Atomic Standards of Frequency and Time

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ABSTRACT

The National Bureau of Standards scale of time is provided by an atomic frequency standard. Thus, for the first time in our civilization, the basis of our measurement of time is atomic instead of astronomical. The major reasons for this change are that modern science can measure the resonance of an atom more accurately than it can measure the motions of stars and planets, all of the factors affecting atoms are better understood, and the atomic resonance appears to be more stable than planetary motions. This change has improved our accuracy of measurement by three orders of magnitude.

Presently, the best atomic clocks are based on atomic cesium beams such as the three at NBS. Further research, however, may reveal a better choice of atom or method. NBS is using four radio stations to distribute time (and its reciprocal, frequency) to the nation and over much of the globe, but again, research is being conducted on newer techniques that offer higher accuracies.

The change from astronomical to atomic time will have little effect on our daily living habits, but it will permit our technology to accomplish things we couldn't do before and to do the same things more economically.

In the Garden of Eden, when Adam and Eve wanted to check the time between apples, they must have done so by watching the sun pass overhead. Ever since, at least up until the last decade or so, when man has sought the most accurate measure of time, he has based his measurement on the movement of some planet or star.

Of course, through the years the measurement of astronomical time has become more sophisticated. Today the most accurate formula for measuring time astronomically includes hundreds of elements and considers the gravitational effect of most planets in the solar system. By using such a formula, and by averaging measurements over several years, astronomers can now measure time to a few parts in 10^9—equivalent to a variation of no more than one second in 30 years.

Such accuracy represents a tremendous achievement in the astronomical measurement of time, but it also represents the limit of this type of measurement. Today, in the frontier areas of research and technology, we need a more accurate measure of time and we need to realize it within a few hours or minutes.

To meet these needs, a revolution is taking place in man's measurement of time. For the first time, he is measuring it with molecules and atoms instead of with stars and planets: he is going from the largest clock imaginable to probably the smallest possible. In so doing he is increasing his accuracy of measurement about 1,000 times and expects to do even better within the next few years, and he can make such measurements in a matter of minutes.

The facts which make this change possible are that the instruments of modern science can measure the resonance of an atom more accurately than they can measure the motions of stars and planets, that all of the factors affecting atoms are better understood, and that the atom's resonance appears to be more stable than planetary motions.

In this paper we shall consider the general problem of time measurement, the principal methods of measuring time astronomically, the developments

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His work at the National Bureau of Standards has been in microwave physics, including microwave spectroscopy, microwave interferometry, and physics of ionized gases—especially as these fields have bearing on standards and physical constants.

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leading to the atomic measurement of time, the operation of the present standard of time and frequency for the NBS (a cesium beam device), and the methods used to make the NBS standard of time and frequency available to the nation and to much of the world.

Fundamental Clocks

To consider the broad question of time measurement, observe the parameter t in equations which validly describe portions of the physical world. Consider Newton's law governing the position s of a falling body, $s = \frac{1}{2}gt^2$, where g is the acceleration of gravity. In this equation, and in others such as Maxwell's equation for electromagnetic induction, or Schrödinger's time-dependent equation governing transitions between energy states of an atom, or the Poisson distribution for the probability of observing radioactive disintegrations, t appears in ways which give us various methods of measuring time. Each equation can be integrated or otherwise manipulated to obtain a functional relationship between some observable—such as position, voltage, or radioactive counts—and the parameter t; in each case we can observe some physical phenomenon to measure time. There is, then, a wide choice of methods for measuring time, and a device based on any such method may be called a clock.

Now we may expect that if we make a lot of clocks using one of these laws they will all seem to agree: all tell the same time. The remarkable thing is that if we make a variety of clocks using different laws, they also seem to agree. Thus it seems that our concepts of measuring time are valid, and we need only select the method which will best meet our needs.

Note that a cyclic phenomenon has an advantage in that it continues indefinitely, and counting the occurrence of cycles is one of the simplest operations of measurement. These are the two basic things needed for the best clock—a cyclic phenomenon and a counting device.

The concept of a good clock as a device that counts the cycles of some oscillation, which occurs with some definite frequency, brings in the relationship between time and frequency. We make a point of this here because, as is described later, the basis of atomic time is an atomic standard of frequency.

What other things do we seek in a clock to serve as our standard of time? Some primary considerations are these: First, it should have the highest possible accuracy. It should, in other words, be at least as uniform as all other clocks, and its output should be such that it can be observed precisely. Second, it should be reproducible. No two pendulum clocks, for example, can be made exactly alike. Thus, if a master pendulum clock were destroyed, it would be impossible to reproduce it exactly. Third, its output should be in units of time which are convenient to work with—not too large, not too small—and this output should be available without great experimental difficulty. Notice that the best way to meet the first two goals (accuracy and reproducibility) is to base the measurement of time on a universal constant of nature.

Thus we have defined some broad aspects of time measurement and our main goals for an ideal timepiece. Before ending this discussion of general concepts, let us briefly consider the place of time in our system of physical measurement. The International (metric) System of measurement is a consistent system in which the units for the basic quantities—length, mass, time, and temperature (the meter, kilogram, second, and degree Kelvin)—are established independently and arbitrarily; the units for all other physical quantities are defined in terms of these basic units in accordance with the equations of physics. Thus the standard of time is basic to our systems of science and technology.

An interesting footnote is that we can now measure time and frequency far more accurately than we can measure any other physical quantity. The atomic clock maintained by the Radio Standards Laboratory of the National Bureau of Standards can measure time (or time interval) to a few parts in 10^{12}. Yet length and mass can be determined only to parts in 10^9.

Astronomical Time

As mentioned, astronomical clocks have, without competition, been the foundation of the measurement of time since the dawn of history. One of the first standards of time was the apparent sun—the sun we see when we look up. When it crossed the local meridian, the time was taken to be noon. This apparent movement of the sun is created, of course, by the earth's daily spin on its axis and by the revolution of the earth about the sun. Apparent solar time, however, is very nonuniform, mainly because of variations in the earth's orbital speed. Even cuckoo clocks easily detect its irregularities.

Through the years, in a search for higher accuracy, various averages and corrections have been applied to the rotation of the earth and to the revolution of the earth about the sun. These refinements have led to Ephemeris Time, sidereal time, and Universal Time. Those motions of the earth

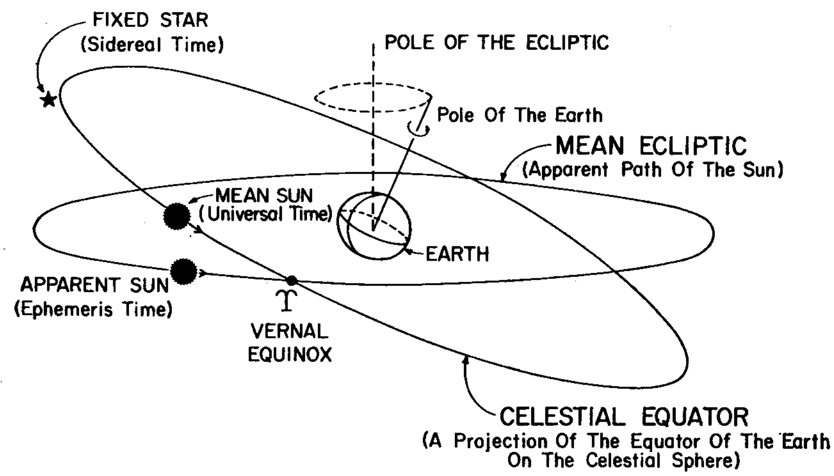


Figure 1

which are most important to these measurements of time are shown in Fig. 1.

The basis of Ephemeris Time in principle is the annual orbital motion of the earth about the sun as seen in the equivalent motion of the apparent sun about the earth. Sidereal time and Universal Time are based on the daily rotation of the earth. Sidereal time is determined by measuring the rotation of the earth with respect to a fixed star. Universal Time (formerly called mean solar time) is given in principle by the rotation of the earth about its axis with respect to the imaginary mean sun traveling along the celestial equator. (This imaginary sun moves uniformly eastward along the celestial equator instead of the ecliptic.)

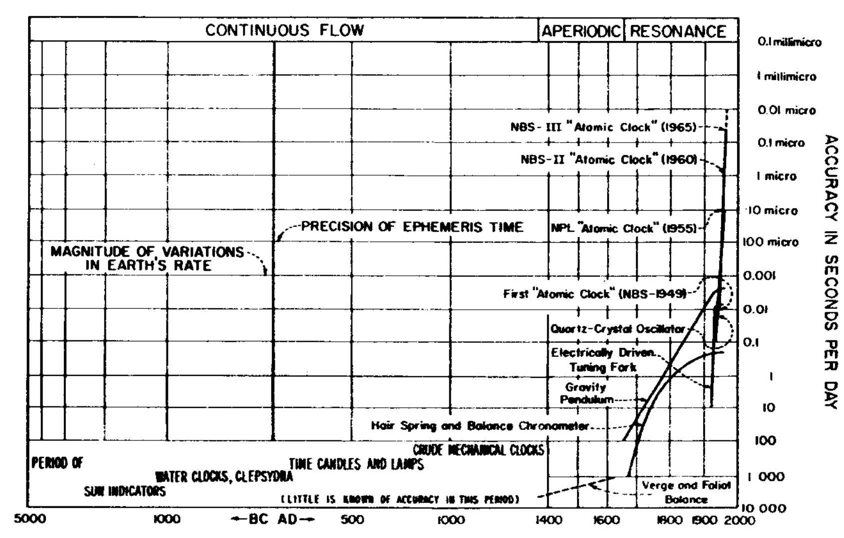
The most refined astronomical unit —the ephemeris second—was adopted in 1956 as the fundamental unit of time by the International Committee of Weights and Measures, and this action was confirmed in 1960 by the General Conference of Weights and Measures—the international body, consisting of representatives of 39 nations, that makes decisions on international uniformity of measurement. This unit is taken from the scale of Ephemeris Time as a certain fraction of the tropical year. (The tropical year is, with sufficient exactness for this discussion, the time between successive arrivals of the apparent sun at the vernal equinox—see Fig. 1.) The ephemeris second can be determined to a few parts in 10^9, but it has its complexities. For example, the tropical year gets shorter all the time and is now 0.3 second shorter than in 1900. So this unit of time has had to be defined as a particular fraction of a particular tropical year to define a fixed or invariant interval of time. The fraction is 1/31,556,925.9747. The tropical year is chosen arbitrarily as 1900, again with sufficient exactness for this discussion.

In practice, the sun's position cannot be observed accurately enough for the short-term determination of Ephemeris Time and extrapolation to 1900 with great precision. Therefore, we observe the moon, which moves faster and has a sharper edge, and we get the desired result from the theory of the moon's motion since this theory also contains the sun's motion. **Even with these refinements, however, to measure within a few parts in 10^9, measurements must be averaged over several years. This result may be slightly improved in the future but will be limited by the following problems: (1) the theory of the moon's motion is not complete, (2) because of atmospheric refraction the apparent edge of the moon is not so sharp as it must be to give sufficiently precise readings, (3) the moon is not quite circular so there is doubt concerning the precise location of its center of mass, (4) constants in the theory of motion are inexact, and (5) ambiguities lie with special problems such as the value of tidal friction and the moment of inertia of the earth. Thus, most astronomers agree that the ephemeris second will never match the** accuracy of the atomic second.

This brief description of astronomical time reveals several problems other than the fact its accuracy appears to be limited to a few parts in 10^9. One problem is that the period measured isn't of convenient size. For example, an interval of at least a day exists between observations of Universal Time. Thus, man has always supplemented astronomical clocks with clocks of shorter period, as illustrated in Fig. 2.

Another problem with astronomical clocks is that accurate measurements are not easily made. As mentioned, to achieve an accuracy of parts in 10^9 requires averages of measurements

THE ACCURACY OF TIMING THROUGH HISTORY



After W A Morrison, BTSJ (1948)

Figure 2

made over several years. Well equipped observatories and facilities for reducing the many observations are therefore needed.

Astronomical clocks, however, have at least two prime virtues. First, they are continuous. They obviously never stop running—at least for periods of time far longer than the duration of our civilization. This feature means that they are very good for automatically measuring epoch—a measure of the occurrence of any instant with respect to a conventional, arbitrarily selected, initial instant. The continuous operation of astronomical clocks precludes any lapse which would destroy the relationship of the present epoch to the initial epoch. Their long periods also help avoid miscounting of cycles even with infrequent observation.

A second virtue of astronomical clocks is that they provide us directly with information needed for celestial navigation; astronomical time must be used when one is shooting the sun or the stars for a fix.

(For a thorough description of the astronomical measurement of time see the "Explanatory Supplement to the Ephemeris," prepared by the Nautical Almanac Offices of the United Kingdom and the United States, and printed by Her Majesty's Stationery Office, London, 1961.)

Atomic Frequency Standards

As astronomy was moving toward the refinement known as the ephemeris second, atomic frequency standards were being developed in the field of quantum electronics.

It had long been known that atoms and molecules emit or absorb periodic electrical oscillations at sharply defined frequencies (spectral lines). This realization goes back to the beginning of spectroscopy. The problem was that there was no suitable tool for using these extremely high frequencies as the basis for a frequency or time measuring device.

The first step toward solving this dilemma was the observation of lower frequencies in the microwave range. In 1934 Cleeton and Williams at the University of Michigan reported the first experimentally observed microwave spectral line—the (3, 3) inversion of ammonia. Extensive and accurate measurements of even these frequencies, however, had to wait the refinement of microwave techniques. World War II provided these techniques with the development of microwave radar.

In 1948, Harold Lyons and his staff at the National Bureau of Standards built the world's first atomic clock, based on the (3, 3) absorption line of ammonia which occurs at a frequency of 23,870,100,000 hertz (cycles per second—abbreviated Hz). Lyons has described this clock in an article, "Atomic Clocks," which appeared in *Scientific American*, Vol. 196, February 1957, page 71.

This first atomic clock was stable to only a part in 10^7, and it had only a simple counting device, but it proved that atomic frequencies offered high potential. It was soon realized, however, that atomic beam devices offered promise of higher accuracies than did the microwave absorption of a gas.

The atomic beam technique was based on the studies of I. Rabi, 1944 Nobel Laureate for his fundamental work on the effect of the nuclear magnetic moment on the energy levels of the alkali atom. About 1945 Rabi suggested that some of these spectral lines could be used as frequency standards. To date cesium has been most used, principally because the cesium atom, like the ammonia molecule, has a natural resonance frequency (9,192 MHz) in the microwave region and thus can be easily handled by present techniques. Also, the atomic beam technique appears to come closest to the ideal of a single atom in a field-free state—unperturbed by collisions and free of Doppler shift.

If cesium atoms are placed in an electromagnetic field which oscillates at 9,192 MHz, resonance occurs, and the atom can absorb or emit energy with a corresponding change in its energy. This process provides the basis for a frequency standard. (A detailed description of the cesium frequency standard is given in the appendix.)

During the next few years, several laboratories concentrated on the building and refining of atomic frequency standards. The first such continually operable standard was a cesium atomic beam device built by L. Essen of the National Physical Laboratory in England. It was placed in regular operation in 1955 and is still in weekly use. During the 1950's work was also undertaken by Bonanomi in Switzerland, by Kalra in Canada and in the United States by McCoubrey and Holloway of the National Company and by H. Lyons, R. C. Mockler and associates at the National Bureau of Standards.

Construction and testing of the first NBS cesium atomic beam device was completed in 1958. This was not accepted as a standard, however, until a second device was completed and independently tested. A comparison between these two was made over a period of several months and showed frequency agreement to about 1.5 parts in 10^{11} with a measurement precision over a period of several hours of 2 parts in 10^{12}. On January 1, 1960, these cesium atomic beam devices were adopted as the U.S. Frequency Standard (USFS). Since this date a third cesium beam device (see cover photo) has been built by NBS and its accuracy, reported just last year (1965), is 5 parts in 10^{12}—equivalent to a variation of no more than one second in 6,000 years. For a two-hour sampling period its precision is 1 part in 10^{13}. We think it is fair to say that the cesium beams in Boulder, Colorado, developed by R. C. Mockler and his group, are the most accurate and thoroughly evaluated frequency standards in the world.

It may be useful to define what we mean by the terms accuracy and precision. Let us consider accuracy—how shall we discuss the accuracy of an ultimate standard where there is no higher standard with which it can be compared? To do this we break the idea of a standard into two parts. First is the ideal concept, in this case a particular resonance of the cesium atom. The concept, of course, is infinitely exact. Second is the physical apparatus required to realize the concept, and this involves unavoidable experimental errors. We therefore consider accuracy to mean the degree to which a prescribed observation on the physical apparatus approaches the ideal concept of the definition.

Now let us consider precision, which is the degree of agreement among repeated measurements and is a property of a measurement process and not of an instrument alone. Thus, concerning the cesium atomic beam, accuracy is a measure of how closely we can measure the actual cesium resonance, and precision is a measure of how closely we can repeat successive measurements. Note that in specifying the accuracy, the precision must be included as a source of error.

A full and quite readable description of these and other terms important to precise measurement is given in "The Reliability of Measured Values—Part 1 Fundamental Concepts" by Churchill Eisenhart in *Photogrammetric Engineering,* Vol. XVIII, No. 3, June 1952.

Atomic Clocks

To relate atomic and astronomical time—to specify the length of an atomic second in terms of the astronomical second—there had to be a careful determination of the number of cesium cycles in the international unit of time, the ephemeris second. This determination was done in 1958 by Markowitz and Hall of the U.S. Naval Observatory and Essen and Parry of the National Physical Laboratory, and the measurements showed the cesium frequency to be 9,192,631,770 ± 20 cycles per ephemeris second as defined in 1956. (The ambiguity of ± 20 cycles per second was the result of uncertainties in the astronomical observations.) It now became desirable to develop an atomic time scale which could be continually compared with the astronomical time scales. But first, some method of accumulating atomic seconds over long periods had to be found.

It is not practical to operate Cs frequency standards of the complexity of those used at NBS for long periods because of possible power failures and need for maintenance. Thus, to construct an atomic time scale—to accumulate atomic seconds—it is necessary to use some secondary standard and frequently calibrate this in terms of the atomic standard. Quartz oscillators serve well as secondary standards since they are simple, reliable, and operate continuously.

If an oscillator's frequency were exactly correct, a clock operated from this oscillator would neither gain nor lose time. When the frequency, however, is too high (or too low) the clock gains (or loses) time proportional to its frequency error. This notion can be expressed mathematically by denoting the interval of time indicated by the clock by $\Delta\tau$, the interval of atomic time by Δt, the "ideal" frequency of the oscillator by f_1, and its actual frequency as calibrated by the atomic standard by f. These quantities can then be combined in the equation

$$\Delta t = \frac{f_1}{f} \Delta\tau,$$

giving atomic time in terms of f, f_1, and $\Delta\tau$.

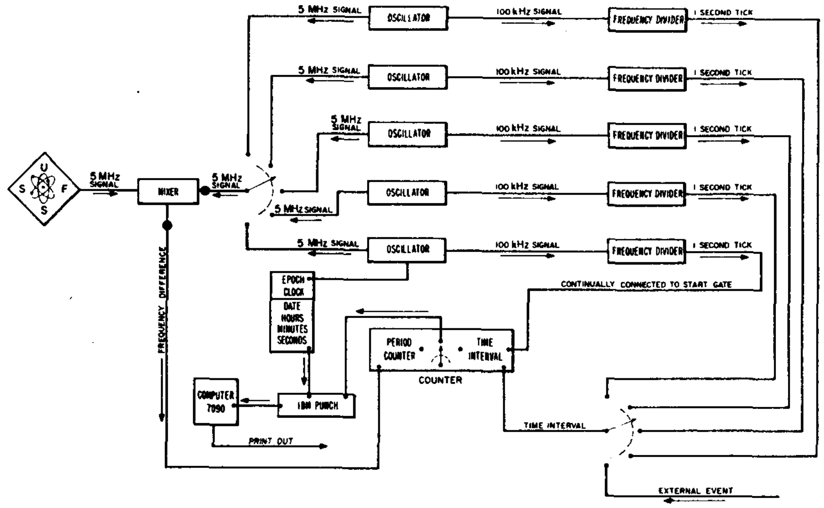


Figure 3

The procedure is to observe f every day or so, taking about one hour for the measurement. To get the continuous atomic time scale, we sum (or integrate) these daily results assuming a linear variation of f between calibrations.

Using this concept, J. A. Barnes and his group at the NBS Radio Standards Laboratory have developed a system of counting and accumulating atomic seconds. To ensure reliability, 5 oscillators are involved (four quartz and one atomic frequency device using the atom of rubidium) as illustrated in Fig. 3. These run continuously. The cycles of each oscillator are counted to get the indicated time $\Delta\tau$; the frequency of each is checked daily against that of the cesium beam; and, with a computer, a weighted average of the five results for Δt is used to form the atomic time scale known as NBS-A. The accuracy of this time scale is equivalent to the cesium beam —5 parts in 10^{12}.

Thus, in effect, the cesium beam serves as the master control for the five oscillators. These oscillators then serve as the continuously running pendulum of the atomic clock, and the total units counted by this composite clock form an atomic time scale.

The NBS scale of atomic time (NBS-A) has been extended uninterruptedly back to the fall of 1957 by the assignment of atomic times to time signals broadcast by the NBS radio station WWV. This was possible because a comparison of WWV signals and an atomic device has been made by A. H. Morgan and his group in Boulder since 1957. (At first the device consisted of a commercial cesium instrument; this was followed in 1958 by an NBS cesium standard.)

First Steps Toward Changing The International Unit of Time

These achievements, coupled with those of other laboratories, led to official recognition by the General Conference of Weights and Measures that time is now being measured by atomic devices. It is still uncertain, however, which atom and which method will turn out to give the most accuracy. In view of the uncertainty, the General Conference decided not to reword the present definition of the second; it is still the ephemeris second, defined as a fraction of the tropical year 1900. At the same time, however, the conference assigned the frequency 9,192,631,770 Hz to the cesium transition and designated its use for the practical measurement of time.

Thus, although the wording of the definition of the unit of time remains unchanged, the *de facto* definition can be said to be an atomic second. The first step has been taken toward officially changing the definition of the unit of time from an astronomical to an atomic basis.

The Need for High Accuracy

Having described how we can measure time with an accuracy equivalent to the variation of no more than one second in 6,000 years, perhaps we should pause to consider who needs such accuracy.

The first scientific use is simple and obvious: new clocks can be used to study old clocks, and thus atomic clocks can be used to study 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 motions of the stars.

Also, Ephemeris Time can be compared with atomic time. If there should turn out to be a relative acceleration between these two, then either the theory of relativity is wrong, or the quantum theory, or both.

Many of the most precise measurements of physical constants are made in terms of a frequency measurement. Thus, improvement in frequency measurement provides an immediate and direct benefit in these measurements.

But the new precisions and accuracies are useful in applied as well as in pure science. A survey was taken in 1964 by the Radio Standards Laboratory of those in the electronic field who use the NBS standard time and frequency broadcasts. Forty-two percent of the 3,000 respondents have interest in atomic frequencies and time. Nearly half of these (44 percent) are interested almost solely in the atomic quantities, having little or no interest in astronomical time. Letters urging the broadcast of atomic frequencies and time have been received from such organizations as a large electronic instrument manufacturer, from a large supplier of the aerospace industries, and from a research laboratory that is concerned with monitoring satellites and deep space probes.

This situation reflects the most urgent needs for precise time and frequency today—the navigation and tracking of missiles, satellites and space vehicles.

It is dangerous to speculate about the future, and we have no intention of really attempting to unmask it. As a hint, however, we'll mention three examples of how atomic frequency standards might soon be applied.

First, systems of ultra-narrow bandwidth conserve radio spectrum and reduce receiver noise (an absolute necessity for deep space communication). Atomic oscillators may be used for their calibration and control.

Second, imagine an aircraft obtaining its range from a ground transmitter by integrating the Doppler shift of the received signal (as measured by an ultra-stable local oscillator). That is, the pilot obtains his radial velocity from the Doppler effect and then integrates over time to get range. For an accuracy of 30 meters (one wavelength at 10^7 Hz) during a trip of 1 day (10^5 seconds), stability of 1 part in $10^5 \times 10^7 = 10^{12}$ is needed. Such a technique may offer practical economies over existing pulse ranging systems in power, bandwidth, cost, and weight.

Third, as we move deeper into space the requirements for precise tracking of deep space probes will become more critical. For example, the National Aeronautics and Space Administration hopes eventually to measure a distance comparable to that between the earth and the sun with a precision of one foot, and they wish to make this measurement during the relatively short period of about 10 seconds. This task turns out to require a national frequency standard whose rating is better than a part in 10^{14}.

Major Time Scales

Having considered the development of atomic devices to measure time and frequency, we logically consider next how the NBS distributes time signals and standard frequencies to users. Quite briefly, this is done through four radio stations maintained by the NBS Radio Standards Laboratory. Before describing these stations, however, let us first consider several major time scales, since these scales presently govern the values of time and frequency which are broadcast.

Figure 4 shows the relation between five time scales. At the top is the atomic time scale NBS-A maintained by the NBS Radio Standards Laboratory. This is the NBS standard atomic scale of time—a scale, common to all observers, to which other scales can be related.

Just below this scale in the figure is the scale A. 1, maintained by the U.S. Naval Observatory. These two scales are somewhat independent. Their divergence is caused partially by small experimental errors and partially by a random-walk phenomenon. Thus the rate of change in scale A. 1 with respect to scale NBS-A is now better than 1 part in 10^{11}. The time markers that are generated by these two scales were in coincidence on 1 January 1958, but there is now about a 10 millisecond difference because of the tiny rate difference.

The next point of interest is the scale marked UT-2. (You will recall from the first part of this paper that the time scale defined by the rotation of the earth with respect to the imaginary mean sun is called Universal Time. It has three degrees of refinement which need not concern us here. Nevertheless, after these refinements are made we obtain a scale called UT-2 which is the astronomical time scale most widely used today for navigation and for some scientific applications.)

RELATIONS BETWEEN FIVE TIME SCALES

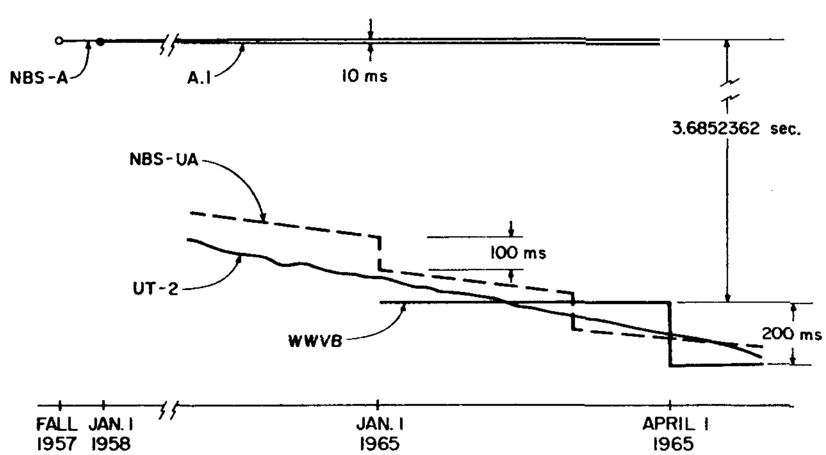


Figure 4. Relations between five time scales. Astronomical time (UT-2) is steadily diverging from the atomic time scales shown at the top. To meet the need of various users NBS broadcasts two types of time scales. One, NBS-UA, is tied to astronomical time both in its cumulative measure of time and in the length of its unit intervals. The other, marked WWVB, is tied to astronomical time in its cumulative measure of time; but the seconds pulses are identical to those of the national and international standard of time (as measured atomically).

Note that the UT-2 scale is diverging markedly from the atomic scales. The major reason for this divergence is that UT-2 and atomic scales are functioning at different rates. To illustrate this, imagine that you had two clocks of perfect uniformity. One of these, however, is running slow and the other is running fast relative to the other. Thus, while each alone could give useful measurements of time and time differences, and indeed the readings of each could be corrected to agree, the two clocks would yet tell different time, that is, display a different epoch.

The reason for the different rates in the UT-2 and atomic scales is that, as mentioned, the size of the atomic second was purposely chosen to be equal to the ephemeris second. This in turn was chosen as approximately equal to the average size of the universal second (1/86,400 of the mean solar day) over the last few hundred years. Thus the values of unit interval for these two time scales (atomic and universal) are different.

The second reason for the divergence is the variation in the earth's speed of rotation. This variation is thought to be caused by such things as tidal friction, atmospheric winds, interplanetary matter, electromagnetic fields interacting with the earth's core, earthquakes, and so forth. Over the last few centuries the total effect of this variation has been a slowing down of the earth's speed of rotation.

Since, as mentioned, UT-2 is widely used, it is desirable to have time signals which are in accord with this time scale. Thus the radio broadcasts of three of the four NBS radio stations, and many other standard frequency broadcasts throughout the world, are intentionally offset in frequency from atomic frequency so that they will approximately track the evolution of UT-2. The NBS atomic scale with this offset is designated NBS-UA. You can see from the figure that despite the offset the tracking is imperfect because of fluctuations in the rotation of the earth. Thus every few months the time signals on the radio broadcasts gain on UT-2 by amounts up to 100 milliseconds. When the two scales differ by this much, a step adjustment in the time signal broadcast is made and recorded. This adjustment again brings the broadcast time signals into approximate coincidence with UT-2.

Despite its virtues, however, the UA time scale does not directly meet the needs of all users. Since the value of the offset changes with variations in the earth's rotation, an engineer in an electronics laboratory, using an NBS broadcast of UA to calibrate a frequency standard, has to take this offset into account to determine the true value with respect to the U.S. standard of frequency, and he has to keep up with any changes (made annually if needed) in this offset to avoid errors in his own standard and thus in his manufactured product.

Further, any group which maintains a large number of oscillators, such as a missile range or a group of satellite-tracking stations, can encounter a fairly large conversion problem whenever the amount of the offset is changed. Depending on the equipment involved, it might take several weeks to adjust the frequency of an oscillator and establish its new rate exactly.

To help these groups, the Radio Standards Laboratory has experimented with the time scale marked WWVB on Fig. 4. This line represents time and frequency signals broadcast by the National Bureau of Standards radio station WWVB in Fort Collins, Colorado. This station provides a broadcast of frequency and of time intervals (seconds) which are directly equivalent to the atomic standard of time. Thus the WWVB scale is shown proceeding parallel to the NBS-A scale.

But, at present, it is also desirable to have the time *scale* from WWVB coincident with UT-2 within about 100 milliseconds. Therefore, whenever WWVB leads UT-2 by more than 100 milliseconds a step adjustment of 200 milliseconds is made as shown on the chart.

Notice that while this 200 millisecond retardation retards the WWVB time scale as a whole—sets the WWVB clock back—it does not change the length of the WWVB second. Thus the WWVB time scale changes to stay within about 100 milliseconds of UT-2, but the WWVB second remains the same length as the NBS-A second and thus retains the constant value of the U.S. standard of time interval. On the other hand, the NBS-UA time scale, described above, is offset from atomic time (NBS-A), and this offset is changed from year to year to help keep NBS-UA in line with UT-2; thus the length of the NBS-UA unit interval is adjusted yearly by an amount estimated to equal the average change of UT-2. (The amount of this offset is set by the International Time Bureau in Paris. For 1965 the offset was 150 parts in 10^{10}; for 1966 this offset is 300 parts in 10^{10}.)

To put it in a nutshell, over the three NBS radio stations which transmit the NBS-UA scale, the broadcasts of frequency, time interval, and time scale are all tied to within 100 milliseconds of UT-2. On WWVB, however, only the time scale is changed to keep it in step with the changes of UT-2; the carrier frequency and units of time interval remain constant with the U.S. frequency standard.

These relationships are confusing but, for those who understand them, they probably are no more complicated than the relationships between the Kelvin, Celsius, and Fahrenheit scales of temperature. Yet, we in the business hope that experience with these various scales will lead to the adoption of some simplicity.

Getting the Standards to the Users

Time signals and standard frequencies are most easily disseminated to the users by radio, and, as mentioned, NBS uses four radio stations to meet the needs of various groups. These stations, under the direction of D. H. Andrews and associates, consist of two short-wave stations, WWV in Maryland and WWVH in Hawaii, and two low frequency stations which are both located at Fort Collins, Colorado, WWVB (60 kHz) and WWVL (20 kHz). (WWV will be relocated at Fort Collins on December 1, 1966.) The main characteristics of these stations are given in Table 1. As this table indicates, a wide range of services is provided by these stations, and the widest range of services is provided by the short-wave stations. The short-wave stations have by far the largest audience including radio and television stations, electric power companies, radio amateurs, many businesses, and the general public. The two low-frequency stations were built in 1963 to offer higher accuracy for research laboratories, instrument manufacturers, and government installations.

Reception of the low-frequency signals at a distance is more accurate because of the difference in the propagation characteristics of low and high frequencies. The high-frequency signals of WWV and WWVH bounce between the earth and the ionosphere and depend upon the mirror-like qualities of the ionosphere in order to be reflected to distant points. This reflective quality of the ionosphere, however, varies with its ever-changing state. These variations cause the time for a high-frequency signal traveling between two points to change continually and sometimes cause the signal to be entirely lost in outer space.

The low-frequency transmissions follow the curvature of the earth since the ionosphere and the ground act as upper and lower boundaries of a gigantic duct to guide the signals over the globe. In such cases the ionosphere serves primarily as a boundary, not a direct reflector, and it has only a small effect on the speed of the waves. The lower frequencies thus travel a more direct route between points on the surface of the earth as illustrated in Fig. 5.

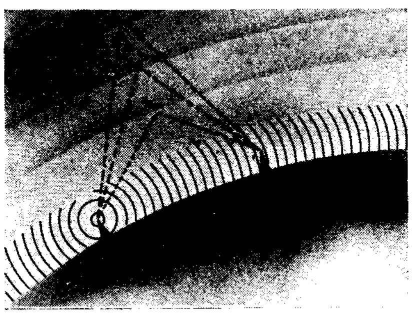


Figure 5. Very low-frequency broadcasts (shown as wave fronts in the figure), with wavelengths of about 10 miles, move across the surface of the earth in a giant duct formed by the ionosphere and the earth's surface. High frequency signals (shown as rays), with wavelengths of about 30 meters, travel around the earth by bouncing between the earth's surface and various layers of the ionosphere. As a result, the low-frequency signals have 1,000 times the stability of signals in the high-frequency band.

The 60-kHz transmission of WWVB is particularly designed to serve users in the continental United States, since signals at this frequency propagate with more stability than those at 20 kHz, for distances up to about 2,000 miles. The WWVL 20-kHz broadcast is still experimental; but it is designed to eventually provide accurate time signals, a means for clock synchronization, and standard frequency transmission with very narrow band signals over most of the world.

Because of their propagation characteristics, the low-frequency stations offer markedly higher accuracies. The instabilities of high-frequency propagation necessitate the averaging of signals from WWV for a period of up to 30 days to achieve a precision of 1 part in 10^{10}—the directly attainable precision is only about 1 part in 10^7—and reliable reception of any one frequency is limited to a distance of a few thousand miles. The 20-kHz broadcast offers a precision of 1 part in 10^{10} or better, on a global basis, with a 1-day observing period. Within the same 1-day observation period the 60-kHz transmission offers a precision of 5 parts in 10^{11} or better within the continental United States. The precision of both the 20- and 60-kHz transmissions can be improved over longer averaging periods.

The approximate continental and global coverage of WWVB and WWVL is shown in Fig. 6.

A relatively new method for disseminating time to remote places is by the actual carrying of a portable clock, atomic or otherwise. Several trips have been made around this country and between this country and Europe and between this country and Japan. Experiments indicate that an intercontinental roundtrip of an atomic clock can be made with a closure error of only a few microseconds. It is therefore technically possible to synchronize clocks on a world-wide basis to within a few microseconds by using portable clocks, and then to keep them in synchronization by phase control using the VLF radio reception.

Also, intercontinental time synchronization to about one microsecond has been accomplished by communications satellite. These capabilities may be the basis of as yet unconceived applications to navigation or other operations.

A detailed description of the broadcast facilities and of the services provided by each of the four stations is given in Miscellaneous Publication 236 of the National Bureau of Standards, which is available from the U.S. Government Printing Office for 15 cents a copy.

TABLE 1

NBS RADIO STATIONS AND THEIR SERVICES

Station	Carrier Frequency	Approximate Stability (parts in 10^{10} per day)	Services
WWV Greenbelt Maryland	2.5, 5, 10, 15, 20, 25 MHz	0.2	Standard radio frequencies Standard audio frequencies of 440 and 600 Hz UT2 time ± 100 milliseconds UT2 time intervals of 1 universal second; 1 and 5 minutes Propagation forecasts for North Atlantic Geophysical alerts Timing Code Corrections to attain UT2
WWVH Maui Hawaii	2.5, 5, 10, 15 MHz	1	Same as WWV except: No propagation forecasts No timing code
WWVB Fort Collins Colorado	60 kHz	0.1	Standard radio frequency UT2 time ± 100 milliseconds NBS-A time intervals Corrections to attain UT2 Timing Code
WWVL Fort Collins Colorado	20 kHz	0.1	Standard radio frequency No time information

Conclusion

In the last decade our basis of timekeeping has moved from the macroscopic to the microscopic. This change has simplified our method of measurement, has improved our accuracy by three orders of magnitude, and has shown promise for even greater improvement.

No one can yet say that an atomic beam is the ultimate method or that cesium is the best atom. The present limits on atomic standards are systematic errors and environment control, and there is room for several orders of magnitude improvement before the basic limitation of random fluctuations will be reached.

To refine the present systems, various laboratories are working to eliminate as many outside influences as possible and to make thorough comparisons of atomic instruments which use different techniques and which measure different atoms. At the NBS Radio Standards Laboratory the staff is investigating thallium beams and hydrogen masers. Other laboratories have similar work on these devices. Such studies will help define the best technique and the best atom and will help determine the relative values of different atomic frequencies.

In the light of such precision, the frequent question from the layman is, "How is all this going to affect my life?" The answer is, "Probably not at all," assuming of course that he means only whether or not it will noticeably change the time he gets out of bed. But these higher accuracies will per- our society to advance its technology so that we can do things we couldn't do before and we will be able to do the same things more economically.

Appendix—

How an Atomic Beam Operates

The accuracy of atomic devices lies in the fact that atoms emit or absorb radiation at a precise frequency providing they are undisturbed. The problem is to measure this frequency as accurately as possible while disrupting the atoms as little as possible.

All atomic frequency standards are based on the frequency f corresponding to a transition between two atomic states separated in energy $E_2 - E_1$ according to the Bohr relation

$$hf = E_2 - E_1,$$

where h is Planck's constant. The cesium beam frequency standard is based on the existence of two energy

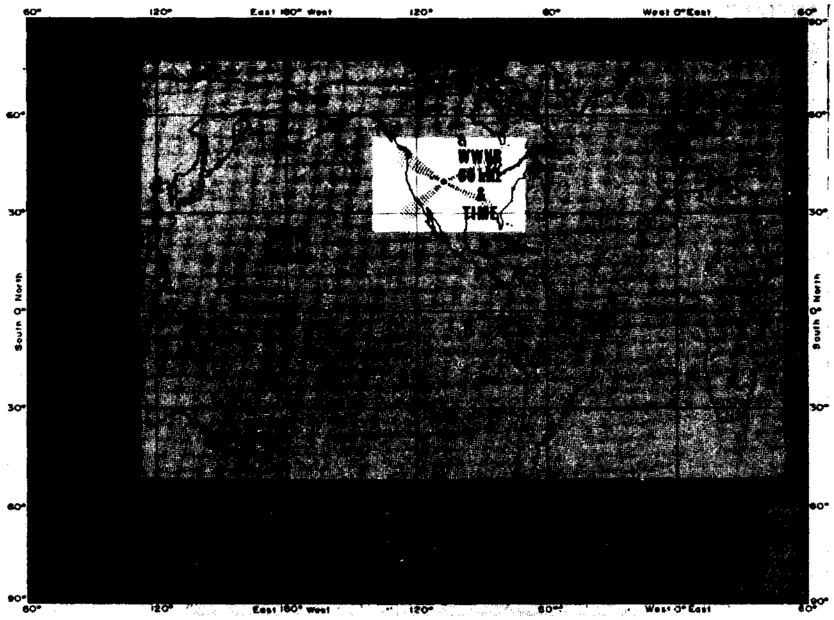


Figure 6. Approximate coverage of WWVL and WWVB.

levels, within the ground state of cesium, which are separated by about 9,192 MHz. These energy levels rise from the interaction of the magnetic moment created by the spin of the electron with the magnetic moment created by the spin of the nucleus.

A very qualitative physical picture of this situation is given in Fig. 7. This figure shows the cesium nucleus with its magnetic moment oriented upward. (For simplicity, the figure is drawn in a frame of reference based on the nucleus so it does not show the precession of the nucleus which actually occurs.) Around the nucleus, the valence electron orbits with its magnetic moment in either of two directions—roughly parallel or antiparallel to the nuclear moment— and it precesses in the magnetic field of the nucleus. In the correspondence principle limit, the frequency of radiation which can be absorbed or emitted is equal to the frequency of precession. From the quantum point of view, however, the energy of interaction of these two magnetic moments for the parallel and antiparallel case is different by $E_2 - E_1$, and the 9,192 MHz is absorbed or emitted when a change of state occurs.

The method of observing these transitions is shown in Fig. 8. Individual cesium atoms, some of which are in the two states of interest, diverge from the oven on the left. Magnet A is designed as a magnetic lens to focus the trajectories of some atoms of both states at the collimator slit, quite analogously to the focusing of light rays by a glass lens. The beam then continues, diverging from this focus.

In the central part of the figure the atoms are shown passing through two regions of a rf-stimulating field, separated to provide certain experimental advantages. If this *stimulating rf field is in resonance* with the transition, change of state of the atoms will occur, and conversely.

Because of the crossover at the collimator, magnet B, identical to magnet A, *will now focus those atoms which have undergone a transition onto the detector and will defocus those which have not.*

(In detail, the magnetic lens action depends upon the fact that a magnetic dipole in a nonuniform magnetic field experiences a deflecting force. The strong field of magnet A induces a dipole moment of about 1 Bohr magneton in the cesium atom, much greater than its field-free magnetic

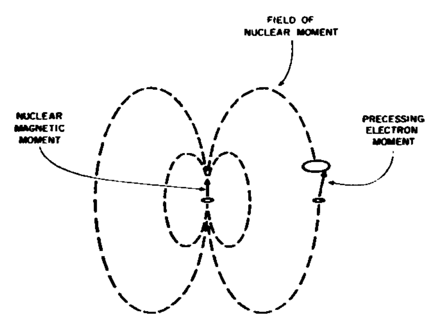


Figure 7. The basis of the cesium transition used for frequency standards is the interaction between the nucleus and the valence electron.

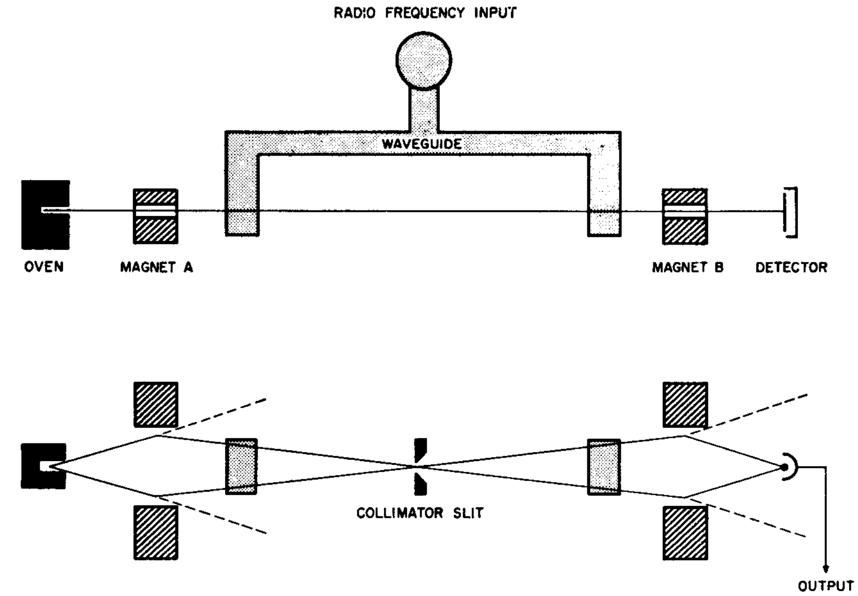


Figure 8. The purpose of the cesium beam apparatus (shown in side and top views) is to furnish a controlling signal that adjusts the frequency of an external crystal oscillator. Atoms in energy states F = 3 and F = 4 leave an oven and are deflected by magnet A. (For the two $m_F = 0$ sub-levels, deflection is equal and opposite.) Then they drift in a low field where they are excited by radiation from an external source. If the exciting radiation is at the 9,192 MHz resonance line, $m_F = 0$ atoms (and these only) undergo state transitions by stimulated emission. Magnet B deflects towards the hot-wire detector *only those atoms that have undergone transitions.*

moment. The direction of the induced magnetic moment will correspond to the direction of the magnetic moment of either of the two field-free energy states previously discussed and, like them will have either of two opposite directions in space. Furthermore, the field of magnet A is nonuniform, as required. The direction of the deflecting force will be opposite for the two directions of magnetic moment and hence for the two energy states. These circumstances are sufficient to permit design of the magnets to control the trajectories of individual atoms as desired, depending on what state they are in and what direction they are going. The reader may apply these concepts to the trajectories in Fig. 8 to get an alternate and detailed explanation of the operation.)

The detector commonly consists of a hot tungsten wire. The tungsten has a greater affinity for electrons than the cesium atom. Hence the cesium atoms striking it are ionized. They are rather quickly "boiled" off the surface of the wire as positive ions and are then collected and measured as a current to an electrode partially surrounding the wire. The resulting detected ion current has its maximum value when the stimulating oscillator has the same frequency as the radiation characteristic of the transitions in the cesium atoms.

Thus for this condition (maximum positive ion current) we know that the frequency of the oscillator is that of the radiating cesium atoms. Circuit arrangements are made to keep the exciting oscillator at the resonance frequency of the cesium atoms.

The NBS Radio Standards Laboratory has now built three cesium beam devices, which have served as the United States Frequency Standard, and which differ primarily in that the newer models have a longer drift space.

The above description of the cesium beam illustrates certain general principles of all existing atomic frequency standards. First, a pure quantum state is selected and prepared. Second, this state is arranged so that it has a long lifetime. (In the cesium beam apparatus the lifetime is approximately equal to the length of the beam divided by the velocity of the atoms.) By the uncertainty principle the uncertainty in energy times the uncertainty in the lifetime is approximately equal to Planck's constant. Equivalently, the uncertainty in the frequency times the uncertainty in the time is about equal to unity, and long lifetimes lead to narrow spectral lines. Third, the prepared state is stimulated to emit or absorb in a way which is free of first-order Doppler effect. (In the cesium beam there is no Doppler shift because the atom interacts with a standing wave instead of a traveling wave.) Fourth, a change of state is detected by some convenient means, such as the impinging of the atoms on the ionization detector.

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