# of time and the atom . . .

The current international standard for the physical measurement of time is based on the use of atomic-frequency control devices that are now being studied intensively in the search for an ultimate basis for the precise definition of time. The author is assistant chief of the Physics Division of the NBS Radio Standards Laboratory, Boulder, Colo., where the atomic-frequency standard is being actively investigated.

By George E. Hudson

In 1952, Harold Lyons[1] of the National Bureau of Standards put into brief operation an atomic clock of the ammonia-absorption type, and thus reflected the intense interest in devising atomic standards for measuring time intervals. This interest has grown rather than diminished. As progress continued with the advent of cesium-beam frequency controls—first with L. Essen and J. V. L. Parry[2] at the National Physical Laboratory in England, and later with the models investigated[3, 4] at the Boulder Laboratories of the NBS, and by Bonanomi in Neuchatel, Switzerland, by Kalra in Canada, and by McCoubrey and Holloway of the National Company in the United States—the standard for time measurement of highest possible accuracy was removed in effect from the astronomic realm to the atomic. In collaborating with Essen, W. Markowitz of the US Naval Obsevatory[5] determined in 1958 the frequency characteristic of the cesium standard in terms of the accepted international unit of time, the ephemeris[6] second. Since the international adoption of a temporary atomic standard to realize the unit of time, the figure they gave with a considerable uncertainty,

$$9\ 192\ 631\ 770\ \text{Hz},$$

must be regarded not as a measured value, but rather as an exactly defined one, accurate to any number of significant figures. The uncertainty of 2 or 3 parts in 10^9 that originally attached to the measurement was evidently due to the uncertainties and inconvenience in the methods used to realize the ephemeris second; that is, the limitation lay in the astronomical observations, not in the atomic device.

As a result of this situation, the transition has finally become formalized by the pronouncement of the International Committee of Weights and Measures at its meeting in Paris in October 1964 that, for the physical measurement of time, the international standard of time interval to be used is to be temporarily based on the frequency of emission or absorption associated with the change in state,

$$|F = 4, m_F = 0> \leftrightarrow |F = 3, m_F = 0> ,$$

of the cesium-133 atom.[7, 8] The size of the unit is still defined to be the invariable ephemeris second—the fraction 1/31 556 925.9747 of the tropical year at 12 hours Ephemeris Time on 0 January 1900 (i.e., December 31, 1899).

The Institute of Basic Standards of the National Bureau of Standards is charged by Congress with the improvement, maintenance, and development of the standards whereby the basic physical units are realized and disseminated in the United States. The list includes the standard of length (already an atomic one utilizing the wavelength of a krypton line) and those of mass, temperature, and electric charge. It also includes frequency.

The United States Frequency Standard (USFS) is maintained in the Radio Standards Laboratory in Boulder, Colo. The standards of time and frequency have the unique property that they can be disseminated to the general public via radio broadcasts. In fact, the time signals sent out by NBS Station WWV in Greenbelt, Md., have long been used for navigation, surveying, and other technical purposes, and recently these emissions have been strictly regulated by comparison with the USFS in Boulder via very-low-frequency transmissions from NBS Station WWVL in Fort Collins, near Boulder.[9]

Traditionally it was the province of the astronomical observatories to tell time by means of the courses of the stars and other heavenly bodies, this being the most accurate way to measure time. It has also been a necessary activity of the US Naval Observatory since there is a direct relationship between time told this way and the navigation of ships. Anyone interested in a detailed account can consult, for example, the *Explanatory Supplement*

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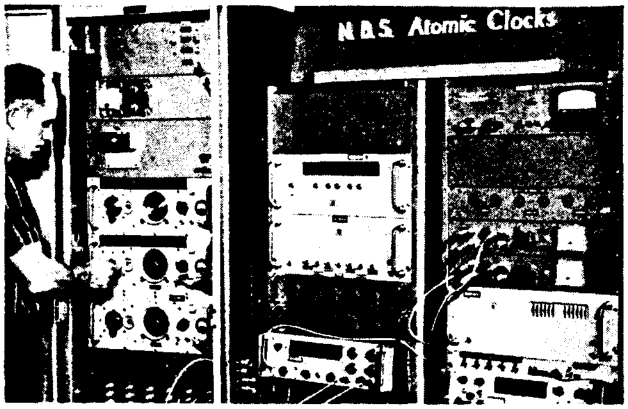

Fig. 1. D. Allan of the Boulder Laboratories adjusts the setting of the universal scale for the NBS atomic-clock system.

to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac.[10] What is of importance here is the basic fact that modern, accurate measurement of time is accomplished with a standard-frequency generator. A brief description of the standard atomic clock situated at NBS Boulder Laboratories and the standard time scale generated by it may help in understanding how this is done. (See Fig. 1.)

First, how does the frequency standard work? A beam of cesium atoms in a variety of states (among which are the $|F = 3, m_F = 0 >$ and $|F = 4, m_F = 0 >$ states) is directed down the axis of a long tube, with the aid of a magnetic lens. It converges to a focus through a collimating slit midway, and then diverges. At the far end of the tube is a similar second magnetic lens, followed by a detector of cesium atoms working in accordance with the principle of surface ionization. If the atoms do *not* change state, the second lens serves to disperse the beam still more and very few of the atoms can be detected. However, if the atoms in one of the states,

$$|F = 3, m_F = 0 > \text{ or } |F = 4, m_F = 0 > ,$$

undergo a transition into the other state (by absorption in the first case, or by emission in the second, of a quantum of radiation of frequency $\nu_s = 9\,192\,631\,770$ Hz), then the second magnetic lens brings them again to a focus and they are detected. Such transitions are induced by electromagnetic radiation of nearly this frequency introduced into the tube from an external oscillator through a waveguide. In this way, when one registers a maximum detection signal, he knows the external oscillator has the standard frequency—by definition—except for errors.

Now, if one should maintain such an external oscillator continuously "on frequency," and count the cycles of oscillation, n, in a given time interval to be measured, then clearly the time elapsed is

$$t = \frac{n}{\nu_s} .$$

Unfortunately, it is neither convenient to operate the primary frequency standard continuously, nor is it desirable from the point of view of reliability to generate a continuous time scale from a single oscillator.

A solution to this problem can be obtained if one recognizes and applies the natural extension of the relation: time equals cycles divided by frequency. Formally, the general relation is

$$t = \int_0^n \frac{dn'}{\nu(n')} ,$$

where $\nu(n)$ is the frequency of some periodic device measured frequently enough in terms of the frequency standard that its variation with the number of cycles n can be accurately followed. Then t is the time elapsed while the device oscillates n times (of course, n need not be an integer). All that is needed is to measure the frequency $\nu(n)$ against the standard and to count the number of cycles. J. Barnes, in collaboration with L. Fey[11] of NBS-BL, has accomplished exactly this. To insure reliability there are five oscillators (one is a rubidium gas cell; the other four are high-quality quartz-crystal oscillators) whose frequencies are measured daily in terms of the USFS. This is often enough. The cycles are counted—actually an accumulated total is kept—and by a suitable weighted average of the five, the time of any event may be determined to an accuracy equal to that of the USFS—that is, to one part in 10^{11}. (This accuracy is attained only after the fact, since a computer program must be used to evaluate the equivalent of the integral and the required average).

This is the A scale of time, and it has been extended continuously and uninterruptedly back to the fall of 1957 by the assignment of atomic times to the occurrence of the time signals of WWV. Beginning January 1, 1958, a composite time scale, known as the A1, was computed from weighted averages of frequencies from several standards laboratories. This was done at the US Naval Observatory. However, it is not yet clear whether such an average yields a time scale which is more meaningful than that derived from a single standard. As has been remarked, a time scale generated by one device will "walk away" in a statistical sense from any time scale generated by another device, even though both may be based on the same type of frequency standard. This is related to the well-known random-walk phenomenon. At any rate, the early establishment of an atomic time scale had the important consequence of confirming the presence of

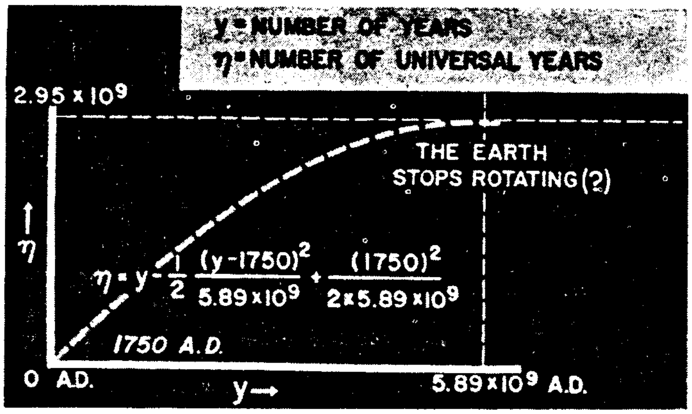

Fig. 2a. Relation between the universal scale and the uniform ephemeris time scale.

previously discovered erratic changes in the earth's motion, and of demonstrating the feasibility of atomic timekeeping. A comparison between the A scale and the A1 scale has shown[12] a very minor fractional difference in scale of perhaps 0.2 parts in 10^{10}. A similar comparison has been made with the TA_1 scale, itself established in 1957, and maintained by the Laboratoires Suisse de Recherches Horlogères, with the Cs transition defining its fundamental unit since July 1960. The observed deviation between TA_1 and NBS-A is about 3 parts in 10^{11}. It is fair to say that the present A scale is one of the most accurate single atomic time scales in existence.

What was the immediate consequence of the establishment of methods of atomic timekeeping? Did it mean that people everywhere forgot about the stars or the earth as a basis for telling time? Did it mean that the internationally accepted unit of time, the ephemeris second, was immediately disseminated for use by the scientific public? Not at all; first, the use of the earth to tell time for rough purposes is far too convenient and easy; second, navigation is based on the scale derived from the earth's motion. The US Naval Observatory continues to circulate its "Time Service" announcements[13] which are widely used to obtain approximations to the UT2 scale of time, useful to navigators. NBS's radio station WWV continues to broadcast time signals based on this scale, or rather an approximation to it called the universal atomic scale, with code broadcast of differences which may be applied to come as close as possible to the UT2 scale insofar as it is known at the moment of broadcast.

There is a disadvantage in the indefinite, unmodified, continuation of this system. The time ticks from WWV are not one second apart, nor does the time scale called UT2 have the international ephemeris second as its basic unit. It has what is called the mean solar second as its basis. This interval is obtained by a process of calculating from theory and reducing observational data and applying the resulting corrections for the motions of the earth's poles and then applying a smoothing procedure to observations of the earth's rotation.

Thus the UT2 interval is in essence the "second" that your clock ticks off if it is adjusted to tick 86 400 (= 24 × 60 × 60) times per mean solar day, while the earth rotates once on its axis. Such a time interval is not equal in length to the international unit of time interval, the second. That is, it is neither an atomic nor an ephemeris second.

The time between WWV ticks is longer than a second, because the earth is rotating too slowly on its axis to make the universal scale agree with the international (ephemeris or atomic) scale. Back about 1750 it was presumably rotating just about at the speed it should in order that one 86 400th part of a day would equal one international second as now defined. Before that time it was rotating too rapidly, and since then, too slowly. It has slowed down so much that the (universal) year of 365¼ days is between one-half and one second longer than it was in 1750. The approximate empirical relationship [14] (see Fig. 2a) is, on the average and in round numbers,

$$\tau = t - \frac{(y - 1750)^2}{380} + \frac{(1750)^2}{380},$$

τ = number of (universal) mean solar seconds which have elapsed since the year 0 AD,
t = number of seconds since 0 AD $= 31 \times 10^6 \times y$,
y = number of (ephemeris) years since 0 AD.

The parabolic form indicates that the earth is slowing down in its axial rotation and would stop in about 6 billion years if this law were to persist (time to get off?). The fact that the days are longer than they were in 1750, reflects that the earth is rotating more slowly—not that it is *slowing* down an additional one-half second or more each year. The deceleration figure is actually about 1/190 sec/yr each year. Differentiation of this relation also gives

$$\frac{d\tau}{dt} = 1 - \frac{y - 1750}{190}\,\frac{dy}{dt},$$

where $$\frac{dy}{dt} = \frac{1}{31 \times 10^6} \text{ years/sec},$$

so that the rate at which the universal scale increases is less than the ephemeris rate—or universal scale units are longer than one second, and are getting longer as y increases. The quantity

$$\frac{y - 1750}{190 \times 31 \times 10^6}$$

is called the *average* fractional offset. About the year 1750, the two scales progressed at the same rate, since

$$d\tau = dt \text{ when } y = 1750.$$

It must be re-emphasized that these are only rough average figures and do not reflect short term variations in the earth's rotation. (See Fig. 2b.)

Apart from the empirical relationship mentioned above, there are theoretical arguments, based on considerations of tidal friction and the concomitant recession of the moon, which indicate that in something less than 50 billion years the earth will present a fixed face to the moon, while the moon rotates about the earth every 47 days.[17,18] Following this, the earth's rotation would continue to slow down gradually due to solar tidal effects until it rotates once on its axis each year. However, a relation between τ and t has been published by Brouwer,[14] which he deduced from observational data; his relation yields numbers slightly different from mine which were obtained from information communicated to me privately by W. Markowitz of the US Naval Observatory. The year 1750 would be replaced by 1779, and the denominator 380 would be replaced by 334. However, for the short span of observation time available, the difference has no practical consequence, especially since the relation describes only the average rotation. It is interesting that, despite the extreme extrapolation involved, theory and observation yield very roughly comparable results.

In any event, since the atomic (or ephemeris) second is shorter than the unit of universal time, the mean solar second, a decision had to be made. There were several choices open, and one was selected. An international agreement relating to the broadcast of time signals and standard frequencies was arrived at and concurred in by many governments via the organization known as the International Radio Consultative Committee (CCIR). It had the support of the various astronomical laboratories and of standards laboratories in many countries, including the US, the UK, and the USSR. In the light of subsequent natural occurrences, hindsight indicates that what was agreed upon may not have been the wisest thing.

It seemed so easy at first. The earth was rotating too slowly. So let there be broadcast from stations like WWV, GBR, and NBA a carrier frequency which is too low in the same proportion.[15] At the time when this decision was taken, the fractional offset in frequency amounted to —130 parts in 10^{10}. The time ticks which occurred every so many cycles were more widely spaced, and for a time the system worked well—until about a year later. Mother Earth began to swing her weight around, still more slowly, and the time signals not only did not indicate seconds, but they did not even indicate mean solar (universal) seconds! Adjustments in phase of these ticks were called for about two or three times a year, to keep them within about 0.1 seconds of the universal scale, UT2. Also, an additional adjustment in the fractional frequency offset seemed in order, and was carried out. It was changed to —150 parts in 10^{10} in 1964. But now people became worried, particularly at the National Bureau of Standards, which has the mission of accurately disseminating the basic standards of frequency and time interval; what was being broadcast or what was contemplated was a kind of variable or rubber standard, from which the international second can be obtained, somewhat inconveniently, by applying the known correction. Superimposed on the average rate of increase of the fractional frequency offset (1.7 parts in 10^{10} per year) are large random fluctuations of several parts in 10^9. Attempts to follow these fluctuations by adopting different offset values from time to time necessitate major revisions in existing equipment, which is not good.

Faced with such a situation, the best thing is to admit the difficulty and to take steps toward resolving it. It was not possible to get the international CCIR agreement modified so quickly and to include recognition and coordination of direct broadcasts of an un-offset second and carrier frequency as a desirable aim, though it soon may be. The United States CCIR Study Group VII, of which the author is chairman, is charged with the study of standard-frequency and time-signal broadcasts and regulations. It met during the summer and fall of 1964 to mull over the implications of the forthcoming international atomic-time-standard pronouncements, as requested by the corresponding international CCIR Study Group, headed by B. Decaux of the National Telecommunication Study

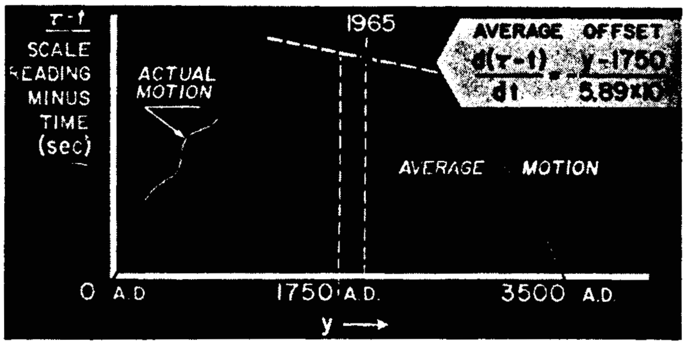

Fig. 2b. Earth motion and the universal scale offset. The average earth motion produces a parabolic relation between the universal scale and the ephemeris scale. The slope of this parabola at any point is a measure of the average offset in frequency. The actual motion of the earth produces fluctuations around this parabolic trend.

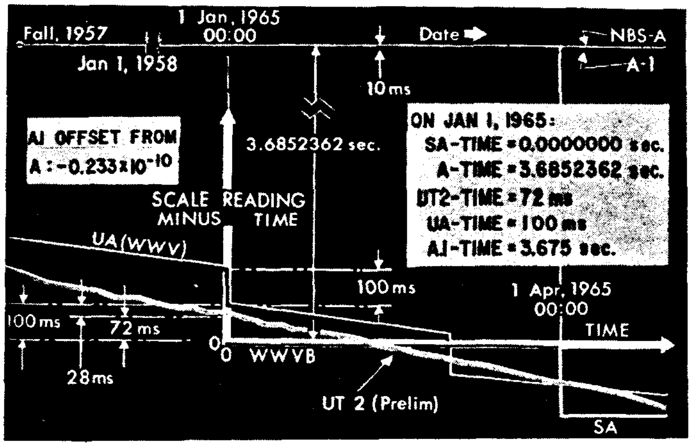

Fig. 3. Relations between time scales. On January 1, 1965, radio station WWVB began broadcasting intervals of one second shown by horizontally stepped line marked SA (stepped atomic). Due to the frequency offset the time intervals broadcast by WWV and other coordinated stations are longer than one second, as shown by sloped and stepped line.

Center in Paris and to see what could be done about the offset question. A positive approach was taken, later augmented by suggestions adopted by the international Study Group meeting at an interim session in Monte Carlo during March 1965. It was decided that experimental broadcasts and studies should be made to study how best to broadcast the interval of time and the epoch of UT2 in the same radio emissions. This is exactly what is being done. Radio Station WWVB, under the management of D. Andrews (who also directs the broadcasts from NBS stations WWV, WWVH, and WWVL) of the NBS Boulder Laboratories, began on January 1, 1965,[16] to broadcast time ticks derived from the A-scale of the National Bureau of Standards with an accuracy of $\pm 2 \times 10^{-11}$. (See Fig. 3.) The controlling element is, of course, the atomic clock incorporating the United States Frequency Standard. The carrier frequency of WWVB is 60 kHz, and is without intentional offset. This is allowable since the frequency offset of WWVB is not specifically regulated internationally. The only frequency corrections which might need to be made are those introduced by slight disturbances in radio transmission and control. These amount, typically, to less than 0.02 parts in 10^{10}, averaged over a month, with a daily rms deviation of $\pm$ 0.06 parts in 10^{10}, and are published by the NBS in the "Standard Frequency and Time Notices" of the *Proceedings* of the IEEE (correspondence). Every few months, the times of occurrence of the ticks from WWVB will be shifted uniformly by a two-tenths-of-a-second step adjustment without changing the length of the subsequent intervals between successive pulses. This keeps them within about 0.1 second of the UT2 scale. Thus, navigators need have no fear of using such stepped atomic signals. Adjustments may need to be made no more often than with the frequency-offset-plus-one-tenth-second-step-adjustment system. Moreover, physicists have directly available the international standard of time interval.

One cannot say as yet that this system is the ultimate one to be used, nor has it been decided that the Cs beam is to serve as the ultimate basis for atomic timekeeping. The hydrogen maser is already a top competitor, both commercially and in scientific research; one is completed and being thoroughly investigated at NBS-BL and another is under construction. One can only say, along with Xenophenes, that "in the course of time, through seeking, men find that which is the better—for all is but a woven web of guesses."

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