THE NBS-A TIME SCALE—ITS GENERATION AND DISSEMINATION

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The NBS-A Time Scale—Its Generation and Dissemination

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Abstract—**In conjunction with the United States Frequency Standard (USFS) located at the National Bureau of Standards, Boulder Laboratories, two time scales have been established. The NBS-A time scale is referenced to the USFS in accordance with the definition of the atomic second as adopted by the 12th General Conference of Weights and Measures in October, 1964. The epoch of this scale was set to be nearly coincident with the epoch of UT-2 at 00:00 hour January 1, 1958. The NBS-UA time scale is also referenced to the USFS but the frequency offsets and shifts in epoch as announced by the Bureau International de l'Heure (BIH) in Paris are incorporated in this time scale. Thus, NBS-UA is an atomically interpolated approximation to UT-2.**

The accuracies of time interval measurements referenced to these time scales are believed to have essentially the accuracy of the USFS [1]—the accuracy of the USFS is about one part in 10^{11}. The NBS-UA time scale is presently being disseminated by the NBS radio stations WWVL, WWVH, and WWV. The phases of WWVL transmissions have been maintained coherent with the NBS-UA time scale with a precision of about ± 3 μs and the epoch of the WWV transmissions with a precision of about ± 10 μs since January, 1964. Since January 1, 1965, the WWVB phase has been maintained coherent with NBS-A.

Introduction

A CLOCK SYSTEM or time scale is obtained by summing up small "time intervals" or "units of time." The time scale usually has as its origin some rather arbitrary event in the remote past. The time indicated by the clock, usually called "epoch" (for example, the epoch of some event might be 10:46 AM, December 7, 1964), is obtained by summing up the "units of time" ever since the origin of the time scale.

The basic unit of time, the second, as adopted by international agreement, has undergone an extensive evolutionary process. Prior to 1956 the second was defined as one/86 400th part of the time required for an average rotation of the earth on its axis with respect to the sun. This "second" of time was discovered to have certain irregularities and thus in 1956 the ephemeris second was adopted. The ephemeris second is defined as the fraction 1/31 556 925.9747 of the tropical year for 1900, January 0 at 12:00 ephemeris time.

The uncertainties arising in astronomical observations have limited the precision of measurement of this unit of time to about two parts in 10^9 and thus in October, 1964, the 12th General Conference of Weights and Measures at its meeting in Paris temporarily adopted an alternate definition of the second based on a transition of the cesium atom. The exact wording of the action of the 12th General Conference was: "The standard to be employed is the transition between the two hyperfine levels $F=4$, $m_F=0$ and $f=3$, $M_F=0$ of the fundamental state $^2S_{1/2}$ of the atom of cesium 133 undisturbed by external fields, and the value 9 192 631 770 Hertz (Hz) is assigned." This atomic second is reproducible

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with a much greater precision than the ephemeris second.

In spite of this definition, nations have also been committed by international agreement to the broadcast of approximate UT-2 time. The time scale, UT-2 is essentially mean solar time corrected for such things as the migration of the poles, etc. The length of a UT-2 "second" is not constant in terms of the present internationally defined atomic second. The Bureau International de l'Heure (BIH) in Paris determines a reasonable approximation of the UT-2 "second" in terms of the atomically defined second and all coordinated broadcasts emit this approximate "second" of UT-2 time. This difference between the approximate UT-2 "second" and the atomic second (presently the approximate UT-2 "second" is 150×10^{-10} seconds longer than the atomic second) is determined and set for each year and announced by BIH. By "summing up" these UT-2 "seconds" an approximation to UT-2 (epoch) time is obtained. Occasionally step adjustments are needed in this approximate UT-2 scale to maintain it within 0.1 seconds of the astronomically determined, true UT-2 epoch.

Thus it is that the National Bureau of Standards has maintained two time scales for the past several years: 1) the NBS-A time scale is based on the present international definition of the atomic second with the resonance of the appropriate cesium transition being used by the United States Frequency Standard (USFS); the epoch of NBS-A was set in coincidence with UT-2 on January 1, 1958, in cooperation with the United States Naval Observatory, and 2) the NBS-UA time scale is also based on the USFS but the frequency offsets and step adjustments in epoch as released by the BIH are incorporated to make an interpolated "universal" time scale from an atomic time scale. The NBS time scales have thus accumulated about 3.6 seconds difference (NBS-UA being late relative to NBS-A) since January 1, 1958.

The clock system maintaining NBS-A and NBS-UA has evolved with the state-of-the-art in frequency and time measurements. The present system is believed to have a precision and accuracy of time interval measurements which is limited only by the USFS itself for time intervals longer than a few days. The accuracy of the USFS [1] is about one part in 10^{11}. For time intervals of the order of one day or less the clock system contributes an additional uncertainty to the relative error of the time interval measurements of about 3×10^{-12}.

The NBS-UA time scale, prior to January 1, 1965, was disseminated by the radio stations WWV, WWVL, WWVB, and WWVH. The signals emitted by these transmitters were phase coherent with the NBS-UA time scale such that the standard deviation of the time error between a clock run from these signals and the NBS-UA time scale is 3 μs for the WWVL/B signals and 10 μs for the WWV signals.

On January 1, 1965, radio station WWVB (60 kHz from Fort Collins, Colo.) began operation without offset from the atomic definition of the second. The phase of the transmitter for WWVB is phase-locked to the NBS-A time scale while WWVL, WWVH, and WWV maintain coherence with the NBS-UA time scale. The epoch of the one second "ticks" on the carrier of WWVB is shifted in increments of 200 ms in order to maintain synchronism with UT-2 to within about 100 ms.

The NBS-A and NBS-UA Time Scales

The Clock System

The NBS-A and NBS-UA clock system has undergone considerable evolution since its beginning in 1957. Starting on October 9, 1957, the National Bureau of Standards assigned atomic times to the pulses of radio station WWV on a daily basis in terms of the United States Frequency Standard; this was the beginning of the NBS-A time scale [2]. The epoch of NBS-A time was set to agree within about 0.1 ms with that of the A.1 atomic time scale maintained by the U. S. Naval Observatory on January 1, 1958. In this way the NBS-A standard time scale became a continuation of the time sequence of events used to synchronize observers everywhere. Its continuously generated epoch forms an easily accessible reference scale for all events. This is a prerequisite for all standard time scales. Time continued to be generated for NBS-A at WWV until a more precise clock system was constructed at the National Bureau of Standards, Boulder, Colo., in July, 1962. On April 24, 1963, synchronization occurred to within ± 5 μs between WWV and the Boulder clock system via a portable clock [3]. Since that time, the NBS-A time scale has been maintained at the National Bureau of Standards in Boulder, having the very desirable feature of being located in close proximity to the USFS so that radio propagation is no longer a part of the measuring scheme.

The NBS-UA time scale is also generated by the same clock system generating NBS-A. Its direct synchronization with WWV was accomplished in the same clock transport of April 24, 1963 [3].

The present clock system consists of four quartz crystal oscillators and one rubidium gas cell. Each oscillator has coupled to it a clock to count cycles; the 100 kHz nominal frequency from the oscillator is divided down and generates indicated time intervals of about one second. Each of the five clock combinations is left to run freely except when its frequency exceeds its nominal frequency by more than one part in 10^8; it runs independently of all of the other four, and hence from each a time scale can be constructed.

Time is determined in the following fashion. It has been found that as a good quartz crystal oscillator ages, its frequency drift rate approaches a constant, and that after a relatively short time (of the order of a few weeks) the oscillator can be assumed to a very good approximation to have a frequency drift which is linear with the indicated time. Most approximately-periodic devices whose true frequency f can be measured sufficiently often in terms of a standard may be used to generate time. If the nominal frequency of such a device is f_n, and the number of oscillations (periods) in the true time t is N, then the indicated time τ for this interval is

$$\tau = N/f$$

or for infinitesimal fractions of a cycle dN

$$d\tau = dN/f_n.$$

On the other hand, the actual time elapsed for this same small fraction of a period is

$$dt = dN/f. \tag{1}$$

Substitution and integration leads immediately to the expression for the total elapsed time

$$t = \int_0^\tau \left(\frac{f_n}{f}\right) d\tau \tag{2}$$

in terms of the indicated time. Now the defined frequency of the standard f_s which is identical with its true frequency by definition, is a certain multiple r of the true frequency of the clock, i.e., $f_s/f = r$. In general, r depends on the indicated time. Hence, one can write

$$t = \frac{f_n}{f_s}\int_0^\tau r d\tau. \tag{3}$$

If the clock were the standard itself, then one would have $r = 1$, and $t = \tau$. The frequency standard would also be the time standard. In actual practice, this is not convenient, and the time may be calculated from accumulated data on the value of the function r. Since f differs only slightly from f_n, r may be written in the form

$$r = f_s/f_n + \delta r$$

where δr is a small quantity relative to f_s/f_n. Thus the true atomic time is given by the expression

$$t = \tau + \frac{f_n}{f_s}\int_0^\tau \delta r d\tau. \tag{4}$$

The second term is generally a very small correction, and is approximated by a summation of discrete measurements. In fact, this integral is approximated by a sum of terms based on the assumption of a linear drift in frequency between measurements of δr.

The assumption of a linear frequency drift for a quartz crystal oscillator between daily calibrations is at variance with certain perturbations often observed in the frequency of quartz oscillators. These variations are due to fluctuations in the ambient temperature and in the 60 Hz line voltage; there have been frequency shifts due to a change in load on an oscillator, and inherent circuit noise has been observed to induce statistical fluctuations which cause an oscillator to depart from the predominant linear frequency drift behavior. All but the last of these effects can and have been controlled by proper electronic design and laboratory techniques. The interesting problem of statistical fluctuations caused by inherent oscillator noise has stimulated a great deal of study by several people in order to determine the statistical characteristics of the noise and its effect on the time error and precision of various types of oscillators [4]. Recently some additional results, not yet published, have been established by the authors. One result is that the deviation in the incremental time accumulated by a quartz crystal oscillator during one calibration interval is almost completely independent of the deviations obtained in previous intervals so that the errors compound by nearly a random walk process. As an example this "rms time error" for our best oscillator is 0.3 μs for one day (or 3 parts in 10^{12}). If one were to make daily measurements on the oscillator for 100 days, the rms time error would be $\sqrt{100} \times 0.3$ or 3 μs for approximately three months (or 3 parts in 10^{13}). The conclusion is that as time progresses the relative precision of the NBS-A time scale approaches that of the standard rather than that of the clock system, in the sense that the ratio of the accumulated error in time to total elapsed time approaches zero as $t^{-1/2}$, so that the accuracy of the time scale approaches that of the USFS for long elapsed time.

Various experiments have been conducted by the authors to determine if systematic errors are present in the oscillators. One quite conclusive experiment was to compare two of the oscillator clocks as independent time generators. One of these was a quartz crystal oscillator and the other was the rubidium gas cell, each in different rooms, at different temperatures, and under basically different operating conditions. The divergence between the two could be explained entirely in terms of the random walk phenomenon. Moreover, if systematic errors were present, they were less than 5×10^{-13}.

Typically, each oscillator is compared to the USFS for approximately fifteen minutes each working day. The integration of (4) is approximated on the basis of a linear frequency drift between calibrations.

Comparison With Other Time Scales

Regardless of the confidence limits one assigns to the NBS-A time scale due to internal consistencies, it is desirable to make external measurements to help insure that no significant, undiscernible, systematic errors exist in the system. Comparisons have been made with Laboratoire Suisse de Recherches Horlogères (LSRH), Neuchatel, Switzerland, and with the United States Naval Observatory.

The modus operandi of the LSRH atomic time scale (denoted TA_1) is very similar to that of NBS-A in that it employs cesium^{133} as the standard, and high quality quartz crystal oscillators coupled with clocks to interpolate time and frequency between calibrations in terms of the standard. In spite of these basic similarities, the fact that TA_1 is completely independent of NBS-A indicates that a comparison between the two should be very significant.

The comparison [5] was made using the NBS con-

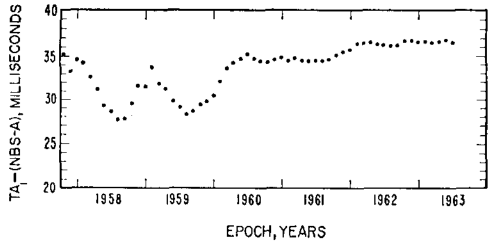

Fig. 1. Comparison on the time scales TA_1 and NBS-A.

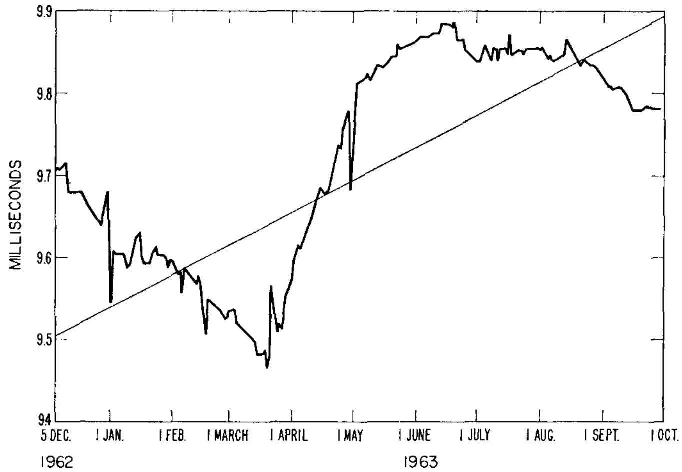

Fig. 2. Arrival time of Loran C pulses on the NBS-UA time scale.

trolled radio station, WWV, Greenbelt, Md. Figure 1 shows a plot of the reception times of pulses on the TA_1 time scale since 1957 minus the emission times of the corresponding WWV pulses on the NBS-A time scale. The standard deviation for each data point plotted is about 0.2 ms, and the propagation delay is of the order of 25 ms, determined roughly from the distance.

It is interesting to note the effect exhibited by the curve in 1960 when the United States adopted the laboratory cesium beam standard, NBS-II, as the USFS, and LSRH changed from the $N^{14}H_3$ maser to Cs^{133} as their standard. The divergence over-all is $\sim 3\times 10^{-11}$ s/s; from epoch 1962.2 on, the divergence is $\sim 1\times 10^{-11}$ s/s, with TA_1 high in frequency relative to NBS-A. This latter divergence is just the stated accuracy for each of the standards involved. In June 1964, L. Cutler and A. S. Bagley [6] carried two portable cesium beam standards to Neuchatel, Switzerland, and measured the frequency of the LSRH cesium standard and then traveled to Boulder and measured the frequency of the USFS. Assuming no change in the portable standards during travel, the frequency of the USFS agreed with that of the LSRH standard to within 1×10^{-11}.

The Loran C master is basically the Naval Observatory's approximation to UT-2 controlled in terms of the scale A.1, and hence the comparison of A.1 with NBS-A was accomplished by monitoring the arrival time of the Loran C pulses on the NBS-UA time scale. A plot of these reception times on the NBS-UA time scale is shown in Fig. 2. The straight line least squares fit to the data shows a divergence rate (slope) of 1.5×10^{-11} s/s with the Loran C master being low in frequency relative to the NBS-UA time scale.

The Automatic Generation of a Time Scale

The computer typically takes two weeks of data before the individual times of each of the five clocks are calculated and averaged to yield NBS-A and NBS-UA. In this situation one cannot determine the time an event occurred, as measured by any one of the clocks in the system, until after the computer has processed the data. Therefore, it was very desirable to construct a clock that is on time and on frequency. Such a device would have great utility in the immediate dissemination of time and frequency. A uniform frequency and time generator was therefore constructed at the NBS Boulder Laboratories. The idea for the device was conceived by L. Fey; concurrently and independently a commercial concern constructed a similar one. The device called a Drift Corrected Oscillator (DCO) utilizes the characteristic of a good quartz crystal oscillator mentioned earlier: Its frequency drift rate after aging is nearly constant. The utilization is accomplished by cascading two mechanical ball disk integrators and coupling the output to a continuous phase shifter; the phase shifter in turn is inserted on the output of a good quartz oscillator. The combination generates a stable frequency and a nearly uniform time scale which approximates NBS-UA.

A DCO has been maintained to approximate the NBS-UA time scale since November, 1963, and has been controlling the time and frequency transmissions of the NBS since January 17, 1964. The standard deviation from the NBS-UA scale of the time pulses from this device since it began operation is 3 μs, and the standard deviation of its fractional frequency offset determined in terms of the USFS, has been 5×10^{-12} on a daily basis, 4×10^{-12} on a weekly basis, and 2×10^{-12} on a monthly basis.

The Dissemination of NBS-UA

The NBS-UA time scale is available to the public through the NBS broadcasting services. NBS directly controls the broadcasts from four different stations: WWV (2.5 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, 25 MHz) and WWVH (5 MHz, 10 MHz, 15 MHz), high-frequency stations known and used for many years; WWVB (60 KHz), a low-frequency station initiated at Boulder in the mid-fifties and rebuilt at Fort Collins in 1963; and WWVL (20 KHz), a very low-frequency station started in 1960 at Sunset, Colo., and rebuilt at Fort Collins in 1963.

The Atomic Frequency and Time Interval Standards Section provides signals suitable for controlling precision broadcasts which are maintained within close tolerances to the USFS and NBS-UA. This constitutes the first step in disseminating these standards.

The second step occurs in relating this information to the LF and VLF broadcasts at Fort Collins. This is accomplished as follows: The LF and VLF signals broadcast from Fort Collins are phase monitored at NBS, Boulder; the phases of these signals are compared with the standard reference signal; error signals with appropriate sense and magnitude are transmitted by FM to Fort Collins; these error signals drive servosystems to accomplish the required transmitted phase corrections for both frequencies so that each is directly related to the standards provided.

This system reduces the transmitted phase variations received at Boulder to the point where the actual transmitted phase is coherent with the reference phase to a tolerance of ± 0.1 μs. The complete system, to be described in detail elsewhere, has proven to be very reliable, well-engineered, and adequate for present needs.

The third step in disseminating the frequency and time standards is to relate the HF broadcasts from WWV and WWVH to WWVB and WWVL and thence directly back to NBS-UA.

This is accomplished at present by phase monitoring WWVB and WWVL at the HF stations and using this information to control the operating oscillators. Thus, WWV is phase-locked to WWVL which in turn is phase-locked to NBS-UA, just as synchronous electric clocks are phase-locked to the 60 Hz power line. Until now no attempt has been made to control WWVH to tolerances better than 1 ms but WWV has been the subject of experimental efforts to determine the best tolerance limits which could be applied realistically to frequency and time control of a remote station.

Using the signals from WWVL as a reference, the operator at WWV was instructed on January 18, 1964, to maintain his oscillator by incremental adjustments as needed to maintain phase with Fort Collins. These adjustments were to be limited to a part in 10^{11} or less.

The results of this experiment are as follows:

Date	Clock at WWV relative to NBS-UA
April 24, 1963	On time (by definition) [2]
March 3–5, 1964	508 μs fast
May 4, 1964	524 μs fast
May 18, 1964	517 μs fast
May 23, 1964	512 μs fast
July 22, 1964	518 μs fast
September 14, 1964	518 μs fast

The data tabulated here were accumulated by portable clock carrying techniques using both commercially available clocks and NBS built clocks of the crystal oscillator type. The agreement of the measurements on a round-trip basis indicate a measurement accuracy approaching a microsecond.

An examination of the complete data over this period reveals the fact that WWV, since the middle of January, 1964, has been time controlled to NBS-UA within a tolerance of ± 10 μs. This is a positive improvement in time dissemination.

It is desirable to indicate several steps that must be taken in the future to improve the control of a remote oscillator.

1) Continuous drift compensation in place of present incremental adjustments in the remote oscillator system.
2) Improved VLF receivers to provide greater accuracy and redundancy.
3) Development of techniques to correct for propagation time variations.

Conclusion

The National Bureau of Standards has established and maintained an atomic time scale (NBS-A) and an atomically controlled approximation to UT-2 (NBS-UA), with their beginnings in late 1957. Since that time many improvements both in the United States Frequency Standard and the clock systems accumulating the time scales have taken place. The present system, located entirely at the Boulder Radio Standards Laboratory, Institute of Basic Standards, of the National Bureau of Standards, is believed to have a timing precision of 0.3 μs for a one day interval and is limited primarily by the accuracy and precision of the USFS (accuracy of one part in 10^{11} and precision of two parts in 10^{12} for fifteen minute averages) for longer intervals.

The standard frequency broadcast stations WWVB and WWVL are directly phase controlled by the auxiliary continuously generated approximation to the NBS-UA scale. It is, therefore, possible to make use of the properties of LF and VLF propagation to hold any number of clocks at quite remote locations in very precise (± 10 μs) synchronism indefinitely with the NBS-UA scale and hence with each other. Experiments at radio station WWV have proven the feasibility of this mode of time control.

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References

[1] R. C. Mockler, R. E. Beehler, and C. S. Snider, "Atomic beam frequency standards," *IRE Trans. on Instrumentation*, vol. I-9, pp. 120–132, September 1960.
[2] J. Newman, L. Fey, and W. R. Atkinson, "A comparison of two independent atomic time scales," *Proc. IEEE* (*Correspondence*), vol. 51, pp. 498–499, March 1963.
[3] J. A. Barnes and R. L. Fey, "Synchronization of two remote atomic time scales," *Proc. IEEE* (*Correspondence*), vol. 51, p. 1665, November 1963.
[4] W. R. Atkinson, L. Fey, and J. Newman, "Spectrum analysis of extremely low frequency variations of quartz oscillators," *Proc. IEEE* (*Correspondence*), vol. 51, p. 379, February 1963.
[5] J. Bonanomi, P. Kartaschoff, J. Newman, J. A. Barnes, and W. R. Atkinson, "A comparison of the TA_1 and the NBS-A atomic time scales," *Proc. IEEE* (*Correspondence*), vol. 52, p. 439, April 1964.
[6] L. S. Cutler and A. S. Bagley, "A new performance of the 'flying clock' experiment," *Hewlett-Packard J.*, vol. 15, pp. 1–5, July 1964.