THE CESIUM BEAM FREQUENCY STANDARD - PROSPECTS FOR THE FUTURE

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ABSTRACT

The present and future role of the cesium beam frequency standard in time and frequency metrology is briefly discussed. The present limitation of the cesium beam device is the uncertainty in the determination of the first- and second-order Doppler shifts. These are fundamental problems of all frequency standards and possible solutions in cesium clocks and other standards are mentioned.

The purpose of this paper is to put the cesium beam frequency standard into perspective; that is, to see how it compares with the new ideas for frequency standards, many of which are discussed in other papers from this conference. Perhaps it should be mentioned that cesium may have gotten some unfair treatment in the sense that the physics and the idea for the basic machine are fairly old, and therefore it may not have quite the flair or interest that some of the new ideas have. However, a good case can be made for pushing research on cesium further.

The advantages of the cesium beam standard are several. It is still the most accurate (reproducible) frequency standard available by at least an order of magnitude, and its long-term stability ($\sim 10^{-14}$ for weeks) is also unsurpassed. Another advantage and probably the reason for its longevity as a frequency standard is that by today's criteria it is a very simple device, hence it can be made rugged and has applications outside of the laboratory environment. Furthermore, it operates in the microwave region where frequency and time measurements are easily made. This is to be contrasted with the optical frequency standards which require a high quality multiplier from the radio-frequency range to the operating frequency in order to accomplish precise timing. Finally, its present limits are those which plague all frequency standards and these problems may prove to be more tractable with the cesium beam.

To give an idea of the present status of cesium beam standards, data are given for NBS-6, the primary cesium standard of the National Bureau of Standards. These data are not necessarily representative of other primary standards, notably those of the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the National Research Council (NRC), Canada, although uncertainties in output frequency are comparable at about 1 part in 10^{13} and the most important systematic frequency shift appears to be due to cavity phase shift. Table 1 shows the results of a recent evaluation of the systematic errors in NBS-6 [1]. The largest errors are those numbered 1(b), 3, 6(a), 6(b). The problems of second harmonic distortion and pulling by neighboring transitions are not serious or fundamental ones, and with sufficient care they could be reduced to give less than 1 part in 10^{14} error in NBS-6. More fundamental and serious problems are caused by the cavity phase shift and second-order Doppler shift correction.

The second-order Doppler shift is the familiar time dilation effect experienced by the atoms which move with respect to the laboratory-stationary clock apparatus. The uncertainty in the effect is governed by the imprecision of a velocity distribution determination or more precisely the imprecision of a determination of v^2 (proportional to temperature) averaged over the beam. Various techniques have been employed to measure this effect [2]; with care the uncertainty could be reduced below 1 part in 10^{14}. More importantly, this is a problem which all frequency standards encounter and at present the cesium standard can ascribe the smallest uncertainty due to this effect.

More serious is the problem of cavity phase shift. This is a form of residual first-order Doppler shift and is due to losses in the Ramsey microwave cavity. This residual effect affects all frequency standards to varying degrees; for example, in optical saturated absorption it results from wave front curvature. In cesium the effect is straightforwardly measured to first-order by reversing the direction of the beam, thereby changing the sign of the frequency shift. A problem occurs because the phase shift may be different at different locations in the microwave cavity; this occurs if, for example, one side of the cavity is more lossy than the other. This is really only a problem if, when the beam is reversed, we can not obtain exact beam retrace. Hence, the uncertainty in the determination of cavity phase shift is due to the uncertainty in obtaining retrace on beam reversal. The details of this measurement are further described in Ref. 1. It should be noted that this effect appears to be a main limitation in other primary cesium standards.

Outlined above are the factors which limit the accuracy of NBS-6. Rather than trying to speculate on the ultimate accuracy of cesium beam devices it may be useful to examine what is necessary to obtain accuracy better than 1 part in 10^{14}. To reach these accuracies one must first achieve stabilities which are significantly better than this. Therefore, one must locate and correct for those effects which degrade long-term stability. For example, in NBS-6 the frequency stability "floor" is limited to about 1 part in 10^{14} primarily because of magnetic field fluctuations. It is also important to increase the short-term stability (i.e., signal-to-noise) so that the time required to reach the stability "floor" is not impractically long.

The most significant problem is of course the uncertainty in the cavity phase shift determination. One solution of this may be a "software" solution. In the past, most measurements have been made by observing the change in line center for various parameter changes on the standard. However, the entire Ramsey resonance pattern contains information on cavity phase shift and other distortions and this information should be fully used [3]. This may involve a fairly extensive set of measurements since one must make assumptions about the form of the spatially distributed cavity phase shift, the form of the beam density <u>and</u> velocity distribution across the cavity and also requires an accurate knowledge of beam geometry.

An attractive solution to the cavity phase shift problem which eliminates the need for the above assumptions is to use superconducting Ramsey cavities. In this case, the low loss implies that the phase shift across the cavity is essentially constant; if this is true, one does not need to make assumptions about beam geometry or velocity distribution across the cavity.* In fact, one does not need to obtain exact beam retrace if the velocity distributions can be accurately measured for both beam directions. The limits of accuracy in this case would be provided by measurements of unloaded cavity Q which would a priori set upper limits on the spatially distributed cavity phase shift.

A more fundamental solution to the problems of first- and second-order Doppler shift is to slow the atoms down. In a cesium beam device this may be provided by laser radiation cooling [4] although rather strict requirements are placed on the laser if significant cooling (to temperatures of a few degrees Kelvin) is to be achieved. Another solution is to thermalize the atoms with a low temperature source. Both solutions require that beam intensities remain sufficiently high that short-term stability is not degraded.

For the long-term future it appears that the problems of first- and second-order Doppler shift must be solved in a fundamental way. This would be required of any frequency standard and implies that the atom must be slowed down. Aside from the above possibilities for cesium, an attractive solution exists with ion traps where radiation pressure cooling can be accomplished with a single frequency low power laser [5]. Any device using slow atoms (ions) must still of course have sufficient signal-to-noise to make precision measurements possible in a practical length of time.

*The overall cavity Q could be kept low by loading the cavity at the input, thus avoiding cavity pulling problems. It is most important to have the cavity lossless at the ends where the cesium beam passes through.

REFERENCES

[1] Wineland, D. J., Allan, D. W., Glaze, D. J., Hellwig, H., and Jarvis, S. Jr., "Results on limitations in primary cesium standard operation." To be published in IEEE Trans. on Instrumentation and Measurement.

[2] See for example:
Jarvis, S. Jr., "Determination of velocity distributions in molecular beam frequency standards from measured resonance curves," Metrologia, Vol. 10, pp. 87-98, 1974.

Hellwig, H., Allan, D. W., Jarvis, S. Jr., Glaze, D. J., "The realization of the second," Atomic Masses and Fundamental Constants 5, Plenum Press, New York pp. 330-336, 1976.

[3] One such example is discussed by G. Becker (PTB) at this conference. Also see:
Audoin, C., Lesage, P., Mungall, A. G., Second-order Doppler and cavity phase dependent frequency shifts in atomic beam frequency standards," IEEE Trans. Instr. Meas., IM-23, pp. 501-508, Dec. 1974 or Daams, H., "Corrections for second-order Doppler shift and cavity phase error in cesium atomic beam frequency standards," IEEE Trans. Instr. Meas., IM-23, pp. 509-514, Dec. 1974.

[4] Hänsch, T. W., and Schawlow, A. L., "Cooling of gases by laser radiation," Optics Comm. 13, pp. 68-69, Jan. 1975.

[5] Wineland, D., Dehmelt, H., "Proposed 10^{14} $\Delta\nu<\nu$ laser fluorescence spectroscopy on Tl^+ mono-ion oscillator III." Bull. A.P.S. 20, 637 (1975).
This is further discussed by H. Dehmelt in a paper at this conference.

TABLE I

	Bias	Bias (Δy)	Uncertainty
1.	Servo system offsets		
	(a) Amplifier offsets	0	$.02 \times 10^{-13}$
	(b) 2nd harmonic distortion	0	$.15 \times 10^{-13}$
2.	Magnetic field effects		
	(a) Offset due to finite field	$+ 536 \times 10^{-13}$ (Typical)	$.03 \times 10^{-13}$
	(b) Magnetic field inhomogeneity	$+ .02 \times 10^{-13}$	$.02 \times 10^{-13}$
	(c) Majorana transitions	0	$.03 \times 10^{-13}$
3.	Pulling by neighboring transitions	$+ .4 \times 10^{-13}$	$.20 \times 10^{-13}$
4.	Cavity pulling	0	$.01 \times 10^{-13}$
5.	RF spectrum	0	$.02 \times 10^{-13}$
6.	(a) Second order Doppler shift	-3.1×10^{-13} (Typical)	$.10 \times 10^{-13}$
	(b) Cavity phase shift (for a particular direction)	$+ .25 \times 10^{-13}$	$.80 \times 10^{-13}$
	Total error due to systematic frequency biases		
	(a) Root mean square	--	$.85 \times 10^{-13}$
	(b) Sum of errors	--	1.38×10^{-13}
7.	Random uncertainty	0	$.31 \times 10^{-13}$