The National Bureau of Standards Atomic Time Scales: Generation, Dissemination, Stability, and Accuracy

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Abstract—**The independent atomic time scale at the National Bureau of Standards AT(NBS), is based upon an ensemble of continuously operating cesium clocks calibrated occasionally by an NBS primary frequency standard. The data of frequency calibrations and interclock comparisons are statistically processed to provide nearly optimum time stability and frequency accuracy. The long-term random fluctuation of AT(NBS) due to nondeterministic perturbations is estimated to be a few parts in 10^{14}, and the present accuracy is inferred to be 1 part in 10^{12}.**

A small coordinate rate is added to the rate of AT(NBS) to generate UTC(NBS): this small addition is for the purpose of maintaining synchronization within a few microseconds of other international timing centers. UTC(NBS) is readily operationally available over a large part of the world via WWV, WWVH, WWVB, and telephone; also via some passive time transfer systems, e.g., Loran-C and the TV line-10 system; and also experimentally via satellite and WWVL. The precision and accuracy of these dissemination systems will be discussed.

THE independent atomic time scale at the National Bureau of Standards AT(NBS), is based upon an ensemble of continuously operating cesium clocks calibrated occasionally by an NBS primary frequency standard from which the AT(NBS) scale derives its accuracy. The stability of the ensemble between calibrations is of fundamental importance.

The instabilities of each clock in the ensemble are bicategorized. First, there are deterministic processes that must be considered for each clock; e.g., frequency and time offsets, changes in these offsets, and frequency drift. Changes or drifts in frequency are best determined by calibrations with a primary frequency standard. Time offsets or jumps are best determined by referring to the realization of time across the ensemble. Second, there are random fluctuations (nondeterministic). The noise spectrum of these random fluctuations for each clock is deduced by comparing each clock with all the others. This noise spectrum is shown to be reasonably represented by a simple mathematical model, with parameters determined by the random behavior of the clock. These noise parameters are used to provide nearly optimum filtering of each clock's noise in order to have a best estimate, in the sense of minimum squared error of prediction, of the apparent time and frequency of each clock with respect to the clock ensemble. Knowing the noise spectrum for each clock allows an estimate of the noise of the ensemble. An estimate of the random fluctuation of the ensemble is shown in Fig. 1. The

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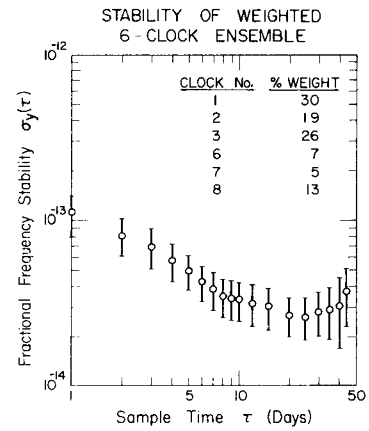

Fig. 1. Random noise fractional frequency stability of weighted 6-clock ensemble as determined from individual clock estimates. Clocks currently numbered 4 and 5 were not in the AT(NBS) clock ensemble at the time of this evaluation; however, the NP3 hydrogen maser was available and its signal was utilized during the evaluation [3]. This does not include any allowance for possible linear frequency drift of the ensemble.

data shown in this figure are nominally modeled by

$$\sigma_y^2(\tau) \simeq (3 \times 10^{-11}\ s^{+1/2})^2\ \tau^{-1} + (3 \times 10^{-14})^2, \qquad (1)$$

where $\sigma_y^2(\tau)$ is an Allan variance [1], [2]. The data shown in Fig. 1 resulted from measurements taken from November 1969 to February 1970 [3]. The instabilities of the ensemble have decreased since these measurements from that given by the first term (white noise FM) on the right in (1), and the second term (flicker noise FM) has fluctuated up and down in intensity since that time. These changes and improvements in stability have resulted from an increase in the number of clocks in the ensemble (currently eight) and from deterioration of individual clocks as components fail and/or the cesium detector signal-to-noise ratio degrades with the aging of the tube. From the preceding measurements plus additional measurements since that time the random fluctuations of the AT(NBS) clock ensemble is estimated as being better than or nominally equal to that given in (1) over the range $1\ s \lesssim \tau \lesssim 10^7\ s$ [4].

The inaccuracy of a primary frequency standard may also be bicategorized. Through the procedure of evaluation of the parameters that affect the frequency of the primary standard, there is associated with each parameter both a bias (possibly zero) and a random uncertainty in our knowledge of its effect [5]. Excellent stability of the time scale allows the possibility of averaging the random portion—in an appropriate weighted sense—of all the frequency calibrations with a primary frequency standard. The random portion is assumed to be characterized by white-noise frequency modulation, which would be expected if the uncertainties from one calibration to the next were independent.

The AT(NBS) scale in overview is an ensemble of eight commercial cesium beam clocks maintained independently. The clocks are statistically weighted and filtered to generate a time scale, AT(NBS), with nearly optimum stability. This scale is used as a memory for frequency in utilizing all of the frequency calibrations with respect to the NBS primary frequency standards. These calibrations are then used after appropriate weighting and filtering to determine the proper[1] rate and the accuracy of the AT(NBS) scale. The method employed for generating the AT(NBS) scale is based on a particular clock model. This model assumes that a linear frequency drift, a frequency offset, a time offset, changes in any of these, and random noise can all perturb the time of a clock. A convenient recursive filter has been employed to process the data in a nearly optimum way and to filter properly the perturbations introduced by all but the frequency drift. The frequency drift is measured over a sustained period with a primary frequency standard and is then properly accounted for. Other time prediction algorithms are being studied where a maximum likelihood estimator is used rather than as now with a minimum mean-square time error [6].

The AT(NBS) time scale along with the atomic time scales of six other laboratories is used to generate the International Atomic Time Scale (IAT) at the Bureau International de l'Heure (BIH). The fractional frequency difference of IAT with respect to three of the evaluable primary frequency standards in the world are as follows: for PTB $(+12 \pm 4\ \{1\sigma\}) \times 10^{-13}$, March–July 1970 [7]; for NRC $(+4.4 \pm 15\ \{2\sigma\}) \times 10^{-13}$, July 2–November 9, 1970 [8], [9]; and for NBS $(+7.4 \pm 5\ \{1\sigma\}) \times 10^{-13}$, May 1969 [10]. There is reason to believe that IAT is stable to about 1×10^{-13} for $\sigma_y(\tau \sim 1$ year) and is probably the most stable reference time scale available [11], hence the preceding values may provide reasonable comparisons among the primary frequency standards of these laboratories. AT(NBS) was in rate agreement to within 1×10^{-13} of the NBS primary frequency standard NBS-III in May 1969. Since that date NBS-III has been disassembled. All that remains is the vacuum system that has been employed in the construction of NBS-5 (a state-of-the-art primary standard to be first evaluated during Fall 1972). The rate of IAT with respect to AT(NBS) as of January 1, 1972 was about $+12 \times 10^{-13}$ via Loran-C [12]. If IAT were perfect the preceding would imply a decrease in the rate of AT(NBS) of $\sim 5 \times 10^{-13}$ in approximately three years, which is consistent with the bias uncertainties (at present, $\sim 1 \times 10^{-12}\ \{1\sigma\}$) internally assigned to the AT(NBS) scale.

The accuracy goal for NBS-5, a state-of-the-art cesium beam primary frequency standard presently under construction at NBS, is 1×10^{-13}. Attainment of this goal obviously would

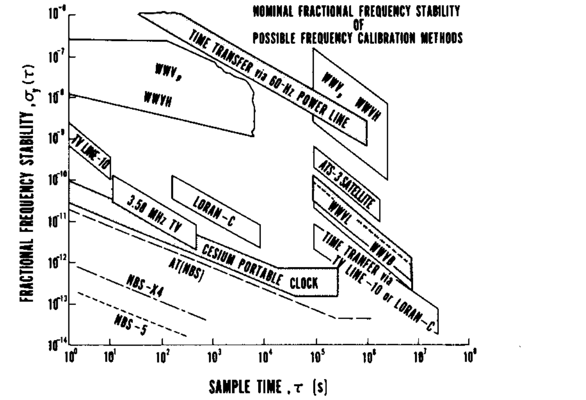

Fig. 2. Fractional frequency stability as a function of sample time for several UTC(NBS) dissemination techniques as of Spring 1972. The lines labeled NBS-X4 and NBS-5 represent the design stabilities (predicted) of the two respective laboratory cesium-beam frequency standards under construction at NBS. The television active time code will have nearly the same or better stability than the TV line 10 time transfer system [4], [23], [24]. The nominal stability of the television color subcarrier signal (3.58 MHz) is also shown; and, though not listed in Table I since it is more useful as a frequency transfer device, the frequencies are published monthly [19], [25].

allow a significant improvement in the accuracy of the rate of AT(NBS)—especially since fairly frequent calibrations are expected to occur.

In conjunction with the AT(NBS) proper time scale, we also generate the coordinate time scale UTC(NBS). This latter scale is kept synchronized (coordinated) to within a few microseconds of the UTC(BIH) scale as well as being mutually coordinated with the UTC(USNO) scale [13], [14]. This coordination is accomplished by small discrete rate changes (of a few parts in 10^{13}) in UTC(NBS) and in UTC(USNO). One-second time jumps are made as announced by the BIH for keeping these scales within ± 0.7 s of the UT1 scale.

The determination of a date on the AT(NBS) scale or on the coordinated UTC(NBS) scale requires some method of access to them. In Fig. 2 are plotted fractional frequency stabilities $\sigma_y(\tau)$ for the main methods of communicating the time and/or frequency of these two scales. The stability data for Fig. 2 were taken from the literature [15]–[18] or were measured and computed by the authors. Typically the UTC(NBS) scale is the one that is directly disseminated and the relationship between it and AT(NBS) is published monthly [19]. For comparison purposes the estimated random fluctuation of AT(NBS) is plotted—the random fluctuations of UTC(NBS) are the same. The anticipated stabilities of two laboratory cesium beam frequency standards NBS-X4 and NBS-5 are also plotted.

The date on the UTC(NBS) scale is communicated from NBS, Boulder, Colo., to the NBS radio stations (WWV, WWVB, and WWVL) near Fort Collins, Colo., via the TV line-10 passive time transfer system [4], [20]–[22], and time and frequency are communicated to WWVH at Kekaha, Kauai, Hawaii, via WWVB transmissions and portable clocks. WWVH in turn provides time and frequency over the Pacific Ocean and adjoining areas.

Note that the signals from Loran-C, 60-Hz power line, and TV line-10 of necessity are used in a passive time transfer

[1] Proper is used here in the relativistic sense.

TABLE I
UTC(NBS) ACCESSIBILITY

Method of Access	Coverage	Times Available	Nominal Accuracy for Date Transfer	Additional Equipment Cost to User ($)
WWV and WWVH	hemisphere	continuously	$\lesssim$ 1 ms	~ 200–2000
WWVB	North America	continuously	~ 50 μs	~ 400–4000
Television active time code	USA	proposed—during live telecasts from major networks	< 100 μs	~ 2000
ATS-3 satellite	hemisphere	experimental—1700 to 1715 UTC and 2330 to 2345 UTC, daily	10–50 μs	~ 150
Telephone (303) 499-7111 Boulder, CO	North America	continuously	$\lesssim$ 0.03s	price of phone calls
Portable cesium clock	global	per user's desire	~ 0.1 μs	~ 19 000
Portable rubidium clock	global	per user's desire	~ 1 μs	~ 12 000
Loran-C (ground wave)	east of Rocky Mountains (N. America) through Europe	1700 UTC each work day	$\lesssim$ 3 μs	~ 5000–10 000
Line-10 television	requires common reception of east USA network TV programs	~ 1330 local time (Boulder) each work day	path must be calibrated; ~ 2.5 ns $\tau^{1/3}$ s$^{-1/3}$ 33 ms < $\tau \lesssim 10^7$ s	~ 100–500
60-Hz power line	USA and some adjacent areas	proposed	path must be calibrated; ~ 1 ms τ^0, 17 ms $\leqslant \tau \leqslant 10^7$ s	~ 10–100
Omega navigation system	global	proposed	< 10 μs	~ 16 000

The coordinated time scale UTC(NBS) is made available via the methods tabulated. The general coverage, the times of day during which the disseminated signals can be related to UTC(NBS), the accuracy of transferring the date of UTC(NBS) to a point within the coverage indicated, and the approximate cost to the users of the receiving equipment are also listed.

mode [4], [22]; i.e., the date of arrival of the signal on the UTC(NBS) scale must be differenced with the date of arrival of the signal ascertained with the user's clock in order to determine if a change has occurred in the user's clock time since the last measurement. For these methods the path delay must be calculated or calibrated, e.g., with a portable clock, for time transfer (though not for frequency transfer).

Table I has been compiled to show the general accessibility of the UTC(NBS) scale. From the user's point of view there are additional factors that need to be considered: reliability, skill required, etc. (see [15]). Although not indicated in Table I, personnel at NBS also monitor other radio stations (NAA, GBR, NLK), and these may be used in the previously mentioned time transfer mode to communicate UTC(NBS). The readings are published monthly [19].

The cost effectiveness to the user for the precision and accuracy achieved using the TV line-10 technique and the ATS-3 satellite technique, respectively, is very good. Insertion of an active time code on one of the lines in the blanking interval of the TV transmissions has been experimentally tested [23], [24], and has the potential of being extremely cost effective for the excellent precisions ($\lesssim$ 1 μs) achievable, plus having a useful accuracy for maintaining the date once the path has been calibrated. This time code (Television Active Time Code in Table I) is being considered for an operational service. The ATS-3 date transfer experiment is scheduled to terminate August 1, 1972. However, because of the success of the experiment, an extension is being considered. There are also plans for an NBS experiment that would provide time from UTC(NBS) continuously using a Department of Commerce satellite. A more complete version of this manuscript is in preparation for later publication.

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