Astronomical Times

There are two widely used time standards. One is the rotation of the earth, and the other is the frequency of atomic oscillations (mainly the cesium-133 atom). The earth's rotation is not uniform. Its rate exhibits both periodic changes and long term drifts on the order of a second per year. Atomic standards are the closest approximations we currently have to a unform time with accuracies on the order of microseconds per year.

Since the advent of atomic time in 1955 there has been a steady transition from reliance on the earth's rotation to the use of atomic time as the primary standard. Before atomic time, the closest approximation to a uniform time was Ephemeris Time (ET), which used the best available theory of the earth's rotation to remove its known changes in rotation rate. The use of Ephemeris Time continued until 1984. It was the time independent variable for planetary ephemerides until then.

Several important time scales still follow the rotation of the earth, most notably civil and sidereal time, but of these are now derived from atomic time through a combination of earth rotation theory and actual measurements of the earth's rotation and orientation. Chapter 2 of the most recent Explanatory Supplement to the Astronomical Almanac [ref 1] gives an extensive summary of time standards and a list of original literature references. The kinds of time typically encountered in astronomy are briefly described below.

You will notice that many of the time acronyms are reversed from their full English names. That's because they are acronyms from French (TAI = *Temps Atomique International*) since France has a long and continuing history as a primary source of time standards, now through the *Bureau International des Poids et Measures*.

Atomic Times

TAI - International Atomic Time

International Atomic Time (TAI) is the primary time standard in the world today. It is the combined input of many clocks around the world, each corrected for known environmental and relativistic effects. A few clocks, such as the cesium clock ensemble at the U. S. Naval Observatory, carry considerable weight in the TAI. In relativistic terms, TAI is an earth-based time since it is defined for a gravitational potential and inertial reference on the surface of the earth. TAI is the standard for the SI (*System International*) second. The zero point of TAI was somewhat arbitrarily defined by early atomic clocks, and its offset from Ephemeris Time was precisely defined as 32.184 seconds for January 1, 1977. See TDT below.

UTC - Coordinated Universal Time

Coordinated Universal Time (UTC) is the time broadcast by WWV and other services. By definition, UTC and TAI have the same rate, but UTC stays close to Mean Solar Time by adding integer numbers of seconds, called leap seconds, from time to time. This keeps solar noon at the same UTC (averaged over the year), even though the rotation of the earth is slowing down. The offset is changed as needed to keep UTC within about 0.9 seconds of earth rotation time, UT1. Leap seconds are typically added once per year at the end of December or June, but they can be added (or subtracted) at other designated times throughout the year. The offset between TAI and UTC is currently 30 seconds, e.g., 20:00:00 UTC = 20:00:30 TAI.

```
UTC = TAI - (number of leap seconds)
```

Before UTC, the time broadcast by WWV and other services was a close approximation to Greewich Mean Time (GMT) [ref 2]. GMT is an earth rotation time and is now called UT1 or simply UT.

TDT or TT - Terrestrial Dynamic Time

Before atomic clocks, Ephemeris Time (ET) was the closest available approximation to a uniform time for planetary motion calculations. Terrestrial Dynamic Time, which is tied to atomic time by a constant offset of 32.184 seconds, replaced ET at the beginning of 1984. The purpose of the offset is to maintain continuity between ET and TDT at the transition. Planetary motions are now computed using Barycentric Dynamic Time (TDB), which is more uniform than TT because it accounts for relativistic corrections due to the earth's motion in the gravitational potential of the solar system.

```
TT = TAI + 32.184 = UTC + (number of leap seconds) + 32.184
```

There is a subtle relativistic distinction between coordinate time and dynamic time, which is not significant for most practical purposes. The counterpart to TT is Geocentric Coordinate Time (TCG) which differs in rate from TT by about 0.7 parts per billion [ref 3]. TT and TCG were coincident on January 1, 1977 and now differ by 0.42 seconds. The rate difference from TT can be important to long term measurements, so make sure you know which time is being used when comparing observations. Some physical constants are different in coordinate time. You are not likely to encounter TCG in the literature.

TDB - Barycentric Dynamic Time

Barycentric Dynamic Time (TDB) is the same as as Terrestrial Dynamic Time (TT) except for relativistic corrections to move the origin to the solar system barycenter. These corrections amount to as much as about 1.6 millisends and are periodic with an average of zero. The dominant terms in this correction are have annual and semi-annual periods.

```
        TDB = TT + 0.001658 sin( g ) + 0.000014 sin( 2g )  seconds
where
        g = 357.53 + 0.9856003 ( JD - 2451545.0 )          degrees
```

and JD is the Julian Date. A more accurate formula, with adds terms smaller than 20 microseconds, is given in the Explanatory Supplement to the Astronomical Almanac [ref 4]. Planetary motions are now computed using TDB.

There is a subtle relativistic distinction between coordinate time and dynamic time, which is not significant for most practical purposes. The counterpart to TDB is Barycentric Coordinate Time (TCB) which differs in rate from TDB by about 15.5 parts per billion [ref 5]. TDB and TCB were coincident on January 1, 1977 and now differ by 9.3 seconds. The rate difference from TDB can be important to long term measurements, so make sure you know which time is being used when comparing observations. Some physical constants are different in coordinate time. You are not likely to encounter TCB in the literature.

Earth Rotation Times

UT1 - Universal Time

Universal Time (UT1) is a measure of the actual rotation of the earth, independent of observing location. UT1 is essentially the same as the now discontinued Greenwich Mean Time (GMT). It is the observed rotation of the earth with respect to the mean sun corrected for the observer's longitude with respect to the Greenwich Meridian and for the observer's small shift in longitude due to polar motion.

Since the earth's rotation is not uniform, the rate of UT1 is not constant, and its offset from atomic time is continually changing in a not completely predictable way. As of December 1995, UT1 was drifting about 0.8 seconds per year with respect to atomic time (TAI or UTC). Since UTC is intentionally incremented by integer seconds (leap seconds) to stay within 0.9 seconds of UT1, the difference between UT1 and UTC is never greater than this. The difference, DUT1 = UT1 - UTC is monitored by the International Earth Rotation Service and published weekly in IERS Bulletin A along with predictions for a number of months into the future.

```
UT1 = UTC + DUT1 (from the IERS Bulletin A)
```

Note that when a leap second is added to or subtracted from UTC, the value of DUT1 is discontinuous by one second. UT1 is continuous, and UTC is incremented or decremented by integer seconds to stay witin 0.9 seconds of UT1.

UT0

UT0 (UT-zero) is an observatory-specific version of UT1 in the sense that UT0 contains the effect of polar motion on the observed rotation of the earth. Polar motion is equivalent to a change in latitude and longitude of points on the earth's surface with respect to the earth's instantaneous rotation axis. Since UT1 is now determined from observations from an ensemble of obsevatories, often as part of VLBI interferometers, the practical use of UT0 has dwindled. The conversion from UT1 to a local observatory time with respect to the mean sun or stars is now done as a set of coordinate rotations that do not explicitly use UT0 as an intermediate step.

From ref [7]

```
UT0 = UT1 + tan(lat) * (x * sin(long) + y * cos(long))
```

where `x` and `y` are the pole offsets published in IERS Bulletin A, and `lat` and `long` are the observatory's nominal station coordinates. `x` and `y` are published in arcseconds so they must be converted to time (one time second = 15 arcseconds).

UT2

UT2 appears to be of mostly historical interest. Before 1972 the time broadcast services kept their time signals within 0.1 seconds of UT2, which is UT1 with annual and semiannual variations in the earth's rotation removed. The formal relation between UT1 and UT2 is

```
UT2 = UT1 + 0.022 * sin(2 * Pi * t) - 0.012 * cos(2 * Pi * t)
          - 0.006 * sin(4 * Pi * t) + 0.007 * cos(4 * Pi * t)
```

where

```
t = 2000.0 + (MJD - 51544.03) / 365.2422
```

is the Besselian day fraction, and MJD is the Modified Julian Date (Julian Date - 2400000.5). See ref [6] and the Explanatory Supplement to IERS Bulletins A and B.

GMST - Greenwich Mean Sidereal Time

Sidereal time is the measure of the earth's rotation with respect to distant celestial objects. Compare this to UT1, which is the rotation of the earth with respect to the mean position of the sun. One sidereal second is approximately 365.25/366.25 of a UT1 second. In other words, there is one more day in a sidereal year than in a solar year.

By convention, the reference points for Greenwich Sidereal Time are the Greenwich Meridian and the vernal equinox (the intersection of the planes of the earth's equator and the earth's orbit, the ecliptic). The Greenwich sidereal day begins when the vernal equinox is on the Greenwich Meridian. Greenwich Mean Sidereal Time (GMST) is the hour angle of the average position of the vernal equinox, neglecting short term motions of the equinox due to nutation.

In conformance with IAU conventions for the motion of the earth's equator and equinox [ref 7] GMST is linked directly to UT1 through the equation

```
GMST (in seconds at UT1=0) = 24110.54841 + 8640184.812866 * T
                           + 0.093104 * T^2 - 0.0000062 * T^3
```

where `T` is in Julian centuries from 2000 Jan. 1 12h UT1

```
T = d / 36525
d = JD - 2451545.0
```

It might seem strange that UT1, a solar time, is determined by measuring the earth's rotation with respect to distant celestial objects, and GMST, a sidereal time, is derived from it. This oddity is mainly due our choice of solar time in defining the atomic time second. Hence, small variations of the earth's rotation are more easily published as (UT1 - Atomic Time) differences. In practice, of course, some form of sidereal time is involved in measuring UT1.

GAST - Greenwich Apparent Sidereal Time

Greenwich Apparent Sidereal Time (GAST) is Greenwich Mean Sidereal Time (GMST) corrected for the shift in the position of the vernal equinox due to nutation. Nutation is the mathematically predictable change in the direction of the earth's axis of rotation due to changing external torques from the sun, moon and planets. The smoothly varying part of the change in the earth's orientation (precession) is already accounted for in GMST. The right ascension component of nutation is called the "equation of the equinoxes" [ref 9].

```
GAST = GMST + (equation of the equinoxes)
```

LMST - Local Mean Sidereal Time

Local Mean Sidereal time is GMST plus the observer's longitude measured positive to the east of Greenwich. This is the time commonly displayed on an observatory's sidereal clock.

```
LMST = GMST + (observer's east longitude)
```

LST - Local Sidereal Time

The definition of Local Sidereal Time given in the glossary of the Explanatory Supplement to the Astronomical Almanac is "the local hour angle of a catalog equinox." This fits the common text book definition

```
Hour Angle = LST - Right Ascension
```

where the right ascension can be specified in one of the catalog coordinate systems B1950 (FK4) or J2000 (FK5), for example. In practice, LST is used more loosely to mean either LMST or "Local Apparent Sidereal Time" = GAST + (observer's east longitude). The operational definition probably varies from one observatory to the next.

IAU Source Code

You can find FORTRAN source code for computing TAI - UTC, TDB - TT, GMST for a given UT1 and the Equation of the equinoxes at this IAU web site.

References

[1] Seidelmann, P.K., Guinot, B., Dogget, L.E., 1992, "Time", Chapter 2, p. 39, *Explanatory Supplement to the Astronomical Almanac*, Seidelmann, P.K., Ed., U. S. Naval Observatory, University Science Books, Mill Valley, CA.

[2] ibid., p. 86.

[3] ibid., p. 47.

[4] ibid., p. 43.

[5] ibid., p. 46.

[6] ibid., p. 85.

[7] ibid., p. 50.

[8] Archinal, B.A., 1992, "Terrestrial Coordinates and the Rotation of the Earth", Chapter 4, p. 253, *Explanatory Supplement to the Astronomical Almanac*, Seidelmann, P.K., Ed., U. S. Naval Observatory, University Science Books, Mill Valley, CA.

[9] Hohenkerk, C.Y., Yallop, B.D., Smith, C.A., Sinclair, A.T., 1992, "Celestial Reference Syatems", Chapter 3, p. 116, *Explanatory Supplement to the Astronomical Almanac*, Seidelmann, P.K., Ed., U. S. Naval Observatory, University Science Books, Mill Valley, CA.

Last updated January, 30, 1996.

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