Frequency Standards Based on Atomic Hydrogen

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Invited Paper

The current state of hydrogen maser frequency standards is briefly reviewed. Particular emphasis is placed on the discussion of physical mechanisms which affect long-term stability. While questions concerning absolute accuracy still remain, recent experiments suggest that long-term stability can be at least as good as the best primary standards (1×10^{-13}/year). This long-term stability can be realized by small passive hydrogen maser field standards, a fact which makes these attractive alternatives to cesium field standards. Hydrogen masers already exhibit the best short-term stability of any room-temperature atomic clock and this could be improved by a factor of 100 with the development of hydrogen masers operating at cryogenic temperatures.

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I. INTRODUCTION

Of all the present atomic-based microwave frequency standards, room-temperature hydrogen masers have the best short-term frequency stability. This is a consequence of the long storage times that can be achieved in a teflon-coated storage bulb, and the large number of atoms that can be used [1], [2]. The storage feature of the hydrogen maser also virtually eliminates residual first-order Doppler shifts but introduces a frequency shift due to the atoms colliding with the wall [1]. Significant advances have been made in understanding and lowering the uncertainty of this and several other systematic frequency shifts which affect hydrogen masers [1], [3]–[6].

Until fairly recently, the long-term frequency stability was primarily limited by the frequency drift of the microwave cavity pulling the atomic resonance. New electronic approaches have demonstrated about a factor of 100 reduction in frequency drift due to this effect, and also permitted a factor of approximately 10 reduction in size [6], [7]. As a consequence, the stability of some new small passive hydrogen masers is now better than the best commercially available cesium frequency standards and even national time scales for periods of at least weeks [6]. The use of cavity control electronics on full-sized masers should provide even greater improvement in stability than that observed with the new small masers [8]. For the purpose of this paper hydrogen masers will be classified as active masers (oscillation is self-excited), compact regenerative masers (oscillation requires additional gain), and passive masers (oscillation requires an external local oscillator to probe the resonance).

Fundamental improvements in short-term stability could be realized in the new cryogenic masers which are under development [9]–[11]. Although it is still very difficult to project long-term stability and accuracy, it is clear that the short-term stability could easily exceed that of all present room-temperature hydrogen masers by a factor of 100 due to the higher densities available, and lower thermal noise.

II. SYTEMATIC EFFECTS AND LONG-TERM FREQUENCY STABILITY

Systematic effects which can perturb the output frequency of room temperature hydrogen masers are listed in Table 1. An excellent review of current state of the art and forecast along with a very complete compendium of references are given in [12]. Typical offsets as well as the expected effect on stability are given. Although the second-order Doppler effect is large, it is relatively easy to control [1]. The atoms thermalize on the walls of the storage bulb in several bounces and very accurately follow its temperature. Therefore, thermal control of the storage bulb to 0.01 K stabilizes this effect to 1.4×10^{-15}. The wall shift has been studied by several investigators with somewhat inconsistent results [5], [12]–[14]. The absolute offset could only be determined to about 1×10^{-12} due to an apparent lack of reproducibility of the coating process. This lack of reproducibility may be due to magnetic inhomogeneity shifts (discussed below) not accounted for in the early work and not the teflon coating [3]. Studies of two full sized hydrogen masers where the cavity was carefully retuned for each measurement show that the frequency can be reproduced to within 2×10^{-14} over 45 days [15]. Tests done at the same facility on a small passive maser with automatic cavity control also agreed to within 2×10^{-14} over the same period. Independent tests on two models of small passive masers produced similar results [4], [6]. These two masers were compared with the cesium-based time scale at the National Bureau of Standards. Work by Morris [16], Hibbard [17], and Gaigerov *et al.* [18] indicate that under some conditions aging of the wall shift does occur. It's not clear as yet whether it is due to the particular teflon batch or the application procedures. Gaigerov *et al.* [18] report that their best devices approach an aging of $\approx 1 \times 10^{-14}$/year. Taken together these results indicate that the changes in the wall shift can be less than 3×10^{-16}/day or 1×10^{-13}/year, which is approximately the current uncertainty of the cesium-based national time scales. Although questions of absolute accuracy still remain, the stability of the best wall coating seems to be as good as the stability of our best long-term references.

Spin exchange shifts are typically of order $\Delta\nu/\nu = 2$ to 20×10^{-13} [4], [6]. Generally, spin exchange shifts are compensated for by controlled offset tuning of the microwave cavity and residual uncertainties are probably not significant at the 2×10^{-14} level immediately after tuning [15], [16].

Table 1 H-Maser Frequency Perturbations

Effect	$\Delta\nu/\nu$	Typical Large Active Maser	Typical Miniature Passive Maser
Cavity pulling and servo errors	$-\frac{Q_C}{Q_H}\frac{\nu_c - \nu_0}{\nu_0}$	2×10^{-12} compensated by spin exchange	$\leq 1 \times 10^{-13}$ includes servo errors
2nd-order Doppler	-1.38×10^{-13} T	-4×10^{-11}	-4×10^{-11}
Wall shift	$\frac{-K \text{ area}}{\nu_0 \text{ volume}}[1 - \alpha(T - 313)]$	1×10^{-11}	2×10^{-11}
Magnetic field	$2.75 \times 10^{-11}\ H^2(\mathrm{T})$	$2\text{–}10 \times 10^{-14}$	$2\text{–}10 \times 10^{-14}$
Spin exchange	$\frac{\lambda n_a V_r}{8\pi\nu_0}(\rho_{1,0} - \rho_{0,0})$	2×10^{-12} compensated by cavity pulling	$1\text{–}2 \times 10^{-13}$
Spin exchange	$\frac{e_H n_a V_r \sigma}{2\pi\nu_0}$	$1\text{–}3 \times 10^{-13}$	included above
Magnetic field inhomogeneity	$[K'(\rho_{1,1} - \rho_{1,-1})]$		
	$\frac{H_r^{RF}}{H_Z^{RF}}\ H^{dc}$ bulb	$1\text{–}10 \times 10^{-13}$	2×10^{-13}

However as the cavity drifts away from the tuning point, frequency shifts are generated. The sensitivity to cavity mistuning is given by $\Delta\nu/\nu = Q_c/Q_h\ (\nu_c - \nu_h)/\nu_h$, where Q_c is the loaded quality factor of the cavity, Q_h is the quality factor of the hydrogen transition, ν_c is the cavity frequency, and ν_h is the hydrogen frequency. For a full-sized cavity, one typically observes a drift rate of order 1×10^{-14}/day in the output frequency. At least five different styles of prototype masers utilizing cavity control have been evaluated [4], [6]–[8], [17]. In all of these devices, significant improvements in frequency stability to measurement times of days have been observed. Several months of data on two types of passive hydrogen masers show no frequency drift versus the National Bureau of Standards cesium-based time scale to within 3×10^{-16}/day or 1×10^{-13}/year. [4], [6]. This shows that the effect of cavity drift can be virtually eliminated at the present level of our best long-term references. Changes in the nonspin exchange contribution to the linewidth causes frequency changes in the output frequency of the present design of active masers which leads to an "apparent" frequency drift through the e_H term of Table 1. These effects are not directly present in masers which are not spin-exchange tuned.

Magnetic-field sensitivity of the separation of the hyperfine levels of hydrogen is relatively high compared to cesium. However, the working magnetic field is generally so low as to make the sensitivity of the output frequency to small changes in the external field comparable for the two kinds of clocks. Typically one observes sensitivities $\Delta\nu/\nu$, of order 1 to 10×10^{-14} per 10^{-4} T change in the externally applied magnetic field. This sensitivity is a combination of both the inherent hyperfine sensitivity (reduced by the magnetic shield configuration) and the magnetic field inhomogeneity shift. In many cases, the second effect is the dominant one. This effect is caused by the combination of induced Majorana transitions between the state selector and the storage bulb, a component of microwave radial magnetic field, and curvature in the applied dc magnetic field [3]. The effect is greatly exacerbated by large holes in the magnetic shields, and probably explains many of the

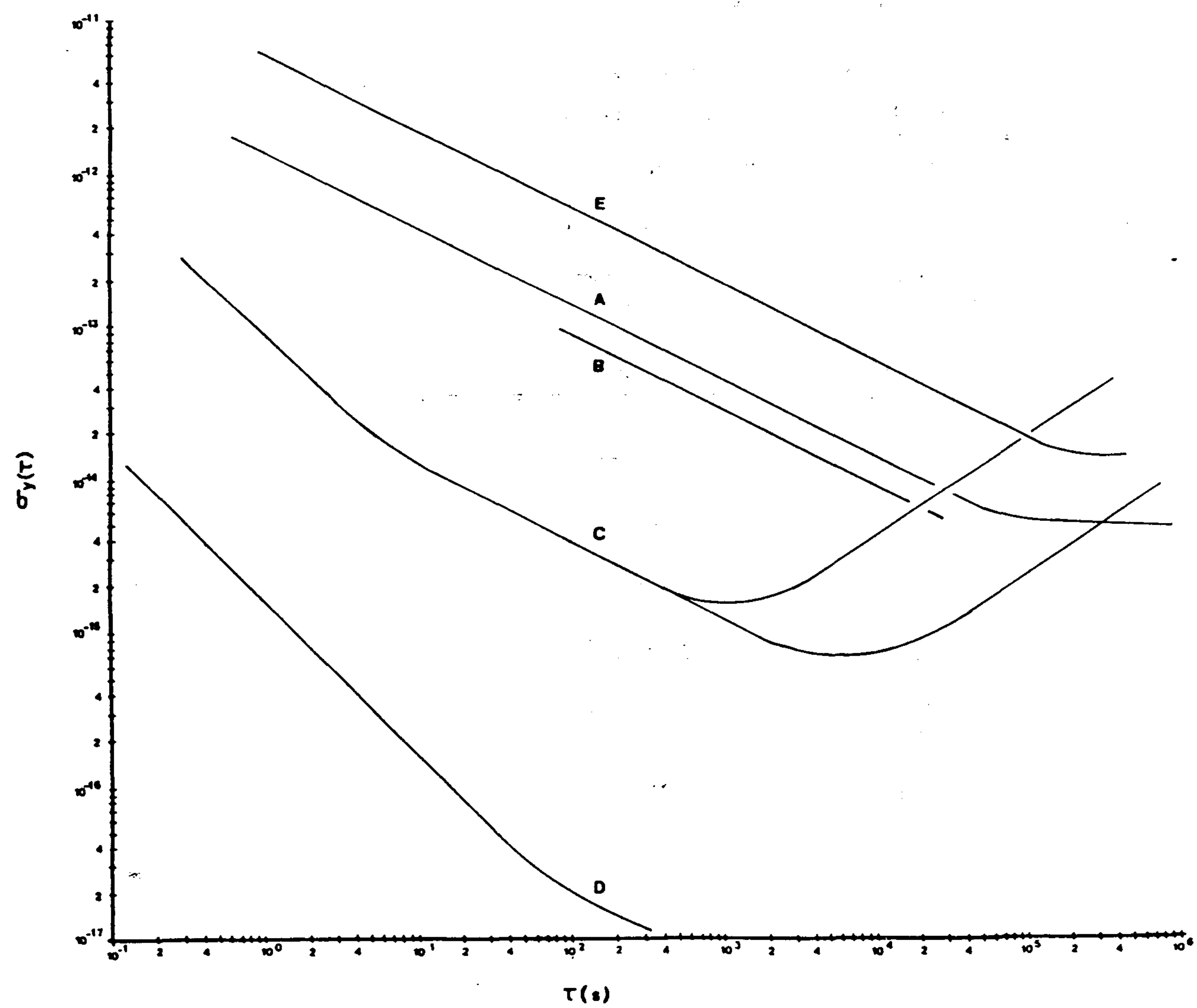

Fig. 1. Frequency stability of several passive masers *A* [6], compact regenerative masers *B* [7], active masers *C* [10], [15], expected cryogenic masers *D* [10], and high-performance cesium standards *E* [2].

inconsistent results and drifts observed in the early work. The use of a shield around the beam path from the state selector to the entrance of the magnetic shield package can greatly reduce this effect. Magnetic field induced frequency changes as low as $\Delta\nu/\nu = 2 \times 10^{-15}$ for $\pm$ 1.5×10^{-5} T have been reported [6].

Electronically induced frequency offsets vary greatly depending on the exact approach used to interrogate the atomic resonance. In active masers, the electronic offsets appear primarily through phase fluctuations and cavity offset. In the passive masers, additional frequency offsets and fluctuations can appear due to various errors in the servo systems [4], [6], [18]. Recent tests on the miniature passive masers developed at the National Bureau of Standards indicate that these offsets are less than about 1×10^{-13} and are extremely stable for a specific unit. The output frequency recovers to within $\pm$ 2×10^{-13} upon substitution of various electronic subassemblies or even cycling to atmospheric pressure for servicing. The best specification currently available on commercial cesium standards is 3×10^{-12}, and the nominal value for primary cesium standards is of order 3 to 10×10^{-14} [6].

III. MINIATURE HYDROGEN MASERS

The new electronic concepts used for cavity control make it possible to use small microwave cavities which could never oscillate in the standard maser configuration [1], [4], [6], [7], [17]. Q_c is typically of order 4000 in these devices, compared to about 30000 in a standard full-sized maser. The short-term frequency stability is significantly reduced by the lower cavity Q factor since [16]

$$\sigma_y(\tau) \sim \frac{K}{Q_h}\sqrt{\frac{kT}{IQ_c\tau}} \tag{1}$$

where k is Boltzmann's constant, I the atomic flux, and K depends on the exact method of interrogation. The optimum atomic flux is determined by the competition between power delivered by the atoms and spin exchange broadening of the resonance which lowers Q_h [16].

However, the small passive masers currently are much more stable in the long term than full-sized masers, due to the virtual elimination of cavity drift. Over time periods of many weeks at least one type has proven to be as stable as the U.S. national time scale [6]. This is not fundamental to the small size and one would expect to see both better short-term and long-term frequency stability in full-sized masers as they incorporate some of these new ideas [8]. Fig. 1 compares the published frequency stabilities of several passive masers with active masers and high-performance commercial cesium devices.

The weight of current prototype small masers vary from about 20 to 30 kg, while full-sized masers are typically 150 to 700 kg. They are much smaller in volume and they should be much less expensive than standard active masers. Small environmental sensitivities are also somewhat easier to obtain due to the smaller physical size.

IV. CRYOGENIC MASERS

Recent work shows tremendous potential for cryogenic hydrogen masers [9]–[11]. From (1), one can see that lowering the temperature to a few kelvins greatly reduces the thermal noise contribution from the cavity and probably from the amplifier as well. In addition, at these low temperatures, the spin exchange cross section is reduced by about a factor of a thousand thereby permitting much higher densities of atoms before serious broadening shifts occur [9]. The combination of these two effects alone could improve the short-term frequency stability by a factor of approximately 300. The cavity Q factor should also be improved yielding further gains. There are some problems, however. The wall shift at cryogenic temperatures is quite large—about 3×10^{-11} for hydrogen on superfluid ^{4}He [9] and about 10^{-9} for hydrogen on solid Ne [11]. The repeatability for superfluid ^{4}He should be excellent, whereas that for solid Ne is more questionable. Some of the problems with ^{3}He and ^{4}He are shown in Fig. 2. The temperature must be very carefully controlled in order to stabilize the wall shift. Moreover, the mean free path of the hydrogen/helium collision at 0.5 K is smaller than the dimensions of the bulb [9]. This will require creative methods for state preparation, and it removes one of the most powerful features of room-temperature masers; namely, the ability of the atoms to average over the entire sample volume and thereby greatly reduce the effects of gradients. Even though there are many unanswered questions, the potential improvements in short-term stability are very exciting.

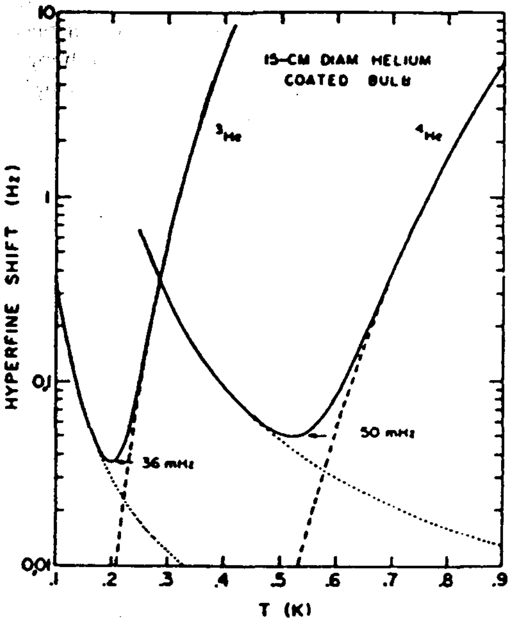

Fig. 2. Predicted hyperfine shift versus temperature for a 15-cm-diameter bulb coated with liquid ^{3}He and ^{4}He [9].

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