Fountains of Time

Tossing cold atoms like confetti, atomic-fountain clocks launch a new era in timekeeping

By PETER WEISS

NIST

A sea of lenses and mirrors controls laser beams in the NIST F-1 atomic-fountain clock. The beams cool, trap, and toss atoms into the silvery shaft at the top of the instrument. They also excite and detect atoms' energy states.

In the 1970s, Judah Levine would periodically lug a shiny aluminum suitcase aboard a commercial airliner, strap it into the seat next to him, and head for France. Inside the heavy luggage was one of the world's most precise clocks. Levine's mission was to compare its time with that of clocks at the International Bureau of Weights and Measures near Paris, which keeps time for the world.

Hand carrying clocks to Paris "was the standard method then" for maintaining accurate world time, recalls the physicist, who works at the National Institute of Standards and Technology (NIST) in Boulder, Colo. Transmitting time by telephone or radio was too imprecise because of variable signal delays.

By the 1980s, however, the United States and much of the world were relying on orbiting satellites rather than scientist travelers to keep accurate time. Because each navigation satellite in the Global Positioning System (GPS) carries a good atomic clock of its own, national metrology laboratories use the spacecrafts' time and frequency transmissions to compare their ground-based master clocks. With the advent of GPS, Levine and other scientists gave up their flights.

Now, atomic-clock technology is entering a new phase. At the pinnacle of time and frequency measurement, a novel device known as the atomic-fountain clock is about to displace the reigning thermal-beam atomic clocks. The new instruments toss ultracold atoms upward and let them fall under the influence of gravity. Thermal-beam clocks, in contrast, use fast-moving streams of relatively hot atoms to mark time.

The use of cold atoms represents "a fundamental change in the way we build atomic clocks," says NIST's Steven Jefferts, also in Boulder. Chilling atoms improves atomic-clock performance because cold atoms move more slowly, making it possible to detect more precisely their response to microwaves of a critical frequency.

Already, the first clock of this new generation has joined the rank of the world's primary frequency standards—the most accurate clocks on the planet. The handful of clocks in that exclusive club, formerly only thermal-beam devices, enable the Paris bureau to determine whether the world's official clock is running fast or slow.

The unveiling of the first fountain clock in 1994 by a French team set off a scramble among standards labs around the world to make similar devices of their own. Some 15 countries have made it known that they intend to build fountain clocks. About a half-dozen of the clocks have already been built or are expected to be finished in the next year or two.

"It's a big, exciting time for the clock community," says Jefferts, one of the leaders in the construction of the first NIST fountain clock expected to become a primary standard.

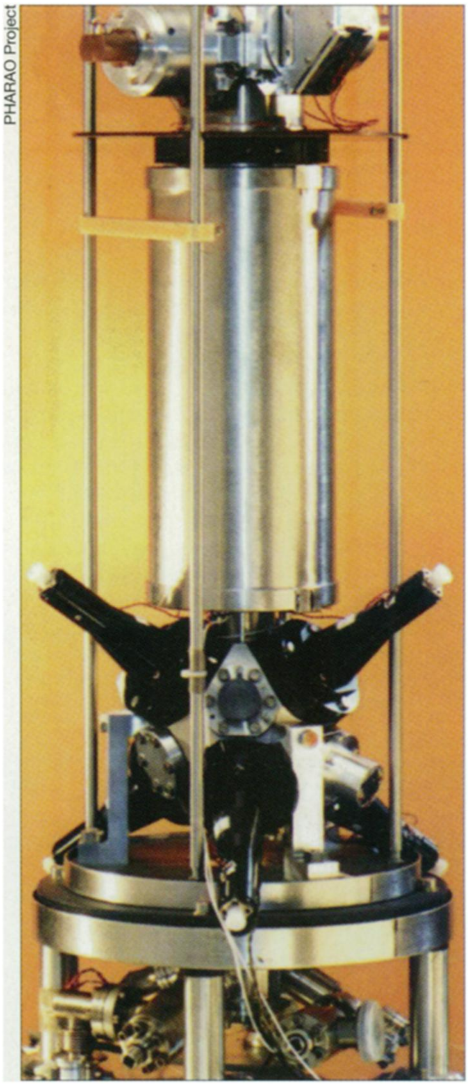
Clock experts say that the advent of fountain clocks will spur demand for greater precision from many quarters—especially for military and civilian telecommunications and certain areas of astronomy and physics research. Projects to make fountain-type clocks adapted to zero gravity for the International Space Station are also under way in France and at NIST.

Ironically, the leap forward to fountain clocks is expected to turn back the clock, at least temporarily, to the days before the GPS. Because fountain clocks are too precise to be adequately compared via satellite transmissions, labs may again have to send atomic timing devices on airplanes to meet each other face-to-face.

Since the first thermal-beam atomic clock was built in 1949, designers have boosted the accuracy of such clocks from 1 second of error in 300 years to 1 second in 6 million years (SN: 5/1/93, p. 76). Moving at about 100 meters per second, atoms in a thermal beam get a kick to a new energy level as they pass through chambers filled with microwaves of adjustable frequency. The instrument tunes its microwave emissions to maximize production of the excited atoms. The tuned signal then serves as a frequency reference, or its oscillations can be counted off electronically to generate clock ticks.

In the past few years, the hope of much further improvement in these devices had dimmed. The thermal beam clock "was up against the wall," Jefferts says.

To burst through that wall, scientists have devised the atomic-fountain clock. It also tunes microwaves to the excitation of atoms in a cavity. However, the atoms are first cooled to microkelvin temperatures and then launched at a few meters per second up through the microwave cavity, which is kept in a vacuum. Before falling back down again, the atoms become momentarily motionless.


PHARAO Project

Have Tube, Will Travel: This cylinder, the fountain part of the PHARAO prototype atomic-fountain clock, detaches neatly from the rest of the instrument. Modular design is making it possible for such clocks to travel from lab to lab and into space.

"They toss just as your car keys do," says Christopher R. Ekstrom of the U.S. Naval Observatory in Washington, D.C., who is building a fountain clock there for the military's timekeeping needs.

Slower atoms spend a longer time travelling through the device—about a half second for fountain atoms versus about 10 milliseconds for thermal-beam atoms. The precision of the clock can improve in rough proportion to that increase in time, or by a factor of 10 to 100. "The longer you can look at an atom in your [clock] the better you can do," Ekstrom notes.

Although fountains will eventually dislodge thermal-beam clocks as primary standards, scientists say, the older technology will persist in other ranks of the world time system.

Some 250 very good thermal-beam clocks generate the timing data from which the Paris bureau calculates an approximate time reference, or "flywheel," for the world. Its rate is then "steered," or adjusted according to the roughly half-dozen primary standards. Many labs and companies also buy atomic clocks from manufacturers whose technology of choice for now remains the thermal beam.

The idea of a fountain clock is not new. In the late 1950s and early 1960s, Jerrold R. Zacharias of the Massachusetts Institute of Technology attempted unsuccessfully to make a fountain clock using hot atoms. Decades later, the development of methods to cool and trap atoms with lasers opened the way to clocks based on cold atoms. Steven Chu of Stanford University and his colleagues created the first laser-controlled fountain of cold atoms in 1989, suggesting then that it might lead to a better atomic clock (SN: 8/19/89, p. 117).

Other researchers agreed, but the French team led by André Clairon of the Paris Observatory pursued the goal with unusual devotion. "Ten years ago, it was very difficult to decide which would be the next step," says Stefan Weyers, who is working on a fountain clock for Germany's standards lab in Braunschweig.

Clock builders distinguish between accuracy and precision. A very accurate clock counts off a second that's extremely close in duration to the world's definition of that unit of time—i.e., the period in which 9,192,631,770 oscillations of a particular microwave frequency emitted by the cesium-133 atom take place. A very stable, or precise, clock produces an oscillating signal whose frequency varies extremely little.

The world's most accurate clock—the original fountain built by Clairon's team—currently performs about six times as well as the best thermal-beam standard. Clock developers say there may be ways to achieve another 10-to-20-fold improvement in accuracy from fountain clocks, driving the clock error down to about 1 second in 300 million years or better.

Recently, the French researchers, working with Christophe Salomon of the École Normale Supérieure in Paris and scientists at the University of Western Australia in Nedlands, demonstrated that they can achieve not only the best accuracy but also unprecedented stability with a fountain clock. In the June 7 Physical Review Letters, the researchers report eliminating all frequency irregularities except fundamental noise inherent in detecting properties of atoms.

Atomic-fountain clocks keep time with spectacular accuracy, but they can't compete with an ordinary wristwatch in terms of reliability. Although the clock Jefferts' team is building, called NIST F-1, "is a pretty sophisticated piece of equipment, it's hard to keep it running," says Thomas E. Parker, head of NIST's atomic standards group, which includes Jefferts' team. "We can keep it running for a couple of days," which, for now, is typical of such instruments, he says.

So far, Jefferts' team at NIST is the closest, after the French, to completing a fountain clock suitable as a primary standard. The team expects to supply data on the performance of NIST F-1 to the Paris bureau by the end of this summer. German researchers are roughly half a year behind NIST.

"This is the hottest I've ever seen this field," says Donald B. Sullivan, who heads the Time and Frequency Division of NIST in Boulder.

In the world of time and frequency, the science is typically a decade ahead of demand. Although the precision of thermal-beam clocks still satisfies practical demands, those demands are expected to grow as fountain clocks become more common.

"In the first years, the ultrastable [fountain] clocks will probably be of interest to physicists only. But once something is available, users will probably jump on the bandwagon," says Gérard Petit, interim time-service director at the Paris bureau.

Clock improvements typically enable physicists to test more rigorously the predictions of relativity theory and the immutability of fundamental constants of nature and physics. The French clock makers are using their fountain clocks to compare the ratio of atomic-transition frequencies of different atoms—cesium and rubidium—to test the stability of the so-called fine-structure constant, a combination of elementary physical quantities that turns up frequently in atomic physics.

Others who can always use more accurate clocks include astrophysicists studying star remnants known as pulsars and facilities that track and control spacecraft.

Outside the basic-research community, the first customers for more precise timepieces will probably be telecommunications developers, both military and civilian, clock developers say. Moving data faster means slicing time ever-more finely. Particularly for secure communications, in which remote computers exchange encrypted messages—and so must both switch to a new code at the same moment—the demand for extremely exact timing is on the rise.

"They want to keep going faster and faster, and that means better synchronization," Parker says.

For the past 2 decades, GPS has made it relatively easy to compare clocks at the world's widely separated metrology laboratories. The labs measure the difference between signals from a chosen satellite and their clocks at a prearranged time, allowing a straightforward determination of the time difference between the two laboratory clocks.

Although fluctuations in the atmosphere and random noise degrade the transmissions, until now, instability in the satellites' clock signals themselves exceeded the transmission noise. For fountain clocks, however, the reverse is true: The fine scale at which they measure time can't be preserved in the transmissions.

For the International Space Station, the French group has built a prototype of a compact timepiece, dubbed PHARAO, that uses a variation on fountain-clock technology. In parabolic test flights that cause brief weightlessness, the researchers have demonstrated that the prototype works, says Giorgio Santarelli of the Paris Observatory. Because there is not enough gravity in space to bring back down cold atoms tossed upward, this device instead propels the atoms slowly across a microwave cavity.

On the ground, however, the compact clock uses a fountain configuration, but one that's unusual because it's portable. In July, the team returned from the device's first road trip, a truck ride to the Max Planck Institute for Quantum Optics in Garching, Germany, where the clock was used in measurements of a property of hydrogen atoms.

Clairon says that he anticipates sending scientists on airplane trips with this portable fountain clock to compare its performance with fountain clocks at other laboratories.

Will the new era of timekeeping really call for a return to the old ways?

Parker says there are solutions under way to extend the use of satellite comparisons by taking advantage, for instance, of higher-frequency signals that are already broadcast by GPS satellites. If these plans pan out, just a few trips may be needed to double-check that those improvements in transmission quality are real.

That's probably good news for Levine and other metrologists. Whisking a clock off to Paris may sound glamorous, says Levine, but the transatlantic journeys were really "a lot of work." □