TIME AND ITS INVERSE

by John M. Richardson

Cesium has a resonance at 9,192,631,770 ± 20 cps. Some atomic clocks are even more precise. But time itself remains nebulous

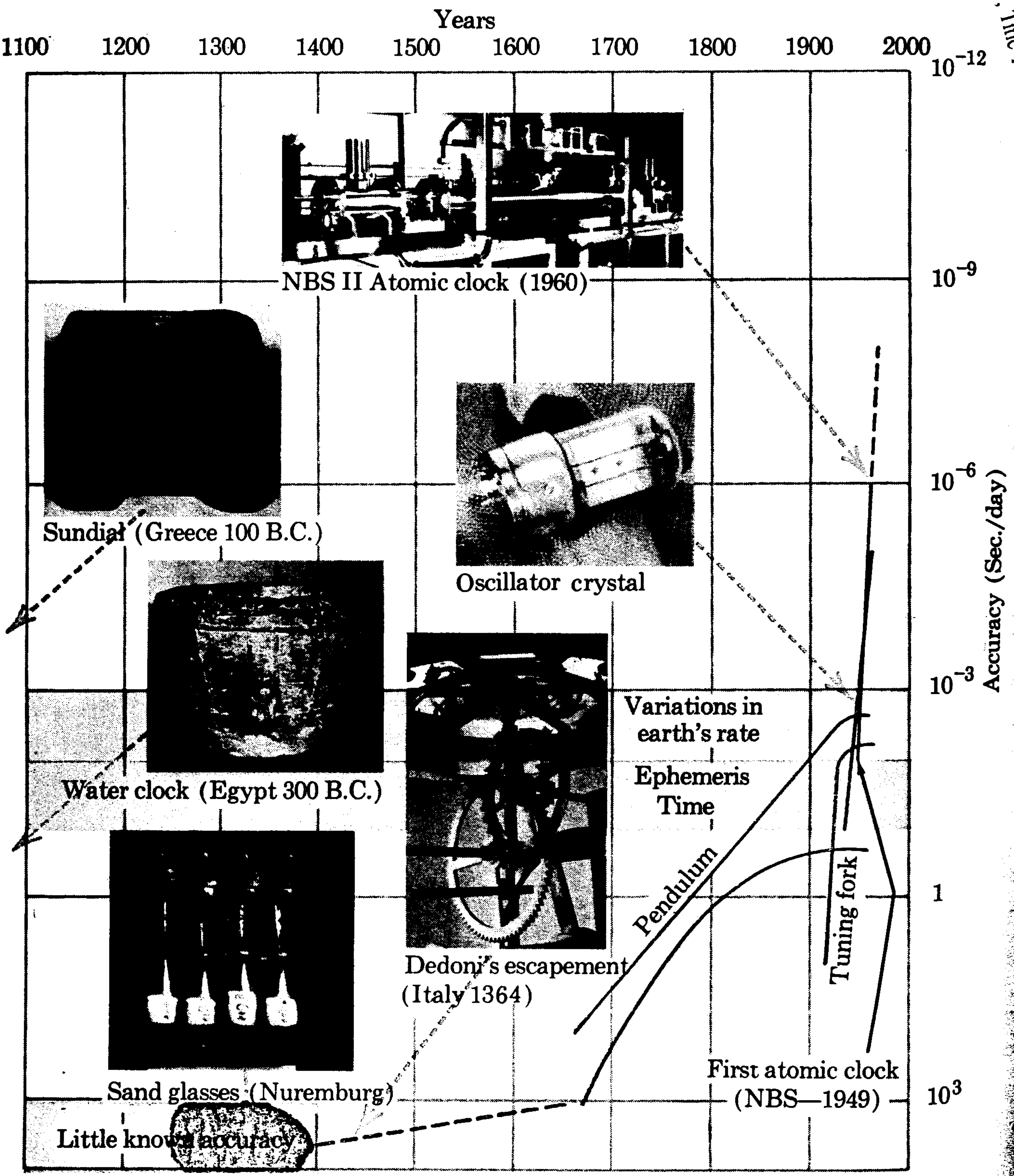


Fig. 1. Man's first clock may have been his stomach. Step by step he's made more accurate clocks by using more nearly reproducible phenomena. Today unvarying atomic resonances promise a clock more accurate than ephemeris time, based on earth's revolution about sun and limited by observational difficulties.

IN BRIEF: *Despite the concern of a hundred generations of scholars with its definition time (frequency*$^{-1}$*) remains an elusive quantity, best treated operationally as a basic parameter in our physical laws. Of all the clocks built around these laws, astronomy offered the best standards available—until now. But technological needs and advances have outstripped the astronomical standard; a new scale is needed. Frequency standards using atomic or molecular resonances offer timekeeping accuracies to parts in* 10^{10} *and* 10^{11}. *(And 13 places are in sight.) Besides, the laws of physics assure us that these new clocks inherently carry within themselves the basic, immutable reference.*—R.G.N.

■ "What time is it?" In these four words lies one of the most absorbing stories in the history of measurement. The story begins as primitive man feels the rebirth of spring or the chill of winter. It continues as an Egyptian priest analyzes the heavens to predict the flood of the Nile. This brief question touches on cosmology and embraces hardware, hardware which has, in this decade, given us the ability to make absolute measurements of time that are two orders of magnitude more precise than those of any other quantity.

Atomic frequency standards, or more popularly "atomic clocks," can easily mark off intervals of a day, a month, or even years to parts in 10^{10} or 10^{11}. Yet, the leading national laboratories of the world can determine length and mass only to parts in 10^9. These clocks are a different breed than the pendulums and balance wheels we have known. Yet they share this basic concept: they count some type of cyclical phenomenon. Instead of totaling the swings of a pendulum, the new clocks use the microscopic properties of cesium or rubidium atoms or of ammonia molecules. Their great accuracy has led to an internationally agreed intention to recommend an atomic standard in place of the astronomical one which, in one form or another, has served us for fifty centuries.

Time and frequency

To consider suitable criteria for a time standard, we clarify our notion of what time really is. "What is time?" Descartes, Newton, Eddington, Einstein and Bridgman all tried to answer the question, and the answers we have are still not entirely satisfactory. Let's follow Bridgman's operational method and stick closely to what we know. Time appears as a quantity or a parameter, t, in a number of interesting physical equations which seem to describe portions of the physical world. Consider Newton's Second Law of Motion,

$$m \frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}$$

or Maxwell's equation for electromagnetic induction,

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t},$$

which relates the electromotive force in a circuit to the rate of change of magnetic flux. Schrödinger's time-dependent wave equation,

$$\frac{h}{2\pi i}\frac{\partial \psi}{\partial t} = \left(\frac{h^2}{8\pi^2 m}\nabla^2 - V\right)\psi$$

seems to describe the world of quantum mechanics in great detail. Still another, the Poisson distribution, gives the probability of observing n radioactive disintegrations as

$$P(n) = \frac{(at)^n}{n!}e^{-at}$$

where a is some constant appropriate to the nucleus involved.

Thomas Gold has pointed out the curious fact that all the above laws are symmetrical in t; that is, substitution of $-t$ for t still gives physically interpretable results. This means that we do not know whether our clocks are running backwards or forwards, or indeed, whether there is any physical meaning to the terms "backwards" and "forwards"! He notes that thermodynamics always points the arrow of time in the direction of increasing entropy.

So far we can say that time seems to be a parameter that enters a variety of interesting physical equations, and that these equations validly predict observations. A strange thing is that the parameter seems to take on successive values all by itself. We don't have to set the time as we set voltage or pressure. It could run uniformly, or nonuniformly, it could even run in discrete jumps like a motion picture film. All we really know is that the equations hold when the parameter t goes through its automatic paces.

Those equations can be integrated or otherwise manipulated to obtain a functional relationship between some observable, such as position, voltage, or counts, and the parameter t. By using some phenomena described by these equations to make a "clock," we can infer a quantity which we understand to be time. A clock, then, is simply a device which permits the observation of some chosen time-dependent physical phenomenon. We have a wide choice: we can use Newton's law for the position of a body; or Maxwell's equation describing the alternation of an electric current; or Schrödinger's equation of energy levels in an atom; or the Poisson distribution to predict radioactive decay.

Let us put down some integrals of these equations to see the applications. One integral of Newton's equation is $s = s_0 + gt^2/2$; by observing a falling body we have a clock. Apply Newton's equation to planetary motion under the action of a central force. In a particularly simple case we find

$$\theta = \theta_0 + \sqrt{GM/r^3}\, t$$

which states that the angular position of a planet is some initial angle plus a constant, involving the universal constant of gravitation, the mass of the sun, and the distance, times the time. If we observe a planet describing a circle about some force center we use the planet as a clock.

In an electrical oscillator we find an equation of the same form, $\phi = \phi_0 + \omega t$, stating that the phase of the oscillations equals an initial phase plus some constant (the angular frequency) times the time. The National Bureau of Standards has built another sort of clock which uses the principle that the number of radioactive atoms of Ta^{182} in a sample at any time is an exponentially decaying function of time. It has been put into a cornerstone in the hope that some civilization 10,000 years from now will dig it up and tell when it was made by us.

Now, a remarkable thing is that if we make a lot of clocks using one of these laws they all seem to agree; they all tell the same time. Even more remarkable is that if we make a variety of clocks using different laws, they also seem to agree — within the limits of experimental error. This is a very pleasant situation, and we think we have something approaching a general concept that we can call "time." But we should still stay pretty close to an operational definition and about all we can say at the moment is that *time is a physical quantity which can be observed and measured with a clock of mechanical, electrical, or other physical nature.* Thus, with the tacit reservation that we may have to look out for a possible discrepancy in the time kept by clocks based on different laws, our choice of a standard clock is dictated only by convenience.

What do the new atomic standards, which are really *frequency* standards, have to do with clocks, or time standards? The two devices, of course, represent dual aspects of the same phenomenon. Consider our general definition of a clock as a device which embodies some one-to-one correspondence, $\phi = \phi\ (t)$, or the inverse, $t = t^{-1}\ (\phi)$, between some observable ϕ and the parameter t. This relationship need not even be analytical; it may be tabular. With a time scale based on a particular ϕ, we adopt an initial instant t_0 corresponding to an initial condition ϕ_0. "What time is it?" then means "What is the value of $t - t_0$?"

For astronomical clocks based on diurnal or annual motion of the earth, $t - t_0$ is often referred to as "epoch," that is, the interval elapsed from the arbitrary origin. The question, "What is the lapse of time between event E_1 occurring at t_1 and event E_2 occurring at t_2?" is answered by giving $\Delta t = (t_2 - t_0) - (t_1 - t_0) = t_2 - t_1$. We see that Δt is independent of its position on the scale relative to t_0, i.e., independent of epoch. On our scale we obtained the unit of time defining the size of an interval $t_2 - t_1$ corresponding to observables ϕ_2 and ϕ_1.

If there is any irregularity in ϕ, we have a nonuniform scale. This actually occurs in the scale UT (universal time). Even the unit is irregular, since in this scale ϕ_2 and ϕ_1 mark the beginnings of any two successive mean solar days, rather than of two specific ones. Irregularities in the mean solar day therefore cause fluctuations in the mean solar second.

For convenience, ϕ is usually taken as the argument or phase of some sinusoid (as voltage in an oscillator). We take $v = \sin \phi(t)$ or $\phi(t) = \sin^{-1} v$. It is then natural to speak of the instantaneous radian frequency, given by

$$\omega = \frac{d\phi}{dt} = \lim_{\Delta t \to 0} \frac{\phi(t + \Delta t) - \phi(t)}{\Delta t}$$

Thus in principle, we have related the physical observable ϕ, time t, and frequency ω; that is we have *calibrated* the derived quantity, ω in terms of the fundamental quantity, t. As a practical matter, devices which are primarily clocks or time sources, like the daily rotation of the earth, require rather long Δt intervals between the observations of ϕ (say transits of a star over the meridian), and so the limiting process of obtaining ω is operationally hard to accomplish.

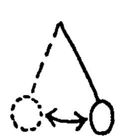
A frequency standard, however, is a source of an instantaneous frequency, $\omega(t)$. We obtain phase by integrating,

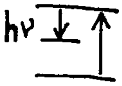
$$\phi\ (t) = \int_{t_0}^{t} \omega(t)dt$$

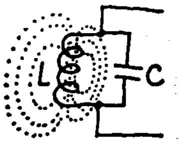
and we can infer time from the previously established relationship between ϕ and t, specifically by looking up t for the observed value of ϕ either in our table or by solving an assumed analytical relationship for t. Clearly, given an atomic frequency standard with constant ω, we can derive inseparably both an excellent unit of time and an excellent time scale, on which intervals elapsed from t_0, or any other instant, can be measured. Ergo, there is no fundamental difference between a time standard and a frequency standard.

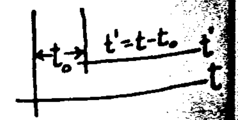
Clocks and the sun's motion

Of all the clocks indicated above, astronomical clocks have, without competitor, been the most accurate until recently. One of the first standards of time was the apparent sun, the sun we see when we look up. When it crossed the meridian the time was taken to be noon. Apparent solar time is very nonuniform; even cuckoo clocks easily detect its irregularities. Through the years, various averages and corrections have been applied to the motions involved in the rotation of the earth. These have led to UT2, the most uniform time scale that









we can define with the rotation of the earth; it's good to a part in 10^8 or so. Still, unpredictable and irregular changes in the rotation of the earth led to its abandonment in 1960 as the scientific standard of time. In its place we now use Ephemeris Time, based on the motion of the sun about the ecliptic. (Fig. 2.) The unit of time, the second, is taken from this scale as a particular fraction of the tropical year, which in turn is nearly (but not precisely) the time for the sun to make one full revolution. In this way, the ephemeris second can be determined to a few parts in 10^9, but it also has its limitations.

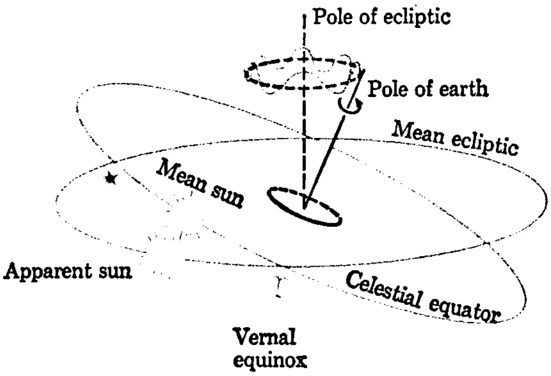


Fig. 2. By Kepler's laws, the sun's annual motion along the ecliptic is fastest when earth and sun are closest. So we think of a fictitious mean sun traversing the celestial equator at constant rate, i.e. the mean *rate of the apparent sun.*

Because of the long interval of at least a day between observations of solar time, for example, we have had to supplement the astronomical clocks by other clocks of shorter period. This development is indicated in Fig. 1. The introduction of resonant oscillatory devices, improved precision several orders of magnitude over that obtained with clocks based on flow or relaxation principles. The "best buy" of clocks considering precision, cost, and reliability is probably the thermostatically controlled quartz crystal. Of course these must be rated by a standard, since it is not yet possible to predict precisely the frequency of quartz by absolute measurements of mass, length, and so on. Yet quartz oscillators are indispensable as drivers and interpolators for present atomic standards. Without the stability of quartz crystals the narrow atomic resonances could not even have been observed.

About 1945, I. Rabi, Nobel Laureate for his fundamental work on the effect of the nuclear magnetic moment on the energy levels of the alkali atoms, suggested that some of these resonance lines could be used as frequency standards, by utilizing the relation $E_2 - E_1 = h\nu$. About that time, C. H. Townes suggested the similar application of certain microwave absorption lines in gases. H. Lyons, at NBS in about 1948, began research that realized an atomic frequency standard. Shortly thereafter, L. Essen of NPL, in England, succeeded in building an excellent cesium standard, which he put into regular operation and which is still in weekly use. R. C. Mockler and his group at NBS have carried the work on these devices to a high state of development, and I think it's fair to say that the two cesium beams in Boulder serving as the United States frequency standard represent the most accurate and thoroughly evaluated frequency standards in the world today.

Atoms as clocks

Transitions with outstanding properties occur in cesium, ammonia, and hydrogen. A transition between hyperfine levels in the ground state of Cs^{133} arises from interaction of nuclear and electronic angular momenta. It is insensitive to electric and magnetic fields and at a convenient frequency (9192 Mc). The inversion of $N^{14}H_3$ at 23,870 Mc (22,789 Mc for $N^{15}H_3$) is useful for its high intensity and permits power oscillations. The 1420 Mc line of H is very narrow, contributing to high precision. Other transitions which have been studied are in the ground state of the alkali metals Na^{23} (1772 Mc), Rb^{87} (6834 Mc), and of Tl^{205} (21,311 Mc).

The operation of an atomic beam device using cesium is indicated in Fig. 4. This type has been the most widely investigated to date and has been the most satisfactory, probably because it's closest to the ideal of a single atom in field-free space unperturbed by collisions and free of Doppler shift. Atoms leave the oven with various velocity vectors and are deflected by the nonuniform magnetic field. Then they drift in the low field space C and are excited with microwave radiation.

At resonance, change of state occurs by absorption or stimulated emission depending on whether the atom was initially in the upper or lower F state. Upon traversing the second identical deflecting field, only those atoms having undergone transitions are deflected toward the detector. At the detector, atoms strike a hot wire, are ionized and observed by the resulting current. The current indication may then be used to regulate the frequency of an external crystal oscillator (either manually or automatically). The crystal output is then raised and injected into the Cs beam through a waveguide. When the rf injected into the beam is exactly at the chosen transition frequency, the detector output current is a maximum.

The width of resonance is governed by the uncertainty principle, $\Delta\nu \; \Delta t \sim 1$ where Δt is the time of flight of the atom. Precision increases as the beam lengthens, until the

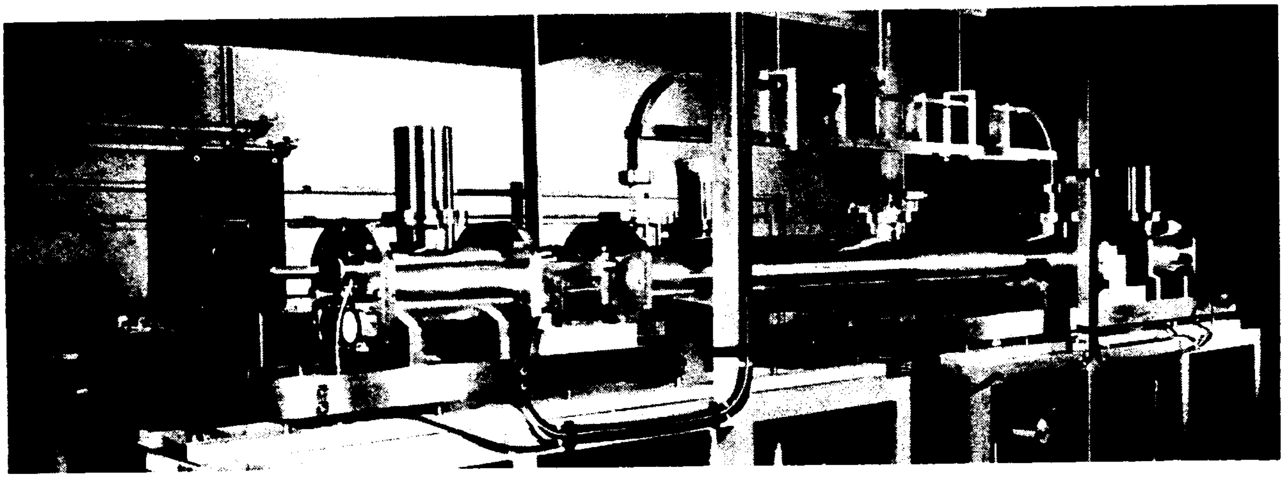


Fig. 3. NBS II, at Boulder, represents the high state of development to which Cesium-beam standards have been brought. Frequency stability on the order of parts in 10^{13} has been achieved. Current plans at the Bureau are to use Thallium-205 in the beam next.

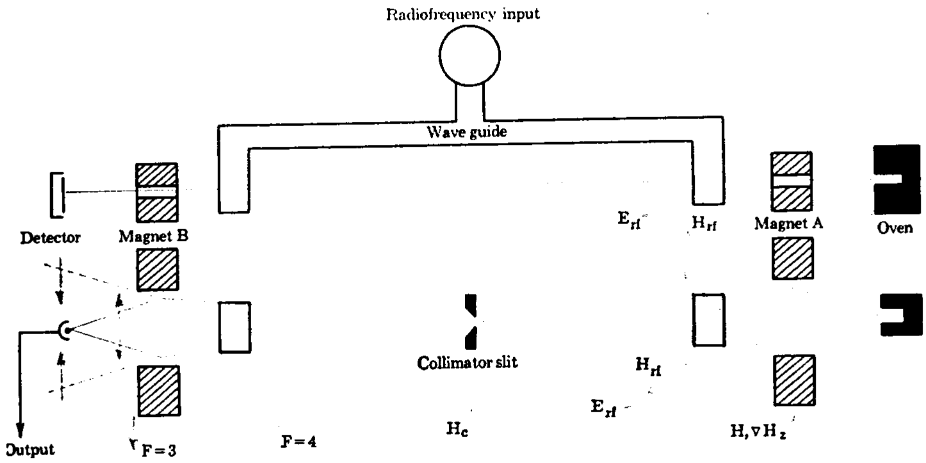


Fig. 4. The purpose of the Cs beam apparatus is to furnish a controlling signal that adjusts the frequency of an external crystal oscillator. To do this, atoms in energy states $F = 3$ and $F = 4$ leave an oven and are deflected by magnet A. (For the two $m_F = 0$ sub-levels, deflection is equal and opposite.) Then they drift in low-field where they are excited by radiation from an external synthesizer. If the radiation is at the 9,192 Mc resonance line, m_F 0 atoms (and these only) undergo state transitions by absorption or by stimulated emission. Magnet B deflects towards the hot-wire detector only those atoms that have undergone transitions.

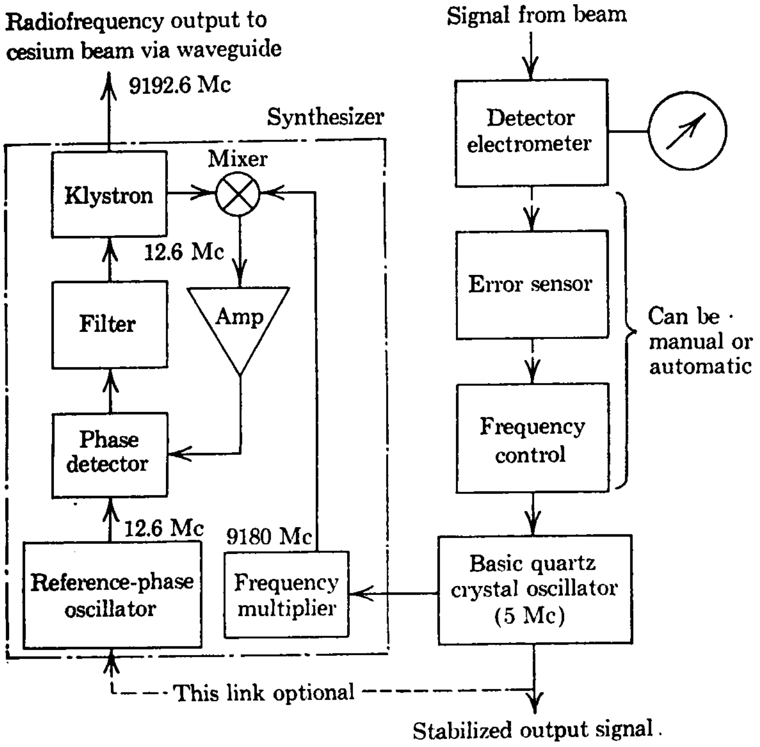
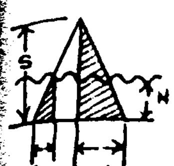


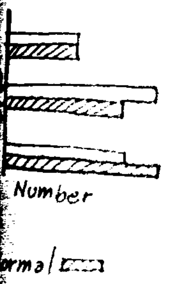
Fig. 5. A quartz crystal oscillator supplies the actual output signal and controls the frequency of the synthesizer which pumps the beam. The crystal oscillator, in turn, is controlled (usually via a reactance tube) by the amplified current from ionization of Cs atoms by a hot-wire detector. For manual control, the electrometer amplifier's half-power point is read on a meter; for automatic control, the peak power point is used.

secondary effects (attainable vacuum, magnetic focusing optics, field homogeneity in the drift space, spectral impurity or phase jitter of the exciting rf) become important.



The basic limitation to precision is noise, as roughly shown in the margin. The noise level N makes the setting on, say, the half-power point of a spectral line of width $\Delta\nu$ uncertain by amount $\delta\nu$. By similar triangles, $\delta\nu = (N/S)\ \Delta\nu$, so we want a narrow line and high signal-to-noise ratio. By careful evaluation of all known systematic errors, the NBS group has assigned an uncertainty of 1.1 parts in 10^{11} to its standard in approaching the idealized Cs resonance (Fig. 3).

Common to all atomic frequency standards are: (a) atoms (or molecules) in a pure state (by focusing, pumping, or other way); (b) conditions for long lifetimes in that state, (with a long drift space or by insuring non-disorienting collisions); (c) stimulated transition to another state by microwave rf in a manner free of Doppler effect; and (d) detection of the transition.



The ammonia maser can also be used as an atomic clock. A beam of NH_3 is sorted by a multipole electrostatic focuser which focuses atoms in the upper state and defocuses those in the lower state; the focused atoms enter a microwave cavity where they are stimulated to emit by an existing microwave field. This energy is stored in the cavity to produce further stimulated emission and to supply losses of the cavity and external loads. Masers can selectively amplify applied signals near their resonance, or they can oscillate with high spectral purity. The relative line width is, in practice, only a few parts in 10^{12}—better than any other rf source. The actual frequency is sensitive to conditions like cavity tuning, cavity Q, beam flux, and Doppler shift (due to traveling waves in the cavity feeding local losses, such as at an exit iris). These must be held closer than the Cs conditions to get comparable reproducibility (parts in 10^{10}).

In the rubidium vapor standard, Rb vapor at about 10^{-7} mm Hg is excited from some of its ground hyperfine sublevels to an upper electronic state by filtered or polarized light at resonance. With collisions, excited atoms become more or less equally distributed among the sublevels of the upper state and spontaneously radiate to all lower levels. The upper hyperfine level of the ground state can be enhanced at the expense of the lower. If transitions are induced between these levels by microwave radiation, there is a change in the absorption, scattering, or polarization of the exciting light by the altered populations.

Rubidium standards are now commercially available with excellent stabilities of a few parts in 10^{12} over several days. But they must be calibrated against a standard of the cesium type because of various instrument shifts. Commercial cesium standards have accuracies with respect to the Cs resonance line of up to 1 part in 10^{10} and stabilities of the same order.

The newest atomic frequency standard is the atomic hydrogen maser announced in 1960 by Ramsey, Goldenberg and Kleppner. Molecules dissociated by an electrical discharge supply H atoms, which are selected in the upper hyperfine level of the ground state by magnetic deflection. These are captured in a chamber lined with a noninteracting wall coating, so wall collisions won't destroy the prepared state. The atoms radiate by maser action and the long lifetime against collision results in very narrow line width. The hydrogen maser promises a way to higher stability, and perhaps closer approach to the unperturbed transition frequency. Stabilities to parts in 10^{13} have been achieved. Accuracies to match these stabilities are anticipated.

The present limits on atomic standards are systematic errors in environment control. There is room for several orders of magnitude improvement before the basic limitation of random fluctuations will be reached. These devices are self-calibrating in that they carry an immutable reference with them. And they are handy, requiring only a few cubic feet and a few hundred watts.

Uses—navigation, communications

So far we seem to have been talking accuracy for its own sake. Are there any real uses for such accuracies? Very accurate frequency measurement does not, of course, extend to dimensions other than time; these are limited by the lesser accuracy available in length, mass, or current, as the case may be.

Simply and obviously, new clocks can be used to study old clocks, the astronomical clocks. As the French astronomer A. Danjon put it, atomic clocks will cut a vicious circle: heretofore the motions of the stars could not be studied except by time which was itself defined by the motions of the stars!

Navigation and tracking are other areas. The uncertainty in the position of a low satellite by visual tracking corresponds to about a millisecond at satellite velocity; improvement to 0.1 ms is imminent. To reduce timing errors, it would be handy to track such a satellite over its lifetime of perhaps several years on a time scale which is uncertain to no more than 0.1 ms. So it's desirable (although not necessary) to have long-term timing to parts in 10^{11}. Available gear heretofore limited such navigation systems as Loran to principles needing frequency control about 10^{5} to 10^{6}.

Imagine an aircraft obtaining its range from a ground transmitter by integrating the Doppler shift of the received signal (as measured by an ultrastable local oscillator). It derives its relative velocity; then integrates over time to obtain position. For an accuracy of 30 m (one wavelength at 10Mc) during a

SOME STANDARD TIME SIGNALS AND THEIR FREQUENCIES

Station	Carrier frequency	Stability (parts in 10^{10} per day, approx.)	Special properties
W W V **Greenbelt, Md.**	2.5, 5, 10, 15 20, 25 Mc	0.5	Voice signals; Time code; Geophysical announcements
W W V H **Hawaii**	5, 10, 15 Mc	2	Geophysical announcements; No time signals
W W V B **Boulder, Colo.**	60 kc	0.3	High stability; Presently low power; No time signals
W W V L **Sunset, Colo.**	20 kc	0.3	Presently low power; No time signals
N B A **Balboa, Canal Zone**	18 kc	0.5	Essentially world-wide
G B R **Rugby, U K**	16 kc	1	Essentially world-wide
M S F **Rugby, U K**	2.5, 5, 10 Mc; 60 kc	1	Voice signals
J J Y **Tokyo, Japan**	2.5, 5, 10, 15 Mc	1	Voice signals; Geophysical announcements
H B N **Neuchâtel, Switzerland**	2.5, 5 Mc	0.5	———
C H U **Ottawa, Canada**	3.330, 7.335, 14.670 Mc	2	Voice signals
——— **Moscow, USSR**	10, 15 Mc	Unknown	———

trip of 1 day (10^5 sec), stability of 1 part of 10^{12} is needed. Such a scheme may offer practical economies, over existing pulse systems, in power, bandwidth, cost, and weight.

Ultranarrow band systems conserve radio spectrum and reduce noise (an absolute necessity for deep space communication). Atomic oscillators may be used for their calibration and control. Many of the most precise measurements of physical constants are made in terms of a frequency measurement.

As a bonus we gain the rich electronic and digital techniques available for handling frequency data. For example, through the gyromagnetic ratio of the proton, magnetic field is proportional to a frequency; this is now the handiest method for measuring fields up to parts in 10^6. Voltage, electric field, dielectric constant, plasma electron density, permeability, displacement, and velocity can all be related to frequencies or frequency shifts, with gains in measuring convenience. The shifts may be small, but the inherent precision of frequency scales makes them easily observable.

So that stable frequency and accurate time may be disseminated to all who wish to use it, the NBS, the USN and corresponding institutions in other countries maintain radio broadcasts (Table). The accuracy of instantaneous frequencies in the megacycles (outside ground-wave range) is degraded, down to parts in 10^7, by ionospheric reflections, and signal strength is lost by scattering. At very low frequencies, around 18-20 kc, the ionospheric effects are small. Perturbations are minor and propagation is enhanced. (See Fig. 6.) Hence vlf is of global range. And just as vlf is a means of propagating stable signals, so stable signals themselves are a means of studying fine variations in the propagation medium, such as those caused by solar flares.

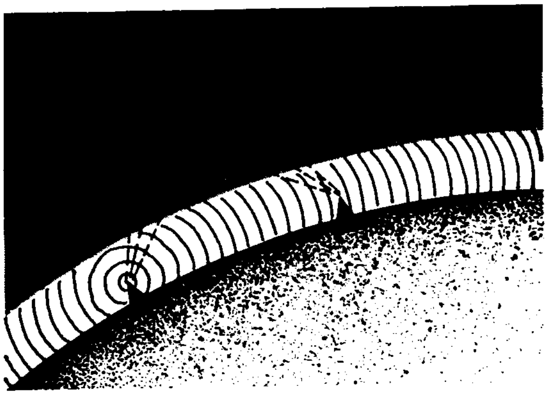


Fig. 6. Very low frequency transmissions, with wavelengths of the order of 10 miles, are much less affected by ionospheric variations than transmissions with wavelengths of, say, 30 meters. As a result, VLF signals have 1000 times the stability of signals in the higher frequency 30 meter band.

With pulse transmissions at 100 kc, it is technically feasible to synchronize clocks separated by 100 miles to about 1μs. More precision will mean longer averaging times, or transporting stable clocks from place to place, as Reder has already done to synchronize (to a few microseconds) clocks thousands of miles apart. More accuracy requires considering relativistic effects like the Einstein red shift of frequency with gravitational potential (1.76×10^{13} parts/mile of altitude at the earth's surface) and the quadratic Doppler shift (a part in 10^{12} at 700 mph).

$$\nu = \nu_0\left(1 \pm \frac{\text{velocity}}{c}\right)$$

Doppler

Atomic and astronomical standards

Universally applicable measurements must be expressed in terms of a standard. The standard must be at least as uniform as all other available clocks. It must be observable with precision and continuous enough to preserve its origin during our longest physical experiments. Besides, it must be renewable in case of loss or lapse and it should be generally accessible.

The unit size should be convenient like the meter and the kilogram. Since time standards

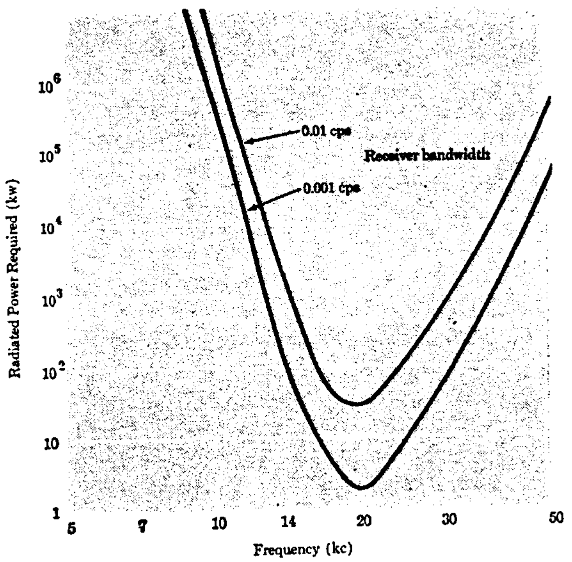


Fig. 7. Requirements for a world-wide standard frequency transmitter located near Boulder and giving coverage 90% of all hours at a receiver in the vicinity of Madagascar (estimated most difficult service area). Calculations are based on an observing time of one hour.

nearly always are of the form $f(t) = f(t) + 2\pi\, n/\omega$), where n is an integer, we average over large values of n for precision or take the Fourier frequency transform of a large number of cycles. Thus, ω should be large so that these operations can be applied to convenient intervals. Also, because of the characteristics of practical circuits, frequencies of many cycles per second are much more convenient to handle than are frequencies of one cycle per day or per year. Frequency measurement is essentially a counting process; the standard must not be too rapid for counting. This effectively limits us to below about 300×10^9 cps at the present state of the art.

Astronomical clocks best fulfilled these criteria for 5000 years. Yet we have troubles with even the most refined astronomical unit, the Ephemeris Second. For example, the tropical year gets shorter each year and is now 0.3 second shorter than in 1900. So we must define the unit of time at a particular instant: it's 1/31,556,925.9747 of the tropical year appropriate to 12 hours Ephemeris Time (ET) on January 0, 1900 (i.e., December 31, 1899). Thus, our definition has more significant figures than our measurements.

In practice, we can't observe the sun accurately enough for the short term determination of ET and extrapolation to 1900 with great precision, so we link the sun's motion to the moon (which moves faster and has a cleaner limb) by a theory of the moon's motion. This way the unit of ET can be determined to a few parts in 10^9—if one devotes several years to the job. This may improve slightly in the future but will be limited by the following: (1) The theory of the moon's motion is insufficiently exact. (2) The limb of the moon is not sharp enough to give sufficiently precise readings. (3) The necessary constants in the theory of the motion are not sufficiently exact; special problems are the value of tidal friction and the moment of inertia of the earth.

As a result, many astronomers generally agree that the Ephermeris Second will never match atomic standards, for precision. And so, the General Conference of Weights and Measures, at its 1960 sexennial sessions, urged active pursuit of studies of atomic frequency standards. That resolution directed its executive arm, the International Committee of Weights and Measures, to recommend some action by 1966. The inevitable subcommittee, the Committee for the Definition of the Second, in April 1961, committed itself to formulate the recommendation. This follows the meter, which at those sessions became "that length equal to 1,650,763.73 vacuum wavelengths of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the atom of Kr^{86}." But the time scale is also unique among our standards: we must preserve the origin of time with adequate relative accuracy.

Provided there are no catastrophic failures in the equipment, I think there is no reason why such a scale could not be kept and improved as long as our civilization survives. If civilization blacks out for a few thousand years, people can reconstruct the origin with sufficient accuracy for their needs by looking at the sun again. For this reason I don't see any real difficulty in abandoning astronomical means of rating clocks and using instead atomic standards with a frequency integrator. Of course, the need to correlate with the various astronomical time scales, as determined by the national observatories still remains. To relate the old and the new definitions and scales, we will agree on a common origin and match the atomic second and the former astronomical second as closely as we can. The best available relationship was reported in 1958 by Markowitz, Hall, Essen, and Parry as $\nu_{\mathrm{Cs}} = 9{,}192{,}631{,}770 \pm 20$ cps (of ET). It's unlikely that this will be much refined in the next few years. In effect, once and for all, publication of this number calibrates all atomic frequency standards, and converts time to atomic time standards.

The significance of this is that the Ephemeris Second is recognized as inadequate for precision measurement, and that a change to an Atomic Second will follow. The choice of a particular transition, the conditions under which this transition is observed, and the assignment of a particular frequency to this transition will result during the next couple of years.

To dig deeper into the annals of time turn to page 73.