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THE CAESIUM RESONATORS OF THE NATIONAL BUREAU OF STANDARDS

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Recently, two caesium beam frequency standards of independent design and construction have been completed, evaluated and intercompared at Boulder. The main constructional characteristics of the devices are listed in Table I.

It is apparent that the large amount of work on atomic frequency standards will ultimately lead to the proposal of a particular atomic resonance as the scientific unit of time, so that atomic resonance devices will become the standard (*i.e.* the embodiment of the unit) of time interval and frequency. Therefore it is most important to estimate how closely a particular device approaches the idealized

TABLE I

CHARACTERISTICS OF NBS Cs FREQUENCY STANDARDS

	NBS I	*NBS II*
Characteristics		
Length	50 cm	164 cm
Line width	300 c/s	120 c/s
Shields	single	double
Cavity Q	5000	5000
Corrections to frequency		
C field	7×10^{-11}	2×10^{-11}
Phase shift	0.8×10^{-11}	0
Neighbouring lines	0	0.1×10^{-11}
Uncertainties in frequency		
C field	$\pm 4 \times 10^{-12}$	$\pm 8 \times 10^{-12}$
Phase shift	$\pm 2 \times 10^{-12}$	$\pm 2 \times 10^{-12}$
Power, tuning, monochromaticity, neighbouring transitions	0	0
Measurement precision	$\pm 2 \times 10^{-12}$	$\pm 2 \times 10^{-12}$
Total	$\pm 0.8 \times 10^{-11}$	$\pm 1.2 \times 10^{-11}$
Measured difference, NBS II–NBS I:	1.7×10^{-11}	

resonance frequency, γ_0. This degree may be spoken of as the accuracy of the device with respect to γ_0. At this point, we agree thoroughly with Dr. Essen's remark of a previous session that atomic time should be provided by a single good machine rather than by some average of several machines of lesser accuracy and precision.

Therefore, the corrections and uncertainties in those corrections in approaching γ_0 have been carefully considered, and are listed also in Table I. The extrapolation to zero bias or C field is one of the corrections. The field is produced by a rigid conductor for stability and homogeneity. It is measured in three different ways: by the field-dependent microwave transitions, by the low-frequency transitions for which $F = 0$, and by fluxmeter. The uncertainty assigned to the frequency from this cause is arrived at as a result of the observed degree of agreement among these methods. Another correction is difference in phase of the separated oscillating fields caused by non-uniform absorption of microwave power over the surface of the cavity. This can be physically observed by rotating the cavity structure through 180°. In NBS II no effect of phase shift was observed. In NBS I a total effect of 1.6 parts in 10^{11} was observed, half of which is applied as a correction. This effect was possibly caused by visible imperfections of fabrication in the cavity wall. A slight correction of 1.5 parts in 10^{12} for the effect of neighbouring transitions at the low field in use with NBS II was applied. Correction for other effects, such as applied power level, spectral purity of the driving signal and cavity turning, have been found to be negligible under proper adjustment.

The uncertainty in approaching γ_0 because of the above effects is shown in Table I. To these must be added the random uncertainty of making the frequency measurements themselves, as limited by the stability of the flywheel oscillator. One observation of frequency on either device requires from ½ to 1 minute. The standard deviation of one such measurements is of the order of 1 part in 10^{11}. Thus the standard deviation of the mean of 10 or 15 of such measurements made over 5 to 15 minutes is 2 parts in 10^{12}. This is taken as the precision of the measurement of frequency and of frequency difference between the machines. Upon adding these uncertainties to obtain a limit of error, we find that we do not expect NBS I to differ from γ_0 by more than $\pm$ 0.8 parts in 10^{11} and we do not expect NBS II to differ from

γ_0 by more than $\pm$ 1.2 parts in 10^{11}. Furthermore, we do not expect them to differ from each other by more than 2 parts in 10^{11}. Actual measurement over eight months shows a difference

$$\text{NBS II} - \text{NBS I} = 1.7 \times 10^{-11} \text{ parts}$$

The estimate of error and the measurement are then consistent, and we state the accuracy with which either machine approaches γ_0 to be $\pm 1.7 \times 10^{11}$, and a precision of measurement somewhat better than this.

International comparison of the British and Canadian standard has been carried out by radio link over a seven-month period with the following results:

			Relative frequency
NPL–NBS	II via	WWVB (60 kc) NRC MSF	$+0.6 \times 10^{-10}$
NPL–NBS II	via	Atomichron 106 (Boulder) WWV Atomichron 112 (Cruft) MSF	$+1.2 \times 10^{-10}$
NRC–NBS II	via	WWVB (60 kc)	$+4.7 \times 10^{-10}$

Some new developments have proved useful in this work. The liquid helium cooled quartz oscillator is useful over periods of several hours as a flywheel comparison oscillator. A maser stabilized crystal oscillator has recently given a cleaner Cs output signal, presumably because of greater spectral purity of the exciting signal, and has speeded up measurement time to 10 sec. The consistent behaviour of the data in random distribution and variance give confidence in attempts to measure to smaller fractions of a line width as a means of increasing accuracy in addition to attempts to narrow the line. The maser has proved a useful tool for spectral analysis of oscillator outputs.

Work in progress includes development of a servo-loop between the Cs line and oscillator, quadruple focussing to improve intensity, careful lengthening of the beam to keep the problems of C field homogeneity and intensity loss under control, trial of thallium as a suitable material and initiation of monitoring of VLF station NBA to provide international comparison of atomic frequency standards to higher accuracy.

Since many performance data are already at hand from several countries, and since more data will apparently be available on Cs and other atoms in the next three years, it is believed that it is time now to request the General Conference of Weights and Measures to undertake considerations directed toward the adoption of an atomic unit of time in three or six years.