(Preprint) AAS 13-523

CONSIDERING TIME-SCALE REQUIREMENTS FOR THE FUTURE

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Requirements for time scales can be specified for a variety of desirable features. Among these considerations are precision, accuracy, stability, accessibility, reproducibility, relation to the spatial reference frame in which they are defined, and utility as an independent variable in equations of motion. Some might be described numerically while others might be more difficult to specify quantitatively. However, user requirements for each of these categories depend on the intended application as well as the level of technology available to the user. Coordinated Universal Time (UTC) as defined currently has served as the standardized basis for civil timekeeping throughout the world since 1972. The continued acceptance of that definition or any alternative will depend on the requirements of the users of the future. Each of the requirement categories is explored with regard to the potential users and potential time scales for the future.

INTRODUCTION

A time scale can be defined as an arrangement of events used to measure duration. We can further define the process of measurement as 'the assignment of numerals to things so as to represent facts and conventions about them.' … in the broadest sense … defined as the assignment of numerals to objects or events according to rules. The problem then becomes that of making explicit

a) the various rules for the assignment of numerals,

b) the mathematical properties (or group structure) of the resulting scales, and

c) the statistical operations applicable to measurements made with each type of scale.[1]

A time scale is a particular kind of measurement scale. In general, measurement scales can be characterized by four properties. These are:

1. Identity meaning that each value on the measurement scale has a unique meaning;
2. Magnitude meaning that values have an ordered relationship to one another (some values are larger and some are smaller);
3. Equal intervals meaning that units along the scale are equal to one another over all levels of the scale; and
4. A minimum value of zero meaning that the scale has a true zero point, below which no values exist.[1]

However, any scale used as a time scale lacks the last property, and is therefore called an interval measurement scale. Some scales traditionally called time scales may also lack the third property of equal intervals. The International Astronomical Union has stated that a useful time scale is generated by any process which enables dates to be assigned to events.[2]

S. S. Stevens notes that "Any particular scale, sensory or physical, may be objected to on the grounds of bias, low precision, restricted generality, and other factors, but the objector should remember that these are relative and practical matters and that no scale used by mortals is perfectly free of their taint."[1] As a result, society has made use of a variety of time scales throughout history. These scales have evolved, and will continue to evolve, to meet the needs of society. To attempt to forecast the types of time scales to be used in the future, it is helpful first to look at the past scales. It is important then to assess the requirements of tomorrow and apply those to likely candidates for future use.

TIME SCALE EVOLUTION

Our earliest ancestors surely recognized the cycles of the most basic apparent motions of the Sun and the Moon in the sky, and so these formed the basis for our earliest time scales, which are still in use today.

Solar Time Scales

Apparent solar time is equivalent to the local hour angle of the Sun. Time measured in this way depends on the longitude of the site in question. If the observer is on the "Greenwich meridian" we call it Greenwich apparent solar time, and for any other location it is called local apparent solar time. Because the length of a day varies during the year due to the inclination of the Earth's orbit to the equator, and because of its orbital eccentricity, the basic unit of this scale, the second as measured by the fraction of $^{1}/_{86,400}$ of the day, is not equal. Nevertheless it was the argument in the nautical almanacs and national ephemerides until the early 19th century.

The ancient astronomer Ptolemy recognized this fact and devised the concept of mean solar time. Today that scale uses the concept of a fictitious point moving uniformly along the equator of the celestial reference system. The angle measure equivalent to the local hour angle of this point became known as mean solar time. As with apparent solar time, the mean solar time depends on the longitude of the observer's location, but it also depends on the mathematical description of the motion of the fictitious point. Mean solar time was introduced in almanacs in England in 1834 and in France in 1835. The difference between mean and apparent solar time is called the *equation of time.* It reaches a maximum value of approximately +14 minutes about 6 February and a minimum value of about −16 minutes about 3 November, as shown in Figure 1.[3]

The rotation of the Earth can also be measured with respect to the stars. Because of the difficulty in making observations of the Sun, time measured with respect to the stars became a useful measure to define mean solar time, using an adopted relationship between the two types of time measurements. The time, equivalent to the hour angle of the origin of the celestial frame, is called sidereal time. Since the Sun appears to move in the sky by approximately one degree each day, sidereal time is quite different from solar time. Apparent sidereal time is affected by both precession and nutation, which introduces periodic variations into apparent sidereal time. Mean sidereal time is only affected by the motion due to precession. Apparent sidereal time minus mean sidereal time is the equation of the equinoxes.[3]

Mechanical and Electronic Time Scales

The advent of mechanical timekeeping offered a means to obtain time without celestial observations. However, the motions of celestial bodies continued to provide the most accurate standard for calibration purposes. The term Universal Time (UT) was recommended by the IAU in 1935 to designate mean time on the meridian of Greenwich reckoned from midnight. UT1 is derived from direct observations of the Earth's rotation angle in space, and although often called a "time scale," was never used as a time scale in practice. It does, however, remain as a means to characterize the Earth's rotation angle in space. UT2 was used as a time scale in practice. It is created by applying a conventional mathematical expression to the observed UT1 to correct for the annual seasonal variation in the Earth's rotational speed and is rarely used today.[4]

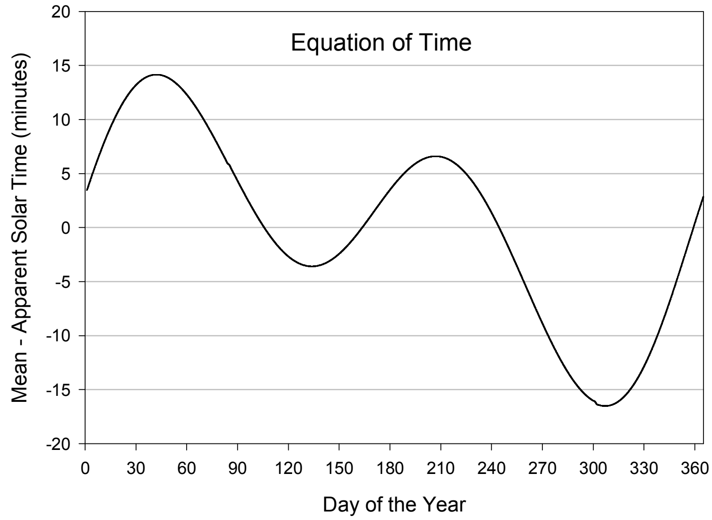

Figure 1. Equation of Time.

For many years clocks, based on both mechanical and quartz electronic oscillators, as well as radio time signals, were adjusted in rate and offsets to match the UT2 that was determined from star transits. Many countries, or organization, broadcasted their own time scales. On 1 January 1960 the United Kingdom and the U. S. began coordinating adjustments made to their time scales. The resulting time scale began to be called "Coordinated Universal Time." Laboratories from other countries also began to participate over time, and in 1961 the Bureau International de l'Heure at Paris Observatory began to coordinate the process internationally. In 1965 the IAU officially approved the name "Coordinated Universal Time" with the abbreviation UTC.[5] By that time, however, the variable rotational speed of the Earth was well recognized and it was clear that a more uniform time scale was desirable to meet the needs of society.[3]

Ephemeris Time

The quality of any time scale based on the Earth's rotation, however, depends on the uniformity of the Earth's rotation. Problems with this assumption eventually led to the development of dynamical time scales. The first such scale was called Ephemeris Time (ET). Ephemeris Time was adopted by the 10th General Assembly of the International Astronomical Union in 1958 with the following: "Ephemeris Time is reckoned from the instant, near the beginning of the calendar year A.D. 1900, when the geometric mean longitude of the Sun was 279° 41′ 48.04″, at which instant the measure of ephemeris time was 1900 January 0^d 12^h precisely." [6] The IAU had already adopted the second of Ephemeris Time in 1955 as the fraction 1/31 556 925.975 of the length of the tropical year for 1900.0."[7] The numerical value of the fraction was based on Newcomb's formula for the geometric mean longitude of the Sun for the epoch of January 0, 1900, 12h UT [8] given by $L = 279°41′46.04″ + 129\ 602\ 768.13″T + 1.089″T^2$, where T is the time reckoned in Julian centuries of 36525 days. From the value of the linear coefficient in Newcomb's formula, the tropical year of 1900 would then contain [(360×60×60)/129 602 768.13] ×36 525×86 400 = 31 556 925.975 s. With these definitions, ephemeris time was equivalent to the system of time in Newcomb's Tables of the Sun and the second was, in practice, defined by the duration of the second used by Newcomb in the analysis of the mid-nineteenth century astronomical observations.

Atomic Time Scales

The first clock based on an energy-level transition in the Cæsium-133 atom was established at the National Physical Laboratory in UK in 1955. The frequency of that transition was measured in terms of the second of ET to be 9 192 631 770 ± 20 Hz.[9] This second, defined by the duration of 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the Cæsium-133 atom, was adopted as the definition of the Système International d'unités (SI) second in 1967. Consequently, atomic time scales continue to use a second based on the ET second that, in turn, corresponds to the second measured by the Earth's rotational speed of the mid-nineteenth century.

International Atomic Time (abbreviated TAI) is a time scale in a geocentric reference frame with the SI second realized on the rotating geoid as the scale unit. It is a continuous atomic time scale that was determined first by the Bureau International de l'Heure (BIH) since 1958, and now maintained by Bureau International des Poids et Mesures (BIPM). It was set equal to UT2 on January 1, 1958, 0^h. It was developed from time scales maintained at various international laboratories. It was originally called AT (or TA) in 1969 and became TAI in 1971.

In 1970 the International Radio Consultative Committee, abbreviated "CCIR," approved proposals at its XIIth Plenary Assembly that provided the current definition of UTC based on TAI. It specified that

a) radio carrier frequencies and time intervals should correspond to the atomic second based on the Cæsium atom;

b) step adjustments should be exactly one second to maintain approximate agreement with UT; and

c) standard time signals should contain information on the difference between UTC and UT. The new system began on 1 January 1972, and introduced the use of "leap seconds" to ensure that $|\mathrm{UT1}-\mathrm{UTC}| < 0.9\mathrm{s}$.

The use of the term "UT" in various publications is ambiguous and care should be exercised to make sure of the specific usage.[10]

Dynamical Time Scales

Improved observational accuracy and the need to consider relativity led to two new time scales in 1984. These were Barycentric Dynamical Time (TDB) and Terrestrial Dynamical Time (TDT). They were considered to be continuations of Ephemeris Time, but defined to correspond with their respective reference frames, either the geocenter or the barycenter. To achieve the continuity, TDT was specified with respect to TAI with an offset and rate to match ET. It was specified that TDB would only differ from TDT by periodic terms, so the epoch and rate of the two would agree. This would prove to be impossible to accomplish with sufficient accuracy. In 1991 the IAU renamed TDT as Terrestrial Time (TT).[3]

Coordinate Time Scales

In special and general relativity we consider two types of time, proper and coordinate. Proper time is measured by a physical clock insensitive to environmental conditions, gravity, and accelerations accompanying the observer. However proper time cannot be used to describe phenomena in extended domains, where coordinate time must be used. Coordinate time is an unambiguous way of dating in a specific reference system and is to be used as the time basis in the theory of motion in the system. In metrology it can be argued that coordinate time cannot be measured, but only computed. The relation of proper time of an observer to coordinate time is provided by a metric that takes into account the surrounding masses and energy.

With these considerations in mind, and following the adoption of the IAU resolutions defining the Barycentric and Geocentric Celestial Reference Systems, two time scales, Barycentric Coordinate Time (TCB) and Geocentric Coordinate Time (TCG), were introduced and the relationships between these time scales and Terrestrial Time (TT) were clarified. Barycentric Dynamical Time (TDB) was defined in 2006 as a linear scaling of TCB having the approximate rate of TT. TCG is the time coordinate for the four dimensional geocentric coordinate system, and in terms of the theory of relativity, differs slightly in rate from TT. TCB is the time coordinate for the four dimensional barycentric coordinate system of the solar system, differing both in secular and periodic effects from TT and TCG, according to the relativistic metric being used. These time scales, and the time scales leading up to their development, are outlined in Figure 2.[3, 11]

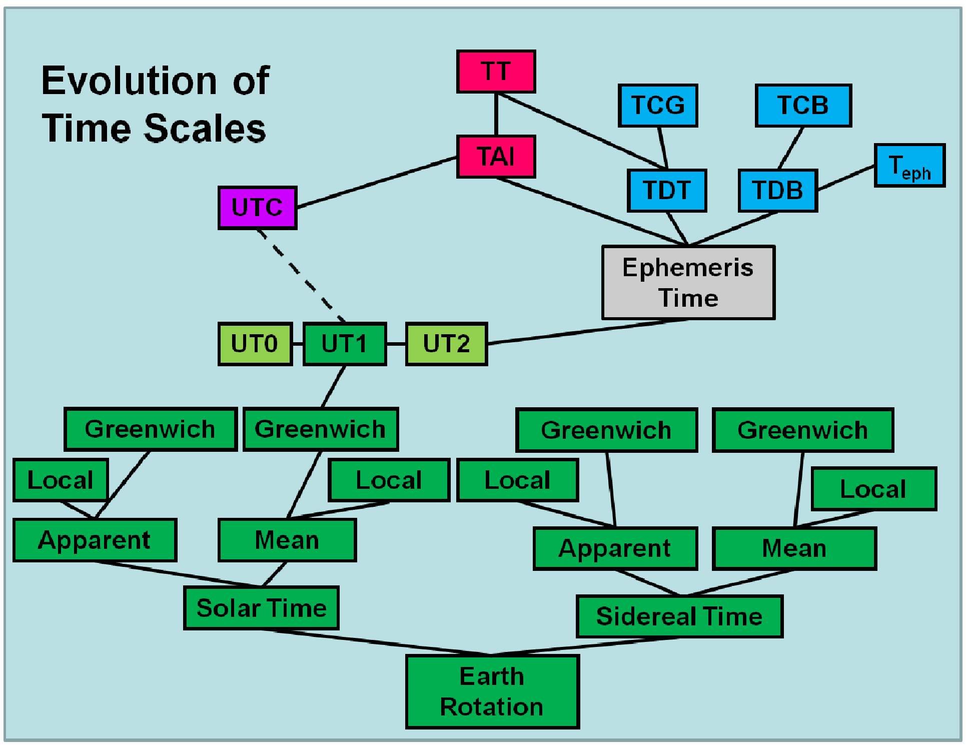

Figure 2. Evolution of Time Scales.

Specialized Time Scales

The development of global navigational satellite systems (GNSS) has led to the creation of internal time scales devoted to the specialized navigational requirements of particular systems. In order to ensure continuous operational capability, these scales ignore the one-second leap-second adjustments that are made to UTC currently. They are formed using internal atomic clocks that are adjusted in frequency and epoch as required to meet their operational needs. As a result, these scales are not suitable to meet definitions for standard time scales.

EARTH ROTATION

The observation of time astronomically requires definitions of terrestrial and celestial reference systems with accuracy commensurate with the accuracy attainable in the observations. The International Celestial Reference System (ICRS) was introduced in 1992 and is now maintained by the International Earth Rotation and Reference system Services (IERS), and realized in practice by the directions to a set of quasars in the radio wavelengths and the directions to stars in the Hipparcos Catalogue in the visual wavelengths. Similarly, the IERS also maintains the International Terrestrial Reference System (ITRS) that is realized by the adopted positions of a large number of observing sites on the Earth's surface. UT1 is a critical angle in the transformation between those two systems.

It is clear from the discussion above that our time scales have largely been based on the Earth's rotation in the past. Unfortunately we know that the rotational speed is variable and suffers from a wide spectrum of variation. Although knowledge of the Earth's rotation angle in space may no longer play the role that it used to play in everyday timekeeping, it is nevertheless critical for the operation of GNSS systems (*e.g.* GPS, GALILEO), the analysis of artificial Earth satellite orbits, and for space navigation. It is a vital element in the transformation of spatial coordinates between a celestial and terrestrial reference frame. The rotation angle has, in practice, been described in part by the numerical value UT1−UTC. It was an important consideration in celestial navigation, and it was for this reason that UTC was defined such that $\left|\text{UT1}-\text{UTC}\right|$ would never exceed 0.9s.

The transformation between celestial and terrestrial systems can be expressed mathematically:

$$[\mathbf{CRS}] = \mathbf{PN}(\mathbf{t})\mathbf{R}(\mathbf{t})\mathbf{W}(\mathbf{t})[\mathbf{TRS}], \tag{1}$$

where **[CRS]** and **[TRS]** represent the Celestial and Terrestrial Reference Systems respectively, **PN(t)** represents the Precession-Nutation matrix, **W(t)** represents the polar motion matrix**,** and **R(t)** represents the rotation angle matrix. That matrix is expressed either by

$$\mathbf{R}(t) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

or

$$\mathbf{R}(\mathbf{t}) = \begin{pmatrix} \cos GST & -\sin GST & 0 \\ \sin GST & \cos GST & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{3}$$

where θ is the Earth Rotation Angle, *GST* is Greenwich Sidereal Time, and

$$\theta(\mathrm{T_U}) = 2\pi\,(0.779\,057\,273\,264\,0 + 1.002\,737\,811\,911\,354\,48\,\mathrm{T_U}, \tag{4}$$

$$\mathrm{T_U} = (\text{Julian UT1 date} - 2451545.0), \tag{5}$$

$$\text{UT1} = \text{UTC} + (\text{UT1}-\text{UTC}), \tag{6}$$

$$GST = ERA(\text{UT1}) - EO, \tag{7}$$

$$EO = -0.01450600'' - 4612.15653400''t - 1.391581700''t^2 + 0.0000004400''t^3 - \Delta\psi\cos\varepsilon_A - \mathrm{P}, \tag{8}$$

where t = [Terrestrial Time (TT)−2451545.0TT] / 36525 and $\Delta\psi \cos\varepsilon_A$ is the classical equation of the equinoxes, and P represents a series of periodic terms[3, 11] given in Table 5.2e of the *IERS Conventions* (2010).[12]

Observed values of UT1−UTC as well as forecasts of future values are made available in printed bulletins, and electronically by IERS. This information is provided in near real time. The accuracy of the observed values is generally in the range from ±1 to ±10 microseconds of time or ±15 to ±150 microseconds of arc. Predicted values are provided with accuracies that reach ±0.001 4s for 10 days in the future. The current definition of UTC also provides a very low precision value of UT1 as it is encoded in UTC so that users may assume that UT1 = UTC with an accuracy of 1 second. It is also anticipated that future navigational messages broadcast by GNSS will provide high accuracy values of UT1-UTC.

LEAP SECONDS

The current definition of UTC calls for the occasional introduction of one-second adjustments to the epoch of the time scale called "leap seconds." However this procedure has been called into question and there is currently an international discussion on a possible change in that definition.

The current UTC definition appears to be at odds with the very definition of an interval measurement scale. As noted above, that type of scale should have the property of equal intervals. However, in the case of UTC, there can be minutes of either 60 or 61 seconds. Similarly the number of seconds in a day could be either 86,400 or 86,401. The process is equivalent to stopping all of the world's clocks at the same time for one second. As currently defined, the introduction of leap seconds occurs at 0^h UTC, which can be in the middle of day in Asia, creating serious infrastructure issues. They argue that the discontinuities in UTC reduce the reliability of systems that depend on precise time and introduce the possibility of catastrophic failure in modern infrastructure. They further note that the long-term history of the Earth's rotational speed indicates that we can expect to see an increasing frequency of these discontinuities in the following centuries. Interruptions can be caused in any process that relies on a strictly increasing seconds count, and the fact that they cannot be predicted with sufficient lead time to be built into modern software can cause significant problems in maintaining operations when leap seconds are introduced. Communications and air traffic control are two areas that have been affected significantly by these one-second time discontinuities. These issues cause system developers to institute internal time scale that do not introduce discontinuities in order to ensure smooth operations. This, in turn, causes concerns regarding a potential increase in the number of unrelated time scales and the possibility of confusion among users. Finally, not the least of the problems is the significant cost in resources necessary for this to be carried out throughout the world.

On the other hand, it is expensive to change legacy software used in artificial Earth satellite orbit analyses and telescope pointing applications, and that removing the relationship to the Earth's rotation will cause time to fall out of synchronization with the Earth's relationship to the direction of the Sun in the sky. Another concern is the fact that data formats have been used in practical applications that have assumed that $|\mathrm{UT1-UTC}|$ will never be greater than 1second. In view of these concerns it is appropriate to examine the desirable aspects of a time scale for future use as a worldwide standard.[10]

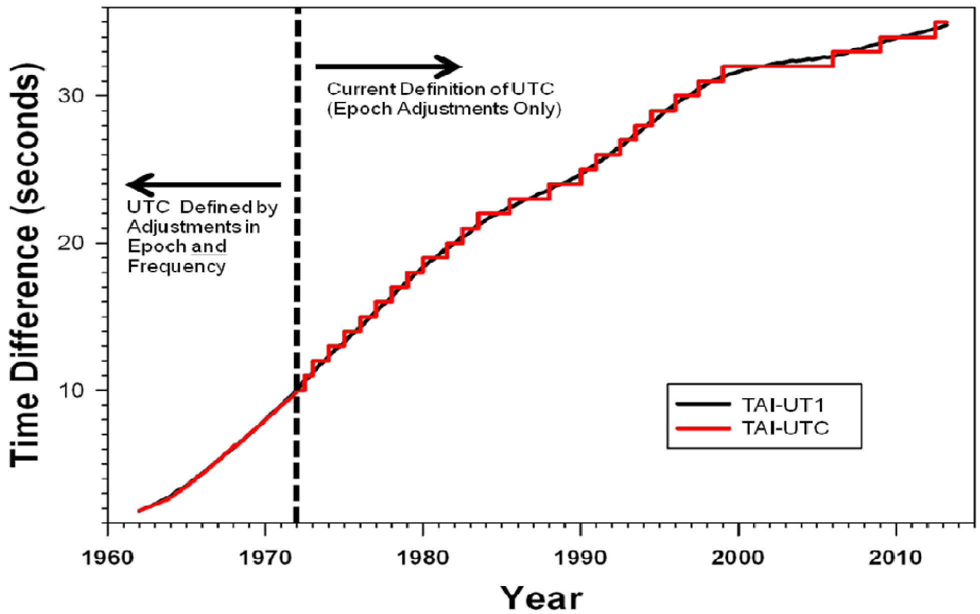

Figure 3. Difference between TAI and UT1 and UTC illustrates the use of leap seconds.

DESIRABLE FEATURES OF A STANDARD TIME SCALE

We can begin listing the qualities of an ideal time scale with the three features of an interval measurement scale, namely

(1) Identity, meaning that each value on the measurement scale has a unique meaning,

(2) Magnitude, meaning that values have an ordered relationship to one another, and

(3) Equal intervals, meaning that units along the scale are equal to one another over all levels of the scale.

In addition to these, we might also add the features of accuracy, precision, responsiveness to user requirements, continuity, consistency with other physical standards, consistency with measurement capability, well-defined origin, unambiguous naming convention, correspondence with the direction of the Sun in the sky, and easy accessibility.

Measurement Capability, Accuracy and Precision

It is appropriate to discuss these qualities together. Atomic standards are now capable of providing measures of the duration of a second with a precision better than 1 part in 10^{15} at averaging times of 1 day. The estimate of the true accuracy of these measurements depends on the ability to compare standards in different environmental conditions. This ability is currently limited by the ability to transfer time at a distance. For short distances this accuracy is of the order of a few picoseconds (10^{-12}). With these values in mind, it seems appropriate to suggest that any future time scale should aim to provide time with accuracy of a few picoseconds.[13]

Continuity

A criticism of the current definition of UTC is that it produces a step-function relationship with atomic time scales. With respect to that relationship let us look at the mathematical definition of continuity. If we let $f(t)$ be a function defined on an interval around a point T_L, $f(t)$ is said to be continuous from the left at T_L iff

$$\lim_{t \to T_L^-} f(t) = f(T_L), \tag{9}$$

and $f(t)$ is said to be continuous from the right at T_L iff

$$\lim_{t \to T_L^+} f(t) = f(T_L). \tag{10}$$

$f(t)$ is said to be continuous at T_L iff

$$\lim_{t \to T_L^-} f(t) = \lim_{t \to T_L^+} f(t) = \lim_{t \to T_L} f(t) = f(T_L). \tag{11}$$

So, if

$$f(t) = \begin{Bmatrix} L & t < T_L \\ L+1 & t \geq T_L \end{Bmatrix}, \tag{12}$$

as is the case with the function $f(t)$ = UTC−TAI, the limit of this function as t approaches T_L from left is different from the limit as t approaches T_L from right. Thus the function is discontinuous at T_L and we conclude that UTC−TAI as currently defined cannot be said to be continuous.

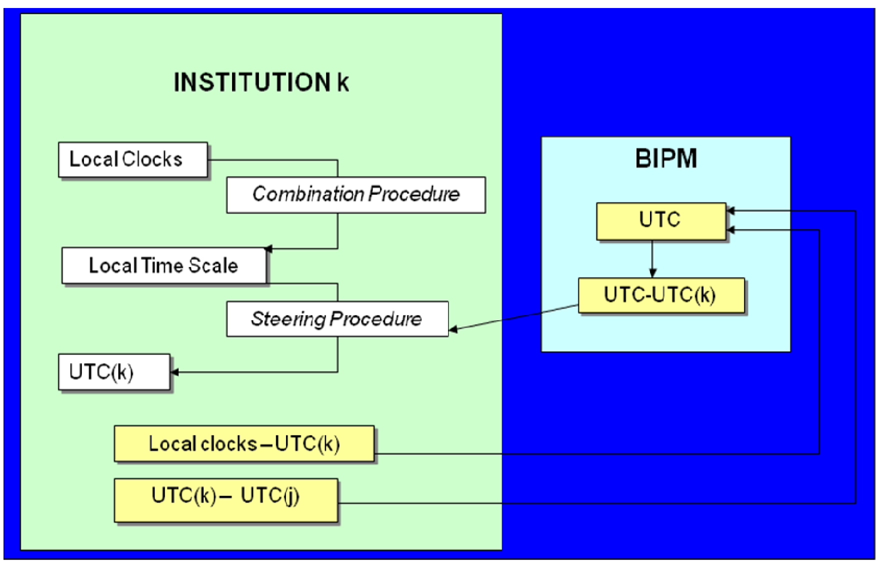

Figure 4. Realization of UTC.

Accessibility

It is apparent that any time scale, in order to be user-friendly, must be easily accessible to the user. The current means of providing UTC is a model for future distribution of a time scale. UTC is currently produced from the combination of clock comparison data from un-steered clocks at national laboratories around the world (Figure 4). This process is carried out at the BIPM and that organization is currently investigating the possibility of making available in near real time the resultant UTC suitable for national laboratories. The association of the time scale calculation with the BIPM also ensures the consistency of the time scale with other world standards.

User Requirements

Perhaps the most difficult feature to forecast is the need to be responsive to user requirements. Modern infrastructure depends critically on time and frequency. Users include GNSS navigating inside structures, telecommunications services, computer networks, government, aerospace, defense, enterprise information technology, high-frequency financial trading, broadcast infrastructure, underwater exploration and navigation, electrical grids, industrial processes, air traffic control, intelligent transportation systems, radio frequency identification and location systems (RFID), scientific research and development. Within that list, some users may be satisfied with accuracy of the order of a second, but others may demand nanosecond accuracy. Some of the most demanding of these requirements in the future are likely to be those related to transportation, for example air traffic control and intelligent transportation systems which will rely on accurate timing to manage traffic with much tighter tolerances. RFID promises to have capabilities of tracking inventories and equipment with much improved precision, and navigation inside buildings will also become a critical safety issue in the future. All of these rely on the fact that one nanosecond of time roughly corresponds to one foot in spatial coordinates when considering the travel time of electromagnetic radiation.

The accuracy for all of these requirements varies widely. Perhaps more critical to users, however, is the reliability of the time and frequency information. Users want to be confident that there will be no breaks in continuous services. It is probably safe to conclude that any time scale for the future should not have built-in accuracy limits, but instead be capable of providing the most accurate time and frequency information technically possible.

Well Defined Origin and Unambiguous Naming Convention

An aspect of an interval measurement scale is the lack of a true zero point, below which no values exist. A critical aspect of a time scale, however, is the existence of a well-defined, albeit conventional, origin. Along with that we require an unambiguous naming convention for the units in the scale. The currently defined UTC has an arbitrarily assigned conventional set of epochs. These are, indeed, well-defined. However, ambiguities do occur. A day, for instance, may contain 86,400 seconds or 86,401 seconds. A minute may be either 60 or 61 seconds in duration. There is no naming convention for the extended minute or extended day. Another concern in this area is the fact that few equipment manufacturers allow properly for the display of a leap second that should be labeled “60.” Clocks generally go from a second labeled “59” to one labeled “0.” As a result, many clocks register the leap second without any label or register two seconds with the same label, generally “59.” The ideal system of the future should strive to eliminate that source of ambiguity.

Correspondence with the Sun’s Direction in the Sky

Traditionally, the time of day has been linked with the direction of the Sun in the sky. Consequently there is a concern that any future changes in time scales retain that relationship. Currently the hour angle of the Sun at local civil noon can be as large as 5 hours in China because China has elected to have the entire country in one time zone. So we would expect that any future change in a time scale should not be so large as to impose a solar hour angle greater than 5 hours at noon. As an example, Figure 5 shows the solar hour angle at Greenwich, England, at noon currently and for the situation that might be expected in about the year 2500 should there be no further leap second insertions.

Summary of Requirements

From the discussion above we conclude that the standard time scale for the future should be maintained by the BIPM (or a similar international standards organization), be continuous, have no ambiguities in its scale units, be accurate and precise at the level of a few picoseconds, and be easily accessible. It should not impose technical limitations to providing the most accurate time and frequency information available.

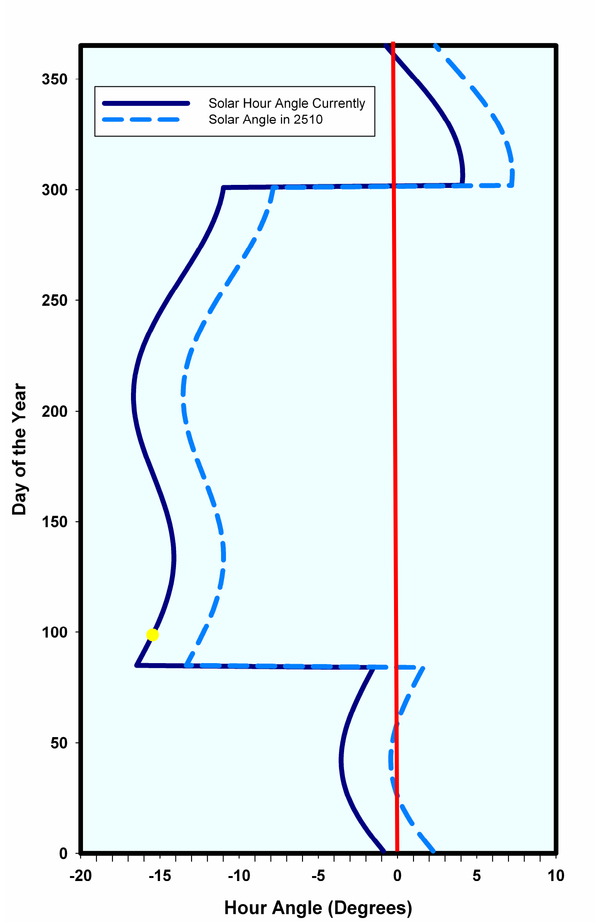

Figure 5. Solar Hour Angle at Greenwich Civil Noon.
The dashed line shows the projected hour angle in 2510 if there were no leap seconds introduced in UTC. The angular size of the Sun is indicated by the yellow circle.

OTHER POSSIBLE TIME SCALES

GNSS time scales (*e.g.* GPS System Time or simply GPS Time) are sometimes suggested as candidates for a standard time scale. However these time scales are limited by the fact that they are based on clocks internal to the GNSS itself. The clocks are steered by system operators to correspond in time and frequency with external standards and so they cannot be considered as possible standard time scales in the future.[14]

A likely contributor to the time scales of the future may be a pulsar time scale. Timing based on pulsar signals is a possible contribution to the long-term stability of future time scales. The IAU currently is investigating this possibility by means of a working group devoted to the topic.[15, 16]

CONCLUSION

Both time scales and Earth rotation information are critical components of modern infrastructure, and they are likely to be even more significant in the future. Consequently, it is important that some planning is carried out now to ensure that the most accurate, least ambiguous services are provided for future users. Any improvements in making Earth rotation information in near real time will be helpful. Failure to provide a source of continuous time and frequency information particularly could result in potentially dangerous or expensive problems in the future.

Users are likely to demand improved time and frequency products and the means to access standard timing information. The requirements for that information have been summarized above. A relatively easy solution for the issue of future time scales that involves minimum disruption is to change the definition of UTC by eliminating the relationship to UT1 that is currently created by the encoding of UTC to provide the low accuracy angular UT1 information (*i.e.* UT1 = UTC). If that happens it is also critical that state-of-the-art UT1 data be provided or improved to meet future requirements for Earth orientation information. If such a change were made it is likely, however, that the future time scale would truly satisfy the requirements for a time scale, namely identity, magnitude, equal intervals, accuracy, precision, responsiveness to user requirements, continuity, consistency with other physical standards, consistency with measurement capability, a well-defined origin, unambiguous naming convention, socially acceptable correspondence with the direction of the Sun in the sky, and easy accessibility.

REFERENCES

[1] S. S. Stevens, " On the Theory of Scales of Measurement." *Science,* Vol. 103, 1946, pp. 677-680.

[2] E. A. Müller, Jappel, A. ed., *Proceedings of the Sixteenth General Assembly, Grenoble 1976,* D. Reidel, Dordrecht, 1977.

[3] D. D. McCarthy, Seidelmann, P. K., *Time: from Earth rotation to atomic physics* (Wiley-VCH, Weinheim, 2009).

[4] D. D. McCarthy, "Astronomical Time." *Proc. IEEE,* Vol. 79, 1991, pp. 915-920.

[5] L. Perek ed., *Proc.13th General Assembly, Prague,* Reidel, Dordrecht, 1967.

[6] D. H. Sadler ed., *Proc. 10th General Assembly, Moscow, 1958,* Cambridge University Press, New York, 1960.

[7] R. Coutrez, "Transactions of the International Astronomical Union." *Ciel et Terre,* Vol. 73, 1957, pp. 472.

[8] S. Newcomb, *Tables of the Sun* (U.S. Govt. Printing Office, Washington, D.C., 1895).

[9] W. Markowitz, Hall R. G., Essen L., Parry J. V. L. , "Frequency of Cesium in Terms of Ephemeris Time." *Phys. Rev. Lett.,* Vol. 1, 1958, pp. 105-107.

[10] R. A. Nelson, McCarthy, D. D., Malys, S., Levine, J., Guinot, B., Fliegel, H .F, Beard, R.. L., Bartholomew, T. R., "The leap second: its history and possible future." *Metrologia,* Vol. 38, 2001, pp. 509-529.

[11] S. E. Urban, Seidelmann, P.K. ed., *Explanatory Supplement to the Astronomical Almanac,* University Science Books, 2012.

[12] P. Petit, Luzum, B. ed., *IERS Conventions (2010),* Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, 2010.

[13] B. Wang, Gao, C., Chen, W.L., Miao, J., Zhu, X., Bai, Y., Zhang, J. W., Feng, Y.Y., Li, T.C.,Wang, L.J., "Precise and Continuous Time and Frequency Synchronisation at the $5x10^{-19}$ Accuracy Level." *Scientific Reports,* Vol. 2, 2012, pp. 556-560.

[14] J. H. Hahn and E. D. Powers, *Implementation of the GPS to Galileo Time Offset (GGTO)Proceedings of the 36th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, L. Breakiron (ed.), 2005, held 7-9 December 2004 in Washington, D.C. (Washington, D.C.: U.S. Naval Observatory), 508 pp.. Piscataway, N.J. : Institute of Electrical and Electronics Engineers, 2005 ISBN: 0-7803-9053-9, p.33*, 2005).

[15] G. Hobbs, et al., "Development of a pulsar-based time-scale." *Monthly Notices of the Royal Astronomical Society,* Vol. 427, 2012, pp. 2780-2787.

[16] D. Chen, G. Hobbs, W. Coles, and R. Manchester, "Pulsar time scale and its future application." *Proceedings of the International Astronomical Union,* Vol. 291, 2013, pp. 365-365.