What is the Time?

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Throughout the nineteenth century and before the answer was easy: we took the time from the rotation of the Earth. It was the best - that is the most regular - clock that we knew about. It rotates on its axis every 23 hours 54 minutes 4.0916 seconds (give or take a bit). We know the *Sidereal Day* has this length because astronomers can make observations of the interval between a star crossing the *meridian* on successive nights. (The meridian is the imaginary line on the sky from due South to North) over many nights. Why do we think that our day is 24 hours long? That is because a a *Solar Day* is defined to be the time interval between the Sun crossing the meridian on successive days, and because the Earth is also orbiting the Sun and moves around the orbit a little during the day it takes a little longer than the Sidereal Day for the Sun to get back overhead (just about four minites which is one day divided by 365). The Solar Day is not very good as a time standard because the Earth's orbit is eliptical, not circular, and at some times of the year it is moving more quickly and at other times more slowly, so sometimes the Solar Day is a bit more than 4 minutes longer than the Sidereal Day and at other time a bit shorter. Hence, until the beginning of the Twentieth Century the civil standard of time was based on the mean length of the Solar Day - averaged over a complete year - and in particular *Greenwich Mean Time* (GMT) became the standard method of measuring time for applications such as ship navigation. Nevertheless, because the apparent size of the Sun is quite large in the sky, it was observations of the stars at midnight that were actually used to tie down the time standard.

Time standards were particularly important for ship navigation, because navigators measured the position of the ship by comparting observations of stars with data in a large book called the *Astronomical Ephemeris,* which is published every year by the *Royal Greenwich Observatory* and which tabulates the positions of stars and planets against time (until the Twentieth Century they were tabulated against Greenwich Mean Time). Every ship needed a very good clock (called a chronometer) and a copy of the *Ephemeris.* (When I worked at the RGO as a student a department of the observatory still repaired and regulated the Royal Navy's clockwork chronometers. Even though more accurate electronic clocks were starting to appear, fighting ships still wanted clockwork backup, which could not suffer from power failure during a battle. This job happened at an observatory because these most accurate of mechanical clocks still had to be checked against the stars.)

There are other clocks in the sky, in particular the motion of the planets round their orbits. By the beginning of the Twentieth Century more accurate astronomical observations and improved clocks were making it clear that the Earth's rotation was actually slowing down. This is not at all surprising and was expected theoretically, because the Moon raises tides in the oceans and these slowly dissipate the energy of rotation. As soon as clocks became better than the Earth at keeping regular time we needed a new standard of time, known as *Ephemeris Time* which is effectively defined to be the time that make all the movement of the planets in the Solar System obey Newton's Laws of gravitation. (Except Mercury! This was a long standing puzzle until Einstein solved it with General Relativity.) We now have two standards of time that do not keep pace with each other. We still need the standard based on the Earth's rotation because navigators need to know the position of the Earth with respect to the sky each day, even if it is slowing down. We also need to more regular ephemeris standard because, for example, we need to know whether the anomalous motion of a planet is caused by a real physical effect or a problem with our clocks.

During the Twentieth Century GMT formally becomes UT1 (UT for universal time, named because the mean time is now defined by averaging observations from many observatories round the World, not just Greenwich. The "1" distinguishes it from UT0, a slightly different time standard which we will not talk about because it has rather specialist application.)

GMT[1] and the ephemeris time is replaced by UTC (Universal Coordinated Time) which is again an average of time defined by a number of laboratories round the World. These days the regularity of time is guaranteed by atomic clocks at places such as the National Physical Laboratory and equivalent labs in Paris, Washington and other locations. These clocks define the International Atomic Time (TAI) standard. The length of UTC seconds is now defined to be the same as TAI seconds, though as we will see UTC is offset from TAI by a few seconds (see below).

UT1 is still tied to Earth rotation (and UT1 seconds are therefore slightly longer than TAI and UTC seconds). This day, a number of astronomical observatories around the World log the transit times of stars every night in order to work out the absolute orientation of the Earth in space with respect to the fixed stars. This information from the *International Earth Rotation Reference Service System* is distributed every week to all professional astronomical observatories as the current difference between UTC and UT1. We have to keep on doing this because not only is the Earth slowing down, it does so at an irregular pace, partly because seasonal changes in ocean currents and air circulation affect the rotation rate. (Because of this irregularity we only know UT1 to the highest level of accuracy in restrospect, and we may have to correct the precise times of astronomical events logged in the previous week.) Astronomers point their telescopes and measure positions on the the sky using UT1, because they also need to know the position of the Earth with respect to the fixed stars. Large

[1]In the UK "GMT" still has a status as the official standard of civil time. These days, however, it effectively rests on UTC as the underlying standard.

professional telescopes need to be pointed very, very accurately, so 5 ms up or down in the difference between UTC and UT1 is important. In principle, analysis of cosmic ray arrival directions will also be based on the UT1 standard, but in practice it is hard to get very accurate directional measurements so it will make not much difference.

There was a problem: UTC ran at the same rate as Earth Rotation time at a point towards the end of the Nineteenth Century but ever since has been slowly getting ahead, by about 1.3 ms/day. This is small but it accumulates, and UTC is now about 19 seconds adrift from UT1. Every so often, therefore, the committees that agree the time standard insert a "leap second" into UTC so that UTC and UT1 are never further apart than one second. UTC would have agreed exactly with TAI at the beginning of the 20th Century, but because of the leap seconds has now counted 19 more seconds since that time.

From a practical view point, most of us are able to access a very good time standard from the radio signals transmitted by the Global Positioning System satellites. Each of these satellites carries an atomic clock which runs at the same rate as TA1. (In fact, because of General Relativity effects the atomic frequency standard is running slightly faster than an equivalent Earth-based clock, but that is taken account of.) GPS time does *not* include the leap seconds used in UTC, so maintains a constant offset from TAI (TAI-GPS=19 s). However, every minute or so each satellite transmits an additional bit of information that tells a GPS receiver how far away its clock is from UTC - 17 seconds in June 2015. (When you first switch on a GPS receiver in some consumer GPS gadgets the clock may be about 17 seconds, or more, wrong compared to UTC for the first minute, until it gets the correction data.)

This is all quite confusing (and believe me, I have simplified the full tale). Even worse, a lot of modern computer networks that need to synchronise with each other and show time to users that looks like what they see on the BBC and so on ("wall clock time") sometimes get themselves tied in knots dealing with leap seconds. (A millisecond can be a long time when looking after trades in City of London banks. You may need to know *precisely* who made an electronic trade when to know who got the stock on offer.) There is therefore some current discussion about stopping the introduction of leap seconds and letting UTC drift further and further away from UT1 ("Earth" time), so for example, sundials would get further and further away from UTC.

Having taken account of all these complications a commercial GPS receiver is probably good for a time signal certainly accurate to better than10^{-7}seconds (or 100 nanoseconds) Theoretically it could be good to 14 nanoseconds in optimum conditions with a sophisticiated receiver. One of the remaining problems is that the radio signals have to travel through the ionosphere which slows them down slightly (very slightly) but in an irregular, variable and hard to predict way. (Very sophisticated and expensive GPS receivers, such as military system, can do slighty better by using a number of signals from the satellite transmitted on several different frequencies. The ionosphere affects different frequencies differently, so they can make a continuously updated estimate of the ionospheric delay along the signal path.) Note that a radio signal or a cosmic ray particle can travel 30 meters in 100 nano seconds so if we wish to get reliable arrival direction information from CR detectors by logging arrival times using GPS time they need to be separated by much more than 30 meters. (However, two detectors in the same station connected to the same data logging system by cables can distinguish *relative* arrival times much more accurately than that.)

GPS time is hugely important in the modern World. For example, your mobile phones rely on a network of base stations that synchronise their operations using GPS time. If the GPS satellites were switched off or damaged by extreme space weather our mobile phone networks would no longer function.

As I write there are discussions going on about using the regular radio pulses emitted by some rapidly rotating neutron stars ("pulsars") as an even more accurate time standard available to anyone with a good radio receiver and a computer, and the atomic clocks in the standards laboratories will probably soon become much more accurate because they will move away from using the jumps of electrons in the energy levels on the outer parts of an atom (which may still be *slightly* affected by stray electric and magnetic fields) to the better shielded energy transitions in atomic nuclei. Accuracies of better than 1 second in the age of the universe is *still* not good enough for some modern physics experiments.

Measuring time accurately is therefore of crucial important for our everyday life and for scientific experiments - especially astronomical observations. If we need the highest levels of accuracy, however, it is not at all straightforward. We need to choose the right type of clock. Sometimes we need a very regular clock which ticks at a uniform rate. At other times we need a clock that keeps pace with the irregular rotation of the Earth. (Note that all scientific experiments ignore "Daylight Saving Time", or "Summer Time". Logging events against the "wall clock time" can cause great confusion.)

And I have not even begun to discus the effects of relativity that are now becoming important when synchronising clocks in spacecraft with those on the Earth (so there is an additional theoretical time standard as set by an atomic clock positioned well away from gravitating bodies but moving along at a steady velocity that tracks the motion of the Sun though space).

You may also come across "Julian Days" when dealing with astronomical observations. These are simply a count of the number of days from a starting point which is conventionally a long time before any historic astronomical data (1st January 4713BC - there is a reason for this date but it is complicated and arcane). Logging observations against Julian Day makes is very easy to work out time intervals between events (rather than converting conventional dates to day counts). This was a much bigger deal before computers, and astronomers would look up the Julian Day in the *Astronomical Ephemeris* for each nights work. Note that you need to know which type of Julian Day because there are some working variants that have different starting points to avoid the large day-number counts of the definitive standard. Astronomers conventionally started the day at 12 noon, so that observations made at night would all be in the same Julian Day. However, with modern satellite observations and radio telescopes working 24 hours a day this convention has lost its original justification.