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Atomic Clocks and Their Applications

by Norman F. Ramsey (MA)

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ATOMIC CLOCKS AND FREQUENCY STANDARDS

The fundamental features of any clock are a mechanism to provide a regular periodicity (such as the swinging motion of a pendulum), a source of energy to maintain motion without significantly affecting the periodicity (as provided by the escapement mechanism of a pendulum clock), and a means for counting the periods and displaying the time.[1,2] In discussing the characteristics of clocks, it is necessary to distinguish between three different but related properties: accuracy, reproducibility, and stability. Accuracy measures the degree to which a clock agrees with the value specified in the definition of the unit of time. Reproducibility is a measure of the extent to which properly adjusted independent devices of the same design agree. Stability is a measure of the degree to which a device gives the same results in successive intervals of time. Because the stability and accuracy of a clock are primarily determined by the mechanism providing the periodicity, this feature is emphasized in discussions of the precise measurement of time.

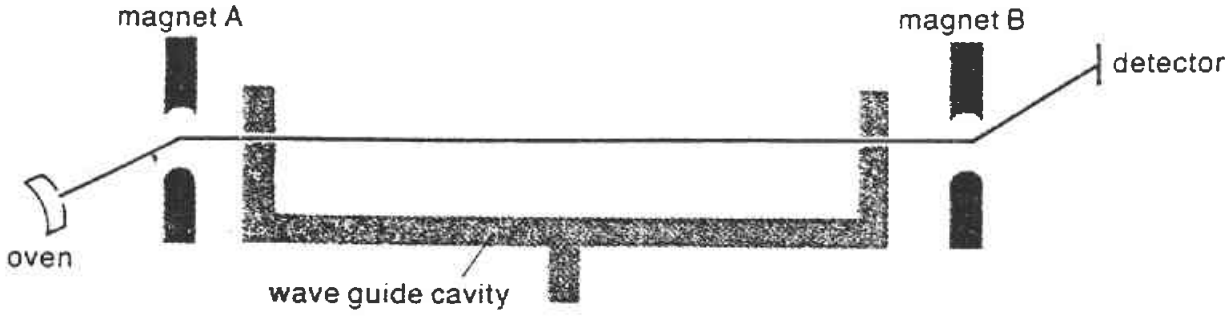
Time and frequency are closely related, since frequency is by definition the number of cycles of oscillation per second (hertz) and the period is the number of seconds per cycle. Provided the counting of the cycles is correct, an accurate measurement of time provides an equally accurate measurement of frequency; conversely, a device oscillating at a stable frequency can be the source of the periodicity that is measured by a clock. The earliest clocks were developed primarily for measuring the passage of time. However, the initial incentive for the development of tuning forks, quartz crystal oscillators, and atomic clocks was the measurement of frequency.

Since in atoms the transitions between different quantized energy levels produce highly stable frequencies, these frequencies can be used as the basis for accurate atomic frequency standards. In particular, by quantum mechanics and the conservation of energy, if an atom makes a transition from a quantized atomic level of energy W_1 to a level of energy W_2, it must either absorb or emit a photon of energy hf where

$$hf = W_1 - W_2 \quad (1)$$

and where f is the frequency of the photon and h is Planck's constant that is fundamental to quantum mechanics. The second is now defined in terms of the oscillations associated with the hyperfine transitions between atomic energy levels which differ by the different relative orientations of the nuclear and electron magnetic moments of the cesium atom. The cesium hyperfine frequency is measured by the separated oscillatory field method invented by Ramsey[4-6] as a modification of Rabi's[3] molecular beam magnetic resonance method. A typical atomic cesium clock is shown schematically in Figure 1. A beam of atoms is boiled out of the oven into the evacuated region, is deflected by the inhomogeneous magnetic field of magnet A, and is subjected to a weak magnetic field in the main part of the apparatus. As the beam makes its first and second passage through the wave guide cavity,

Figure 1. In the diagram magnets A and B have been rotated 90 degrees above a vertical axis to show the tips of their poles.



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it is subjected to weaker perpendicular and coherent oscillatory magnetic fields. It is then deflected again by the inhomogeneous magnetic field of magnet B and finally converted to positive ions by a hot wire ionizer in the detector. The ions are counted electrically. If the frequency of the oscillating magnetic field equals the hyperfine frequency given in equation (1), the orientation of the electrons' magnetic moment is reversed by the resonant field and the force on the atom is reversed so it follows the indicated path with a maximum of detected intensity. The detected intensity is then used through a normal feedback circuit to adjust slightly the frequency of the quartz crystal oscillator which drives oscillating field to provide maximum detected beam intensity and thereby to stabilize the oscillator to the atomic hyperfine frequency. Such an oscillator is so much more stable than previous ones that in 1967 the definition of the second was changed from one based on the motion of the earth about the sun to 9,192,631,770 periods of the cesium atom. Such a cesium atomic clock can achieve an accuracy of several parts in 10^{14}. An optically pumped atomic rubidium clock is often used because it is less expensive than an atomic cesium beam clock, but it is also much less accurate.

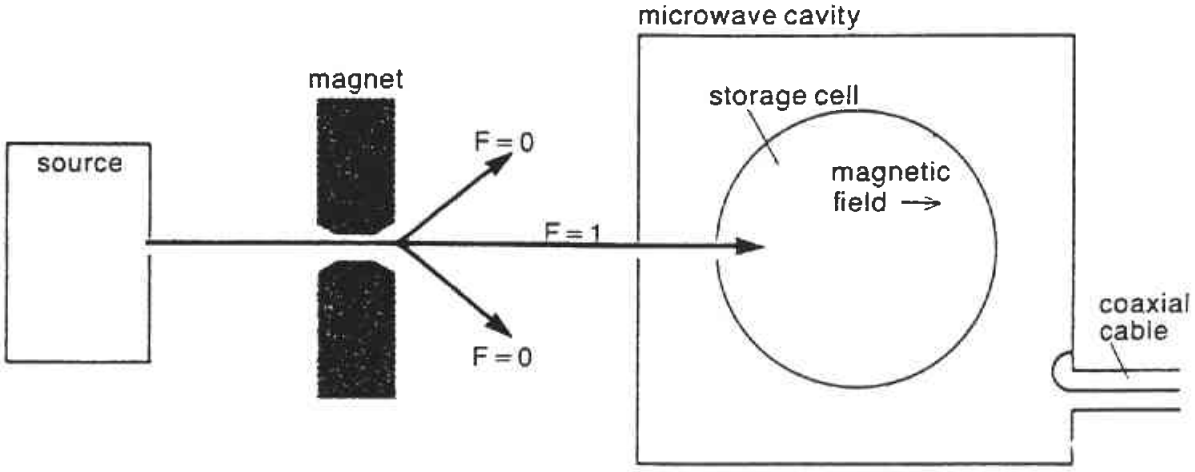
For many applications which require even higher clock stability over a few hours, such as measurements in radio astronomy, the best existing clocks are atomic hydrogen masers, invented by Ramsey and Kleppner[10] and shown schematically in Figure 2. Hydrogen atoms pass through a low-pressure region (10^{-6} torr) into a state-selecting magnet. In the magnet, atoms in the low-energy hyperfine state (F = 0) diverge from those in the high-energy hyperfine state (F = 1). Most of the latter enter the storage cell, a 15-cm diameter bulb whose inner surface is coated with teflon. Exposed to microwave radiation, these atoms release their energy by stimulated emission and the released energy will make the microwave radiation stronger—that is, the device will be a microwave amplifier by stimulated emission of radiation or a maser. If the storage cell is placed inside a tuned cavity, an oscillation at the resonance frequency will be increased in magnitude until an equilibrium value is reached, at which level the oscillation will continue indefinitely. The energy to maintain the oscillation comes from the continuing supply of hydrogen atoms in the high energy state. The oscillations of the microwave radiation that emerge through the coaxial cable provide the periodicity required for a highly stable atomic clock. Over periods of several hours, the hydrogen maser's stability is better than one part in 10^{15}.

FUTURE IMPROVEMENTS

It might appear that there is little room for improvement in the measurement of time, but that is not the case. Improved versions of the cesium beam clocks are being designed and built with the state-selecting magnets replaced with state selecting resonant lasers and with two atomic beams going through the transition region in opposite directions to reduce the harmful effect of phase shifts. Likewise new coating materials that result in smaller and more stable wall shifts are being developed for hydrogen masers and some masers have electronically tuned cavities.

Atomic frequency standards at laser frequencies are being developed. Measurements to the same fraction of a cycle at higher frequencies correspond to smaller fractions of the frequency. The first-order Doppler shift is large, but various ingenious methods have been devised to reduce or eliminate it. Saturated absorption spectroscopy and two-photon spectroscopy employ two laser beams at the same frequency going in opposite directions so that the first-order shifts cancel.[9–11] Concurrent with

Figure 2. Schematic view of atomic hydrogen maser.



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the development of stable oscillators at much higher frequencies, intense efforts have also been made to multiply and divide such frequencies so that valid comparisons can be made between standards at all frequencies.

Although ions cannot be stably trapped in static electric fields, it has been known for a long time that they can be trapped in a static uniform magnetic field in combination with a suitable nonuniform electrostatic field (Penning trap) or in suitable nonuniform electric fields whose polarities and gradients alternate in time at radio frequencies (Paul traps). Dehmelt and his associates[10] pioneered the use of traps for studying atomic spectroscopy. Since ions can be stored for long intervals in traps and since there are no wall effects, trapped ions have attractive features as time and frequency standards. Until recently, the ions had high velocities in traps and consequently large Doppler shifts. Used in combination with the laser cooling method discussed below, however, ion traps are very effective. Fortunately the electric trapping fields do not significantly affect the ion's resonance frequency, but the space charge from the ions limits the number of ions that can be usefully trapped which in turn limits the signal to noise ratio.

More recently, various techniques have been invented to trap neutral atoms with nonuniform laser beams.[10,11] The forces arise in some cases from the gradient of a beam's electric field and in other cases from the momentum imparted to an atom when it scatters a photon. Although some of the traps are quite shallow, the laser cooling techniques help to overcome this disadvantage. With atom traps, space charge is no problem, but the trapping laser fields so badly distort the resonance that they must be turned off during the measurements and gravity limits the measuring time to about one second with a corresponding limitation on accuracy.

Laser cooling is a method by which a beam of light can be used to damp the velocity of an atom or ion.[11,12] The basic mechanism utilizes a laser beam tuned slightly lower in frequency than a strongly allowed resonance transition. When the velocity of the ion or atom is directed against the laser beam, the light frequency in the ion's frame is Doppler shifted closer to resonance, and the light scattering takes place at a higher rate than when the velocity is in the same direction as the laser beam. Since the photons are re-emitted in random directions, the net effect over a motional cycle is to damp the ion's velocity by absorption of photon momentum. Using pairs of counter propagating laser beams along each of three mutually perpendicular axes, one can obtain a three-dimensional laser-cooled region in which the atoms move very sluggishly; such a region is frequently called "optical molasses." Atoms have been laser-cooled[14–17] to an absolute temperature of about a millionth of a degree Kelvin (10^{-6}K), and narrow resonances have been observed with a single cooled and trapped ion. The laser cooling not only overcomes the first order Doppler broadening but also virtually eliminates the second-order Doppler shift, which remains in all atomic clocks unless the atoms are sufficiently cooled.

It is too soon to say which combination of trapping and cooling will be most effective, but there is a high probability that one or more of the new techniques will lead to even more stable periodicities, which can in turn provide the basis for even more stable atomic clocks.

APPLICATIONS OF ATOMIC CLOCKS

It might seem that there should be no need for time measurements of such high accuracy as those already achieved, much less those contemplated with future improvements; but there are many applications, some of which push current techniques to their limits.

In radio astronomy one looks with a parabolic reflector at the radio waves coming from a star, just as in optical astronomy one looks with a telescope at the star's light waves. Unfortunately, the wavelength of the microwave radiation is about a million times longer than the wavelength of light, so the resolution of the normal radio telescope is about a million times worse than that of an optical telescope, depending as it does on the ratio of the wavelength to the telescope aperture. However, if there are two radio telescopes on opposite sides of the earth looking at the same star and if the radio waves entering each are matched in time, it is equivalent to a single telescope whose aperture is the distance between the two telescopes, and the resolution of such a combination exceeds that of even the largest single optical telescope. For precise matching in time, each of the two radio telescopes needs a highly stable clock.

Precision clocks are also needed to measure the periods of pulsars—stars that emit their radiation in short pulses—and the changes in their periods, which sometimes occur smoothly but sometimes abruptly. Of particular interest are millisecond pulsars, whose remarkably constant periods rival the stability of the best atomic clocks. In fact, one of these pulsars is so stable that it may eventually be suitable as a standard of time over long periods.[18] Another millisecond pulsar is part of a rapidly rotating binary star that is slowly changing its period of rotation. This change can be attributed to loss of energy by the radiation of gravity waves—the first experimental evidence for the existence of gravity waves.

Accurate measurements of time permit measurements of the variability of quantities that were once thought to be constant. As we have seen, the rotation period of the earth, which once served as the basis for defining the unit of time, is now known to vary by a few parts in a hundred million from winter to summer and from year to year. Some of the variation is regular and some unpredictable. Different atomic clock rates have been accurately compared over long periods of time to see if there might be changes in their relative rates which could correspond to

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a change with time in the fundamental physical constants, but no such change has yet been discovered.

Precision clocks make possible an entirely new and more accurate navigational system, the global positioning system or GPS. A number of satellites containing accurate atomic clocks transmit signals at specific times so that any observer receiving and analyzing the signals from four such satellites can determine his position to within ten yards and the correct time within one hundredth of a millionth of a second (10^{-8} s).

Time can now be measured so accurately that wherever possible other fundamental measurements are reduced to time measurements. Thus the unit of length has recently been defined as the distance light travels in a specified time, and the practical realizations for the basic units of voltage and resistance are now expressed in terms of frequencies.

Accurate clocks have provided important tests of both the special and general theories of relativity. The above mentioned orbits in binary pulsars are measured with atomic clocks and provide particularly critical tests of the general theory of relativity. In a quite different test of relativity experiment, the periodic rate of a hydrogen maser carried in a rocket 10,000 km up changed with speed and altitude by the amounts predicted by the special and general theories.[19,20] In other experiments observers have measured the delays predicted by relativity for radio waves passing near the sun. Future improvements in the stability of clocks should make possible even more rigorous tests of fundamental theories.

Summary

Measurements of time depend on the observations of periodicities such as the oscillations of a pendulum or the vibration of an electrically excited quartz crystal. The greatest accuracy and stability are achieved by atomic clocks which depend on periodicities associated with internal interactions within an atom—usually atomic rubidium, cesium or hydrogen. Stabilities better than one part in a thousand million million can now be achieved. Promising new developments should increase the stability of atomic clocks even more. Ions can be trapped in electric and magnetic fields and neutral atoms can be trapped in suitably focussed laser fields. Such ions and atoms can be cooled with focussed laser beams to temperatures as low as 1 microkelvin. At such low temperatures both first and second order Doppler shifts are extremely small and it is hoped that atomic clocks using these methods will eventually be several hundred times more stable than the present best time and frequency standards.

Atomic clocks are used for many fundamental measurements in astronomy, physics, navigation and communication. Such clocks, for example, provide important tests of the validity of both special and general theories of relativity.

About the Author

Professor Ramsey is the author of four technical books; he has received many honorary degrees, numerous medals and prestigious prizes, including the Presidential Certificate of Merit and the Nobel Prize for Physics. He is now the Higgins Professor of Physics, Harvard University, Cambridge, Massachusetts.

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