Reprinted from the PROCEEDINGS OF THE IEEE
VOL. 55, NO. 6, JUNE, 1967
pp. 815-821

Some Characteristics of Commonly Used Time Scales

GEORGE E. HUDSON

Abstract—**Various examples of ideally defined time scales are given. Realizations of these scales occur with the construction and maintenance of various clocks, and in the broadcast dissemination of the scale information. Atomic and universal time scales disseminated via standard frequency and time-signal broadcasts are compared. There is a discussion of some studies of the associated problems suggested by the International Radio Consultative Committee (CCIR).**

I. INTRODUCTION

SPECIFIC PROBLEMS noted in this paper range from mathematical investigations of the properties of individual time scales and the formation of a composite scale from many independent ones, through statistical analyses of the properties of realized scales in actual use in broadcasts or proposed for use. How to determine the most efficient and most useful system for broadcasting time and frequency signals is a difficult question. Its answer requires a type of information and operation analysis used in current investigations of electromagnetic frequency spectrum conservation problems. The diverse needs and ideas of many different types of scientists (e.g., geodesists, electronics engineers, physicists, astronomers, geologists) and of many different large groups of users (e.g., military and space agencies, industrial standards laboratories, watch and clock industry) must be taken into account.

We describe (Section III) some broadcast time-dissemination methods and some relevant properties of their associated time scales. The role of the universal scales in furnishing information for the earth sciences and astronomy as well as for navigation is noted (Section II), and the need for supplying this information adequately and simultaneously by standard frequency and time-signal broadcast systems is emphasized (Section III). Finally, we show that nature has posed such a difficult problem in confronting us with diverse important time scales that it is not yet possible to settle on time information-dissemination techniques which are finally acceptable to all users. Moreover, it should be noted that studies of timekeeping and time scales are also important partly because of the close relationship of time-scale properties to the foundations of gravitation and atomic theories [1].

II. SOME TIME SCALES

A. Examples

1) Atomic Scales: In the United States, a precision atomic clock, NBS(A), is maintained at the National Bureau of Standards to realize one international unit of time [2]. As noted in the next section, it realizes the atomic time scale, AT (or A), with a definite initial epoch. This clock is based on the NBS frequency standard, a cesium beam device [3]. This is the atomic standard to which the non-offset carrier frequency signals and time intervals emitted from NBS radio station WWVB are referenced; nevertheless, the time scale SA (stepped atomic), used in these emissions, is only piecewise uniform with respect to AT, and piecewise continuous in order that it may approximate to the slightly variable scale known as UT2. SA is described in Section II-A-2).

The properties of hydrogen maser standards and cesium beam standards have been and are continuing to be studied in great detail, but detailed discussion of experiments with these devices is not properly in the context of the present paper [4], [5].

A contribution to a composite single atomic scale is now made by hydrogen maser frequency standards maintained at the U. S. Naval Research Laboratory. The composite scale is the A.1 scale, maintained by the U. S. Naval Observatory. It is widely used as a reference scale; NBS(A) and A.1 have differed very slightly since their common initial epoch on January 1, 1958 [3], [6]. The present difference in epoch amounts to about 10 ms, and is presently being determined to a much greater precision by a cooperative program undertaken between NBS and USNO. The accuracy of the NBS(A) scale is believed to approach that of the NBS cesium frequency standard—about 5 parts in 10^{12}. There are, of course, several other atomic time scales and frequency standards maintained throughout the world—among these are TA1 at the LSRH (Laboratoire Suisse de Recherches Horlogères), Neuchâtel, Switzerland, and that maintained at NPL (National Physical Laboratory), Teddington, England [7]–[9]. On the basis of some of these scales, the composite one, A.1, was determined for a time by W. Markowitz at the U. S. Naval Observatory. It is now based on several high-quality commercial cesium frequency standards at the Observatory. The hydrogen maser serves as the "flywheel" of this atomic clock. The existence of several independent atomic *clocks* is certainly not to be deplored on scientific grounds since many useful statistical and operating data are obtained via their intercomparison. It does pose the problem, however, of how best to determine a composite "most uniform" and reliable realization of the atomic scale. This certainly is a subject worthy of cooperative consideration by the best scientific and engineering

Manuscript received March 27, 1967.
The author is with the National Bureau of Standards, Boulder, Colo.

minds that can be devoted to it. A promising start on this problem was made by E. L. Crow [10], at the instigation of J. M. Richardson of the Radio Standards Laboratory, NBS-BL. An extension of such theoretical studies combined with the experience of the Naval Observatory in forming the composite A.1 scale is very desirable.

2) *Universal Scales:* An astronomical time scale known as the universal scale, UT, is a slightly nonuniform one, relative to the atomic time scale, AT. UT is commonly known as Greenwich Mean Time (GMT), when epochs (the times of occurrence of the "ticks") need be specified to no better accuracy than 0.1 second. UT is obtained via interpolation between successive observations of the sidereal time of nearly periodic events (such as the zenith transits of a star) which is then transformed to mean solar time by means of a ratio. The interpolation is accomplished by means of a free-running oscillator driving a clock at nearly the correct rate. The zenith observations and the ratio are used to correct this clock rate so that it ticks off 86 400 intervals, each one nearly one second long, between successive transits of the "mean sun" each day [11]. The scale thus defined locally at an observatory is called UT0. Five slightly different universal time scales now being used are designated respectively as UT0, UT1, UT2, universal atomic (UA), and stepped atomic (SA). UT1 is obtained from UT0 by applying a correction for polar motion specified by data furnished by different observatories. UT2 is derived from UT1 by applying a periodic correction having a maximum amplitude of 0.03 second [12], for annual and semiannual seasonal variations [13]–[15]. Despite these corrections, UT2 is still known to be somewhat nonuniform. The knowledge of UT2 (or even better, UT1) yields information directly concerning the rotational position of the earth about its axis. UA is a piecewise uniform scale which approximates the universal time scale, UT2, within about 0.1 second. It is a "stepped offset" scale (offset pulse rate, stepped pulse epoch) and is derived by making adjustments in offset and epoch from the uniform atomic time scale. The SA scale is a piecewise uniform one derived from the atomic scale by step adjustments in pulse epoch only in order to approximate UT2 within about 0.1 second. All universal scales need be defined and realized only to an accuracy of a few ms [16], [17] due to refraction limitations on astronomical observations, but in view of their definitions the UA and SA scales have the ultimate accuracy of the atomic scale.

Because the rate of occurrence of UT2 markers has been variable and less than the rate of occurrence of seconds markers, UT2 readings were about 5.31 seconds behind A.1 readings on January 1, 1967; on January 1, 1958, at 00:00 GMT, A.1 and NBS(A) epochs were set equal to that of UT2. At present (1966 and 1967) there are 0.94 fewer scale intervals over a year in the UT2 scale than in the more uniform atomic scale, AT.

The importance of UT for celestial navigation, in determining longitude, must be pointed out [18], [19]. The essential principle is simple. By some means, one obtains information that the earth, in rotating on its axis, is in a certain orientation relative to the "fixed" stars at a given instant. In that orientation, tables show that various known stars will have certain elevations above the horizon, in the east-west direction, depending on the longitude of the observer, which can thus be determined. The orientation information is furnished from the epoch of UT1, since successive scale intervals of UT1 (mean solar "seconds") correspond to equal increments (15 arcseconds) of rotation of the earth with respect to the universal mean sun. (Fifteen arcseconds equal about 1/4 nautical mile at the equator.) Conversion to rotation relative to the stars (Sidereal Time) is accomplished by use of the ratio of the length of the mean solar day to the mean sidereal day, about 1.00275.

Universal scales are clearly nonuniform relative to atomic time due to variations in the earth's rotation rate. Nevertheless, the importance of their use in furnishing information about the earth's position on its axis cannot be denied and insures the necessity for their continued dissemination in some suitable form, via radio broadcast [17], [18].

B. Specific Trends in UT

The variations in UT scales or earth rotation rates have been studied extensively by Brouwer [20] and many others [14], [21], [22]. In this article, we need only point out the general nature and size of the variations which have been observed. The reason this is important here is to give the reader some background indication of the kind of data which are encountered in attempts to make both UT information (usually UT2) and more uniform time and frequency information available on the same broadcasts from radio stations. Brouwer's study covered a long period of time; the curves shown in Fig. 1 summarize much of his data

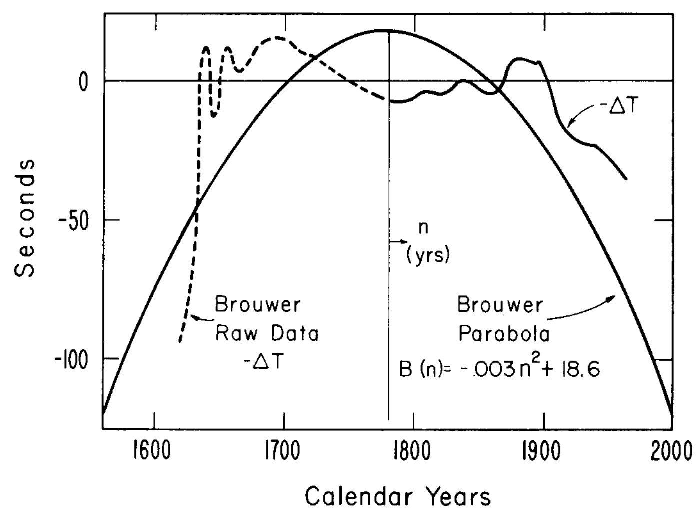

Fig. 1. Trend of $-\Delta T = UT - ET$. The difference $-\Delta T$ in readings of the two scales, UT and ET, is plotted versus the date, which is proportional to ET. The slope of this graph is proportional to the offset in marker rate of UT with respect to that of ET. The parabola represents Brouwer's suggested average trend. Random effects in $-\Delta T$ are evidently present. ET (ephemeris time) is an astronomical time scale which may be considered for present purposes to be uniform with respect to AT [24].

and analysis. They reflect the random behavior [22] of UT, marked on occasion by sudden erratic changes [23].

As specified in the figure, the abscissas are proportional to the astronomical time scale known as ephemeris time, ET. At present ET can be considered uniform with respect to AT [24]. It is a good comparison scale to be used in detecting long-term properties of a time scale.

A study [25] of the trend of UT2 relative to the uniform atomic scale has shown that over a recent 7 1/2-year interval the difference between UT2 scale readings and atomic scale readings was representable by the sum of the Brouwer average parabola (Fig. 1) and a sinusoidal term having a period of 24.1 years and an amplitude of 2.56 seconds. This study was found useful in making short-term predictions of UT2 and as a summary of fluctuation sizes over the interval. The residual difference from the smooth trend has an rms deviation of 16 ms and a maximum of 40 ms. A maximum of the sinusoid occurred at the beginning of 1967.

III. Some Characteristics of Broadcast Scales and Systems

A. Some Specific Systems

1) CCIR Considerations: In the XIth Plenary Session of the CCIR in Oslo, Norway, during the summer of 1966, there was specifically recognized by Study Group VII the possibility of a great many *systems* for broadcasting universal and atomic time information, on the same emission. Moreover, nonuniform time scales, in particular some broadcast ones, as has been noted [17], [26]–[35], have many different properties. The number of possible signal systems increases if one offsets carrier-signal frequencies in various ways from their nominal values to achieve occasional desired adjustments in the pulse rates of time signals. This problem has been noted in various CCIR documents approved by the Assembly, details of which can be found in the published Volume III of the Assembly proceedings. Some documents are indicated by numbers in parentheses in the next paragraph.

For this discussion, we refer especially to the suggestion that experiments and studies be made of how to provide both epoch of UT and the international unit of time interval in the same emission, and how various user requirements can be met by the emission of a single time scale (Opinion 26). We also point to the recommendation (Rec. 374.1) of the use of several international time systems coordinated by the BIH (Bureau International de l'Heure) which were designed for the broadcast of both UT and AT information. Two are called the UTC and SAT systems. We call attention to a report (Rept. 365) comparing these systems statistically for 1965, and finally to a report (Rept. 366) suggesting one method of classification of emission systems which yield standard frequency and time information.

It should be expressly understood that the existence of the two systems SAT and UTC is to be regarded as a step in the evolution and adoption of a single practicable world-wide system which will be internationally acceptable. Thus, it seems important to exhibit here briefly a method of characterization of systems which can be used to fulfill various needs, but which require further study.

2) A Classified Listing of Systems: Systems for broadcasting time and frequency information can be classified according to the method adopted in Tables I and II. A system may utilize more than one time scale. If so, two or more columns would be used under the heading *entry*, in constructing such a table. An *entry* Yes, or No, indicates whether or not a specified property is indicated directly on a broadcast by the time markers (pulses) and the use of piecewise constant carrier frequencies (but not codes). Under additional remarks, specify when an adjustment in a property may be made, how large it is to be, what the known relation between pulse (marker) and carrier phase is, which universal or uniform scale is being approximated, and what the relations are to these scales (e.g., how closely approximated).

As examples, the UTC system is so classified in Table I, and the SAT system is classified in Table II. Both systems are coordinated by the BIH and are currently in use. The UTC system is used by a large number of stations, and the SAT system, an experimental but coordinated one, is used at present only by stations WWVB in Fort Collins, Colo., and DCF77, in Mainflingen, West Germany.

Other possible systems also can be so classified. For example, the system used by station HBG in Switzerland differs from the UTC system (Table I) only in that (as in Table II) the carrier is not offset (Item A) and the time markers and carrier signals are not phase-locked (Item D). Hence, by an appropriate pulse generator locked to the received carrier signal, a clock yielding a time scale which is very close to AT and whose pulse rate need never be adjusted, can be constructed, just as with the SAT coordinated system carrier signals (Table II, Item F). Time signals emitted following any one coordinated system must be synchronized to 1 ms.

It is to be hoped that the experimentation with and study of various systems for yielding both UT information and AT information, on the same broadcast emission, will lead to a suitable format acceptable to most if not all users in the next few years. Toward this end, several coordinating groups of the U. S. Preparatory Committee, Study Group VII, CCIR, have been appointed. One object is to study the deplorable problem raised by the existence of a great variety of auxiliary time scales, some denoted by a random nomenclature. Since the initiation of the SAT system on January 1, 1967, the ad hoc name SAB for the signals disseminated by WWVB has been dropped. WWVB's control clock is now called NBS(SA), just as WWV's and WWVH's is called NBS(UA). Another more important requirement, which has been noted by many international organizations, is to eliminate carrier-frequency offsets. It seems appropriate at this point to give a more technical discussion of offsets in frequency and in pulse rates.

TABLE I

SYSTEM—UTC

Name(s) of Scale(s)	UA	Universal Atomic
Property	**Entry**	**Additional Remarks**
A) Carrier offset	Yes	Adjusted, when necessary, on the first of a year by a positive, negative, or zero integral multiple of 50 parts in 10^{10} to follow UT2.
B) Marker rate offset	Yes	Same adjustment as A).
C) Epoch steps	Yes	Phase of markers adjusted on first of a month, when necessary, by 100-ms steps to follow UT2.
D) Marker-carrier phaselocked	Yes	None.
Contains time markers which:		
E) Yield universal scale	Yes	UA approximates UT2 within about 0.1 second.
F) Yield uniform scale with respect to AT	Yes	By correcting for the offset and the step adjustments, AT can be found, but correction information must be obtained from additional signals or a supplementary historical log.
G) Made up of more than one broadcast time scale	No	Voice or code can, of course, be used to supply information in F), or a better knowledge of (preliminary) UT2.

TABLE II

SYSTEM—SAT

Name(s) of Scale(s)	SA	Stepped Atomic
Property	**Entry**	**Additional Remarks**
A) Carrier offset	No	None.
B) Marker rate offset	No	Except at moment of epoch adjustment.
C) Epoch steps	Yes	200-ms steps to follow UT2 made on the first of a month, when necessary.
D) Marker-carrier phaselocked	Yes	None.
Contains time markers which:		
E) Yield universal scale	Yes	Approximate UT2 within about 0.1 second.
F) Yield uniform scale with respect to AT	Yes	Differs from AT by $0.2n$ seconds, where n is a positive, negative, or zero-integer which must be obtained from supplemental information. During March, 1967, $n=28$. An AT scale can be generated by phase-locking to carrier.
G) Made up of more than one broadcast time scale	No	Voice or code can, of course, be used to supply the information in F), or a better knowledge of (preliminary) UT2.

B. Offsets, Steps, and Trends in Some Broadcast Time and Frequency Signals

1) Offsets: For a long time, oscillators whose frequencies are deliberately offset from their nominal values measured relative to atomic standards have been used to control time and frequency signals emitted from various United States radio stations, e.g., from WWV and WWVH, as well as NSS and NBA [18]. At present, adjustments in this offset are introduced on the first of a year into the emitted carrier frequency in accordance with some of the adjustments required by the definition of the commonly used broadcast (piecewise uniform) time scale UA belonging to the UTC system.

Figure 2 shows the history of WWV carrier-frequency offsets since 1957. The improvement in frequency control is evident and may be directly ascribed to improvements in standards and phase-lock control techniques. The trend should be compared with the fitted-offset trend of the UT2 scale marker rate to judge how well the broadcast offset approximated it. Beginning January 1, 1960, the time pulses emitted from WWV were locked to the carrier frequency, as was true for many other time broadcasts. Thus, the rate of emission of the time pulses was controlled by varying the carrier-frequency offsets. This is still the method in use for stations following the UTC system.

2) Steps and Trends: Figure 3 is a summary comparison of realizations of all the various scales considered for the nine years since 1957. Ordinates plotted are the differences between the reading on a given scale or clock at a given epoch and the simultaneous corresponding reading on the atomic scale. The slope of a trend on such a plot, when divided by 31.5×10^6 (the number of seconds per year), is the offset rate from that of the reference clock. In addition to NBS(UA), SAB, and UT2, the average long-term Brouwer trend is shown [20]. One sees that the average marker-rate offset of UT2 from the more uniform atomic scale would ultimately become indefinitely large, if the long-term Brouwer trend were to persist. It is also clear that the UT2 scale and offset undergo large fluctuations about their long-term average trends. A smooth fit to the UT2 data, shown by the dotted curve, has been represented over this period by a sinusoidal plus a parabolic function. The amplitude of the sinusoidal component is about 2.56 seconds, although the rms deviation of the data from the curve-fit is only about 16 ms.

3) Comparisons in 1956 and 1966: In the following, certain statistics relating to the "stepped offset" (epoch steps, pulse rate and carrier frequency offset), or UTC, system for broadcasting UT and AT information are compared with similar statistics relating to the "stepped" system utilizing

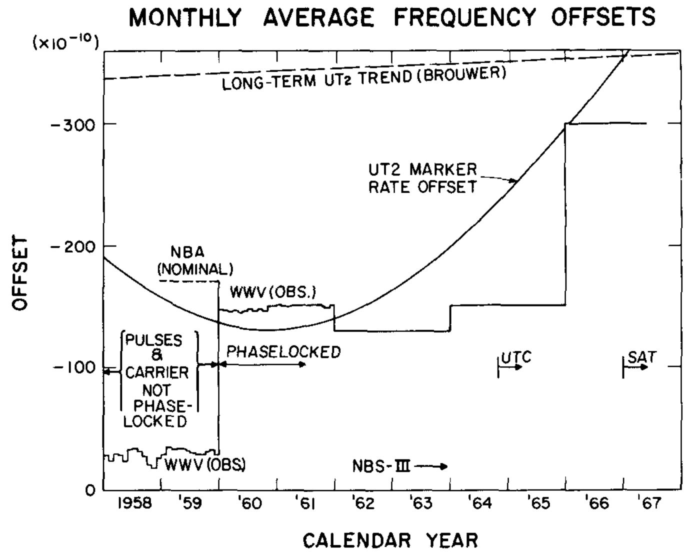

Fig. 2. The recent history of frequency offsets. Since the long-term trend of the UT2 scale seems to be parabolic, its long-term trend in offset marker rate is linear, shown dashed. Fluctuations in UT2 produce the (smoothed) offset trend about the long-term one shown by the solid curve. The NBS frequency standard of course is not offset, as indicated by the bottom horizontal line. Improvement in frequency control is evident in the step "approximation" to UT2; the UTC system, inaugurated as a continuation of the former coordinated "signal" system in 1964, led to the offset of -300×10^{-10} in transmissions in 1966 and 1967 in an attempt to follow more closely the UT2 fluctuating trend.

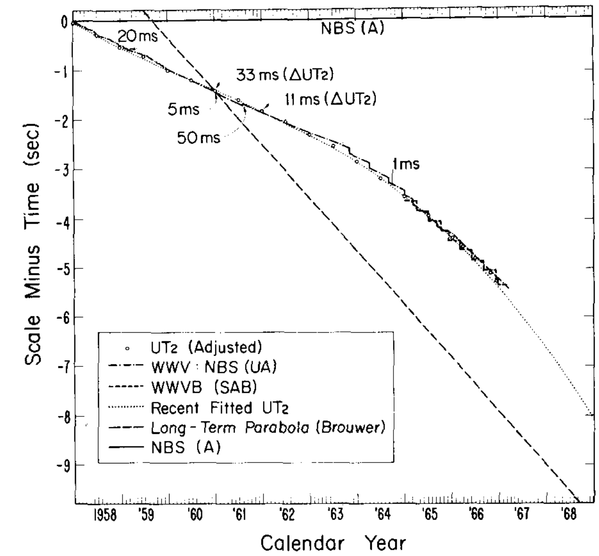

Fig. 3. Summary of broadcast time-scale trends. All scale trends are indicated by plotting as ordinates the number of nominal seconds decreased by the number of seconds (atomic scale) which have elapsed since January 1, 1958. The long-term parabolic Brouwer trend in UT2 is shown dashed; the broadcast scale for WWV is indicated by the tilted stepped curve, with step retardations of 100 ms since 1964, and that for WWVB is shown at the right by the step approximation to the UT2 trend with step retardations of 200 ms. The UT2 (adjusted) points are plotted after removing the discontinuities due to redetermination of various observatories' coordinates; the dates and sizes of these discontinuities are indicated. The nonoffset trend of the atomic scale, as generated by the NBS clock, is shown by the top horizontal line.

SAB (stepped atomic, WWVB). Such data may contribute toward an answer to the CCIR-suggested studies.

The data for 1956 and 1966 may be represented conveniently by plotting aginst the calendar date, for each realized scale, NBS(UA) and SAB, respectively, the difference between the number of scale markers (nominally seconds pulses) since the beginning of January, 1958 (i.e., the scale reading) and the number of seconds pulses, AT, since that epoch. The trends for 1965 and 1966 are shown in Fig. 4. The solid curve represents the smooth curve-fit to UT2 (shown by circles) using a sinusoid plus parabola. The portion of this curve from August 1, 1965, to December 31, 1965, was drawn before the data points shown were known. It therefore constitutes a prediction of the trend of UT2 for the latter portion of 1965 and was good to better than 40 ms. Also shown in Fig. 4 (dashed) is the long-term parabolic trend analyzed by Brouwer [20].

Various statistical data are evident from Fig. 4. Although both the UA and SAB scales satisfied stated conditions for ship navigation, and were within about 0.1 second of UT2 (corresponding to a "fix" of about 150 feet at the equator) there is some distinction to be made in the closeness of approximation measured by the absolute deviation and percent departure time in favor of UA. The improvement since 1963 in the approximation of UT2 by such stepped, offset methods is evident. In terms of mean deviations there is a small distinction between SAB and UA in favor of SAB.

Because of the offset (or slope), the UA scale markers of course are separated by intervals which are longer than one second. The corresponding SAB intervals are one second long. Both scales are piecewise uniform and piecewise continuous with respect to AT. If it seems desirable to retain the goal of broadcasting directly signals which approximate UT2 to the highest accuracy, and which on the same emission directly yield atomic time and frequency information and the international second, then the best method has not yet been found.

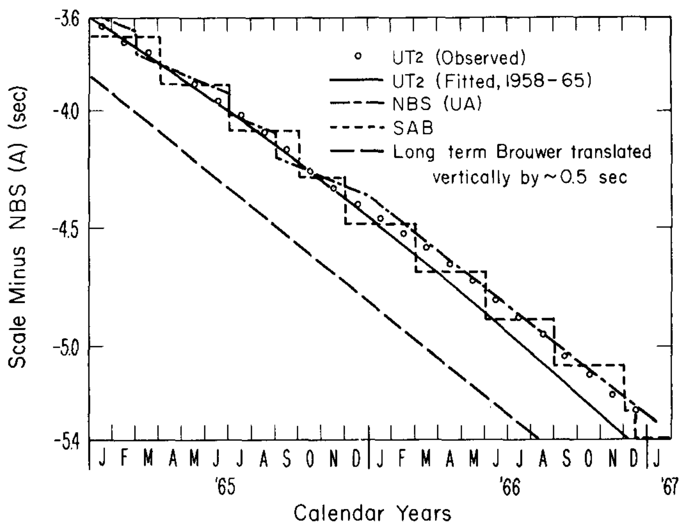

Fig. 4. Trends in SAB and NBS(UA) during 1965 and 1966. The trend in the NBS(UA) clock reading, following the UTC system, is indicated by the slanted (i.e., offset), stepped (100 ms) approximation to the UT2 data, represented by dots. The fitted trend UT2 is shown by the solid curve, and the SAB stepped (200 ms) scale trend is also indicated. The ordinate magnitudes represent lag times with reference to the scale readings of the NBS time standard or clock, NBS(A).

C. Possible Future Trends in the Broadcast of UT and AT Signals

The investigations reported here summarize preliminary attempts at resolving the CCIR question of how to broadcast UT and AT signals, satisfactorily, on the same emission. A few comments regarding the possible future status of these two kinds of signals would seem to be appropriate. There should soon be advances in the scientific analyses of information concerning the properties and trends of the slightly variable universal scales of time. These should take the form of statistical and trend analyses of the ever-increasing store of data concerning the earth rotation rates and the development of appropriate physical theories. There probably will be improvements in the overall coordination of national and international standard transmissions of time signals as more atomic frequency standards are adopted [8], [9]. There may be wider adoption of atomic scales not only for synchronization purposes, but also for epoch determination, in conjunction with the astronomical ephemeris time scale, ET [24], [34], [35]. In this fashion, it may become more commonly recognized that the primary and important role of universal scale transmissions is not that of a source of uniform time, but of essential geological information useful in tracking, navigation, and scientific studies of the environment.

It should be emphasized that both present coordination methods, UTC and SAT, described herein, furnish UT and AT information on the same broadcast. Yet each requires either the broadcast, or other communication, of additional information before AT or UT2 itself (or, perhaps more directly useful, the earth's rotational position obtained by correcting UT2 to UT1) can be determined from the broadcast pulses, as accurately as they can be known at a given moment. The same can be said for some other simpler methods which have been suggested, such as the straightforward broadcast of an atomic time scale. For example, with no adjustments save an occasional renaming of a particular second from time to time, i.e., by occasionally inserting or deleting a few seconds, or a minute, the atomic scale, so modified, could keep approximately in phase with UT, but would not lead directly to UT information of sufficient accuracy for some purposes.

Celestial navigators who use UT information now require the use of tables noting star positions versus UT. It may soon prove desirable and possible, however, for astronomers to prepare supplementary tables of UT versus AT (or ET) well within the requisite accuracy limits and sufficiently far in advance for the ready use of celestial navigators.

Alternatively, quite accurate broadcasts of preliminary UT epoch information (within 10 ms) might prove feasible, by a modification of the present UTC method. Adjustments made every month, in offset, or in epoch, or both, which are a known multiple of a small increment in relative offset (say, 50×10^{-10}) or a small time interval (say, 10 ms) have been suggested. It may appear that UT1, in fact, would be the appropriate universal scale to follow for this purpose. It would be very important, even essential, for reference and synchronization purposes, to have available, on the same broadcast, standard, "uniformly" spaced, *clearly marked* atomic time pulses interspersed with the UT pulses, say at 5- or 10-second intervals. Or the desirable choice might be to have more widely spaced universal time pulses to indicate closely the earth's position, with a background of seconds pulses for reference. The solution of the problem will depend on time-sharing studies and determination of user needs.

Everyday users would not need to be concerned about the introduction of an occasionally modified, atomic scale of time. Various local universal times, standardized by convention, such as Mountain Standard Time (MST), differ from GMT [36] by an integral number of hours, depending on locations. Such local time scales are often adjusted periodically by one-hour steps to yield "daylight savings time," or to return to "standard" time. Similar local times could be derived just as well from an atomic scale, by similar adjustments and zoning, and by the deletion, every few years, of a small number of "one-second leaps" or, alternatively, in about 50 years, a "one-minute leap." In this way, approximate epochal coherence with the rising and setting of the sun would be retained, and there need be no fear of a radical departure from solar time for "everyday" purposes.

It should be emphasized that the coordinated methods which have been used to broadcast UT and AT information, or which have been discussed or mentioned herein, are only a few of the possible ones.

IV. Concluding Remarks

We list here a few concluding statements about problems and information which have been discussed in the foregoing.

1) The practical use of universal scales (UT) as a navigational aid and for yielding other information concerning the rotational position of the earth cannot be denied. Suitable methods for disseminating a suitably accurate universal scale separately, and in combination with, a more uniform scale must be studied, experimented with, and discussed.

2) It should not be held that UT is the only kind of time for "everyday" use. Unadjusted atomic scales will not diverge from UT by more than a few seconds every few years and differences could easily be removed, on occasion, by proper adjustment. These adjustments would be far smaller in magnitude than similar adjustments already in common use under the headings of daylight savings time, leap year day, and reference to the mean sun instead of the visible apparent sun.

3) The invention of physically different time scales, such as a nuclear-based one [37], should be regarded as a desirable scientific activity; but the proliferation of artificial derived scales is to be deplored.

4) There is a need for intensive study of the formation and properties of composite time and frequency standards and time scales. Many competent laboratories maintain

their own precise instrument standards founded on fundamental readily accessible phenomena of nature. This is indeed an evident trend which occurs in other standards areas. Thus, here is clearly a need for coordination in the use, dissemination, and intercomparison of such standards.

5) The CCIR is attempting to stimulate further investigations of the need and use of more uniform scales of time on broadcasts, better ways to present universal scale information of use in the study and use of earth rotation rates and positions, the more efficient use of the electromagnetic spectrum for these broadcasts, and the international definition of a composite, more uniform, reference scale of time.

6) The action of national and international committees in defining and calling attention to problems and needs, and in stimulating research and development is an extremely important one, as well as their function in keeping the overall scope in proper perspective. They also perform a needed general recommendatory function, as exemplified by the CCIR documents; they certainly assist in maintaining a uniform level for specifying operating procedures and standards.

7) The technological study of improvements in the methods of giving time and geological information simultaneously on standard broadcasts is an important example of a general problem now being recognized more formally on a broad scale. This is the scientific and efficient technological use of the electromagnetic frequency spectrum.

Acknowledgment

The basic researches by Dr. R. C. Mockler, Dr. J. A. Barnes, R. E. Beehler, R. L. Fey, and Dr. J. M. Richardson on atomic time and frequency standards made it imperative for me to learn from them, by conversations and reading, the essential background in this field. I am indebted to my predecessor, the late W. D. George, and to Dr. Y. Beers, A. H. Morgan, and D. H. Andrews, for my education in the fascinating art and science of time and frequency standard dissemination by radio broadcasts.

Collaboration with Mrs. M. Cord in making the current studies of the properties of time scales, some results of which are reported herein, is gratefully acknowledged. The contributions of all other co-workers and colleagues, including secretaries Mrs. L. Canaday and Miss C. Nielsen, are sincerely appreciated.

References

[1] R. Dicke, "Gravitational theory and observation," *Phys. Today*, vol. 20, pp. 55–70, January 1967.

[2] CIPM, *Comptes Rendus des Séances de la Douzième Conférence Générale des Poids et Mesures*. Paris: Gauthier-Villars, 1964, p. 93.

[3] J. A. Barnes, D. H. Andrews, and D. W. Allan, "The NBS-A time scale—its generation and dissemination," *IEEE Trans. on Instrumentation and Measurement*, vol. IM-14, pp. 228–232, December 1965.

[4] R. E. Beehler, R. C. Mockler, and J. M. Richardson, *Metrologia*, vol. 1, pp. 114–131, July 1965.

[5] R. Vessot, H. Peters, J. Vanier, R. Beehler, D. Halford, R. Harrach, D. Allan, D. Glaze, C. Snider, J. Barnes, L. Cutler, and L. Bodily, "An intercomparison of hydrogen and cesium frequency standards," *IEEE Trans. on Instrumentation and Measurement*, vol. IM-15, pp. 165–176, December 1966.

[6] 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.

[7] J. Bonanomi, P. Kartaschoff, J. Newman, J. A. Barnes, and W. R. Atkinson, "A comparison of the TA1 and the NBS-A atomic time scales," *Proc. IEEE* (*Correspondence*), vol. 52, p. 439, April 1964.

[8] L. U. Hibbard, "Atomic frequency standards," *At. Energy* (*Australia*), vol. 7, pp. 21–26, October 1964.

[9] A. G. Mungall, R. Bailey, and H. Daams, "Atomic transition sets Canada's time," *Canad. Electronics Engrg.*, vol. 37, pp. 23–27, August 1965.

[10] E. L. Crow, "The statistical construction of a single standard from several available standards," *IEEE Trans. on Instrumentation and Measurement*, vol. IM-13, pp. 180–185, December 1964.

[11] E. W. Woolard and G. M. Clemence, *Spherical Astronomy*. New York: Academic, 1966, pp. 326–375.

[12] *B.I.H. Bulletin Horaire* (*Paris*), p. 2, January–February 1964.

[13] W. Markowitz, "Variations in the rotation of the earth, results obtained with the dual rate moon camera and photographic zenith tubes," *Astron. J.*, vol. 64, pp. 106–113, April 1959.

[14] W. H. Munk and G. D. F. MacDonald, *The Rotation of the Earth*. London: Cambridge University Press, 1960, ch. 8.

[15] Kuiper and Middlehurst, *Telescopes: Stars and Stellar Systems*, vol. I. Chicago: University of Chicago Press, 1960, ch. 7.

[16] Société Suisse de Chronométrie, *Proc. Congrès Internat'l de Chronométrie Lausanne*, Neuchâtel, Switzerland, pp. 157–174, June 1964.

[17] J. Kovalevsky, "Astronomical time," *Metrologia*, vol. 1, pp. 169–180, October 1965.

[18] U. S. Naval Observatory and Royal Greenwich Observatory, *Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac*. London: Her Majesty's Stationery Office, 1961, pp. 443–453.

[19] U. S. Naval Observatory, *The American Ephemeris and Nautical Almanac for the Year 1968*, Washington, D. C.: U. S. Gov't Printing Office, 1966, pp. 468–485.

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

[21] W. Markowitz, "Latitude and longitude, and the secular motion of the pole," in *Methods and Techniques in Geophysics*, S. K. Runcorn, Ed. London: Interscience, 1960, pp. 325–361.

[22] R. B. Blackman and J. W. Tukey, *The Measurement of Power Spectra*. New York: Dover, 1958, pp. 151–159.

[23] S. Iijima, N. Matsunami, and S. Okazaki, "On the abrupt change in the earth's rotation at the beginning of 1963," *Ann. Tokyo Astron. Observatory*, 2nd ser., vol. VIII, pp. 207–217, August 1964.

[24] W. Nicholson and D. Sadler, "Atomic standards of frequency and the second of ephemeris time," *Nature*, vol. 210L, p. 187, April 1966.

[25] M. Cord and G. E. Hudson, "Some trends in UT," to be published.

[26] I. Newton, *Principia*, rev. transl. by F. Cajori. Berkeley, Calif.: University of California Press, 1947, p. 6.

[27] R. B. Lindsay and H. Margenau, *Foundations of Physics*. New York: Wiley, 1936, pp. 72–78.

[28] H. Margenau, *The Nature of Physical Reality*. New York: McGraw-Hill, 1950, ch. 7.

[29] *Van Nostrand's Scientific Encyclopedia*, 3rd ed. Princeton, N. J.: Van Nostrand, 1958, pp. 1691–1692.

[30] J. M. Richardson, "Time standards," in *Encyclopedic Dictionary of Physics*, suppl. vol. 1. Oxford: Pergamon, 1966.

[31] ——, "Time and its inverse," *Internat'l Science and Technology*, pp. 54–76, June 1962.

[32] G. E. Hudson, "Of time and the atom," *Phys. Today*, vol. 18, pp. 34–38, August 1965.

[33] J. M. Richardson and J. Brockman, "Atomic standards of frequency and time," *Phys. Teacher*, vol. 4, p. 247, September 1966.

[34] G. Becker, "Von der astronomischen zur atomphysikalischen Definition der Sekunde," pts. I and II, *PTB Mitteilungen*, no. 4, pp. 315–323 and no. 5, pp. 415–419, 1966.

[35] G. C. McVittie, *General Relativity and Cosmology*. Urbana, Ill.: University of Illinois Press, 1965, pp. 89–90.

[36] "Frequency and time standards," Frequency and Time Division, Hewlett-Packard Co., Appl. Note 52, pp. 1–2, 1965.

[37] L. A. Khalfin, "A fundamental method for measuring time," *Soviet Physics JETP*, vol. 12, pp. 353–345, February 1961.