Astronomical Time

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Invited Paper

Astronomical time serves as the basis for civil time and is required to describe the orientation of the Earth with respect to an inertial reference frame. The definitions of astronomical time scales are reviewed as well as observational methods. The causes of the variations in the Earth's rotation are explained and a brief overview of international efforts to maintain astronomical time scales is presented.

I. Introduction

Astronomical time is based on the repetition of astronomical events for frequency standards. The most obvious astronomical event on which to base a time scale is, of course, the regular occurrence of night and day which we know to be caused by the rotation of the Earth. Another rather obvious astronomical phenomenon on which to base timing is the regular occurrence of the seasons caused by the revolution of the Earth around the Sun. However, because the Earth is not truly a rigid symmetric body and because it interacts with other members of the solar system gravitationally, both of these motions vary with time. Although these phenomena do not produce uniform time scales, the times which are derived from them are important. They find use not only in everyday life, but they also are required for observers on the Earth who find it necessary to know the orientation of the Earth in an inertial reference frame. This includes navigators, astronomers, and geodesists.

II. Astronomical Time Scales

Astronomical time scales are based on the rotation of the Earth or on the revolution of the Earth about the Sun. Both types have particular applications in modern timekeeping.

A. Rotational Time

Time determined from the rotation of the Earth is based on the uniformity of its rotational speed. In order to provide a useful time scale, then, a procedure for precise measurement of the Earth's rotation must be devised. An obvious method is to observe the apparent motion of stars with respect to defined directions on the Earth. This kind of time is known as *sidereal time*. Astronomically it is defined as the local hour angle of the vernal equinox. The vernal equinox is the direction in the sky determined by the intersection of the projection of the Earth's equatorial plane and the plane of the Earth's orbit about the Sun, where the Sun appears to move from the southern to the northern hemisphere. This direction serves as the origin of the celestial reference system and is defined in practice by the positions and motions of stars listed in star catalogs. The local hour angle of a celestial point is the angle between the local meridian plane (defined by the plane containing the center of the Earth, its rotational pole and the local vertical) and the plane containing the center of the Earth, its rotational pole and the vector in the direction of the object. However, because the Earth orbits the Sun, the Sun appears to move in the sky with respect to the stars. Thus while the Sun might be directly overhead, the sidereal time could indicate midnight, making sidereal time inconvenient for civil use although essential for astronomers.

For most general purposes *solar time*, for which the rotation of the Earth is measured with respect to the Sun, is more appropriate. Historically, some form of solar time has usually been the basis for civil time, the definition and the measurement procedures depending on available technology and precision requirements. In modern practice, *mean solar time* is defined using a fiducial direction defined mathematically in the celestial reference system. This direction is referred to as the Mean Sun. The concept is based originally on the work of Simon Newcomb [1] who defined a point whose position in the sky is related to the position of the actual Sun. Its mathematical description however seeks to eliminate the apparent variations in the uniform motion of the Sun with respect to the stars caused by the Earth's elliptical orbit. Were the orbit circular, the Sun would appear to trace out a more uniform motion with respect to the stars.

Mean solar time is defined, then, as the hour angle of this fiducial point. Both sidereal and mean solar time depend on the longitude of the user. For this reason ephemerides generally refer to *Greenwich sidereal time* which is just the sidereal time which corresponds to zero longitude. In addition, a distinction may be made between

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Greenwich *apparent* sidereal time and Greenwich Mean Sidereal Time, the difference being that mean sidereal time does not account for the periodic variation in the direction of the Earth's rotation axis due to nutation while apparent sidereal time does take this phenomenon into account. The difference between these two is called the Equation of Equinoxes and is tabulated in astronomical ephemerides.

The relationship between sidereal time and mean solar time is given on page 75 of [2]. With improving definitions of the celestial reference frame and the astronomical constants used in its realization, however, the relationship was redefined [3] to be

$$\begin{gathered}\text{GMST1 of } 0^h \text{ UT1} = \\ 24\ 110^s\!.548\ 41 + 8\ 640\ 184^s\!.812\ 866\ T_u{}' \\ +0^s\!.0931\ 04\ T_u{}'^2 - 6.2 \times 10^{-6} T_u{}'^3\end{gathered} \tag{1}$$

where $T_u{}' = d_u{}'/36525.0$, and $d_u{}'$ is the number of days since Julian Date (JD) 2 451 545.0 UT1 (2000 January 1, 12^h UT1), taking on values of ±0.5, ±1.5, ±2.5, ... The ratio between sidereal and solar time intervals is given in [3] as

$$\begin{gathered}\text{sidereal time interval/solar time interval} = \\ 1.002\ 737\ 909\ 350\ 795 + 5.906 \times 10^{-11} T' - 5.9 \times 10^{-15} T'^2\end{gathered} \tag{2}$$

where T' is the number of Julian centuries (consisting of 36 525 days) of 86 400 seconds of dynamical time each) elapsed since JD 2 451 545.0 TDB. (Dynamical Time, more fully discussed below, is a uniform time scale based on atomic frequency standards; TDB refers to Dynamical Time as defined at the solar system barycenter.)

Equation (1) provides the Greenwich mean sidereal time at 0^h UT1. At some arbitrary time other than 0^h, the Greenwich Mean Sidereal Time can be determined by multiplying the UT interval elapsed since 0^h by the ratio of solar to sidereal time given in expression 2 and adding that product to the GMST at 0^h. An alternate method is to use the expression

$$\begin{gathered}S(T') = \\ 18^h\ 41^m\ 50^s\!.54841 + (876600^h + 8640184^s\!.812866))T' \\ +0^s\!.093104 T'^2 - 6^s\!.2 \times 10^{-6} T'^3.\end{gathered} \tag{3}$$

This provides what may be called "Dynamical Sidereal Time" at time T′ which practically speaking is the same as Greenwich Mean Sidereal Time.

Once GMST is obtained, a longitude correction should be applied to give local mean sidereal time (LMST). This correction should be of the form:

$$\text{LMST} = \text{GMST} - \text{site longitude}$$

where the site longitude is measured westward from the Greenwich meridian. In order to obtain local *apparent* sidereal time, it is necessary to apply nutation corrections to the already determined local mean sidereal time.

By the mid 1930's it became apparent from astronomical observations that the Earth's rate of rotation was not a constant [4]–[6]. However, the Earth's rotation continued to be the source of civil time with astronomical observatories correcting mechanical clocks to conform to the observed mean solar time. In 1925, *Universal Time (UT)* came into general use although it was referred to by different names in various ephemerides. UT was defined as mean solar time beginning at midnight.

By 1956 a system of UT came into general use. In this system UT0 designates the time which was observed locally at an observatory. UT1 designates the true rotation angle of the Earth with respect to the defining fiducial point. It is the hour angle of the fiducial direction observed at longitude zero degrees. It was formed originally from a combination of observed values of UT0 contributed to the Bureau International de l'Heure (BIH) in Paris corrected for the observed motion of the rotational pole with respect to the surface of the Earth.

Because the axis of symmetry of the Earth is not aligned precisely with the axis of rotation, the Earth executes a motion about its center of mass known as polar motion. This motion, caused by meteorological and geophysical effects on and within the Earth, is not predictable with accuracy, and must be observed continuously to provide the most precise information on the orientation of the Earth. Polar motion is characterized mainly by approximately 435-day circular and 365-day periodic elliptical motions of the axis of rotation on the surface of the Earth. The radius of the motions is of the order of 5 m (16 ft), but this may vary.

UT2 is defined as UT1 corrected for the observed annual and semiannual variations in the Earth's rotational speed, and was originated to serve as a more uniform type of mean solar time. Currently, it is used only for research purposes and has no use in civil timekeeping. UT2 can be derived from UT1 using the expression,

$$\begin{gathered}\text{UT2} - \text{UT1} = \\ 0.0220\ \sin 2\pi t - 0.0120\ \cos 2\pi t \\ -0.0060\ \sin 4\pi t + 0.0070\ \cos 4\pi t\end{gathered} \tag{4}$$

the unit being the second, and t being the date in Besselian Years,

$$t = 2000.000 + (\text{MJD} - 51544.03)/365.2422$$

where MJD = JD − 2 400 000.5.

Coordinated universal time (UTC), designates the coordinate clock time scale which approximates the rotational time of the Earth. From the time of its inception its rate and/or epoch have been adjusted to keep it near UT1. The current practice is to adjust UTC in epoch by integral seconds (leap seconds) to keep the difference between UT1 and UTC less than 0.9 seconds. UTC as defined by the International Radio Consultative Committee (CCIR) Recommendation 460-4 (1986), differs from Temps Atomique International (TAI) by an integral number of seconds. TAI is the atomic time scale of the Bureau

International des Poids et Mesures (BIPM). Its unit is exactly one Systeme International (SI) second at sea level. The origin of TAI is such that UT1−TAI is approximately 0 on January 1, 1958. The instability of TAI is about 6 orders of magnitude smaller than that of UT1. UT1 is often obtained by users through tabulations of the differences UT1−TAI or UT1−UTC.

The decision to introduce a leap second in UTC is the responsibility of the International Earth Rotation Service (IERS). According to the CCIR Recommendation, first preference is given to the opportunities at the end of December and June, and second preference to those at the end of March and September. Since the system was introduced in 1972, only dates in June and December have been used. The basic unit of the UTC time scale is the SI second defined by the frequency of an atomic transition in the Cesium atom. UTC serves as the basis for civil time in most of the countries of the world. DUT1 is the difference UT1−UTC, expressed with a precision of ±0.1 seconds, and broadcast with time signals. IERS notifies users of changes in DUT1.

Until recent times the rotation of the Earth has served as the definition of time. The assumption was made that the rotational speed of the Earth was essentially constant and repeatable, and that the length of the day which resulted from this constant rotational speed was naturally useful as a measure of the passage of time. Astronomical observations, however, have shown that the speed with which the Earth is rotating is not constant with time. The variations in rotational speed may be classified into three types: secular, irregular, and periodic [7], [8].

The secular variation of the rotational speed refers to the apparently linear increase in the length of the day due chiefly to tidal friction. The Moon raises tides in the ocean. Friction carries the maximum tide ahead of the line joining the center of the Earth and Moon. The resulting couple diminishes the speed of rotation and this reacts on the Moon to increase its orbital momentum. This effect causes a slowing of the Earth's rotational speed resulting in a lengthening of the day by about 0.0005 to 0.0035 seconds per century.

The irregular changes in speed appear to be the result of random accelerations, but may be correlated with physical processes occurring on or within the Earth. These cause the length of the day to vary by as much as 0.001 seconds over the past 200 years. Irregular changes consist of "decade fluctuations" with characteristic periods of five to ten years as well as variations which occur at shorter time scales. The decade fluctuations are related apparently to processes occurring within the Earth. The higher frequency variations are now known to be related largely to the changes in the total angular momentum of the atmosphere.

Periodic variations are associated with periodically repeatable physical processes affecting the Earth. Tides raised in the solid Earth by the Moon and the Sun produce variations in the length of the day with amplitudes of the order of 0.00005 seconds and with periods of 18.6 years, 1 year, 1/2 year, 27.55 days and 13.66 days, and others. A standard model including 62 periodic components, can be employed to correct the observations for tidal effects. UT1R designates UT1 corrected for the short-term part of the model, i.e., the 41 components with periods under 35 days. UT1R−UT1 is smaller than 2.5 ms in absolute value. Seasonal changes in global weather patterns occurring with approximately annual and semiannual periods also cause variations in the length of the day of this order.

Changes in the total angular momentum of the atmosphere have also been shown to be correlated with changes in the length of the day [9], [10]. The conservation of angular momentum of the Earth requires that changes in the Earth's moments of inertia produce changes in the speed with which the Earth is rotating. The moments of inertia are dependent on the distribution of mass on and within the Earth. This includes the mass contained in the atmosphere and in the oceans. As mass is redistributed, the moments of inertia change, producing the subsequent changes in the rotational speed of the Earth. Precise calculations of the total angular momentum using global observations of the wind speed and direction have been used to demonstrate this effect. The variations in the rotational speed are apparently caused by the interaction of the winds with the Earth's topography, and may be the leading cause for all of the irregular variations in the rotation of the Earth.

The rotational speed of the Earth remains essentially unpredictable in nature due to incompletely understood variations. Because of this, astronomical observations continue to be made regularly with increasing accuracy, and the resulting data are the subject of continuing research in the field.

B. Time Determined from Solar System Motions

Increasing demand for a more uniform time scale resulted in the definition of *Ephemeris Time* (ET) in 1950 [11]. This time scale is defined in terms of the revolution of the Earth about the Sun, its second being defined as the fraction 1/31 556 925.9747 of the length of the tropical year at January 0 1900 12^h ET. Its theoretical foundation is the time argument inherent in the integration of the equations of motion of the solar, lunar, and planetary ephemerides. Thus it obtained the name, "Ephemeris Time". Astronomical observations of the Sun with respect to the stars could be made which would provide the position of the Sun at some instant of UT. Knowing the position of the Sun, the time when an ephemeris showed the Sun to be in that position could be determined (Ephemeris Time) and the difference ΔT = ET−UT1 calculated. The observational differences were tabulated and made available to those requiring a more uniform time scale. In practice however, observations of the Moon were used rather than solar observations because of the relative ease with which they could be made in comparison to solar observations and the faster motion of the Moon. Again, Ephemeris Time was determined observationally and no clock could be said to be keeping Ephemeris Time. Because of this fact Ephemeris Time found little general use. However, with the advent of atomic time standards the frequency of Cesium was defined in terms of Ephemeris Time and thus the current standard definition of the second rests on the observations of the Moon and Ephemeris Time [12].

In 1979, the term "Dynamical Time" was substituted for Ephemeris Time. *Terrestrial Dynamical Time* (TDT) was defined as TAI + 32.184 seconds. This provided a more accessible form of ET. Barycentric Dynamical Time (TDB) was defined as TDT corrected to the barycenter of the solar system taking into account relativistic terms in the transformation between the two locations. TDT can be thought of as the continuation of the Ephemeris Time scale. TDB finds use in the integration of the equations of motion in celestial mechanical problems. The difference between UT and Dynamical Time reflects the gradual slowing of the rotation rate of the Earth as well as the other variations in its speed of rotation. The IERS Standards [13] gives the procedure for the transformation between TDB and TDT.

III. Determination Of Astronomical Time

Astronomical observations of stars, radio sources, quasars, the Moon, and artificial Earth satellites are used to determine astronomical time within an inertial reference system defined by the positions and motions of the celestial objects.

A. Determination of Rotational Time

Rotational time has been determined from astronomical observations which have included analyses of eclipse records, naked eye and telescope timings of star transits, radio interferometry, and laser ranging to artificial Earth satellites and the Moon. The times and locations of past eclipse observations provide historical information on the length of the day. If the Earth has changed its speed of rotation since ancient times, the path of an eclipse which occurred thousands of years ago would be displaced in longitude with respect to the path that would have occurred if the rotational speed had remained constant. Ancient records of eclipses, while not made with great accuracy, are valuable for the reason that they were made long ago. Comparison of very old observations of the longitude of the Sun with current theories of the motion of the Sun based on a uniform time scale has also been used to estimate the increase in the length of the day since ancient times.

Observations of the transits of stars across the local meridian served as the basis for the correction of clocks, particularly with the advent of the telescope. Various kinds of telescopes were used over the years, the most precise being the photographic zenith tube, an instrument designed to record the time of transit of stars through the local zenith. This instrument was capable of providing rotational time with an accuracy of ±0.005 seconds in one night's observations [14].

Currently, UT1 is determined from multiparameter solutions of very long baseline interferometry (VLBI), satellite laser ranging (SLR), and lunar laser ranging (LLR) [15]–[18]. This UT scale (UT1) is compared with time scales known to be more uniform in nature such as Dynamical Time or atomic clocks (International Atomic Time). Variations in the differences among these types of time scales may be used to determine variations in the rotational speed of the Earth. Astronomical observations of time are made routinely by a number of observatories located around the world for this purpose.

B. Determination of Time from Solar System Motions

Ephemeris Time was determined astronomically using a camera which recorded the position of the Moon on a stellar background [12]. This permitted the position of the Moon to be determined with high precision in the reference system of the stars used. With the position of the Moon known, the Ephemeris Time corresponding to the UT of the observation could be found, and the difference $\Delta T = ET - UT$ determined. Figure 1 shows a plot of this quantity.

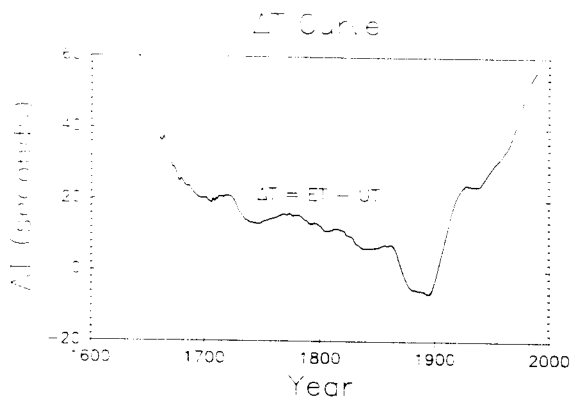

Fig. 1. Observed $\Delta T = ET - UT$.

Analyses of astronomical observations reveal the three types of variations in the speed of rotation. The ancient observational data form the basis for estimates of the secular deceleration in the speed of rotation. The more recent information, having been obtained with higher accuracy and more regularity, has shown the changes in the acceleration causing the irregular variations in the length of the day. These data have also been used to detect the periodic variations in the length of the day. Figure 2 shows the difference between the rotational time (UT1), a time scale based on the Earth's rotation (UTC) and a uniform time scale (TAI).

Figure 3 shows a plot of the excess length of day in milliseconds (thousandths of a second) since 1985.

Figure 4 shows the difference between UT1 and UTC during 1990 illustrating typical observed variations in UT1 due to changes in the Earth's rotation rate.

IV. International Coordination

The International Earth Rotation Service (IERS) is the international organization responsible for the coordination of observations of polar motion and nutation as well as astronomical time. The Central Bureau is located at the Paris Observatory. Subbureaus devoted to rapid service

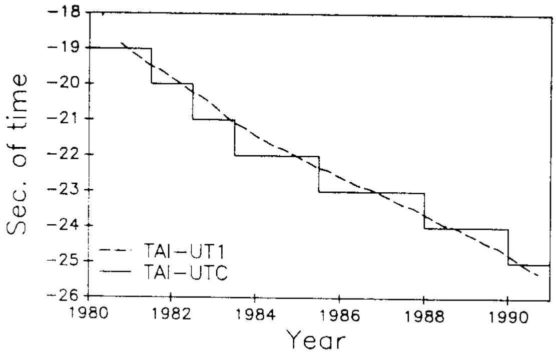

Fig. 2. The difference between TAI and UT1 and UTC.

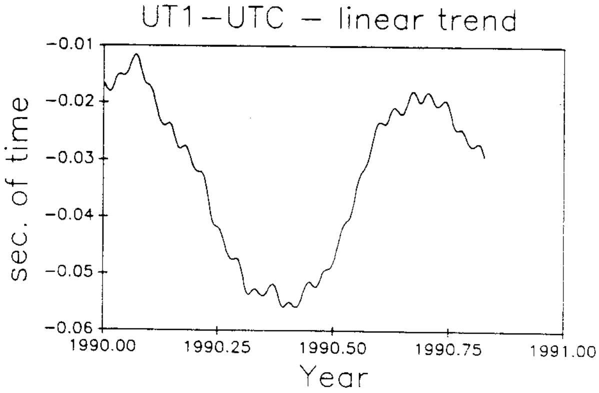

Fig. 4. UT1−UTC during 1990 with a linear trend removed.

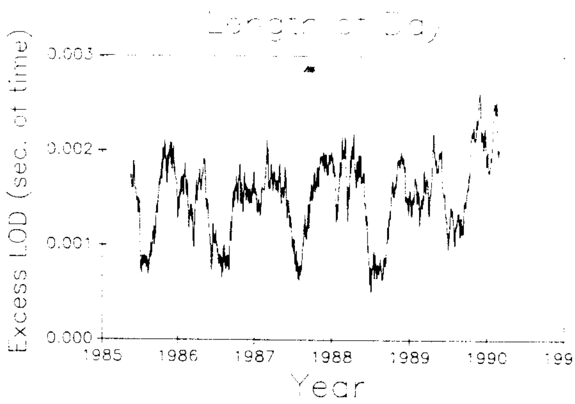

Fig. 3. Excess length of day.

and predictions, atmospheric angular momentum, and possible use of GPS in the determination of Earth orientation are located at the U.S. Naval Observatory, the National Meteorological Center and the Jet Propulsion Laboratory, respectively. Observations are contributed to the IERS by observatories and laboratories about the world and treated at analysis centers. Quick-look results are transmitted weekly in parallel to the Subbureau for Rapid Service and Predictions and to the Central Bureau. Refined results are transmitted yearly to the Central Bureau. The Central Bureau and the Subbureau for Rapid Service and Predictions combine the data to provide more accurate estimates by eliminating systematic errors. This involves the application of systematic corrections and statistical weighting. These data are then disseminated to users. The Subbureau for Rapid Service and Predictions publishes a weekly bulletin (IERS Bulletin A) and the Central Bureau publishes a monthly bulletin (IERS Bulletin B) and Annual Report. The Annual Report, issued six months after the end of each year, contains information on the data used, the models, the algorithms and the reference frames, as well as revised solutions for past years.

The accuracy of these solutions is given in Table 1. Bulletins A and B provide predictions of UT1−UTC for up to one year in the future with variable accuracy.

Bulletin A is distributed by the Rapid Service Subbureau, at the U.S. Naval Observatory by 0^h UTC of Friday of each week via airmail, GE Mark 3 (RC28 Catalog, contact: EARTH), EARN/BITNET (contact: EOP@USNO01.USNO.NAVY.MIL, SPAN (contact: 6899::EOP), and INTERNET (contact: EOP@USNO01.USNO.NAVY.MIL). Bulletin B is distributed by the Central Bureau, at the Paris Observatory between the 1st and the 6th day of each month by airmail, GE Mark3 (RC28 Catalog, contact: IERS-CB), EARN/BITNET (contact: IERS at FRIAP51), and SPAN (contact: IAPOBS::IERS)

Table 1 Accuracy of the Various Solutions

Solutions		UT1−UTC 0.0001 s
Bulletin A	daily	0.8
prediction	10d	14.
	40d	70.
	90d	138.
Bulletin B		
smoothed	1–d, 5–d	0.6
raw 5–d		0.9
prediction	10d	18.
	40d	60.

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