# Observational Astrophysics
# 15. Time

Rodolfo Smiljanic
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Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
ul. Bartycka 18
00-716 Warsaw, PL

**E-mail:** rsmiljanic@camk.edu.pl
**Office:** 115

`http://users.camk.edu.pl/rsmiljanic`

## 1 Introduction

Astronomical observations of periodically repeating phenomena provided the first ways of systematizing the passage of time (e.g., the daily motion of the Sun, the monthly changes of the phases of the Moon, the yearly change of seasons). Man-made devices for measuring the passage of time probably started with sundials. The clepsydra (water clock) is one of the oldest devices that did not depend on the observation of celestial objects. Hourglasses, other mechanical devices, and pendulums were then used to measure the passage of time. Experiments with electric clocks started in the 1800s. The next big step was the discovery of the quartz crystal oscillator properties, which allowed the accuracy of time measurements to go beyond what was possible with astronomical measurements (see Marrison 1948, for a history of the quartz clock development)[1]. Nevertheless, fundamental concepts of time (second, day, year) were tied to astronomical observations. One can say, then, that astronomers were still the keepers of time.

But then, things started to change. Thanks to accurate devices like quartz clocks, it was discovered that the Earth's rotation rate is actually not a constant (Scheibe & Adelsberger 1936)[2]. Then the work on developing atomic clocks started. The idea is based on the principle that all atoms of the same element can absorb or release energy of the exact same frequency, creating a perfect standard (see Lombardi 2011, 2012, for some of the history)[3].

Finally in 1967, the definition of the second, which had always been tied to the astronomical day or the astronomical year, changed. The SI second was newly defined in terms of the hyperfine transition of the ground level of caesium 133 ($^{133}$Cs), beginning the era of the physicists as the keepers of time[4].

[1] `https://ieeexplore.ieee.org/document/6773029`

[2] I could not track down the original, but Scheibe & Adelsberger (1950) in `https://ui.adsabs.harvard.edu/abs/1950ZPhy..127..416S/abstract` gives a later report by the same authors of further work on the issue (in German).

[3] `https://ieeexplore.ieee.org/abstract/document/6086901` and `https://ieeexplore.ieee.org/abstract/document/6145262`

[4] Conference generale des poids et mesures 1967–68, Resolution 1, CR, 103. "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom"; See `https://www.nist.gov/pml/special-publication-330/sp-330-appendix-1` for this resolution and a few others that modified it.

## 2 Read this text

There are a series of definitions, e.g. Julian date, modified Julian date, sidereal time, among others, that are used in astronomy. Knowledge about these definitions can be key for identifying the correct objects for observation based on their coordinates but also for understanding observations of variable quantities. On the topic of temporal reference systems, please read Section 4.3 of the book "Observational Astrophysics" by Léna et al. (2012)[5]. This text, however, misses the definition of sidereal time. For that, I also give Section 5.3.4 from the book "Astrophysical Formulae - Part II" by Lang (1999)[6].

## 3 Summary of concepts

- The solar day is defined to be the time between two consecutive crossings of the local meridian by the (center of the) Sun.
- The apparent solar time is the hour angle of the center of the apparent (or true) Sun. The length of the apparent solar day changes because of the eccentricity of the Earth's orbit and the inclination of Earth's rotation axis with respect to the ecliptic. The apparent solar time is not uniform and not useful for defining a time scale.
- One then defines the "mean Sun" to be moving along the celestial equator at a constant rate that is given by the mean rate of the true Sun over the year.
- The mean solar time is the hour angle of the mean Sun. The mean solar time is the apparent solar time corrected from all irregularities of the true Sun movement.
- The civil time is based on the mean solar time plus 12 hours (so that the day starts at midnight).
- The equation of time is the name given to the quantity that describes all the corrections needed to transform between the two solar times. The value of the equation of time for each day is compiled in astronomical almanacs and ephemerides. The equation of time varies during the year by up to about 16 minutes (Fig. 1). The equation of time is the east or west component of the analemma.
- The legal time of a place makes use of concept of time zones, that divide longitude spans of roughly 15° as differing by one hour. The legal time is the civil time of the central meridian of that time zone.
- The Universal Time (UT) is the civil time at the meridian that marks 0 degrees of longitude (at Greenwich, England). The local mean solar time anywhere can be known if UT and the longitude are known.
- The universal time is still affected by irregularities of the Earth's rotation rate. One component of these irregularities are variations in the Earth's rotational speed. Another component is the so-called polar motion, a change in the orientation of the Earth's rotation axis relative

[5] `https://link.springer.com/book/10.1007/978-3-642-21815-6`

[6] `https://link.springer.com/book/10.1007/978-3-662-21639-2`

to its crust (i.e. the physical position where the rotation axis crosses the surface is not always the same). This happens because the rotation axis is not the symmetry axis (and events like ice melting or earthquakes can change the distribution of mass). The main component of the polar motion is the Chandler wobble[7], which changes the location of the poles within a circle of about 9m radius with a period of about 433 days (Malkin & Miller 2010)[8].

- The universal time that has not been corrected for the polar motion is called UT0. The value of UT0 depends on the place of the observation. The polar motion can change the position of the meridian of a certain place, changing its longitude. Notice, however, that at the equator (the mid-point of the meridian) the change is zero.

- The universal time that *has* been corrected for the polar motion is called UT1. The value of UT1 is the same everywhere on Earth. Most of the time when someone refer to the UT, the meaning is that of the UT1.

- The coordinated universal time (UTC) is an atomic timescale that is periodically modified to be maintained within 0.9s of the UT1 (using leap seconds when needed). For most applications, UTC can be used as an approximation of UT1. UTC uses SI seconds and it differs from the international atomic time (TAI) by a certain integer number of seconds. The UTC is meant as an atomic time scale that agrees with the rotation of the Earth.

- The international atomic time (TAI) is maintained by the International Bureau of Weights and Measures (BIPM, France)[9]. It is a weighted average of the time kept by several atomic clocks distributed worldwide.

- The sidereal day is defined to be the time between two consecutive crossings of the local meridian by the vernal point/equinox. The mean solar day is about 4 minutes longer than a sidereal day (because of the movement of the Earth around the Sun).

- The apparent sidereal time is the hour angle of the vernal equinox. In other words, it is the right ascension crossing the local meridian.

- The vernal equinox is not a fixed point on the celestial sphere. Its position is affected by the precession and nutation of the Earth. The local meridian is also not fixed, as the location of the poles changes.

- Correcting by the effect of nutation, one can define a mean vernal equinox and a mean equator (or mean positions for the poles). The resultant sidereal time is called the mean sidereal time.

- The difference between the apparent and mean sidereal times is called the equation of the equinoxes (which is also given in astronomical almanacs and ephemerides, and is smaller than 1 second).

- The previous astronomical definitions of time intervals made use of the Earth rotation which, as we saw, is not uniform (contrary to what was believed for a long time). The necessity of a uniform time scale for use in the study of movements lead to the concept of a dynamical time scale.

[7] Named after the American astronomer Seth Chandler, see `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_262` for a biography. For a historical account of the discovery see Carter & Carter (2000) in `https://ui.adsabs.harvard.edu/abs/2000ASPC..208..109C/abstract`.

[8] `https://ui.adsabs.harvard.edu/abs/2010EP%26S...62..943M/abstract`

[9] `https://www.bipm.org/en/home`

- The ephemeris time (ET) was the first attempt of realizing such dynamical time scale. It was based on the orbital motions of the Earth, Moon and planets. The idea was introduced by Clemence (1948)[10] and realized based on the "Tables of the Motion of the Earth on its Axis and Around the Sun" (Newcomb 1898)[11] by the American astronomer Simon Newcomb[12]. That work contains a mathematical development of a theory and of tables of celestial motions. The ET is given by applying a correction to UT. The epoch and initial value of this correction were chosen so that the ET agrees with the UT on 0 of January of 1900 at 12h[13]. The ET is not known in advance, but depended on a comparison between theory and observations. Soon it was realized that the accuracy obtained from observations of the Sun was not good enough. The ET also did not take into account relativistic corrections.

- To take into account relativity, two new scales were created connected to two different reference points. The Terrestrial Dynamical Time (TDT), a coordinate system with reference to the Earth's surface, and the Barycentric Dynamical Time (TDB), a coordinate system with reference point at the barycenter of the solar system (see Guinot & Seidelmann 1988)[14]. The TDT has the SI second as its unit and was defined to be ahead of TAI by 32.184s on January 1, 1977.

- In 1991, a few extra definitions were introduced by the IAU. The terrestrial time (TT) replaced the TDT, and is identical to it by definition. It is meant to be used for time-measurements of astronomical observations made from the surface of the Earth. In addition, the Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB) were introduced. They are times in systems that have spatial origins at the center of mass of the Earth and at the solar system barycenter, respectively. See Seidelmann & Fukushima (1992)[15] for a discussion of the motivations and a description of the relationship between the timescales.

- To compare astronomical observations performed over periods of many years, it would be useful to have a continuously running counting system for days. This system exists as the Julian dates (JD). The system was proposed by Justus Scalinger[16] in 1583. Days are counted from noon on January 1, 4713 BC, when started Julian day 0. The system was named after his father, Julius Caesar Scaliger.

- The Julian date is often replaced by the modified Julian date (MJD), where MJD = JD - 2400000.5 (where the 0.5 is to change the beginning from noon to midnight). This was introduced by the Smithsonian Astrophysical Observatory in 1957 to record the orbit of Sputnik using a small bit space in their computer.

- A Julian year is defined to have exactly 365.25 days. Note that a Julian year does not correspond to years in the Julian calendar (where the year had on average 365.25, but leap years were used).

[10]See `https://ui.adsabs.harvard.edu/abs/1948AJ.....53..169C/abstract`. For a biography of the American astronomer Gerald Clemence, see Sadler (1975) in `https://ui.adsabs.harvard.edu/abs/1975QJRAS..16..210S/abstract`.

[11]See a scan in `https://babel.hathitrust.org/cgi/pt?id=uc1.32106005816399&view=1up&seq=15&skin=2021`

[12]See `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_1006` for a biography.

[13]In astronomical scales, sometimes the counting starts from 0 and not 1, so here it is the day before January 1st. This was adopted by the IAU in 1958, see the resolution in `https://www.iau.org/static/resolutions/IAU1958_French.pdf` (but in French only).

[14]`https://ui.adsabs.harvard.edu/abs/1988A%26A...194..304G/abstract`

[15]`https://ui.adsabs.harvard.edu/abs/1992A%26A...265..833S/abstract`

[16]Joseph Justus Scaliger was a French religious leader and scholar.

- As we saw before, the origin of the equatorial coordinate system changes with time, so that the coordinates need to be give with reference to to a standard epoch. Some of the standard epochs used before, B1900.0 and B1950.0, were based on the Besselian[17] year. The Besselian year is the interval of time necessary for the mean Sun to return to right ascension 18h40m, corrected for aberration and measured from the mean equinox of the date. This right ascension was chosen because it falls near the beginning of the corresponding Gregorian calendar year.

- The use of Besselian years has become obsolete, and standard epochs are now given in the Julian system, like J2000.0 which very closely corresponds to the calendar date of January 1st, 2000 at 12.00 h.

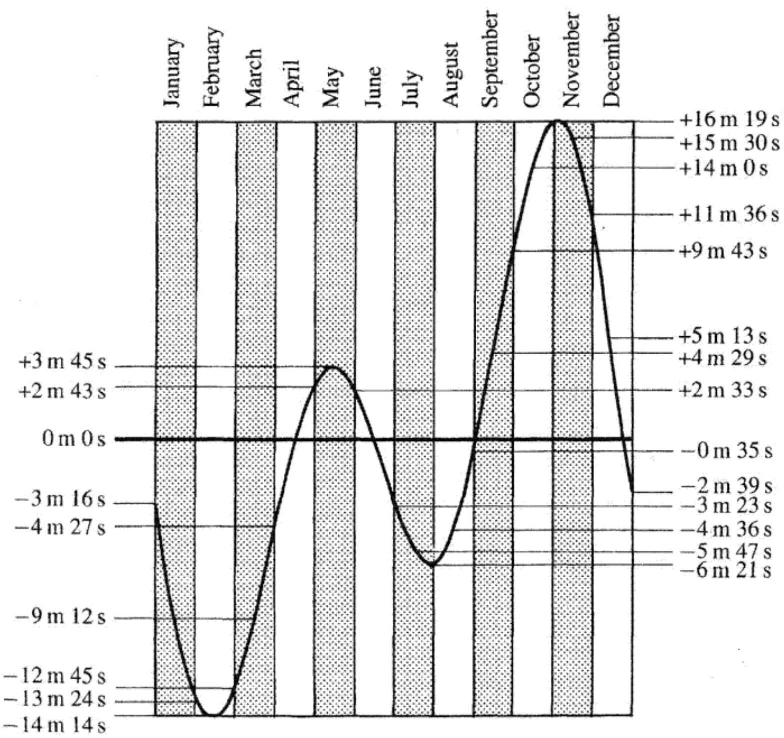


**Fig. 5.17.** Variation of the Equation of Time through the year. Add the time given here to Civil Time, or clock time, to obtain the True Sun Time

Figure 1: Variation of the equation of time during the year. Credit: Figure 5.17 from Lang (1999) see `https://link.springer.com/book/10.1007/978-3-662-21639-2`.

[17]Named after the German mathematician and astronomer Friedrich Bessel, the first to measure a stellar parallax. See `https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_144` for a biography.

# 4 Additional reading

For reviews about time scales, see McCarthy (2011)[18] and Seidelmann & Seago (2011)[19]. For a history of the UTC and its calculation see Panfilo & Arias (2019)[20].

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[18] https://ui.adsabs.harvard.edu/abs/2011Metro..48S.132M/abstract
[19] https://ui.adsabs.harvard.edu/abs/2011Metro..48S.186S/abstract
[20] https://ui.adsabs.harvard.edu/abs/2019Metro..56d2001P/abstract