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The Evolution of Time Measurement, Part 4: The Atomic Second

Before the invention of atomic clocks, the second was defined by *dividing* the period of an astronomical event into a shorter time interval. For example, the second was once defined by dividing the average period of one revolution of the Earth on its axis. The *mean solar second* was equal to 1/86,400 of the mean solar day. To create a more stable unit of time interval, the second was redefined in 1956 as 1/31,556,925.9747 of the tropical year 1900. The *ephemeris second* was indeed more stable than the mean solar second but was nearly impossible to use as a time reference and of little use to metrologists or engineers. In retrospect, it seems almost ridiculous that another astronomical definition of the second was accepted during a period when atomic clocks were already being built [1], [2]. A clean transition from the mean solar second to the atomic second would have made more sense. Doomed from the start, the ephemeris second would be easy to forget about except for one thing – it became the comparison reference for the atomic second.

Ephemeris time was determined by measuring the position of the Earth's moon with respect to several surrounding stars. The best moon observations had been recorded at the United States Naval Observatory (USNO) in Washington, DC by the astronomer William Markowitz. By 1952, Markowitz was performing moon observations with a sophisticated dual-rate moon camera of his own design [2], [3]. Moon observations were a tedious practice and results were obtained slowly. Sir Edward Bullard, the director of the National Physical Laboratory (NPL) in the United Kingdom, wrote in 1955 that it would take four years of moon observations to determine time with the same accuracy as their new cesium clock. He also noted that "atomic clocks will be improved, probably by a greater factor than the astronomical determinations," which in retrospect was a considerable understatement [4]. It was already clear that atomic clocks represented the future of timekeeping.

NPL and the USNO measured the cesium resonance frequency with respect to the ephemeris second from 1955 to 1958. The USNO standard was a quartz clock steered to ephemeris time by applying corrections obtained with the moon camera; the NPL standard was their new cesium clock [5], now accurate to within 5×10^{-10}. Because the two clocks were located across the Atlantic from each other, the comparison was made by simultaneously comparing each clock to radio signals that could be received at both laboratories, a measurement technique now known as common-view time transfer. Several time signal broadcast stations including WWV in the United States and MSF and GBR in England [3], [5] were involved in the measurement. Four different solutions were made to determine the effects of using different data. The final result was the average of the four solutions and was published as 9 192 631 770 cycles/s in August 1958, with an estimated measurement uncertainty of ±20 cycles/s [6]. This historic measurement linked atomic and astronomical time, but nearly a decade passed before the definition of the second was officially changed. The second was redefined in 1967 as, "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom" [7].

To understand the definition, consider that cesium is a complicated atom with F = 3 and F = 4 ground states (Fig. 1). Each atomic state is characterized not only by the quantum number F, but also by a second quantum number, mF, which can have integer values between –F and +F. The splitting of the F = 3 and F = 4 states into the various mF sublevels occurs in the presence of a magnetic field. There are 16 possible mF sublevels in the ground state of cesium, but the frequency of the $|4, 0\rangle \leftrightarrow |3, 0\rangle$ hyperfine transition was chosen to define the second. The $|4, 0\rangle \leftrightarrow |3, 0\rangle$ transition had several advantages that made it the best choice

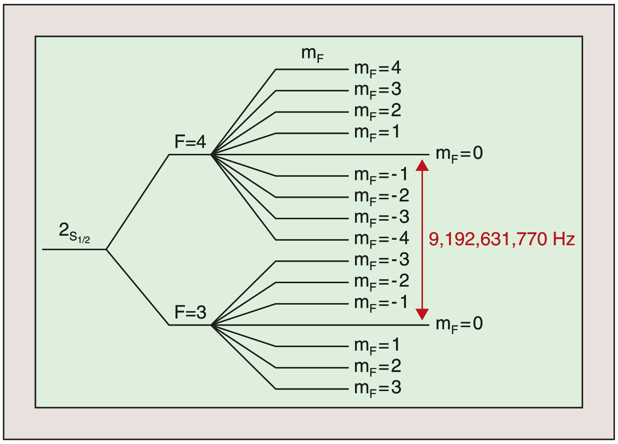

Fig. 1. The cesium clock transition.

for clocks. There was a very low probability of a spontaneous transition occurring during the observation time. The transition was also fairly easy to detect with electronic systems that were already available when Rabi and others began their experiments. Perhaps most importantly, the transition was relatively insensitive to electric fields, so small electric fields in the vicinity of a cesium clock would have little effect on its frequency.

The new definition made cesium clocks the official world timekeepers. It was known, of course, that atomic time would gradually diverge from astronomical time, so periodic corrections would be needed to keep the new atomic time scale, called Coordinated Universal Time (UTC), in step with astronomical time. By 1972, these corrections were made in the form of *leap seconds*. The purpose of leap seconds was to always keep UTC within ±0.9 s of UT1, an astronomical time scale based on the mean solar second. Adding a leap second to UTC stops atomic time for one second so that astronomical time can catch up. From 1972 to 2008, 24 leap seconds were added to UTC. The exact relationship between astronomical and atomic time is difficult to model or predict, but there are two general reasons why leap seconds are needed. The first reason relates to the Markowitz/Essen measurement – they measured the atomic second with respect to the ephemeris second and not with respect to the mean solar second. Ephemeris seconds were slightly shorter than mean solar seconds, and this characteristic was passed along to the atomic second, making leap seconds inevitable [3]. Reason two is that the mean solar second is gradually getting longer because the Earth's rotational rate is gradually slowing. Although more widely cited, the second reason has had much less influence on the number of leap seconds than the first reason.

Some organizations have found the leap second to be cumbersome to implement and support, and there is currently an International Telecommunications Union (ITU) proposal to stop the insertion of leap seconds. However, the practice of inserting leap seconds is still in effect at this writing (2011), and the issue remains unresolved.

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Commercial Cesium Clocks

Cesium clocks were sold before the publication of the atomic definition of the second. The first commercial cesium clock was introduced in October 1956, just slightly more than one year after the introduction of the NPL clock. Called the Atomichron, the clock was developed by a team led by Jerrold Zacharias [8]. The National Company of Malden, Massachusetts sold at least 50 Atomichrons between 1956 and 1960.

The first cesium clocks were large and not particularly reliable, but the technology quickly matured through the efforts of Len Cutler and his colleagues at the Hewlett-Packard Company. Hewlett-Packard produced a series of cesium clocks that were reliable enough to run continuously for years and small enough to fit into standard equipment racks. The first of these clocks was the 5060, introduced in 1964. It soon reached a specified accuracy of about 1 μs/d (1 × 10^{-11}) [9]. It was followed by the 5061, manufactured from 1967 until the early 1990s, and the 5071, which debuted in 1991. With an internal microprocessor and an improved cesium beam tube, the 5071 was more stable and accurate than all of its predecessors [10]. It has a specified accuracy of about 20 ns/d (2 × 10^{-13}) and can be adjusted to keep time within a few nanoseconds per day (parts in 10^{14}). Now manufactured by Symmetricom, the 5071 continues to serve as the primary standard of frequency and time at many laboratories.

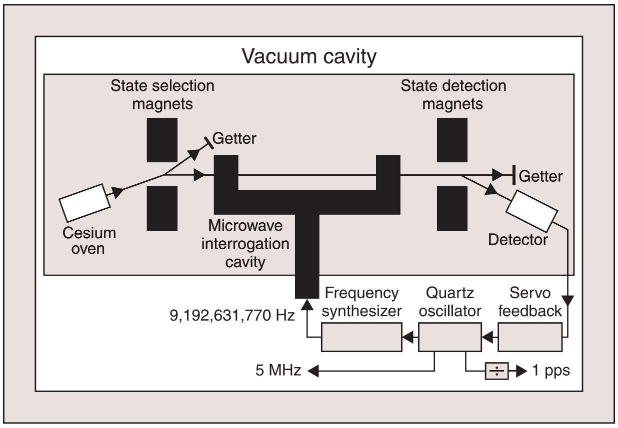

Fig. 2. Schematic of a cesium beam clock.

Fig. 2 is a simplified schematic of a cesium beam clock. The design details of commercial cesium clocks can vary significantly from model to model, but the basic principles of operation can be traced back to the seminal work of Rabi and Ramsey. As shown on the left side of Fig. 2, ^{133}Cs atoms are heated to a gaseous state in an oven. A beam of atoms emerges from the oven at a temperature near 100 °C and travels through a magnetic field, where the beam is split into two atomic beams with different magnetic states. One beam is absorbed by the getter and is of no further interest. The other beam is deflected into the microwave interrogation cavity (commonly known as the Ramsey cavity).

While inside the Ramsey cavity, the cesium beam is exposed to a microwave signal. This signal is generated by a frequency synthesizer driven by a quartz oscillator. If this frequency equals cesium resonance, some of the atoms will change their magnetic state. After leaving the Ramsey cavity, the atoms pass through a second magnetic field. These magnets direct only the atoms that changed state to the detector; the other atoms are directed to a getter and are absorbed. The magnets located on both sides of the Ramsey cavity serve as a "gate" that allows only those atoms that undergo the desired $|4,0\rangle \leftrightarrow |3,0\rangle$ energy transition discussed earlier to pass through and reach the detector. The detector sends a feedback signal to a servo circuit that continually tunes the quartz oscillator so that the maximum number of atoms reaches the detector, thereby increasing the signal strength. This process is analogous to carefully tuning a radio dial until the loudest and clearest signal is heard and keeps the quartz oscillator locked as tightly as possible to cesium resonance [11]-[13]. When a cesium clock runs out of cesium or becomes unlocked due to other reasons, it simply becomes a free running quartz clock.

The world's most accurate cesium clocks are known as cesium fountains. These clocks were specifically designed so that the cesium atoms could be observed for a longer period than allowed by conventional cesium clocks.

The *Q* factor of a commercial cesium clock is near 10^8. The beam tube is typically less than 0.5 m in length, and the atoms travel at velocities of greater than 100 m/s inside the tube. This limits the observation period to a few milliseconds and the resonance width to a few hundred hertz.

Cesium Fountain Clocks

The world's most accurate cesium clocks are known as cesium fountains. These clocks were specifically designed so that the cesium atoms could be observed for a longer period than allowed by conventional cesium clocks. The idea of a fountain clock was first introduced by Zacharias in the 1950s, shortly before he developed the Atomichron [8], [14]. His original idea was simply to build a vertical cesium beam standard with one microwave cavity. This would allow slow atoms from the cesium oven to pass through the cavity while traveling upward, stop and reverse their direction under the influence of gravity, and then pass through the cavity again on their way down. The two passes through the cavity reproduced Ramsey's two-pulse interaction scheme, but if the flight of the atoms reached a height of about one meter the observation period would increase to nearly 1 s, more than 100 times longer than the observation period of a cesium beam clock. Unfortunately, due to collisions between the atoms in the beam, Zacharias never got his fountain clock to work. The slow atoms were scattered out of the beam by the fast atoms that overtook them [15].

Steven Chu and his colleagues at Stanford University revived Zacharias' idea and built the first working fountain clocks in the late 1980s. Chu's group built fountains using sodium atoms [16] and later using cesium atoms [17], although neither device was used as a time standard. Credit for the first fountain clock used as a time standard goes to researchers at the Bureau National de Métrologie – Systèmes de Référence Temps Espace (BNM-SYRTE) in France, who published their results in 1995 [18]. Researchers at numerous metrology laboratories have since built cesium fountain clocks to serve as national frequency and time standards.

The key to making a fountain clock work is laser cooling. First proposed in 1975 [19], laser cooling was successfully demonstrated by Dave Wineland and his colleagues at NBS in 1978 when they applied the technique to magnesium ions [20]. There are numerous laser cooling techniques, but fountain clocks generally implement a scheme known as optical molasses. This technique exerts a damping force on the atoms by using three pairs of oppositely directed lasers (Fig. 3). The lasers are tuned to a frequency slightly below the optical resonance of the atoms. Atoms at the intersection of the six laser beams are cooled to a temperature of less than 1 μK in a few tenths of a second. As if they were moving through molasses, the cold cesium atoms slow down to about 1 cm/s, a tiny fraction of their ~100 m/s speed at room temperature. This allows a large sample or "ball" of atoms to be gathered together and confined in one place.

The lasers provide an opposing force to the atoms' natural motion. Atoms absorb photons from the laser beam toward which they are moving, and each absorbed photon carries momentum in the direction opposite to the atoms' motion. Atoms reemit photons in a random direction, and because the laser is tuned below the resonance frequency, the atoms reemit slightly more energy than they absorb. The process can be thought of as a bowling ball being bombarded by a stream of ping pong balls. The opposing force that each atom receives from each scattered photon is so small it would appear to have no effect. However, the atom's momentum is gradually reduced, and when this tiny force is repeated often enough, it can reduce an atom's velocity to near zero.

From late 1998 to the present (2011), the United States national standard for frequency and time has been a cesium fountain clock called NIST-F1 (Fig. 4), which was designed by a team at the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards (NBS), led by Steve Jefferts [21]. The NIST-F1 laser cools a sample of about 10^8 cesium atoms at the intersection of six laser beams (Fig. 3). The atoms are launched upwards at a velocity of about 4 m/s to make a moving optical molasses. The "ball" of atoms, about

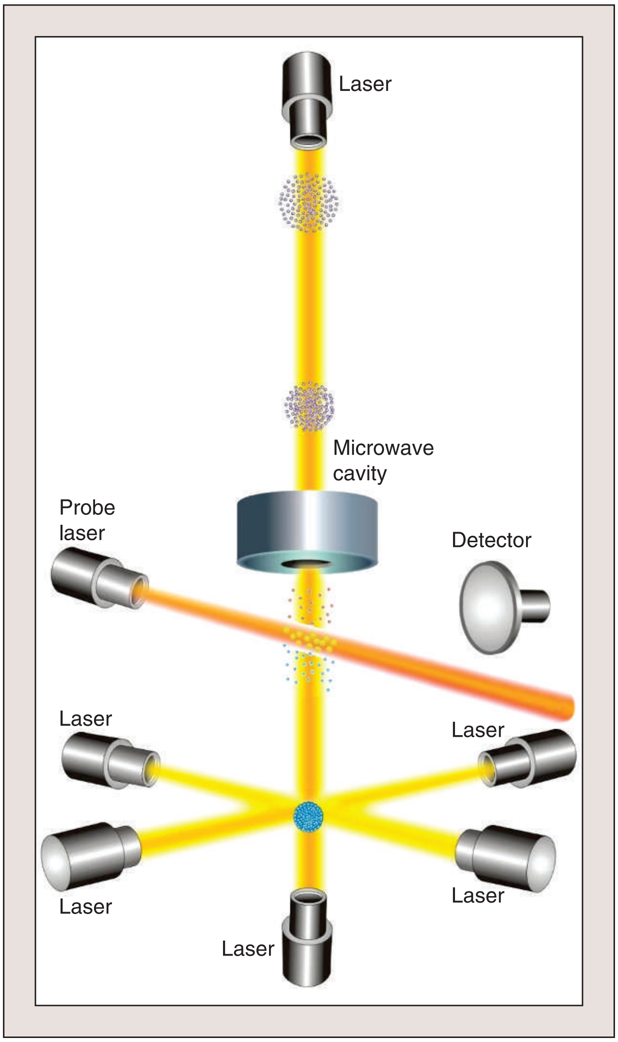

Fig. 3. Simplified schematic diagram of a cesium fountain that uses laser cooling.

Fig. 4. The cesium fountain clock NIST-F1.

1 cm in diameter, is typically in the F = 4 ground state, but all mF levels are populated. A short microwave pulse drives the $|4, 0\rangle$ atoms into $|3, 0\rangle$ and leaves the other F = 4 atoms unperturbed. The remaining F = 4 atoms are removed from the cloud with a short optical blast. At this point the remaining cesium atoms, all in the $|3, 0\rangle$ state, enter the microwave cavity with a velocity of around 3 m/s. The atoms reach a height of about 1 m above the cavity before turning back down due to gravity. The falling atoms then pass through the cavity a second time about one second after their first passage.

As Zacharias had originally expected, this long interaction period allows cesium fountain clocks to be far more accurate than cesium beam clocks. NIST-F1 has a line width, Δf_a, of about 1 Hz and a Q factor of about 10^{10}. These numbers are about 100 times better than commercial cesium clocks, and NIST-F1 is at least 100 times more accurate. The current accuracy of NIST-F1 is about 3×10^{-16}, or about 0.03 ns/d [22].

Future cesium fountain clocks will be even more accurate, perhaps dropping slightly below the 1×10^{-16} threshold. However, microwave clock technology is nearing its limits. Future advances in accuracy will come from the optical clocks discussed in the next section.

Optical Clocks

The atomic clocks of the future will almost certainly be based on optical atomic transitions. Optical clocks operate at much higher resonance frequencies and have much higher Q factors than microwave clocks; their resonators are stabilized lasers that operate at frequencies near 10^{15} Hz, as opposed to less than 10^{10} Hz for cesium. As a result, optical clocks promise accuracies that are least 100 times better than those of cesium fountain clocks. Optical clocks have been built at NIST utilizing single-ion techniques based on mercury (^{199}Hg+) and aluminum (^{27}Al+), as well as neutral atom techniques based on calcium (^{40}Ca), ytterbium (^{174}Yb), and strontium (^{87}Sr). It appears likely that the definition of the second will change once again, with the new definition based on one of these optical atomic transitions [23].

As we have seen, the amazing accuracy and stability of atomic clocks has revolutionized time measurement. Even so, an atomic clock still needs to be synchronized to a reference source before it can be used to keep time. In the fifth and final installment of this series, we'll look at clocks that automatically synchronize to time signals received by radio.

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