CHAPTER 5 – PART A

IMPROVEMENTS IN ATOMIC CESIUM BEAM FREQUENCY STANDARDS AT THE NATIONAL BUREAU OF STANDARDS

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Contents

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"Science moves, but slowly, slowly, creeping on from point to point."
Alfred Tennyson,
Locksley Hall, I. 134

The National Bureau of Standards Frequency Standard, NBS–III, a cesium beam with a 3.66-meter interaction region, has been in operation since 1963. The last published (1966) accuracy capability for NBS–III was $1.1 \times 10^{-12} (1\sigma)$. Recently, several new solid-state broadband frequency-multiplier chains have been constructed. Reduction of the random phase noise by more than 20 dB compared to the previous state of the art has been obtained consistently. In addition, a solid-state servo system has been installed to control the frequency of the 5-MHz slave oscillator.

Comparisons were made between NBS–III and one of the commercial cesium standards in the NBS clock ensemble. The relative fractional frequency stability $\sigma(N=2,\ T=7 \text{ days},\ \tau=1 \text{ day}) = 1 \times 10^{-13}$ was observed for nine weekly comparisons. The very-long-term frequency stability for this recently improved NBS–III system has not been evaluated fully. Due to the improvements both in electronic systems and evaluative techniques, however, an accuracy of 5×10^{-13} (1σ) for a single evaluative experiment is reported.

Substantial effort is being expended toward improvements of the accuracy of figure of merit (presently 10) of the NBS cesium standard. The modified system, to be called NBS–5, is expected to be in operation in the latter half of 1970 and to exhibit a figure of merit in excess of 500.

Key words: Accuracy of NBS–III; cesium beam frequency standard; double beam system; error budget, NBS–III; frequency stability, NBS–III; NBS–III precision; NBS–III servo system; NBS frequency standard; noise effects; quartz crystal reference.

5A.1. INTRODUCTION

THE NATIONAL Bureau of Standards Frequency Standard, NBS-III, a cesium beam with a 3.66-meter interaction region, has been in operation since September 1963. From that time until October 1965, NBS-III together with NBS-II, a cesium beam with a 1.64-meter interaction region, comprised the National Bureau of Standards Frequency Standard (NBSFS). By December 1965, NBS-II had been converted to an experimental thallium standard, and two Varian Associates H-10 atomic hydrogen masers and one Hewlett-Packard 5060A cesium beam were operating temporarily at the NBS [1]. The subsequent intercomparison of frequencies among the commerical frequency standards and NBS-III provided the most accurate measurement of any physical quantity, namely the frequency of the hyperfine separation of hydrogen. During these measurements the accuracy capability consistently obtained from NBS-III was 1.1×10^{-12} (1σ). Improvement of both the accuracy capability and the precision of the NBSFS is a prime objective of the NBS. There are several improvements that have been made since 1965 in NBS-III, the present NBSFS, shown in Fig. 1.

5A.2. MODIFICATIONS TO THE NBS-III SYSTEM

During the 1965 intercomparisons mentioned above, it became evident that phase-difference instability in the NBS-III Ramsey cavity [2] was the major source of uncertainty in the frequency of NBS-III [1], [3]. As expected, replacement of the oil-diffusion pumps with ion pumps in mid-1966 reduced both the phase-shift instability and the ultimate pressure. The pressure was improved by a factor of 10 to about 10^{-8} torr (1.3×10^{-6} N/m^2), but the phase-difference instability was reduced only by a factor of 2.

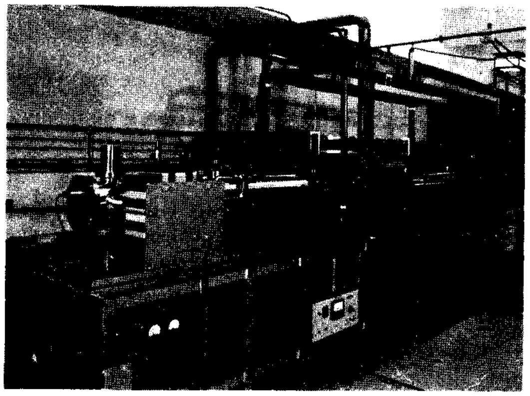

Fig. 1. The NBS-III cesium beam frequency standard, August 1966–August 1969.

The phase-difference instability was not significantly reduced until a precise procedure was followed whenever it was necessary to open the vacuum system. This procedure includes the use of dry highly purified argon gas as the pressurizing agent, as well as thermal control to prevent water condensation. When these techniques were used, the discrepancy between the fractional frequency changes for two reversals of beam direction was 4.0×10^{-13}. These two reversals were made, one at the beginning and one at the end of a 9-month period, as part of independent frequency calibrations. Also the vacuum system was opened several times during this period to recharge the cesium oven. There was no evidence during this period to suggest any phase-difference instability worse than 4×10^{-13}. As a result, the magnitude of the fractional frequency bias correction applied during this period for the phase-difference effect in NBS-III was $(38.8 \pm 2) \times 10^{-13}$. The uncertainty of 2×10^{-13}, listed as item 7) in Table I, is one-half the discrepancy noted above. It is apparently attributable to some small amount of chemical reaction on the cavity walls.

Although the results for cavity phase-difference stability are improving, it should be stated that the author regards the proper solution of this long-standing problem to be fourfold.

1) Construct the Ramsey cavity with a low phase difference such that frequency bias due to this effect is not larger than 1×10^{-13} [4].

2) Baffle and getter the beam-coupling holes to the extent that the cesium contamination becomes unimportant.

3) For long interaction-length laboratory standards such as NBS-III, where the highest possible accuracy is

required, construct a double oven and detector system so that beam-direction reversals through the cavity can be accomplished in a matter of hours without breaking the vacuum seals [3].

4) Construct simple electronic systems to monitor with ease the long-term stability of the cavity phase difference, and calibrate these systems initially by means of the double-beam system in item 3). These improvements are presently under construction at NBS and will be installed as modifications to the NBS-III system (see Section IV).

Other improvements have been made, and these are concerned primarily with the NBS-III electronic systems. The basic configuration of the frequency-lock servo system is shown in Fig. 2. The servo system used to control the frequency of the 5-MHz oscillator is a solid-state unit with an improved phase modulator. The modulator is a passive device employing varactor phase modulation of a tuned circuit resonant at 5 MHz. The modulator operates at a fundamental modulation frequency of 18.75 Hz with a second-harmonic level 85 dB below the level of the fundamental modulation. This is an improvement of 30 dB compared to the higher second-harmonic level of the previous modulator and reduces the frequency-pulling effects of modulator second-harmonic distortion to insignificant levels. The remainder of the servo system has numerous test points for measurements to ensure that errors associated with parameters such as demodulator asymmetry, demodulator dc offset, and integrator dc offset can be reduced to low levels. For example, the dc offsets in the demodulator and integrator are typically stable enough and low enough so that no errors as large as 1×10^{-13} accumulate in a two-week period. It is relatively simple to readjust these parameters for an important frequency calibration or to monitor them occasionally during a long run. The stability of this servo is about ten times better than the system it replaced in mid-1968; consequently, the reliability and long-term stability of NBS-III have improved accordingly.

Indeed, the relative fractional frequency stability $\sigma(N = 2, T = 7 \text{ days}, \tau = 1 \text{ day}) = 1 \times 10^{-13}$ was observed for nine weekly comparisons of NBS-III with one of the two commercial cesium standards that are part of the present NBS clock ensemble [5]. Here σ^2 is the Allan variance [6], T is the period of the sampling, and τ is the sample time. Each standard, then, is not worse than 1×10^{-13}, and if the two standards were assigned equal weighting, then one would assign to each the value of $\sigma = 0.7 \times 10^{-13}$ for the one-day samples just described.

The frequency stability of the cesium beam standard is ultimately limited by the shot noise of the particle detection (surface ionization of the cesium atoms is measured with an electrometer). It is important that the performance of the standard is not degraded by other noise sources, such as a flicker of phase noise process occurring in the frequency-multiplier chains [7] or a flicker of frequency noise process occurring in the 5-MHz quartz-crystal oscillator. These processes are described in detail by Allan [6] and by Cutler and Searle [8]. In order to meet fully the requirements of improved NBS cesium beam tube designs, it was decided to lower the noise levels generated by the frequency-multiplier chains. Several new solid-state 5–60 MHz multipliers were constructed using local radio-frequency negative feedback in the lower frequency stages to reduce the flicker of phase noise, as suggested and proved by Halford *et al.*, [7]. Improvements in the phase noise level by at least 20 dB compared to the previous state of the art have been obtained consistently. One of these frequency-multiplier chains is presently in use in the 5–60 MHz section of the 9.2-GHz excitation system shown in Fig. 2. For use in future NBS frequency standards, three more of the 5–60 MHz multipliers have just been incorporated in new, all solid-state, 5 MHz–9.2 GHz excitation systems. As expected, the measured phase noise levels of these new systems are also improved by at least 20 dB compared to the levels in previous excitation systems. Fig. 3 demonstrates this fact, and the data shown were obtained at the output frequency of 9.2 GHz.

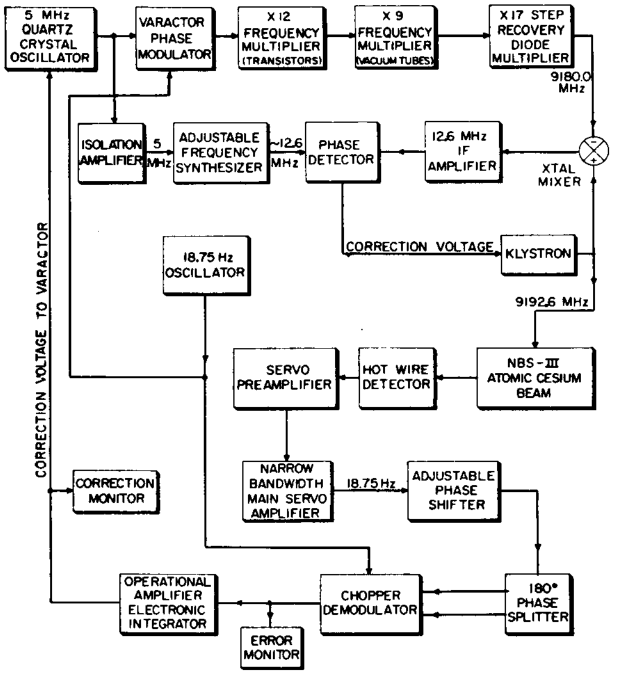

Fig. 2. The NBS-III frequency-lock servo system. The varactor phase modulator and the solid-state frequency multiplier are improved low-noise units.

The quantity $\mathcal{L}(f)$ in Fig. 3 is a convenient frequency-domain measure of phase fluctuations, and it is defined for one device only, that is, for one amplifier or one frequency-multiplier chain, etc. It is the ratio of the power in one phase-noise sideband, referred to the input carrier frequency, on a per-hertz-of-bandwidth basis, to the total signal power, at Fourier frequency f from the carrier. The subscript -1 on $\mathcal{L}_{-1}$ means that the component of $\mathcal{L}$ that varies as f^{-1} is under discussion. In Fig. 3, $\mathcal{L}$ is seen to vary as f^{-1} in the vicinity of the modulation frequency (18.75 Hz), that is, flicker of phase noise is the dominant effect. In order to measure their $\mathcal{L}$ spectrum, the two chains were driven from a single 5-MHz quartz-crystal oscillator, and the phases of the output signals to the phase detector were adjusted for maximum sensitivity to phase noise (phase quadrature). The upper dashed line shows the previous state of the art.

Some improvements had already occurred in reduction of power line related sideband levels, and the new solid-state 5 MHz–9.2 GHz chains are designed to further reduce these effects. These chains are not completely tested so that valid data on power-line related sideband levels are not yet available.

The flicker of phase and the flicker of frequency noise evels observed in the best 5-MHz quartz-crystal oscillators are approximately at the level of the shot noise of the detected beam in the improved cesium beam standards under construction at NBS, evaluated at the optimum frequency of modulation of about 1 Hz. Further improvement in the white frequency noise of cesium beam standards will necessitate improvement in quartz-crystal oscillator frequency stability. A project with the goal of improving the stability of slave oscillators was established at NBS n July 1969.

5A.3. ACCURACY CAPABILITY OF NBS-III (1969)

In Table I are listed those effects that contribute significantly to the inaccuracy of NBS-III. The last item is the purely random scatter of the measured NBS-III frequency with running time, for 1-hour averages, in large part due to the shot noise of the beam. All of the other ten tems are bias uncertainties. The bias uncertainties do not represent fluctuations with running time, but are nstead a measure of the uncertainty of the size of the frequency offset (bias) due to each effect. These offsets tend to remain constant from one measurement interval to the next. However, these offsets may vary whenever changes are made in the apparatus. It is the view of the author that the term "accuracy capability" should be applied to Table I until the long-term behavior of the mproved NBS-III system can be evaluated more completely. Accuracy capability is the accuracy attained when a set of evaluative tests is made, as distinct from the accuracy of the standard when left undisturbed for a ong period of time [9].

Table II lists a typical set of all the frequency bias corrections applied to NBS-III for each beam direction. All other biases are estimated to be zero within the uncertainties listed in Table I.

Items 1)–6) in Table I, though examined more recently, are identical to the results obtained in 1966 [1], [3] and will not be discussed in detail here. Of these, items 1), 3), and 5) are actually estimated to be slightly smaller than 1.0 × 10^{-13}; however, since these effects are examined rather infrequently, the uncertainty values were rounded upward to 1.0 × 10^{-13}. Item 7) was already discussed in Section II.

In order to evaluate item 8), it was necessary to ascertain the power dependence of the frequency of NBS-III for each beam direction through the resonant cavity [3]. At first it appeared to be impossible to achieve the desired fractional frequency stability of the reference standard of 1 or 2 parts in 10^{13}, because no suitable atomic reference standards existed at the NBS after 1965. It was suggested by Halford[1] that a high-quality quartz-crystal oscillator be used for the reference.

TABLE I
Accuracy Capability of NBS-III (1969)

Source	1σ Estimate Parts in 10^{13}
1) Uncertainty in average C-field magnitude $\lvert\bar{H}_C\rvert$	≤ 1.0
2) Use of $\overline{H_C}^2$ for $\overline{H^2}_C$	0.3
3) Uncertainty due to first- and second-order Doppler shifts	≤ 1.0
4) Uncertainty due to inequality of average C-field magnitudes in cavity and drift regions, $\lvert\bar{H}_C(l)\rvert \neq \lvert\bar{H}_C(L)\rvert$	0.3
5) Uncertainty in C-field polarity-dependent shifts	≤ 1.0
6) Uncertainty in cavity tuning	≤ 0.3
7) Uncertainty due to cavity phase-difference instability	2.0
8) Uncertainty in power dependent shifts	2.6
9) Multiplier chain transient phase-shifts	≤ 2.0
10) Uncertainty due to phasing problems and dc offsets in servo-system electronics	≤ 2.5
11) Random uncertainty due to shot noise of beam, for measurement τ = 1 hour	1.6
Total 1σ estimate of accuracy capability (square root of sum of squares)	≤ 5.1 × 10^{-13}

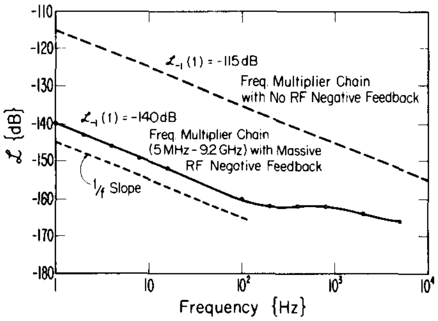

Fig. 3. Normalized spectral density of phase noise power for NBS frequency-multiplier chains.

TABLE II
Typical Fractional Frequency Biases in NBS-III (1969)

	Beam Direction 1	Beam Direction 2
Magnetic field	+ 1087.8 × 10^{-13}	+ 1087.8 × 10^{-13}
Cavity phase difference	−38.8 × 10^{-13}	+38.8 × 10^{-13}
Finite radiation field intensity (power dependence)	+7.8 × 10^{-13}	+7.8 × 10^{-13}
Second-order Doppler	−1.8 × 10^{-13}	−1.8 × 10^{-13}

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[1] D. Halford, private communication, 1968.

The quartz-crystal oscillator is an excellent solution to the problem, as can be seen in Fig. 4, where the methods of Allan are applied [6]. The quantity r is defined as the ratio of T to τ, where T is the sum of the dead time and the sample time. A suitable sample time τ lies between the cesium beam servo time constant ($\sim$1 second for NBS-III) and point I, the intersection of the two curves of Fig. 4. To achieve a high precision, then, the method of synchronous detection is employed. In other words, the microwave power incident on the NBS-III cavity is alternately switched between two predetermined levels 1 and 2, and averaging of the frequency difference occurs for an interval τ at each power level. The process continues until the desired quantity of data is obtained. The frequency-difference data are then tabulated in the order in which they occurred, and algebraic differences between the first and second, second and third, etc., are computed and also tabulated. These frequency differences, then, represent the changing frequency of NBS-III as the microwave power alternates between the two levels 1 and 2. The precision obtained in this manner is limited by the number of independent frequency differences obtained, and it is not degraded by crystal-oscillator frequency drift or flicker noise level. In this manner the slopes of the power dependences of the frequency of NBS-III, from the optimum operating power of 1.4 mW down to 0.4 mW, have been determined with precisions consistently between 1 and 2 parts in 10^{13} for both beam directions through the cavity. Harrach [3] has shown that the slopes so obtained from the point of optimum microwave power (that power for which the detected beam intensity is maximized) decreasing downward toward zero power are sufficiently linear that the zero-power extrapolation can be based accurately on these data. The method described by Harrach [3] for extrapolation to zero microwave power was used to estimate the uncertainty quoted in item 8) of Table I. This value agrees reasonably well with the one obtained in 1965 [1], where hydrogen masers provided the high-stability reference standard. The less expensive quartz-crystal oscillator is ideal for this application.

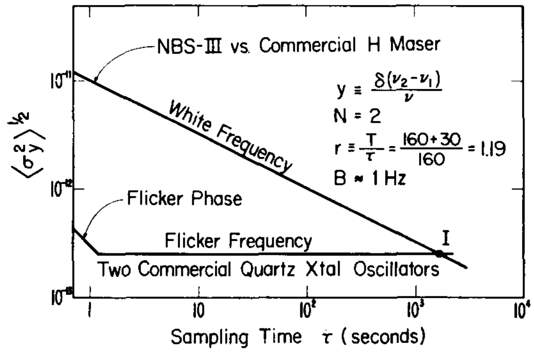

Fig. 4. Relative fractional frequency stability versus sampling time: NBS-III versus a commercial atomic hydrogen maser, and two commercial quartz-crystal oscillators versus each other.

Items 9) and 10) are improved significantly with respect to the situation existing in 1965 [1]. This improvement is directly attributable to the improved design and performance of the solid-state servo and modulator systems, and the solid-state frequency-multiplier chains as discussed in Section II.

5A.4. SOME IMMEDIATE GOALS

A new solid-state servo system has been designed with particular attention given to reduction of long-term transient effects and leakage signals. It is of even more advanced design than the solid-state servo mentioned in the earlier sections. Also, new completely solid-state 5 MHz–9.2 GHz frequency-multiplier chains have just been constructed, and testing is being conducted now.

Components have been completed for a "double-beam system," that is, a system with an oven and detector at each end of the beam tube. This arrangement should ensure that the phase difference of the new Ramsey cavity can be measured easily, and with high accuracy. The cavity is to be constructed with a very small and very stable phase difference. These components together with new dipole deflecting magnets are to be assembled into a complete, computer-optimized beam optics system [10] using the NBS-III beam tube. Because of the extensive modifications for improved accuracy and precision, the standard will be redesignated NBS-5. It is expected to exhibit a precision σ of measurement for τ = 1 second of better than 2×10^{-13}. This requires a figure of merit [11] exceeding 500. This corresponds to an improvement by more than a factor of 50 over the present NBS-III system. NBS-5 is expected to be in operation in the latter half of 1970.

5A.5. CONCLUSIONS

It is evident that considerable effort is being expended by National Standards Laboratories to advance the accuracy and precision capabilities of cesium beam frequency standards [12], [13]. It appears likely that development will occur soon of laboratory cesium beam frequency standards with accuracy capabilities of from 1 to 2 parts in 10^{13} (1σ).

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Dr. D. Halford for many helpful discussions and suggestions regarding electronic designs, experiments, and the preparation of this paper. Others of the NBS staff whose efforts are similarly appreciated are Dr. J. A. Barnes for many helpful discussions of the analyses of power spectra and servo systems; A. E. Wainwright for design, development, and test of the phase modulator and of the frequency-multiplier chains; C. S. Snider for assistance in the operation and maintenance of NBS-III, and for considerable mechanical design on NBS-5; and D. W. Allan for very valuable assistance in data acquisition and analysis.

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Manuscript received February 5, 1970. This work was supported by the National Bureau of Standards, Boulder, Colo. It is based on a talk presented at the 16th General Assembly of the International Scientific Radio Union (URSI), Ottawa, Ont., Canada, August 1969, by Dr. J. A. Barnes, Time and Frequency Division, National Bureau of Standards, Boulder, Colo.

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IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT
Vol. IM-19, No. 3, August 1970