Laser-Cooled and Trapped Atoms, (Proceedings of the Workshop on Spectroscopic Applications of Slow Atomic Beams, held at NBS, Gaithersburg, MD, 14-15 April 1983) Ed. by W. D. Phillips, Natl. Bur. Stand. (U.S.) Spec. Publ. 653 (1983).

Limitations of Atomic Beam Frequency Standards

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ABSTRACT

Atomic beam frequency standards may be placed into two categories: field standards and laboratory standards. While this distinction is somewhat artificial, because the two types of standards are interdependent, each category does have different requirements of accuracy, size, and cost. Despite this separation, generally the developments which produce the best laboratory standards eventually give rise to improved field standards. Existing field standards are limited in long term fractional frequency stability to $\sigma_y(\tau) \sim 3 \times 10^{-13}$, for $\tau \sim 6$ months. A laboratory standard such as NBS-6, the U. S. primary cesium standard, is limited in inaccuracy to $\Delta y \sim 8 \times 10^{-14}$. Proposed new cesium field standards are expected to yield long term stabilities of $\sigma_y(\tau) \sim 1 \times 10^{-14}$ ($\tau = 6$ months). Stored ion standards, prime candidates for new laboratory frequency standards, are expected to have better than $\Delta y = 1 \times 10^{-15}$ inaccuracy. As other approaches to atomic beam frequency standards are considered, they should attempt to compete favorably with these emerging technologies.

Key Words: atomic beams, atomic frequency standard, cooled atoms, optical pumping.

General Characteristics of Atomic Beam Standards

Atomic frequency standards may be divided into two categories--field standards and laboratory standards. The distinction is useful because the most highly desired characteristics in each category often preclude the realization of the properties most sought after in the other category. For example, a field standard must be durable, portable, reliable, and easily operated, with unsupervised operating periods of months to years. A laboratory standard, on the other hand, must attain the highest possible accuracy, even if the device requires considerable space, power, money, and the patience of five Ph.D. physicists. In discussing the limitations of existing standards, or in projecting the usefulness of proposed new standards,it is helpful to keep in mind the category of interest, as the criteria vary with application. At the same time, it is important to realize that this distinction is somewhat artificial, as field standards have historically descended from the laboratory standards. Generally, the knowledge and technologies which have been developed in order to adequately describe the frequency offsets and uncertainties in high accuracy laboratory standards have been sucessfully applied to the development of field standards. A good example of this relationship between research and application is the production of the commercial cesium beam standard, which followed the creation of the laboratory cesium standard. Because of this widespread use of cesium beams, this paper will discuss the limitations of atomic beam frequency standards in terms of the of velocity distributions) by reversal of the atomic beam direction. Roughly speaking, the average of the clock frequencies for the two directions is the correct value. This frequency offset is about 3.6×10^{-13} in NBS-6. To the degree that the atomic beam path is retraced upon beam reversal, the frequency shift due to distributed cavity phase shift (a consequence of residual 1st order Doppler) is also cancelled. In NBS-6, the size of this effect is about 1×10^{-13}/mm of spatial offset of the atomic beam [2]. Fractional frequency offsets Δy_ϕ due to microwave cavity phase shift $\Delta\phi$ are given by

$$\Delta y_\phi = \frac{\Delta\phi/2\pi}{(L/V_p)} \nu_o , \tag{1}$$

where L is the interaction length, V_p is the effective atomic beam velocity, and ν_o is the resonance frequency. This expression shows explicitly that the effect of cavity phase shift can be reduced by increasing the interrogation time $\tau = (L/V_p)$.

If cavity phase shifts in commercial standards are comparable in size to those in NBS-6, then the expected frequency shifts due to distributed cavity phase shifts should be

$$\Delta y_\phi \sim \frac{Q(\text{laboratory std})}{Q(\text{field std})} \times 10^{-13} = 3 \times 10^{-12}.$$

This would suggest that cavity phase shifts may be a limiting systematic in field standards as well as in laboratory cesium standards.

Of the remaining systematics, those of most concern for improving standards' performance are second order Doppler and the various electronics servo limitations. For an atomic beam of effective velocity V_d, the clock fractional frequency is shifted by an amount

$$\Delta y_d = -\tfrac{1}{2} \frac{V_d^2}{c^2} \tag{2}$$

Evaluation of this systematic requires knowledge of the atomic beam velocity distribution, as seen by the complete microwave resonance spectrometer. In the past this distribution has been determined by using pulsed interrogation techniques [5] and by unfolding the microwave spectrum at different microwave power levels [6]. While the uncertainty in this shift is quoted at the 1×10^{-14} level, it is anticipated that an order of magnitude reduction of the uncertainty may be had with exercise of considerable care in the measurement. This process is greatly helped if a narrower velocity distribution is used in the atomic beam.

The evaluation of NBS-6 requires that the electronic servo find the center of the microwave resonance to better than about one part in 10^5. Implicit is the assumption that the physical resonance itself is symmetric to this level. This assumption is supported by the fact that no significant frequency shift is observed when the amplitude of microwave phase modulation is changed. Further checks on frequency shifts due to imperfect electronics include measurement of integrator input offsets and frequency shifts with microwave power change. Again, the demands placed upon the servo are reduced with increase in microwave interaction time, since a narrower microwave resonance need not be split as finely.

A further refinement of this method is to use two lasers for optical pumping [11]. One laser may be tuned to the $^2S_{\frac{1}{2}}$, F=3 $\leftrightarrow$ $^2F_{3/2}$, F'=3 transition using π polarization. This pumps all magnetic midlevels of the F=3 ground state HFS into the F=4 HFS, with the exception of the m=0 sublevel. The second laser, tuned to the $^2S_{\frac{1}{2}}$, F=4 $\leftrightarrow$ $^2P_{3/2}$, F'=3 transition pumps atoms back to the F=3 HFS. After many cycles of this process, most atoms should reside in the F=3, m=0 sublevel. An example of this process is given in Figure III, where the pumping into m=0 is incomplete because of an insufficient number of pumping cycles. Further work on this technique is in progress.

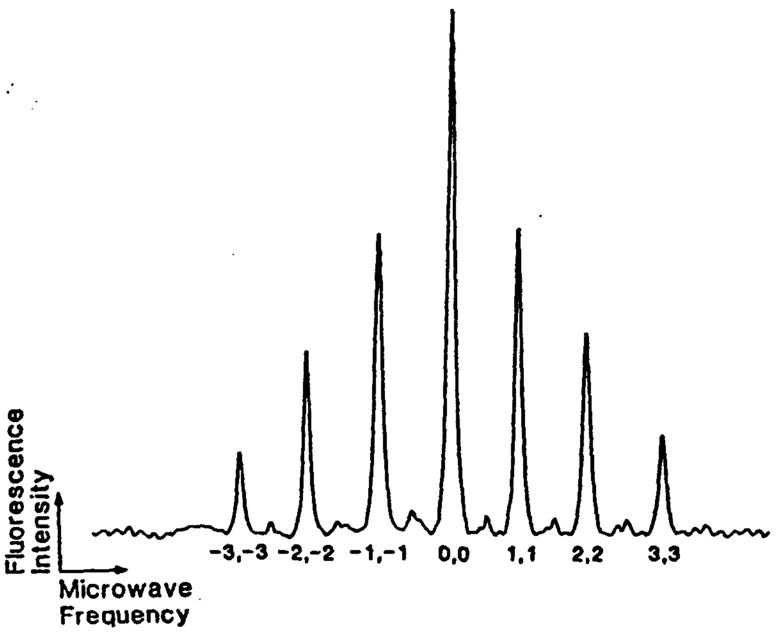

Figure III. Two-laser optical pumping, using both F=4 $\leftrightarrow$ F'=4, σ-polarization and F=3 $\leftrightarrow$ F'=3, π-polarization pump lasers, and a F=4 $\leftrightarrow$ F'=5 detection laser.

Optical pumping is expected to improve the performance of field standards by both reducing the size of systematics and by allowing more precise evaluation of their uncertainties. Since nearly all atoms are selected and detected, regardless of their spatial position or velocity, the effect of the distributed cavity place shift is simplified. A smaller cesium beam diameter is possible, resulting in a smaller microwave cavity window, which should give a smaller frequency offset [4]. In addition, since atoms which have been pumped into the F=3 HFS are invisible to the F=4 $\rightarrow$ F'=5 detection laser, it may be possible to operate simultaneously counterpropagating cesium beams, which would permit the evaluation of the cavity phase shift in a field standard.

Other benefits of optical pumping and fluorescence detection in a field standard include increased S/N, more symmetric microwave spectra (of the Zeeman split lines), and reduced liklihood of Majorana transitions, which may produce fairly substantial frequency shifts [12,13].

Further improvement in the performance of the proposed standard comes from use of on-board systematics evaluation. This "introspective" approach involves the measurement of sytematic effects by monitoring the atoms themselves. For example, the Zeeman splitting can be measured to give a value of the magnetic field which will shift the clock resonance a known amount. Other systematics to be measured in similar ways include second order Doppler and microwave power dependence.

where S/N is the power signal-to-noise in a one hertz bandwidth, and K is a constant which depends upon the resonance lineshape. Generally, K lies between 0.1 and 1.0. For traditional cesium standards, $K \sim 0.2$. The quantity S/N is generally limited by the "shot noise" on the number of atoms in the atomic beam, which decreases relative to the signal as the beam flux is increased. The short term stability should be sufficient to permit measurement of clock performance within a reasonable period of time. In a field standard, this means $\sigma_y(\tau) < 1 \times 10^{-11}\tau^{-\frac{1}{2}}$. In a primary standard, $\sigma_y(\tau) < 1 \times 10^{-12}\tau^{-\frac{1}{2}}$.

4. Transverse heating. As an atomic beam is cooled, increased energy is associated with the atoms' transverse motion, resulting in a spreading of the beam. This effect might be reduced with the use of additional lasers or some other cooling mechanism. However, whatever method is chosen to prevent loss of beam flux through transverse heating, it must not introduce additional systematics, such as frequency shifts associated with the microwave cavity.
5. Cavity phase shift. In itself, this frequency shift is expected to be reduced in a slow atomic clock. (See Eq. 1). However, slow atoms are perturbed for a longer time by gravity and acceleration, resulting in larger deflection angles of the atomic beam. This can produce larger clock frequency shifts associated with the distributed cavity phase shift as discussed above.
6. Gravity. As longer and longer observation times are employed with free neutral atoms, gravity plays a more and more important role. Some effects are interactive, such as the cavity phase shift mentioned above. A more direct consequence is size and geometry, as a clock which uses very slow atoms must accomodate the falling atoms.
7. Light shifts. The use of lasers to perform the cooling of the atoms, and the concommitant fluorescence light can introduce substantial light shifts [20]. Methods would need to be developed to greatly reduce or eliminate this effect on the standard's performance.

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Table II. NBS-6 Evaluation, April 1982.

Systematic	Value ($\times 10^{14}$)	Uncertainty ($\times 10^{14}$)
C-field	5335	3
Mag. field Inhomo.		0.2
Majorana		0.3
tail pulling		2
cavity pulling		0.1
RF spectrum		1.0
2nd order doppler	26	1.0
cavity phase shift	36	8.0
amplifier offset		1.0
2nd harmonic distortion		2.0
uncertainty in ϕ_C due to $\delta[\rho(v)]$		1.0
blackbody shift	1.7	0.0
		RSS 9.2
		random 1.0
		total (RSS) 9.3