EXPLORING THE UNIVERSE WITH ATOMIC CLOCKS

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Introduction

The most accurate physical measurements are those of time and frequency made with atomic clocks. As a result atomic clocks are powerful tools for exploring the universe and its laws. Before studying the applications, however, the principles of the leading atomic clocks will be briefly reviewed.

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] In discussing the characteristics of clocks, it is necessary to distinguish between three different but related properties; accuracy, repro-ducibility, 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 ad-justed 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 incentives for the develop-ments of tuning forks, quartz crystal oscillators, and atomic clocks were measurements of frequency.

In atoms the transitions between different quantized energy levels produce highly stable frequencies. These frequencies can be used as the bases 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[2] as a modification of Rabi's molecular beam magnetic resonance method.[3]

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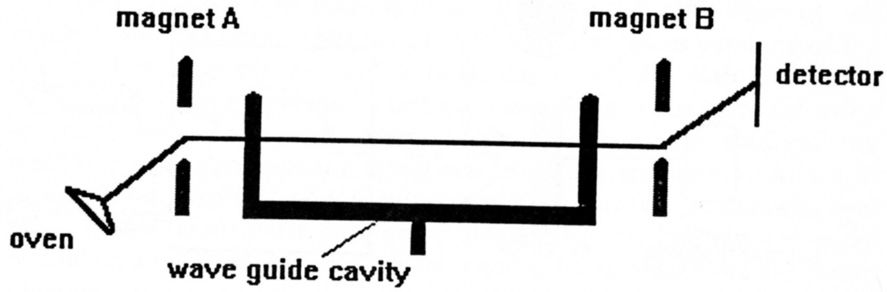
[1] D J Boorstin, *The Discoverers* (Random House, New York, 1983) and D S Landes, *Revolution in Time* (Harvard University Press, Cambridge, MA, 1983).

[2] N F Ramsey, *Molecular Beams*. (Oxford Univ. Press, 1956 and 1984); N F Ramsey, History of Atomic Clocks, *Journal of Research National Bureau of Standards* 88 (1983) 301.This article contains extensive references to the original publications on the subject. N F Ramsey, “The method of successive oscillatory fields,” *Physics Today* 33(7) (1980) 25.

[3] I I Rabi, J R Zacharias, S Millman and P Kusch, “A new method of measuring nuclear magnetic moments,” *Physics Review* 53 (1938) 318.



A typical atomic cesium clock is shown schematically in Figure 1 above. In the diagram magnets A and B have been rotated 90° about a vertical axis to show the tips of their poles.

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, it is subjected to weaker perpendicular and coherent oscillatory magnetic fields. It is then deflected again by the in-homogeneous 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 the 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 a 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.

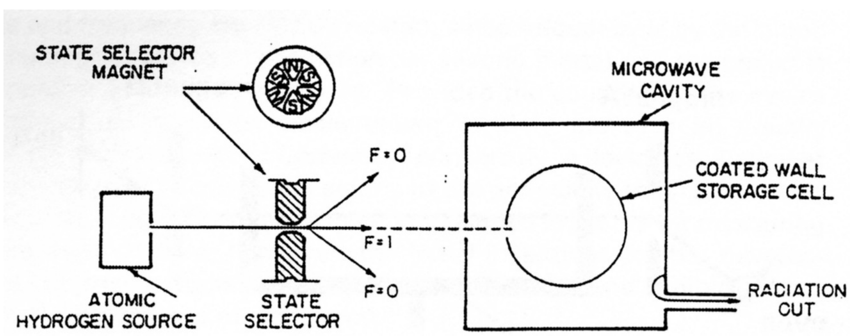


Figure 2. Schematic view of atomic hydrogen maser.

For many applications which require even higher clock stability over a few hours, such as measurements in radio astronomy, the best exis-ting clocks are atomic hydrogen masers, invented by Ramsey and Kleppner [4] and shown schematically in Figure 2 above. 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) are magnetic defocusing states which diverge from the focusing high-energy hyperfine states (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

[4] N F Ramsey, "The Atomic Hydrogen Maser," *American Scientist* 56 (1968) 420.

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 mic-rowave 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. That is not the case. Improved versions of the cesium beam clocks are being designed and built with the state-selecting magnets replaced by optical pumping, or 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 including superfluid helium. 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 Doppler shifts cancel.[5] Concurrent with 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[6] 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 limit 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. [7] 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.[8] 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[9] to an absolute temperature of about a millionth of a degree

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[5]F T Arecchi, F Strumia, and H Walther, eds, *Advances in Laser Spectroscopy*, (New York: Plenum, 1983); and D J Wineland and W M Itano, “Laser Cooling,” *Physics Today* 40(6) (1987) 34.

[6]Theo W Hänsch and Y R Shen, eds, *Laser Spectroscopy*, vol 7, (Berlin; New York: Springer-Verlag, 1985).

[7]Ibid and Wineland, “Laser Cooling” *Physics Today* 40(6) 1987. 34

[8]R S Van Dyck, Jr, and E N Fortson, eds., *Atomic Physics Proceedings* vol. 9, “Spectroscopy of stored Atomic Ions,”(Singapore: Scientific Publishers, 1984). 3-27.

[9]P D Lett , W D Phillips, et al., *Physical Review Lett*ers 61 (1988) 169; A Aspect, C Cohen-Tannoudji, et al., *Physical Review Lett*ers 61 (1988); J Dalibard, C Cohen-Tannoudji, et al., *Optical Soc*iety *of America* B6 (1989) 2023, 2046 and 2112; M Kasevich, E Riis, S Chu and R S DeVoe, *Phy-sical Review Letters* 59 (1987) 2631, 1989. 63:612 and 64:1658.

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.

Exploring the Universe and Other Applications

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 appli-cations, some of which push current techniques to their limits.

Very Long Baseline Interferometry (VLBI) in Radio Astronomy

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 a single 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, provided the two telescopes each have highly stable atomic clocks to beat their signals against so that the reduced frequency signals can be transmitted to a central station without significant loss of phase. For some years, up to and including the present, hydrogen masers have provided the highest stability clocks for VLBI. Arrays of up to 12 radiotelescpoes and atomic clocks have been matched together with their detected signals synthesized by high speed computers into a two dimensional sky map with an angular resolution of 200 micro arc seconds which is 250 times better than the best optical telescopes, including the Hubble Space Telescope.

Pulsar Periods

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. [10]

Variability of Earths Rotation Rate and of Other Periodic Phenomena

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. Atomic clocks are also used to test the stabilities of many other periodic phenomena such as oscillatory crystals and planetary orbital periods.

Tests of Constancy of the Fine Structure Constant α.

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 a change with time in the fundamental physical constants, but no such change has yet been discovered. The lowest limit to the possible variations on α is now given by analyses of the fission products of an ancient African nuclear reactor as (dα_/_dt) / α__< 10 - 1 / yr. At present form comparisons between hydrogen maser and cesium beam clocks over a two year interval provide a limit of only (dα_/_dt) / α__< 10 - 12yr. However, with improved clock precision and longer running time the clock experiments should even-tually be more sensitive.

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[10] Rawley, L A, J H Taylor, M M Davis, and D W Allan, "Millisecond Pulsar PSR 1937 21: A Highly Stable Clock," *Science* 238 (1987) 761.

Precision Navigation

Accurate 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 a few meters and the correct time within one hundredth of a millionth of a second (10^{-8} s). Although the intrinsic accuracy of the GPS system alone is about 1 m, the US Military which operates the system, for reasons I do not understand, is currently using a system called Selective Availability (SA) which puts artificial fluctuations on the signals which limit the civilian location accuracy to about 30 m. The Military promises to phase out these artificial fluctuations within next the decade. Even with the artificial fluctuations the position accuracy can be improved to better than 1 m with Differential GPS (DGPS), by having nearby ground stations at a known fixed locations receive the GPS signals and transmit small corrections to nearby GPS receivers. For surveying, the relative locations of two nearby GPS receivers can be measured to about 0.01 meters. The US Coast Guard is currently installing DGPS along the US coasts for ship navigation and other nations are doing likewise. GPS and DGPS are proving to be of great value in many sciences including geographical exploration, geology, archeology, paleontology, civil engineering, surveying, and en-vironmental studies.

Earth's Crustal Dynamics

The most accurate measurements of distance and changes of distance on the surface of the earth are those between the radio telescopes of Very Long Baseline Interferometry. These give valuable information on crustal dynamics. For example, the distances from Haystack radiotelescope in Massachusetts to Owens Valley, California, was found to vary less than 0.03 m over an entire year whereas the distance to Palo Alta, on the other side of the San Andreas fault, grew by 0.3 m in one 11 week period. The GPS can also be used to study the earth's crustal dynamics.

Navigation in Outer Space

Atomic clocks are essential to navigation in outer space, In the voyager mission to Neptune, the location of the Voyager spacecraft was determined by three radar telescopes each with two hydrogen masers to measure the time for the radar signals to go from each telescope to the satellite and to return. Similar observations were made by VLBI telescopes which are also based on atomic clocks.

Expression of Other Physical Quantities in Terms of Time

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 realization for the unit of voltage is now expressed in terms of frequency.

Test of the Special and General Theories of Relativity

Accurate clocks have provided important tests of both the special and general theories of relativity. The periodic rate of a hydrogen mas-er carried in a rocket to 10,000 km changed with speed and altitude by the amounts predicted by the special and general theories.[11] 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.

The most severe tests of general relativity have been those of Joseph Taylor and his associates[12] on millisecond pulsars that are one member of a binary pair (two stars so close together that the period of their orbital motion about the common center of mass is typically 10 hours or less). Although these binary stars are too distant to be resolved with either an optical or a radiotelescope, their orbits can be measured with exquisite accuracy by the modulation of the pulsar rate through the Doppler shift as the pulsar in its orbit successively

[11] R F C Vessot et al., "Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser," *Physical Review Letters* 45 (1980) 2081; J P Turneaure, C M Will, B F Farrell, E M Mattison, and R F C Vessot, "Test of the Principle of Equivalence by a Null Gravitational Red-Shift Experiment," *Physical Review* D27 (1983) 1705.

[12] Taylor et al and Thibault Damour, J H Taylor, "Strong-field Tests of Relativistic Gravity and Binary Pulsars," *Physical Review* D45 (1992) 1840-1867.

approaches and recedes from the earth. Taylor and associates found that the orbital period of the binary is changing by just the amount expected from the loss of energy by the radiation of gravity waves predicted by the Einstein general theory of relativity—the first experimental evidence for the existence of gravity waves. The orbit is measured so well that it tests the strong field as well as the radiative aspects of relativity. The measurements confirm the Einstein form of the general theory of relativity and leave little room for alternative theories. The ratio of the observed rate of change of the binary period to that calculated from the Einstein theory of relativity including strong field aspects and gravity waves is 1.0032 ± 0.0050. In a sense, these binary pulsar measurements permit a determination of the velocity of propagation of gravity waves since the excellent agreement between observations and calculations disappears when the velocity of propagation of gravity waves in the theory is allowed to differ from the velocity of light c by more than 0.1%.