The times, they are a-changin'

More accurate timepieces could lead to better global positioning systems, insights into fundamental physics and a redefinition of the second. David Adam rates the runners in the race to build tomorrow's atomic clocks.

It's perhaps not the ultimate race against time, but rather the race to keep ultimate time. In a handful of labs around the world, physicists are developing a new generation of clocks so accurate that they should lose just one second in 100 billion years. By taking the pulse of laser light synchronized to the beating of atoms or ions, the researchers are confident that they can create clocks up to 1,000 times more accurate than today's best timepieces.

Such precision won't make much difference in the everyday world — trains will still run late and eggs will still take around four minutes to boil. But with the proposed optical clocks, studies of fundamental physical constants could become much more powerful. Global positioning systems (GPS) should also see a boost in precision, allowing them to pin down locations to within a few centimetres. What's more, if the optical clocks become established — and a prototype has already been built — they could force scientists to redefine the way we measure the basic unit of time itself: the second.

The push towards the new clocks is being led by the national standards laboratories in Britain, Canada, France, Germany and the United States. Each centre is developing its own particular design, but they all have one thing in common. At their hearts are the two basic components of every timepiece invented since the sundial: an oscillator, to provide events that repeat with a regular period, and a counter.

The most accurate existing timepieces, known as atomic clocks, measure a second using caesium atoms. By absorbing microwave photons of a particular frequency, these atoms move between two closely spaced energy states, emitting a photon as they return to the original state. Clock operators tune the frequency of the microwave radiation so that it resonates with the movement of the atoms between energy states, searching for resonance by monitoring the number of photons absorbed. The second is then defined as 9,192,631,770 cycles of the microwave radiation at this resonant frequency. The best caesium clocks can measure a second accurately to 15 decimal places.

Atoms and ions can also be excited to higher energy states by absorbing optical photons. And in the same way that a grand-

First timer: Scott Diddams' prototype mercury clock was the first timepiece to use optical wavelengths.

father clock with a pendulum that swings once a second is more accurate than a sundial, which repeats its cycle over 24 hours, so clocks that can count transitions driven by the higher frequencies of optical radiation are potentially much more accurate than microwave systems. In theory, an optical clock could measure a second down to a staggering 18 decimal places.

The current undisputed leaders in this effort are Scott Diddams and his colleagues at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. In

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August 2001, they demonstrated a prototype optical clock for the first time (S. A. Diddams *et al. Science* **293**, 825–828; 2001). Diddams' clock harnesses the 10^{15} oscillations per second made by a laser that is exciting a single mercury ion. The way in which the ion absorbs the laser light is monitored, and the laser is adjusted so that it resonates with the ion's movements between energy levels. The researchers are currently trying to establish how accurate the clock is. "There's still a long road ahead to make real devices that can function day-in and day-out," says Diddams.

To improve matters, the NIST team is studying the factors that control the accuracy and stability of their clock. These are two separate issues — accuracy defines how closely a clock's output matches the desired time interval, whereas stability is a measure of how steady that output is. A clock that loses precisely a second each day is inaccurate but stable, for example.

G. WHEELER/NIST

Patrick Gill (left) and Alan Madej predict that optical clocks will rise to prominence within a decade.

The clock's height above sea level, for instance, influences its accuracy, as the rules of general relativity dictate that gravity affects observations of all timepieces — in this case the resonant frequency of the mercury ion. To achieve maximum accuracy, differences in height between the laser and the apparatus that counts the laser's oscillations need to be corrected for. Minute motions in the laser, on the other hand, can shift the frequency of the laser light and cause stability problems. Alan Madej of Canada's Institute for National Measurement Standards in Ottawa is working on an optical clock that uses a strontium ion as its pace-maker. He points out that stability can be compromised if the laser moves by as little as the diameter of a neutron.

Timely developments

None of these problems should be insurmountable, however, and Madej says that optical clocks that outperform the best existing microwave clocks will probably be developed and tested within a decade or so. Movements due to vibration can, for example, be reduced by mounting equipment on tables that float on cushions of air. And several groups are working on clocks based on millions of atoms, which resonate together when excited by laser light and produce stronger and more stable signals. Collisions between the atoms do, however, cause shifts in the tell-tale resonant frequency, and different arrangements of atoms produce different shifts. So what this design gains in stability, it may lose in accuracy.

If optical clocks can be made to work, GPS could be one of the first areas of technology to benefit. Currently, receivers calculate positions using the time signal from in-range satellites run by the US military, each of which contains a basic microwave atomic clock. At present, the system can measure locations to within tens of metres, or better if the receiver is within range of one of the ground stations, which use more

accurate clocks. Improving the accuracy of the satellites' clocks could enable receivers to measure their positions to within a centimetre.

Some physicists who are interested in fundamental constants are also in need of new clocks. In 1999, a team of astronomers led by John Webb of the University of New South Wales in Sydney provocatively suggested that the fine-structure constant, which determines the strength of electromagnetic forces, may not actually be constant (J. K. Webb, V. V. Flambaum, C. W. Churchill, M. J. Drinkwater and J. D. Barrow *Phys. Rev. Lett.* **82**, 884–887; 1999). Webb's team looked at light emitted by very bright objects known as quasars, which are thought to be distant galaxies powered by a supermassive central black hole. During the billions of years it takes for their light to arrive at the Earth, certain frequencies of this light are absorbed by interstellar dust.

But analysis of the quasars' light showed that the absorption, which depends on the value of the fine-structure constant, did not match that predicted from laboratory experiments. This, Webb suggests, may be due to the fact that the value of the constant has changed during the light's long journey — although many astronomers argue that his data are not sufficiently robust to make such a bold claim.

New optical clocks could help to test Webb's controversial idea. The value of the

Spot-on: could optical clocks improve GPS?

fine-structure constant influences the resonant frequency of ions, so researchers want to compare the beats of two clocks made from different ions. If the ratio changes over time, variations in the fine-structure constant could be the cause. Attempts to investigate this by analysing the time signal from conventional atomic clocks have so far not produced any positive results, but this could be because they cannot measure time accurately enough.

Second thoughts

With caesium clocks currently being used to define the second, the development of a new optical clock could also put pressure on the International Committee for Weights and Measures, the guardian of global measurement standards, to redefine this unit. "It's likely that in maybe a decade we'll be thinking of a redefinition of the second using an optical clock," says Patrick Gill, who works on optical clocks that use ytterbium or strontium ions at Britain's National Physical Laboratory in Teddington, near London. But with several different countries all pouring money and effort into their own designs, it would be a brave decision to pick one as a model system. "I don't think there will ever be anything to say that one clock is really head and shoulders above the others," argues Madej. "I have a feeling that, politically, the second will not be revised."

The availability of different designs will, however, help physicists to test their devices. Researchers currently have to assess the performance of optical clocks using the lower frequencies produced by caesium clocks. This isn't as contradictory as it sounds. Ted Hänsch, a physicist at the Max Planck Institute for Quantum Optics in Garching, Germany, has developed a system that multiplies the frequency of the microwave signal, producing a new signal with a frequency that is in the optical range (T. Udem, J. Reichert, R. Holzwarth and T. W. Hänsch *Phys. Rev. Lett.* **82**, 3568–3571; 1999), and which can be compared to the output of the optical clocks. The system works for now, as the accuracies of optical and microwave clocks are similar.

But this technique will fail when more accurate optical clocks are developed. The first such clock will, by definition, have no other device with which to calibrate it. "When an optical clock finally surpasses the accuracy of microwave clocks, the most rigorous way to verify that is to build a second one," Diddams says. And it may not stop there. If the second clock disagrees with the first, another will be needed. "If you have only one clock then you don't know what time it is, but if you have two then nobody knows what time it is," points out Diddams. "You actually need three clocks." Even when the race to develop the first accurate optical clock has been won and lost, the physicists involved won't be left with time on their hands. ■

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