

Astronomical Time Keeping

<http://www.maa.mhn.de/Scholar/times.html>

Introduction:

Time keeping and construction of calendars are among the oldest branches of astronomy. Up until very recently, no earth-bound method of time keeping could match the accuracy of time determinations derived from observations of the Sun and the planets. All the time units that appear natural to man are caused by astronomical phenomena: The year by Earth's orbit around the Sun and the resulting run of the seasons, the month by the Moon's movement around the Earth and the change of the Moon phases, the day by Earth's rotation and the succession of brightness and darkness.

If high precision is required, however, the definition of time units appears to be problematic. Firstly, ambiguities arise for instance in the exact definition of a rotation or revolution. Secondly, some of the basic astronomical processes turn out to be uneven and irregular. A problem known for thousands of years is the non-commensurability of year, month, and day. Neither can the year be precisely expressed as an integer number of months or days, nor does a month contain an integer number of days. To solve these problems, a multitude of time scales and calendars were devised of which the most important will be described below.

Sidereal Time

The sidereal time is deduced from the revolution of the Earth with respect to the distant stars and can therefore be determined from nightly observations of the starry sky. A sidereal day can be defined in a first approximation as the time interval between two successive passages of the same star through the meridian. Here, the meridian of an observational site is the great circle passing through the two celestial poles and the zenith of the site. Expressed in different words, the meridian is the projection of the circle of the site's geographical longitude onto the celestial sphere if projected from the Earth's centre. The passage through the meridian is thus a more accurate determination of the point in time when -- in colloquial speech -- "the star is due south" (at least for observers on the northern hemisphere). The duration of a sidereal day in units of Universal Time is 23h 56m 04.0905s.

To define more precisely the length of a sidereal day and to establish a zero-point for the counting of sidereal time, the terms "hour angle," "ecliptic," "celestial equator," and "vernal equinox" must be introduced. Through any point on the celestial sphere -- for example the position of a star -- and the two celestial poles passes a uniquely defined great circle that in general does not coincide with the meridian but cuts the meridian at the celestial poles. The cutting angle is called the hour angle of the particular point. This angle isn't usually measured in degrees but in hours, minutes and seconds (hence the name). The full circle of 360 degrees corresponds to exactly 24 hours. Because of Earth's rotation, the hour angle grows by 24 hours within one sidereal day.

The celestial equator is the set of all points on the celestial sphere that are 90 degrees away from the celestial poles, or -- equivalently -- the projection of Earth's equator onto the celestial sphere, if projected from Earth's centre. The ecliptic is the Sun's path on the celestial sphere, among the stars, during the year. The celestial equator and the ecliptic do not coincide (a consequence of the Earth's rotation axis being tilted) but cross each other in two points one of which is called the vernal equinox.

“0 o'clock” sidereal time is defined as the instance when the vernal equinox passes through the meridian. This definition can be generalized to: “sidereal time is the hour angle of the vernal equinox.” Of course, the vernal equinox is a fictitious point on the celestial sphere and cannot be observed directly. From the known coordinates of observed stars, however, the location of the vernal equinox can be deduced. From the above it is also clear that a sidereal day is the interval between two successive passages of the vernal equinox through the meridian. According to this final definition, a sidereal day is shorter by about 9 milliseconds than the approximation given at the beginning. This is a consequence of the fact that due to Earth's precession the vernal equinox is moving with respect to the stars.

The above definition refers to the local meridian and therefore leads to a sidereal time that is dependent on the place of observation. To define a global standard of sidereal time, one refers to the meridian of Greenwich and calls the time scale so derived the “Greenwich Mean sidereal Time” (GMST). To convert between GMST and local sidereal time, the geographical longitude of the observation site must be known.

From the sidereal time and the celestial coordinates of a star (in particular the right ascension) the hour angle of the star and hence its current apparent position (that is constantly changing because of Earth's rotation) can be computed. Moreover, sidereal time is one of the constituents of Universal Time.

Solar Time

Solar time follows the apparent revolution of the Sun around the Earth. A solar day is the interval between two successive passages of the Sun through the meridian, or -- colloquially -- from noon to noon. Of course, this apparent revolution only reflects the true rotation of the Earth. However, because in the run of one day the Earth also travels a considerable part of its orbit around the Sun, a complete rotation with respect to the Sun lasts longer than a complete rotation with respect to the stars. Consequently, a true solar day is longer by about 4 minutes than a sidereal day.

The reference point of the true solar time again can be expressed as an hour angle. Since the time reading at the Sun's passage through the meridian should be 12 h, though, the true solar time comes out as the hour angle of the anti-sun (which is the fictitious point on the ecliptic opposite to the Sun). A sundial displays the true solar time at its location.

The duration of the true solar day varies with the seasons. This is a consequence both of the eccentricity of the Earth's orbit and the obliquity of the ecliptic (the tilt of Earth's rotation axis). Firstly, the Earth moves at different speeds in different parts of its elliptical orbit, according to Kepler's second law, hence the Sun seems to move at different speeds among the stars. Secondly, even with a perfectly circular Earth orbit, the Sun would move evenly along the ecliptic but its projection onto the celestial equator would move at varying speeds. In spring and autumn, the Sun is close to the crossing points of ecliptic and celestial equator. Its movement from day to day therefore is slanted to the equator, the projected velocity is thus reduced. During summer and winter, however, the Sun is close to a vertex of the ecliptic and moves parallel to the celestial equator, making the projected velocity large. Both effects result in a variation of the 4 minutes correction to the sidereal day, with the obliquity of the ecliptic having the slightly larger influence.

To obtain a more even time scale, one defines a fictitious “Mean Sun”. This Mean Sun takes the same time from one vernal equinox to the next as the true Sun, but it is supposed to move with constant velocity along the celestial equator. Mean Solar Time is therefore the hour angle of the mean anti-sun.

The difference between True and Mean Solar Time is called the equation of time. Because two different effects with different time scales overlap (the eccentricity causes a period of one year, the obliquity of the ecliptic one of half a year), the equation of time has two minima and two maxima per year:

~ 11.Feb	~ -14.5 min
~ 14.Mai	~ +4 min
~ 26.Jul	~ -6.4 min
~ 3.Nov	~ +16.3 min

The equation of time also causes asymmetrical shifts of the rising and setting times of the Sun. The earliest sunset, for instance, does not happen on the winter solstice on Dec 22 but about 11 days earlier. The latest sunrise on the other hand happens about 10 days after the winter solstice. For the same reason, morning and afternoon have different lengths on the equinoxes on Mar 21 and Sep 23.

Universal Time (UT), Greenwich Time

The Universal Time (UT) was introduced in the year 1926 to replace the Greenwich Mean Time (GMT). At this time, several definitions of GMT were in use, sometimes with considerable differences. The term GMT had thus become useless and was dropped and replaced by a more stringent definition of UT.

For most practical purposes, UT is equivalent to the Mean Solar Time for the Greenwich reference meridian. The relation between UT and local Mean Solar Time is the same as between Greenwich Mean sidereal Time and local sidereal Time. Basically, however, UT is not a solar time in the sense that the observed solar position would be used to define this time. The achievable accuracy for a measurement of the Sun's position is far too insufficient for this purpose. Instead, UT is derived from the more precise sidereal Time by means of a mathematical formula. This formula accounts for the known shape of Earth's orbit with which the position of the fictitious Mean Sun can be calculated. Consequently, UT and sidereal Time are not independent time scales but two forms of the same scale, although with units of different length.

Upon closer inspection, the Universal Time UT has to be differentiated further. The directly observable sidereal Time, converted to the Greenwich reference meridian and subjected to the transformation formula determines the time UT0. Due to the slight movements of the Earth's poles of rotation the difference in geographical longitude between the place of observation and the reference meridian varies. Therefore, the conversion to the reference meridian according to tabulated common longitudes is incorrect. If the pole variation is accounted for, one obtains the time UT1. This timescale is consistent for all places on the Earth but still irregular since the rotational velocity of the Earth is known to be variable. A correction of UT1 for the strongest and most regular variations yields the time UT2. This correction amounts to +/- 30 milliseconds at most. UT2 is the most uniform timescale that can be predicted from Earth's rotation. Because of the availability of time standards that are more precise and easier to obtain (atomic clocks) UT2 has hardly any practical use. The Universal Time commonly adopted in astronomy is therefore the UT1 scale.

UT1 has the advantage of predicting the solar position to sufficient accuracy. Its disadvantage, however, is that the length of a second derived from UT1 varies noticeably (caused by the irregularities of Earth's rotation). Therefore, a timescale named Coordinated Universal Time (UTC) was invented in which the SI-second -- as implemented by atomic clocks -- is the unit of time. In addition, it is required that the absolute value of the difference UTC - UT1 never exceeds 0.9 seconds. UTC therefore offers both a highly constant unit of time as well as agreement with the position of the Sun. For this reason, UTC is

the basis for all civil time keeping today. It is distributed publicly by DCF77 radio transmitters and other time services, together with an extrapolation of the current time difference $DUT1 = UTC - UT1$. (This difference has to be extrapolated because UT1 must be determined from observations and cannot be calculated and distributed instantly.)

Since UTC, as well as Atomic Time TAI, is based on the SI-second, both timescales are basically in step with each other. However, the SI-second does not agree with the UT1-second, therefore UTC drifts with respect to UT1. To account for the above-mentioned requirement about UTC-UT1, leap seconds must occasionally be inserted into or dropped from UTC. This happens -- if necessary -- on Jun 30 or Dec 31 at the end of the last minute of the day. Currently, about two leap seconds must be inserted in an interval of three years. The need for a leap second is determined by the Bureau International de l'Heure (BIH) in Paris, after consultation with several time laboratories.

The need for leap seconds is not caused by the secular slowdown of Earth's rotation (which is less than 2 milliseconds per century) but by irregular variations in this rotation and by the fact that the definition of the SI-second is fixed on the duration of the year 1900 which was shorter than average.

Time zones

The establishment of time zones accounts for the fact that for any given instance the Sun is rising on one place on the Earth, is standing high in the south at noon for another place, and is setting for a third place. Considering these astronomical facts, it makes sense to use different civil timescales at different places on the Earth. Ultimately, however, the adoption of a local timescale is a political decision and is therefore handled differently in individual countries.

A time zone is a region of a common civil timescale that is in general oriented along a meridian of constant geographical longitude. The local time of a time zone usually differs by an integer number of hours from Universal Time, although sporadically other differences occur. The difference "local time" minus "Universal Time" is positive for time zones east of Greenwich and negative for western time zones. Frequently mentioned time zones are:

- West European Time (= Universal Time, difference 0 hours)
- Central European Time (+1 hour)
- in the USA:
 - Atlantic Standard Time (-4 hours)
 - Eastern Standard Time (-5 hours, east coast)
 - Central Standard Time (-6 hours)
 - Mountain Standard Time (-7 hours)
 - Pacific Standard Time (-8 hours)
- Moscow Time (+3 hours)
- Tokyo Time (+9 hours)

Daylight saving time is decreed for entirely political reasons and has no astronomical basis.

Atomic Time

In the Systeme Internationale of units of measurements the second is defined as the duration of 9 192 631 770 cycles of a particular hyperfine structure transition in the ground state of Cesium-133. This

definition was chosen to match as best as possible the length of the ephemeris second that was used before.

The SI-second only defines an abstract atomic time. To obtain a timescale of practical usability a device is required that attempts to realize the SI-second. Such a device is called an atomic clock. Real-world atomic clocks do not agree fully with each another. Therefore, the weighted mean of many atomic clocks -- distributed over various laboratories on the whole Earth -- is used to define the Atomic Time TAI (French Temps Atomique International). TAI is currently the best realization of a timescale based on the SI-second, with a relative accuracy of $\pm 2 \times 10^{-14}$ (as of 1990).

According to the General Relativistic Theory, the time measured depends on the location on Earth (or more precisely, on the altitude) and also on the spatial velocity of the clock. TAI thus refers to a location on sea level that rotates with the Earth.

Ephemeris Time, Dynamical Time Scales (TDT, TDB)

Ephemerides are tables that list the positions of Sun, Moon, planets and their respective moons at different times. Formerly, the positions were given as a function of Greenwich Mean Time (GMT) which led to recurring problems, in particular with predictions for the Moon's motion. Finally (at about 1930), it was realized that Earth's rotation is irregular and that any timescale derived from it must be erratic. However, the application of dynamical laws of motion -- like for instance Newton's laws of force -- requires a smoothly flowing time as the independent variable. The Ephemeris Time (ET) was consequently defined as the timescale that together with the laws of motion correctly predicts the positions of celestial bodies, and it is therefore used as the argument in the ephemerides. The current Ephemeris Time is thus determined by comparing the observed positions with the ephemerides.

Formally, ET was defined by Newcomb's theory of the Sun. In 1958, the International Astronomical Union (IAU) at its 10th general assembly stipulated that

“... Ephemeris time is reckoned from the instant, near the beginning of the calendar year AD 1900, when the geometric mean longitude of the Sun was 279 degrees, 41 minutes 48.04 seconds, at which instant the measure of Ephemeris Time was 1900 January 0, 12 o'clock precisely.”

With respect to the unit of time, the IAU and the International Committee for Weights and Measures agreed on the definition

“The second is the fraction $1/31\,556\,925.9747$ of the tropical year at 1900 January 0, 12 o'clock Ephemeris Time.” (Translation DH)

which was published in 1957. With these definitions, Ephemeris Time is equivalent to the time values in Newcomb's tables of the solar position.

For practical time measurements, however, the quoted definitions are unsuitable because precise determinations of the actual solar position are difficult. Instead, the difference ΔT between ET and UT was deduced from observations and ephemerides of the Moon. Observationally, the Moon is well suited for this purpose because of its fast apparent motion on the celestial sphere. However, the computation of its ephemerides is difficult and requires the knowledge of some physical constants (like for instance the

flattening of Earth's figure and the tidal friction) in addition to the gravitational constant. Between the years 1960 and 1984 the Moon theory was repeatedly improved on, each time with consequences for the realization of Ephemeris Time. For precise computations, the applied realization of ET (named as ET0, ET1, and ET2) must therefore be taken into account.

In addition to being dependent on the details of the Moon theory, ET has the further disadvantage of not accounting for effects to be expected according to the theories of Special and General Relativity. When this deficit became important as the accuracy of measurements and the demands on theoretical prediction increased, ET had to be replaced by better timescales. These successors are generally called dynamical timescales because they are based (like ET) on planetary and lunar motions calculated from dynamical laws. In contrast to ET, relativistic equations of motion are used here.

In the context of the theory of relativity, time measurements depend on the reference point. Such reference points with astronomical importance are the Earth's surface and the solar system's centre of mass. The two timescales created for these reference points depend in different ways on the dynamical theory (where we accept the possibility that the theory of relativity does not correctly describe the true dynamics of the system). One is free, however, to define one of these two timescales.

In 1977, the general assembly of the IAU in Grenoble, France defined the timescale TDT (Terrestrial Dynamical Time) of a reference point on Earth's surface through the requirements that the unit of TDT time should be the SI-second and that the instant 1977 January 1, 0 o'clock TAI corresponds to 1977 January 1, 0 hour 0 minutes 32.184 seconds TDT. The difference of 32.184 seconds is in keeping with the difference between TAI and ET at that time and was chosen for continuity in the change from ET to TDT. Despite the reference to the common SI-second, TAI and TDT are basically not identical timescales. TAI is subject to possible systematical errors in the realization of atomic time whereas TDT is an idealized uniformly flowing time. In the foreseeable future, the difference is at best noticeable in the timing of milli-second pulsars. (It should also be pointed out that the above definition makes TDT basically an atomic time that not necessarily describes correctly the dynamics due to gravitation. Up until now though, no evidence exists for a divergence between ideal atomic time and ideal dynamical time.)

The above-mentioned general assembly of the IAU also decreed that timescales that refer to the centre of gravity (the barycentre) of the solar system differ from TDT only in periodical terms. Such timescales are called TDB (Barycentric Dynamical Time). In practice, they are calculated from TDT with consideration of the constants, positions, and motions of the Sun, the Moon, Jupiter, Saturn, and the barycentre of the solar system and the assumption of a theory of gravitation. For the latter, the theory of General Relativity is employed nowadays. The TDB so derived differs by at most 10 milliseconds from TDT. This difference is negligible for most applications.

Further timescales with the names Terrestrial Time (TT), Geocentric Coordinate Time (TCG), and Barycentric Coordinate Time (TCB) were introduced by the IAU in the year 1991, in an attempt to clarify the relations between space-time coordinates. All these timescales are proper times in the diction of the General Relativistic Theory. TT refers to the surface of Earth (at sea level) and is identical to TDT. TCG measures the proper time at Earth's centre and differs from TT by a constant scale factor that follows from the different gravitational potentials at the two reference points. TCB is the proper time of the barycentre of the solar system. It deviates from TDB by a constant scale factor, due to some slightly altered astronomical constants and also because of the above-mentioned requirements that TDB should

differ from TDT only by periodic terms. TDB is therefore tied to the proper time on Earth's surface and because of distinct potentials progresses at a different speed than TCB.

Julian Day Numbers

The Julian day number -- or simply the Julian day -- is a continuous count of days, starting with the day 0 that began on the 1st of January, 4713 BC (in the proleptic Julian calendar, see below) at 12 o'clock noon. Consequently, a new Julian day always begins at 12 o'clock noon that originally gave European astronomers the advantage that all observations of any particular night happened at the same Julian day. This property is unimportant today.

The Julian day count can easily be extended to a precise measure of time by appending the fraction of the day elapsed since 12 o'clock noon. For instance, JD 2 451 605 signifies the day that will begin on March 1, 2000, 12 o'clock noon whereas JD 2 451 605.25 means the point of time at 18 o'clock of the same day. This extension is called the Julian date in many texts (as for example in the *Astronomical Almanac*). Other sources propose to restrict this designation to date specifications in the Julian calendar to prevent confusion. This proposal has not carried through, yet.

Julian days were formerly (if nothing else was specified) counted according to Mean Solar Time, today in UT. Alternatively, specifications were given in Ephemeris Time which was indicated by appending the letters JED or JDE. Also today it is sometimes appropriate to specify Julian Days in another timescale than UT. The employed timescale should then be appended to the time specification, for instance JD 2 451 545.0 TDT for January 1, 2000, 12 o'clock noon as measured in TDT.

Occasionally, time specifications are given in a Modified Julian Day format (MJD). The most common definition of a MJD follows from

$$\text{MJD} = \text{JD} - 2\,400\,000.5$$

with a zero point on November 17, 1858 at 0 o'clock (!) UT, However, there exist other definitions as well so one has to be careful when dealing with times in MJD. For this reason, the International Astronomical Union does not approve of MJD and advises against its use.

In modern astronomy, Julian day numbers are readily employed because they allow compact unambiguous time specifications and the easy computation of time differences, periods etc.

The Julian day number was introduced in 1581 by the French scholar Joseph Justus Scaliger (in his book "Opus novum de emendatione temporum") to define a non-ambiguous time reckoning without negative year numbers. To this end, the beginning of time reckoning had to be sufficiently far back in pre-historic times. Scaliger first construed a Julian Period with a length of 7980 years by combining the following cycles:

- the 28 year-long Sun cycle in which (in the Julian calendar) the calendar dates repeat on the same days of the week (this cycle would be 400 years long in the Gregorian calendar);
- the 19 year-long Metonic cycle in which the phases of the Moon and the Moon eclipses repeat on almost the same calendar dates; and
- the 15 year-long cycle of indiction that was used in the Roman empire for tax collection and census.

The last year in which all three cycles simultaneously began a new period was 4713 BC. Scaliger started his reckoning of time on January 1 of this year. For most people of that time, this date was entirely fictitious as according to their religious belief the world was created a long time after that. Scaliger himself believed Earth was created in the year 3267 BC.

As for the naming of this day count, some contradictory statements can be found in the literature. According to some sources Scaliger named the scale in honor of his father Julius Scaliger. Other sources maintain that Scaliger defended the Julian calendar (against reformatory efforts in the Vatican) and chose the name in this context; the name would then go back to Julius Cesar.

References

The following list mentions books with different demands on knowledge and willingness to learn. It starts with more general or popular-style books and ends with heavy-weight works for specialists.

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Jean Meeus: **Astronomical Algorithms**, Willmann-Bell, Richmond/Virginia, 1991,
ISBN 3-335-00318-7

P.Kenneth Seidelman: **Explanatory Supplement to the Astronomical Almanac**, University Science Books, 1992, ISBN 0-935702-68-7

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