Advances in Primary Frequency Standards[1]

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Abstract

This paper describes the newest generation of primary frequency standards as well as advances that are anticipated during the next decade. In part, these new standards are a result of the development, over the last decade, of methods for using lasers to control the energy states and motions of atoms. The paper describes NIST's new optically pumped, cesium-beam frequency standard and the process involved in establishing its present uncertainty at $5 \cdot 10^{-15}$. This is followed by a description of France's new cesium-fountain frequency standard now exhibiting an uncertainty of $3 \cdot 10^{-15}$. The final description is of a new class of standards involving trapped ions. These standards promise dramatic increases in accuracy, mainly because the ions are fixed in space and laser-cooled to near 0 K. This minimizes Doppler shifts and allows for very long observation times.

Introduction

Since its beginning in 1949, the atomic timekeeping era has witnessed dramatic improvements in the accuracy and stability of atomic standards. Cesium-beam frequency standard technology has increased in accuracy by a factor of nearly 10 every 10 years. This trend continues today through the use of optical techniques to control both the atomic states and physical motion of atoms. Such optical manipulation of atoms represents the state of the art in primary frequency standards, leading to frequency uncertainties as low as $3 \cdot 10^{-15}$. Below is a brief review of some of the milestones in atomic timekeeping leading to this point.

Review of Cesium Clock Technology

No physical quantity can be measured with greater precision than frequency and its

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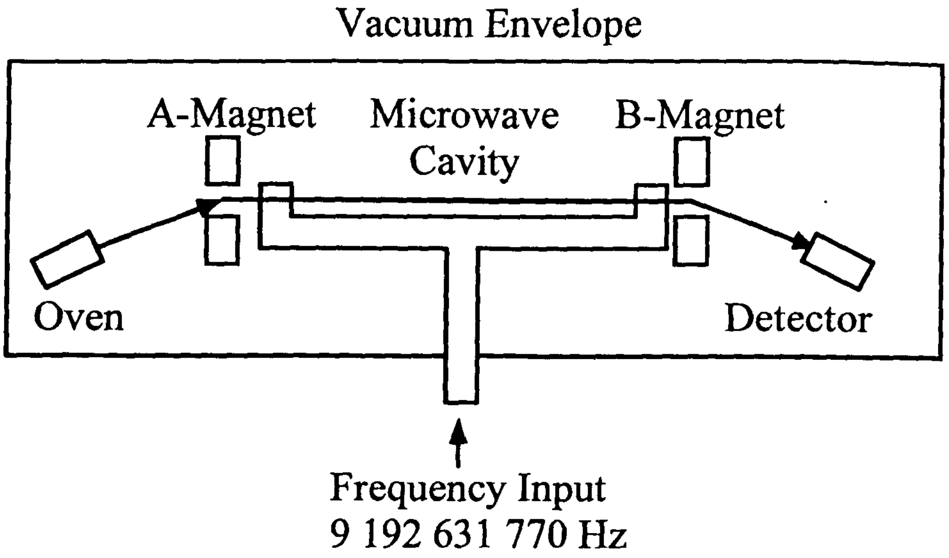

Figure 1: Schematic of a Cesium-Beam Atomic Clock.

inverse, time. This is due in part to advancements in electronic measurement techniques. With improvements in electronics and the stability of quartz oscillators came the realization that the basis for the definition of the second, the orbital motion of the Earth, was not constant. This lead in 1967 to the redefinition of the second. The 13th General Conference on Weights and Measures decided that:

> The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom cesium-133. [1]

Below is a general description of a traditional cesium-beam frequency standard.

Figure 1 is a simplified diagram of a traditional cesium-beam atomic clock. An oven generates a continuous supply of cesium atoms in the form of a narrow beam. Atoms that are in a particular low-energy state are deflected by a magnet (the A-magnet) so that they follow a trajectory through a U-shaped microwave cavity. Atoms in other states are rejected. The selected atoms travel through holes in the ends of the cavity, seeing first one pulse of microwave radiation, then another as they traverse the clock. If the frequency of the electrical signal applied to the cavity coincides with the characteristic frequency of the cesium atom then the atoms can absorb this microwave energy, raising their energy state in the process. Such atoms are selected by another magnet (the B-magnet) and deflected toward a detector. By measuring the number of atoms that have changed their state, we can determine the agreement between the applied frequency and that of the cesium atom which is, *by definition*, 9 192 631 770 Hz.

There are, however, physical effects and technical imperfections in such clocks that can alter the observed resonance frequency of the cesium atom. For example, the definition of the cesium resonance frequency applies to atoms that are at rest. The atoms in a hot beam are not at rest, but moving at several hundred meters per second. This motion gives rise

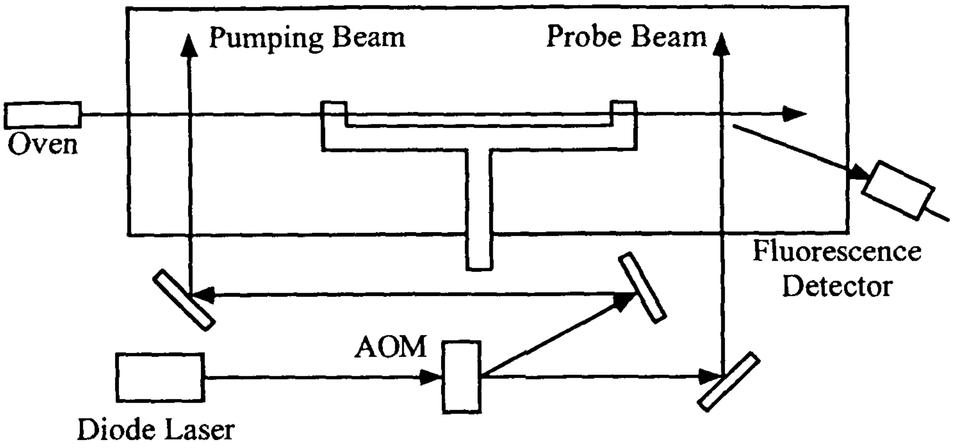

Figure 2: Schematic of NIST-7, an optically pumped cesium-beam standard. The magnets of Figure 1 have been replaced with laser beams. A semiconductor diode laser is used to both prepare and detect the cesium atoms. The device labeled AOM is an acousto-optic modulator. It shifts the frequency of one of the laser beams since optical pumping and detection employ different optical transitions.

to a relativistic Doppler shift of the atoms' resonant frequency. The U-shaped microwave cavity in Figure 1 is designed to be symmetric; its two arms should have equal length. In practice, there is always some residual asymmetry from one end to the other. As a result, the atoms see two pulses of microwave energy that have a slight difference in phase. This phase difference, when divided by the atoms' transit time across the cavity, introduces an apparent bias of the atoms' resonance frequency. This bias is one of the leading sources of frequency error in cesium-beam clocks.

A method that is used to measure this bias in frequency standards is called beam reversal. The success of this method relies on the fact that as the direction of the atomic beam is reversed (the oven is replaced with a detector and the detector is replace by an oven) the sign of the bias changes. Thus, we can compensate for this bias by simply averaging two frequency measurements taken with the atoms traveling in opposite directions. This technique assumes that the direction of the atomic beam is the only change between frequency measurements and that all other cavity related errors remain unchanged. This assumption is often difficult to verify in traditional cesium-beam clocks that use magnets (magnets A and B in Figure 1) since the trajectory of an atom through the clock depends on its velocity and the magnetic field. Diode laser technology however, has led to improved clock designs, reducing the impact of cavity asymmetry on the frequency uncertainty as will be discussed in the next section.

Optically Pumped Cesium-Beam Clocks

Figure 2 is a schematic of NIST-7, the U.S. primary frequency standard.[2] The technological advancement that distinguishes this device from previous cesium-beam clocks is the use of diode lasers for atomic state preparation and detection. The state-selection magnet (A-magnet) has been replaced by a laser beam (pumping beam in Figure 2) that is tuned to an optical transition in the cesium atom at 852 nm. This transition is in the near-infrared portion of the electromagnetic spectrum. As they pass through this laser, the atoms are optically pumped up to a very high energy state. They then relax to a lower energy state, most of them arriving at the desired state because of quantum state-selection rules. The atoms still pass through a microwave cavity as in the previous design; however this new design also employs laser beams to determine if the cesium atoms have made the tell tale transition to a new energy level. The benefits from such a design are many. The Probe Beam illuminates the atoms in such a way that each atom that absorbs a microwave photon reveals this fact by scattering many infrared photons, increasing the signal strength. The removal of the magnets permits a more uniform magnetic field within the clock. The trajectories of the atoms in this optically pumped frequency standard are now much more nearly symmetric upon beam reversal. This leads to a much more accurate determination of the cavity asymmetry phase shift described above. Using these laser techniques, NIST has developed a very accurate cesium-beam primary frequency standard. NIST-7 has a frequency uncertainty of no more than $5 \cdot 10^{-15}$. Despite the benefits of optical pumping using diode lasers, there is a drawback. The magnets of a traditional cesium clock passed only atoms with a narrow spread of velocities. Optically pumped clocks perform no velocity selection. This larger spread of atomic velocities introduces a larger uncertainty into the relativistic Doppler correction described above. Fortunately, lasers can also be used to reduce this spread of velocities in a radically different type of atomic clock called a cesium fountain.

The Cesium Fountain

Over the past several years, great progress has been made in laser cooling of neutral atoms.[3] Lasers can now be used to cool cesium atoms to nearly 0 K. Such a situation seems ideal for the advancement of atomic clock technology. Laser-cooled atoms mov very slowly, greatly reducing the relativistic Doppler shift. Laser-cooled atoms can be held stationary using a set of six intersecting laser beams. Thus, measurement of the microwa resonance frequency can take place over a longer time, with a corresponding improvem in precision. Unfortunately, the same lasers that cool the atoms also perturb their natu resonant frequency. Any measurement of the atomic resonance must take place in the da One method of achieving this is shown in Figure 3. Six intersecting laser beams de a region of "optical molasses." It is called molasses because the atoms experience a that is proportional to their velocity in any direction as in a viscous medium. Whe molasses region is full, the cold atoms are gently tossed upward using the two vertical beams. (The atoms can travel up to 1 meter at the upper limit of their trajectory.) O the atoms are in flight, all of the lasers are turned off so that the atoms may dri the dark. Like the cesium-beam standards described earlier, the atoms will experienc pulses of microwave radiation. In a traditional cesium standard, the atoms pass through arms of a microwave resonantor. In a cesium fountain, the atoms travel through the microwave cavity twice: on the way up, and again on the way down. This represent of the cesium fountain's fundamental improvements. The cavity asymmetry, which troublesome for thermal beam standards, is absent. Similarly, the problems associated the large range of atomic velocities in an optically pumped standard are eliminated the cold cluster of cesium atoms in a fountain is essentially monokinetic. Furthermo Doppler shifts are much smaller and the observation time for any given atom is substa

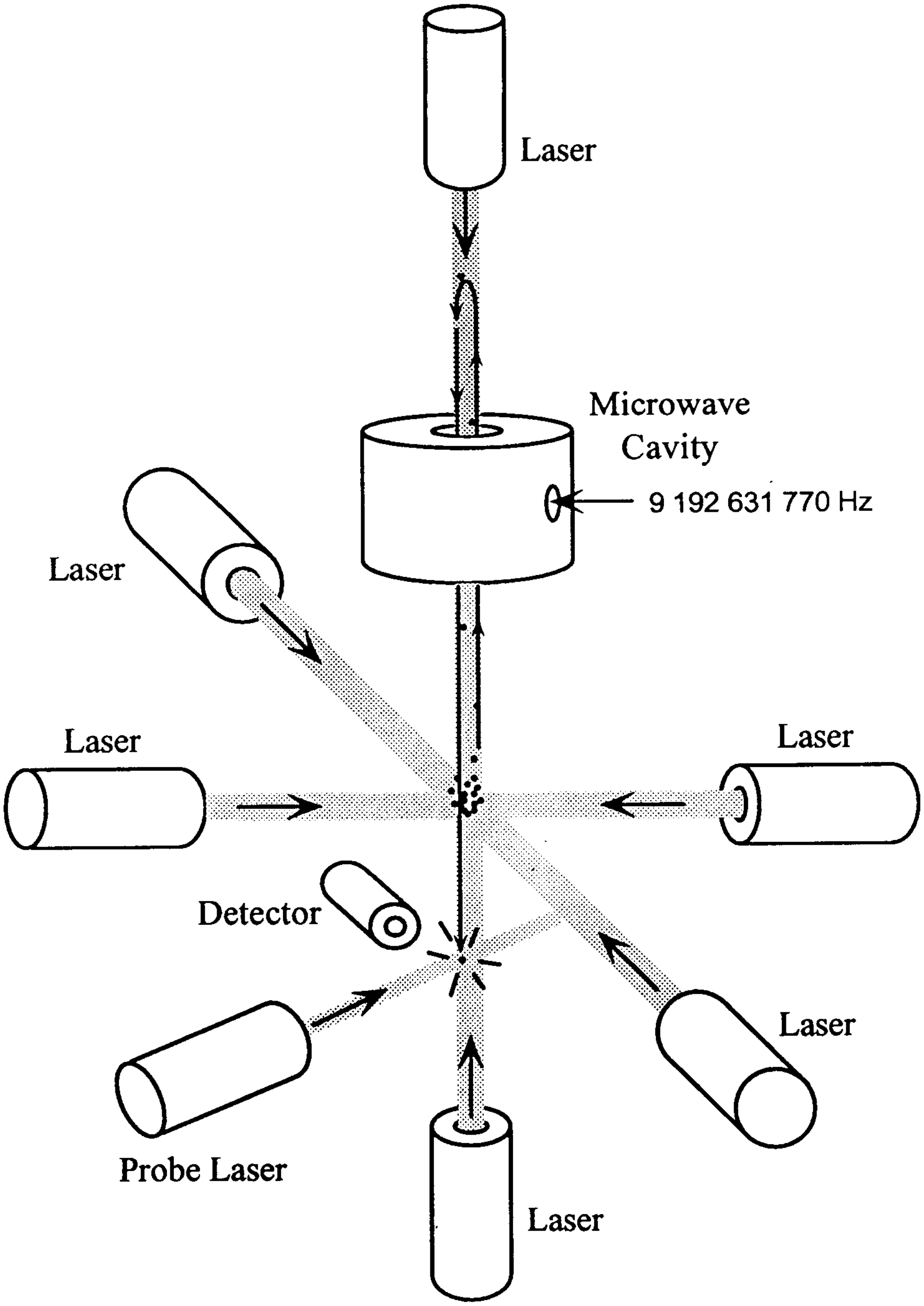

Figure 3: Schematic of a Cesium Fountain.

longer than in a traditional cesium-beam device. Longer observation times lead to narrower resonance linewidths. Researchers at the Primary Laboratory of Time and Frequency in Paris have constructed a cesium fountain and have obtained the best frequency accuracy to date: $3 \cdot 10^{-15}$.[4] With this new clock technology using laser manipulation of atoms, the lifespan of cesium technology has been greatly extended.

Future Frequency Standards

Cesium has served as the basis for the definition of the second since 1967 and will likely do so well into the next century. It will be difficult, however, to reach accuracies below $1 \cdot 10^{-16}$ using cesium technology. The future of primary frequency standards most likely involves laser-cooling and electromagnetic trapping of charged ions. Work is presently underway at NIST to develop a frequency standard based on trapped ions.[5] A few dozen ions can be loaded into a linear electromagnetic trap. They are held in space by a combination of static electric fields, oscillating fields, and their own electric charge. Additional laser-cooling reduces the motion of the ions. The relativistic Doppler shift that plagues moving cesium atoms is virtually eliminated using this technique, improving the potential accuracy. In addition, we are no longer restricted to observing the ions for a short time interval as they traverse the apparatus. These ions can be held in the trap for long times (as long as 1 day) so that precise measurements can be made of their natural resonance frequency. Researchers believe that the residual frequency biases in such a clock can be understood with an uncertainty of $1 \cdot 10^{-18}$. Achieving this uncertainty poses many challenges, but the accuracy potential is better than that of any other proposed approach. When the ultimate limit of cesium technology has been reached, such stored-ion clocks appear to be likely successors.

Conclusion

Measurement of frequency, like any measurement, is a process of comparison. In practice, we measure the frequency of an oscillator with respect to a trusted reference. At some point the chain of comparison must end with a primary frequency standard whose frequency cannot be *measured*, but must be *stated* along with a corresponding uncertainty. The goal of primary frequency standards research is to reduce this uncertainty. Recent advances in primary standards have been driven by new optical methods for manipulating the energy states and motion of atoms. The use of diode lasers as compact, reliable sources of laser light has not only led to improvements in primary frequency standards but also may yield more accurate commercial devices, delivering this improved accuracy to the field.

References

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