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DESIGN CONSIDERATIONS AND PERFORMANCE OF NBS-6, THE NBS PRIMARY FREQUENCY STANDARD

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Abstract. - The construction and performance of NBS-6, the U.S. cesium primary frequency standard, are summarized. A brief description of evaluation procedures and sources of uncertainty are given.

Introduction. - The United States' primary frequency standard, NBS-6, was placed into service in 1975. The cesium clock was built upon the basic framework provided by NBS-5, but various improvements of the device were radical enough to warrant a new standard designation. The basic design uses dipole-magnet state selectors, a conventional U-shaped, rectangular cross-section Ramsey cavity, and reversible multichannel collimator and hot-wire detector.

For the last several years, annual evaluations of NBS-6 have been made in order to provide steering information to the National Bureau of Standards (NBS) embodiment of atomic time, AT(NBS). The standard has not been operated continuously as a participant in the NBS time scale. This philosophy has been supported by recent data giving the relative performance of NBS-4 (which is operated continuously as part of the NBS time scale); the unofficial working time scale at NBS, UTC(8/S); and a small passive hydrogen maser (SPHM). Figure 1 shows the stability obtained by comparing SPHM with NBS-4 and with UTC(8/S). NBS-4 is normally a large contributor to UTC(8/S). However, much of this particular data was taken when NBS-4 was turned off for maintenance. These curves indicate not only that the joint stability of SPHM vs. NBS-4 is about $2 \times 10^{-12}\ \tau^{-\frac{1}{2}}$ for $\tau < 10^5$ s, but that the long-term stability of UTC(8/S) is about 2×10^{-14} for $\tau < 10^6$ s. An effort is in progress to complete additional masers to add to the NBS time scale. When these clocks join the scale, it will become even more unnecessary to operate a primary standard continuously.

The short-term and long-term stability of NBS-6 were designed to enable us to achieve the accuracy limited by cavity phase shift in the clock. The accuracy is limited by the degree of retrace upon beam reversal, which restricts the level of cancellation of cavity phase shift. The most uncertain component of the cavity phase shift is the distributed shift across the microwave cavity windows.

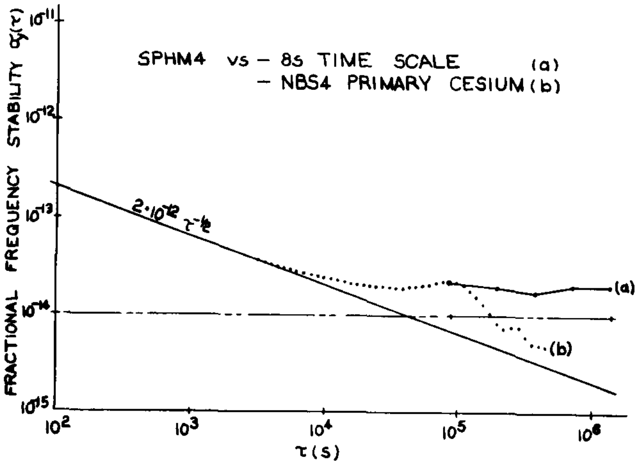

Figure 1. - Fractional frequency stability of SPHM vs. UTC(8/S) and SPHM vs. NBS-4.

This produces a fractional uncertainty in frequency of about 10^{-13} [1]. In order to measure to this level of accuracy with confidence, the short-term stability must be adequate to resolve ~ 10^{-14} at one day, which means that $\sigma_y(\tau) < 3 \times 10^{-12}\, \tau^{-1/2}$. This in turn restricts the beam current to values greater than about 2 pA. In addition, in order to make systematic checks, and to complete a beam-reversal cycle, the long-term stability of the primary standard should be better than 10^{-14} for several days. This performance has been demonstrated by stability measurements made between NBS-6 and NBS-4 [1] and between NBS-6 and a large passive hydrogen maser [2].

Construction. - A description of the construction of NBS-6 is given in Ref. 3. For completeness, a summary is presented here.

A two-beam, flop-in arrangement was chosen, where one beam corresponds to state selection of the F = 4 hyperfine level, and the second corresponds to selection of the F = 3 level. While originally two separate hot-wire detectors were used [3], the lack of spatial resolution of the two beams, coupled with the better noise performance of a single detector, made the latter arrangement preferable. With an oven temperature of 90 °C, a beam cross section of about 2 mm x 9 mm, and a total path length of about 5.4 m, the detected beam current is about 2 pA. The degradation of the signal magnitude from previously reported values is due to a higher background pressure in the vacuum system (about 2.7×10^{-5} Pa or 2×10^{-7} torr at the pump). The increase in pressure is due to aging of the 400 ℓ/s ion pumps, which are now being replaced after about seven years of service. The Ramsey cavity is 3.74 m in length with an average atomic velocity of less than 200 m/s, which gives a microwave resonance linewidth of about 30 Hz. The beam passes through the microwave cavity a half-wavelength from the shorted end. When originally constructed, the end-to-end cavity phase shift was less than 1 mrad.

A sliding cylinder with both an oven and a detector is mounted at each end of the beam tube. Each oven is separated from its companion detector by a metal partition, in order to reduce background from room-temperature cesium vapor. Seals for the cylinders are rubber O-rings coated with silicon grease. In order to extend the lifetime of a charge of cesium when the oven is moved out of the main vacuum system, an auxiliary ion pump has recently been added to the oven chamber. In this way, failures due to oxidation of cesium are avoided when the detector chamber is in place for long periods of time.

Magnetic shielding for NBS-6 consists of two rectangular moly permalloy shields within a cylindrical armco shield. C-field windings are placed close to the inside surface of the innermost shield. A baffle shield between the two ends of the microwave cavity serves to reduce magnetic field distortions produced by the cavity feed opening. Originally, the magnetic field inhomogeneity was less than 5×10^{-8} T peak to peak at an operating C-field strength of about 6×10^{-6} T. The shields are degaussed whenever the C-field value is changed, and generally several days are necessary for the shields to relax to a fixed value after degaussing.

Microwave modulation in NBS-6 is sinusoidal phase modulation of the 5.00688 MHz quartz oscillator output, at a frequency of 18.75 Hz. The modulated 5.00688 MHz signal is multiplied to 9.19263177 GHz and applied to the microwave cavity. Typically, all sidebands are less than - 50 dBC, and symmetric to better than 5 percent.

Beam current detected at the hot wire is amplified by an FET source amplifier with an input resistance of about 10^{10} ohms. The modulation component at 18.75 Hz is extracted by means of a square-wave, phase-sensitive detector and integrated to form a correction signal which tunes the quartz oscillator to line center. The stability of the quartz oscillator alone is better than 10^{-12} for times less than 100 s, which allows times of the order of seconds to lock to the microwave resonance. This servo system should resolve line center to better than one part in 10^{6}, which in turn would limit fractional resolution of the microwave frequency to about 3×10^{-15}.

Evaluation. - A complete evaluation of NBS-6 is performed approximately once a year, for the reasons outlined above. A more complete description of the limitations in operation of NBS-6 is found in Ref. 1. Table 1 gives a summary of uncertainties obtained in the 1980 evaluation. As many uncertainties as possible are determined at the time of evaluation, but the measurement of the magnetic field inhomogeneity was possible only at the time of original construction. Even this uncertainty is believed to have not changed, since the symmetry of the Ramsey features associated with each Rabi microwave resonance is still excellent.

TABLE I. NBS-6 Uncertainties, 1980 Evaluation.

	Source of Uncertainty	Bias ($\sigma_y \times 10^{13}$)	Uncertainty (x 10^{13})
1.	(a) Cavity Phase Shift (for one direction) (residual first-order Doppler Shift)	3.3 (typical)	0.80
	(b) Second-order Doppler Shift	-2.8 (typical)	0.10
2.	Pulling by neighboring transitions	+0.3	0.20
3.	Magnetic Field Effects		
	(a) Offset due to finite field	+1767 (typical)	0.02
	(b) Magnetic field inhomgeneity	+0.02	0.02
	(c) Majorana transitions	--	?
4.	Servo System Offsets		
	(a) Amplifier offsets	0	0.1
	(b) Second harmonic distortion	0	0.2
5.	RF Spectrum	0	0.1
6.	Cavity Pulling	0	0.01
	RSS error due to systematic frequency biases		0.87
	Random Uncertainty		0.15

1.(a) As mentioned above, the largest source of uncertainty is the cavity phase shift. The value of this frequency shift is obtained by comparing NBS-6 frequencies for oppositely directed cesium beams. It is assumed that all other sources of frequency bias are either measured or are invariant upon beam reversal. Since the 1976 evaluation, the fractional frequency bias introduced by cavity phase shift has steadily increased from 0.25×10^{-13} to the present value of about 3.3×10^{-13}. The uncertainty in this number was determined by measuring the position dependence of the frequency. A more complete set of measurements of the change of frequency with beam position is now in progress with the 1981 evaluation of NBS-6.

(b) The second-order Doppler shift is determined from an analysis of the Ramsey lineshapes at different microwave powers. The uncertainty in this bias ($\Delta y \sim 1.0 \times 10^{-14}$) comes from an estimate of the limitation of the model used to fit the Ramsey curves. This limitation is not seen as a fundamental restriction to accuracy, and future standards may well have second-order Doppler shifts measurable to $\Delta y \sim 1.0 \times 10^{-15}$.

2. Since the state-selection magnets in NBS-6 deflect atoms with different M values differently, the magnitudes of the seven Rabi resonance peaks are not symmetric about the central peak. At low C-field values, this introduces an asymmetry at the central Ramsey resonance associated with the unequal slopes of the wings of the adjacent Rabi lines. The size of this effect is estimated by measuring the difference in signal size at equal frequency steps on each side of the Ramsey peak. In addition, the C-field is chosen to give a Zeeman splitting of these lines which reduces the effect to an acceptable level.

3.(a) The quadratic magnetic field dependence of the $M = 0 \rightarrow M = 0$ transition introduces a rather large frequency shift. This frequency offset is determined by measuring the Zeeman splittings of the $M = \pm 1 \rightarrow M = \pm 1$ Ramsey lines, which provides a very accurate measure of the average magnetic field. The uncertainty in this bias is given by the accuracy of the Zeeman frequency measurement, which can be made to almost arbitrary precision.

(c) The effect of Majorana transitions on frequency in primary Cs clocks is unknown [4]. Some authors have suggested that such effects may produce fractional shifts as large as 10^{-12} [4,5]. In the case of NBS-6, it should be noted that great care has been taken to avoid sharp changes in magnetic field from the state-selection magnet regions. This has been accomplished in large part with the use of shields in the transition regions. The present evaluation of NBS-6 includes a brief study of the frequency shift with C-field change, which may shed some light on this subject.

4.(a) Based upon servo-system design calculations, it should be possible to obtain the microwave resonance line center to better than 10^{-6}. In addition, measurement of frequency shifts upon reduction of loop gain indicate that amplifier offsets contribute less than 10^{-14} to the fractional uncertainty. It is interesting to note that recently the beam current in NBS-4 (which has an identical servo system to NBS-6) dropped from 10 pA to 0.1 pA as the cesium oven became depleted. The standard remained locked to the microwave resonance, with a fractional frequency shift of less than 2 x 10^{-13}.

(b) It very difficult to measure the actual second harmonic distortion in the modulated microwave signal which drives the Ramsey cavity. Instead, since frequency shifts that arise from such distortion are closely related to the modulation amplitude, the modulation amplitude is varied. This procedure gives an upper limit to such shifts of about 2 x 10^{-14}.

5. As described earlier, sidebands on the microwave spectrum are symmetric, producing offsets of less than 10^{-14}.

6. The uncertainty in offsets due to cavity pulling is estimated from a combination of the uncertainty in our ability to set the cavity to the cesium frequency and our ability to set the microwave power to optimum. It is not a problem in NBS-6, entering at the 10^{-15} level.

The RSS error due to these systematic frequency biases is 8.7 x 10^{-14}, with an additional random uncertainty of 1.5 x 10^{-14}. Consequently, the total uncertainty (rms) in NBS-6 is less than 9 x 10^{-14}.

An additional correction in the frequency of primary cesium standards has recently come to light [Itano, W. M., Lewis, L. L., and Wineland, D. J., to be published]. Room temperature blackbody radiation should produce a differential ac Stark shift of the ground-state hyperfine levels of cesium. The size of the fractional correction is about-1.7 x 10^{-14} at 300 K. This correction has not been included in previous evaluations of NBS-6, but will be included in the 1981 evaluation.

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