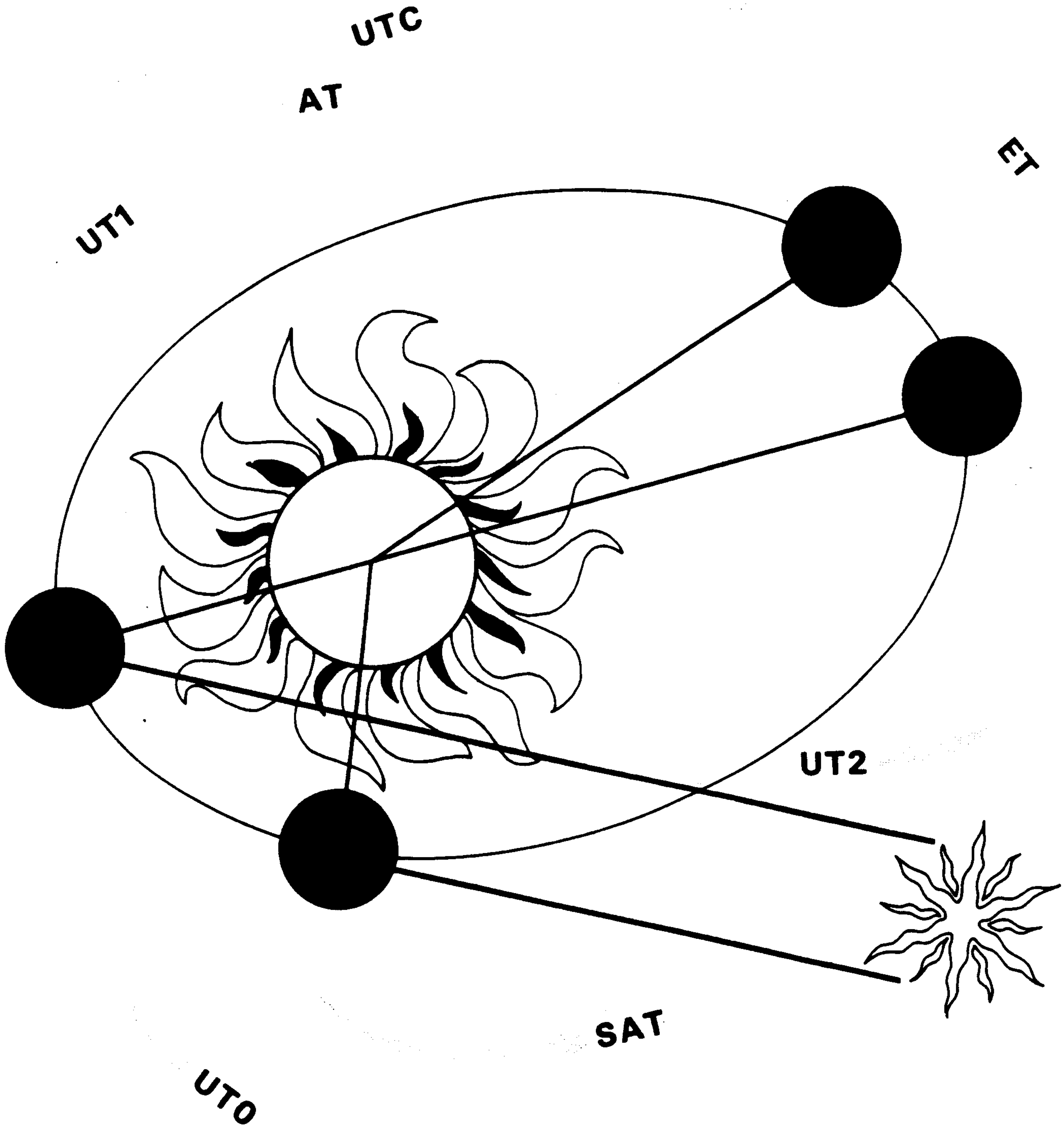
TIME SCALES



REPRINTED FROM On Frequency VOL. II, NO. II, MAY 1971

*A NON-MATHEMATICAL DISCUSSION OF SOME BASIC CONCEPTS OF PRECISE TIME MEASUREMENT

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Introduction.

The measurement of time is a branch of science with a very long history. For this reason it is difficult to understand the current operations of time and frequency measurements without some background. This section presents a brief history of the scientific and engineering aspects of time and frequency measurement.

Clocks.

In early times, the location of the sun in the sky was the only reliable indication of the time of day. Of course, when the sun was not visible, one was unable to know the time with much precision. People developed devices (called clocks) to interpolate between checks with the sun. The sun was sort of a "master clock" that could be read with the aid of a sundial. An ordinary clock, then, was a device used to interpolate between checks with the sun. The different clock devices form an interesting branch of history but will not be reviewed to any extent here.

Thus, a clock could be a "primary clock" like the position of the sun in the sky, or it could be a secondary clock and only interpolate between checks with the primary clock or time standard. Historically, some people have used the word "clock" with the connotation of a secondary time reference, but today this usage would be too restrictive.

Date and time interval and synchronization.

One can use the word "time" in the sense of date. One can also consider the concept of time interval or "length" of time between two events. The difference between these concepts of date and time interval is important and has often confused the single word "time". We will have a great deal more to say on this point.

Recently, people in the U.S. have used the word "epoch" for date. This is an unfortunate choice as can be seen by reference to a good dictionary. "Epoch" often simultaneously embodies concepts of date and duration (i.e., a specific time interval at a specific date). Other countries have not accepted the use of the word "epoch." Because of its potential confusion with, say geological uses of the word, we discourage its use in preference to the word "date." Thus, the date of an event might be: 30 June 1970, 14h, 35m, 37.278954s, UTC, for example, where h, m, s denote hours, minutes, and seconds. (The designation UTC, meaning universal time coordinated, will be discussed below.)

In addition to the concept of date and time interval, there is the important concept of time synchronization. As an example, two people who wish to communicate with each other might not be critically interested in the dates, they just want to be synchronized as to when they use their communications equipment. Many sophisticated electronic navigation systems (and proposed collision avoidance systems) do not depend on accurate dates but they do depend upon very accurate time synchronization. Even ordinary television receivers require accurate time synchronization.

Time scales.

A system of assigning dates to events is called a **time scale**. The apparent motion of the sun in the sky constitutes one of the most familiar time scales but is certainly not the only time scale. Note that to completely specify a date using the motion of the sun as a time scale, one must count days (i.e., make a calendar) from some initially agreed upon beginning. In addition (depending on accuracy needs) one measures the fractions of a day in hours, minutes, seconds, and maybe even fractions of seconds. That is, one counts cycles (and even fractions of cycles) of the sun's daily apparent motion around the earth. Time derived from the apparent position of the sun in the sky is called apparent solar time. A sundial can indicate the fractions of cycles (i.e., time of day) directly. Calendars, like the Gregorian Calendar, aid in counting the days and naming them.

Copernicus gave us the idea that the earth spins on its axis and travels around the sun in a nearly circular orbit. This orbit is not exactly circular, however, and, in fact, the earth travels faster when nearer the sun (perigee) than when further from the sun (apogee). The details of the earth's orbit and Kepler's law of "equal areas" allows one to see that apparent solar time cannot be a uniform time. There is also an effect due to the inclination of the earth's axis to the plane of its orbit (ecliptic plane).

Universal time (UT0)

It is possible to calculate these orbital and inclination effects and correct apparent solar time to obtain a more uniform time—commonly called Universal Time, UT0. This correction from apparent solar time to Universal Time is called the Equation of Time and can be found engraved on many present-day sundials.

If one considers a distant star instead of our star—the sun—to measure the length of the day then the earth's elliptic orbit becomes unimportant and can be neglected. This kind of time is the astronomers' sidereal time and is generically equivalent to Universal Time since both are based, ultimately, on the spin of the earth on its axis, the second of sidereal time being just enough different to give a sidereal year one more "day" than that of a solar year. In actual practice, astronomers observed sidereal time and correct it to get Universal Time. Historically, Universal

Time was equivalent to mean solar time* as determined at the Greenwich Observatory.

Time, of course, is essential to navigation. In effect, a navigator, using a sextant, measures the angle between some distant star and the navigator's zenith (see Fig. 1). It is apparent that for a given star there is a locus of points with the same angle. By sighting on another star, a different locus is possible and obviously the position of the navigator is at one of the intersections of the two loci. (A third sighting can remove the ambiguity.) The position of this intersection on the earth obviously depends on the earth's rotational position. I feel it is important to emphasize that celestial navigation is basically connected to earth position and only to time because the earth defines a useful time scale.

UT1

In order for the navigator to use the stars for navigation, he must have a means of knowing the earth's position (i.e., the date on the UT scale). Thus, clocks and sextants became the means by which navigators could determine their locations. With navigation providing a big market for time and for good clocks, better clocks were developed and these began to reveal a discrepancy in Universal Time measured at different locations. The cause of this was traced to the fact that the earth wobbles on its axis (see Fig. 2). In effect, one sees the location of the pole wandering over a range of about 15 meters.

By comparing astronomical measurements made at various observatories spread over the world, one can correct for this effect and obtain a more uniform time—denoted UT1.

UT2

With the improvement of clocks—both pendulum and quartz crystal—it was discovered several years ago that UT1 had periodic fluctuations (of unknown origin) with periods of one-half year and one year. The natural response was to remove these fluctuations and obtain an even more uniform time—UT2. Thus, there exists a whole family of Universal Times based on the spin of the earth on its axis and various other refinements (see Fig. 3).

In this historical progression, one notes that UT1 is the true navigator's scale related to the earth's angular position. UT2 is a smoothed time and does not reflect the real, periodic variations in the earth's angular position--in effect it is a true mean solar time. At least in principal, if not in practice, going to UT2 passed by the navigator's needs.

Ephemeris time (ET)

At this point it is desirable to go back in time--near the turn of the century--and trace some other astronomical studies. In the latter 19th century, Simon Newcombe compiled a set of tables, based on Newtonian mechanics, which predicted the positions of the sun, the moon, and some planets for the future. A table of this sort is called an ephemeris.

It was discovered that the predicted positions gradually departed from the observed positions in a fashion too significant to be explained either by observational errors or approximations in the theory. It was noted, however, that if the time were somehow in error, all the tables agreed well. At this point it was correctly determined that the rotational rate of the earth was not constant. This was later confirmed with quartz clocks and atomic clocks.

The astronomers natural response to this was, in effect, to use Newcombe's tables for the sun in reverse to determine time--actually what is called Ephemeris Time. Ephemeris Time is determined by the orbital motion of the earth about the sun (not by rotation of the earth about its own axis) and should not be affected by such things as core-mantle slippage or other geometrical changes in the shape of the earth.

Atomic time (AT)

As it was pointed out above, the date of an event relative to the Universal Time Scale is obtained from the number of cycles (and fractions of cycles) of the apparent sun counted from some agreed upon origin. (Depending on the need, one may have to apply corrections to obtain UT0, UT1, or UT2.) Similarly, atomic time scales are obtained by

*In very precise usage, all "mean" time scales are supposed to count from noon rather than from midnight. Common usage often doesn't make this distinction, however. Universal Time does count from midnight, Greenwich.

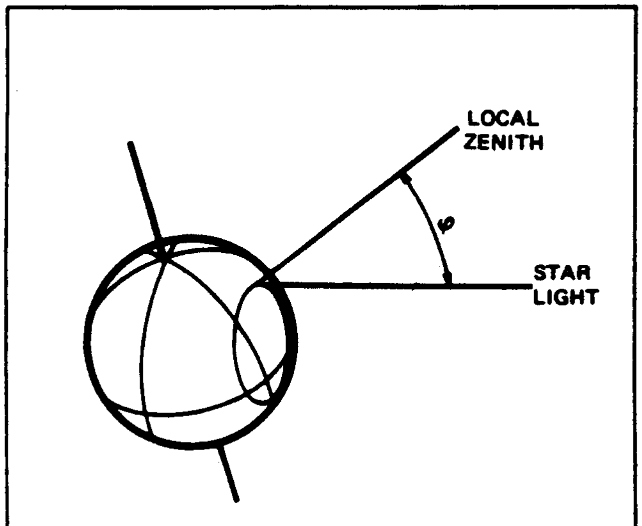

FIG. 1 CELESTIAL NAVIGATION

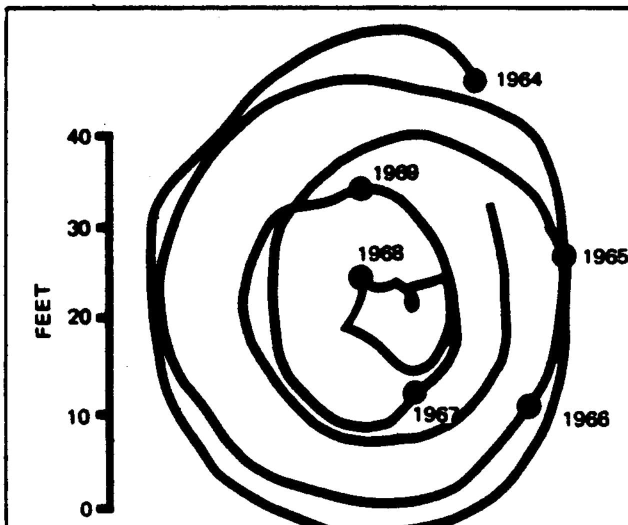

FIG. 2 PATH OF THE POLE

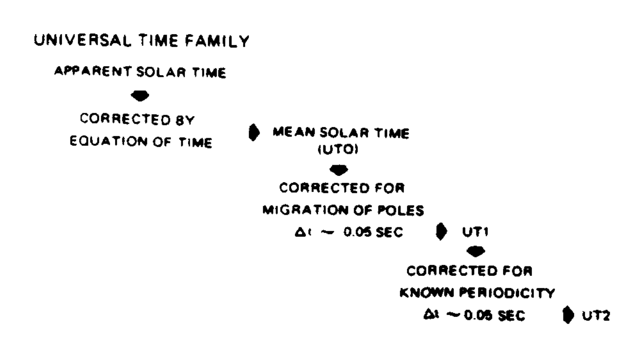

FIG. 3

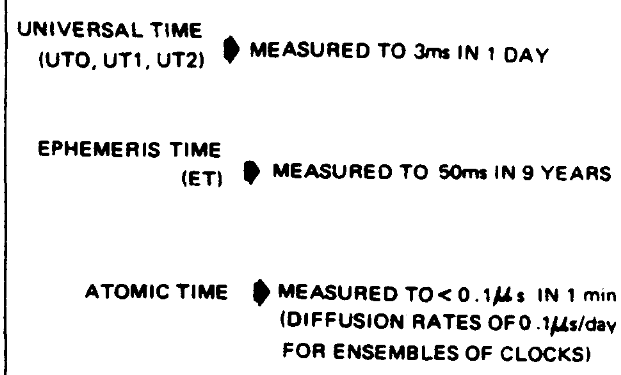

FIG. 4

counting the cycles of a signal in resonance with a certain kinds of atoms. The primary conceptual difference between these two methods is that the cycles of atomic clocks are much, much shorter than the daily cycles of the apparent sun. Thus, the atomic clock requires more sophisticated devices to count cycles than is required to count solar days. This difference is one of technological convenience and is not terribly profound.

In the latter part of the 1940's, Harold Lyons at the NBS announced the first Atomic clock. In the mid-1950's several laboratories began atomic time scales.

As of the writing of this manuscript (1971) the status of international atomic time is not completely clear. The Bureau International de l'Heure (BIH) has been maintaining atomic time for some years and this time scale has received the recognition of the International Astronomical Union (IAU). Beginning January 1, 1972 this atomic time scale will be broadcast (with some modifications) by countries adhering to the Convention of the Meter*.

In review, we have discussed three broad classes of time scales (see Fig. 4).

The Universal Time family is dependent on the earth's spin on its axis; Ephemeris Time depends on the orbital motion of the earth about the sun; and Atomic Time, which depends on a fundamental property of atoms, is very uniform, precise, and not yet officially defined as a time scale. Because of the "slow" orbital motion of the earth (one cycle per year), measurement uncertainties limit the realization of accurate ephemeris time to about 0.05 seconds for a nine-year average, while UT can be determined to a few thousandths of a second in a day, and AT to a few billionths of a second in a minute or less.

Coordinated Universal Time (UTC) prior to 1972

From 1958 through 1971 most broadcast time (e.g., WWV) has been based on a time scale called Coordinated Universal Time (UTC). The rate of a UTC clock is controlled by atomic clocks to be as uniform as possible for one year, but this rate can be changed at the first of a calendar year. The yearly rate was chosen by the BIH. Table I lists the fractional offsets of the UTC scale relative to a pure atomic time scale.

*In 1875 many countries (including the U.S.) signed the Convention of the Meter which established the International Bureau of Weights and Measures (BIPM) in Paris. The definitions of the International System (S.I.) of units are given by a General Conference of Weights and Measures (CGPM) composed of representatives from the countries which have signed the Convention of the Meter.

TABLE I

Year	Offset rate of UTC in parts per 10^{10}
1960	- 150
1961	- 150
1962	- 130
1963	- 130
1964	- 150
1965	- 150
1966	- 300
1967	- 300
1968	- 300
1969	- 300
1970	- 300
1971	- 300
1972 (and for the future)	0

The minus sign implies that the UTC clock runs slow (in rate) relative to atomic time.

The offset in clock rate is chosen to keep the UTC clock in reasonable agreement with UT2. However, one can not exactly predict the earth's rotational rate and discrepancies do accrue. By international agreement, UTC is supposed to agree with UT2 to within 1/10 second (1/20 second before 1963). On occasion it has been necessary to reset the UTC clock by 1/10 second (1/20 second before 1963) in order to stay within the specified tolerances (see Fig. 5). (Probably after 1 January 1972, UTC will have zero offset in rate and the steps will be one whole second.)

Also, by international agreement, the offsets in clock rate have been constrained to be an integral multiple of 5 parts per billion (one part per billion before 1964).

Also, a few stations (e.g., WWVB) have broadcast a Stepped Atomic Time (SAT) signal which is derived directly from an atomic clock (no rate offset) but which is reset periodically to maintain SAT within about 1/10 second of UT2.

The new UTC system

The facts that the clock rate of UTC have been offset (see Table I) from the correct (atomic) rate and that this

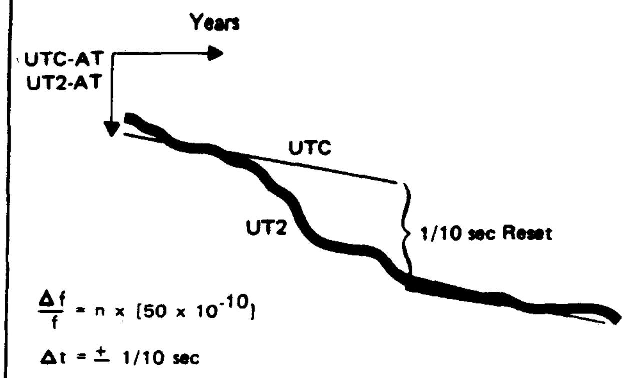

FIG. 5 COORDINATED UNIVERSAL TIME (UTC) (1958 to 1971)

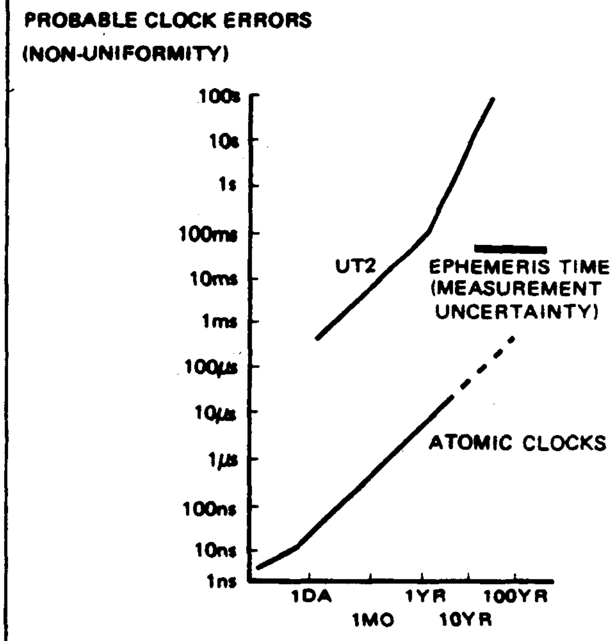

FIG. 6

offset changed from time to time necessitated actual changes in equipment and often even the interruption of sophisticated systems. As the needs for reliable synchronization have increased, the old UTC system became too cumbersome. A new compromise system was needed to account better for the ever-growing needs of precise time synchronizations.

The new UTC system was adopted by the International Radio Consultative Committee (CCIR) in Geneva in February 1971 to become effective 1 January 1972. In this new system all clocks will run at the correct rate (zero offset). This leaves us in a position of having the clock rate not exactly commensurate with the length of the day. This situation is not unique.

The length of the year is not an exact integral multiple of the day. This is the origin of "leap year." In this case, years which are divisible by 4 have an extra day—February 29—unless they are divisible by 100, and then only if they are not divisible by 400. Thus, the years 1968, 1972, 1976, and 2000 are leap years. The year 2100 will not be a leap year. By this means our calendar does not get out of step with the seasons.

With this as an example, it is possible to keep the clocks in approximate step with the sun by the infrequent addition (or deletion) of a second—called a "leap second." Thus, there may be special situations where a "minute" contains 61 (or 59) seconds instead of the conventional 60 seconds. This should not occur more often than about once a year. By international agreement, UTC will be maintained within 0.7 seconds of the navigators' time scale, UT1. The introduction of leap seconds allows a good clock to keep approximate step with the sun. Because of the variations in the rate of rotation of the earth, the occurrences of the leap seconds are not predictable in detail.

Comparisons of time scale uniformity

One can imagine synchronizing a clock with a hypothetically ideal time scale. Some time after this synchronization our confidence in the clock reading has deteriorated. Fig. 6 shows the results of some statistical studies which indicate the probable errors of some important "clocks" after synchronization. There are really two things of significance to note in Fig. 6: First, Atomic Time (state-of-the-art, 1964) is about 4 orders of magnitude more uniform than Universal Time, and second, measurement uncertainty totally limits any knowledge of statistical fluctuations in Ephemeris Time.

Astronomical Time and International Atomic Time (IAT)

The astronomical time scales have an advantage that a single "clock" is available to everyone (since there has been only one solar system available to us for study). The atomic clock in a laboratory might or might not be available to others and, since more than one can easily exist, there is the possibility of disagreement which is not possible when one has only one clock. It might seem the continued motion of the solar system is much more reliable than the continued operation of atomic clocks. Thus, atomic clocks must be made highly reliable to compete at all with astronomical time scales.

For an international atomic time scale to be of value, it must possess the following attributes:

1. It must provide greater accuracy and convenience than the astronomical counterparts.
2. It must be highly reliable with almost no chance of a failure of the clock system. (This can be accomplished by using many clocks dispersed over the world but which can be intercompared accurately.)
3. The atomic time scale must be readily available everywhere.

Indeed, all of these points appear to be more than adequately covered by the atomic time scale of the BIH. It is currently anticipated that the General Conference of Weights and Measures (CGPM) will endorse the BIH atomic time scale as the International Atomic Time scale. Yet, even with the existence of an international atomic time scale, one must recognize that there will be continued need for the astronomical time scales. A person doing celestial navigation, for example, must know earth position (UT1).

Time interval and frequency

Outside the field of cosmology, physics has been primarily interested in time interval. Typically, physical laws are expressed in equations involving small intervals of time (differential equations) and it is not important to know the date when one applies these laws. The base unit of time (interval), the second, is one of the four most basic units of physics (length, mass, time, and temperature).

In terms of the history of time scales, the history of the definition of the second can be expressed very briefly. Prior to 1956, the second was defined as the fraction 1/(86,400) of a mean solar day. From 1956 to 1967 it was the ephemeris second defined as the fraction 1/(31,556,925.9747) of the tropical year at 00 h 00 m 00 s December 31, 1899, and since 1967, in terms of a resonance of the cesium atom.

We should note sources of confusion which exist today in the measurement of time and in the use of the word "second." Suppose that two events occur at two different dates. For example the dates of these two events are December 15, 1970, 15 h 30 m 00.000000 s UTC and December 15, 1970, 16 h 30 m 00.000000 s UTC. At first thought one would say that the time interval between these two events was exactly 1 hour = 3600.000000 seconds, but this is not true. (The actual interval was longer by about 0.000108 seconds [3600 seconds X 300 X 10^{-10}]. See Table I.) Recall that the UTC time scale (like all the UT scales and the ET scale) was not defined in accordance with the definition of the interval of time, the second. Thus, one cannot simply subtract the dates of two events as assigned by the UTC scale (or any UT scale or the ET scale) in order to obtain the time interval between these events. Historically, the reason behind this state of affairs is that navigators need to know the earth's position (i.e., UT1)—not the duration of the second. Yet, many scientists need to know an exact and reproducible time interval. Note that this might also be true of the new UTC system if the particular time interval included one or more leap seconds.

It is also confusing that the dates assigned by the UT, ET, and UTC scales involve the same word as the unit of time interval, the second. For accurate and precise measurements, this distinction can be extremely important.

Another important concept is the concept of frequency. The frequency of a periodic phenomenon is the number of cycles of this phenomenon per unit of time (i.e., per second). The name of the unit of frequency is the hertz (abbreviated Hz) and is identical to a cycle per second. Note that the measurement of frequency can involve the measurement of a time interval. For this reason, frequency and time interval are often closely linked.

Bibliography

J. A. Barnes, "The Development of an International Atomic Time Scale," Proc. IEEE, vol. 55, no. 6, pp. 822-826, June 1967.

B. Decaux and B. Guinot, **La Mesure Du Temps,** *(Presses Universitaires de France, 108, Boulevard Saint-Germain, Paris, 1969).*

J. Kovalevsky, "Astronomical Time," Metrologia, vol. 1, October 1965.

R. E. Beehler, R. C. Mockler, and J. M. Richardson, "Cesium Beam Atomic Time and Frequency Standards," Metrologia, vol. I, no. 3, pp. 114-131, July 1965.

J. M. Richardson and J. F. Brockman, "Atomic Standards of Frequency and Time," The Physics Teacher, vol. 4, no. 6, pp. 247-256. September 1966.

Explanatory Supplement to the Astronomical and The American Ephemeris and Nautical Almanac, *prepared jointly by the Nautical Almanac Office of the United Kingdom and the United States of America, (Her Majesty's Stationery Office, London, 1961).*

E. W. Woolard and G. M. Clemence, **Spherical Astronomy,** *(Academic Press, New York & London, 1966).*

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