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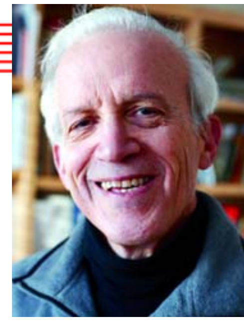
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Time Too Good to Be True

Daniel Kleppner

Without wishing to cause unnecessary distress, I would like to call attention to a couple of issues concerning time. The first is merely calendraic but the second concerns the future of time itself.

The first issue is that we may have to say farewell to leap seconds. Leap seconds, as you might recall, are the occasional one-second adjustments of our clocks that are made to maintain harmony between the astronomical and atomic time scales. Personally, I would be sorry to see leap seconds go because that would cost me the pleasure of mulling over the best way to spend my next one. Although a mere second might seem to be too short to cause jubilation, I believe any gift of time deserves to be treasured. Also, one second is not really that short. It is long enough to record a few million high-energy scattering events, and in femtosecond physics, one second is virtually an eternity. Also, one second is sufficient for a word or quick kiss that might change your life.

The argument about whether to retain leap seconds is reminiscent of the argument about standard time versus daylight savings time: What is convenient for one community can be inconvenient for another. City dwellers generally favor daylight savings time and farmers generally oppose it. Astronomers favor leap seconds because they keep clocks in synchrony with the orientation of the Earth. Synchronization is helpful in deciding where to point telescopes and in interpreting the data in astronomical records. Celestial navigators—that vanishing breed—also like leap seconds. The Global Positioning System, however, cannot tolerate time jumps and employs a time scale that avoids leap seconds. Moreover, all large-scale systems that require precise synchronization are likely to have trouble with leap seconds. For instance, any attempt to introduce a one-second hiccup in the phasing of North American power grids would likely cause a hemispheric blackout.

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The days are growing longer

The underlying reason that leap seconds were introduced is the gradual lengthening of the day due to tidal friction. Tidal friction is caused by the lag between the tidal force of the Moon and Sun and the response of the ocean, atmosphere, and the solid Earth itself. Fortunately, tidal friction is minor, causing the length of the day to increase by merely a few milliseconds per century. Leap seconds, in contrast, are abundant: There have been 23 since they were introduced in 1972. However, nearly all of those would have been avoided if the definition of the second had been slightly different. The second is the time for 9 192 631 770 cycles of the hyperfine transition in ^{133}Cs. That definition was adopted in 1967 and was in harmony with the best available astronomical data. However, if the last three digits had been chosen to be 997 instead of 770, there would have been only three leap seconds, two negative and one positive.[1]

The time scale that the standards laboratories disseminate and that drive the world's clocks is called UTC (coordinated universal time). UTC is based on atomic frequency standards, with a leap second inserted now and then. The decision as to when to add a leap second is made by the International Earth Rotation and Reference Systems Service. If leap seconds are abolished, time will be based on a time scale that advances as uniformly as atomic clocks permit until some future day of reckoning when a time jump—perhaps an hour or a day— will become essential.

The most troubling discrepancies between atomic and astronomical time arise from the unpredictable fluctuations in Earth's rotation rate. We would be happily unaware of most of these vagaries were it not for the invention of atomic clocks. The accuracy of these clocks has improved by roughly a factor of 10 every decade since they were introduced in the mid-1950s and in the next few years the accuracy is expected to reach 1 part in 10^{16}. Furthermore, we are on the threshold of a new age of optical atomic clocks and optical frequency metrology and can look forward to clocks that will eventually achieve an accuracy of 1 part in 10^{18}.

The prospect of a major advance in clock accuracy brings me to the second issue concerning time. At accuracies beyond 1 part in 10^{16}, the gravitational redshift or, more precisely, the gravitational blueshift, predicted by general relativity, scrambles time with Earth's gravity in a rather unmanageable fashion that ultimately upsets what we mean by "keeping time."

Near Earth's surface, general relativity predicts, and accurate experiments confirm, that if a clock is elevated it goes faster by about 1 part in 10^{16} for each meter its altitude is increased. (More generally, the rates of clocks located at gravitational potentials U_2 and U_1 differ fractionally by $(U_2 - U_1)/c^2$, where c is the speed of light.) Not many years ago the possibility of merely detecting the minute effect of gravity on time was enough to inspire experimentalists. Over the years the accuracy of atomic clocks has become so high that the corrections for general relativity are not merely visible, they are so large that overlooking them in comparing the rates of atomic clocks in different laboratories[2] or in the timing algorithms for the Global Positioning System[3] (PHYSICS TODAY, May 2002, page 41) would cause catastrophes.

The duration of the second is measured using signals from state-of-the-art atomic frequency standards in a few primary laboratories augmented by signals from a system of hundreds of commercial frequency standards maintained by about 55 international laboratories. (Those frequency standards are often referred to informally as atomic clocks, but a real clock must continuously count its ticks—more precisely, the cycles of an oscillator that is frequency locked to an atomic transition—which adds a major level of complexity to the art of keeping time.) The clocks are compared by simultaneously observing signals from GPS satellites or by directly relaying signals through commercial satellites. These comparisons can currently be carried out to an accuracy in frequency of about 1 part in 10^{15}. Because of the effect of gravity on time, achieving such accuracy requires knowing the altitudes of the laboratories with an uncertainty of no more than a few meters. That is not trivial but it is possible. To compare frequency standards in different locations to 1 part in 10^{16}, however, the altitudes would need to be known to a fraction of a meter, which is no easy matter. To compare them to a part in 10^{18} the altitudes would need to be known to 1 cm, which, for reasons to be explained, cannot be done unless the atomic clocks happen to be in the same location.

The great geoid search

The altitude required to correct local time for the effect of gravity is not the distance to mean sea level but the distance to the geoid, suitably corrected for the variation of gravity with height. The geoid is a hypothetical surface of constant gravitational potential which, to first approximation, is a spheroid with the major and minor axes of Earth. The geoid has been patiently mapped by years of observations of terrestrial gravity and satellite orbits and its altitude is now known with a typical uncertainty of 30–50 cm.[4] However, the uncertainty in the geoid causes an uncertainty in the relative rates of atomic clocks of typically 3 parts in 10^{17}. In the not-too-distant future, our ability to compare atomic frequency standards and clocks at different laboratories will be limited by our knowledge of the geoid.

The obvious way to deal with the geoid problem is to reverse the argument and employ the gravitational redshift to explore the geoid. If, for instance, one had a portable atomic frequency standard accurate to 1 part in 10^{18} and if it could be compared to a primary standard with the same accuracy, the position of the geoid could be independently and relatively quickly determined to 1 cm. That would cause a revolutionary advance in geodesy. (It should be pointed out that nobody knows how to transfer timing signals with anywhere near this accuracy, possibly because up to now nobody has needed to do it.) Exploiting the gravitational redshift to advance geodesy would demonstrate once again the truth of the adage that a problem is merely an opportunity in disguise. Unfortunately, that cheerful maxim is of no help in dealing with the reality that timekeeping at levels of accuracy beyond 1 part in 10^{16} involves some profound issues.

We would not need to worry about gravitational effects in comparing frequency standards or atomic clocks if the comparisons could be carried out at a single location. So, we might think that the geoid problem could be avoided by simply defining the second in terms of observations to be carried out at some place selected to be the standard location. However, that proposal ignores issues of human nature for which a little history becomes relevant.

The metric system was created by a commission of the French Academy of Sciences that began its work in the final decade of the 18th century. The commission's goal was not merely to create a uniform set of physical standards that was desperately needed by an economy being tied in knots by problems of measurements, but also to create a monument to the ideals of the Enlightenment: standards that would be a set of measures for all mankind, free from political associations or allegiances. Thus, the unit of length would be based not on the length of a king's arm or foot but on the size of Earth, for anyone to measure. Similarly, the second was defined not by a royal clock but in terms of Earth's rotation, making it available to every astronomer.

Politics of science

Unfortunately, political considerations frequently intruded into the commission's plans.[5] It turned out that the line of longitude over which an arc of Earth's circumference was to be surveyed could be none other than that which runs from Barcelona to Dunkirk, which, by chance, passes through Paris, not far from the Observatory. This "French meter" irked Thomas Jefferson, prompting him to lose interest in the commission and the US to lose its earliest and best opportunity to become metric. (Jefferson was also irked by the commission's rejection of his proposal to measure the period of a standard pendulum at the 38th parallel, which happened to pass downhill from his home, Monticello.)

One way to avoid a political brouhaha would be to locate the primary frequency standard in space. However, atomic frequency standards are like babies—they need lots of love and close personal attention. More seriously, a primary standard in space would not overcome the problem of comparing time or frequency at different locations on Earth.

One might hope that the problem of uncertainties in the gravitational blueshift could be overcome by patient mapping of the geoid using the most precise atomic clocks available, and thus establishing a reference point for altitude at each time-standards laboratory. Unfortunately, Nature holds an unpleasant surprise: The geoid does not lie at rest but is tossed around by a host of processes. Solid Earth tides induce fluctuations with amplitudes approaching 20 cm that cause the rates of frequency standards and clocks to vary by almost 2 parts in 10^{17} depending on their location. Other sources of fluctuation include the oceanic tides, effects of atmospheric pressure on ocean levels, redistribution of water due to climatic changes, and such longer-term effects as glacial melting and the uplift of tectonic plates.[6] Together, these cause uncontrollable fluctuations in frequency of several parts in 10^{17}.

At first sight the problem of gravitational potential appears to be yet one more mundane experimental factor that must be controlled to operate an atomic frequency standard, much like temperature, magnetic field, or laser intensity. However, there is a fundamental distinction: the effect of gravity is not to perturb the operation of a clock but to alter time itself. At the level of accuracy of parts in 10^{17} or 10^{18}, comparing clocks scattered around the world would be no more meaningful than comparing the rates of pendulum clocks on small ships scattered in the oceans, each bobbing in its own way and keeping its own time. Which clock could be selected to be the keeper of "true" time? The answer, of course, is "none." Earth's gravity is inextricably entangled with time but the Earth shimmies and shakes unpredictably. It appears that tomorrow's super clocks will be so accurate that as far as life on Earth is concerned, the time that they keep will be too good to be true.

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