Reprinted from "Encyclopaedic Dictionary of Physics
Supplementary Volume 1"
PERGAMON PRESS
OXFORD · LONDON · NEW YORK · PARIS

TIME STANDARDS. A *unit* of measurement for any quantity is usually an abstraction which specifies the idealized concept underlying the realization of the unit. A *standard* on the other hand is a physical embodiment of the unit. Thus standards may occur at any level of use and accuracy. Here, however, we shall concern ourselves only with time standards at the highest level of accuracy and at the most inclusive level of use; namely, at the level of national and international standardization.

An operational definition of time is that time is a physical quantity which can be measured with a clock. A clock in turn is a device which generates a controlled, ordered, nearly continuous sequence of states or phases which can be identified and correlated, by observations, with other ordered sequences characteristic of some chosen phenomenon of interest, or which can associate a number with any single event in question. A unit of time is defined with reference to the particular clock in use. In practice, clocks are often based on nearly uniformly recurring phenomena, so that the unit is defined to be proportional to the period of the clock.

One may specify several requirements for the best possible time standard. It must possess continuity of operation, since time is unique in that it is not sufficient to establish the unit once and for all; one must continually generate and accumulate the units so that any arbitrary interval may be measured whenever desired. Possibly an acceptable substitute for continuity is renewability in the sense of the ability to re-establish the unit at will. This requirement will be acceptable provided that accurate enough other means exist for interpolating between successive determinations of the unit. Secondly, the standard must provide constancy in the size of the unit as time progresses, so far as can be told by comparison with other measures of time. In some cases one may accept a determinable and predictable variability in the period of the standard, so that corrections can be applied which lead to a constant unit. Thirdly, the standard must give an accuracy (with respect to the idealized concept of the unit) which is comparable to or greater than that of all alternate standards. This requirement also embraces, of course, the precision with which the standard is observable. Fourthly, the standard must be accessible to all who need it. Fifthly, the standard should possess a characteristic period of convenient size, because of the need to average over many cycles of the standard in order to improve its precision, to accumulate cycles easily in order to construct large intervals, and to subdivide cycles in order to construct small intervals. Lastly, the standard should be capable of continuously accumulating the unit so as to obtain epoch. Epoch means the state or phase of the standard referred to some arbitrarily selected initial state.

Astronomical standards. At this writing (1964), the internationally defined unit of time, the second, is the fraction 1/31, 556, 925.9747 of the tropical year for 1900 January 0 at 12 o'clock Ephemeris Time. The 1956 resolution of the International Committee of Weights and Measures defining this unit was ratified at the 1960 General Conference of Weights and Measures. This unit, identical with the Ephemeris Second, has supplanted the mean solar second (the second of Universal Time) because of a gain in precision of about one order of magnitude. The accuracy of realizability of this unit from astronomical observations is about 2 parts in 10^9.

This definition reflects the special characteristics of astronomical standards which satisfy the requirements of continuity, constancy, accuracy, and accessibility. The size of the interval characteristic of the standard, that is the tropical year, is not too convenient. It is, perhaps, nearly optimum for precision of observation; but a single observation requires an inconveniently long time; and the tropical year interval must furthermore be subdivided by auxiliary means.

Astronomical standards provide epoch very well because of their continuity and their long characteristic periods, so that ambiguity of phase is easily avoided even with infrequent observation. Furthermore, astronomical standards have important auxiliary applications such as navigation and positional astronomy in which epoch, or state, of the astronomical standard has a use apart from the designation of the time of occurrence of single events.

Atomic standards. Atomic frequency standards are based on the frequency corresponding to a transition between two atomic energy levels. Such devices are now widely used as standards of time interval, that is, differences in time. They are also used to some extent as standards of time, that is, epoch (time as measured from some arbitrary initial instant according to the phase of the clock in use). Atomic standards have the advantage of renewability, although they are not automatically continuous for many thousands of years as are astronomical standards. Nevertheless, present engineering technology has achieved continuity for periods of several years. Constancy of determination of the size of the unit among various atomic standards may be strongly presumed to hold by the nature of atomic energy levels and indeed has been demonstrated to 1 part in 10^{11}. Accuracy with respect to the value of the unperturbed atomic transition is typically about 1 part in 10^{11} now, or about two orders of magnitude better than the accuracy of determination of the Ephemeris Second. Precision of observation is high. Averaging times of only a few hours are long enough to show precision of observation of a few parts in 10^{13}, in the sense of the standard deviation of the mean of several such observations. Atomic standards are universally available either by construction or by purchase. The size of the period characteristic of the standard is convenient, being the reciprocal of the atomic transition frequency. This frequency is typically in the gigacycle-per-second region. Thus it is

easily averaged over many cycles in a matter of minutes, hours, or days. It is easily integrated by electronic means to construct large intervals of time. Small intervals, even down to the nanosecond region, are readily available because of the high frequency of the standard. The epoch of the atomic standard is useful for providing a uniform scale of time, common to all observers, upon which the occurrence of events may be placed. It does not, however, have presently known auxiliary usefulness such as in signifying when it is "noon" or when "spring" begins. Continuous atomic time scales have been constructed and maintained for several years by several laboratories. Techniques vary in detail, but all amount to the observation of the phase of a quartz oscillator with corrections as necessary for any fluctuations in its frequency with respect to an atomic standard. For example, we may define an arbitrary measure of time τ in terms of the elapsed phase $\Delta\varphi$ (that is, number of cycles) of an oscillator. If the oscillator is assigned a fixed nominal frequency ω_n, then its indicated time is $\Delta\tau$ given by

$$\Delta\varphi = \omega_n \Delta\tau, \quad \text{or} \quad \Delta\tau = \Delta\varphi/\omega_n.$$

But if its actual frequency for that interval (assumed sufficiently short), is $\omega_a = \omega_s/r$ in terms of a fixed atomic standard frequency and a ratio r, we have the measure of atomic time Δt given by

$$\Delta\varphi = \omega_a \Delta t = (\omega_s/r)\,\Delta t.$$

Note that these equations state the invariance of the oscillator phase as expressed in either system of time. These concepts define time in terms of a frequency standard; for if the oscillator is the frequency standard itself, then $\omega_a = \omega_s$ and $r = 1$, so that $\Delta t = \Delta\varphi/\omega_s$. In the general case, simple algebra gives

$$\Delta t = (\omega_n/\omega_s)\, r\, \Delta\tau$$

or, for long time intervals,

$$\Delta t = \frac{\omega_n}{\omega_s} \int_{\tau}^{\tau+\Delta\tau} r(\tau)\, d\tau,$$

where $r(\tau)$ accounts for a non-uniformly running oscillator, expressed as a function of τ. We may thus construct intervals of atomic time related to the two observables, the phase of an oscillator (that is, its indicated time τ) and the atomically calibrated oscillator frequency ω_a.

Since it is more practical to run quartz oscillators than atomic standards continuously, it would be desirable to correct for any predictable variations of quartz by programmed phase shifts at the output of the quartz oscillator thereby obtaining a measure of time always very close to atomic time. Mechanical phase shifters have been successfully employed recently to correct for frequency offsets and predicted frequency drift rates. Such systems have given measures of time within $\pm 0{\cdot}3$ μs per day of uniform atomic time. The magnitude of this absolute error increases as the square root of the number of observations; thus for 100 days the accumulated error would be expected to be 3 μs. Since the measure of time itself progresses directly as the elapsed time, the relative error continually decreases and is limited only by the accuracy of the atomic standard.

^{133}Caesium. The transition involved is between the two magnetic hyperfine levels in the ground state ($^2S_{1/2}$) arising from the coupling of the nuclear spin angular momentum I and the electronic angular momentum J. In caesium, J is due only to the spin of the valence electron. The transition is designated as

$$F = 3, \quad m_F = 0 \leftrightarrows F = 4, \quad m_F = 0,$$

where F takes on the integral values ranging from $I + J$ to $|I - J|$. For caesium, $I = 7/2$ and $J = 1/2$. The notation m_F designates the magnetic quantum number for Zeeman splitting of the F levels by an external magnetic field. It gives the component of F along the field. The transition occurs at a frequency of 9,192,631,770 c/s.

The method of observation is by well known atomic beam techniques. Caesium metal heated in an oven vaporizes and atoms effuse from an aperture. These atoms first pass through a strong and inhomogeneous magnetic field. By virtue of the Zeeman splitting of the energy levels, a magnetic moment μ in the neighbourhood of 1 Bohr magneton is induced in the caesium atoms. The atoms are deflected from the instrument axis by the force due to the inhomogeneous field and of magnitude proportional to $(\mu \cdot \nabla)\, H$. The atoms then pass into a drift space where a low, uniform magnetic field exists in order to prevent them from taking random spatial orientations. There an oscillating radio frequency interacts with the atomic dipole moment (which is associated largely with the electronic angular momentum) to induce either absorption or stimulated emission. In practice, the r.f. field is applied in two regions separated by a considerable distance. The separation is chosen variously from 0·5 to 5 m in order to achieve certain experimental advantages such as uniformity of the r.f. field and sharper linewidth for the atomic transition. If the radio frequency is not in resonance with the transition frequency, no transitions occur. The atoms then continue through a second strong deflecting field, are further deflected in the same sense, and miss the detector. If, on the other hand, the r.f. field is in resonance, transitions occur; and the effective dipole moment of the atoms in the strong deflecting fields is just reversed. A compensating deflexion occurs which focuses the atom onto a detecting target. The linewidth of the transition observed by this method is set by the uncertainty principle, $\Delta E\, \Delta t \cong h$, or $\Delta\nu\Delta t \cong 1$, where E is the energy separation of the atomic states, Δt is the time of flight, ν is the transition frequency, and h is Planck's constant. Typically, an experimentally

observed linewidth for a machine of effective length 160 cm is 120 c/s. Often the oscillator exciting the transition is locked to the resonance frequency by a servomechanism. This method has given results as accurate as manual setting of the frequency.

Accuracy is typically of the order of 1 part in 10^{11} with respect to the state separation in the unperturbed atom. Limitations on this accuracy are set by uncertainties in the magnitude and homogeneity of the uniform magnetic field in the drift space and by small but unknown phase shifts between the separated regions of the r.f. field.

Hydrogen maser. The transition involved is between the magnetic hyperfine levels in the ground state ($^2S_{1/2}$) of atomic hydrogen, arising from the same sort of interaction as described for caesium. The transition is designated as

$$F = 0, \quad m_F = 0 \rightleftarrows F = 1, \quad m_F = 0.$$

Here F takes on two values, 0 and 1, since $I = 1/2$ and $J = 1/2$. The transition occurs at 1,420,405,751·80 $\pm$ 0·03 c/s.

The transition is observed in a maser oscillator. The upper state of the transition is prepared by dissociation of hydrogen gas in an electrical discharge, followed by beam formation through mechanical collimation and subsequent magnetic focusing of the $F = 1$ state by the forces due to an inhomogeneous magnetic field on the magnetic moment. Atoms prepared in the upper state enter a storage bulb with a special wall coating such as polytetrafluoroethylene. The coating is chosen to have a weak interaction with the excited atoms to reduce perturbation of their energy levels by collision and to reduce the probability that atoms are lost by reaction at the wall. The bulb is contained in an electromagnetic cavity resonator. Any field present at the proper frequency causes stimulated emission of the atoms from the upper state to the lower state. The radiation emitted is used to overcome internal power losses in the cavity and to provide power for external signals.

This method of operation has several features distinct from the atomic beam technique. The standard is an active oscillator which provides a signal as contrasted to a passive resonator which must be probed by an external signal. The natural linewidth is narrower due to the longer storage time, typically 1–3 sec. There is a high signal-to-noise ratio by virtue of the essentially noise-free process of amplification by stimulated emission. First-order Doppler shifts arising from the atomic motions are effectively cancelled because of the random directions of the atoms. The hydrogen Zeeman spectrum is simpler than that of caesium, consisting only of four levels rather than sixteen; thus overlapping of the tails of spectral lines is easier to avoid. The accuracy of the hydrogen maser with respect to the transition frequency of the unperturbed atom is estimated to be about 1 part in 10^{11}. It is limited by shifts in frequency due to perturbation of the energy levels by collisions with the walls. These may be thought of as cumulative shifts of phase between the atomic dipole moment and the stimulating radiation due to perturbations of the energy levels during each wall collision. Another limitation has been due to temperature changes of the apparatus, which are mainly manifested as changes in cavity resonance frequency and consequent frequency pulling.

^{205}Thallium. The transition involved is in the ground state ($^2P_{1/2}$) of thallium, arising from the same sort of magnetic hyperfine structure as in caesium and hydrogen. The transition is

$$F = 0, \quad m_F = 0 \rightleftarrows F = 1, \quad m_F = 0.$$

Here $I = 1/2$ and $J = 1/2$. The transition occurs at 21,310,833,945·9 $\pm$ 0·2 c/s. The method of observation is by the use of an atomic beam. The detection of neutral thallium by surface ionization is harder than the detection of neutral caesium because of its higher ionization potential. It is also harder to deflect the thallium atoms because of a smaller effective magnetic moment in the strong deflecting field. Accuracy with respect to the transition frequency of the unperturbed atom is conservatively estimated at 2×10^{-11}. The main limitation is the phase shift of the r.f. radiation between the two separated field regions. There are some increased practical experimental difficulties with thallium, although in principle it offers certain advantages over caesium. These advantages are a lesser dependence of transition frequency on residual magnetic field, greater simplicity of the Zeeman spectrum, greater intensity of the beam signal (since a greater fraction of all the atoms in the ground state is in the $m_F = 0$ states used for the standard frequency transition), and a slightly longer time of flight for the same length of beam due to greater mass of the thallium atom.

Other atomic frequency standards. The ammonia beam maser formerly gave promise as an atomic frequency standard, but has been surpassed in accuracy by the above three. A rubidium device has been developed in which the upper magnetic hyperfine level is overpopulated by optical pumping, and transitions induced at the microwave resonance frequency are detected by changes in the absorption of the optical pumping radiation. This device is also of lesser accuracy than caesium, hydrogen or thallium. It does find usefulness, however, because it provides frequency stability of perhaps 1 part in 10^{11} over short intervals of the order of seconds in a simpler instrument than a caesium standard. Commercial models of caesium, hydrogen, and rubidium standards are available.

Dissemination of time standards. The very nature of time requires that its standards be immediately and continuously communicated to the place needed. A

long-standing means of doing this has been by high frequency radio broadcasts from 2·5 to 25 Mc/s. These generally consist of a carrier of precisely controlled frequency and of time markers constructed by precisely modulating the carrier at intervals controlled by the carrier. The carrier generating the time signals is offset from the atomic frequency, and the time signals are jumped as necessary in order to give as good an approximation as possible to UT2. There can be some advantages in making atomic frequencies and time signals derived therefrom directly available by radio broadcast, and this feature may be added to some of the broadcasts in the future. High frequency standard frequency broadcasts cover roughly a continental reception range. The accuracy of frequency reception over a few hours is about 1 part in 10^7 because of variable propagation effects associated with the motion of effective ionospheric height. The accuracy of time pulse reception is about 1 ms.

Very low frequency (VLF) radio broadcasts below 30 kc/s and low frequency (LF) broadcasts from 30 to 100 kc/s have provided a new method of time standard dissemination within the last decade. The range of VLF propagation has long been known to be large. Within the last decade the phase stability has been discovered to be excellent due to the special mode of propagation. This may be pictured roughly as a wave guided between the concentric spheres of the ionosphere and the Earth. It is well known that some guided modes have propagation constants which are insensitive to certain dimensions and boundary conditions of the wave guide. The diurnal rise and fall of the ionosphere does, however, give a small phase shift dependent on the direction and length of the propagation path. This shift is usually less than 2π rad at VLF even for intercontinental paths and usually is highly reproducible to within a few per cent from day to day.

The available bandwidths at 60 kc/s and 100 kc/s are enough to transmit effective time signals. In fact, the Loran C navigation system sends pulses of 100 kc/s radiation of rise time typically 60 μs, enabling time resolution between the arrival of the ground wave and the sky wave. Using special pulse reception techniques, timing accuracy is better than 1 μs and is due to the increased stability of the ground wave propagation over the sky wave. VLF broadcasts at 18 or 20 kc/s do not have the available bandwidth for resolution of time pulses to much greater than ± 1 ms. Nevertheless, these broadcasts have proved highly useful for phase locking remote oscillators separated by continental distances and thus continuously transferring the time standard without slippage of more than a few microseconds. Once the time of the remote oscillator has been set with respect to the standard, it then remains synchronized and partakes of the full accuracy of the standard which drives the broadcasts.

Microwave pulses have been transmitted by communication satellite between continents for the synchronization of remote clocks. Results to 1 μs in the satellite link were obtained. This method largely avoids the influence of the ionosphere on the propagation because the microwave frequency used is less sensitive to ionospheric disturbance and because much of the path is outside the ionosphere.

Portable clocks capable of microsecond time resolution have recently been used to synchronize remotely located time standards. The clocks used have been both quartz and portable atomic standards. Uncertainties have been within a few microseconds for separations of continental scale and within a few tens of microseconds for separations of intercontinental scale. This technique provides a satisfactory way to disseminate time when used in conjunction with the VLF phase lock system described above.

Bibliography

BARNES J. A. and FEY R. L. (1963) *Synchronization of Two Remote Atomic Time Scales, Proc. I.E.E.E.* **51**, 1665.

BONANOMI J. (1962) *A Thallium Beam Frequency Standard, Trans. I.R.E.* I-11, 212.

CLEMENCE G. M. (1957) *Astronomical Time, Rev. Mod. Phys.* **29**, 2.

CRAMPTON S. B. *et al.* (1963) *Hyperfine Separation of Ground-State Atomic Hydrogen, Phys. Rev. Letters* **11**, 338.

ESSEN L., and PARRY J. V. L. (1957) *The Caesium Resonator as a Standard of Frequency and Time, Phil. Trans. Roy. Soc. London* A250, 45.

MOCKLER R. C. (1961) *Atomic Beam Frequency Standards*, in *Advances in Electronics and Electron Physics*, Vol. 15, New York: Academic Press.

J. M. RICHARDSON