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NIST Primary Frequency Standards and the Realization of the SI Second¹

Michael A. Lombardi, Thomas P. Heavner and Steven R. Jefferts

Abstract: As the base unit of time interval, the second holds a place of preeminence in the world of metrology. Time interval, and its reciprocal, frequency, can be measured with more resolution and less uncertainty than any of the other physical quantities. The precise realization of the second was made possible by the development of frequency standards based on the energy transitions of atoms, an event that not only revolutionized the science of timekeeping, but also forever changed many other areas of metrology. The definitions of other units in the international system (SI), including the meter, candela, ampere, and volt, now depend upon the definition of the second. In the approximate half century since atomic frequency standards were first introduced, the progress in time and frequency metrology has been rapid and relentless. Today, the National Institute of Standards and Technology (NIST), maintains the world's most accurate primary frequency standard, a laser-cooled cesium fountain known as NIST-F1. Since its completion in 1998, NIST-F1 has been continuously improved and is currently accurate to within 4×10^{-16} . NIST-F2, a second-generation atomic fountain standard now being built, promises even better accuracy. This paper explores both the history and the technology of NIST primary frequency standards, beginning in the pre-atomic era and continuing through the present day.

1. Introduction

It is hard to overestimate the impact that atomic timekeeping has had on modern society. Many “everyday” technologies that we often take for granted, such as cellular telephones, Global Positioning System (GPS) satellite receivers, and the electric power grid, rely upon the accuracy of atomic clocks. This makes it easy to forget that the era of atomic timekeeping began relatively recently; less than an average lifetime ago. The current year (2007) marks the 40th anniversary of the redefinition of the

International System of Units (SI) second based on cesium (1967). [1] Prior to 1967, the definition of the second had always been based on astronomical time scales. The year 2008 marks the 50th anniversary of the first publication (1958) of the definition of the atomic second, defined as 9,192,631,770 periods of the radiation of the ground state hyperfine transition in cesium. [2] The year 2008 also marks the 60th anniversary of the first prototype of an atomic clock, an ammonia maser that was first demonstrated at the National Bureau of Standards (NBS), later known as the National Institute of Standards and Technology (NIST) in 1948. [3, 4] With these dates in mind, let's begin with a brief look at some fundamental concepts and early standards, and then move on to explore present-day atomic oscillators.

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2. Fundamentals of Frequency and Time

All time and frequency standards are referenced to a periodic event that repeats at a nearly constant rate. The periodic event is produced by a device called a resonator. The resonator is driven by an energy source, and taken together, the energy source and resonator form an oscillator. The oscillator runs at a rate called the resonance frequency. The frequency, f , is the reciprocal of the period of oscillation, T ; therefore $f = 1/T$. Conversely, the period, measured in units of time interval, is the reciprocal of the frequency: $T = 1/f$.

To illustrate this, consider the simple example of a grandfather clock, where a pendulum (and its energy source) serves as the oscillator. The pendulum has a resonance frequency (f) of 1 Hz, and a period (T) of 1 s. Thus, it is easy to see the close relationship between time interval and frequency. All clocks are referenced to an oscillator, and any uncertainty or change in the frequency of the oscillator will result in a corresponding uncertainty or change in the timekeeping accuracy of the clock.

Throughout this paper, we express oscillator performance as $\Delta f/f$, where Δf is the combined uncertainty of the frequency with respect to its nominal value, and f is the nominal value of the frequency. The quantity Δf includes any offset of the frequency from its nominal value, as well as any variation in the frequency over time. Please note that when primary cesium frequency standards are discussed, we quote their performance in terms of accuracy, rather than uncertainty. This is because cesium oscillators are intrinsic standards, and the second, the base unit of time interval, is defined based on the cesium resonance (see Section 7). Therefore, by definition, primary cesium frequency standards serve as the ultimate measurement references for time interval and frequency, and are inherently accurate. Their systematic frequency biases (Type B uncertainties) are periodically evaluated and corrections are applied. The accuracy of a primary cesium standard is limited by the uncertainties associated with these corrections. For purposes of international comparison, these uncertainty esti-

mates have historically been reported by NIST and other national metrology institutes with a coverage factor of one, so $k = 1$ should be assumed while reading this paper.

3. Early Standards

The quest to improve timekeeping is one of mankind's oldest pursuits, and has essentially been a search to find better oscillators. The best oscillators have a period that is well characterized, not easily perturbed, and as stable as possible. Early astronomers quickly noted that the Earth's rotation on its axis served as a natural oscillator, and the second was long defined as a fraction ($1/86\,400$) of the length of the solar day. Later, because the length of the day fluctuates by a large amount seasonally, the second was more accurately defined as a fraction of the average length of the solar day (known as the mean solar second). To create a more stable unit of time interval, astronomers later chose the period of the orbital motion of Earth about the Sun (nominally 1 year) as the basis for the definition of the second. In 1956, the ephemeris second ($1/31\,556\,925.9747$ of the tropical year 1900) was formally adopted by the General Conference of Weights and Measures (CGPM) as the SI second. While the ephemeris second was indeed more stable than the mean solar second, it was impractical to measure, and it was never available or used in metrology laboratories or as a general timekeeping standard. Its few applications were limited to the world of astronomy. [5]

In the pre-atomic era, mechanical and electrical oscillators served as the laboratory standards for time interval and frequency measurements. At NIST (then known as NBS, or the National Bureau of Standards), pendulum clocks originally served as the standards of time interval, while tuned circuits and later quartz oscillators served as the standards of frequency. Pendulum clocks were based on the principles first outlined by Galileo Galilei between 1637 and 1639. Galileo had observed that a given pendulum took the same amount of time to swing completely through a wide arc as it did a small arc, and recognized that this natural periodicity could be applied to



Figure 1. The Riefler pendulum clock, which was the primary standard for time interval measurements from 1904 to 1929, is now on display at the NIST museum in Gaithersburg, MD.

time measurement. Shortly after his death in 1642, reliable mechanisms were designed to keep the pendulum in motion, thus making it possible to build pendulum clocks. [6, 7] For nearly 300 years after Galileo's discovery, pendulum clocks dominated the world of high accuracy timekeeping. Their practical performance limit was reached in the 1920s when W. H. Shortt designed and manufactured a clock with two pendulums, one a slave and the other a master. The slave pendulum moved the clock's hands, and freed the master pendulum of tasks that would disturb its regularity. The Shortt pendulum clock kept time to within a few seconds per year ($\approx 1 \times 10^{-7}$). NBS used a pendulum clock manufactured by Clemens Riefler of Munich, Germany as the national time interval standard from about 1904 to 1929, when it was replaced by a Shortt pendulum. [8] Figure 1 shows the Riefler clock on display in the NIST museum in Gaithersburg, MD, where a Shortt pen-

March 1928 THE HOROLOGICAL JOURNAL

THE PERFECT CLOCK

ASTRONOMERS have now stated that the RATE of the "SYNCHRONOME" FREE PENDULUM at GREENWICH OBSERVATORY

but for the very small growth of the Invar Rod which was known and forecasted, has been INVARIABLE. Over a period of nearly TWELVE MONTHS while it was under the closest observation,

NO CHANGE OF RATE COULD BE DETECTED.

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PROFESSOR W. de SITTER of Leyden, discussing in "NATURE" of Jan. 21st, 1928, this entirely new conception of the possibilities of clocks, asks—

"Can these wonderful clocks be of use as a control upon the uniformity of astronomical time like the motion of the moon, the sun, and the planets? Can the handiwork of man compete with the heavenly bodies?"

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MENTION THE "HOROLOGICAL JOURNAL."

Figure 2. A 1928 advertisement for a dual-pendulum Shortt clock.

dulum also is on display. Figure 2 show a 1928 advertisement for the Shortt pendulum, which was billed by its makers as "The Perfect Clock."

The first frequency standards at NBS were developed beginning in about 1911 to calibrate wavemeters and to support the burgeoning radio industry. Frequency was obtained by calculating the resonance of an inductance-capacitance (LC) circuit. The frequency uncertainty of these tuned circuits was eventually reduced to less than 0.1 %. [8, 9] Quartz crystal oscillators, based on the phenomenon of piezoelectricity discovered by P. Curie in 1880, worked much better, resonating at a nearly constant frequency when an electric current was applied. Credit for developing the first quartz oscillator is generally given to Walter Cady of Wesleyan University, who built laboratory prototypes shortly after the end of World War I [10], and patented a piezoelectric resonator designed as a frequency standard in 1923. Quartz oscillators first appeared at NBS and other metrology laboratories in the early 1920s, and were soon used to control radio transmission frequencies. [11] By 1929, the NBS frequency standard was a group of four 100-kHz quartz oscillators that had been developed by Bell Telephone Laboratories (Fig. 3), with a frequency uncertainty of 1×10^{-7} . [12] By 1950, quartz standards reduced this uncertainty by a factor of 100;

producing frequency within 1×10^{-9} . [13] During this period of rapid advancement in oscillator technology, quartz oscillators replaced pendulum clocks as the NBS standard for time interval. [14] Thus, for the first time, the NBS reference signals for measurements of both time interval and frequency could be obtained from the same primary standard.

Quartz oscillators are now used for an almost limitless number of applications. Billions of quartz oscillators are manufactured annually for use inside clocks, watches, cell phones, computers, radios, and nearly every type of electronic circuit. Even so, quartz oscillators are not ideal frequency standards. Their resonance frequency depends on the size and shape of the crystal; and no two crystals can be exactly alike or produce exactly the same frequency. In addition, the frequency of a quartz oscillator changes slowly over time due to aging, and can change more rapidly due to the effects of environmental factors, such as temperature, humidity, pressure, and vibration. [7] These limitations make them unsuitable for some applications, and the quest for better accuracy led to the development of atomic oscillators.

4. Fundamentals of Atomic Oscillators

Oscillators derived from resonant transitions in atoms or molecules had several advantages over the oscillators that preceded them. An unperturbed atomic transition is identical from atom to atom, so that, unlike a group of quartz oscillators, a group of atomic oscillators should all generate the same frequency. Also, unlike all electrical or mechanical resonators, atoms do not wear out. Additionally, at least as far as we know, atoms do not change their properties over time. [15] These features were appreciated by Lord Kelvin, who suggested using transitions in sodium and hydrogen atoms as timekeeping oscillators in 1879. [16] However, it wasn't until the mid-20th century that technology made his idea possible.

Atomic oscillators use the quantized energy levels in atoms and molecules as the source of their resonance frequency. The laws of quantum mechanics dictate that the energies of a bound system, such as an atom, have certain discrete values. An electromagnetic field at a particular frequency can boost an atom from one energy level to a higher one. Or, an atom at a high energy level can drop to a lower level by emitting energy. The resonance frequency (f_o) of an atomic oscillator is the difference between the two energy levels, E_1 and E_2 , divided by Planck's constant, h :

$$f_o = \frac{E_2 - E_1}{h} \quad (1)$$

The basic principle of the atomic oscillator is simple: Since all atoms of a specific element are identical, they should produce the exact same frequency when they absorb energy or release energy. [17, 18]

Atomic oscillators provided a major breakthrough in both accuracy and stability, easily surpassing the performance of all previous standards. In theory, the atom is a perfect pendulum whose oscillations can be used as a standard of frequency, or counted to measure time interval. However, there are still some fundamental, as well as practical, factors that can limit the stability and accuracy of atomic oscillators. Atoms absorb or emit

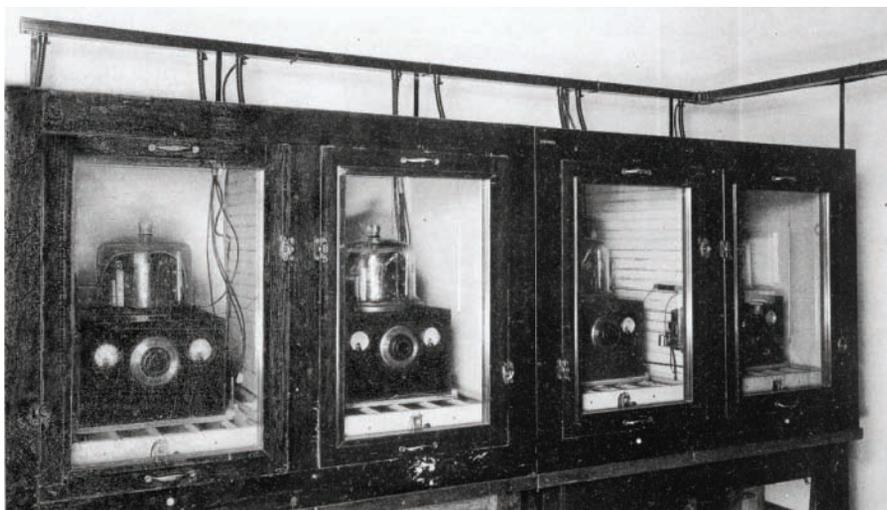


Figure 3. This group of 100 kHz quartz crystal oscillators served as the U.S. national primary frequency standard in 1929.

energy over a small frequency range surrounding f_o , not at f_o alone. All other parameters being equal, the stability of an atomic oscillator is proportional to f_o and inversely proportional to the small spread Δf_a of absorption frequencies surrounding f_o . This spread of frequencies is known as the resonance width, or linewidth. The ratio of the resonance frequency to the resonance width is known as the quality factor, Q , where:

$$Q = \frac{f_o}{\Delta f_a}. \quad (2)$$

Oscillators with higher Q 's are potentially more stable and accurate, so it is desirable to increase Q , either by using an atomic transition where f_o is as high as possible, or by making Δf_a as narrow as possible. [17] In practice, of course, f_o is an inherent property of the atom used in a given device (it is the same for all cesium oscillators, for example) and cannot be changed. However, it is possible to narrow the resonance width by increasing the observation time of the atoms. To illustrate this concept, consider that most atomic oscillators work by frequency-locking an external oscillator (usually quartz) to the resonance frequency of the atomic transition. The external oscillator emits electromagnetic radiation that illuminates the atoms and causes them to change their energy state. The challenge then, is to tune the frequency of the external oscillator so that it matches f_o . The uncertainty of this tuning

process is usually reduced if the atoms are kept in the radiation field for a longer period of time. Mathematically, the resonance width, Δf_a , is set by the period, τ_d , that the atoms spend interacting with the external oscillator. The fractional width of the resonance is given by:

$$\frac{\Delta f_a}{f_o} \propto \frac{1}{\tau_d f_o}. \quad (3)$$

From this equation, it can be seen that the optimum performance is obtained by making the interaction period, τ_d , as long as possible in order to narrow the resonance.

There are many other effects that can limit the stability and accuracy of atomic oscillators. The motion of the atoms introduces uncertainty by causing apparent shifts in the resonance frequencies (the Doppler effect). Similarly, collisions between atoms can broaden the resonance or cause the frequency to shift. Stray electromagnetic fields (including the ever-present thermal, or blackbody radiation) can perturb the resonance frequency and introduce potential errors. [18, 19] Therefore, while atoms are "perfect pendulums" in theory, there are many design features that must be implemented before an atomic oscillator can achieve the lowest possible uncertainties.

5. First Atomic Oscillators

The first atomic oscillator experiments began about sixty years after Lord Kelvin's original suggestion, during the

'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of
Atoms Would Be Used in Most
Accurate of Timepieces

DESIGN TERMED FEASIBLE

Prof. I. I. Rabi, 1944 Nobel
Prize Winner, Tells of
Newest Developments

By WILLIAM L. LAURENCE

Blueprints for the most accurate clock in the universe, tuning in on radio frequencies in the hearts of atoms and thus beating in harmony with the "cosmic pendulum," were outlined yesterday at the annual New York meeting of the American Physical Society, at Columbia University, by Prof. I. I. Rabi, who delivered the Richtmyer Memorial Lecture under the auspices of the American Association of Physics Teachers.

Figure 4. The first public suggestion of an atomic clock, *New York Times*, January 21, 1945.

explosion of advances in quantum mechanics and microwave electronics that took place before, during, and shortly after the World War II. [17] Most of the basic concepts of atomic oscillators were developed by Isidor Rabi and his colleagues at Columbia University in the 1930's and 40's. [20, 21] Rabi had informally discussed applying the molecular beam magnetic resonance technique as a time and frequency standard with NBS scientists in 1939. However, the research was mostly halted during World War II, and he publicly discussed the possibility of atomic clocks for the first time in a lecture given to the American Physical Society and the American Association of Physics Teachers on January 20, 1945, [22] and in a story published in the *New York Times* (Fig. 4) the fol-



Figure 5. The first atomic frequency standard, based on the ammonia molecule (1949). Inventor Harold Lyons is on the right; Edward Condon, then the director of NBS, is on the left.

lowing day. [23] It seems likely that Rabi expected the atomic transition in cesium (^{135}Cs) to be the resonator for the first atomic oscillator. [24] The first experiments to measure the frequency of cesium resonance had been performed in 1940 by Rabi's colleagues at Columbia University, who estimated the frequency of the hyperfine transition in cesium as 9 191.4 megacycles. [25]

As fate would have it, however, the world's first working atomic oscillator was not based on cesium atoms, but instead used the 23.8 GHz inversion transition in the ammonia molecule as its source of resonance. The ammonia device was developed at NBS by Harold Lyons and his associates. It consisted of a quartz crystal oscillator, electronically stabilized by the ammonia absorption

line, and frequency dividers that produced a 50 Hz signal from the stabilized quartz oscillator. Developed for use as a frequency standard, the device (Fig. 5) was first operated on August 12, 1948, although it was not publicly demonstrated until January 1949. The heart of the system, an eight meter long waveguide absorption cell filled with ammonia, is shown wrapped around the analog clock mounted on top of the equipment cabinets. The analog clock itself was there only for cosmetic purposes. Two versions of the NBS ammonia standard were built, with estimated frequency uncertainties of 1×10^{-7} and 2×10^{-8} . Work on a third version was halted when it became apparent that atomic beam techniques offered more promise for frequency standard develop-

ment. [3, 4, 24, 26] Although the ammonia oscillator actually failed to outperform the best quartz standards of its time, it provided a glimpse of what the future would bring, and was widely publicized. Lyons was given a five-minute interview by Edward R. Murrow over the CBS Network on January 14, 1949 [27] and features also appeared in *Time*, *Newsweek*, *Business Week*, and elsewhere. [24] Lyons was even mentioned in a popular cartoon feature a few years later (Fig. 6), although the drawing was not of the ammonia device, but rather of the cesium standard that would later become known as NBS-1 (see Section 9).

During the same year (1949) when Lyons introduced the ammonia frequency standard, Norman Ramsey of Harvard University provided a critical improvement that has since been utilized by all modern primary frequency standards. In the early work of Rabi, the atomic resonance was interrogated with one long microwave pulse. This provided the needed long interaction time between the atom and microwave field, but subjected the output frequency of the standard to Doppler shifts and other uncertainties. Ramsey greatly reduced these problems by inventing the separated oscillatory field method. This method interrogates the atoms with two short microwave pulses, separated by some distance along the beam path. Applying the oscillating field in two steps had many benefits, and made it possible to build much more stable and accurate standards. It narrows the resonance width, reduces the sensitivity to microwave power fluctuations and magnetic fields by factors of 10 to 100 or more, and essentially eliminates the Doppler effect. [17, 21, 28, 29, 30]

6. First Cesium Oscillators

When the ephemeris second (see Section 3) became the SI second in 1957, work on atomic frequency standards had already been progressing for more than a decade. By the early 1950's, work had begun in several national laboratories, notably the National Physical Laboratory (NPL) in England and at NBS in the United States, to build atomic frequency standards based on cesium.

Cesium has several properties that

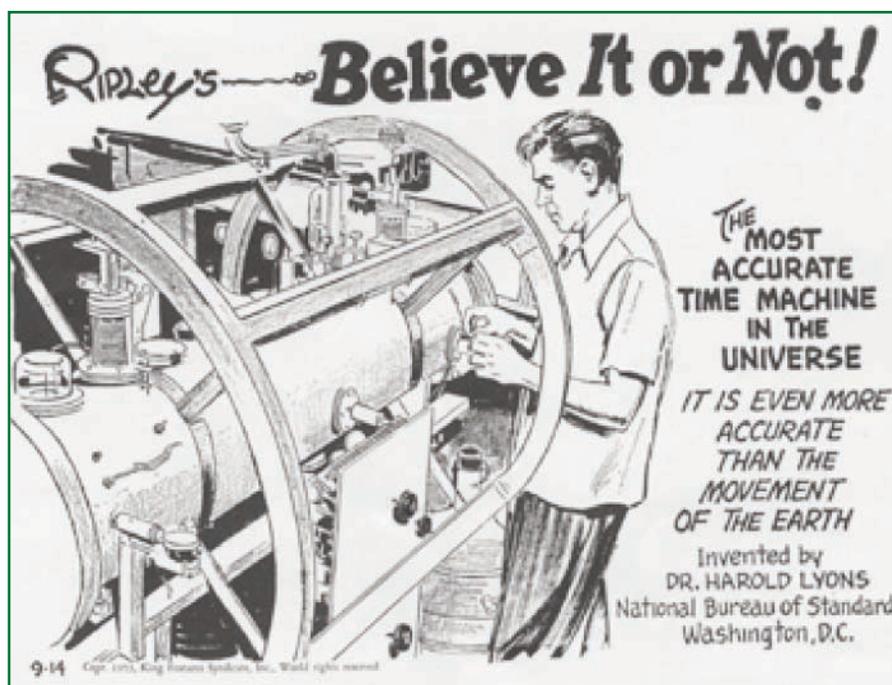


Figure 6. A 1953 cartoon featuring the NBS atomic clock.

made it a good choice as the source of atomic resonance for a primary frequency standard. Somewhat similar to mercury, cesium is a soft, silvery-white ductile metal. It becomes a liquid at about 28.4 °C (slightly higher than room temperature). Cesium atoms are relatively heavy (133 amu), and, as a result, they move at a relatively slow speed of about 130 m/s at room temperature. This allows cesium atoms to stay in the interaction zone longer than hydrogen atoms, for example, which travel at a speed of about 1600 m/s at room temperature. Cesium also has a relatively high hyperfine frequency (~9.2 GHz) when compared to atoms used in other atomic oscillators, such as rubidium (~6.8 GHz) and hydrogen (~1.4 GHz). [30]

By 1950, while work on the ammonia standard was still ongoing, NBS had begun building its first cesium frequency standard. [31] The NBS group, led by Harold Lyons and Jesse Sherwood, constructed a machine using Rabi's magnetic resonance technique, and Sherwood reported the first successful observation of the cesium microwave transition at the 1952 meeting of the American Physical Society. [32] Shortly afterwards, the device was modified to use the Ramsey technique of separated oscillating fields, which reduced the resonance width to

just 300 Hz. Based on these results, Lyons predicted an eventual accuracy capability of 1×10^{-10} . [26, 33]

Unfortunately, the program at NBS to develop a cesium frequency standard was interrupted in 1953 for several years, partially due to budget issues and partially due to decisions made to focus on other areas. Sherwood left NBS in 1953 and Lyons followed in 1955. [8, 27, 34] The cesium standard was completely disassembled and moved from Washington, DC to the new NBS laboratories in Boulder, Colorado in 1954. [27] The device was eventually reassembled with many new components and improved electronics, but it was not until the 1958–1959 period that this original cesium beam frequency standard was used to routinely calibrate the frequencies of the working standards and became known as NBS-1 (see Section 8). [26, 35]

Meanwhile, Louis Essen and his associates at the National Physical Laboratory (NPL) in Teddington, England, had placed a similar cesium beam apparatus with a resonance width of 340 Hz and an accuracy of 1×10^{-9} into operation in June 1955. [36] The NPL device became the world's first cesium standard to be used on a regular basis for the calibration of secondary working frequency stan-

dards. [26] And, as we shall see in the next section, it was used to help redefine the SI second.

7. Atomic Second

Ephemeris time was determined by measuring the position of the Moon with respect to several surrounding stars. The best observations of the Moon had been recorded by the United States Naval Observatory (USNO), where a sophisticated dual-rate Moon camera had been designed and put into operation in 1952 by William Markowitz. [37] Moon observations were a tedious practice, and it was immediately noted by Sir Edward Bullard, the director of NPL, that observations of the Moon over a period of four years would be required to determine ephemeris time with the same precision as was achieved in a matter of minutes by their new cesium standard. [38] In June 1955, due in part to the fact that there were no reliable atomic oscillators then operating in the United States, NPL and the USNO began cooperating in a joint program whose goal was to determine the frequency of cesium with respect to the ephemeris second. [2, 37, 39] Cesium would provide a “physical” second that could be realized in laboratories and used for other measurements.

For a period of almost three years, beginning in mid-1955 and lasting through early 1958, frequency comparisons were made between the USNO and NPL standards. The USNO standard was a quartz oscillator steered to ephemeris time by applying corrections obtained with the Moon camera; the NPL standard was their cesium oscillator, then accurate to less than 5×10^{-10} . [39] The comparisons were made based on common-view observations of signals from several time signal broadcast stations, including NBS radio station WWV, then located in Beltsville, MD, and the British stations MSF and GBR. [37, 39] After averaging and analyzing the results of these comparisons, it was determined that the transition frequency of cesium was 9 192 631 770 Hz, with an uncertainty of ± 20 Hz. The uncertainty was limited not by the cesium standard, but rather by the difficulty of measuring ephemeris time. The calculation of the

cesium frequency was published by Markowitz and Essen and their colleagues in August 1958. It applied to cesium in a zero magnetic field, and to ephemeris time in a given tropical year (1957). [2]

The publication of the cesium frequency made the fate of astronomical time seem certain, but almost a decade passed before the definition of the second was changed. In 1967, the SI second was redefined by the General Conference of Weights and Measures (CGPM) 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 caesium 133 atom.” [1]

The definition ushered in the new era of atomic time. For the first time in history, the second was no longer related to the length of the day or the movement of the planets, but instead to the intrinsic property of an atom. This had an immediate effect on timekeeping. Ephemeris time soon faded into obscurity, but other astronomical time scales were still used, and it was decided that atomic time and astronomical time should remain in relative agreement. To keep the new atomic time scale, known as Coordinated Universal Time (UTC), within ± 0.9 s of an astronomical time scale (UT1) based on the mean solar second, the concept of leap seconds was introduced. [37] From 1972–2007, 24 leap seconds have been added to the UTC time scale. The addition of a leap second essentially stops UTC for one second so that UT1 can catch up.

As of 2007, the definition of the SI second remains the same, except for a slight amendment made in 1997. Calculations made by Wayne Itano of NBS in the early 1980s [40] revealed that black-body radiation can cause noticeable frequency shifts in cesium standards, and his work eventually resulted in an addendum to the definition. The Comite International des Poids et Mesures (CIPM) affirmed in 1997 that the definition refers to “a cesium atom at rest at a thermodynamic temperature of 0 K.” Thus, a “perfect” realization of the SI second

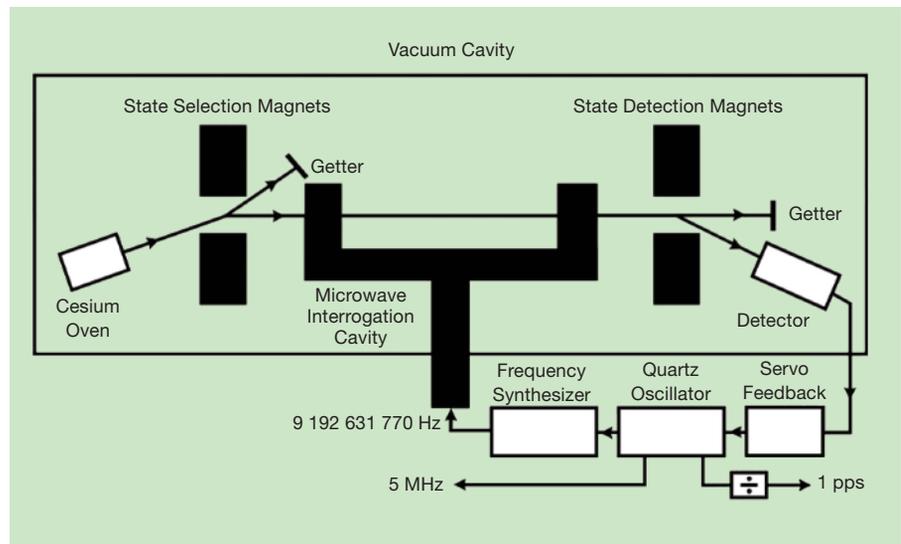


Figure 7. Diagram of a cesium-beam frequency standard using magnetic state-selection and detection. The form of interrogation involves a U-shaped microwave cavity (the Ramsey cavity) where the microwave interrogation fields are spatially separated.

would require the cesium atom to be in a zero magnetic field in an environment where the temperature is absolute zero and where the atom has no residual velocity. Therefore, as will be discussed in Section 10, obtaining the best possible realization of the SI second requires measuring and estimating a number of parameters, and then using the resulting data to apply corrections to the output of a primary frequency standard.

8. Commercial Cesium Frequency Standards

Somewhat surprisingly, the world’s first commercial cesium frequency standard was introduced in October 1956, just slightly more than one year after the introduction of the NPL standard. The commercial standard was manufactured by the National Company of Malden, MA and developed by a team led by Jerrold Zacharias of the Massachusetts Institute of Technology (MIT) [24], who had previously collaborated on early molecular beam experiments with Rabi. [20] The device was called the Atomichron, and at least 50 were sold between 1956–1960. Nearly all of these units were sold to the United States military [24], but at least two were in operation at NBS in 1958–1959, where they were compared to the NBS standard to within parts in 10^{10} . [35]

Cesium frequency standards entered calibration and metrology laboratories in the 1960s, primarily through the efforts

of the Hewlett-Packard (HP) Company, who introduced their model 5060 standard in 1964. Much smaller than previous devices, such as the Atomichron, it fit in a standard equipment rack. The length of the Ramsey cavity was just 12.4 cm, and the device weighed less than 30 kg. [41] By 1966, the HP 5060 had a specified accuracy of 1×10^{-11} . [26].

The HP 5060 was followed by the HP 5061, which was manufactured from 1967 until the early 1990s, and by the HP 5071, which was introduced in 1991. The HP 5071 was microprocessor based, and its internal firmware monitored and controlled many of the parameters that could change its frequency. This microprocessor control, coupled with an improved cesium beam tube, made it more stable and accurate than its predecessors. [42] The HP 5071 was later manufactured by Agilent and is now (2007) manufactured by Symmetricom, Inc. It has a specified accuracy (with the high performance beam tube) of 2×10^{-15} , and serves as a primary standard of frequency at many national and private metrology laboratories worldwide.

Figure 7 provides a simplified schematic of a cesium beam frequency standard. This design can be traced back to the seminal work of Rabi and Ramsey. Note that the design details of a cesium beam standard can vary significantly from model to model, but nearly all commercial cesium oscillators employ basic design principles similar to those

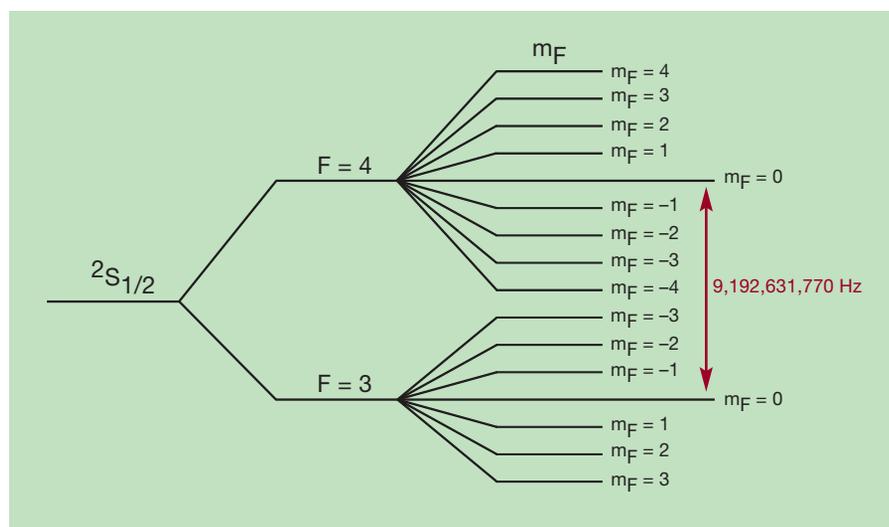


Figure 8. Schematic diagram of the cesium clock transition.

Cesium Frequency Standard	Lifetime as Experimental or Operational Device	Years of Operation as NPFS	Linewidth	Length of Ramsey Cavity	Best Published Accuracy
NBS-1	1952–1962	1959–1960	300 Hz	55 cm	1×10^{-11} [44]
NBS-2	1959–1965	1960–1963	110 Hz	164 cm	8×10^{-12} [44]
NBS-3	1959–1970	1963–1970	48 Hz	366 cm	5×10^{-13} [45]
NBS-4	1965–1990s	NA *	130 Hz	52.4 cm	3×10^{-13} [46]
NBS-5	1966–1974	1972–1974	45 Hz	374 cm	2×10^{-13} [46]
NBS-6	1974–1993	1975–1993	26 Hz	374 cm	8×10^{-14} [48]
NIST-7	1988–2001	1993–1998	62 Hz	155 cm	5×10^{-15} [51]

Table 1. Summary of NIST cesium beam primary frequency standards, including the best published accuracy number.

* NA indicates that NBS-4 was used in conjunction with NBS-5 and NBS-6, but was never officially designated as a standalone NPFS.

described here, as did all NBS/NIST cesium primary frequency standards until the 1990s.

Cesium is a complicated atom with $F=3$ and $F=4$ ground states (see Fig. 8). Each atomic state is characterized not only by the quantum number F , but also by a second quantum number, m_F , which can have integer values between $-F$ and $+F$. Therefore, there are 16 possible magnetic states of cesium, but only the transition between the $|4,0\rangle$ and $|3,0\rangle$ states is useful for a primary frequency standard, because this transition is, to first order, insensitive to magnetic fields. This $|4,0\rangle$

$\leftrightarrow |3,0\rangle$ hyperfine transition produces the frequency used to define the SI second.

As shown on the left side of Fig. 7, ^{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 beams of atoms with different magnetic states. One beam is absorbed by the getter and is of no further interest, but 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 frequency from a quartz-based frequency synthesizer. If this frequency is tuned to precisely match the cesium resonance frequency ($9\,192\,631\,770$ Hz), 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 absorbed. In essence, the magnets located on both sides of the Ramsey cavity serve as a “gate” that only allows atoms that undergo the desired $|4,0\rangle \leftrightarrow |3,0\rangle$ energy transition 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 reach 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 frequency locked as tightly as possible to cesium resonance. [17, 18, 19, 30] Standard output frequencies, such as 1 Hz, 5 MHz, and 10 MHz, are then derived from the locked quartz oscillator and used in the laboratory as reference signals.

9. Cesium Beam Primary Frequency Standards at NBS/NIST

Seven different cesium beam devices served as U.S. national primary frequency standards (NPFS) at NBS/NIST over an approximate 40 year period (1959–1998). The standards were all thermal cesium beam devices that operated by directing a beam of ^{133}Cs atoms through a microwave cavity. They were known as NBS-1 through NBS-6, and NIST-7 (the agency’s name was changed from NBS to NIST in 1988), and dozens of scientists, engineers, and researchers contributed to their development. Some key figures include Richard Mockler, who oversaw the development of the first three standards, Dave Glaze, who contributed to six different standards (NBS-2 through NIST-7), and Bob Drullinger, who led the development of NIST-7. This section briefly describes each of the cesium beam standards, and Table 1 provides a summary of their characteristics.

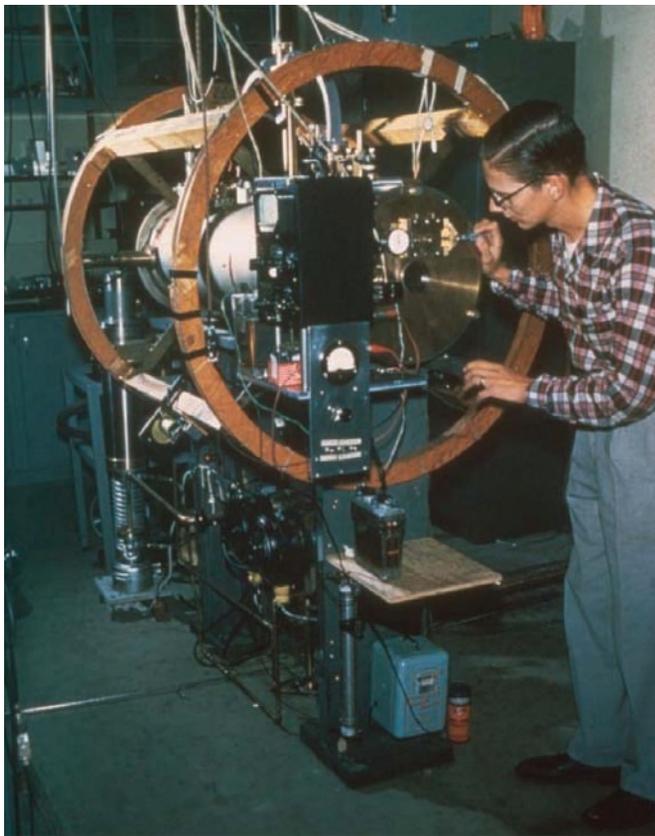


Figure 9. NBS-1.

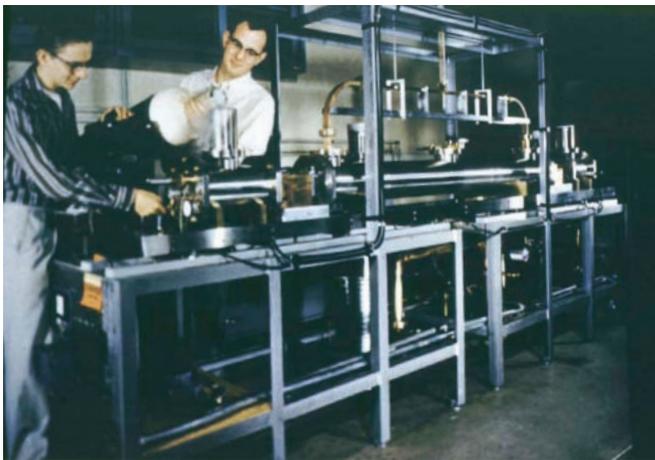


Figure 10. NBS-2.

NBS-1 (Fig. 9) was the original cesium beam primary frequency standard at NBS, previously described in Section 6. The length of its Ramsey cavity was 55 cm and its linewidth was about 300 Hz. [43] After being moved to Boulder, CO in 1954, it was redesigned and eventually designated as the national standard for frequency in the spring of 1959, when its accuracy was reported as 8.5×10^{-11} . [35] On January 1, 1960, it was replaced by NBS-2 as the NPFS, although it continued to be compared to NBS-2 as a secondary standard until 1962, when it had a reported accuracy of 1×10^{-11} . Later that year it was converted to an experimental thallium beam standard. [27, 44]

NBS-2 (Fig. 10) was designed to be much larger than NBS-1,



Figure 11. NBS-3.



Figure 12. NBS-4.

and the length of the Ramsey cavity was increased by a factor of three, to 164 cm. As a result, the linewidth was narrowed to about 110 Hz, and the accuracy was improved to 8×10^{-12} . [44] It was replaced by NBS-3 as the NPFS in September 1963, but continued to be compared to NBS-3 until October 1965. Like its predecessor NBS-1, it was converted to an experimental thallium beam standard after being removed from service. [45]

Work on NBS-3 (Fig. 11) began in 1959. The length of the Ramsey cavity was increased to 366 cm, more than twice as long as NBS-2, and the linewidth was narrowed to just 48 Hz, resulting in a Q factor of 2×10^{-8} , which was considered phenomenal for that era. [27] Its originally published accuracy was 5×10^{-12} , but a series of modifications improved the accuracy by an order of magnitude, reaching 5×10^{-15} by 1969. [45] NBS-3 continued to serve as the NPFS until 1970, when it was completely dismantled. Parts of its vacuum system were later used in NBS-5. [46] During the period from 1970 to 1972 no primary standard was operational at NBS, and commercial cesium standards served as the NPFS while work on NBS-4 and NBS-5 was underway.

NBS-4 (Fig. 12) was the smallest of the NBS/NIST primary frequency standards, and had the longest operating life. Originally known as NBS-X4, it was built as part of a joint effort between NBS and the Hewlett-Packard Company, and was not originally intended to be used as a primary frequency standard.



Figure 13. NBS-5.



Figure 14. NBS-6.

Work on this project began in late 1965, but NBS-4 was not operational until early 1973. [46] NBS-4 was never officially announced as the standalone NPFS. Instead, its role was to serve in conjunction with NBS-5, and later NBS-6, either as a comparison standard or as the primary standard when those devices were not operational. Unlike the other primary standards only, NBS-4 often ran continuously for long periods of time. It had a linewidth of about 130 Hz, the length of its Ramsey cavity was 52.4 cm [47], and its reported accuracy was about 3×10^{-13} . [46] NBS-4 remained operational until the early 1990s, and its beam tube is now on display in the NIST museum in Boulder, CO.

The next two standards, NBS-5 and NBS-6 (Figs. 13 and 14),

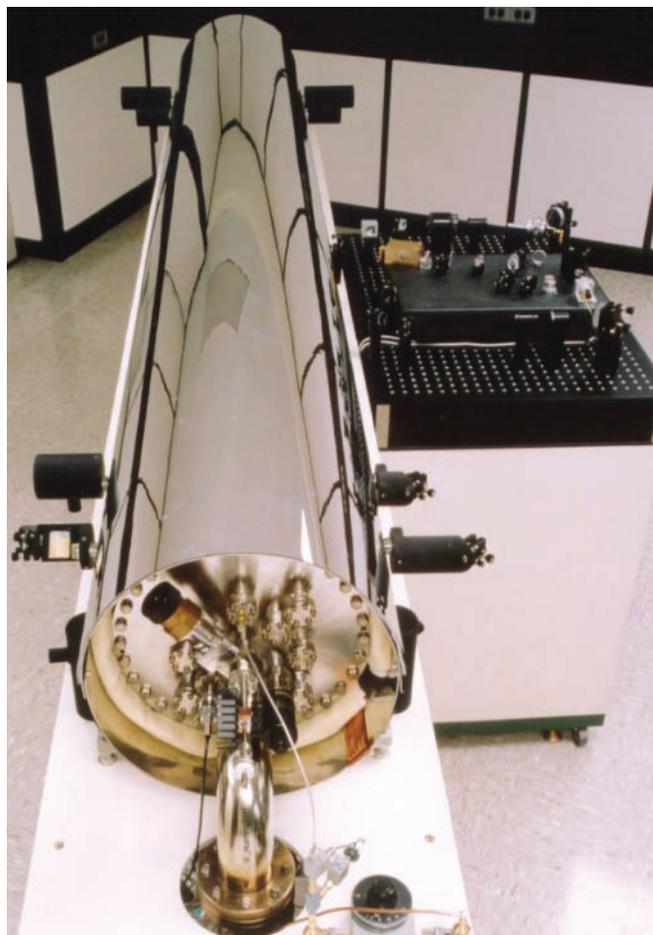


Figure 15. NIST-7.

served as the NPFS for a combined total of more than 20 years. They were really the same standard; NBS-5 became known as NBS-6 after some extensive modifications. Work on NBS-5 began in 1966, and it became the NPFS in January 1973, more than two years after NBS-3 was dismantled. It was a huge machine; the Ramsey cavity was 374 cm in length, and the length of the entire device was about 6 m. The reported accuracy was 1.8×10^{-13} . [46] Significant modifications to NBS-5 began in March 1974, and the linewidth was narrowed from 45 Hz to 26 Hz. The improvement was a direct result of more effective filtering of high velocity atoms, the reduced scattering of low velocity atoms, and the reduced velocity of the atomic beam. The redesigned standard was renamed NBS-6, and became operational in March 1975. [47] NBS-6 eventually reached an accuracy of 8×10^{-14} [48], and served as the NPFS until it was replaced by NIST-7 in 1993. [49]

NIST-7 (Fig. 15) was the last thermal beam frequency standard developed at NIST, and was very different from its predecessors. It used the newly available narrow linewidth lasers for state selection and detection, thus replacing the magnets and detectors (see Fig. 7) found in the earlier standards. Using light instead of magnets had many advantages. Unlike magnetic selection, which merely filtered out atoms in the wrong energy state, the lasers optically pumped as many atoms as possible into the desired energy state. This produced far more atoms and generated a much stronger signal. [17] Work on NIST-7 began

in 1988. The original goal was to build a standard that could provide 1×10^{-14} accuracy [50], or timekeeping accuracy of about 1 nanosecond per day. This goal was exceeded by a factor of two, with the standard eventually reaching an accuracy of 5×10^{-15} . The use of optical state detection enabled NIST-7 to be nearly 20 times more accurate than NBS-6, in spite of the fact that the length of the Ramsey cavity was just 155 cm, and the resonance width was limited to 62 Hz. [19, 51] NIST-7 was replaced as the NPFS in late 1998 by NIST-F1 (see Section 10), but remained operational for a few years afterwards. It now resides in the NIST museum in Boulder, CO.

10. Cesium Fountain Primary Frequency Standards

NIST-7 and other optically pumped thermal beam standards were far more accurate than their predecessors, but their performance was still fundamentally limited by the high velocity of the cesium atoms and the resulting short interaction time. Fountain standards were designed specifically to increase the interaction time. The concept of a cesium fountain was first introduced by Zacharias in the 1950's, shortly before he became involved in the development of the commercial Atomichron standard. [21, 22, 24] His idea was simply to build a vertical cesium beam standard with one Ramsey interaction zone. This would allow slow atoms from the cesium oven to pass through the interaction zone while traveling upward, to stop and reverse their direction under the influence of gravity, and to pass through the same interaction zone while traveling downward. The two interactions with the microwaves reproduced Ramsey's two-pulse interaction scheme, and a ballistic flight traveling only a meter upwards would increase the interaction time to nearly 1 s, instead of the 10 ms interaction that was typical of cesium beam devices. Unfortunately, Zacharias' idea was premature. Because of collisions between the cesium atoms in the beam, no signal was ever seen in his device. Essentially, all of the slow atoms in the beam were scattered out of the beam by the fast atoms that overtook them. [30, 52]

Zacharias' idea was resurrected in the late 1980's by Steven Chu and his colleagues at Stanford University, who built the world's first working fountain standard. Chu's group first built fountains using sodium atoms [53] and later using cesium [54], although neither device was used as a primary frequency standard. Researchers at the Bureau National de Métrologie – Systèmes de Référence Temps Espace (BNM-SYRTE) in Paris, France later built the first primary frequency standard based on Zacharias' fountain concept. [55] Since then, many other researchers at metrology laboratories around the world have built, or are building, laser cooled cesium fountain standards.

The laser cooling of atoms [56] is the key to making a cesium fountain work successfully. Laser cooling was proposed in 1975 [57], and first demonstrated by Dave Wineland and his colleagues at NBS in 1978. [58] It can be thought of as refrigeration; the laser beam is a "sink" at very low entropy that interacts with a sample with much higher entropy (the atomic sample). Entropy is transferred from the atoms to the light field, via optical interactions between the atom and the light field. The entropy of the light field is raised (the atom scatters many photons out of the laser beam with random direction and

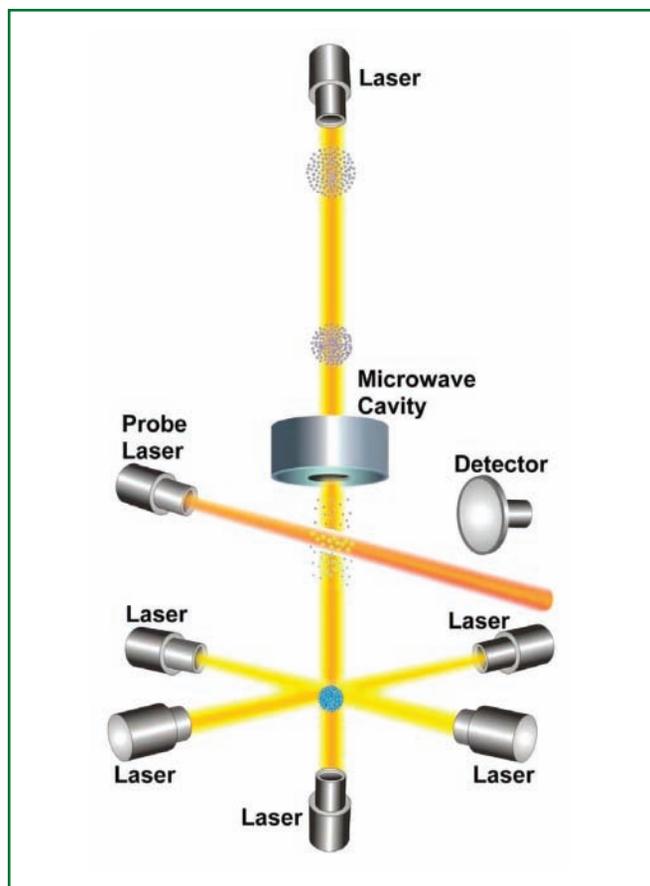


Figure 16. Simplified schematic diagram of a cesium fountain that uses laser cooling.

phase), while the entropy of the atomic sample is lowered.

There are numerous laser cooling techniques, but cesium fountains generally implement a scheme known as optical molasses. This technique exerts a damping force on the atoms by using three pairs of identical oppositely directed lasers (Fig. 16). 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 1 μ K or below in a few hundred milliseconds. As if they were moving through thick molasses, the cold cesium atoms slow down to about 1 cm/s, as opposed to their ~ 100 m/s velocity at room temperature. This allows a large sample or "ball" of atoms to be gathered together and confined in one place. As an alternative to the thermodynamic view presented earlier, this type of laser cooling can also be thought of as the mechanical effect of light on the atom. If the laser is tuned slightly lower in frequency than the optical resonance, the atom will preferentially absorb photons from the laser beam toward which it is moving, as a result of the Doppler effect. Each photon absorbed by the atom carries momentum in the opposite direction of the atomic motion. The atom reemits this photon in a random direction and, because the laser is tuned below resonance, the atom reemits slightly more energy than it absorbed (the atom reemits at the resonance frequency). This cycle of absorbing a photon of slightly lower energy than the reemitted photon is repeated many times per second ($\sim 10^7$) and provides the basic laser-cooling cycle.

After less than three years of development, a cesium fountain

called NIST-F1 became the NIST primary frequency standard in late 1998. [59] Designed by a team led by Steve Jefferts, NIST-F1 (Fig. 17) was the first operational primary frequency standard at NIST to use the fountain technique and also the first to use laser cooling, although an earlier experimental laser-cooled fountain [60] had been built at NIST. Laser cooling made it possible for NIST-F1 to observe or measure atoms for a much longer interval than cesium beam standards, and as a result, to quickly surpass their accuracy.

The basic operation of NIST-F1 proceeds in a sequence of steps: First, a sample of $\sim 10^8$ cesium atoms with a volume of approximately 1 cm^3 are laser cooled at the intersection of the six laser beams (see Fig. 16). The temperature of this sample of atoms is reduced to about $0.5 \text{ } \mu\text{K}$ in a few hundred milliseconds. The atoms are then “launched” upwards at approximately 4 m/s by detuning the frequency of the up and down laser beams to make a moving optical molasses. The laser light is then extinguished by shutters so that no laser light interacts with the cesium atoms along their ballistic flight path. The cloud of launched cesium atoms, about 1 cm in diameter, is typically in the $F = 4$ ground state, but all m_F levels are populated. The “ball” of cesium atoms is next state-selected with a short microwave pulse that 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 (Fig. 16) with a velocity of around 3 m/s . The passage through the cavity on the way up provides the first pulse of the two-pulse (Ramsey) microwave interrogation sequence. The atoms reach apogee about 1 m above the microwave cavity and begin to fall due to gravity. On the way down, the atoms pass through the cavity a second time, about 1 s after their first passage (other fountains have interaction times near 0.5 s). The atoms are detected optically with a laser tuned to the $F = 4 \rightarrow F' = 5$ optical transition, similar to the detection process used in an optically pumped beam standard such as NIST-7. [30]

The increased interaction time allows fountain-based frequency standards to be more accurate than cesium beam standards. The fountain arrangement of NIST-F1 results in a linewidth, Δf_a , of $\sim 1 \text{ Hz}$, much narrower than that of any previous NPFS. The Q factor is about 10^{10} . Several evaluations of the accuracy of NIST-F1 have been published [59, 61, 62], and its present accuracy is $\approx 4 \times 10^{-16}$. Evaluations of other fountain frequency standards have reported nearly equivalent performance. [63-65]

When frequency standards reach accuracies measured in parts in 10^{16} , the limiting factors become fundamental in nature. The accuracy of NIST-F1 is limited by two distinct effects, a blackbody shift [62] and a density shift [61]. The blackbody shift is simply the result of the cesium atoms interacting with the thermal radiation emitted by the walls of the 300 K vacuum enclosure. The magnitude of this shift is large ($\sim 2 \times 10^{-14}$), but it can be corrected in the NIST-F1 design with an uncertainty as small as 2.6×10^{-16} , a figure that corresponds to an uncertainty of 1 K in the temperature of the thermal radiation. Removing this limit will require either a great deal of theoretical calculation to develop an improved theory of

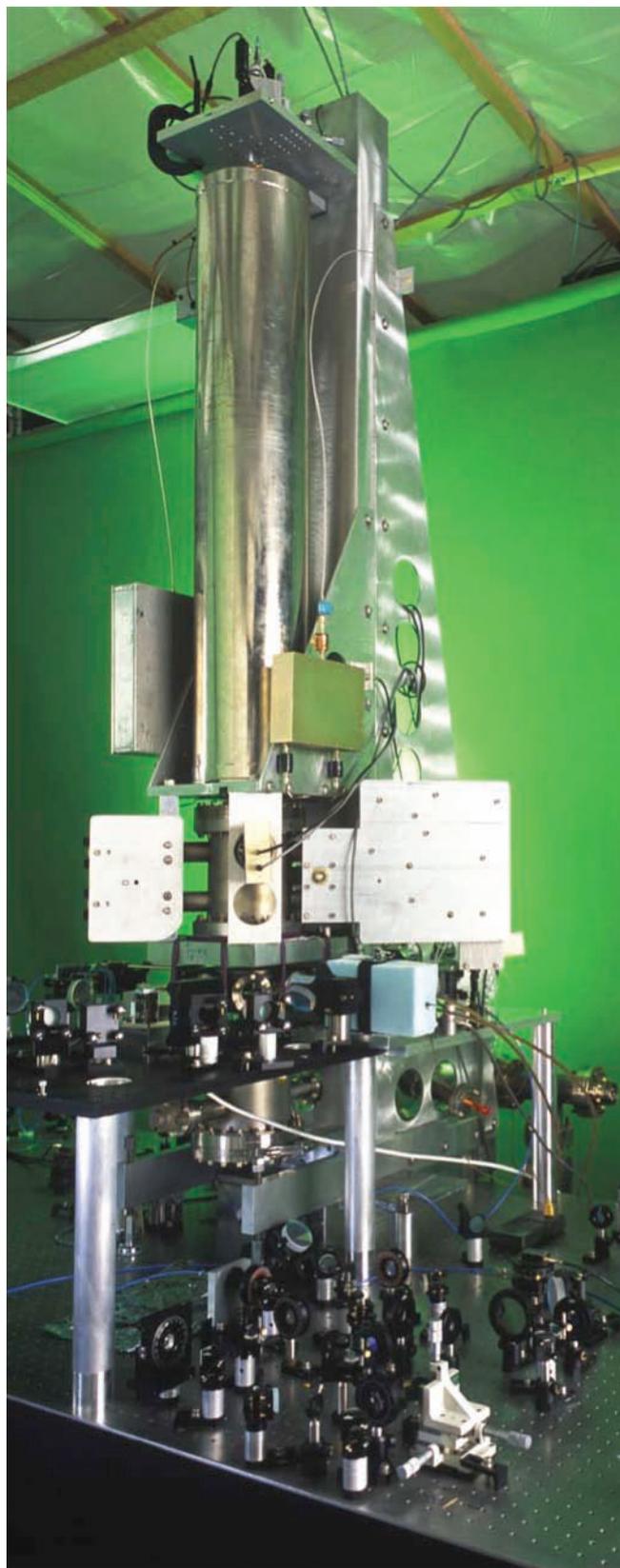


Figure 17. The cesium fountain standard NIST-F1.

understanding the blackbody shift, or developing a cryogenic vacuum system to reduce the magnitude of the effect. The second possibility is now being pursued at NIST.

The density shift is caused by collisions between the cesium

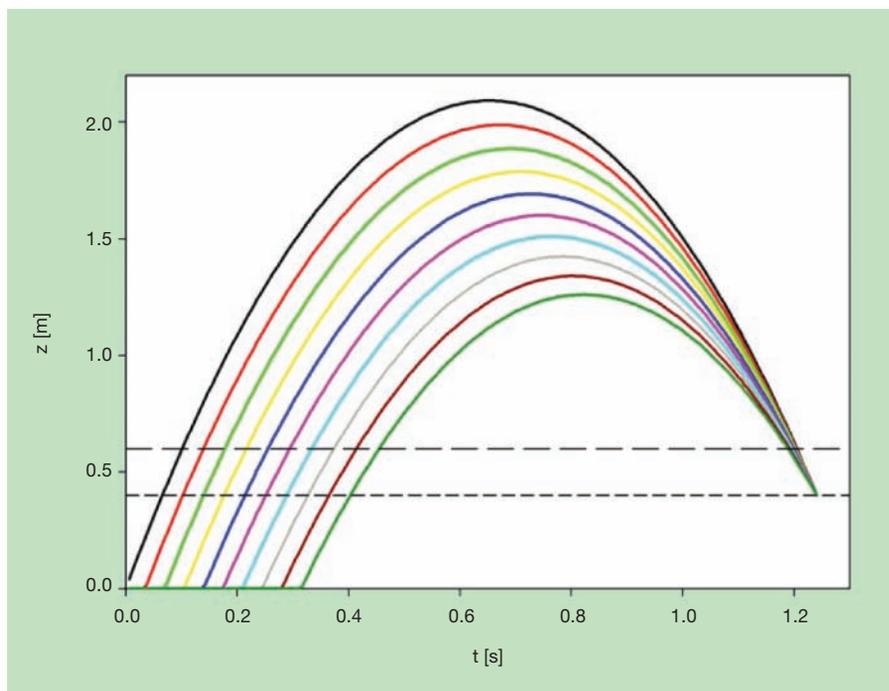


Figure 18. The multiple ball (in this case 10) toss scheme. The horizontal axis in the diagram is the time axis, while the vertical axis is the height above the launch region.

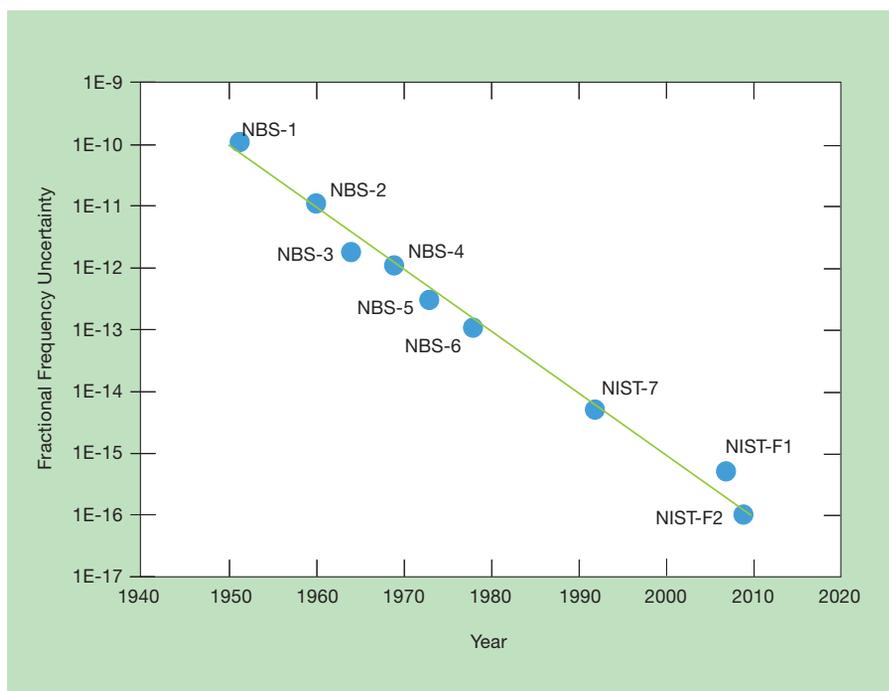


Figure 19. The uncertainty of cesium primary frequency standards developed at NIST as a function of the year they were introduced.

atoms in the launched sample, and is quite large, as much as 4.0×10^{-16} in NIST-F1, with an uncertainty in the correction of 1.0×10^{-16} . There are many proposals for lowering the uncertainty of the density shift correction, but it remains a problem in the present generation of cesium fountains.

Another fundamental limit is presented by the gravitational redshift, an effect that shifts the cesium frequency with respect to its elevation above sea level (by approximately 10^{-16} per meter). A frequency correction for the gravitational redshift is applied to NIST-F1. The uncertainty of this correction, which is

about 3×10^{-17} , is now insignificant, but will be of more concern as future standards become more accurate. [66]

11. Second Generation Cesium Fountain

A new cesium fountain, called NIST-F2, is now under construction at NIST. NIST-F2 is being designed to minimize the uncertainties of both the blackbody shift and the density shift. The blackbody frequency shift [40] has lately been the source of some controversy, with different groups calculating different frequency biases for the shift. [67, 68, 69, 70] Even if one of these competing results is shown to be correct, the uncertainty of the correction for the blackbody frequency shift will still be limited to about 1×10^{-16} . In NIST-F2, a cryogenic ($T = 77$ K) vacuum structure is being built that includes the microwave cavities and flight tube above them. This cryogenic vacuum system is expected to reduce the magnitude of the blackbody shift by a factor of about 250, from about 2×10^{-14} to about 8×10^{-17} . Thus, the blackbody frequency shift will no longer be a major source of uncertainty.

The density shift in NIST-F2 will be significantly reduced by the use of a clever idea theoretically developed at the Istituto Nazionale di Ricerca Metrologica (INRM) in Italy and experimentally demonstrated at NIST. [71, 72] Multiple balls of laser-cooled cesium atoms, as many as 10 in NIST-F2, are launched in quick succession (see Fig. 18) with the first ball of cesium atoms having the highest apogee, while the second ball has an apogee just below the first, etc., so that the trajectories of all the balls intersect in the detection region. This reduces the average cesium density by about a factor of 10, but the signal to noise ratio is preserved, as the same number of atoms is finally detected. This technique should reduce the uncertainty of the density shift by slightly more than a factor of three, to approximately 3×10^{-17} .

As a result of these design improvements, NIST-F2 is expected to eventually reach an accuracy of $< 1 \times 10^{-16}$, limited by effects due to the microwave frequency of the oscillator. It appears likely that NIST-F2 will be the last of the cesium primary frequency standards at

NIST, and that, in the future, better performance will be achieved with optical frequency standards.

Figure 19 shows the frequency uncertainty of all of the cesium primary frequency standards developed at NIST, from NBS-1 to the anticipated performance of NIST-F2, plotted as a function of the year they were introduced. The slope of the line represents a reduction in uncertainty of about one order of magnitude per decade.

12. Role of NIST-F1 in the Realization of the SI Second

In addition to the primary standard NIST-F1, two other systems are needed to generate the SI second. The first system is a continuously running time scale that generates pulses every second in real-time. The second system employs satellite-based measurement techniques to compare the NIST standards to the other standards of the world. The results of these comparisons are then submitted to the Bureau International des Poids et Mesures (BIPM) in France, which uses them to help compute a post-processed “paper” time scale known as Coordinated Universal Time (UTC).

The NIST time scale, or UTC(NIST), is an ensemble of about 10 oscillators (commercial hydrogen masers and cesium beam standards) that are continuously compared to each other. NIST-F1 does not run continuously, but instead is periodically used to measure and calibrate the frequency of the ensemble. Although the hydrogen masers are not inherently accurate, they are very stable, and, once calibrated with NIST-F1, they can maintain the accuracy of the time scale when NIST-F1 is not operational. The time scale output is steered based on a weighted averaged of all of the oscillators in the ensemble, with the most stable oscillators receiving the most weight. [73] The time scale continuously generates and outputs both a 5 MHz sine wave frequency, and 1 pulse per second timing signal, which is a physical, real-time realization of the SI second. UTC(NIST) serves as the standard of time interval, frequency, and time-of-day for the United States. It is distributed to the public (at various levels of uncertainty) through radio stations WWV,

WWVH, and WWVB, through a variety of computer time services, and also to paying customers who subscribe to NIST remote calibration services. [74]

The comparison data sent to the BIPM are collected from common-view observations of the GPS satellites, or by using a geostationary satellite as a relay station, a technique known as two-way satellite time transfer. The BIPM uses the measurement results to compute two time scales, International Atomic Time (TAI), which is used internally by the BIPM and does not account for leap seconds, and UTC, which is simply TAI corrected for leap seconds. [5, 75]

The BIPM uses measurements from primary frequency standards to determine the accuracy of UTC, and the measurements from the other standards (mostly commercial cesium beams and hydrogen masers) to determine the stability of UTC. [76] As a primary standard, NIST-F1 contributes to the accuracy of UTC. Since its completion in 1998, NIST-F1 has undergone about 20 accuracy evaluations (calibrations) that have been submitted to the BIPM. An accuracy evaluation usually requires NIST-F1 to run continuously for about 20 to 40 days. The actual length of the calibration procedure is typically determined by the noise of the satellite time transfer process that is used to relay the measurements to the BIPM.

Since 2004, five laboratories other than NIST have operated cesium primary frequency standards that have contributed to the accuracy of UTC. These laboratories include BNM-SYRTE, INRM, NPL, the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the National Metrology Institute of Japan (NMIJ). An additional group of about 300 oscillators from more than 50 national metrology institutes and astronomical observatories contribute to the frequency stability (and reliability) of TAI and UTC. This group of oscillators includes the commercial standards in the NIST time scale. As is the case with UTC(NIST), a weighted average is used, and the most stable oscillators receive the most weight. However, to keep the most stable oscillators from dominating the time scale, a maximum weight is assigned for every period of calculation.

The maximum weight assigned to an individual oscillator goes down as the number of participating oscillators goes up.

As mentioned earlier, TAI and UTC are post processed time scales, and therefore do not produce any physical signals that can be used in a metrology laboratory. They are distributed only on paper, through a document called the *Circular-T* (published monthly by the BIPM and available at www.bipm.org/en/scientific/tai/). The results are presented in the form of differences between local time scales and UTC, for example as UTC(NIST) – UTC. The results reported in the *Circular-T* verify that the measurements made at NIST and other participating laboratories are traceable to UTC and to the SI second. [75]

13. Summary and Conclusions

The history of atomic oscillators, from the late 1940's to the present era, shows a steady improvement in accuracy: from about 1×10^{-10} in the 1950s to less than 1×10^{-15} today (2007). The present state of the art in cesium primary standards is defined by the cesium fountain NIST-F1, which has achieved an accuracy of about 4×10^{-16} . The NIST-F2 fountain now under development will likely produce better results, with an accuracy of less than 1×10^{-16} projected before the year 2010.

Atomic oscillators, currently based on atomic microwave transitions, will eventually be replaced by devices based on optical transitions, and the SI second will likely be redefined. Atomic oscillators using optical transitions have a much higher resonance frequency ($\sim 10^{15}$ Hz) and are potentially accurate to less than 1×10^{-17} . Optical frequency standards are being investigated in many laboratories worldwide with extremely promising results. [15, 18, 76, 77] However, they are still some years away from replacing cesium devices as the world's time and frequency standards.

14. Acknowledgements

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