Atomic clock accuracy needed

A look at time and timekeeping

The National Institute of Standards and Technology, formerly The National Bureau of Standards, has been working with atomic clocks for over forty years. They have come a long way since they developed the world's first atomic clock. NIST has recently introduced NIST-7, one of the most accurate clocks to date and is expected, after full evaluation, to show an accuracy of one part in 10^{14}, equivalent to one second in three million years. Atomic clocks are based on natural resonances in atoms, which involve highly stable and periodic events at very high frequencies.

A brief history

The continuum of time would exist no matter what. However, our human made definitions of time have been created throughout history to suit specific needs. A time unit can be rather arbitrary, as long as it's definable and repeatable. For example, time measurement could come from the duration between specific natural periodic events, such as tides or sunrises. These are both events which are easily examined by independent observers.

In ancient times, it was realized that the duration between subsequent sunrises was constant. So this was therefore used as an assessment of time (i.e. the "day"). Changes in season, the positions of the stars and phases of the moon were also noticed and patterns recorded, forming crude calendars. The day was also broken down beyond periods of light and darkness using more sophisticated forms of measurement. Systems involving dripping water and falling sand were found to be consistent, so they were used to time events in relation to each other.

However, it was not until the 17th century that the pendulum clock was invented and found to provide reproducible measurements. Reproducibility is an important factor in clocks because in order for timing information to be relevant, some common definition must be referenced. It is this definition that we consider to be a standard. By the early 1900s, pendulum clocks had reached accuracies of hundredths of seconds per day. Soon after, the quartz-crystal clock was invented.

Quartz-crystal clocks are based on the piezoelectric property of quartz crystals to resonate at a constant frequency when a coherent electric field is applied to them. This is a very inexpensive way to achieve stable timing; but, because each quartz-crystal is slightly different, there is a limit to their reproducibility.

Current techniques

Atomic clocks are based on natural resonances of atoms which are very stable and occur at high frequencies. Such resonances are associated with transitions between well defined (quantum) energy states. The resonance frequency f is equal to the energy difference E divided by Planck's constant h. By imposing electromagnetic radiation on atoms, they can be forced to change quantum state. This radiation, at the exact resonant frequency for the given transition, will cause a maximum number of state changes. It is this highly reproducible frequency that provides the basis for atomic clocks. Although atomic clocks have been based on the resonant frequencies of ammonia, cesium, rubidium and hydrogen, only the specific processes of NBS-6 and NIST-7, which use cesium as the resonator, will be explained. By international agreement, the second is defined as the duration of 9,192,631,770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

Cesium is used for atomic standards because of its relatively high resonance frequency (~9.192 GHz), low melting point, relative insensity to the environment, low thermal velocity and easy detectability. In the case of NBS-6, cesium atoms from an oven are collimated and magnetically guided through a vacuum chamber. The magnetic guidance allows only the atoms in the "correct" quantum state to enter a microwave cavity.

Here, a state change is induced by irradiating the atoms with a signal close

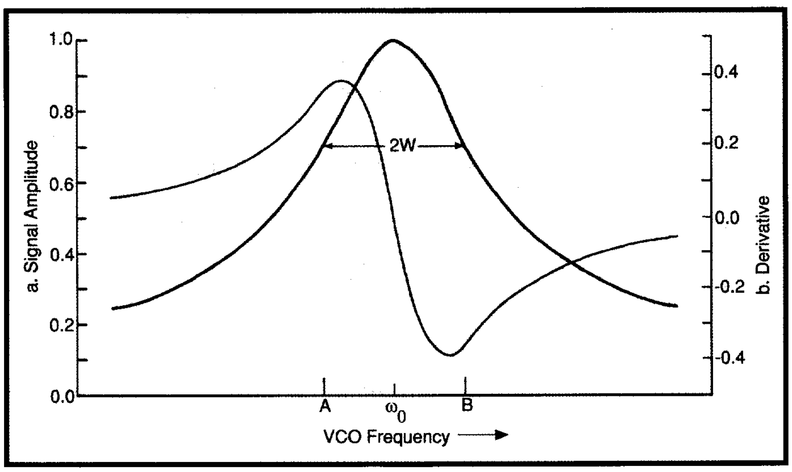

Fig. 1 Reference line a and its first derivative b

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0278-6648/94/$4.00

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to their resonant frequency. This signal comes from a local quartz crystal oscillator (5.006880 MHz) which is multiplied up to 9.192631770 GHz and imposed upon the cavity. The atoms then pass through another magnet that separates the atoms which have undergone the necessary state change from those that have not. The affected atoms reach a hot wire ionizer (at 900°C) which ionizes the atoms by boiling off electrons.

A measurable current is created when these electrons are collected by a detector. This current is converted into a voltage, filtered of broadband noise and used to servocontrol the applied radiation to the atomic resonance. With feedback, the local oscillator is steered so that a maximum number of atoms make the transition.

Servo electronics

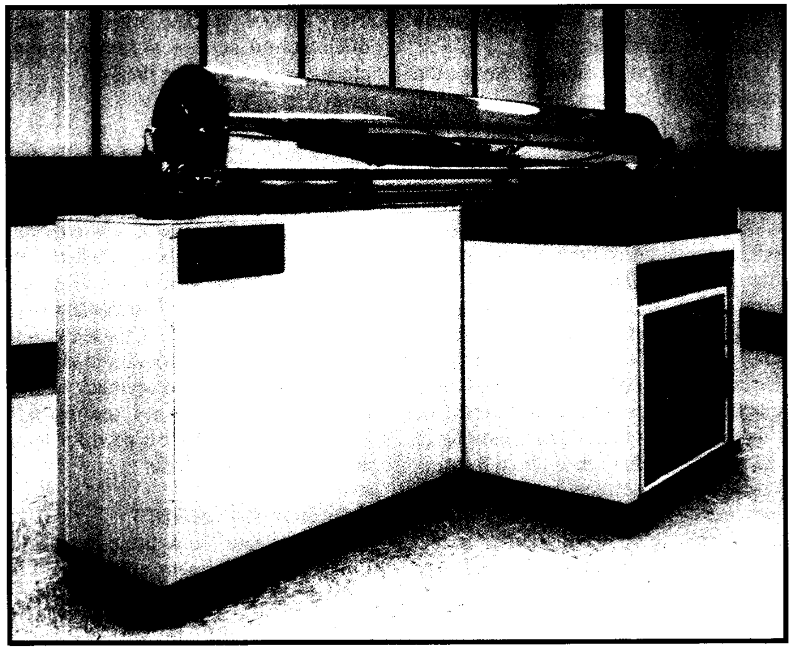
The local oscillator, before being multiplied, is phase-modulated so that, after multiplication, it oscillates in phase by up to one full radian about the cesium frequency. The atomic response to this irradiation is represented by the resonance curve (Fig. 1, line a). The function of the servo system is to center the modulation around the peak of this curve. The error signal is demodulated, leaving a derivative of the resonance response (Fig.l, line b) which, at optimum, will be zero. Finally, the error signal is integrated and fed back to finely tune the local oscillator and lock it onto the atomic resonance frequency.

Accuracy vs. stability

An outside observer sees a five or 10 MHz oscillator which tracks the local oscillator with a phase-locked loop and, in turn, is the highly stable periodic event which is used to derive accurate timing information. The degree of stability of a clock is determined by comparing it to other clocks and measuring the fluctuations of the differences of their frequencies. The level of accuracy of the standard is determined by calculating and summing all of the known inaccuracies. Thus, the stated accuracy is based on a physical model that describes all known sources of error. Once the standard is evaluated, the accuracy of other clocks can be measured against it.

NIST-7

In January, 1993, NIST-7 went into operation as the official United States primary frequency standard. The operation of NIST-7 is similar to that of NBS-6, but NIST-7 utilizes laser technology to gain even higher accuracy and stability. Instead of using only one of the possible electronic states of atoms coming out of the oven, optical-pumping techniques are used for state preparation. Lasers pump most of the atoms into the same state before they reach the microwave cavity. This way the number of atoms changing state is greatly increased. Thus, the elevated signal strength improves the stability of the clock by a significant factor. After the cavity, the atoms which have undergone a state change are exited by another laser, causing them to fluoresce. The photons emitted are collected and converted to a control voltage by a photodetector. Again, this voltage is fed back to the servo-system electronics to adjust the oscillator frequency. The electronics package for NIST-7 is functionally the same as for NBS-6, but has been improved to meet the higher performance requirements.



Error analysis

Inaccuracies in atomic clocks come from some unavoidable difficulties in providing an ideal environment for performing the frequency measurement. For example, cavity phase shifts are caused by microwave cavity imperfections. NIST-7 uses an improved cavity to minimize this effect, but the beam direction must be reversed to assess the error due to such imperfection.

Another problem is Doppler shifts due to the thermal velocity of the atoms in the cavity (~220 m/s). By assuring that the atoms are interrogated at exactly 90° to their path, the first order Doppler shifts can be eliminated. However, second order Doppler shifts are difficult to calculate because the velocities of the atoms are widely distributed. To deal with this error, the velocity profile is measured and a calculated correction is applied.

Yet another concern is that harmonic distortion of the modulation signal can play a significant role in the error feedback system. The NIST-7 electronics reduce this distortion to more than 120 dB below the fundamental. The signal is created and sent through a series of band pass filters at the fundamental frequency and passive notch filters at the second harmonic frequency. The integrity of this signal, however, must be retained throughout the system. The degree of stability currently measured for NIST-7 is 1×10^{15} and the accuracy has been calculated to be 4×10^{-14}, a factor of 2.5 better than that of NBS-6. As measurements are refined, the accuracy should be refined to 1×10^{-14}.

The uses of precision timing

Time and timing information of this precision and accuracy is used in many modern systems. Communication, navigation and tests of fundamental physical theory all require highly accurate timing measurements.

In fact, modern satellite navigation systems have become practical because of advances in atomic-clock performance. In navigation and space travel, it is sometimes critical to know the exact location of a craft. By communicating with multiple satellites, location information can be attained to within a few feet. The Global Positioning System (GPS) transmits these signals, which can be received with commercially available devices to calculate location information. This procedure is based on the precise measurement of time travel of radio signals moving at the speed of light (1 m in about 3 ns).

Relativistic effects have also been measured by synchronizing two atomic clocks and taking one to a different reference frame (on a very fast jet) and back. With time being the most precise standard, other measurement standards, such as the meter and the volt, are now defined on the basis of time. NIST disseminates time information from its three radio stations (WWV, WWVH and WWVB) as well as via satellite and telephone. The newest dissemination service is the Automated Computer Time Service (ACTS), which provides millisecond accuracy for computer clocks using telephone lines.

Future clocks

Atomic clocks are an established institution in modern science, and new developments are constantly being made to improve them. Several new concepts for atomic clocks are being studied. One concept uses the resonance of single laser-cooled atoms held motionless in an electromagnetic trap. This technique should eliminate errors due to doppler shifts, with a projected accuracy of well beyond 1×10^{-16}. As technology advances, there will be a need for more and more accurate clocks.

Acknowledgment

I appreciate the assistance of John Lowe, Bob Drullinger and Don Sullivan with this article and in my work at NIST. Thanks also to Jim Burrus.

Read more about it

•*From Sundials to Atomic Clocks: Understanding Time and Frequency.* J. Jesperson and J. Fitz-Randolph. Dover, 1982.

•P. Kartaschoff and J.A. Barnes, "Standard Time and Frequency Generation," Proc. IEEE, vol. 60, no. 5, May 1972.

•W.M. Itano and N.F. Ramsey, "Accurate Measurement of Time," Scientific American, July 1993, pp.56-65.

•R.E. Drullinger, D.J. Glaze, J.P. Lowe and J.H. Shirley, "The NIST Optically Pumped Cesium Frequency Standard," IEEE Trans. Instrum. Meas., vol. 40, pp. 162-164, April 1991.

NIST time service via telephone

(303) 499-7111 gives Coordinated Universal Time and short term access to WWV.

(301) 975-6776 for information about the ACTS and example software (specify Research Materials #8101).

About the author

Andrew N. Novick is a senior in electrical engineering at the University of Colorado, Boulder. He has worked with NIST-7 and related projects under John P. Lowe for most of his undergraduate years. John P. Lowe is an electrical engineer responsible for the electronics of NIST-7.

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