Primary Frequency Standards at NIST

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Abstract — **The development of primary frequency standards at the National Institute of Standards and Technology (NIST) is traced, and I describe three generations of atomic frequency standards: cesium-beam standards, cesium-fountain standards, and stored-ion standards. The uncertainty of the present NIST frequency standard is 1.7 parts in 10^{15}, but the prospects for substantial improvement are high. Finally, the uncertainties of the most recent NIST standards are displayed relative to the uncertainties of standards of several other countries.**

I. INTRODUCTION

The development of frequency standards at NIST (then NBS, the National Bureau of Standards) began in 1911 with J. H. Dellinger's work on a system for calibrating wavemeters. He used simple LC circuits with values of inductance and capacitance that could be obtained directly from their dimensions. Improvements were thus tied to decreasing the uncertainties in the values of inductors and capacitors through improvement of the mathematical expressions describing them [1]. In the 1920's NBS began to study quartz-crystal oscillators as frequency standards, and by 1935 had established a national primary standard of radio frequency with a set of four quartz oscillators calibrated against the mean solar second [2]. These quartz frequency standards were eventually replaced by atomic frequency standards, the first of which was developed by NBS in 1949 [3]. While the world's first atomic frequency standard was based on an ammonia absorption line at 23.87 GHz, devices based on the cesium atom quickly proved to be better [4]. At this point quartz and ammonia standards were achieving frequency uncertainties of ~2 x 10^{-8}.

In the early 1930's, Isidor Rabi developed the concepts upon which atomic frequency standards are based. In Rabi's beam experiments, the molecules (or atoms) passed through a single resonant cavity where the rf excitation caused transitions between quantum states if the frequency coincided with a molecular or atomic resonance. A small magnetic field (called the C field) was applied to this cavity to establish a quantization axis for the molecules. In order to increase the observation time, longer interaction regions were needed, but it was difficult to maintain a uniform field over the entire region. To solve this problem Ramsey developed a new type of cavity, now called a Ramsey cavity, with the excitation region divided into two spatially separated zones that are driven in phase. Figure 1 shows the basic arrangement of the traditional cesium-beam frequency standard using this type of cavity. Collimated atoms from the oven are first sent through the A magnet, the nonuniform field of which deflects atoms in different hyperfine states by different amounts, so that atoms in only one of the states pass through the first cavity region where the transition is initiated. The atoms then drift to the second cavity region where the second oscillatory field induces a completion of the transition (if the frequency is on resonance). The B magnet (identical to the A magnet) acts to similarly separate the atom states as they exit the cavity, and a detector is arranged to sense a signal only if atoms are caused to change state by the rf excitation. The effect of the Ramsey cavity is to sharpen the resonance and relax requirements for C-field homogeneity. All primary atomic frequency standards now use the Ramsey interrogation method.
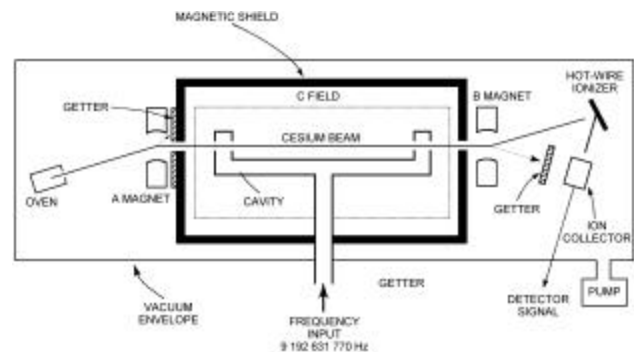

Fig.1. Diagram of a cesium-beam frequency standard using magnetic state selection and detection. The detector is made up of the hot-wire ionizer and ion collector.

These standards are passive devices; the resonance is located by probing the system with an external oscillator that can be tuned across the resonance. Generally, the narrower the linewidth, the less uncertain is the location of the center of the resonance. The linewidth Δf of the resonance at frequency f_0 is reciprocally dependent upon the time t_d the atoms spend being interrogated by the rf field. The fractional linewidth is proportional to

$$\Delta f/f_0 \approx 1/(t_d f_0)$$

(1)

This expression shows that the standard should be operated at as high a frequency as is practical and that the atoms should spend as long a period as possible in the interrogating rf field. Cesium was selected as the basis for the definition of the second in part because it has a relatively high resonance frequency (9 192 631 770 Hz), but also because this resonance is relatively insensitive to external disturbances. As will be seen, Eq. 1 has provided substantial guidance for the designs of NBS/NIST standards described in subsequent sections.

II. ATOMIC-BEAM FREQUENCY STANDARDS

Over a period of about 40 years, NBS (later NIST) constructed and operated 7 primary cesium-beam atomic frequency standards based on the concept shown in Fig. 1. The linewidths of these standards were reduced by extending the length of the microwave cavity, which grew to 3.74 m for NBS-5. This increase in length was achieved at the cost of signal intensity, since the atom beam diverges and fewer atoms thus reach the detector. Improvements in these standards were also achieved by reduction and control of systematic frequency shifts. The uncertainty of a primary frequency standard is determined by measuring and correcting for all known systematic shifts. One such shift is produced by the C field. The magnitude of this shift is determined by measuring the frequency difference between the first Zeeman line and the central resonance. This is a direct measure of the magnetic field. The correction, while large (typically on the order of 10^{-10}) can normally be handled with ease.

There are also several corrections related to the microwave cavity. While the U-shaped Ramsey cavity shown in Fig. 1 can be machined to very high tolerance to assure a high degree of symmetry of the fields in the end regions, it is impossible to hold the tolerances needed to assure that the phase of the field is exactly the same in the two regions. In later versions of these beam standards, the effect of this asymmetry in phase was determined by reversing the beam through the standard. The mean of the two frequencies obtained in such reversal is the correct measure. For NIST-7, this mean frequency differs from the frequency for either direction by a factor that is more than 100 times greater than the uncertainty of the standard, so this correction can be seen to be very important. These Ramsey cavities are constructed to resonate at the resonance of the cesium atoms, and the standing wave at each end (where the cesium atoms pass through the cavity) can be seen to be made up of the wave propagating from the tee and the wave reflected from the shorted cavity end. Since there are losses in the copper cavity walls, there is an attenuation that produces a small transverse phase variation over the dimensions of the cavity apertures (typically a few mm in diameter) through which the atoms pass. This small effect is evaluated by moving a smaller aperture around over this atom aperture and determining the resonance frequency as atoms are permitted to pass through only a portion of the aperture.

NIST-7 represents a major departure from earlier NBS beam standards in that the magnetic systems used for state selection and detection were replaced by laser systems. In this standard, a state-selection laser is tuned so that atoms in the ground hyperfine states efficiently absorb light and are excited to higher electronic states. In relaxing back to the set of hyperfine ground states, the excited atoms are restricted by quantum selection rules, so that they can in general relax to only a limited set of the various ground-state levels. Using these optical pumping techniques, most of the atoms are converted to the desired hyperfine state, rather than being rejected as is done by magnetic-state selection. This results in a much higher signal-to-noise ratio and eliminates the troublesome transverse dispersion of atoms associated with the fact that slow and fast atoms in the Maxwellian distribution of atom velocities take different paths through the magnetic optics of the systems. NIST-7 also incorporates a special Ramsey cavity that is designed to minimize the transverse phase variation across the atom aperture. It has achieved a frequency uncertainty of 5 x 10^{-15} [5].

III. CESIUM FOUNTAIN FREQUENCY STANDARDS

The fountain concept for extending atom observation time was introduced by Zacharias in 1954, but the means for implementing the concept were not then available. Zacharias believed that it might be possible to direct a thermal beam of atoms upward and then depend on finding that a small number of slower atoms in the Maxwellian velocity distribution would reach apogee within the device and return to the source. While there would be dramatic loss of signal, the time of flight for atoms going up 1 m and returning would be on the order of 1 s, resulting in a much narrower resonance linewidth. Furthermore, atoms could traverse the same microwave cavity twice (on the way up and on the way down), and this would provide for Ramsey interrogation (temporal rather than spatial separation) without the end-to-end cavity phase shift found in beam standards. Unfortunately, fast atoms collide with the very slow ones and remove them from the beam, and returning atoms were not detected.

In 1978, staff at NBS were able to demonstrate for the first time that trapped ions could be cooled (slowed) to very low temperature [6], and subsequent NBS work demonstrated similar radiation-pressure cooling of neutral atoms [7]. This was the step needed to realize the Zacharias fountain. The first fountain was then demonstrated at Stanford University in 1989, and the first primary fountain frequency standard was demonstrated in France several years later [8]. Fig. 2 shows the concept for the fountain frequency standard.
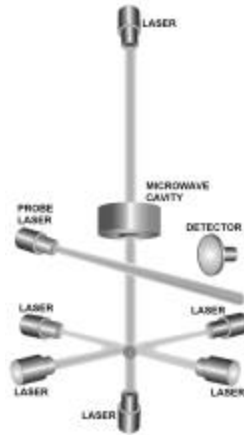

Fig. 2. Fountain concept. Atoms are trapped at the intersection of the 6 orthogonal laser beams and are tossed vertically by offsetting the frequencies of the two vertical lasers and then turning off all 6 lasers. The atoms rise and fall through the microwave (TE_{011}) cavity and undergo state interrogation below the microwave cavity by means of the probe laser and detector.

A NIST-designed cesium-fountain frequency standard, designated NIST-F1, has now been in operation for several years. It achieves an uncertainty of 1.7×10^{-15}, and it appears that this can be reduced to about 5×10^{-16}. The linewidth of this standard is ~1 Hz (Q 10^{10}), nearly 100 times smaller than that achieved in the best of the beam standards. The key systematic effects that previously limited beam standards are easily handled, and it is a new frequency shift, produced by collisions between cesium atoms, that seems to limit the fountain uncertainty.

IV. STORED-ION FREQUENCY STANDARDS

Since the atom observation time for a fountain scales as the square root of the toss height, it cannot be extended much beyond 1 s. For example, to obtain a 3 s observation time, one needs a toss height of ~10 m, which is not practical. This limit does not exist in stored-ion frequency standards, where laser-cooled ions can be held indefinitely using electromagnetic traps that have little effect on the

ions. At NIST, stored-ion frequency standards based on Be^+ ions (resonance at 303 MHz) and Hg^+ ions (40.5 GHz) have already been demonstrated. The best of these has an uncertainty comparable to that of the best fountain frequency standard. However, since the definition of the second is based on neutral cesium, stored-ion standards cannot yet serve as primary standards, but the definition could eventually be changed if the ion standards prove to be much more accurate.

Recent work suggests that optical resonances in ions can be used as frequency standards. From Eq. 1, it can be seen that the fractional linewidth depends reciprocally on resonance frequency. For a standard operating at 10^{15} Hz, the improvement in fractional linewidth (over fountain frequency standards) is of order 10^5. While optical frequency standards have been studied for some years, until now they have not been considered practical primary standards, because there were no means for counting cycles and thus obtaining an output at a convenient rf frequency. However, researchers in Germany have recently demonstrated mode-locked laser systems that produce frequency combs, which in a single step bridge the gap between laser and microwave frequencies [9]. The principle of these devices is simple. If the repetition rate of the output (femtosecond) pulses is locked to a microwave oscillator, the Fourier transform of the pulse string is a broad spectrum (bridging a large frequency range) made up of discrete lines, the separations of which are exactly the microwave oscillator frequency. Thus, the frequency of an optical signal in coincidence with one of the teeth of the comb is simply a large integer times the microwave reference frequency. Surprisingly, these relationships are exact, at least out to an uncertainty of 1 part in 10^{17}. This provides the long-needed means for coupling optical and microwave frequencies.

NIST had already demonstrated an exceptional optical frequency standard based on a resonance in a single Hg^+ ion at a wavelength of 282 nm (1.06×10^{15} Hz). The Q of the resonance in this standard is $>10^{14}$. Systematic frequency shifts in this ion appear to be understood and controllable at a level of better than 1 part in 10^{17}. In the first reported experiments involving the combination of this standard with the comb generator, the optical frequency of the standard was measured (relative to the cesium frequency) with an uncertainty that is limited by the uncertainty of the fountain standard [10]. The comb generator system can also be operated in a mode where a tooth of the comb is locked to the optical frequency, and the repetition rate f_1 of the pulse string is then equal to f_0/n, where f_0 is the optical frequency and n is the comb integer. The short-term stability of the output (at f_1), which translates down nicely from the outstanding stability of the optical standard, is

more than an order of magnitude better than the stability of the best quartz oscillator.

V. SUMMARY AND DISCUSSION

While the rate of accuracy improvement of NIST standards has not been exactly uniform over the last 5 decades, on average the uncertainties have been decreasing by better than one order of magnitude per decade. There is every reason to expect this trend to continue. The timing performance demanded by current navigation and telecommunication systems is adequately served by present standards, but if past developments are any guide to the future, still better standards will be needed.

Frequency scales at the various international standards laboratories are well coordinated by means of satellite frequency-comparison techniques, which also provide for comparison of the accuracies of primary frequency standards. Fig. 3 compares the uncertainties of 6 of these standards over a period of >1000 days. This comparison utilizes the intermediary of an ensemble of 5 hydrogen masers [11]. While the comparison could also have been made using International Atomic Time, the short-term noise of this scale (resulting from frequency-comparison noise) is not as good, so comparisons using this scale would show more noise than the one below. In addition to 2 NIST standards, Fig. 3 shows data for 2 standards from Physikalisch-Technische Bundesanstalt (PTB) in Germany and 2 from the Laboratoire Primaire du Temps et Frequences (LPTF) in France. Half of these are fountain standards (designated with an F) and half are beam standards.
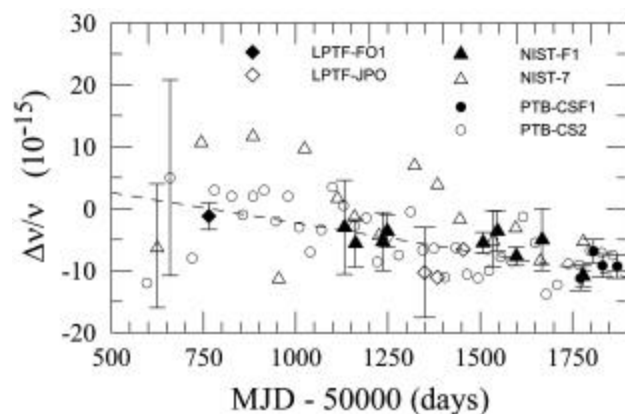

Fig. 3. Comparison of uncertainties of 6 primary frequency standards against a scale composed of 5 hydrogen masers. The error bars are 1 σ confidence levels. Data on the PTB and LPTF standards are obtained through the Bureau International des Poids et Measures. NIST

measurements are made directly against this scale. The downward drift is a characteristic of the hydrogen-maser ensemble. MJD is the modified Julian date.

While there are a few points that are outside the error bars, the agreement among the various, independently designed standards is remarkable good, suggesting that the evaluation of systematic effects is good. The stored-ion systems have not yet been run routinely as part of the international standards process, but scatter in the best results would certainly be no worse than that seen in this figure. All in all, one is led to conclude that the state of frequency standards is healthy, and that the prospects for continued improvement are excellent.

ACKNOWLEDGEMENT

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