# CHAPTER 1

## BASIC CONCEPTS OF PRECISE TIME AND FREQUENCY*

**James A. Barnes†**

## Contents



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† Time and Frequency Division, Institute for Basic Standards, National Bureau of Standards, Boulder, Colorado 80302.

"What is time? The shadow on the dial, the striking of the clock, the running of the sand, day and night, summer and winter, months, years, centuries—these are but arbitrary and outward signs, the measure of time, not time itself . . ."

Longfellow,
*Hyperion*, Bk. ii, Ch. 6.

This chapter describes some elements of timekeeping and gives basic concepts of time and frequency such as date, time interval, simultaneity and synchronization. This chapter details characteristics of numerous time scales including astronomical, atomic, and compromises of both. The universal time scales are based on the apparent motion of the sun in the sky, while atomic time scales are based on the periodic fluctuations of a radio signal in resonance with a certain species of atoms. The chapter includes a description of the UTC time scale both before and after January 1, 1972, and delineates requirements of an International Atomic Time scale.

Key words: Atomic time; clocks; ephemeris time; frequency; navigation/time; TAI scale; time; time interval; time scales; universal time; UTC system.

## 1.1. INTRODUCTION

The measurement of time is a branch of science with a very long history [1, 2, 3].[1] For this reason, it is difficult to understand the current operations of time and frequency measurements without some background. This chapter presents a brief history of the scientific and engineering aspects of time and frequency. The discussion commences with a basic consideration of clocks and concepts involved in time measurements. Time scales are described and delineated as either astronomical, atomic, or compromises thereof. Universal time scales are based on the apparent motion of the sun in the sky, while atomic time scales are related to periodic fluctuations of a radio signal in resonance with a certain species of atoms. This chapter includes a description of the UTC system which commenced January 1, 1972. Characteristics and requirements of an International Atomic Time (TAI)[2] scale indicate that the atomic time scale of the Bureau International de l'Heure (BIH) is a logical choice. However, the TAI scale will not replace some of the needs for astronomical time scales which are necessary for earth position. The reader is referred to Chapter 9 for details of constructing and maintaining an atomic time scale.

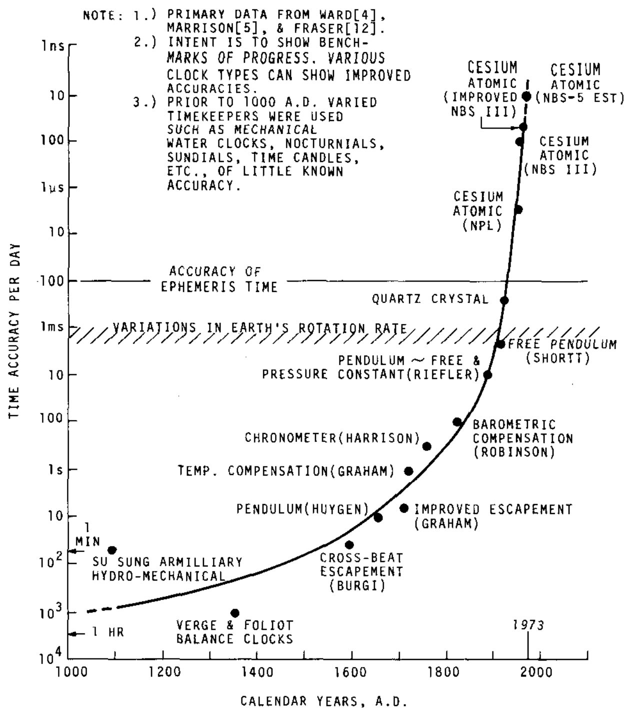


Fig. 1.1. Progress in timekeeping accuracy.

## 1.2. CLOCKS AND TIMEKEEPING

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; we will not review them to any extent here except to point out their gain in accuracy over a period of years as shown in figure 1.1 and to refer the reader to the works of Ward, Marrison, and Hood [4, 5, 6]. (Timekeeping has shown nearly 10 orders of magnitude improvement within the last 6 centuries with about 6 orders occurring within 70 years of the 20th century.) 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.

[1] Figures in brackets indicate the literature references at the end of this chapter.

[2] The 6th Session of the Consultative Committee for the Defintion of the Second recommends that International Atomic Time be designed by *TAI* in all languages (July 1972).

When one thinks of a clock, it is customary to think of some kind of pendulum or balance wheel and a group of gears and a clock face. Each time the pendulum completes a swing, the hands of the clock are moved a precise amount. In effect, the gears and hands of the clock "count" the number of swings of the pendulum. The face of the clock, of course, is not marked off in the number of swings of the pendulum but rather in hours, minutes, and seconds.

One annoying characteristic of pendulum-type clocks is that no two clocks ever keep exactly the same time. This is one reason for looking for a more stable "pendulum" for clocks. In the past, the most stable "pendulums" were found in astronomy. Here one obtains a significant advantage because only one universe exists—at least for observational purposes, and time defined by this means is available to anyone—at least in principle. Thus, one can obtain a very reliable time scale which has the property of universal accessibility. In this chapter, time scale is used to refer to a conceptually distinct method of assigning dates to events.

In a very real sense, the pendulum of ordinary, present-day electric clocks is the electric current supplied by the power company. In the United States the power utilities generally synchronize their generators to the National Bureau of Standards (NBS) low frequency broadcast, WWVB [7]. Thus, the right number of pendulum swings occur each day. Since all electric clocks which are powered by the same source have, in effect, the same pendulum, these clocks do not gain or lose time relative to each other; i.e., they run at the same rate. Indeed, they will remain fairly close to the time as broadcast by WWVB (±5 seconds) and will maintain the same time difference with respect to each other (±1 millisecond) over long periods of time.

It has been known for some time that atoms have characteristic resonances or, in a loose sense, "characteristic vibrations." The possibility therefore exists of using the "vibrations of atoms" as pendulums for clocks. The study of these "vibrations" has normally been confined to the fields of microwave and optical spectroscopy. Presently, microwave resonances (vibrations) of atoms are the most precisely determined and reproducible physical phenomena that man has encountered. There is ample evidence to show that a clock which uses "vibrating atoms" as a pendulum will generate a time scale more uniform than even its astronomical counterparts [8, 9, 10].

But due to intrinsic errors in any actual clock system, one may find himself back in the position of having clocks which drift relative to other similar clocks. Of course, the rate of drift is much smaller for atomic clocks than the old pendulum clocks, but nonetheless real and important. If at all possible, one would like to gain the attribute of universal accessibility for atomic time also. This can be accomplished only by coordination between laboratories generating atomic time. Both national and international coordination are in order.

## 1.3. BASIC CONCEPTS OF TIME

One can use the word "time" in the sense of date. (By "date" we mean a designated mark or point on a time scale.) 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 been confused in the single word "time". This section explores some basic ideas inherent in the various connotations of time.

The *date* of an event on an earth-based time scale is obtained from the number of cycles (and fractions of cycles) of the apparent sun counted from some agreed-upon origin. Similarly, atomic time scales are obtained by counting the cycles of a signal in resonance with certain kinds of atoms. (Several atomic time scales [9] have chosen the "zero point" at zero hours January 1, 1958 (UT–2), but this is not universal among all atomic time scales in existence today.) One of the major differences 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 are required to count solar days. The importance of this difference is a matter of technological convenience and is not very profound. Of technological significance are the facts that atomic clocks can be read with much greater ease and with many thousands of times the precision of the earth clock. In addition the reading of an atomic clock can be predicted with almost 100,000 times better accuracy than the earth clock.

In the U.S. literature on navigation, satellite tracking, and geodesy, the word "epoch" is sometimes used in a similar manner to the word "date." However, dictionary definitions of epoch show gradations of meanings such as time duration, time instant, a particular time reference point, as well as a geological period of time. Thus, epoch often simultaneously embodies concepts of both date and duration. Because of such considerable ambiguity in the word "epoch,"[3] its use is discouraged in preference to the word "date," the precise meaning of which is neither ambiguous nor in conflict with other, more popular usage. Thus, the date of an event might be: 30 June 1970, 14 h, 35 m, 37.278954 s, UTC, for example, where h, m, s denote hours, minutes, and seconds. (The designation UTC, meaning Universal Time Coordinated, will be discussed later.) On the other hand, "date" should not be interchanged indiscriminately with "epoch" or "time."

Another aspect of time is that of *simultaneity;* i.e., coincidence in time of two events. For example, we might synchronize clocks upon the arrival of portable clocks at a laboratory. Here we introduce an additional term, *synchronization,* which implies that the two clocks are made to have the same reading in some frame of reference. Note that the clocks need not be synchronized to an absolute time scale. As an example, two people who wish to communicate with each other might not be critically interested in the date, 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. We thus see some of the complexities involved in concepts of time and how varied combinations of time aspects are embodied in and influence various time-related activities.

## 1.4. TIME SCALES

A system of assigning dates to events is called a *time scale.* The apparent motion of the sun in the

[3] This suggestion awaits definitive recommendations or statement of terms by parties such as the CCIR Study Group 7, Interim Working Party 7/2 on "Forms of Expression for Use of the Standard-Frequency and Time Signal Service"; International Council of Scientific Unions; and the IEEE Standards Committees, among others.

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 (i.e., "time of 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.

There are both astronomical time scales [11] and atomic time scales [9] which can provide a basis for precise synchronization. A sensible use of the unqualified word "time" is the use which embodies all of these various aspects of time scales, time measurement, and even time interval (or duration). This is totally consistent with the dictionary definition of the word. Thus, the study of synchronization would be properly said to belong to the broader study of time in general. Thus, it is not only misleading but wrong to say that "time" is only determined by astronomical means. Indeed, there are many classes of time—astronomical time, biological time, and atomic time, to name a few [12].

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 [13]. 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 (perihelion) than when further from the sun (aphelion). 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 [14]. There is also an effect due to the inclination of the earth's axis to the plane of its orbit (ecliptic plane). A pictorial diagram of the sun-earth-moon relationships is shown in figure 1.2.

### 1.4.1. 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 mean solar time. This correction from apparent solar time

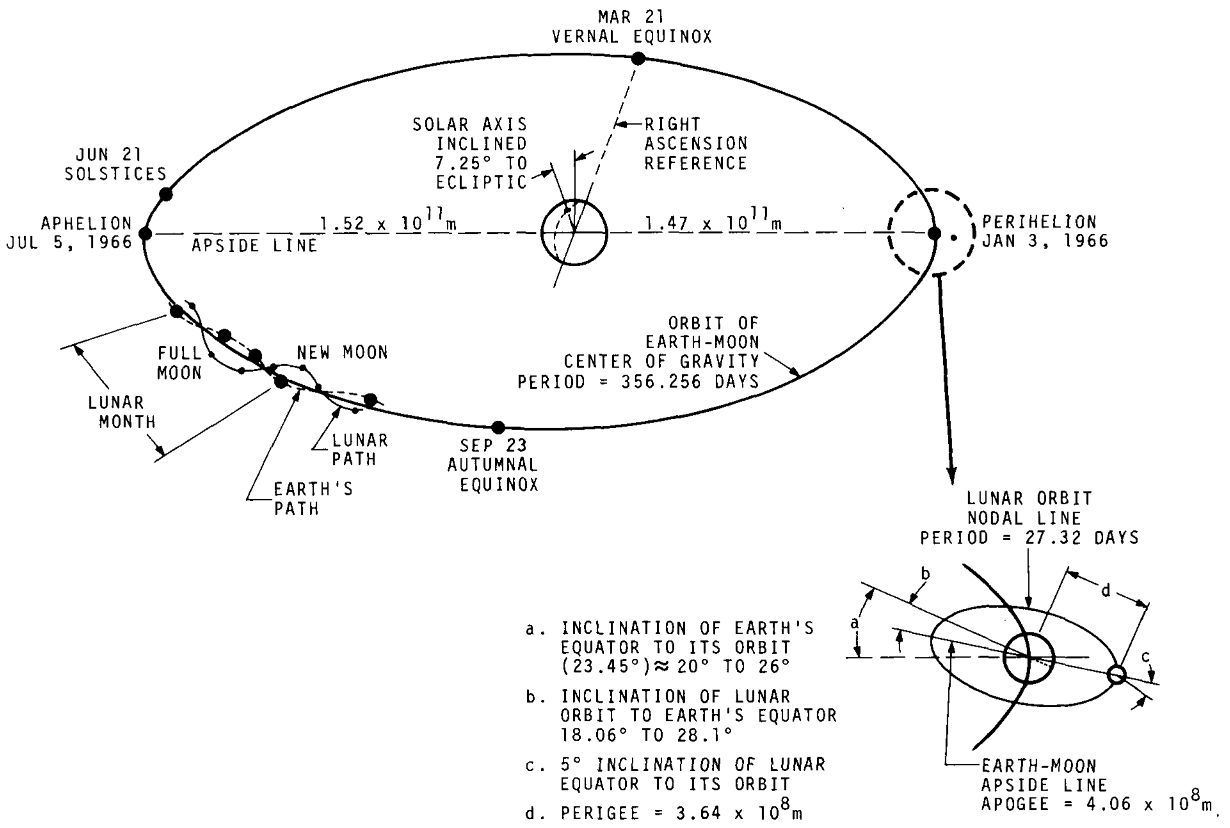


Fig. 1.2. Sun, earth, moon ralationships. (Courtesy of A. D. Watt)

to mean solar time is called the Equation of Time and can be found engraved on many present-day sundials [13].

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 astronomer's sidereal time and is generically equivalent to mean solar 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 usually observe sidereal time and correct it to get mean solar time. Universal Time (UT0) is equivalent to mean solar time as determined at the Greenwich Meridian, sometimes called Greenwich Mean Time (GMT).

Time, of course, is essential to navigation in determining longitude [15]. In effect, a navigator using a sextant measures the angle between some distant star and the navigator's zenith as shown in figure 1.3. 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. It is important to emphasize that celestial navigation is basically connected to earth position and only to time because the earth also defines a useful time scale.

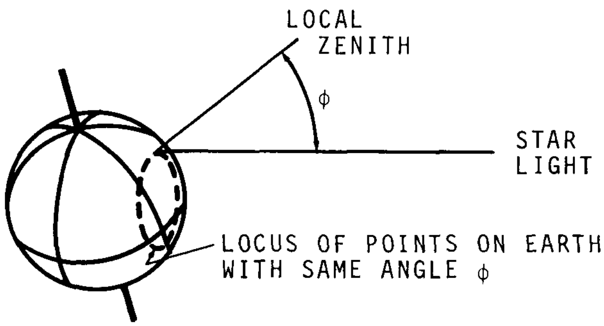


Fig. 1.3. Principle of celestial navigation.

### 1.4.2. Universal Time 1 (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 together 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; the location of the pole as it intersects the earth's surface is plotted for 1964–69 in figure 1.4. 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 [16].

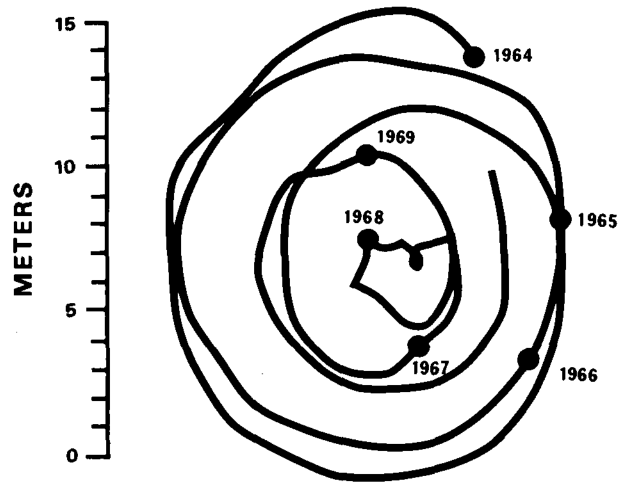


Fig. 1.4. Path of earth's pole 1964–1969.

### 1.4.3. Universal Time 2 (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 as diagrammed in figure 1.5. 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.

### 1.4.4. 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,

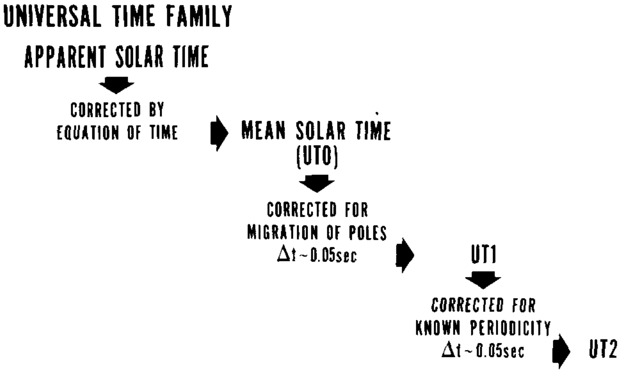


Fig. 1.5. Universal time family interrelationships.

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 [17, 18, 19]. 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 coremantle slippage or other geometrical changes in the shape of the earth.

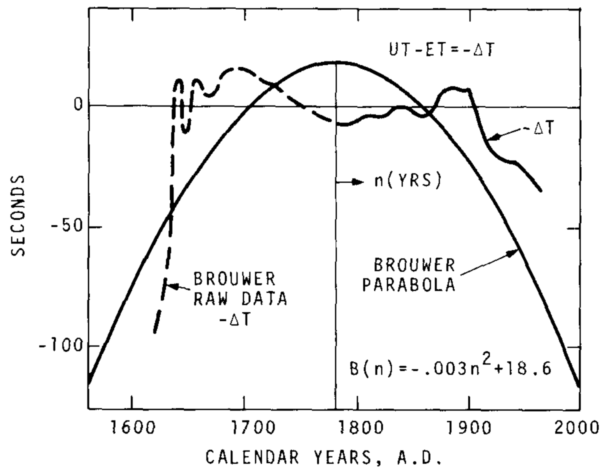


Fig. 1.6. Trend of UT–ET for over three centuries (data from Brouwer [20]).

The variations in UT scales or earth rotation rates have been studied extensively by Brouwer and many others [20, 21, 22]. In this chapter, we need only point out the general nature and size of the variations which have been observed. Brouwer's study covered a long period of time; the curves shown in figure 1.6 summarize much of his data and analysis. They reflect the random behavior [23] of UT, marked on occasion by sudden erratic changes such as seen in 1963 [24]. The abscissas in figure 1.6 are proportional to the astronomical time scale, ET. At present ET can be considered uniform with respect to AT [25] and is a good comparison scale to be used in detecting long-term (gross) properties of a time scale. It is of value to recognize that Brouwer determined that the random processes which affect the rotation of the earth on its axis caused the rms fluctuations in Universal Time to increase as $t^{3/2}$, for $t$ greater than one year. For periods of the order of a year or less it appears that the variations in the UT2 time scale cause the rms fluctuations to increase as the first power of $t$ (flicker noise frequency modulation) [26]. The coefficient of this linear term is about $2\times10^{-9}$ or almost a factor of $10^5$ worse than some cesium clocks. The present means of determination of ET are not adequately precise to allow definitive statements about possible systematic variations of ET [11].

### 1.4.5. Atomic Time (AT)

As was pointed out previously, 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 counting the cycles of a signal in resonance with certain kinds of atoms.

In the latter part of the 1940's, Harold Lyons at the National Bureau of Standards announced the first Atomic Clock [27]. During the 1950's several laboratories began atomic time scales [28, 29, 30]. The Bureau International de l'Heure (BIH) has been maintaining atomic time for some years now, and this time scale received the official recognition as International Atomic Time (TAI) of the General Conference of Weights and Measures (CGPM) in October 1971 [31] (see ann. 1.A). Beginning 1 January 1972, this atomic time scale has been broadcast (with some modifications) by most countries (see "The new UTC system" in sec. 1.4.7).

In review, we have discussed three broad classes of time scales as illustrated in figure 1.7. 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 and precise. Because of the "slow"

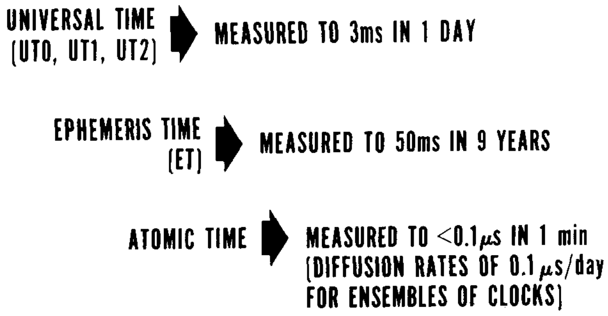


Fig. 1.7. Classes of time scales with typical accuracies.

orbital motion of the earth (1 cycle per year), measurement uncertainties limit the realization of accurate ephemeris time to about 0.05 second for a 9-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.

### 1.4.6. Coordinated Universal Time (UTC) Prior to 1972

From 1960 through 1971 many broadcast time signals (e.g., MSF, WWV, CHU) were based on a time scale called Coordinated Universal Time (UTC) [32]. The rate of a UTC clock was controlled by atomic clocks to be as uniform as possible for 1 year, but this rate could be changed at the first of a calendar year. The yearly rate was chosen by the BIH. Table 1.1 lists the fractional offsets in rate of the UTC scale relative to a pure atomic time scale.

TABLE 1.1. *Frequency Offsets of UTC from 1960 to 1972*

| 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→future | 0 |

The minus sign implies that the UTC clock ran slow (in rate) relative to atomic time. The offset in clock rate was chosen to keep the UTC clock in reasonable agreement with UT2. However, one could not exactly predict the earth's rotational rate and discrepancies would accrue. By international agreement [33], UTC was supposed to agree with UT2 to within 1/10 second (1/20 second before 1963). On occasion it was necessary to reset the UTC clock by 1/10 second (1/20 second before 1963) in order to stay within the specified tolerances as shown in figure 1.8. Also, by international agreement [33], the offsets in clock rate were constrained to be an integral multiple of 5 parts per billion (1 part per billion before 1963). In addition, a few stations (e.g., WWVB) broadcast a Stepped Atomic Time (SAT) signal which was derived directly from an atomic clock (no rate offset) but which was reset periodically (more often than UTC) to maintain SAT within about 1/10 second of UT2 [34].

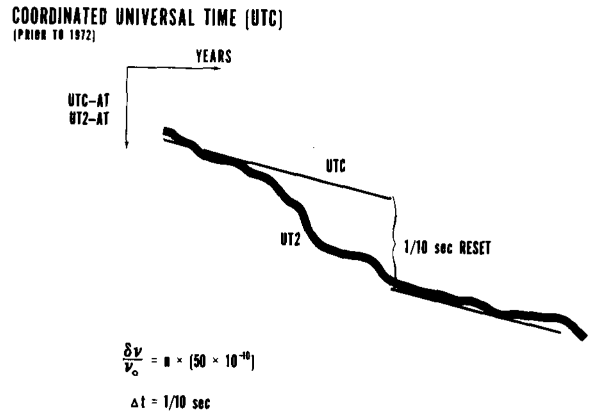


Fig. 1.8. Relationship between UTC and UT2 time scales—prior to 1972.

### 1.4.7. The New UTC System

The facts that the clock rate of UTC have been offset (see table 1.1) from the correct (atomic) rate and that this offset changed from time to time necessitated actual changes in equipment and often interrupted 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 synchronization.

A new UTC system was adopted by the International Radio Consultative Committee (CCIR) in Geneva in February 1971 [35, 36] and became effective 1 January 1972 (see ann. 1.B). In this new system all clocks 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 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 also 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 about 0.7 second 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, however, the occurrences of the leap seconds are not predictable in detail.

### 1.4.8. Comparisons of Time Scales

It is of value in comparing time scales to consider four significant attributes of some time scales:

a. accuracy and precision,
b. reliability,
c. universal accessibility,
d. extension.

In the areas of accuracy and precision, atomic time scales have a clear advantage over their astronomical counterpart. Atomic clocks may be able to make a reasonable approach to the reliability and accessibility of astronomical clocks, however, astronomical time scales are based on a "single" clock which is available to everyone (i.e., only one solar system is available for study). Also, many atomic clocks can show disagreements, an impossibility with only one clock. The extension of dates to past events (indeed, remote, past events) is a feature which atomic clocks will never possess. Their utility for future needs, however, is quite another matter. The needs of the general scientific community and, in particular, the telecommunications industries are making ever greater demands on accurate and precise timing covering longer time intervals. Often these needs cannot be met by astronomical time. However, the continued motion of the solar system gives a reliability to astronomical time scales which atomic clocks have not yet attained.

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. Figure 1.9 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 figure 1.9: First, Atomic Time (state of the art, 1964) is about 10,000 times more uniform than Universal Time, and second, measurement uncertainty totally limits any knowledge of statistical fluctuations in Ephemeris Time.

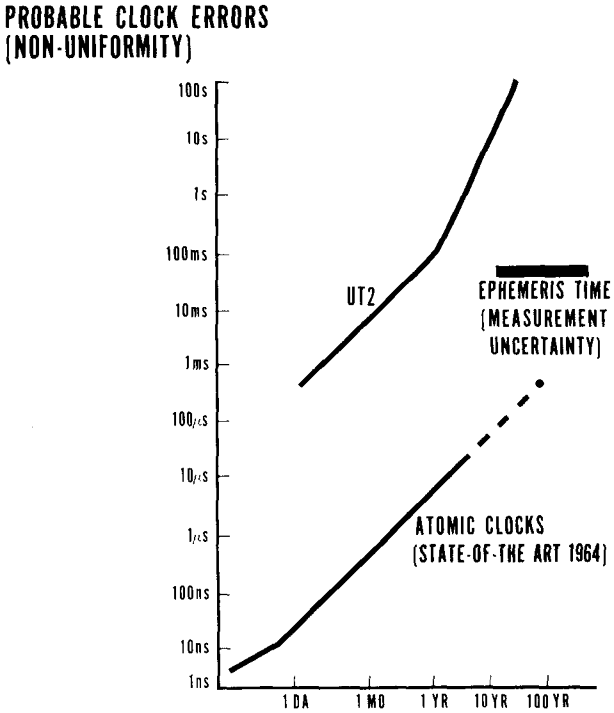


Fig. 1.9. Probable errors of 3 clock types after synchronization.

#### 1.4.8.1. Reliability and Redundancy

In the past, reliable operation of atomic frequency standards has been a significant problem. Presently, however, commercial units with a Mean Time Between Failure (MTBF) exceeding 1 year are not uncommon [37]. Finite atom source lifetime prevents unlimited operation without interruption, however.

It is true that a MTBF exceeding 1 year reflects significant engineering accomplishments, but this is far from comparable to the high reliability of astronomical time. The obvious solution is to introduce redundancy in the clock system. One can use several atomic clocks in the sytem and this should certainly be the best approach in the sense of accuracy and reliability—it is expensive, however.

Suppose the synthesizer-counter subsystem of a clock system should jump a small amount and cause a discontinuity in its indicated time. It is possible that such a transient malfunction could occur with no outwardly apparent signs of malfunction of the apparatus. It is also apparent that if only two clocks are available for intercomparison, it is impossible to decide which clock suffered the transient malfunction. Thus, three clocks (not necessarily all atomic) constitute an absolute minimum for reliable operation. If one or more of these has an extended probable down time (e.g., while the atom source is replenished) then 4 or 5 clocks become a more workable minimum.

It should be noted here that one could assemble a large group of clocks into one system and the system MTBF calculated from the individual MTBF's might extend into geologic time intervals. This system MTBF is undoubtedly over-optimistic due to neglect of the possibilities of catastrophes or operator errors. Nonetheless, with various atomic clocks spread over the earth, it should be possible to maintain an atomic time scale with a reliability that could satisfy almost any future demand.

## 1.5. INTERNATIONAL ATOMIC TIME (TAI) SCALE

In recent years the General Conference of Weights and Measures (CGPM) has been encouraged to adopt an International Atomic Time (TAI) scale [38] (see ann. 1.A). For such a scale to be of value the following attributes are required:

a. It must provide greater accuracy and convenience than the astronomical counterparts.
b. 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.)
c. 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. In October 1971 the CGPM endorsed the BIH atomic time scale as the International Atomic Time scale [31] (see ann. 1.A) defined as follows:

> "International Atomic Time is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks functioning in various establishments in accordance with the definition of the second, the S.I. Unit (International System of Units) of time."

The Atomic Time (AT) scales maintained in the U.S. (by both NBS and USNO) constitute $\sim 37\frac{1}{2}$ percent of the stable reference information used in maintaining a stable TAI scale by the BIH [39]. The question of the accuracy of rate of the TAI scale is not now completely specified [40]. There is a question of formal averaging procedures for correcting TAI. A special meeting of the Consultative Committee for the Definition of the Second (CCDS) was held in Paris, France, July 1972, to consider the status of atomic frequency standards and improved realization of the TAI, among other pertinent questions. Recommendations of this committee (6th Session of CCDS) are given in Annex 1.C.

Dr. Guinot, Director of the BIH, recommended a new method of calculation of TAI. By using individual clock data in place of local time scales from various laboratories, improved weighting of clock data is anticipated [40]. Some advantages of the individual clock procedure he pointed out are as follows:

> "1. Most of the local time scales are based on a small number of clocks. Irregularities of TAI are due to changes of frequencies of certain TA(i) which cannot be seen at the local level when the number of standards in effective use has to be less than 3. This happens frequently. In a global treatment, such irregularities would be visible.
> 2. Isolated standards could be employed. For example, at least 12 cesium standards conveniently available and compared to the Loran C pulses or TV pulses are available in Europe, not including those at the Loran C stations.
> 3. The treatment of all the standards would be unified, described in detail, and understood by all. At present, it is practically impossible to understand how TAI is calculated since it is necessary to understand the methods of each participating laboratory, methods which are not always published.
> 4. The direct calculation of TAI would allow a complete freedom to the laboratories in order to establish the TA(i), according to their criteria, without which they have to be preoccupied with the criteria adopted by TAI."

A tentative schedule for work of the BIH for improving TAI is given in Annex 1.C. A complete description of the construction of a local atomic time scale is treated by D. Allan et al. in chapter 9.

The UTC scales of the USA are coordinated with UTC(BIH) to within a tolerance of about $\pm 10$ $\mu$s. All of the UTC scales are supposed to agree with UTC(BIH) to $\pm 1$ millisecond by International Radio Consultative Committee (CCIR) agreement [36]. For those desiring accurate UT information, corrections are encoded into standard time broadcasts [36]. 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).

## 1.6. THE CONCEPTS OF FREQUENCY AND TIME INTERVAL

The four independent base units of measurement currently used in science are length, mass, time, and temperature. It is true that, except for fields of science such as cosmology, geology, and astronomy, time interval is the most important concept, and (astronomical) date is of much less importance to the rest of science. This is true because the "basic laws" of physics are differential in nature and only involve small time intervals. In essence, physical "laws" do not depend upon when (i.e., the date) they are applied.

Based on these laws and extensive experimentation, scientists have been able to demonstrate that *frequency* can be controlled and measured with the smallest percentage error of any physical quantity. 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 (Hz) and is identical to a cycle per second (cps). Since most clocks depend upon some periodic phenomenon (e.g., a pendulum) in order to "keep time," and since one can make reliable electronic counters to count the "swings" of the periodic phenomenon, we can construct clocks with timekeeping accuracy (rate accuracy) equal to the accuracy of the frequency standard.

In terms of the advancement 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 00h 00m 00s 31 December 1899, and since 1967, in terms of a resonance of the cesium atom [41] (see ann. 1.A). The present definition of the second states:

> "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium−133 atom". (13th CGPM (1967), Resolution 1), [42].

Today's most precise and accurate clocks incorporate a cesium atomic beam as the "pendulum" of the clock.

### 1.6.1. Time Interval and Time Scales

One should note sources of confusion which can exist in the measurement of time and in the use of the word "second." Suppose that two events occurred at two different dates. For example the dates of these two events were 15 December 1970, 15h 30m 00.000000s UTC and 15 December 1970, 16h 30m 00.000000s 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 $\times 300 \times 10^{-10}$]. See table 1.1.) 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 precise 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.

## 1.7. USES OF TIME SCALES

The study of time scales can be divided into the study of time scales used for systems synchronization and time scales used for celestial navigation and astronomy.

### 1.7.1. Time Scales for Systems Synchronization Uses

Long ago people were simply content to let the sun govern their lives. Sunrise indicated time to arise and begin work; sunset signalled the day's end. With the advancement of civilization, growth of commerce and city life and technological gains, communities were established which instituted clocks set to agree roughly with the apparent movement of the sun. Thus developed the idea of local time and each community could have its *own* local time. Clearly, when almost all communications and business transactions occur within a given community or locale, this is a workable solution. With the advent of railroads and hence more rapid communications, this "crazy-quilt" maze of individual local times had to end. The railroads are generally credited with unifying the various local times into time zones in the continental U.S., resulting in a much more workable national time system. In 1884 an international conference recommended that the meridian of Greenwich, England be the standard reference meridian for longitude and time [43]. Longitude meridians, each 15°, represent 1 hour time-zone differences ±12 hours east and west of Greenwich. Figure 1.10 shows the standard time zones of the world in effect today.

This brief historical sequence illustrates that, as communications become more rapid and more far-reaching, the greater are the demands on an all-pervasive and unifying convention of synchronizing clocks with each other. That is, this *convention* is a matter of convenience and there is nothing sacred or absolute about what our clocks read; it's just important that they read the same time (or have a well-defined time difference as between the time zones). In the days when the railroads were the primary means of transportation across the North American continent, an accuracy of a few seconds of time was important and sufficient. Nowadays, with the existence of sophisticated telecommunications equipment capable of sending and receiving several million alphanumeric characters each *second*, there are real needs for clock synchronizations at accuracy levels of a millionth of a second and better.

### 1.7.2. Time Scales for Celestial Navigation and Astronomical Uses

As pointed out previously, time is essential for celestial navigation. If one knows what time it is (i.e., solar time) at some reference point – say the Greenwich Meridian – and also his local time as indicated by a sundial – one can figure his longitude,

# STANDARD TIME ZONES OF THE WORLD

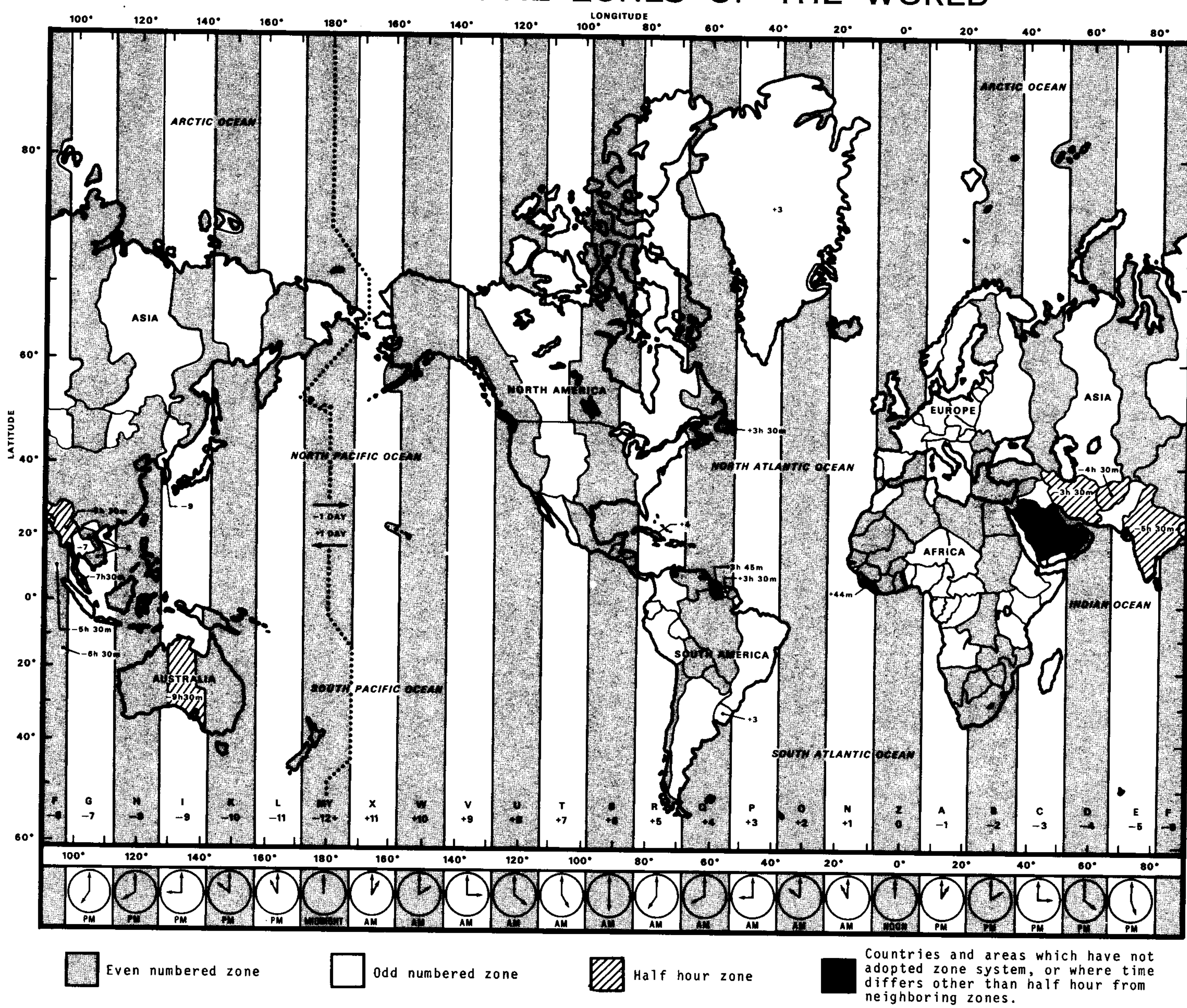


Fig. 1.10. Standard time zones of the world.

since the earth makes one complete revolution (360°) on its axis in about 24 hours. For example, noon Greenwich Mean Time is 0200 Hawaiian Standard Time or 10 hours different. Thus, one can easily calculate that Hawaii is about 10/24 of the way around the world from Greenwich, England—i.e., about 150° west of the Prime Meridian. If this person were to measure the actual position of the sun in the sky using, say, a navigator's sextant, then he could get a rather accurate determination of local solar time. The key problem is knowledge of correct time on the Greenwich Meridian.

Nearly 200 years ago, a man in England named Harrison was awarded £20,000 for designing and building a chronometer which would allow the accurate determination of longitude while at sea (less than 1 minute error after 5 months at sea [44]). Until radio signals were available in the early 1900's, navigation at sea was totally dependent upon good clocks. Today, there are many standard time broadcast stations in the world which can provide time signals accurate to better than 1 second of earth time, UT1 [45].

If astronomical time could be measured with sufficient accuracy and convenience, then astronomical time could be used for system synchronization uses also. In actuality, astronomical time is difficult to measure, and accuracies of a few thousanths of a second may be realized only after the averaging of a whole evening's sightings by a sophisticated and well-equipped observatory. The accurate determination of UT1 involves measurements at, at least, two observatories widely separated in longitude.

## 1.8. CONCLUSIONS

Two very different uses for time have been discussed. The first is a convention which, when universally accepted, allows both rapid and efficient communications systems to function. The needs here are for extremely precise and uniform measurements of time. The second use is for celestial navigation and astronomical observations. Here there is not the need for highly precise time, at least not to the same degree as the first mentioned use.

Because of the conflicting requirements imposed on time scales by these two categories of time scale users, there has been a great deal of effort to obtain a compromise time scale which adequately reflects the relative importance of these two user groups. As one might well imagine, with the growing importance and sophistication of communications systems and the implementation of electronic navigation systems (to replace celestial navigation), the trend in the compromise time scales has been away from time scales based on the earth's rotation (i.e., astronomical time scales) and toward a pure atomic time scale.

In this compromise scale, UTC, one finds himself in a rather familiar situation. There is not a whole number of days in the year and one doesn't want the calendar to get badly out of step with the seasons. Similarly, there is not a whole number of seconds in a solar day and one doesn't want our clocks to get badly out of step with the sun. The solution (as noted above) is analogous to the leap year with its extra day; we have an extra second—a leap second which must be added or deleted on occasion.

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