Correspondence

National Standards of Time and Frequency in the United States*

Time

Time is one of the independent quantities chosen as a basis for the measuring system of science. To establish a time scale, that is, to specify a time coordinate, we must first establish an origin and a constant unit of time and lay off the unit at least as far as all points of interest, in exact analogy to the specification of position. The orbital motion of the earth about the sun provides a time scale, called Ephemeris Time (ET) which is suitable in these respects, and also constitutes a standard from which the unit may always be obtained. In October, 1956, the International Committee on Weights and Measures, with representation from the United States, effectively adopted the second of ET as the fundamental unit of time by resolving that "the second is the fraction 1/31,556,925.9747 of the tropical year for January 0, 1900 at 12 hours Ephemeris Time."[1] The tropical year for any given epoch (or moment) is the interval, taken symmetrically about that epoch, necessary for the mean longitude of the sun to increase by 360°, as measured along the ecliptic from the vernal equinox. This definition of the second has been one of many attempts to define a unit of time 1) which remains constant with epoch, 2) which is physically realizable to high precision, and 3) which is permanently available for observation.

Ephemeris Time is obtained in practice by observations on the position of the moon and reference to tables giving this position as a function of ET. As the fundamental unit, the second of ET replaced the second of Universal Time (UT), a time scale based on the rotation of the earth. The delay in the determination of UT from the astronomical observations is of the order of a month; the delay in the determination of ET to any useful degree of accuracy is of the order of several years.

The maintaining of a national standard of time consists of the process of determining the time scale in the United States from the international standard and making this information available to the user. Often, however, as with position, it is only time differences or time intervals which are of interest. This need for convenient interval determination has led to the common use of other time scales with easier realizability than ET.

Measurements often have been, and still are, expressed in terms of time scales other than ET. These other scales are all related or relatable to ET and to each other through conversion factors with various degrees of precision as to size of unit at least, and in some cases as to origin also. The situation is analogous to using a measuring rod of different length than the standard rod but of known calibration. For example, UT0 is the astronomically observed Universal Time or mean solar time, uncorrected for polar variation and annual fluctuation in the earth's speed of rotation; UT1 is UT0 corrected for polar variation; UT2 is UT1 corrected for annual variation. None of the UT seconds is constant. They are variously determined by several nations. Various other nominal "seconds" are defined by the duration of a specified number of periods of various oscillators or resonators, such as quartz or atomic devices. These all have the outstanding characteristic that they are more readily observable than ET. The atomic time unit, furthermore, is assumed for the present to be as constant as the unit of ET.

The United States Frequency Standard

A national standard of frequency called the United States Frequency Standard (USFS) is maintained at the Boulder Laboratories, National Bureau of Standards, for the purpose of making immediately and continuously available, through the Standard Frequency Broadcasts discussed below, a provisional time scale with which to make measurements. This provisional scale is sufficiently accurate for all civil and most scientific uses. Nevertheless, for the highest possible accuracy, this scale must be continually corrected to or calibrated against the national time scale as finally determined, and it must be relatable to other frequency and time scales in common use.

The USFS in general consists of the weighted value of the outputs (reduced of course to a common basis) of several actual oscillators and resonators maintained at the Boulder Laboratories, these devices being among the best available at any current state of the frequency control art. In particular, the USFS is presently stable to 2 parts in 10^{10} or better over intervals from about 1 to 10^3 minutes; over longer intervals, its value has been maintained as constant as possible prior to October 9, 1957 with respect to the UT2 second as determined by the U. S. Naval Observatory, and since October 9, 1957 with respect to atomic frequency standards. These atomic standards have been compared with other atomic standards via a network comparison. Such atomic standards have been shown to be in agreement and to remain constant with respect to each other to 5 parts in 10^{10} or better.[2,3]

Standard Frequency Broadcasts

The United States Frequency Standard is distributed to interested users by means of standard broadcasts of Radio Stations WWV and WWVH. The frequencies of these stations are kept in agreement with respect to each other and have been maintained as constant as possible with respect to the United States Frequency Standard since December 1, 1957. The nominal broadcast frequencies should, for the purpose of highly accurate scientific measurements, for establishing high uniformity among frequencies, or for removing unavoidable variations in the broadcast frequencies, be corrected either to the United States Frequency Standard, as indicated in the monthly tables published in the IRE,[4] or to a particular time scale as determined by the Naval Observatory, with adequate limits assigned for propagation errors.

Time Signals

Time signals, sufficiently accurate for all civil and most scientific uses, are also carried by the standard broadcasts. The WWV and WWVH time signals are also kept in agreement with each other. They are locked to the nominal frequency of the transmissions, and consequently may depart continuously from other time scales such as UT2. Corrections expressed as the times of reception of the WWV time signals on the UT2 scale are determined and distributed by the U. S. Naval Observatory.[5] Recently, the Observatory has established a particular atomic time scale, A.1, with unit determined by 9,192,631,770 periods of Cs at zero field and origin coinciding with UT2 on January 1, 1958, and has published times of reception of WWV on this scale also.[6] Agreement with time on the UT2 scale, or simply agreement with UT2, within ±30 msec at all times, has been maintained by making step adjustments in time of precisely plus or minus twenty milliseconds on Wednesdays at 1900 UT when necessary. Beginning January 1, 1960, the broadcast frequencies will be offset from the United States frequency standard by a different amount than heretofore in order to establish a unit in substantial agreement with the current value of the unit of UT2. Thus the time signals, locked to the broadcast frequency, will require less frequent adjustment than in the past.

Corrections of the USFS and the Standard Frequency Broadcasts

The method of final correction of the

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[1] Comite International des Poids et Mesures, "Proces-Verbaux de Seances," 1956 Session, Ser. 12, vol. 25, Gauthier-Villars, Paris; 1957.

[2] Essen, Parry, Holloway, Mainburger, Reder, and Winkler, "Comparison of cesium frequency standards of different construction," *Nature*, vol. 182, pp. 41–42; July, 1958.

[3] Mockler, Beehler, and Barnes, "An evaluation of a cesium beam frequency standard," Symposium Record, Office of Naval Research Symposium on Quantum Electronics, Bloomingburg, N. Y.; September 14–16, 1959.

[4] W. D. George, "WWV standard frequency transmissions," PROC. IRE, vol. 46, pp. 910–911; May, 1958, and subsequent months.

[5] "U. S. Naval Observatory Time Signals, I. Preliminary Times of Reception, UT2," Bulletin B, U. S. Naval Observatory, Washington, D. C. (unpublished).
"U. S. Naval Observatory Time Signals, Final Times of Reception, UT2," Bulletin A, U. S. Naval Observatory, Washington, D. C. (unpublished).

[6] "Time Service Notice No. 6," U. S. Naval Observatory, Washington, D. C., January 1, 1959 (unpublished).

USFS and the Standard Frequency Broadcasts to the national time scale has changed over the years as improvements in the measurement of time and frequency have been made.

Fig. 1 shows schematically the relation between the frequencies (*i.e.*, cycles per common unit of time) of hypothetical oscillators which oscillate such as to mark off the unit of the time scales indicated after exactly the same number of cycles in each case. The frequencies are shown relative to the value of the hypothetical oscillator marking off the defined unit of ET. The figure is equivalently interpreted as the reciprocal of the size of the units of the indicated time scale relative to the unit of ET.

The Standard Frequency Broadcasts and Time Signals have been and are related to the UT and A.1 time scales as explained above. From these observations, frequency corrections of the Standard Frequency Broadcasts to these scales are easily made; and in addition, conversion from the UT scale at a given epoch to the ET scale is available after reduction of astronomical observations.[7-9]

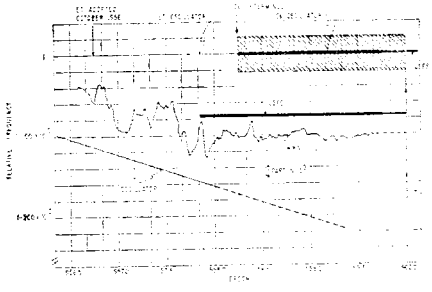

Fig. 1—Relative frequencies of oscillators keeping the time scales indicated; or equivalently, reciprocals of the lengths of unit intervals on the indicated time scales. Width of Cs and USFS lines indicates precision; cross hatching shows assigned accuracy of Cs frequency. The UT2 scale is derived from smoothed data.[5] The UT2 unit is considerably less precise than the other units. The WWV scale is taken from a U. S. Naval Observatory Notice.[6] Values of USFS and WWV transmissions will be altered as indicated on January 1, 1960.

Prior to October 9, 1957, the final value of the USFS was assigned retrospectively on the UT scale from the determination of the frequency of the Standard Frequency Broadcasts on this scale and the known relation between the Standard Frequency Broadcasts and the USFS. These values have not been published, but are a matter of scientific record at the National Bureau of Standards.

With improvement in stability and constancy realized in the maintenance of the USFS by the availability of atomic frequency standards, monthly publications of corrections of the Standard Frequency Broadcasts to the USFS were made from October 9, 1957, to realize the advantage of rapid correction to a more constant frequency than that based on the unit of UT2.

It is thus also necessary to relate the USFS and Standard Frequency Broadcasts to frequencies provided by atomic frequency standards such as cesium. Since the relation of an atomic time unit defined by a given number of periods, N, of an atomic oscillation to the unit of ET has not yet been adopted internationally, we are required to state explicitly an assumed value of N when comparing frequencies or times to an atomic scale. In comparing the USFS to an atomic time scale, the following equality was adopted as of October 9, 1957, and holds to a precision of 1 part in 10^{10}: 100,000.000 . . . periods of the USFS equals N_1 periods of the zero-field (4, 0)↔(3, 0) Cs transition, where N_1 equals 9,192,631,838.

If N_0 is the number of Cs oscillations per unit of ET, then the ratio N_0/N_1 may be used to convert the USFS to the ET scale as soon as N_0 is determined. Markowitz, *et al.*[5] have measured N_0 to be 9,192,631,770 ±20 as the number of Cs oscillations per unit of ET, providing the best and only value expected for several years. Effective January 1, 1960, the value of the USFS will be corrected so that N_1 equals 9,192,631,770, and the published corrections to the Standard Frequency Broadcasts will thus be given with respect to the unit of ET as realized by atomic standards to a precision of the intercomparison of atomic standards (a few parts in 10^{10}) and to an accuracy determined by the work of Markowitz, *et al.* (±22 parts in 10^{10}).

The final correction of the Standard Frequency Broadcasts, and hence the USFS, to the national time scale, will be effected by the Naval Observatory by the observation of the times of reception as described.

In summary, to express a given time interval or frequency in terms of the international standard, it must be referred to a standard broadcast, or some atomic standard with proper regard for the precision of this comparison, and the latter standard must be referred to the ephemeris second as indicated herein with proper regard for the uncertainties involved.

National Bureau of Standards
Boulder, Colo.

WWV Standard Frequency Transmissions*

Since October 9, 1957, the National Bureau of Standards radio stations WWV and WWVH have been maintained as constant as possible with respect to atomic frequency standards maintained and operated by the Boulder Laboratories, National Bureau of Standards. On October 9, 1957, the U.S.A. Frequency Standard was 1.4 parts in 10^9 high with respect to the frequency derived from the UT2 second (provisional value) as determined by the U. S. Naval Observatory. The atomic frequency standards remain constant and are known to be constant to 1 part in 10^9 or better. The broadcast frequency can be further corrected with respect to the U.S.A. Frequency Standard, as indicated in the table; values are given as parts in 10^{10}. This correction is *not* with respect to the current value of frequency based on UT2. A minus sign indicates that the broadcast frequency was low.

The WWV and WWVH time signals are synchronized; however, they may gradually depart from UT2 (mean solar time corrected for polar variation and annual fluctuation in the rotation of the earth). Corrections are determined and published by the U. S. Naval Observatory.

WWV and WWVH time signals are maintained in close agreement with UT2 by making step adjustments in time of precisely plus or minus twenty milliseconds on Wednesdays at 1900 UT when necessary; no time change or adjustment was made at WWV and WWVH during October. Retarding time adjustments were made on November 4 and 18, 1959.

WWV Frequency†

1959		#1	#2	#3
October	1	−23	−29	−26
	2‡	−22	−24	−20
	3	−24	−23	
	4‡	−24	−19	
	5	−34	−29	−24
	6‡	−32	−19	−17
	7	−38	−31	−27
	8	−38	−32	−28
	9	−37	−35	−31
	10	−36	−39	
	11	−36	−36	
	12	−35	−34	−29
	13	−34	−35	−30
	14	−33	−35	−31
	15	−33	−35	−30
	16	−32	−35	−30
	17	−32	−35	
	18	−31	−35	
	19	−31	−34	−30
	20	−30	−35	−30
	21	−30	−35	−29
	22	−30	−35	−29
	23	−30	−34	−30
	24	−30	−35	
	25	−30	−34	
	26	−30	−34	−29
	27	−30	−34	−30
	28	−30	−35	−31
	29	−31	−35	−29
	30	−31	−35	−29
	31	−31	−35	
November	1		−34	
	2		−34	−29
	3		−38	−33
	4		−33	−28
	5		−33	−28
	6		−33	−28
	7		−33	
	8		−32	
	9		−33	−27
	10		−33	−28
	11		−33	
	12		−32	−28
	13		−32	−28

† WWVH frequency is synchronized with that of WWV.

Column #1 Vs NBS‡ atomic standards, Boulder, Colo., 30-day moving average seconds pulses at 15 mc.

Column #2 Vs atomichron at WWV, measuring time one hour at 2.5 mc.

Column #3 Vs atomichron at the U. S. Naval Research Laboratory, Washington, D. C., measuring time 56 minutes at 2.5 mc.

‡ Method of averaging is such that an adjustment of frequency of the control oscillator appears on the day it is made. The following frequency adjustments were made:

October 2—minus 3×10^{-10};
October 4—minus 9×10^{-10};
October 6—minus 7×10^{-10}.

National Bureau of Standards
Boulder, Colo.

[7] Essen, Parry, Markowitz, and Hall, "Variation in the speed of rotation of the earth since June, 1955," *Nature*, vol. 181, p. 1054; April, 1958.

[8] Markowitz, Hall, Essen, and Parry, "Frequency of cesium in terms of Ephemeris Time," *Phys. Rev. Letters*, vol. 1, pp. 105–106; August, 1958.

[9] Brouwer, "A study of the changes in the rate of rotation of the earth," *Astron. J.*, vol. 57, pp. 125–146; September, 1952.

* Received by the IRE, November 27, 1959.