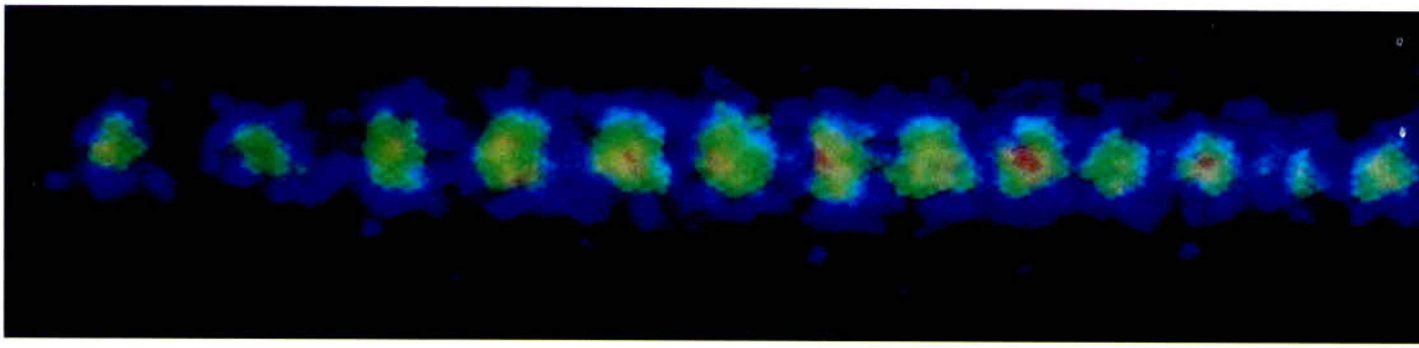
Accurate Measurement of Time

Increasingly accurate clocks—now losing no more than a second over millions of years—are leading to such advances as refined tests of relativity and improved navigation systems

by Wayne M. Itano and Norman F. Ramsey



Few people complain about the accuracy of modern clocks, even if they appear to run more quickly than the harried among us would like. The common and inexpensive quartz-crystal watches lose or gain about a second a week—making them more than sufficient for everyday living. Even a spring-wound watch can get us to the church on time. More rigorous applications, such as communications with interplanetary spacecraft or the tracking of ships and airplanes from satellites, rely on atomic clocks, which lose no more than a second over one million years.

WAYNE M. ITANO and NORMAN F. RAMSEY have collaborated many times before writing this article: Itano earned his Ph.D. at Harvard University under the direction of Ramsey. Itano, a physicist at the Time and Frequency Division of the National Institute of Standards and Technology in Boulder, Colo., concentrates on the laser trapping and cooling of ions and conducts novel experiments in quantum mechanics. He is also an amateur paleontologist and fossil collector. Ramsey, a professor of physics at Harvard, earned his Ph.D. from Columbia University. He has also received degrees from the University of Oxford and the University of Cambridge, as well as several honorary degrees. A recipient of numerous awards and prizes, Ramsey achieved the highest honor in 1989, when he shared the Nobel Prize in Physics for his work on the separated oscillatory field method and on the atomic hydrogen maser.

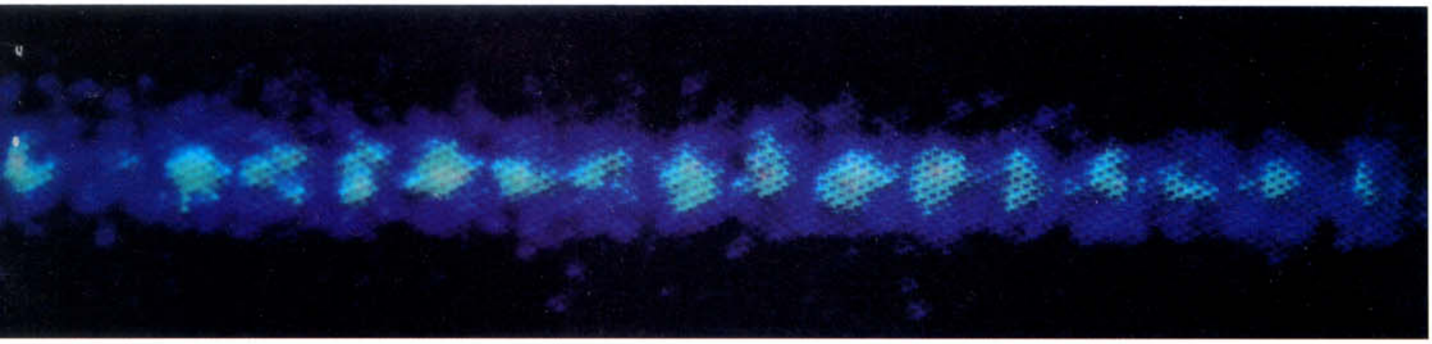
There might not seem to be much room for the improvement of clocks or even a need for more accurate ones. Yet many applications in science and technology demand all the precision that the best clocks can muster, and sometimes more. For instance, some pulsars (stars that emit electromagnetic radiation in periodic bursts) may in certain respects be more stable than current clocks. Such objects may not be accurately timed. Meticulous tests of relativity and other fundamental concepts may need even more accurate clocks. Such clocks will probably become available. New technologies, relying on the trapping and cooling of atoms and ions, offer every reason to believe that clocks can be 1,000 times more precise than existing ones. If history is any guide, these future clocks may show that what is thought to be constant and immutable may on finer scales be dynamic and changing. The sundials, water clocks and pendulum clocks of the past, for example, were sufficiently accurate to divide the day into hours, minutes and seconds, but they could not detect the variations in the earth's rotation and revolution.

A clock's accuracy depends on the regularity of some kind of periodic motion. A grandfather clock relies on the sweeping oscillation of its pendulum. The arm is coupled to a device called an escapement, which strikes the teeth of a gear in such a way that the gear moves in only one direction. This gear, usually through a series of additional gears, transfers the motion to the hands of the clock. Efforts to improve clocks are directed for the most part toward finding systems in which the oscillations are highly stable.

The three most important gauges of frequency standards are stability, reproducibility and accuracy. Stability is a measure of how well the frequency remains constant. It depends on the length of an observed interval. The change in frequency of a given standard might be a mere one part per 100 billion from one second to the next, but it may be larger—say, one part per 10 billion—from one year to the next. Reproducibility refers to the ability of independent devices of the same design to produce the same value. Accuracy is a measure of the degree to which the clock replicates a defined interval of time, such as one second.

Until the early 20th century, the most accurate clocks were based on the regularity of pendulum motions. Galileo had noted this property of the pendulum after he observed how the period of oscillation was approximately independent of the amplitude. In other words, a pendulum completes one cycle in about the same amount of time, no matter how big each sweep is. Pendulum clocks became possible only after the mid-1600s, when the Dutch scientist Christiaan Huygens invented an escapement to keep the pendulum swinging. Later chronometers used the oscillations of balance wheels attached

TRAPPED MERCURY IONS, separated by about 10 microns, fluoresce under illumination by ultraviolet light (*photograph*). The ions are held by oscillating electric fields generated by electrodes (*cutaway diagram*). Static electric potentials (*not shown*) prevent the ions from escaping through the ends of the trap. Strings of trapped ions may lead to new timing devices more stable than conventional atomic clocks.



to springs. These devices had the advantage of being portable.

Considerable ingenuity went into improving the precision of pendulum and balance-wheel clocks. Clockmakers would compensate for temperature changes by combining materials with different rates of thermal expansion. A more radical approach came in the 1920s, when William H. Shortt, a British engineer, devised a clock in which a "slave pendulum" was synchronized to a "free pendulum." The free pendulum oscillates in a low-pressure environment and does not have to operate any clock mechanism. Instead it actuates an electrical switch that helps to keep the slave pendulum synchronized. As a result, the period of the Shortt clock is extremely stable. These clocks had an error of a few seconds in a year (about one part per 10 million) and became the reference used in laboratories.

The next major advance in timekeeping was based on the development of quartz-crystal electronic oscillators. The frequency of such devices depends on the period of the elastic vibration of a carefully cut quartz crystal. The vibrations are electronically maintained through a property of such crystals called piezoelectricity. A mechanical strain on the crystal produces a low electric voltage; inversely, a voltage induces a small strain.

The quartz vibrates at a frequency that depends on the shape and dimensions of the crystal. In some wristwatches, it is cut into the shape of a tuning fork a few millimeters long. In other timepieces, it is a flat wafer. The quartz is connected to an electric circuit that produces an alternating current. The electrical feedback from the quartz causes the frequency of the circuit to match the frequency at which the crystal naturally vibrates (usually 32,768 hertz). The alternating current from the circuit goes to a frequency divider, a digital electronic device that generates one output pulse for a fixed number of input pulses. The divider also actuates either a mechanical or digital electronic display.

In the late 1920s Joseph W. Horton and Warren A. Marrison, then at Bell Laboratories, made the first clock based on a quartz-crystal oscillator. In the 1940s quartz-crystal clocks replaced Shortt pendulum clocks as primary laboratory standards. These clocks were stable to about 0.1 millisecond per day (about one part per billion). Relatively inexpensive, quartz clocks continue to be extensively used. The timekeeping elements of common quartz watches and clocks are simplified and miniaturized versions of quartz frequency standards. Quartz wristwatches became common once the ability emerged to cut the quartz into thin, tuning-fork shapes reliably and to manufacture miniature, low-power digital electronic components.

Yet quartz-crystal clocks prove inadequate for many scientific applications, such as tests of relativity. According to Albert Einstein's calculations, gravity distorts both space and time. The difference in gravitational potential causes time to pass more quickly high in the atmosphere than it does on the surface. The difference is slight. Time runs about 30 millionths of a second per year faster at the top of Mount Everest than it does at sea level. Only atomic frequency standards achieve the requisite precision.

The quantized energy levels in atoms and molecules provide the physical basis for atomic frequency standards. The laws of quantum mechanics dictate that the energies of a bound system, such as an atom, have certain discrete values. An electromagnetic field can boost an atom from one energy level to a higher one. The process can also work in reverse. If the atom is in a high energy level, it can drop to a lower level by emitting electromagnetic energy.

The maximum amount of energy is absorbed or emitted at a definite frequency—the resonance frequency, or the difference between the two energy levels divided by Planck's constant. This value is sometimes called the Bohr frequency. Such frequencies make ideal time standards because they are extremely stable. Time can be kept by observing the frequencies at which electromagnetic energy is emitted or absorbed by the atoms. In essence, the atom serves as the master pendulum whose oscillations are counted to mark the passage of time.

Although we have described general quantum properties, the effects exploited in atomic clocks are slightly more complicated. In most atomic clocks the energy that atoms absorb or release actually results from transitions between so-called hyperfine energy levels. These levels exist because of an intrinsic property of particles known as the magnetic moment. Electrons and the nuclei of most atoms spin about their axes as if they were tops. In addition, they are magnetized, like compass needles oriented along their axes of rotation. These axes can have different orientations with respect to one another, and the energies of the orientations may differ. These positions correspond to the hyperfine levels. The nomenclature comes about because the levels were first observed in spectroscopy as small splittings of spectral lines.

On paper, standards based on atomic processes are ideal. In practice, perfection is elusive. Atoms do not absorb or emit energy precisely at the resonance frequency. Some energy is spread over a small interval surrounding the frequency—a smearing of frequencies, so to speak. All else being equal, the precision to which the resonance frequency can be measured is inversely proportional to this smearing. The greater the spread, the less precise the measurement. The spread is often expressed in terms of the quality factor, or Q, which is equal to the resonance frequency divided by the frequency spread. In many cases, the higher the resonance frequency, the higher the Q. Furthermore, smearing is often inversely proportional to the time the atom is in the apparatus. In those situations, the Q of the resonance, and hence the precision of the measurement, increases as the measuring time increases.

The motions of the atoms also introduce uncertainty by causing apparent shifts in the resonance frequencies. Such changes appear because of the Doppler effect. The phenomenon can be divided into first- and second-order shifts if the atoms are moving much slower than the speed of light. The first-order Doppler shift is an apparent change in the frequency of the applied electromagnetic wave as seen by a moving atom. The amount of the shift is proportional to the velocity of the atom. If the atom moves in the same direction as the wave does, the shift is to a lower frequency. If the atom's motion is opposed to that of the wave, the shift is to a higher frequency. If the directions are perpendicular, the first-order shift is zero.

The second-order Doppler shift comes about as a consequence of time dilation. According to relativity, time slows down for objects in motion; a moving atom "sees" a slightly different frequency than does a stationary counterpart. The effect on the resonance frequency is usually much smaller than the first-order shift. The second-order shift is proportional to the square of the atomic velocity and does not depend on the relative directions of the atomic motion and the electromagnetic wave.

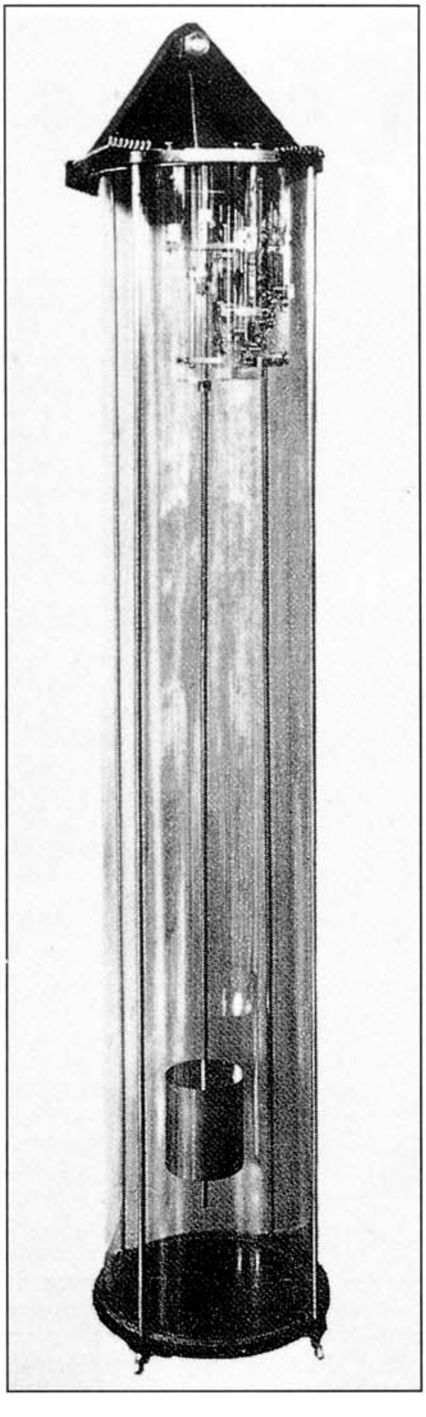
Several other factors affect the quality of the information. Atoms in the system may collide with one another; the impacts add noise to the signal. The surrounding environment can perturb the resonance frequencies. Defects in the electronic equipment, stray electromagnetic fields and the ever present thermal radiation all introduce errors. Therefore, a good atomic frequency standard not only must establish a steady, periodic signal but also must minimize these potential errors.

One of the earliest and now widely used methods to sidestep many of these difficulties is called atomic beam resonance, pioneered by I. I. Rabi and his colleagues at Columbia University in the 1930s. The atoms emerge from a small chamber, exit through a narrow aperture and then travel as a beam. The entire instrument can be shielded from stray magnetic and electric fields and insulated from external sources of heat. Perhaps more important, collisions of atoms are virtually eliminated, because the entire device is housed in a long, evacuated chamber. The pressure in the chamber is so low that the atoms are unlikely to strike anything before reaching the other end.

In simplified form, atomic beam resonance involves three steps. The first is to select only those atoms in the appropriate energy level. This selection is accomplished by using a specially shaped magnetic field, which acts as a kind of filter. It allows atoms in one energy level to pass and blocks all others by bending the beam. Only atoms in the correct energy level are bent the correct amount to reach and pass through the aperture that serves as the entrance to the cavity.

The second and crucial step is to send the selected atoms into another energy level. The task is accomplished by passing the atoms through an oscillating microwave field inside a cavity. The atoms will go to another energy level only if the frequency of the applied oscillating microwaves matches their Bohr frequency.

The third step is to detect those atoms that have changed energy levels. At this point, the beam of atoms passes through another magnetic field filter, which allows only atoms in the correct energy level to strike a detector that records the atoms as current flow. An abundance of such atoms will exist if the frequency of the applied oscillating microwaves precisely matches their natural frequency. If the frequency of the applied microwave field is off the mark, fewer atoms change their energy



MASTER PENDULUM of this 1920s Shortt clock oscillates in an evacuated enclosure. It actuates an electrical switch to synchronize a slave pendulum, which drives the clock mechanism.

levels, and so fewer will strike the detector. One knows, therefore, that the applied microwaves match the natural frequency of the atoms if the number of atoms striking the detector is maximal. An electronic feedback mechanism, called a servo loop, keeps this value constant. If it finds that the current from the detector is falling off, it changes the frequency of the applied field until the current reaches a maximum again.

By keeping the current from the detector at a maximum, the servo loop maintains the frequency of the applied microwave field at the natural frequency of the atoms. To measure time, one couples the applied field to a frequency divider, which generates timing pulses. By analogy, the atoms represent the quartz crystal in a watch or the master pendulum in a Shortt clock. The applied microwave field is the oscillating circuit or the slave pendulum, which actually drives the clock mechanism.

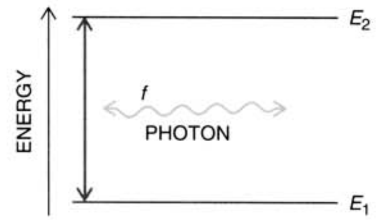
Minor variations of the atomic beam standard exist. For example, in some devices the atoms that undergo a change in energy level are made to miss, rather than strike, the detector. Not much difference in accuracy exists, however. Rather all the versions to some extent represent trade-offs in terms of size, cost and complexity.

A more important modification of the atomic beam came in 1949, when one of us (Ramsey) invented the so-called separated oscillatory field method. Instead of irradiating the atoms with a single applied field, this technique relies on two fields, separated by some distance along the beam path. Applying the oscillating field in two steps has many benefits, including a narrowing of the resonance and the elimination of the first-order Doppler shift. Jerrold R. Zacharias of the Massachusetts Institute of Technology and Louis Essen and John V. L. Parry of the National Physical Laboratory in Teddington, England, adapted this method to working frequency standards in the mid-1950s.

Currently the separated oscillatory field method provides the most reproducible clocks. The best ones are located at a few national laboratories, although smaller and less accurate versions are commercially available. The clocks rely on cesium, which has several advantages over other elements. It has a relatively high resonance frequency—about 9,192 megahertz—and low resonance width, which lead to an excellent Q. Cesium can also be detected readily and efficiently; all that is needed is a hot metal filament. When a cesium atom strikes the filament, it ionizes and becomes observable as electric current.

Resonance Frequency

Atomic frequency standards depend on the quantization of the internal energies of atoms or molecules. A pair of such energy levels, shown here as levels E_1 and E_2, is associated with an atomic resonance. The resonance frequency f, at which it absorbs or emits electromagnetic radiation, is $f = (E_2 - E_1)/h$, where h is Planck's constant. The radiation, however, is not precisely f but instead is spread over a range near f, called Δf. The precision to which f can be measured is proportional to the quality factor, Q, defined by $Q = f/\Delta f$. The higher the Q, the more stable the clock.



The Qs of these standards are about 100 million, exceeding the Q of quartz wristwatches by a factor of several thousand. The greatest reproducibilities are about a part per 10^{14}. The best cesium frequency standards are so much more reproducible than the rate of rotation and revolution of the earth that in 1967 the second was defined as 9,192,631,770 periods of the resonance frequency of the cesium 133 atom.

One of the most promising improvements in cesium atomic-beam standards is the use of optical pumping to select the atomic states. Beginning in the 1950s optical-pumping techniques were developed by Francis Bitter of M.I.T., Alfred Kastler and Jean Brossel of the École Normale Supérieure and others. In this method, light, rather than a magnetic field, selects atoms in the desired states. Before the atoms are subjected to the microwave field, radiation from a laser is used to drive (or pump) the atoms from one energy level into another. In fact, one can control the number of atoms in energy levels by tuning the frequency of the light.

After the atoms have been irradiated by the microwave field, they pass through a second light beam. Only atoms occupying the correct energy level absorb this light, which they quickly reemit. A light-sensitive detector records the reemissions and converts them into a measurable current. As in atomic beam resonance that relies on magnetic selection, one knows that the applied microwave field matches the natural frequency of the atoms if the current from the detector is at a maximum.

Using light instead of magnets has many advantages. Perhaps the most crucial is that, with the right optical-pumping techniques, all the atoms in the beam can be put into the desired energy level. Magnetic selection merely filters out those that are in the other energy levels. Hence, the signal strength from optical pumping is much higher than it is from magnetic selection. Researchers at various laboratories are developing optically pumped cesium atomic-beam clocks. One such clock, at the National Institute of Standards and Technology (NIST) in Boulder, Colo., has recently become the primary frequency standard for the U.S. Designated NIST-7, it has an expected error of one second in about one million years, making it many times more stable than its predecessor.

There is an optically pumped atomic clock that is available commercially. Such a clock is based on the 6,835-megahertz, hyperfine resonance of rubidium 87. Rather than moving through the apparatus as a beam, the rubidium atoms are contained in a glass cell. The cell also houses a mixture of gases that prevents the rubidium atoms from colliding with the cell walls. A discharge lamp containing rubidium vapor, rather than a laser, irradiates the atoms. A photovoltaic sensor on the opposite side of the cell detects changes in the amount of light absorbed by the atoms. The atoms are prepared, the microwaves applied and the light detected in one cell. As a result, rubidium clocks can be made to fit in a cube about 10 centimeters on a side. In contrast, cesium beam clocks can extend from about 50 centimeters to more than five meters. Rubidium clocks are also much less expensive than are cesium ones.

The drawback is that the rubidium devices are generally less accurate and less reproducible. The Q of rubidium standards is about 10 million, a factor of 10 less than the cesium beam's quality factor; their reproducibility is only about a part per 10^{10}. Shifts in the resonance frequency mostly account for the poor reproducibility. The frequent collisions of the rubidium atoms with other gas molecules cause the shifts. But the rubidium standards' short-term stabilities are good—in fact, better than those of some cesium atomic beams.

The atomic clocks described thus far work in a rather roundabout way—by detecting a change in some signal, such as the number of atoms striking a detector, as the frequency of the applied oscillatory field shifts. One way to make use of the radiation emitted by the atoms more directly relies on the principle of the maser (an acronym for microwave amplification by stimulated emission of radiation). In 1953 Charles H. Townes and his associates at Columbia invented the first maser, which was based on ammonia. Beginning in 1960, Ramsey, Daniel Kleppner, now at M.I.T., H. Mark Goldenberg, then at Harvard University, and Robert F. C. Vessot, now at the Harvard-Smithsonian Center for Astrophysics, developed the atomic hydrogen maser, the only type that has been used extensively as an atomic clock.

In this instrument, a radio frequency discharge first splits hydrogen molecules held in a high-pressure bottle into their constituent atoms. The atoms emerge from a small opening in the bottle, forming a beam. Those in the higher energy level are focused by magnetic fields and enter a specially coated storage bulb surrounded by a tuned, resonant cavity.

In the bulb, some of these atoms will drop to a lower energy level, releasing photons of microwave frequency. The photons will stimulate other atoms to fall to a lower energy level, which in turn releases additional microwave photons. In this manner, a self-sustaining microwave field builds up in the bulb—thus the name "maser." The tuned cavity around the bulb helps to redirect photons back into the system to maintain the stimulated emission process. The maser oscillation persists as long as the hydrogen is fed into the system.

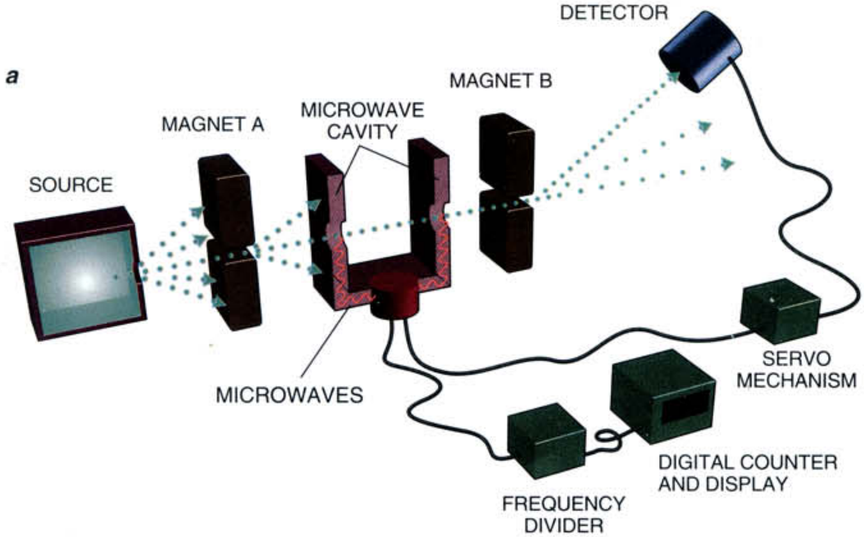
A loop of wire in the cavity can detect the oscillation. The microwave field induces a current in the wire, which leads out of the cavity to a series of circuits. The circuits convert the induced current to a lower frequency signal suitable for generating timing pulses.

The resonance frequency in the hydrogen maser is about 1,420 megahertz, which is much lower than the resonance frequency of cesium. But because the hydrogen atoms reside in the bulb much longer than cesium atoms do in a beam, the maser's resonance width is much narrower. Consequently, the Q of a hydrogen maser standard is about 10^9, exceeding the Q of the cesium atomic clock by an order of magnitude. In addition, a hydrogen maser has the highest stability of any frequency standard, better than one part per 10^{15}.

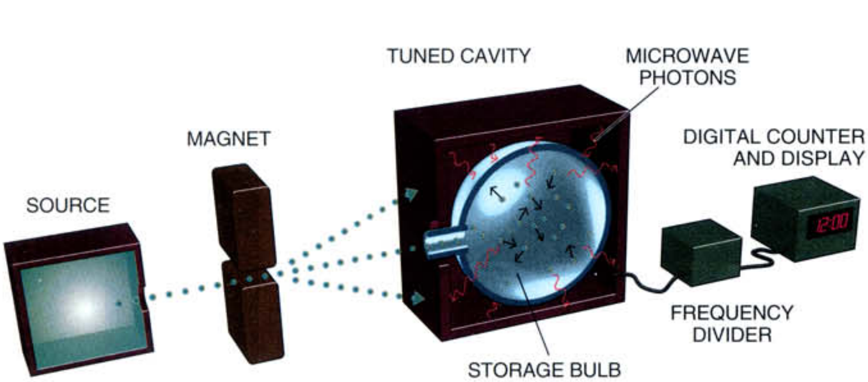
Unfortunately, the maser's superior attributes last just for a few days. Beyond that, its performance falls below that of cesium beams. The stability decreases because of changes in the cavity's resonant frequency. Collisions between the atoms and the bulb shift the frequency by about one part per 10^{11}.

One way to overcome the problem is to operate the hydrogen maser at low temperatures. This condition allows more atoms to be stored (thus resulting in a stronger signal) and reduces electronic noise. Coating the inside of the bulb with superfluid liquid helium also enhances performance. This substance acts as a good surface against which the hydrogen atoms can bounce. More effective magnets, better coating substances and servo loop techniques that keep the cavity resonance centered on the atomic resonance are other approaches now being taken to improve maser stability.

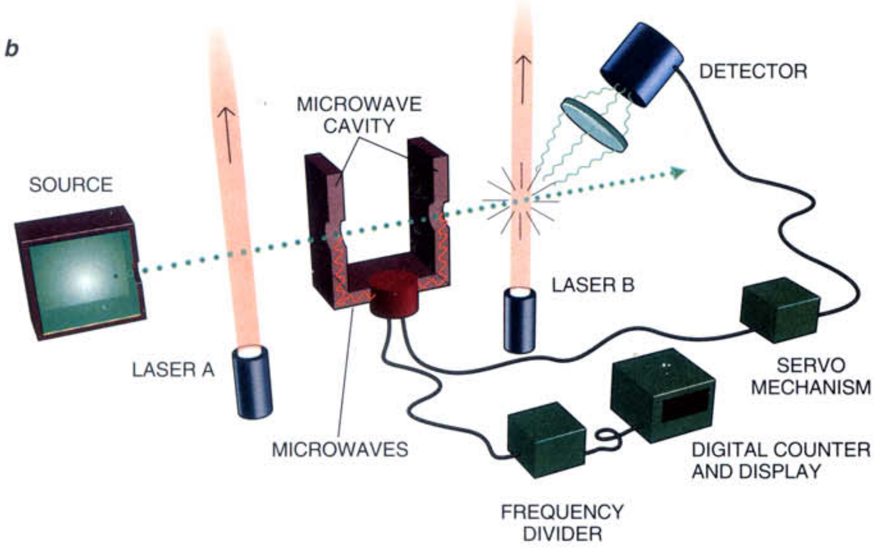
Although the cesium atomic-beam frequency standard is the most accurate, long-term standard we have, several breakthroughs have indicated that it is possible to fabricate even more precise clocks. One of the most promising depends on the resonance frequency of trapped, electrically charged ions. Trapped ions can be suspended in a vacuum so that they are almost perfectly isolated from disturbing influences. The ions themselves stay well separated from one another

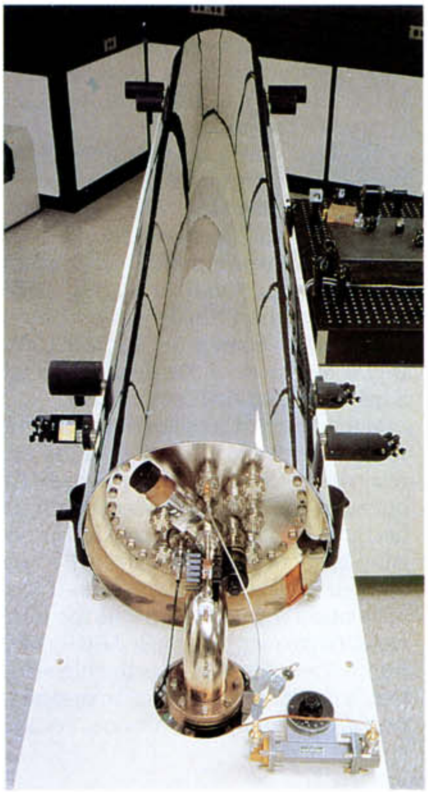


ATOMIC-BEAM frequency standards provide the most accurate, long-term timekeeping. Conventional atomic clocks rely on magnets (*a*). Atoms in the correct energy level are deflected by magnet A through the microwave cavity. Microwave fields oscillating at the resonance frequency of the atoms drive some of them into a second energy level. These atoms are deflected by magnet B so as to strike a detector. The servo mechanism monitors the detector and maintains the frequency of the applied microwaves at the resonance frequency. To keep time, some of the microwaves are



ATOMIC HYDROGEN MASER relies on a self-sustaining microwave field to serve as a frequency standard. Hydrogen atoms in the correct energy level are deflected by a magnet into a storage bulb. Some atoms will drop to a lower level, releasing a microwave photon. The photon stimulates other atoms to drop to a lower level, which produces more photons. The process quickly builds up a microwave field in the bulb. The field induces an alternating current in a wire placed in the cavity. The tuned cavity helps to redirect the photons back into the bulb to maintain the process.





directed to a device that divides the frequency into usable timing pulses. Optically pumped standards (*b*) use light rather than magnets to select atoms. Laser A pumps the atoms into the right energy level, preparing them to be excited by the microwaves. Only atoms placed in the correct energy level by the microwaves absorb light from laser B. They quickly reemit that energy, which is sensed by a photodetector. An optically pumped clock using cesium atoms at the National Institute of Standards and Technology, called NIST-7, now keeps time for the U.S. (*photograph*).

because they have the same electric charge. Hence, they do not suffer collisions with other particles or with the walls of the chamber. Ions can be trapped for long periods, sometimes for days.

Two different types of traps are used. In a Penning trap, a combination of static, nonuniform electric fields and a static, uniform magnetic field holds the ions. In a radio frequency trap (often called a Paul trap), an oscillating, nonuniform electric field does the job. Each type of trap has its own characteristic shortcoming. The strong magnetic fields of Penning traps can alter the resonance frequency. The electric field in Paul traps can create heating effects that cause Doppler shifts. The kind of trap chosen depends on its suitability for a particular experimental setup.

Workers at Hewlett-Packard, the Jet Propulsion Laboratory in Pasadena, Calif., and elsewhere have fabricated experimental standard devices using Paul traps. The particles trapped were mercury 199 ions. This ion was selected because it has the highest hyperfine frequency—40.5 gigahertz—of all the atoms that are appropriate for the trapping technique. A few million such ions are caught between the electric fields generated by electrodes. Then the ions are optically pumped by ultraviolet radiation from a lamp. Subsequent operation resembles that of the optically pumped standards, but the maximum *Q*s of trapped-ion standards exceed 10^{12}. This value is 10,000 times greater than that for current cesium beam clocks. Their short-term stabilities are also extremely good, although they do not yet reach those of hydrogen masers. The second-order Doppler shift limits the reproducibility to about one part per 10^{13}.

The Doppler shifts can be greatly reduced by laser cooling. In 1975 David J. Wineland, now at NIST, Hans G. Dehmelt of the University of Washington, Theodor W. Hänsch, now at the University of Munich, and Arthur L. Schawlow of Stanford University first proposed such a technique. In essence, a beam of laser light is used to reduce the velocities of the ions. Particles directed against the laser beam absorb some of the laser photon's momentum. As a result, the particles slow down. To compensate for the Doppler shifting as the particle moves against the laser, one tunes the beam to a frequency slightly lower than that produced by a strongly allowed resonance transition.

Many laboratories are developing frequency standards based on laser-cooled ions in traps. A standard based on beryllium 9 ions, laser-cooled in a Penning trap, has been constructed. Its reproducibility is about one part per 10^{13}, limited as it is by collisions of the ions with neutral molecules. Improvements in the quality of the vacuum should significantly increase the reproducibility because the uncertainty of the second-order Doppler shift is only about five parts per 10^{15}.

During the past few years, there have been spectacular developments in trapping and cooling neutral atoms, which had been more difficult to achieve than trapping ions. Particularly effective laser cooling results from the use of three pairs of oppositely directed laser-cooling beams along three mutually perpendicular paths. A moving atom is then slowed down in whatever direction it moves. This effect gives rise to the designation "optical molasses." Several investigators have contributed to this breakthrough, including William D. Phillips of NIST in Gaithersburg, Md., Claude Cohen-Tannoudji and Jean Dalibard of the École Normale Supérieure and Steven Chu of Stanford [see "Laser Trapping of Neutral Particles," by Steven Chu; SCIENTIFIC AMERICAN, February 1992].

Neutral-atom traps can store higher densities of atoms than can ion traps, because ions, being electrically charged, are kept apart by their mutual repulsion. Other things being equal, a larger number of atoms results in a higher signal-to-noise ratio.

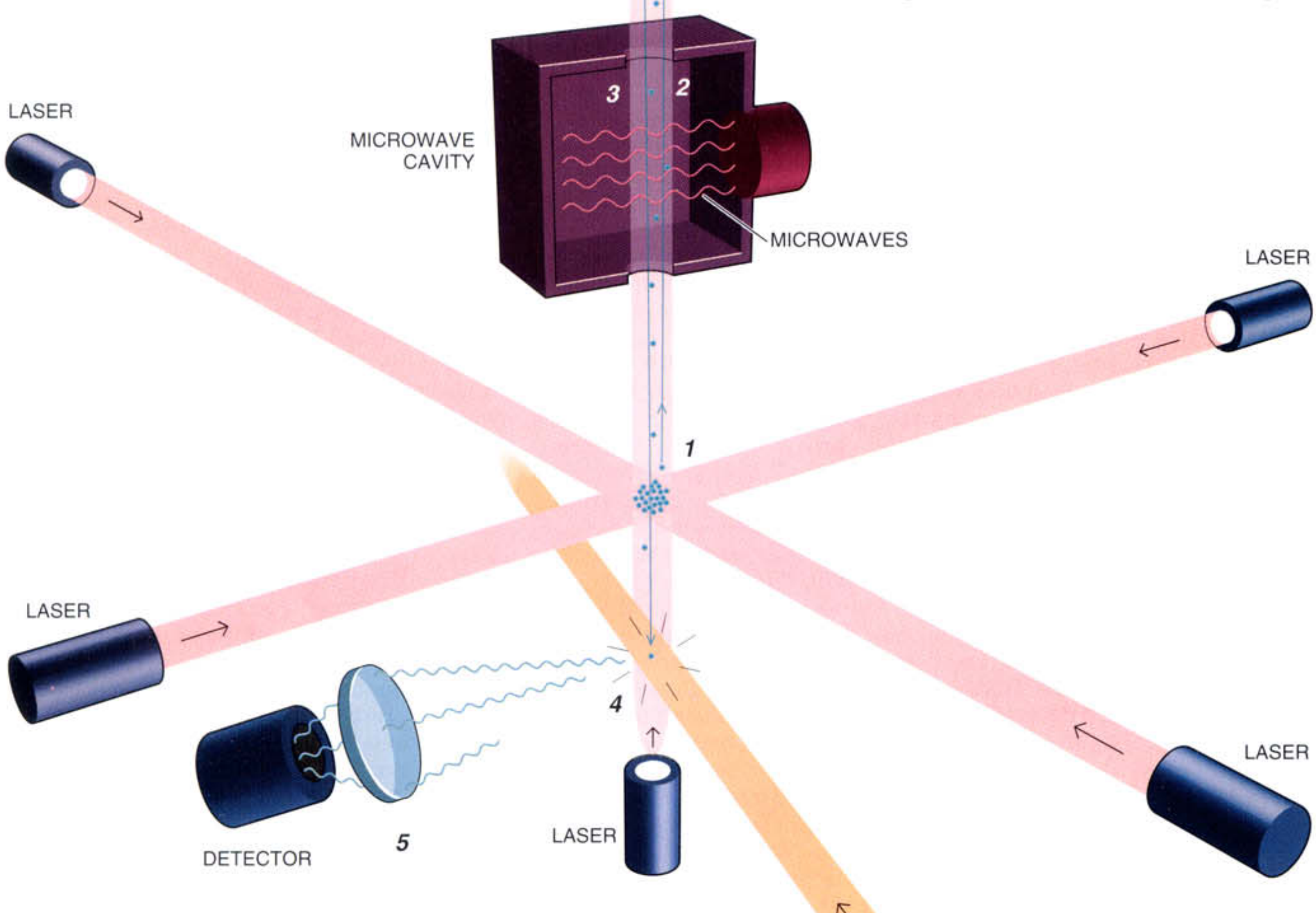
The main hurdle in using neutral atoms as frequency standards is that the resonances of atoms in a trap are strongly affected by the laser fields. A device called the atomic fountain surmounts the difficulty. The traps capture and cool a sample of atoms that are then given a lift upward so that they move into a region free of laser light. The atoms then fall back down under the influence of gravity. On the way up and again on the way down, the atoms pass through an oscillatory field. In this way, resonance transitions are induced, just as they are in the separated oscillatory field beam apparatus.

The *Q* of such a device can be higher than that of an atomic beam because the time between the two passages can be longer. Experiments on atomic fountains have been done by Chu and his co-workers at Stanford and by André Clairon of the Primary Laboratory of Time and Frequency in Paris and Christophe Salomon of the École Normale Supérieure and their co-workers.

Much current research is directed toward laser-cooled ions in traps that resonate in the optical realm, where frequencies are many thousands of gigahertz. Such standards provide a promising basis for accurate clocks because of their high *Q*. Investigators at NIST have observed a *Q* of 10^{13} in the ultraviolet resonance of a single laser-cooled, trapped ion. This value is the highest *Q* that has ever been seen in an optical or microwave atomic resonance. Because of technical difficulties, none of the optical frequency clocks constructed so far, however, has operated over extended periods.

The variety of high-performance frequency standards that exist today might seem to obviate the need for future devices of even greater performance. After all, current atomic clocks are so accurate that they have redefined some of our basic units. As mentioned earlier, the second is now based on the resonance frequency of the cesium atom. Also by international agreement, the meter is defined as the distance light travels in 1/299,792,458 of a second. The voltage unit is maintained by the characteristic frequency associated with a voltage that appears in a so-called Josephson junction in a superconducting circuit.

There are, however, applications that tax the capacity of modern clocks. Radio astronomy is a good example. Astronomers often use several telescopes spaced thousands of kilometers apart



ATOMIC FOUNTAIN uses atoms that have been cooled and trapped by six laser beams (*1*). The vertical beams then briefly impart an upward velocity to the atoms. The atoms rise, passing through the microwave cavity on the way up (*2*) and again on the way down (*3*). The rest of the process resembles optically pumped atomic-beam standards: the atoms pass through another laser beam (*4*), and their fluorescence is recorded by a photodetector (*5*). Servo loops and frequency dividers (*not shown*) generate timing pulses.

to study a stellar object, a technique that dramatically increases the resolution [see "Radio Astronomy by Very-Long-Baseline Interferometry," by Anthony C. S. Redhead; SCIENTIFIC AMERICAN, June 1982]. Two radio telescopes spaced 10,000 kilometers apart have an effective angular resolution more than one million times better than either telescope alone. But to combine the data from each telescope appropriately, investigators need to know precisely when each telescope received the signal. Present-day hydrogen masers have the stability required for such observations. More stable clocks may be needed for space-borne radio telescopes.

Highly stable clocks are essential for the best tests of relativity. Timing measurements of millisecond pulsars, some of which are as stable as the best atomic clocks, offer evidence for gravity waves. In 1978 Joseph H. Taylor, Jr., and his associates at Princeton University found that the period of a binary-pulsar system has been slowly varying by just the amount that would be expected for the loss of energy by gravitational radiation, as predicted by general relativity. Greater precision can be achieved if measurements are taken over many years, so clocks with better long-term stability would be useful.

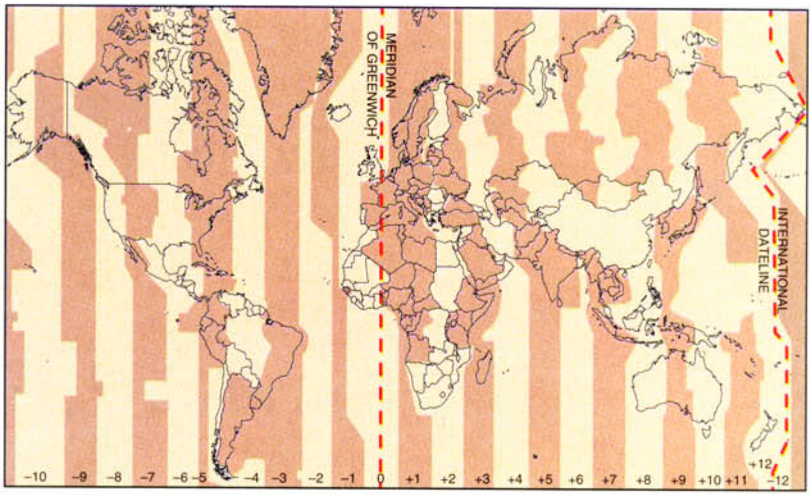
In other tests of relativity, Vessot and his colleagues confirmed the predicted increase in clock rates at high altitudes. They sent on board a rocket a hydrogen maser and measured the small, relativistic clock shift to within an accuracy of 0.007 percent at an altitude of 10,000 kilometers. Highly stable clocks have also been used by Irwin I. Shapiro, now at the Harvard-Smithsonian Center for Astrophysics, to observe the relativistic delay of a light signal passing by the sun.

Ultraprecise timekeeping has more practical applications as well—most notably, for navigation. The location of *Voyager 2* as it sped by Neptune was determined by its distance from each of three widely separated radar telescopes. Each of these distances in turn was obtained from accurate measurements of the eight hours it took for light to travel from each telescope to the spacecraft and return.

Navigation is, of course, also important on the earth. One of the latest applications of precise clocks is the satellite-based assemblage called the Global Positioning System, or GPS. This system relies on atomic clocks on board orbiting satellites. The GPS enables anyone with a suitable radio receiver and computer to determine his or her position to approximately 10 meters and the correct time to better than 10^{-7} second. Two observers monitoring the same satellite can synchronize their clocks to within a few nanoseconds.

It is expected that the GPS will have widespread practical applications, such as pinpointing the positions of ships, airplanes and even private automobiles. The GPS was used during the 1991 Persian Gulf War to enable troops to determine their positions on the desert. Commercial receivers can be purchased for less than $1,000, although these civilian versions are limited to an accuracy of about 100 meters because of deliberate scrambling of the signals transmitted from the satellites. A full complement of 24 satellites would give 24-hour, worldwide coverage. The system is nearly complete.

These and other applications show the importance of time and frequency standards. The anticipated improvements in standards will increase the effectiveness of the current uses and open the way for new functions. Only time will tell what these uses will be.



Coordinating Time Scales

In the article, we discuss the measurement of an interval of time, such as a second or a minute. This process requires only a good clock. But to be able to state that an event happened at a particular time, say, 22 seconds after 12:31 P.M. on July 5, 1993, requires synchronization with a clock that is, by mutual agreement, the standard. The world's "standard clock" exists on paper as an average of the best clocks in the world. The International Bureau of Weights and Measures in Sèvres, France, is responsible for coordinating international time. This coordinated time scale is called International Atomic Time, or TAI.

Many users require a time scale that keeps pace with the rotation of the earth. That is, averaged over a year, the sun should be at its zenith in Greenwich, England, at noon. The day as determined by the apparent position of the sun is irregular but on the average longer than the 24 hours as defined by TAI. To compensate, another time scale, called Coordinated Universal Time, or UTC, is specified by occasionally adding or subtracting a whole number of seconds from TAI. These seconds, or leap seconds, are inserted or deleted, usually on December 31 or June 30, to keep UTC within 0.9 second of the time as defined by the rotation of the earth. The record of leap seconds must be consulted to determine the exact interval between two stated times.

FURTHER READING

FROM SUNDIALS TO ATOMIC CLOCKS: UNDERSTANDING TIME AND FREQUENCY. J. Jespersen and J. Fitz-Randolph. Dover, 1982.

HISTORY OF ATOMIC CLOCKS. N. F. Ramsey in *Journal of Research of the National Bureau of Standards*, Vol. 88, No. 5, pages 301–320; September/October 1983.

PRECISE MEASUREMENT OF TIME. N. F. Ramsey in *American Scientist*, Vol. 76, No. 1, pages 42–49; January/February 1988.

TIME AND FREQUENCY. Special issue of *Proceedings of the IEEE*, Vol. 79, No. 7; July 1991.