DEFINITION, REQUIREMENT, AND THE DETERMINATION OF UT1 BY THE U. S. NAVAL OBSERVATORY (USNO)

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Abstract

Universal Time (UT) is a form of mean solar time, the period of which is a fraction of the rotational period of the Earth measured with respect to a frame of reference fixed in space. The time scale determined from astronomical observations is designated as UT0. The UT1 time-scale is obtained by correcting UT0 for the changing orientation of the rotational pole with respect to the observer. The epoch of coordinated Universal Time (UTC) is adjusted occasionally so that UTC remains within ±0.9 second of UT1.

The UT1 time scale is not only essential for timekeeping purposes but it is also necessary for geodesy; astronomical observations of all kinds; navigation on sea, air, and in space; and astronomical and geophysical research. The definition of UT1 as well as the procedures for observing and determining this time scale will be outlined. It is important that we strive to obtain the most accurate determinations of UT1 since many users have stringent requirements for precision, accuracy, and consistency.

Introduction.

Traditionally time has been based on the rotation of the Earth with respect to the Sun. The present realization of this time scale is called Universal Time. This is a form of mean solar time, the period of which is a fraction of the rotational period of the Earth with respect to a frame of reference fixed in space. Operationally, Universal Time is defined as "12 hours + Greenwich Hour Angle of a point on the equator whose right ascension is given by R_u = 18h 38m $45^{s}.836 + 8640184^{s}.542 T_u + 0^{s}.0929 T_u^2$ where T_u is the number of Julian centuries of 36525 days of Universal Time elapsed since the epoch of Greenwich mean noon (regarded as 12h UT) on 1900 Jan. 0." (Explanatory Supplement, p. 73).

Universal Time is by definition an observational time scale. The point, R_u, referred to in the definition is not identified with any physically observable point. It is only a point used to define Universal Time. The Greenwich Hour

Angle of this point depends on the orientation of the Earth in the reference frame. Since it is known that the Earth experiences small, unpredictable changes in its rotational velocity the time scale is necessarily non-uniform. The time observed at observatory "i" is referred to as UT0(i). This quantity depends on the location of the observer on the surface of the Earth with respect to the instantaneous pole of rotation and its angular distance from Greenwich as well as the rotational speed of the Earth.

Since the rotational pole is moving with respect to the surface of the Earth its position with respect to the Conventional International Origin (CIO) is determined from observations in angular measures in two coordinates (x,y). The x-axis is directed along the meridian of Greenwich while the y-axis is directed along the meridian of 90° west longitude. The time scale UT1(i) is obtained from UT0(i) by correcting for the effect of polar motion using the expression

$$UT1(i) = UT0(i) + (x \sin \lambda(i) - y \cos \lambda(i)) \tan \phi(i)/15, \qquad (1)$$

where $\lambda(i)$ and $\phi(i)$ are the longitude and latitude of observatory i.

In addition, corrections for annual and semi-annual variations in the rotational speed of the Earth due to meteorological and tidal effects may be applied to obtain UT2(i). The empirically determined expression which has been in use as recommended by the Bureau International de l'Heure (BIH) since March 1962 is

$$UT2(i) = UT1(i) + 0\overset{s}{.}022 \sin 2\pi T - 0\overset{s}{.}012 \cos 2\pi T - 0\overset{s}{.}006 \sin 4\pi T + 0\overset{s}{.}007 \cos 4\pi T, \qquad (2)$$

where T represents the fraction of the Besselian year of the observation.

Determination of Universal Time.

In practice UT0(i) is determined from the astronomical observations of the diurnal motion of stars through the intermediary of sidereal time. The sidereal time at any instant at any location is defined as the local hour angle of the equinox at that instant. Since the equinox is not an observable point, stars are observed whose positions with respect to the equinox are well known.

An observation of a star in this case usually is the determination of the time of transit of a star across the observer's meridian on some reference clock. This observation may be affected by accidental and systematic errors in the assumed position of the star, refraction in the atmosphere and by variations in the observer's apparent meridian caused by lunisolar tidal or other geophysical influences on the direction of the vertical.

Astronomical observations used in the determination of Universal Time are made by the U. S. Naval Observatory using photographic zenith tubes (PZT) located in Washington, DC, and Richmond, FL. This instrument has been described by Markowitz (1960). Essentially, it is used to determine the clock time of transit of selected stars across the instrumental meridian.

With the PZT the UT0 time of transit of a star across the meridian of the instrument is computed using the expression

$$T_C = (\alpha + \lambda - ST - EQ)r, \qquad (3)$$

where

α = apparent right ascension of the star,

λ = astronomical longitude of the instrument,

ST = Greenwich mean sidereal time at 0h UT,

EQ = equation of the equinoxes, and

r = ratio of mean solar to mean sidereal interval

(0.997269566414 at epoch 12h UT January 0, 1900).

The apparent right ascension is computed using a standard method allowing for the effects of precession, nutation, stellar and diurnal aberration (Explanatory Supplement, p. 145; Woolard and Clemence, p. 299). The Greenwich mean sidereal time at 0h UT is computed from the expression

$$ST = 6h\ 38m\ 45^{s}.836 + 8640184^{s}.542\ T_u + 0^{s}.0929\ T_u^2 \qquad (4)$$

(Explanatory Supplement, p. 75). The equation of the equinoxes is the difference between apparent and mean sidereal time and is computed from the theory of nutation (Explanatory Supplement, p. 43).

The portion of (3) within the parentheses represents twelve hours of mean sidereal time + the interval in mean sidereal time between the passage of the star and the point R_u across the local meridian. This sidereal interval is then converted to a Universal Time interval using the ratio of mean solar to mean sidereal time interval.

Four exposures of the star are made with the PZT as the star crosses the instrumental meridian. The mean epoch in UTC of the four exposures can be denoted as T_O. The hour angle of the star at T_O is found from the reduction of the measurements of the star's images on the photographic plate and is designated H_O. The difference $T_C - (T_O - H_O)$ is then the quantity UT0-UTC as determined from the observation of that star.

Around 40 stars are observed on each clear night at each of the two sites at which the Naval Observatory has a PZT. The mean value of the individual determinations of UT0 is accepted as the observed value of UT0(i) for that day. The value of UT1 obtained using (1) and polar coordinates provided by the BIH are numerically smoothed and combined to obtain the final values of Naval Observatory UT1 (McCarthy, 1976). Observations of UT0 are also sent to the BIH where they are included in the international scale of UT1.

The internal mean error of one night's observation of UT0 is approximately three to four milliseconds. There seems to be very little dependence of the internal mean error on the number of stars in one sight.

The external mean error of one night's PZT observation may be evaluated using the residuals from a smooth curve fitted to the observations. Analysis shows an external mean error of one sight to be about five to seven milliseconds. The difference between the internal and external errors of the PZT observations for one night lead to the conclusion that a systematic error of about six milliseconds may be present in each night's PZT observation (McCarthy, 1974).

The major sources of error are inaccuracies in the adopted positions and proper motions of the observed stars and refraction anomalies. The catalog positions and proper motions are determined from the observations with the PZT since no fundamental catalog positions and proper motions of the required accuracy exist for the faint stars which are observed. The PZT star positions and proper motions are adjusted to minimize the star residuals. The resultant positions are then corrected by a constant amount determined from the systematic difference between the catalog positions and a catalog of PZT stars observed with a transit circle and referred to the FK4 system (McCarthy, 1973). The systematic errors resulting from the catalog are probably less than three milliseconds which would indicate that the systematic errors found in the PZT observations are largely due to refraction anomalies.

The anomalies in refraction which influence the PZT observations have characteristic periods of a minute and of a day. The short period anomalies affect the determination of time with a single star while the long period anomalies influence the night-to-night differences. Geophysical effects that influence the shape of the local geopotential surface may also provide a source of systematic error which, although probably very small, must be investigated. Instrumental errors can be kept minimal with proper maintenance.

Requirements for UT1.

The time scale UT1 is required by all who need to know the orientation of the Earth with respect to some celestial object. In addition to astronomers and those engaged in geophysical research this includes the fields of surface and space navigation and geodesy. Requirements vary among users and to discuss these needs it must be clear what is meant by the terms precision, accuracy, and consistency in this context.

By precision we mean that the individual star observations made on one night agree internally with each other without regard to any external system. Precision may be estimated from the internal mean error of one night's determination of UT0. Accuracy refers to the day-to-day agreement of the observations with themselves in some defined system. This may be estimated by the goodness of the fit of the observations to some smooth curve. The defined coordinate system may be defined explicitly by the instrumental bias (if any), star catalogs, observational procedures and method of reduction. Consistency refers to the ability to maintain one system over an indefinite period of time. If changes are made in the system, consistency demands that they can be well documented and that new observations may be related to old ones in a known way. These distinctions are important since some users may require extreme consistency but may not be concerned with the observational precision while others may be interested in high accuracy without much concern for the history of past observations and their consistency.

In general, precision is mostly of interest to those directly involved in determining UT1, where measures of precision are used to understand the reliability and workability of their instrumentation. Most actual users are concerned with accuracy and consistency of the data. It is difficult to state specific numbers for the accuracy and consistency required by the user since in most cases the error tolerance in UT1 is part of an error budget which may contain many poorly defined errors. Thus some users may not have a specific numerical value for their tolerance levels. Apparently their needs are being met with currently available data since they have not shown a more specific requirement. Another problem incurred when requirements are assessed is that users will simply say that what is required is simply the best that can be provided. The most accurate and consistent data are, of course, desired by all and there are ongoing efforts to improve the quality of UT1 data. Also, improvements in the quality of UT1 may lead to scientific and technological improvement by the user which in turn may produce more stringent requirements.

Classical celestial navigation on the surface or in the air demands a knowledge of UT1 with an accuracy of $\pm 0\overset{s}{.}5$. Such an error could lead to a maximum uncertainty of 1/4 mile at the equator. This is well within the ±2 mile uncertainty in a typical celestial fix (Dunlap & Shufeldt, p. 649). Navigation by artificial Earth satellites is presently used for navigation to a much higher accuracy and thus requires a more accurate UT1. The Global Positioning System which will be used in the future will have a $\pm 0\overset{s}{.}007$ requirement in accuracy for UT1. Navigation in space imposes a requirement of $\pm 0\overset{s}{.}002$ in accuracy. This is considered by Jet Propulsion Laboratory to be part of the error budget in the location of their monitoring stations.

Astro-geodetic work is an area in which accuracy is important, but consistency is of greater concern. Users in this field must be assured that astronomical longitude is referred to the same system for all of their observations which may extend for over 50 years. Accuracy of ±5 milliseconds may be tolerated in their error budget since the accuracy of a determination of longitude is typically on the order of 15 milliseconds. However the consistency of the system must also be of the order of a few milliseconds so that systematic errors are not introduced in the network of observed astronomical longitudes.

Most astronomers can be satisfied with an accuracy of $\pm 0^{s}.1$. However, there are fields of astronomical research where the best possible accuracy and consistency is required. These include classical and radio astrometry, determination of astronomical constants, and research into the rotation of the Earth. The validity of the research in these areas depends directly on our ability to produce accurate and consistent UT1.

Conclusion.

The determination of UT1 tends to be overlooked in the era of nanosecond timing with clocks. However, it must be realized that there are many requirements for the use of UT1. The determination of UT1 is an area where extreme care must be used to insure that accuracy and consistency is not compromised but further improved for future needs.

References.

1. Dunlap, G. D. and Shufeldt, H. H., Dutton's Navigation and Piloting, 1972, Naval Institute Press, Annapolis.

2. Explanatory Supplement to the American Ephemeris and the American Ephemeris and Nautical Almanac, 1961, Her Majesty's Stationery Office, London.

3. Markowitz, Wm., 1960, "The Photographic Zenith Tube and the Dual-Rate Moon-Position Camera", in Telescopes, G. P. Kuiper and B. M. Middlehurst, editors, University of Chicago Press, Chicago.

4. McCarthy, D. D., 1973, Astron. J. **78**, 642.

5. McCarthy, D. D., 1974, "The Determination of the Rotational Motion of the Earth with a Photographic Zenith Tube", Paper presented to AIAA Mechanics and Control of Flight Conference, (Available from AIAA Library, New York).

6. McCarthy, D. D., 1976, U. S. Naval Observatory Circular No. 154.

7. Woolard, E. W. and Clemence, G. M., 1966, Spherical Astronomy, Academic Press, New York.