

CESIUM BEAM FREQUENCY STANDARDS[†]

W.D. Lee and D.B. Sullivan
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80303

ABSTRACT

This historical review of the development of cesium beam frequency standards covers the period from the announcement of the first atomic frequency standard in 1949 to the present. It describes the concepts as well as the key factors affecting the development of the various cesium standards.

HISTORY OF DEVELOPMENT

While the world's first atomic frequency standard, developed by Lyons and his colleagues [1] at the National Bureau of Standards (NBS), was completed in 1949, the basis for the development was established much earlier by the molecular beam work of the Nobel laureate, I.I. Rabi. He used molecular beams to detect atomic and molecular resonances (transitions) with unprecedented accuracy. It wasn't long before people realized that these resonances could also be used as frequency standards.

The first NBS standard, based on a transition in ammonia, performed no better than the best quartz oscillators of that period, but it opened the door to subsequent developments. At the same time that NBS was introducing its standard, Ramsey, another Nobel prize winner, was inventing the separated oscillatory field method [2]. In this method, a molecular beam passes through two regions of microwave field separated by some distance along the beam path. This was a major improvement over Rabi's

earlier devices. It reduced the observed linewidth and eliminated the first-order Doppler shift. Following the lead of the molecular beam work in the United States, Essen and Parry [3] of the National Physical Laboratory in England adapted this method to cesium-beam frequency standards in the mid-1950's.

Cesium was favored for frequency standards for several reasons. Its relatively high resonance frequency near 9.2 GHz was a good match to the microwave technology that had been developed during World War II. Also, this resonance was particularly narrow and relatively insensitive to magnetic fields. Cesium beams are easy to produce, and cesium is readily detected with a hot filament and current detector. Cesium was selected very early in the game; though much research was conducted using other atoms, none has yet emerged to replace cesium. The cesium devices were so successful that in 1967 the second was redefined 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." This number was based on a comparison, over a 2 3/4 year period, of a cesium beam frequency standard and very careful astronomical observations [4].

The next 25 years saw gradual improvement of the concepts developed in the 1950s and 1960s to a point where these standards could realize the atomic definition of the second with an uncertainty of less than 1×10^{-13} . Even during this period of gradual evolution, the uncertainties

of cesium frequency standards were dropping more than an order of magnitude every 10 years. Electronic components such as frequency synthesizers and servo-control systems were improved and the theory of the devices was worked out in great detail. The separated-oscillatory-field concept was used in all of the successful devices and the various forms of the microwave cavities used to implement this concept became known as Ramsey cavities.

The key problem in the design of these cavities has been the very small microwave phase differences associated with losses in the cavities and with inevitable manufacturing imperfections, particularly as these affect the symmetry of the cavity. These phase differences produce atom-velocity-dependent frequency shifts that have been difficult to handle in traditional standards where atoms have thermal velocities (~ 200 m/s).

The most traditional form of Ramsey cavity involves the central (tee) feed of two equal-length sections of waveguide that are shorted at the ends to reflect the microwave signal and create standing waves. The atoms are typically passed through apertures located $\lambda/2$ from the shorted ends. The phase-difference problems in such a cavity are of two types. The first is called end-to-end cavity phase shift. When atoms pass through the fields in the ends of the cavity, they produce a resonance frequency that is shifted by any phase difference. Fortunately, the shift is equal in magnitude and opposite in sign to that produced when the atoms are sent through the cavity in the opposite direction, so this problem can be resolved.

The second phase shift of concern is the transverse (distributed) phase shift across the apertures. Because of the distributed losses in the walls of the cavity, the traveling waves are slightly attenuated as they travel down the guide. These losses result in a phase shift across the aperture. This phase shift produces complex frequency shifts that are compounded by the broad velocity distribution in the beam and by the magnet optics of the state selection and

detection systems (at both ends of the cavity). A description of the problem is beyond the scope of this paper, but suffice it to say that distributed cavity phase shift produces a critical systematic error.

In the mid-1970's progress toward higher accuracy slowed for two reasons. First, as uncertainties became smaller, it became progressively more difficult to correct for systematic errors associated with the thermal velocities of the atoms. For example, the second-order Doppler shift at these velocities had become larger than the overall uncertainty of the standards. Furthermore, the high velocities limit atom observation times to a few milliseconds resulting in resonance linewidths of many tens of hertz. This placed more stress on the servo-control systems used to locate the center of the resonance. The second reason for a slowing in progress involved the comparison of standards constructed in widely separated laboratories. Standards were compared using radio signals, but propagation delays introduced comparison errors that were greater than the uncertainties of the standards. With no precise means for comparison, motivation for further improvement waned. This limit was removed by the development of satellite time-transfer methods that resulted in comparison improvements of more than 2 orders of magnitude.

During the 1980's, physicists discovered methods for using lasers to control the states and motions of atoms setting the stage for a revolution in frequency standards. We are now in the midst of that revolution.

In 1993, NIST introduced NIST-7 [6], a conceptually new standard that uses optical-pumping methods for both atomic state selection and state detection and now achieves an uncertainty of 5×10^{-15} . Before this development, all cesium beam standards used Stern-Gerlach magnets for both atomic state selection and the detection of transitions induced in the Ramsey cavity. The optical pumping methods result in a much higher atomic beam

current, since atoms in the ‘wrong’ atomic states are forced into the desired states rather than discarded (as done in earlier standards).

Furthermore, elimination of the Stern-Gerlach magnets dramatically simplified the atomic beam optics to a linear geometry.

NIST-7 uses an improved version of the Ramsey cavity introduced by DeMarchi [6]. Rather than creating a standing wave at each end using shorted waveguide, DeMarchi has designed a cavity that splits the traveling wave (at each end) and feeds these together at the aperture. Thus, rather than terminating in a short, each end consists of a small tee-fed waveguide ring with the aperture located opposite the feed. The distributed cavity phase shift is dramatically smaller in this cavity.

The next major development was the so-called cesium fountain frequency standard. This concept was first proposed in an oral presentation in 1954 by Zacharias [7], but was demonstrated only in recent years [8] because the laser-cooling methods, essential to its operation, were not available then. In the fountain standard, laser-cooled atoms are lofted vertically through a microwave cavity, and their states are interrogated as they rise and then fall back through this cavity under the influence of gravity. The benefits of the concept are a much longer ($\times 100$) interrogation time, which results in a comparable narrowing of the microwave resonance, and a large reduction in the second-order Doppler shift. Additionally, the end-to-end cavity phase shift is eliminated, since the atoms turn around and go back through the same cavity. Of course, the problem with distributed cavity phase shift is also reduced because the atoms are moving more slowly.

The concept was first used for a primary frequency standard by Clairon and his colleagues at the Laboratoire Primaire du Temps et des Fréquences in Paris [9]. The uncertainty for this fountain standard is now 3×10^{-15} , but it will certainly go below 1×10^{-15} in the next few years. It is also reasonable to assume that this or

some other version of the cesium frequency standard will achieve an uncertainty on the order of 10^{-16} within the next decade.

REFERENCES

- † Work of the U.S. Government. Not subject to copyright.
- [1] H. Lyons, “Microwave spectroscopic frequency and time standards,” *Electronic Engineering*, Vol. 68, p. 251, 1949.
- [2] N.F. Ramsey, “The method of successive oscillatory fields,” *Phys. Today*, vol. 33, pp. 25-30, 1980.
- [3] L. Essen and V.L. Parry, “An atomic standard of frequency and time interval,” *Nature*, vol. 176, pp. 280-282, 1955.
- [4] W. Markowitz, G. Glenn Hall, L. Essen, and J.V.L. Perry, “Frequency of cesium in terms of ephemeris time,” *Phys. Rev. Lett.*, vol. 1, pp. 105-107, 1958.
- [5] R.E. Drullinger, D.J. Glaze, J.P. Lowe, and J.H. Shirley, “The NIST optically pumped cesium frequency standard,” *IEEE Trans. Instrum. Meas.*, vol. 40, pp. 162-164, 1991.
- [6] A. DeMarchi, J. Shirley, D.J. Glaze, and R. Drullinger, “A new cavity configuration for cesium beam primary frequency standards,” *IEEE Trans. Instrum. Meas.*, vol. 37, pp. 185-190, June, 1988.
- [7] J.R. Zacharias, “Precision measurements with molecular beams,” *Phys. Rev.*, vol. 94, p. 751, 1954.
- [8] K. Gibble and S. Chu, “Laser-cooled Cs frequency standard and a measurement of the frequency shift due to ultracold collisions,” *Phys. Rev. Lett.*, vol. 70, pp. 1771-1774, 1993.
- [9] A. Clairon, S. Ghezali, G. Santarelli, Ph. Laurent, S.N. Lea, M. Bahoura, E. Simon, S. Weyers, and K. Szymaniec, “Preliminary evaluation of a cesium fountain frequency standard,” *Fifth Symposium on Frequency Standards and Metrology*, J.C. Bergquist, Ed. New Jersey, World Scientific, 1996, pp. 49-59.