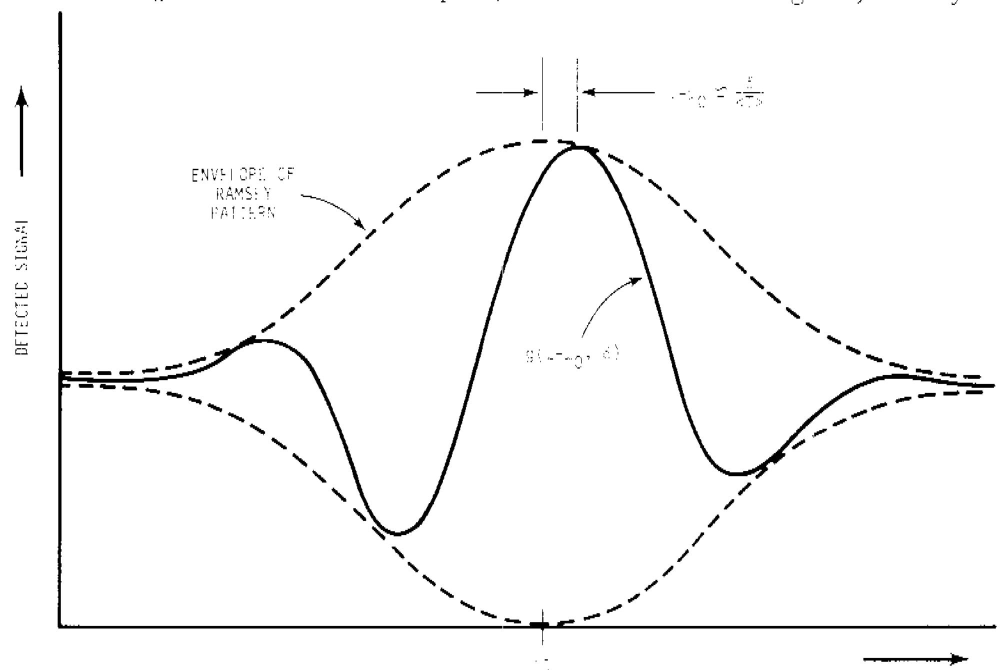


Figure 2. Microwave spectrum (Ramsey pattern) of a cesium tube using a Ramsey cavity.
$\omega_o$ = atomic (angular) resonance frequency,
$\delta$ = cavity phase difference,
<T> average time of flight between the two cavity regions.

with respect to rf phase shifts between the two interaction regions, while the Ramsey pattern itself, in general, is not, due to the cavity phase shift $\delta$ [4]. The central peak of the Ramsey pattern occurs approximately when $\omega - \omega_o \cong \delta/\langle T\rangle$ where $\langle T\rangle$ is the average transit time between interaction regions and where $\omega_o$ is the true atomic (angular) resonance frequency.

## ELIMINATION OF THE CAVITY PHASE SHIFT

The purpose of this paper is to describe briefly a variation of Ramsey's separated oscillatory field technique. In the simplest form of this new technique, the resonance sample is interrogated by two time-delayed pulses of radiation as in the original technique [2]. It differs in that the rf phase of the second pulse is allowed to advance (or recede) at a constant rate; that is, the microwave frequency of the second pulse is offset from that of the first. In its practical realization, the two interrogation regions are not part of a single cavity (as in the traditional Ramsey cavity) but rather independent cavities driven by the frequencies $\nu_1$ and $\nu_2$ as shown in Fig. 3.

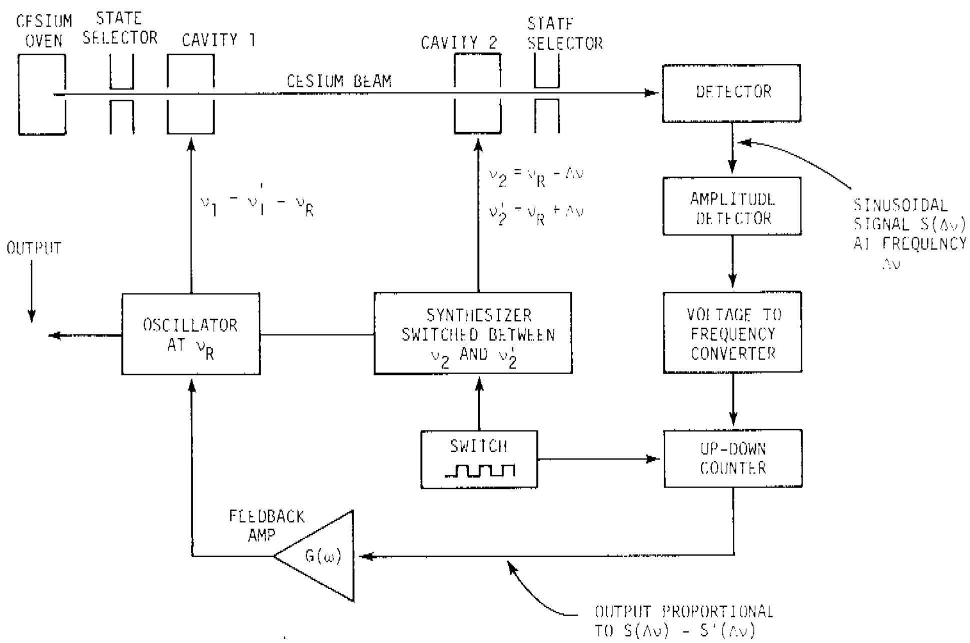


Figure 3. In this example; $\nu_1' = \nu_1 = \nu_R$, $\nu_2 = \nu_R - \Delta\nu$, $\nu_2' = \nu_R + \Delta\nu$ where $\Delta\nu \cong 1/T$ and where T is the approximate transit time of atoms between cavities. The servo finds the condition where $S(\Delta\nu) = S'(\Delta\nu)$ which is true only when $\nu_R = \nu_o$.

These two frequencies have a fixed frequency relationship to each other. The atoms are subjected to first the frequency $\nu_1$ in the interaction region 1, then to the frequency $\nu_2$ in the interaction region 2. To the atom, this is equivalent to a time-varying cavity phase shift between the two interaction regions; this cavity phase shift depends on the time-of-flight of the atoms between the two interaction regions and on the frequency difference $\nu_1 - \nu_2$.

At the detector there is a sinusoidally varying "signal" at frequency $\Delta\nu = \nu_1 - \nu_2$ whose amplitude depends on $\nu_1 - \nu_o$ and $\nu_2 - \nu_o$ where $\nu_o$ is the atomic resonance frequency. If frequencies $\nu_1'$ and $\nu_2'$ are now applied to cavities 1 and 2 respectively where $\nu_2' - \nu_1' = -(\nu_2 - \nu_1)$ then the signal at the detector has the same amplitude only when $(\nu_1 + \nu_1')/2 = \nu_o = (\nu_2 + \nu_2')/2$. For this "resonance" condition, any of the applied frequencies $(\nu_1, \nu_1', \nu_2, \nu_2')$ can be directly related to $\nu_o$. One example is given in Fig. 3.

One slight disadvantage of this method, as compared to traditional cesium standards, is that the Ramsey envelope is broader than the central Ramsey peak obtained in the usual arrangement. However, this loss of resolution should not have to be more than a factor of two for a beam with a broad (e.g., Maxwellian) distribution.

## CONCLUSIONS

The advantages of the above scheme are several:

(1) First-order phase-shift problems such as the cavity phase shift are eliminated in the two frequency separated oscillatory field method.

(2) Background pulling effects are greatly minimized in certain experiments. For example, in cesium clock operation systematic frequency pulling normally occurs due to overlap of the main line with (generally asymmetric) field-dependent transitions [5] ("Rabi" patterns). No signal content occurs at frequency $\Delta\nu$ from these overlapping transitions; this allows use of significantly reduced operating magnetic fields (which would normally increase this background pulling), thus greatly reducing magnetic field sensitivity of the clock transition, or alternatively reducing magnetic shielding requirements.

(3) Separate interaction regions can be constucted with low Q. This is an advantage because:
   (a) Cavity pulling [3] can be made negligible. For example, in a conventional atomic beam resonance apparatus using separated oscillatory fields the Q of the resonant cavity is made very high to make $|\delta|$ small. In the two-frequency method, two separate cavities of low Q can be made by terminating shorted pieces of waveguide at the input, thus making cavity pulling negligible. (We note that rf levels do not have to be the same in the two cavities.)
   (b) This may reduce fabrication complexity and cost. Moreover, superconducting cavities could be installed in laboratory standards such that only the end pieces were superconducting, thus simplifying the required cooling and eliminating distributed cavity phase shifts (see below).

(4) In high-accuracy frequency determinations, beam reversal [3] is no longer necessary, although it would provide a useful check of the method. Elimination of beam reversal would greatly simplify construction of laboratory standards and would give commercial cesium atomic clocks higher accuracy without increased complexity.

(5) Long-term frequency stability of devices using the two-frequency method should be increased. For example, in cesium beam frequency standards greater insensitivity to magnetic field, state selection, or cavity parameter changes should be obtained.

The above method does not completely eliminate systematic frequency offsets due to "distributed cavity phase shifts" [3,6]. This problem arises because the phase shift of the rf field may not be constant across the cross-section of the beam due to losses in the microwave cavity. However, the "distributed phase shift" problem may be more tractable with the two-frequency method. For example, the offset due to distributed cavity phase vanishes if the shape of the velocity distribution is the same on all the atomic trajectories through the cavities. Furthermore, as noted above, the distributed phase shift problem is completely eliminated by using superconducting cavities.

We have initiated an experimental program aimed at demonstrating this new technique. We are modifying an existing cesium beam tube to operate with this new cavity structure and a compatible electronic system along the principles depicted in Fig. 3.

## REFERENCES

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QUESTIONS AND ANSWERS

DR. VICTOR REINHARDT, NASA Goddard Space Flight Center:

What does the asymmetry in the velocity distribution do to this, and also what happens to your frequency stability versus averaging time due to the fact that you now have effectively a smaller line Q?

DR. HELLWIG:

A smaller line Q, as most of you know, effects short-term stability. And a factor of two in line Q means that you need a factor of four more atoms to compensate for that. I think we have that leeway in most tubes. It is not a big sacrifice. It is less than the difference, say, between so-called standard tubes and super tubes right now.

I didn't quite understand your first question--asymmetry and velocity distribution?

DR. REINHARDT:

In your previous slide, you've shown that some of the velocity distributions coming out of some of the beam tubes have had double humps. At first glance, it would seem that that nice picture with the nice envelope could possibly be an asymmetrical one which might lead to some frequency shifts in that case?

DR. HELLWIG:

No, it will not. The asymmetries in the velocity distribution will not cause asymmetries in the envelope at all, except for the second-order Doppler effect, which you know is a basic asymmetry to that pattern anyway. With all present-day tubes, it is of the order of $10^{-13}$ or even less, because of the very heavy low-velocity selection we are entering. So that is not a limitation.

To just comment one step further, if you really want to apply that principle to so-called primary standard laboratory-type devices, and you really want to push to 1 part in $10^{14}$ in accuracy, then you have to watch those. If you use beam reversal, it allows you to reduce an absolute knowledge of the velocity distributions to a symmetry argument. If you have basically similar velocity distributions with the two beams' directions, you are safe as far as the so-called distributed cavity phase shift is concerned, which is still a limitation.

MR. ANDREW CHI, NASA Goddard Space Flight Center:

The cavity phase shift of a cesium beam tube has a very gradual and slow change, which will stay put for a long time before you can observe it continuously. What is the relative gain when you don't shift the phase compared to when you do shift cavity phase? Also, when you try to do that, can you also control the relative amplitude of the side peak of the Ramsey resonance as a way to control its symmetry?

DR. HELLWIG:

I didn't quite get the second question. The first question was, what do you really gain by having rapidly changing phase shifts versus the rather steady and hardly varying phase shift which is present in present-day tubes?

First of all, the two animals are quite different. With the cavity phase shift built into the Ramsey-type cavities, you have a thing which causes you to be sensitive against other parameter variations. I agree with you that the phase shift itself doesn't vary much, but it makes you, for example, microwave power sensitive. It makes you sensitive against other things -- trajectory location effects and beam geometry effects under acceleration. These things transduce via a finite, even totally constant, cavity phase shift. And the electronic cavity phase shift which we are introducing certainly is varying. I just used that illustration as an example. The resonant spectrum of such a tube would be quite different. You will have no residual biases if you have the frequencies $\nu_1$ and the sidebands $\nu_2$ symmetric. Now, there is an easy way to do that: You create $\nu_2$ by having sidebands on $\nu_1$, and it is as symmetric as you want it.

DR. JACQUES VANIER, Laval University:

I did not quite understand this distribution. Is it not coming out to be the same thing as if you had simply one cavity after all?

DR. HELLWIG:

Your question relates back to why a Ramsey cavity is used. It is not equivalent because in a single cavity, you would have traveling waves going along the beam axis. The primary limitation of using a single cavity of a similar length is that you have residual losses and phase variations due to imperfections. You really have traveling waves along the whole interaction region which cause wild first-order Doppler effects. In fact, people have tried to build such things. They typically show parts in $10^{10}$ offsets because of them. This is the main advantage of two separate interaction regions. Additional advantages are the same whether you have it connected coherently or separately -- the averaging between the two regions as far as magnetic fields are concerned, for example. You are only sensitive to the average. Same here. It doesn't change.