CHAPTER 5—PART B

THE NEW PRIMARY CESIUM BEAM FREQUENCY STANDARD: NBS-5*

**David J. Glaze,† Helmut Hellwig,† Stephen Jarvis, Jr.,†
Arthur E. Wainwright,† and David W. Allan†**

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†Time and Frequency Division, Institute for Basic Standards, National Bureau of Standards, Boulder, CO 80302.

"Thus times do shift—each thing his turn does hold; New things succeed, as former things grow old."

Robert Herrick

The design of NBS–5 is discussed in detail including its relation to previous NBS primary cesium beam frequency standards. Stabilities of 3×10^{-14} for one day averaging are reported and tentative data on its accuracy capability are given. Preliminary results give an evaluated accuracy of 2×10^{-13} with indications that this figure may be further improved in the future.

Key words: Cesium beam standard; Doppler effect; frequency accuracy; frequency stability; power shift; primary frequency standard.

5B.1. INTRODUCTION

A primary cesium beam frequency standard serves to realize the unit of time interval, the second, in accordance with the international definition as formulated at the XIII General Conference on Weights and Measures in 1967: "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom" (see chap. 1). The realization of an output frequency from a real device involves several steps of physical and technical processing which may cause frequency deviation of the output frequency from the atomic unperturbed transition frequency. The magnitude of each such bias can be evaluated with the aid of experiments and of theoretical considerations. However, these biases are not known to infinite certainty. The magnitude of these uncertainties depends on the degree of theoretical understanding as well as on the precision with which experimental parameters can be measured. This precision depends on the design and construction of the cesium beam tube and electronics of the primary frequency standard as well as on the frequency stability of the reference frequency standard used in the evaluation of the primary standard. The combined uncertainty of all biases is referred to as the accuracy of the frequency standard.

Since the first atomic clock was realized as an ammonia frequency standard by Harold Lyons at NBS in 1948 [1],[1] several cesium based primary frequency standards have operated at NBS. Standards called NBS–I, NBS–II, and NBS–III served successively as primary frequency standards during the 1950's and 60's [2, 3]. NBS–III, our previous operating frequency standard, was evaluated in 1969 to an accuracy of 5 parts in 10^{13} [3] (see chap. 5A).

The experience gained with NBS–III indicated that the main limitations for accuracy, in addition to significant electronics problems, were the magnetic field—in particular its homogeneity and stability—the second-order Doppler effect, and the cavity phase difference. Therefore the design and construction of a new primary cesium beam frequency standard with the designation NBS–5 was initiated with features incorporated to significantly reduce the above mentioned limitations.[2] The instrument was designed to achieve a frequency accuracy of 1 part in 10^{13}. To facilitate accuracy evaluations, the design also aimed at greatly increasing the stability of the device which is basically given by the available atomic beam intensity and the line-Q. The stability for 1 hour sampling time of NBS–III was 2 parts in 10^{13}. The NBS–5 design aimed at improving this value by at least 1 order of magnitude, thus allowing measurement precisions approaching 10^{-14} within 1 hour. NBS–5 was put into operation during the latter part of 1972, and has since undergone several phases of accuracy evaluation.

[1] Figures in brackets indicate the literature references at the end of this Chapter.

[2] Another cesium beam frequency standard with the designation NBS–X4 was also constructed in cooperation with the Hewlett Packard Company. This device was not specifically designed to be used as a primary cesium beam frequency standard, however, new methodology permits such use.

5B.2. THE NBS–5 SYSTEM

A photographic view of NBS–5 with all electronics systems is depicted in figure 5B.1. The complete system has a length of about 6 meters overall. The vacuum system is basically a stainless steel tube 25 cm in diameter and is evacuated by three 200 l/s ion pumps which can be closed off with valves for servicing. In order to minimize thermal effects, the Ramsey type cavity is located inside the vacuum system. The total length of the NBS–5 cavity is 3.74 meters. The drift region is carefully shielded by three magnetic shields. The typical operating field is about 60 milli-oersted, and a field homogeneity of better than 1 percent (peak-to-peak variation) is achieved along the beam axis. The beam tube permits an atomic beam to traverse the path through the cavity in either direction. Each end of the beam tube is equipped therefore with both identical magnets and oven-detector combinations. This capability of beam reversal allows a measurement of the cavity phase-difference bias. This bias arises because of a (usually small) difference in the phase of the microwave signal in the two interaction regions. Indeed, the NBS–5 cavity phase difference was adjusted (by length trimming of the two halves) to be less than 1mrad before the cavity was installed in the beam tube. The resulting bias changes sign if the beam traverses the cavity in the opposite direction.

The oven-detector combination is arranged in such a way that it can be adjusted in the deflection plane of the atomic beam, perpendicular to the beam axis; in addition, the oven can be aimed independently at different angles. The oven can accept ampules filled with 3 g to 5 g of cesium which yield a projected lifetime of many months of continuous operation. The collimator of the oven is an array of about 500 separate channels producing a beam with a rectangular cross section of 2 mm × 9 mm. With an oven temperature of 100 °C the projected beam intensity at the detector is approximately 10^8 atoms per second. The detector is a platinum ribbon. Because of the relatively high beam intensity and the high purity of the platinum ribbon (total background current is of the order of 0.1 pA), no mass spectrometer and electron multiplier are employed. Instead, a field effect transistor is mounted in close proximity to the detector. The detector signal is processed in low-noise preamplifiers external to the beam tube. If one end operates

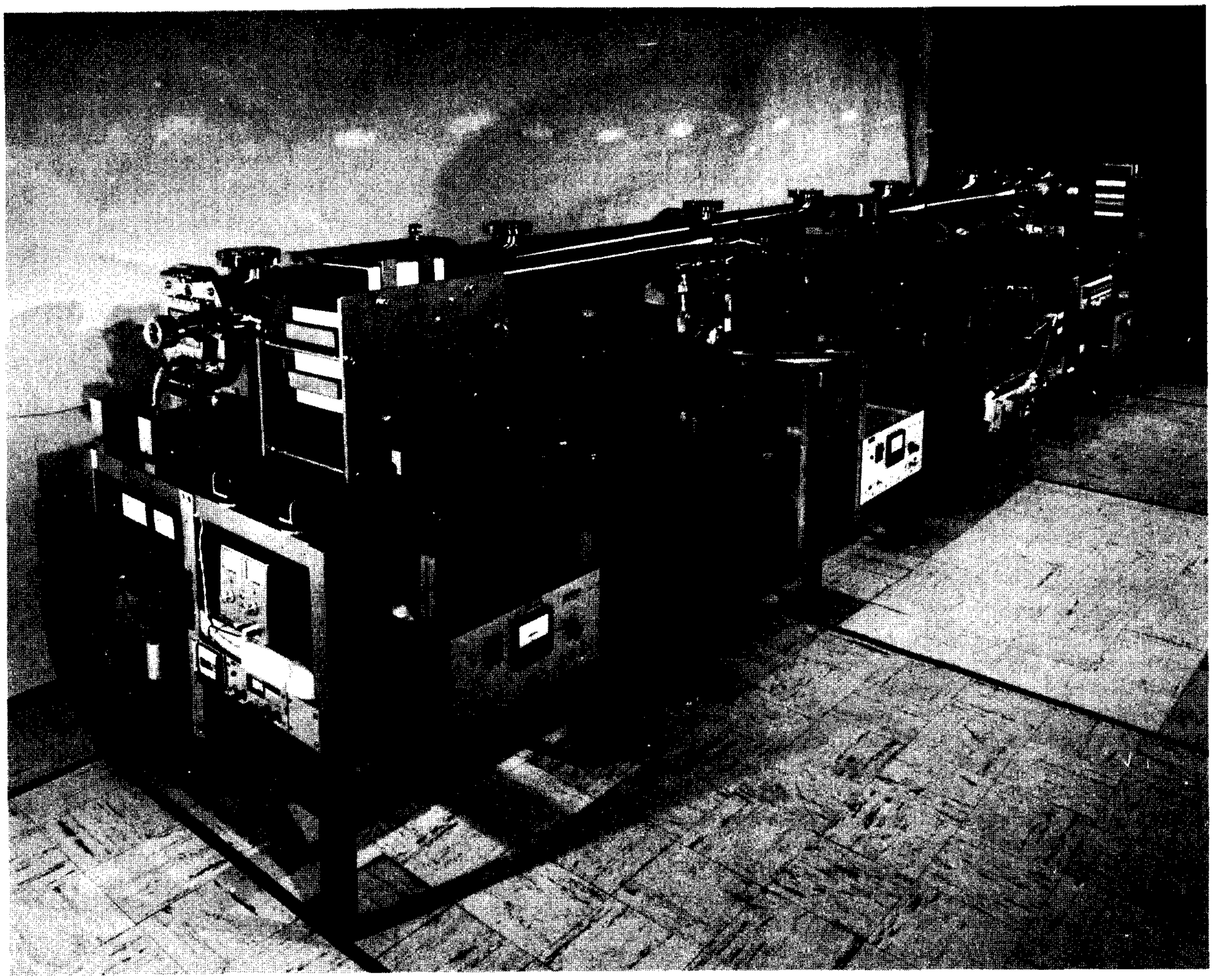

Fig. 5B.1. View of NBS-5. All electronics systems are shown.

in the "oven" mode the detector is moved aside; however, if the end is used in its "detector" mode, the detector can move in front of the oven and, at the same time, a carbon getter plate baffles the oven collimator. Lowering the oven temperature to ~ 24 °C also reduces its output.

The microwave signal is obtained from a crystal oscillator at a basic frequency of 5.00688 MHz, a subharmonic of the cesium transition frequency. An associated low noise multiplier chain which terminates in a step recovery diode produces a signal at the cesium frequency with a power of up to several mW. A sinusoidal frequency modulation can be applied with a fundamental frequency of 18.75 Hz. This modulation is generated with second harmonic suppression of better than 100 dB. The modulation reappears in the beam current at the detector, is amplified, phase detected, and processed in two cascaded integrators and used to servo-control the crystal oscillator. The 5.00688-MHz crystal oscillator frequency is also synthesized to a standard 5 MHz frequency. This signal is used for evaluative and stability measurements, and for time-scale calibrations.

5B.3. PRELIMINARY EXPERIMENTAL RESULTS (STATUS APRIL 1973)

After a preliminary beam alignment, the $(F=4, m_F=0) \longleftrightarrow (F=3, m_F=0)$ transition was observed with a peak to valley amplitude of 4 pA. Since the atomic velocities are determined by the beam optics and the beam alignment, linewidths of 25 to 45 Hz were measured depending on the alignment. The signal to noise ratio was also measured, and from this by Lacey's method [4], the frequency stability for 1 s sampling times was calculated to be 4 parts in 10^{13}. Our best reference sources in stability measurements for very short times were

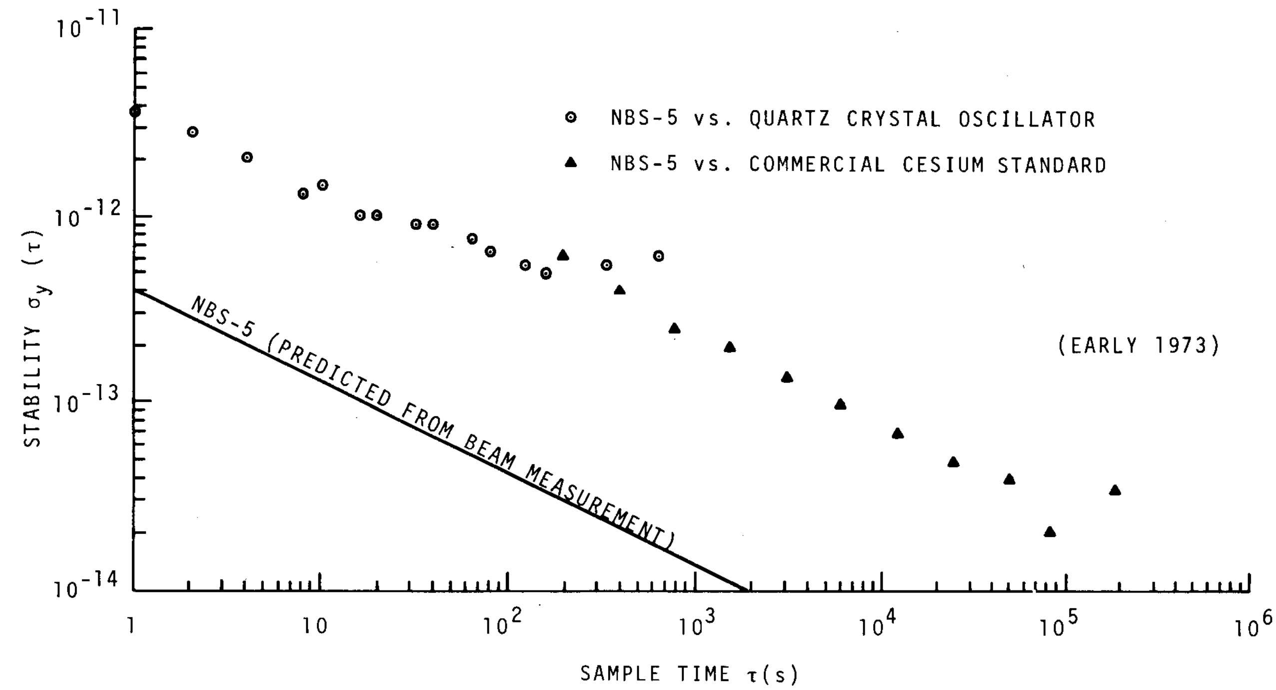

Fig. 5B.2. Measured and calculated frequency stability of NBS–5.

crystal oscillators, and for longer times were commercial cesium beam frequency standards. A plot of the measured square root of the Allan variance using both of these reference oscillators is shown in figure 5B.2 together with the calculated stability of NBS–5. Figure 5B.2 shows that we were able to obtain measurement precisions in the accuracy evaluation of about 3 parts in 10^{14} for sampling times of 10^5 s. The calculated, shot noise limited stability is better than the measured performance. This is mostly due to limitations in the electronics; i.e., due to noise associated with the beam detector electronics, the servoed quartz crystal oscillator, etc. In the long term measurements, the available commercial cesium reference was also limiting the measurements precision.

At the time of this writing, for various technical reasons, we have not proceeded yet with the beam reversal. However, we have preliminary accuracy data based on two other methods:

(1) Power shift measurements [5–7]. This method is based on the fact that the effective mean atom velocity is a function of the interrogating microwave power. To use this method it is necessary (a) to know the velocity distribution in the tube (this can be obtained experimentally from pulsed operation and refined by matching a derived Ramsey spectrum with the experimentally obtained Ramsey spectrum), (b) to calculate numerically the effective mean velocities at given microwave power settings, and (c) to measure the change in the output frequency by comparison with a reference standard at different microwave power settings. This allows a calculation of the cavity phase difference and the corresponding frequency bias. It must be verified, that the microwave spectrum is of sufficient purity so as not to introduce spectrum related power shifts.

(2) Pulse method [6, 7]. This method is based on selecting certain velocities in the beam by pulsing the microwave power. The velocity selection is based on the time of flight between the two cavity interrogation regions. This method also allows a measurement of absolute microwave power levels in the cavity and the determination of the velocity distribution.

With methods 1 and 2 one can obtain the biases due to the second order Doppler effect and the cavity phase difference. Our preliminary results are tabulated in table 5B.1. More detail on the biases and the bias uncertainty can be found in reference [8]. The other biases and bias uncertainties of which we are aware and which we have evaluated in a preliminary way are also listed. Biases not assigned a value are nominally zero within the respective uncertainties shown. From table 5B.1 we can see that the cavity phase difference is about 0.7 mrad which leads to a bias (including the second order Doppler effect) at nominal optimum microwave power of about 1.5×10^{-12}. We have monitored these values every month during the first three

TABLE 5B.1.

Preliminary Accuracy Budget for NBS–5

Influencing factors	Bias	Bias uncertainty
1. 2d-order Doppler and phase difference at nominal optimum power; source: power shift & pulse method	-14.5×10^{-13}	1.6×10^{-13}
2. servo system; source: some variation of servo parameters and calculations based on measured offsets and loop gain	–	1×10^{-13}
3. magnetic field; source: $m_F\neq0$ transitions	$1{,}670.0\times10^{-13}$	0.2×10^{-13}
4. $\overline{H^2}$ versus $\overline{H}^2$; source: $m_F\neq0$ transitions and measurements during assembly	–	0.4×10^{-13}
5. Majorana transitions; source: $m_F\neq0$ transitions and measurements during assembly	–	0.05×10^{-13}
6. pulling of neighboring lines; source: $m_F\neq0$ transitions	-0.05×10^{-13}	0.02×10^{-13}
7. cavity pulling; source: worst estimate	–	0.1×10^{-13}
8. rf spectrum; source: spectrum recording	–	0.4×10^{-13}
9. random uncertainty (1σ at 10 h); source: stability measurements against other cesium standards	–	$<0.4\times10^{-13}$

months of 1973. We could not find any change in the cavity phaseshift within our measurement precision. If all the bias uncertainties are statistically treated, i.e., we assume that they are independent and uncorrelated, we obtain a total accuracy capability of 2 parts in 10^{-13}. It should be noted however, that all of these reported data ought to be regarded as tentative, preliminary values, subject to later verification and/or correction. For the future we plan to understand fully the beam optics alignment and the magnetic field properties of the beam tube. In addition, we expect to compare the computer-aided beam optics design with actual performance. We also intend to further investigate and refine the pulse method as well as the power shift method, and we will attempt to obtain compatible results with beam reversals. Only after all these tests are completed do we feel that final accuracy figures can be quoted for NBS–5. Further improvements in accuracy seem likely in view of new ideas and evaluation methods for NBS–5, and in view of the beam tube performance to date. In addition, the availability of an accurate and very stable reference standard, i.e., NBS–X4, is expected to facilitate evaluation of NBS–5 and to lead to further improvements in accuracy.

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A special word of commendation should be given to Ward T. Roberts who constructed almost all of the NBS–5 beam tube.

Note added in proof: Comparisons between NBS–5 and NBS–X4 in November 1973 led to a measured frequency stability of $\sigma_y(\tau)=1.3\times10^{-12}\tau^{-1/2}$ (for one device), reaching a measured value of 1×10^{-14} in 3.5 hours. Also, successful beam reversal supports the previously obtained values for the bias correction and the associated accuracy claim.

5B.4. REFERENCES

[1] Lyons, H., "Spectral lines as frequency standards," *Ann. N.Y. Acad. Sci.*, **55,** pp. 831–871 (November 1952).

[2] Beehler, R. E., and Glaze, D. J., "The performance and capability of cesium beam frequency standards at the National Bureau of Standards," *IEEE Trans. on Instrum. and Meas.*, **IM-15,** Nos. 1 & 2, pp. 48–55 (March and June 1966).

[3] Glaze, D. J., "Improvements in atomic cesium beam frequency standards at the National Bureau of Standards," *IEEE Trans. on Instrum. and Meas.*, **IM-19,** No. 3, pp. 156–160 (August 1970) (see chap. 5A.)

[4] Lacey, R. F., Helgesson, A. L., and Holloway, J. H., "Short-term stability of passive atomic frequency standards," *Proc. IEEE (Special Issue on Frequency Stability)*, **54,** No. 2, pp. 170–176 (February 1966).

[5] Hellwig, H., Barnes, J. A., Glaze, D. J., and Kartaschoff, P. K., "Frequency shifts due to Ramsey type interrogation in atomic beam tubes," Nat. Bur. Stand. (U.S.) Tech. Note 612, 25 pages (USGPO, February 1972).

[6] Mungall, A. G., "Cavity phase dependent frequency shifts in cesium beam frequency standards," *Metrologia*, **8,** No. 1, pp. 28–32 (January 1972).

[7] Hellwig, H., Jarvis, S., Jr., Halford, D., and Bell, H. E., "Evaluation and operation of atomic beam tube frequency standards using time domain velocity selection modulation," *Metrologia*, **9,** No. 3, pp. 107–112 (September 28, 1973).

[8] Glaze, D. J., Hellwig, H., Jarvis, S., Jr., Wainwright, A. E., and Allan, D. W., "Recent progress on the NBS primary frequency standard," *Proc. 27th Ann. Symp. on Frequency Control* (U.S. Army Electronics Command, Ft. Monmouth, NJ 07703, June 12–14, 1973), pp. 347–356) (Electron. Ind. Assn., Washington, D.C. 20006, 1973).