The Outlook for Advances in the Realization of the SI Unit of Time

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Abstract

The field of time and frequency standards is highly dynamic with active research on the techniques that will lead to the next several generations of standards. In parallel with the development of laboratory standards is the technology of time dissemination. This paper briefly reviews the techniques that will lead to the next 5 orders of magnitude improvement in the realization of the SI unit of time.

Introduction

The current definition of the second is based on the frequency of the ground-state hyperfine transition in cesium. It can now be realized with an accuracy better than 1 part in 10^{13}. Also, we have systems that can provide a precision of 1 part in 10^{12} in a one second measurement and the precision gets better linearly with increased measurement time. This makes time and its inverse, frequency, unique in our system of units with respect to both the ease and the degree with which they can be measured accurately.

The existing primary standards are based on magnetically state-selected, atomic-beam, magnetic-resonance spectrometers[1]. The technology is basically the same as that originally developed by Stern[2], Rabi[3], and Ramsey[4], and after more than 30 years of engineering refinements probably will not yield a great deal more accuracy. However, far from being static, the science and technology of atomic physics that will lead to advanced time standards is highly dynamic. Already, within the limits of on-going laboratory experiments, it is possible to talk with some certainty about the next four generations of time standards. These new standards could extend the accuracy limits to the order of parts in 10^{18} or better.

A necessary adjunct to these standards is the ability to communicate time and frequency to the users. Potential accuracy is of little consequence if it is available only in the standards laboratory. Fortunately, the technology for time dissemination is advancing as fast as standards capability. This paper will briefly outline these developing standards and dissemination technologies, and give references to more complete discussions.

Before we proceed, however, a discussion of the uses of this extreme accuracy may be in order. Time and frequency can be measured 10^6 to 10^9 times more accurately than most other units. How can all of this precision and accuracy be useful, and how can we possibly need more? Those in the field will immediately answer with a list of the high-end users, such as laboratory tests of our fundamental models of physics, deep space navigation, the study of millisecond pulsars, and the like. Of more interest to the real world may be the uses for synchronization of wide-band and secure communication systems (anything from national security to the financial security in computer transfer of money between banking organizations), for navigation (from simple but precise position location to collision avoidance systems to oil exploration), and for the management of power flow in electrical power grids. In the area of metrology, for many quantities of interest there exist transducers that will cast the measurement into a frequency measurement. These transducers are often rather insensitive, for example, one may get only a fractional frequency change of 10^{-6}/K in a temperature transducer. But the extreme ease with which one can measure frequency with precision still makes this the method of choice. For similar reasons, there is a movement in the standards community toward relating other standards to the standard for time. This has already been done in the case of the redefinition of the meter[5] and in practice is done for the volt using the Josephson junction[6,7].

Optically Pumped Cesium

The development of semiconductor laser diodes for optical communications and compact audio disks has made possible the first fundamental change in atomic beam, frequency standards technology in 30 years. Briefly, the concept makes use of laser induced optical transitions within the atoms to manipulate the atoms into the desired state[8]. This is in contrast to the traditional Stern-Gerlach magnetic state selection that just selects those atoms that happen to start in the right state. The result is a large increase in the utilization of the available atomic flux. This, in turn, translates into a large improvement in the short term stability of the standard. Correspondingly, the long term stability and accuracy are improved by the elimination of the Stern-Gerlach magnets which allows much better control over systematic errors. This technology is developing rapidly and the first laboratory standards to use it will be going through initial evaluations in the next year[9-11]. It should result in about an order-of-magnitude improvement in both accuracy and stability over existing standards.

When the full potential of this technology becomes available to commercial, field-portable standards, the impact will be equally dramatic. Using the possibility for self evaluation allowed by this technology, small standards under microprocessor control will be able to evaluate and control their systematic errors. This will result in a stand-alone, calibration-free capability with an accuracy approaching that of todays laboratory standards. Unfortunately, significant laser development is necessary before the total, user-friendly potential can be realized.

Like all previous atomic standards, this new technology will use atoms moving with thermal velocities. The motion of the atoms in the measurement apparatus results in Doppler shifts (both first and second order) which limit the accuracy of the standards. Optically pumped cesium will probably be the last generation of standards to use atoms moving with velocities corresponding to ambient temperature.

Optically Cooled Atoms

The advent of tunable lasers with their high spectral brightness has brought with it a number of exciting new possibilities, among them, the possibility to use photon momentum to manipulate atomic momentum[12]. If an atomic system can be cast in such a way that after absorption of a photon to create an excited state, the excited state must decay back to the original ground state, then the process can be repeated many times. In this way, the small but finite momentum of many absorbed photons can be made to add to that of the absorbing atom. If the exciting laser radiation is arranged either by geometry or Doppler shift to interact with the atoms primarily when the atomic momentum is opposed to the photon momentum, then the atomic momentum can be decreased. This process can be used to cool the atoms and to dramatically reduce Doppler effects.

The first use of this cooling technology in the realization of the SI unit of time will probably be some form of the famous but never realized Zacharias fountain[13,14]. In this device, very slow atoms (velocity of a few meters per second) will be injected upward into the atomic-beam drift tube. Under the action of gravity, they will decelerate and fall back to near the starting place. In this way an interaction time of about one second will easily be achieved. This is about two orders-of-magnitude longer than for thermal beam standards, and the gain in interrogation time will map into an equal gain in accuracy and stability.

A slightly more speculative use of slow atoms in standards involves something we call a "deBroglie box". When an atom is moving very slowly, its deBroglie wavelength is large compared to normal atomic dimensions. As the atom approaches a surface, it should interact in such a way that it just slowly turns around and goes the other way with nearly no perturbation from the wall interaction[15]. Experiments to test this hypothesis are currently under way in several labs. If the idea proves correct, one should be able to store very cold atoms in a box with almost no perturbations. In this case, even longer interrogation times and higher accuracies can be attained than in a fountain or free, cooled atom standard.

By this point in standards development, the cesium transition's residual sensitivity to magnetic fields and its relatively low clock frequency will probably require a change in the definition of the second. We cannot now say with any certainty what atomic system will represent the best choice for the new definition. However, it is possible to predict several characteristics necessary in such a standard and point to emerging technology that is likely to be used.

An atom with one electron removed (an ion) still represents the type of quantum mechanical oscillator that we find suitable for atomic time and frequency references. Furthermore, it provides a strong coulomb handle by which it can be held in an electromagnetic trap for indefinite periods. Research has already shown that such trapped ions, cooled by lasers, have the potential for control of systematic errors at the parts in 10^{18} level and coherent interaction times of 10^3 seconds have been demonstrated. To use this level of accuracy in a finite measurement time will probably require clock transition frequencies in the optical region (10^{14} to 10^{15} Hz). This in turn, will require new frequency measurement technologies. Techniques for these measurements are presently being studied experimentally.

Dissemination

The methods for disseminating the advanced accuracy and stability of these new standards to users form a necessary adjunct to the development of the standards themselves. Earth orbiting satellites provide the basis of the required systems.

The navigation system of military satellites called the Global Positioning System (GPS) can provide worldwide timing accuracy to at least 10 ns[17]. In this system, the ground stations are passive receivers of a timing signal originating in the on-board atomic clocks. When the receiving stations compare their clocks with common pulses from the same satellite, the on-board clock errors cancel. The resulting time transfer accuracy is limited only by ionospheric propagation differences along the signal paths to the two end stations. To achieve the full accuracy and stability of this system requires several day averages over several satellites.

An evolving technology called "two way time transfer" requires active ground stations relaying timing signals through commercial communication satellites. Exchanging timing signals in both directions through the satellite, it is possible to nearly perfectly cancel all of the path and system delays. Such systems have already demonstrated a precision of 20 ps in a 100 second averaging time and it is thought that subnanosecond timing accuracy will be achieved in the near future[18].

Summary

The coming application of laser technology to the realization of the SI unit of time will have a dramatic impact. Laser induced optical state selection and detection is about to advance time keeping accuracy by about an order of magnitude. The rapidly developing field of laser cooling of atoms and ions could soon be in a position to contribute to future standards. A fountain of cold cesium atoms could lead to a standard with accuracy of parts in 10^{16}. Beyond that, it may be possible to hold very cold atoms in a deBroglie box for still higher accuracy. The ultimate standard may well be an optical transition in a laser cooled, trapped ion. Present analysis indicate that the systematic errors in such a standard could be controlled to parts in 10^{18}.

The advancing techniques of satellite time transfer (GPS common view and "two way") will continue to allow the full use of time-keeping accuracy in nonstandards labs throughout the world.

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