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NIST-7, THE NEW US PRIMARY FREQUENCY STANDARD*

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Abstract

NIST-7, an optically pumped, cesium-beam frequency standard has replaced NBS-6 as the official US primary frequency standard. The present short-term stability of the standard, measured with respect to an active hydrogen maser, is characterized by $\sigma_y(\tau) \approx 8 \times 10^{-13} \tau^{-1/2}$. Our first evaluation has resulted in an uncertainty of 4×10^{-14}. An improved servo-electronic system is being developed and this should improve stability and allow for more precise evaluation of the various systematic errors.

INTRODUCTION

An optically pumped, thermal atomic-beam frequency standard developed at NIST and known as NIST-7 has officially replaced NBS-6 as the US primary frequency standard. In the preliminary operation reported here, the standard has been shown to have both accuracy and stability that are several times better than NBS-6. Furthermore, these parameters are expected to improve in the near future with improved servo electronics.

The standard has been described elsewhere [1]. Briefly, the Ramsey cavity is 1.55 m long, and the atomic beam is 3 mm in diameter. An axial C-field geometry is employed and the atomic beam goes through the X-band waveguide cavity parallel to the long dimension of the waveguide. The microwave field, therefore, varies as a half-sine wave in the direction of the atomic beam; this results in Rabi lineshapes with very smooth and rapidly damped tails (see Fig. 1). The cavity ends are designed so the Poynting vector vanishes in the center of the atomic beam window [2], thus minimizing distributed-cavity phase shift.

For the evaluation reported here, a single, grating-feedback diode laser (linewidth ≤ 100 kHz) was frequency-locked to the $F = 4 \rightarrow F' = 3$ saturated-absorption feature in an external cesium cell. Approximately 0.1 mW in a 3 mm diameter ($2w_0$) light beam with linear polarization was used for state preparation. The optical pumping beam was orthogonal to the atomic beam and was retroreflected with its polarization rotated by 90°. This creates a zone of "randomized polarization" which leads to complete optical pumping (≥ 99.9%) and avoids the problem of coherence trapping [3]. An acousto-optic device was used to synthesize a second light beam with the ≈ 450 MHz offset necessary to drive the $F = 4 \rightarrow F' = 5$ cycling transition in the detection region. The power density in this beam was adjusted to scatter approximately 10 photons per atom. The overall fluorescence collection and detection efficiency is ≥ 40%.

Measurements of frequency shifts reported here were made relative to an active hydrogen maser. At present, the stability of the standard is characterized by $\sigma_y(\tau) \approx 8 \times 10^{-13} \tau^{-1/2}$ (Fig. 2) and is limited by phase noise in the microwave radiation. The standard is designed to operate with an oven temperature of 110°C at which point the atomic shot-noise limited stability should be $\approx 3 \times 10^{-13} \tau^{-1/2}$. The frequency biases and their associated uncertainties are quoted throughout this paper in terms of fractional frequency change in the standard.

EVALUATION

The first evaluation of the standard has been reported in detail elsewhere [4] and will only briefly be presented here with the results summarized in Table 1. The correction for second-order Zeeman effect is made by measuring the first-order Zeeman splitting. Errors caused by field inhomogeneity are less than 10^{-15}. At present, the correction for the second-order Doppler shift has been made by a theoretical calculation which takes into account the

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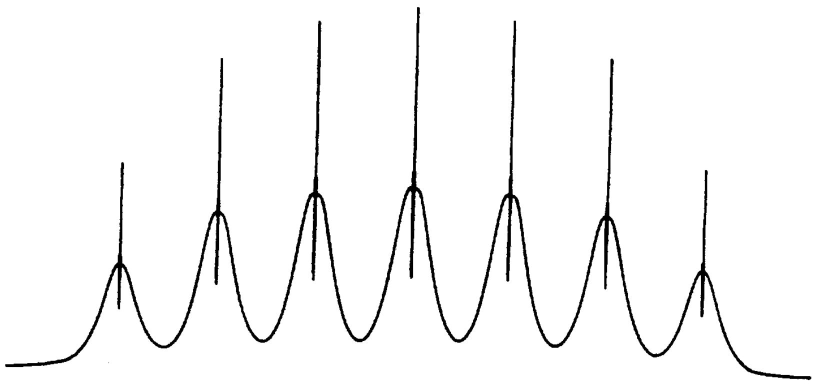

Fig. 1. Zeeman spectrum of the F = 3 to F = 4 transition. The microwave power level is about 7 dB below optimum and the C-field corresponds to a first order Zeeman splitting of 24.2 KHz ($\nu_{0,0}$ - $\nu_{1,1}$).

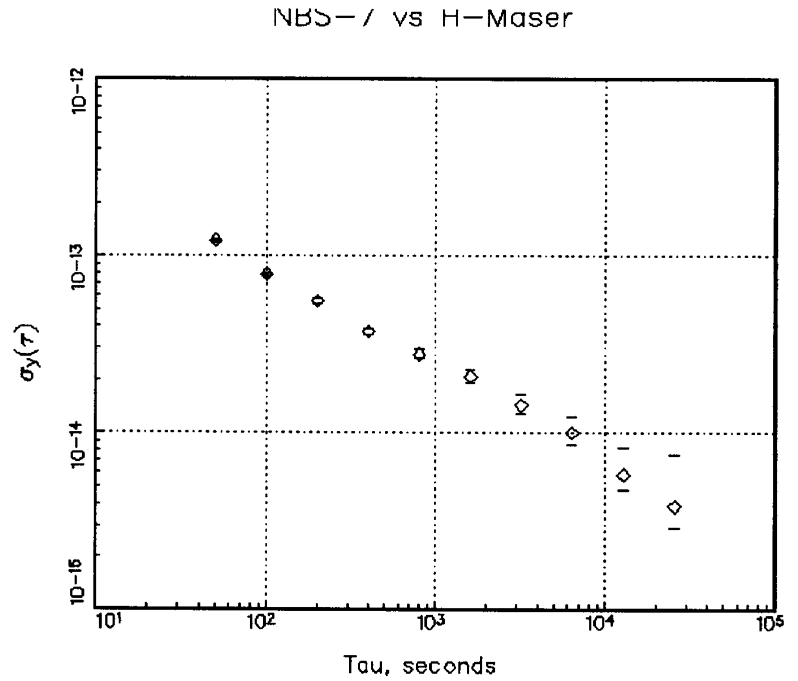

Fig. 2. Frequency stability of NIST-7 measured against an active hydrogen maser. The error bars represent 1σ on the statistics of the measurement.

velocity distribution, the microwave power, and the modulation parameters. A thermal velocity distribution, weighted by $1/v$ for detection by a cycling transition, was assumed. It predicts a Ramsey lineshape differing by only 1 or 2 % from the measured lineshape. The quality of this fit together with uncertainties in microwave power, and modulation parameters, leads to an uncertainty in the second-order Doppler correction of $\sim 2 \times 10^{-14}$.

The end-to-end cavity phase shift has been measured by beam reversal. The frequency shift on beam reversal at optimum power was 1.52×10^{-12} with an uncertainty of 3×10^{-14}. A search for distributed-cavity phase shift by alternately blocking one-half of the atomic beam near one end of the Ramsey cavity or the other showed no effect at the 1×10^{-14} level. The cavity Q of 600 and measured mistuning lead to cavity-pulling errors of less than 10^{-14}.

Line overlap shifts have not been evaluated in depth. But in an optically pumped standard with the high spectral symmetry demonstrated in Fig. 1, these effects are expected to lead to errors of less than 10^{-15}. The shift due to blackbody radiation [5] can be calculated to very high accuracy since the temperature of the atomic beam tube of NIST-7 is regulated. The fluorescence light shift in NIST-7 is expected to be $\leq 10^{-16}$ [6]. Using different optical powers and atomic beam fluxes we have observed no frequency shifts at the 10^{-14} level.

Frequency errors coming in through the electronics and arising from RF spectral purity, modulation distortion or offsets in the integrators or DC gain stages have been shown to be less than 1×10^{-14}.

SUMMARY

NIST-7 has undergone a preliminary evaluation and been shown to be several times more accurate than NBS-6. As of January 1, 1993, it has become the official US primary standard for frequency. It will be used to steer the long-term behavior of the NIST time scale while it continues to be developed and improved. As the error budget is reduced, international comparisons will be performed with other high-accuracy standards.

ACKNOWLEDGEMENTS

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Effect		Bias	Measurement Uncertainty (1σ)
2nd-order	Zeeman	$\approx$10 000	1
2nd-order	Doppler	$\approx$ 30	2
Line overlap			---
AC Stark		1.9	1
Cavity phase		76	3
Electronics			1

Table 1. Summary of systematic errors in NIST-7. The size of the resulting bias is given together with the associated uncertainty (all in units of 10^{-14}).