SUPPLEMENT 1

CONTEMPORARY TIME COUNT SYSTEMS
(an overview is based on Wikipedia articles)

Solar time

The Solar time is time kept or measured by the sun. Two kinds of solar time, ***apparent solar time*** and ***mean solar time***, are among the three kinds of time that were recognized and measured by astronomers up to the 1950s. The measures of all these kinds of time depend on the rotation of the earth. Nowadays both kinds of solar time, along with sidereal time, stand in contrast to newer kinds of time measurement, introduced from the 1950s onwards (starting with ephemeris time), which were designed to be independent of earth rotation.

Apparent solar time or **true solar time** is given by the daily apparent motion of the true, or observed, Sun. It is based on the ***apparent solar day***, which is the interval between two successive returns of the Sun to the local meridian. Solar time can also be measured (to a limited precision) by a sundial.

The length of a solar day varies throughout the year, and the accumulated effect of these variations (often known as the equation of time) produces seasonal deviations of up to 16 minutes from the mean. The effect has two main contributory causes. First, Earth's orbit is an ellipse, not a circle, so the Earth moves faster when it is nearest the Sun (perihelion) and slower when it is farthest from the Sun (aphelion) (see Kepler's laws of planetary motion). Second, due to Earth's axial tilt (often known as the *obliquity of the ecliptic*), the Sun moves along a great circle (the ecliptic) that is tilted to Earth's celestial equator. When the Sun crosses the equator at both equinoxes, the Sun is moving at an angle to the equator, so the projection of this tilted motion onto the equator is slower than its mean motion; when the Sun is farthest from the equator at both solstices, the Sun moves parallel to the equator, so the projection of this parallel motion onto the equator is faster than its mean motion (see tropical year). Consequently, apparent solar days are shorter in March (26–27) and September (12–13) than they are in June (18–19) or December (20–21). These dates are shifted from those of the equinoxes and solstices by the fast/slow Sun at Earth's perihelion/aphelion. (In addition to these two main effects there are others, due to lunar and planetary perturbations, which can produce a few more seconds in the equation of time.)

Mean solar time conceptually is the hour angle of the fictitious mean Sun, assuming the Earth rotates at a constant rate. Currently (2009) this is realized with the UT1 time scale, which is constructed mathematically from very long baseline interferometry observations of the diurnal motions of radio sources located in other galaxies, and other observations. Though the amount of daylight varies significantly, the length of a ***mean solar day*** does not change on a seasonal basis. However, the length of a mean solar day increases at a rate of approximately 1.4 milliseconds each century. It was exactly 86,400 (i.e. 24 hours × 60 minutes/hour × 60 seconds/minute) SI seconds in approximately 1820. Currently, the length of a mean solar day is approximately 86400.002 SI seconds. An apparent solar day may differ from a mean solar day by as much as nearly 22 seconds shorter to nearly 29 seconds longer. Because many of these long or short days occur in succession, the difference builds up so that mean time is greater than apparent time by about 14 minutes near February 6 and mean time is less than apparent time by about 16 minutes near November 3. An analemma is a graph of this relationship. Since these periods are cyclical, they do not accumulate from year to year. The difference between apparent solar time and mean solar time is called the equation of time.

The length of the mean solar day is increasing due to the tidal acceleration of the Moon by the Earth, and the corresponding deceleration of the Earth by the Moon.

Civil time systems based on the rotation of the Earth

Coordinated Universal Time (UTC) is the basic of civil time. It is a time standard based on *International Atomic Time* with leap seconds added at irregular intervals to compensate for the Earth's slowing rotation. Leap seconds are used to allow **UTC** to closely track UT1, which is mean solar time at the Royal Observatory, Greenwich.

Universal Time (UT) is a timescale based on the rotation of the Earth. It is a modern continuation of Greenwich Mean Time (GMT), i.e., the ***mean solar time*** on the meridian of Greenwich, and **GMT** is sometimes used loosely as a synonym for **UTC**.

The difference between **UTC** and **UT1** is not allowed to exceed 0.9 seconds, so if high precision is not required the general term ***Universal Time*** may be used.

In casual use, when fractions of a second are not important, ***Greenwich Mean Time*** can be considered equivalent to **UTC** or **UT1**. Owing to the ambiguity as to whether **UTC** or **UT1** is meant, **GMT** is generally avoided in technical contexts.

Time systems based on atomic clock and relativistic models

Terrestrial Time (TT) is a modern astronomical time standard defined by the International Astronomical Union (IAU), primarily for time-measurements of astronomical observations made from the surface of the Earth. In this role, TT continues ***Terrestrial Dynamical Time***, which in turn succeeded ephemeris time (ET). The unit of TT is the SI second, the definition of which is currently based on the cesium atomic clock, but TT is not itself defined by atomic clocks. It is a theoretical ideal, which real clocks can only approximate. TT is distinct from the time scale often used as a basis for civil purposes, Coordinated Universal Time (UTC). TT indirectly underlies UTC, via International Atomic Time (TAI).

A definition of a terrestrial time standard was adopted by the IAU in 1976 and later named Terrestrial Dynamical Time (TDT). It was the counterpart to Barycentric Dynamical Time (TDB), which was a time standard for Solar system ephemerides, to be based on a dynamical time scale. Both of these time standards turned out to be imperfectly defined. Doubts were also expressed about the meaning of 'dynamical' in the name **TDT**.

In 1991 the IAU redefined **TDT**, also renaming it "Terrestrial Time". **TT** was formally defined in terms of Geocentric Coordinate Time (TCG), defined by the IAU on the same occasion. TT was defined to be a linear scaling of TCG, such that the unit of TT is the SI second on the geoid (Earth surface at mean sea level). This left the exact ratio between TT time and TCG time as something to be determined by experiment. Experimental determination of the gravitational potential at the geoid surface is a task in physical geodesy.

Observers in different locations, that are in relative motion or at different altitudes, can disagree about the rates of each other's clocks, owing to effects described by the theory of relativity. As a result, TT (even as a theoretical ideal) does not match the proper time of all observers.

In relativistic terms, TT is described as the proper time of a clock located on the geoid (essentially mean sea level). However, TT is now actually defined as a coordinate time scale. The redefinition did not quantitatively change TT, but rather made the existing definition more precise. In effect it defined the geoid (mean sea level) in terms of a particular level of gravitational time dilation relative to a notional observer located at infinitely high altitude.

The present definition of TT is a linear scaling of ***Geocentric Coordinate Time***, which is the proper time of a notional observer who is infinitely far away (so not affected by gravitational time dilation) and at rest relative to the Earth. TCG is used so far mainly for theoretical purposes in astronomy. From the point of view of an observer on the Earth's surface the second of TCG passes in slightly less than the observer's SI second. The comparison of the observer's clock against TT depends on the observer's altitude: they will match on the geoid, and clocks at higher altitude tick slightly faster.

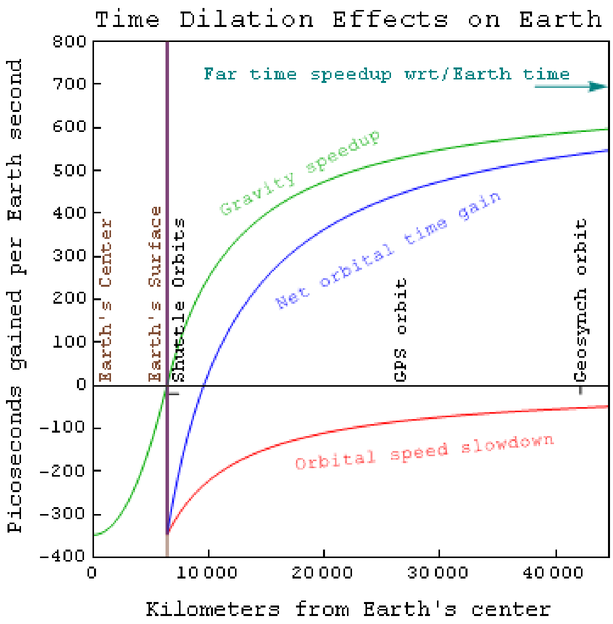
Timekeeping in GPS

While most clocks are synchronized to ***Coordinated Universal Time*** (UTC), the ***atomic clocks*** on the satellites are set to *GPS time*. The difference is that *GPS time* ***is not corrected to match the rotation of the Earth***, so it does not contain leap seconds or other corrections which are periodically added to UTC. GPS time was set to match ***Coordinated Universal Time*** in 1980, but has since diverged. The lack of corrections means that GPS time remains at a constant offset with ***International Atomic Time*** (TAI) (TAI - GPS = 19 seconds). Periodic corrections are performed on the on-board clocks to correct relativistic effects and keep them synchronized with ground clocks.

The GPS navigation message includes the difference between GPS time and UTC, which as of 2009 is 15 seconds due to the leap second added to UTC December 31, 2008. Receivers subtract this offset from GPS time to calculate UTC and specific timezone values. New GPS units may not show the correct UTC time until after receiving the UTC offset message.

As opposed to the year, month, and day format of the ***Gregorian calendar***, the GPS date is expressed as a week number and a seconds-into-week number.

Relativity



Satellite clocks are slowed by their orbital speed but sped up by their distance out of the Earth's gravitational well.

A number of sources of error exist due to relativistic effects that would render the system useless if uncorrected. Three relativistic effects are the time dilation, gravitational frequency shift, and eccentricity effects. For example, the relativistic time *slowing* due to the speed of the satellite of about 1 part in 10^{10}, the gravitational time dilation that makes a satellite run about 5 parts in 10^{10} *faster* than an Earth based clock, and the Sagnac effect due to rotation relative to receivers on Earth.

According to the theory of relativity, due to their constant movement and height relative to the Earth-centered, non-rotating approximately inertial reference frame, the clocks on the satellites are affected by their speed. Special relativity predicts that the frequency of the ***atomic clocks*** moving at GPS orbital speeds ***will tick more slowly than stationary ground clocks*** by a factor of $v^2/2c^2 \approx 10^{-10}$, or result in a delay of about 7 μ s/day, where the orbital velocity is v = 4 km/s, and c = the speed of light. The time dilation effect has been measured and verified using the GPS system.

The effect of ***gravitational frequency shift*** on the GPS system due to general relativity is that a clock closer to a massive object will be slower than a clock farther away. Applied to the GPS system, the receivers are much closer to Earth than the satellites, ***causing the GPS clocks to be faster*** by a factor of 5×10^{-10}, or about 45.9 μ s/day. This gravitational frequency shift is also a noticeable effect.

When combining the time dilation and gravitational frequency shift, the discrepancy is about 38 microseconds per day; a difference of 4.465 parts in 10^{10}. Without correction, errors in position determination of roughly 10 km/day would accumulate. In addition, because GPS satellite orbits are not perfectly circular, their elliptical orbits cause the time dilation and gravitational frequency shift effects to vary with time.

This eccentricity effect causes the clock rate difference between a GPS satellite and a receiver to increase or decrease depending on the velocity orbital altitude of the satellite.

To account for the discrepancy, the frequency standard on board each satellite is given a rate offset prior to launch, making it run slightly slower than the desired frequency on Earth; specifically, at 10.22999999543 MHz instead of 10.23 MHz. Since the atomic clocks on board the GPS satellites are precisely tuned, it makes the system a practical engineering application of the scientific theory of relativity in a real-world environment. Placing atomic clocks on artificial satellites to test Einstein's general theory was proposed by Friedwardt Winterberg in 1955.

GPS observation processing must also compensate for the Sagnac effect. The GPS time scale is defined in an inertial system but observations are processed in an Earth-centered, Earth-fixed (co-rotating) system, a system in which simultaneity is not uniquely defined. A Lorentz transformation is thus applied to convert from the inertial system to the ECEF system. The resulting signal run time correction has opposite algebraic signs for satellites in the Eastern and Western celestial hemispheres. Ignoring this effect will produce an east-west error on the order of hundreds of nanoseconds, or tens of meters in position.

When more than four satellites are available, a decision must be made on whether to use the four best or more than four taking into considerations such factors as number of channels, processing capability, and geometric dilution of precision. Using more than four results in an over-determined system of equations with no unique solution, which must be solved by least-squares or a similar technique. If all visible satellites are used, the results are always at least as good as using the four best, and usually better. Also the errors in results can be estimated through the residuals. With each combination of four or more satellites, a geometric dilution of precision (GDOP) factor can be calculated, based on the relative sky directions of the satellites used. As more satellites are picked up, pseudoranges from more combinations of four satellites can be processed to add more estimates to the location and clock offset. The receiver then determines which combinations to use and how to calculate the estimated position by determining the ***weighted average of*** these positions and ***clock offsets***.

> ***Therefore, regardless the fact that GPS uses atomic clocks which, by themselves, are extremely precise, it does not provide us with the "etalon" of Time: due to a series of relativistic effects it always provides us with some mean time.***

Timekeeping systems for greater time intervals

The problem of timekeeping is also actual on considering long time intervals.

Without defining, the terms 'day' and 'year' remain correct just for the everyday purposes. This is so because the length of a day is increasing unevenly, and the length of a year, in any unit, depends on how the origin is defined (Sidereal, tropical, anomalistic years etc.).

Therefore, not only a year contains a fractional number of solar days, this number is decreasing.

For these reasons, the time is counted both in Solar days (Mayan calendar) and in mean solar days (Julian day numbers) and greater units (Julian centuries).

As well, for civil and scientific purposes the calendars are used where the Tropical, Sidereal or Moon years are correlated with the Solar days (Gregorian calendar, Julian calendar, etc.).

Besides, special cosmological models and physical observations are used in order to define a cosmological time – as a timekeeping system for the observable Universe.