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TIME AND FREQUENCY MEASUREMENT AT NIST: THE FIRST 100 YEARS

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Abstract

During this, the NIST Centennial Year, I look back on the first 100 years and summarize NIST work on time and frequency measurement, a topic of some prominence from the early years of the institution. Initial work at NIST (then NBS, the National Bureau of Standards) focused primarily on frequency standards needed to support the control of broadcast frequencies in the early days of radio. The Time and Frequency Division was not created until 1967, by which time a number of primary atomic frequency standards had already been developed, and it was clear that a broader program in this field was needed. This paper describes a variety of programs including the development of primary frequency standards, the international coordination of standards, statistical techniques for characterizing noise, dissemination methods, and methods for measuring optical frequency.

1. Introduction

The National Bureau of Standards (NBS) was established by the U.S. Congress in 1901 to develop a consistent measurement infrastructure for the United States. NBS was designed to be not a regulatory agency, but rather one that worked with science and industry to establish measurement standards that could be used to support commerce and trade, scientific research, and the general welfare. The base units of measurement were the natural purview of this new organization. The agency would undertake scientific studies to advance the state of measurement and would coordinate its standards with those of other countries. While the basic role of NBS remained relatively fixed through the years, Congress periodically added tasks that reflected changing times. Then, in 1988, Congress added substantial new components, including the Manufacturing Extension Program and the Advanced Technology Program, and in recognition of these expanded roles renamed NBS to the National Institute of Standards and Technology (NIST). Since this is an historical paper, and the history covers the institution under different names, I will variously refer to it as NBS, or NIST, or simply the Bureau.

The second, being one of the base units of physical measurement, was of immediate interest to NBS, as was frequency, being the basis for clocks and timekeeping. The program that is today called the Time and Frequency Division was shaped over time by a variety of practical requirements. Of course, the way in which this program developed was naturally affected by budgetary constraints and the individual championing of programs by a number of technical leaders.

Since this is a history, it is tempting to deal with events in chronological order, but I do that only partially. Since the program has many elements, I have organized the paper to treat each element separately, with events within each element arranged chronologically. Thus, the paper is divided into topics covering (1) primary frequency standards; (2) laser cooling of atoms, (3) the speed of light, (4) dissemination of timing signals; and (5) statistics, metrology, time scales, and time coordination.

This is not meant to be a comprehensive history of the program. More detailed historical information is available in papers by Beehler [1] and Ramsey [2] and in books by Cochrane [3], Passaglia [4], Schooley [5], and Snyder and Bragaw [6]. My primary goal in this paper is to broadly summarize work within this program. I have added enough references to steer the reader to certain key bodies of work, but the reference list is by no means comprehensive.

Finally, I should warn the reader that this is a history of time-and-frequency work at one institution. No real effort is made to fully describe the context in which this work took place. I do not intend to imply that NBS (NIST) did everything in this field. In fact, as in many fields of scientific and technical endeavor, NBS (NIST) has been but one contributor to the field. Where NIST made particularly significant contributions, I try to indicate this, and similarly, I have tried to give credit where work at another institution has substantially influenced the directions of NIST efforts. I know that I won't have given credit in a completely consistent and correct way, but I would enjoy hearing from you if you have a different view of any of the events in this history, and I'll endeavor to correct any mistakes or misrepresentations. As I have been associated with this program for only 16 years, I know of previous times only through the written record of them, and through discussions with NIST staff members.

2. Primary Standards

Pendulum Clocks

The earliest work by NBS in this field involved time-interval measurement using two different pendulum clocks, both of which are now in the museum at the NIST-Gaithersburg site. The first standard, the Riefler pendulum clock [7], was purchased from Clemens Riefler of Munich in 1904. The Riefler clock has an Invar pendulum, which substantially reduces sensitivity to temperature change, and the particular model purchased by NBS has a system that raises the clock weight every 30 seconds with an electromagnet. This assures that the torque applied to drive the clock is continuous and constant. The Riefler clock routinely achieved a time-interval uncertainty of about 10 ms per day, but it required calibration. For most of the work done at NIST, this calibration was achieved through reception of time signals broadcast by the U.S. Naval Observatory (USNO).

The Riefler clock was replaced in 1929 by the Shortt clock [7], which was purchased from the Synchronome Co. of London. This clock, developed by W.H. Shortt of the Edinburgh Observatory near the end of 1921, has two pendulums, one a slave pendulum that drives the clock works and that is in turn synchronized electrically to another master pendulum that swings freely in an evacuated vessel. The freedom of the primary pendulum from the friction associated with driving the clock works allows this clock to achieve an uncertainty in time-interval measurement of about 1 ms per day.

While the Shortt clock replaced the Riefler clock in 1929, a 1941 NBS publication [8] indicates that timepieces were still being tested at NBS with the Riefler clock serving as reference. It appears that the Shortt clock had been removed to another laboratory to serve as a reference for the determination of G, the gravitational constant, and that the Riefler clock was still deemed sufficiently accurate for the testing of time pieces.

Electronic Frequency Standards

Work on frequency standards at NBS began in 1911 with J.H. Dellinger's development of a system for calibrating wavemeters. He obtained frequency from a simple calculation of the resonance of an inductance-capacitance (LC) circuit. During the next few years, the development of better mathematical expressions for inductance and capacitance provided for considerable improvement in frequency measurements using these types of standards [9]. The measurement of frequency thus rested on the measurement of the physical dimensions of capacitors and inductors and on the dielectric properties of the materials used in the capacitors. Methods of synthesizing or measuring frequency ratios allowed these wavemeter standards to cover a broader frequency range. By 1929, the practical range of measurement was 18 kHz to 4600 kHz and the uncertainty of measurement was 0.1 % or better [6].

It is interesting to note that there seems to be no record of reconciliation of these early frequency measurements with the time-interval measurements made using pendulum clocks, which were in turn calibrated against the mean solar day. During this early period, the measurement of time-interval, at least for longer intervals, was substantially more accurate than the measurement of frequency. However, as the demand for higher accuracy in the measurement of frequency exceeded the performance of the wavemeter methods, NBS turned to astronomical calibration (provided by USNO).

Quartz Oscillators

In the early 1920s the Bureau began studies of quartz-crystal oscillators as frequency standards. This work was stimulated by W.G. Cady, who sent four quartz oscillators to NBS for frequency calibration in 1920. Cady sent four more quartz devices to the Bureau in 1922 and seven more in 1923. After working with and calibrating these oscillators, it became clear that they could serve as good standards for radio frequency, and a program of study was initiated. This work was further stimulated by the increasing demand for better accuracy in the measurement and control of radio frequency posed by the growth of commercial and amateur radio broadcasting.

To meet the growing demand for better accuracy, NBS sought outside partners, and began collaboration on oscillators with the Naval Research Laboratory and Bell Telephone Laboratories. By 1929 these collaborators agreed that such oscillators could provide for measurement of frequency with an uncertainty of only 1 part in 10^5. Later that year, Bell Telephone Laboratories delivered four complete temperature-controlled oscillators to NBS. These four 100 kHz oscillators quickly became the national primary standards of radio frequency [10]. Figure 1 shows a picture of these devices installed in the laboratory. By 1952, the facility involved a larger number of oscillators and the measurement uncertainty had been reduced to about 2 parts in 10^8. The rate (frequency) of these standards was compared regularly with USNO signals broadcast from their transmitter in Arlington, Virginia.

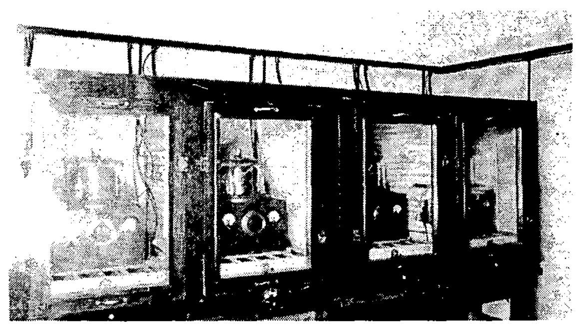

Figure 1. The first quartz-oscillator primary frequency standards installed at NBS in 1929.

By this same time the first atomic frequency standard had been demonstrated, and the future of the effort on quartz standards was coming into question. However, the NBS work on quartz oscillators as primary frequency standards continued until the summer of 1959 with experimental work aimed at reducing drift. By operating the oscillators at a temperature of 4 K, drift had been reduced by more than an order of magnitude and the quality (Q) factor had been increased to as high as 5×10^7. Even so, the advances in atomic frequency standards were so large that the program was discontinued.

The First Atomic Frequency Standard

As early as 1879, Lord Kelvin published the statement (attributed to James Clerk Maxwell) that atoms could serve as natural standards of time and length [11]. By the late 1940s, a body of academic work on microwave spectroscopy of atoms and molecules was growing, and reliable electronics for microwave measurements became available through development of radar systems used in the war. Thus, the stage was set for someone to turn these ideas into a real frequency standard.

The events surrounding the ensuing atomic-frequency-standards work at NBS are well chronicled by Forman [12]. In early 1948, Harold Lyons, Chief of the Bureau's Microwave Standards Section, along with several colleagues, began work on a frequency standard that used an ammonia absorption line at 23 870.1 MHz as its reference. By late summer of that year, the device was tested for the first time, and a press announcement of the development was made in January of 1949.

This clock (Fig. 2) consisted of a 100 kHz quartz oscillator that drove a frequency multiplier chain to develop the signal that probed the ammonia resonance in a waveguide absorption cell [13]. The uncertainty of the standard was 1 part in 10^7. A second model of the ammonia standard was quickly developed. This device incorporated a servo system that corrected for drift in the quartz oscillator without affecting its short-term stability. The stability of this standard was 2 parts in 10^8, comparable to that of the existing quartz standards.

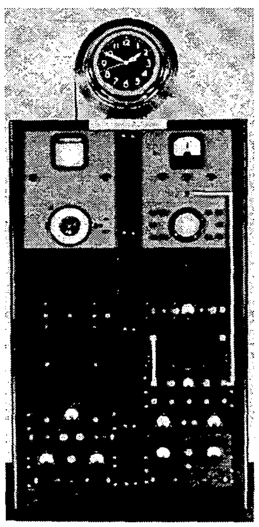

Figure 2. The world's first atomic frequency standard (clock) as it appeared in January 1949. This frequency standard was transferred to the Smithsonian Museum, where it was displayed for several years in an exhibit on atomic timekeeping.

Neither the first nor the second model of this device was ever used extensively for frequency calibrations, which continued to be done using the quartz standards described above. The development of the ammonia clock was simply the first step into the era of atomic standards. During these early years, other atoms and molecules were considered as standards, but the key discussion was on the method to be used. For a variety of reasons the atomic-beam method gained favor and became the basis for the next standards.

Cesium-Beam Frequency Standards

Rabi's pioneering work on molecular beams [14] laid the foundation for the next generation of atomic frequency standards. These ideas were advanced substantially by Ramsey, and his method of successive oscillatory fields [15] (referred to in the literature as the method of separated oscillatory fields) would prove to be exceptionally useful.

In late 1948 NBS initiated a program to develop an atomic-beam standard, and engaged Kusch, a coworker of Rabi, to act as a consultant on the development of this device. Again, this period of development is nicely described by Forman [12]. Kusch foresaw many of the design features now used in cesium-beam standards, and the Bureau's program progressed rapidly [6]. The cesium hyperfine lines were first observed in 1951 and the frequency of 9192.632 ± 0.002 MHz reported in 1952 (obtained using single-cavity excitation) was exceptionally close to the number eventually accepted. The experimental device, later called NBS-1, was converted to Ramsey excitation with a Ramsey cavity length of 55 cm, and the predicted increase in Q was observed.

Forman [12] describes problems at NBS that at this point caused the program to falter. In particular, budget cutbacks and an emphasis by Lyons on a second approach, which consumed at least half the resources of the group, brought progress to a standstill. A few years later the program and equipment, including the cesium standard, were transferred with the Central Radio Propagation Laboratory to Boulder. As a result of this general turmoil, and the excellent competitive work of the National Physical Laboratory (NPL) described below, NBS failed to capitalize on its successes. The first successful primary cesium standard would not be demonstrated by NBS.

Louis Essen of the NPL had followed the NBS work on atomic clocks quite closely and visited the Bureau on several occasions. Essen, who already had expertise in precision microwave measurements, received NPL funding for a development program in 1953, and in two years succeeded in building a reliable cesium-beam frequency standard [16]. Over the next several years, he collaborated with Markowitz of USNO on the measurement of the cesium resonance frequency, which was then reported as 9192.631770 ± 0.000020 MHz [17]. This was the number eventually accepted for use in redefining the second. It is interesting to note that the NPL standard on one side of the Atlantic was compared with the USNO astronomical measurements on the other side using common-view measurements of signals from NBS radio station WWV, which was then located on the East coast of the United States.

The NBS frequency standard, while considered to be operating occasionally at an uncertainty approaching 1 part in 10^{10} in the early 1950s, did not achieve reliable operation until well after it was moved to Boulder in 1954. It was completely rebuilt in 1958 and finally put into regular operation in 1959. NBS-2 was completed at about this same time and careful comparisons of these two standards showed agreement at a level of 1.5 parts in 10^{11}. The NPL program ended during this period. A second standard was under development to replace the original standard, but this was never completed. The key programs on frequency standards until 1995 became those at NBS/NIST, the National Research Council (NRC) in Canada, and the Physikalisch-Technische Bundesantalt (PTB) in Germany, with the last of these achieving leadership in the later years of cesium-beam standards.

Over the next nearly 40 years, NBS/NIST constructed five additional cesium-beam frequency standards with uncertainties that decreased by better than a factor of 10 per decade. The entire sequence of seven NBS/NIST cesium-beam standards is shown in Fig. 3.

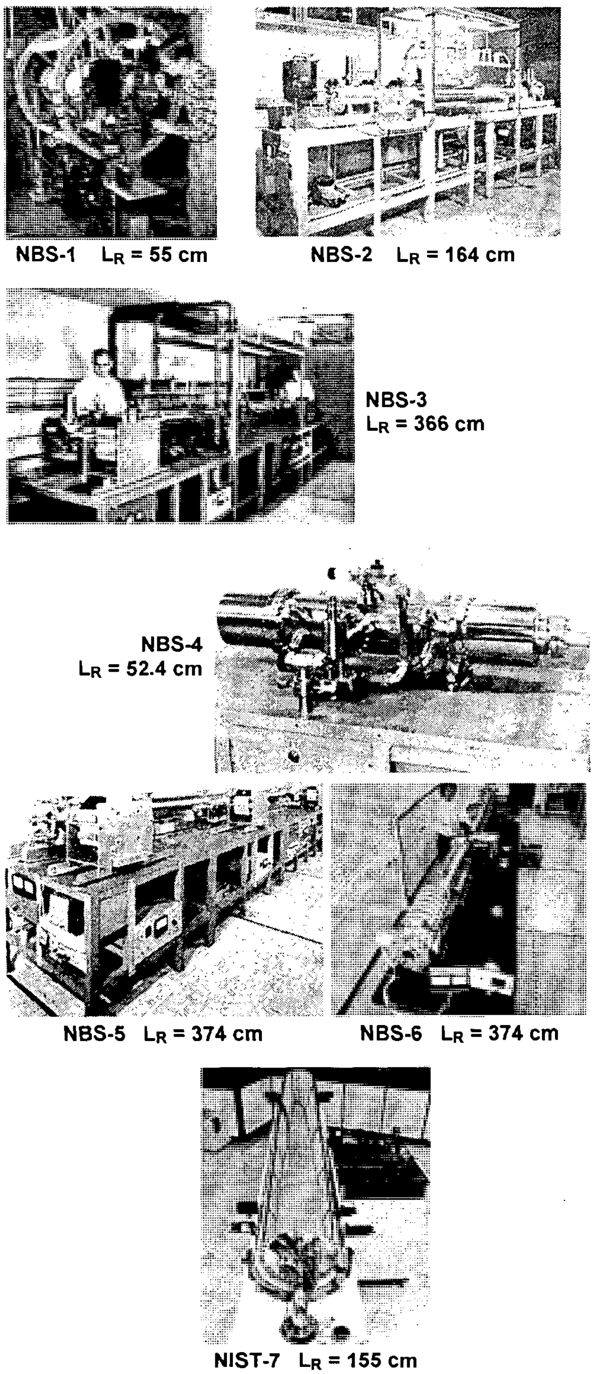

Figure 3. Photographs of the entire set of cesium-beam frequency standards produced and used by NBS/NIST during the period from 1950 to 2000. L_R is the length of the Ramsey cavity in each standard. NBS-6 was a modification of NBS-5 in which the Ramsey cavity was unchanged.

The development of the first five of these standards is described by Snyder and Bragaw [6]. The trend toward increased Ramsey-cavity length reflects an effort to increase the Q factor, which in turn makes it easier to locate the center of the resonance. The departures were NBS-4, which was developed jointly with Hewlett-Packard to study issues of stability, and NIST-7, which involved a radical change in state selection and state detection and used a digital servo system to more accurately locate the center of the resonance.

Aside from the benefits accruing from the increase in line Q associated with increasing the length of the Ramsey cavity, the improvements in accuracy of these standards can be traced primarily to better understanding and control of systematic frequency shifts. The large frequency shift associated with end-to-end cavity phase shift was virtually eliminated in NBS-5, NBS-6, and NIST-7 through the use of reversible beams. Of course, improvements in stability through the use of better quartz (local) oscillators and the reduction of noise to the atom shot-noise limit was also significant, since this allowed measurements at a given uncertainty to be made in a shorter period. NBS-6 used a two-beam (atoms in both the F=3 and F=4 levels) flop-in arrangement [18] to achieve an increase in signal level. This standard was really a major modification of NBS-5, and used the same Ramsey cavity.

NIST-7 represents the largest single departure in design through this series of standards [19]. Whereas Stern-Gerlach magnets had been traditionally used for state selection and detection, essentially deflecting (rejecting) atoms in unwanted states from the beam, NIST-7 used lasers to optically pump atoms into the desired ground state and for fluorescence detection of the states of atoms following Ramsey excitation. This was a simplifying change, which eliminated the transverse dispersion of atoms, wherein the slow and fast ones followed different trajectories because of the variation in the amount of deflection by the inhomogeneous magnetic fields. A unique Ramsey cavity was also developed to reduce the variation of microwave phase transverse to the atomic-beam direction and thus reduce the frequency shift due to this variation [20]. And of course, the development of digital servo methods substantially improved the performance and reliability. The best (lowest) uncertainty reported for NIST-7 was 5 parts in 10^{15}. This standard has now been replaced by the fountain standard described in the next section.

Cesium-Fountain Frequency Standards

While Zacharias developed the fountain concept in 1954 [21], it was not a practical option until atoms could be cooled by lasers. [Laser cooling of atoms is discussed as a separate topic in Section 3.] The first demonstration of the fountain concept was at Stanford University in 1989 [22] and the first primary frequency standard based on the idea was developed shortly thereafter by a group at the Laboratoire Primaire du Temps et Frequences (LPTF) [23]. In this device atoms are trapped at the intersection of six orthogonal laser beams and are tossed vertically by slightly offsetting the frequencies of the vertical lasers and then turning all six lasers off. The atoms rise and fall through a single TE_{011} microwave cavity and undergo state interrogation (laser fluorescence method) below the cavity.

The advantages of the method should be obvious. The atoms are now moving so slowly that the linewidth drops to ~ 1 Hz ($Q=10^{10}$). Systematic shifts are dramatically reduced and the end-to-end cavity phase shift disappears, since Ramsey excitation is achieved through a time separated passage (twice) of the atoms through the same microwave cavity.

While NIST, because of its lead role in the development of laser-cooling techniques, should have been in a good position to develop the first primary standard based on the concept, the separation of the neutral-atom-cooling program in Gaithersburg from the Time and Frequency Division in Boulder was not conducive to rapid adoption of the concept. In addition, NIST had already embarked on the development of NIST-7, and budgetary constraints would not have allowed for simultaneous development of two primary standards. In the end, the very great success of the LPTF fountain project made it clear that NIST would have to build a similar device and development was initiated in 1997.

The NIST cesium fountain, shown in Fig. 4 became operational at the end of 1999 [24]. The uncertainty for NIST-F1 is now 1.7×10^{-15}, a value comparable to the uncertainties of the fountains operated by LPTF and PTB. During the last year, a careful comparison of the fountains at PTB and NIST was made [25], and these were found to agree within their stated uncertainties. It appears that the fountain uncertainty, which is now limited primarily by the spin-exchange frequency shift, can be reduced by at least a factor of 3 to a level of 5×10^{-16} or below.

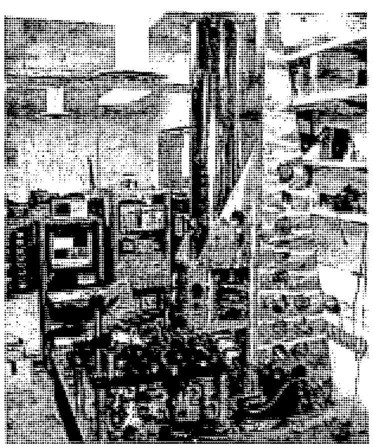

Figure 4. The NIST cesium-fountain primary frequency standard, NIST-F1.

Stored-Ion Frequency Standards

The key advantage of using stored ions for frequency standards is that they can be contained for long periods (hours to days and even weeks are common) with, in some cases, exceedingly small systematic frequency shifts. Also, very long observation times (compared to those for the cesium standards) of the benignly trapped particles can produce very narrow resonance linewidths. Ramsey interrogation is accomplished by subjecting the ions to pairs of microwave pulses, and the linewidth is then inversely proportional to the time interval between the pulses. Because the ions are basically at rest, the end-to-end cavity phase shift of cesium-beam standards is absent, and there is no first-order Doppler shift.

The first prototype stored-ion frequency standard that exhibited a reasonably small uncertainty (1×10^{-13}) was a Be^+ ion standard operating at 303 MHz [26]. While this standard used a modest ion cloud (~ 10^4 ions), the standards described below use only a few ions. Despite the small number of ions, very competitive stabilities have been achieved for a microwave-frequency standard using mercury ions [27]. Storage methods include both radio-frequency traps (called Paul traps), which use an ac electric field (and sometimes a combination of static and ac electric fields) to achieve confinement, and Penning traps, which confine ions using a combination of static electric and magnetic fields. Figure 5 shows an image of a single mercury ion stored in a Paul trap. A prototype frequency standard using a few $^{199}Hg^+$ ions stored in a linear rf trap to produce a 40.5 GHz frequency standard was demonstrated in 1997 [27], but work on this was halted when new concepts on optical standards started showing great promise.

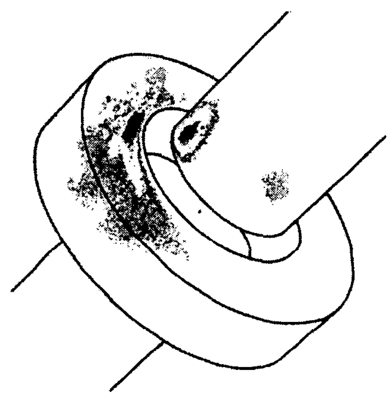

Figure 5. Ultra-violet image (negative) of a trapped ion. The small fluorescence at the center of the trap is from a single mercury ion contained in the Paul trap. The trap electrodes were added to this image, which also shows laser light scattered from surfaces of the electrodes.

The prototype optical frequency standard developed by the Stored Ion Group is based on the 282 nm (frequency of 1.06×10^{15} Hz) transition of $^{199}Hg^+$, which has a natural linewidth of 1.7 Hz. In implementing the standard, a linewidth of 6.7 Hz was realized [28]. This is the highest Q ever achieved in optical spectroscopy, and the potential accuracy of a standard with such characteristics is enormous. The key difficulties with such standards have been the problems of relating their outputs to the microwave region and of counting optical cycles. While optical-frequency synthesis methods had been developed previously for measuring the speed of light and for realizations of the meter (see Section 4), these systems were large and cumbersome, and too complex for routine use with optical-frequency standards.

In the last several years the barriers facing optical-frequency standards have disappeared with the development of relatively simple optical combs [29, 30] that allow for accurate connection between the microwave and visible regions. In fact, this new method has provided the basis for the most accurate measurements ever made of optical frequencies [31] and the demonstration of a mercury optical frequency standard with an output in the microwave region [32].

This work clearly signals the development of a whole new generation of frequency standards with uncertainties and stabilities far exceeding those of even the best cesium-fountain standard. Of course, until the second is redefined in terms of another atom or ion, its realization cannot be any better than that done with the present cesium standards. Over the next few years, other atoms and ions will be studied at many laboratories to determine which, if any, might eventually replace cesium. International accord on such a change will naturally be needed before use of cesium is abandoned.

3. Laser Cooling of Atoms

I digress at this juncture to discuss the question of laser cooling of atoms, since the first cooling of ions, and then later neutral atoms, was done at NIST. Any history on frequency standards work at NIST must surely describe the events surrounding these developments.

The concept of radiation-pressure cooling of atoms was independently suggested in 1975 for the case of a gas of neutral atoms by Hänsch and Schawlow and for atomic ions bound in an electromagnetic trap by Wineland and Dehmelt. While the notion that momentum exchange from a counter-propagating photon could slow an individual atom was well understood, until this time no one had come up with a means for producing an aggregate cooling of a larger ensemble (a gas) of atoms. If all atoms of a hot gas of atoms absorb photons, then some will be heated and some cooled, and the ensuing equilibrium temperature is not lowered. The general feature of the cooling concepts is that a gas of atoms or ions can be cooled by assuring that photon absorption takes place preferentially when the atoms or ions are moving against the flow of photons from a laser.

In 1978, following these ideas, Wineland, Drullinger and Walls performed their seminal experiment [33] and demonstrated the very first radiation-pressure cooling below ambient temperature of any atomic species. The key to the experiment was the variation in photon absorption associated with the Doppler frequency shift. They used a collection of positive magnesium ions contained in an electromagnetic trap subjected to laser radiation near the ~280 nm resonance in the magnesium ion. When this laser radiation was tuned slightly below resonance, cooling to below 40 K was observed. For this particular tuning, those ions with motions opposing the laser radiation are Doppler-shifted toward resonance and are more likely to absorb photons, thus slowing their motions. Ions moving away from the source are Doppler-shifted away from resonance and are thus less likely to absorb photons. Since the re-radiation from this excited state is symmetric, the net effect averaged over the ensemble of atoms is a cooling of the gas of ions.

The very next year, Wineland and Itano [34] published a paper providing the first detailed theoretical analysis of laser cooling, which served as the foundation for rapid development of this field. In ensuing years, they improved their methods and soon cooled ions to millikelvin temperatures.

The experimental demonstration of laser cooling of trapped ions stimulated the development of a number of ion-cooling groups around the world and encouraged others to attempt to cool neutral atoms. In fact, it was only a few years later (in 1982) that Phillips and his collaborators at NIST cooled a beam of neutral (sodium) atoms [35]. This first neutral atom cooling involved a fixed-frequency laser beam and a counter-propagating beam of atoms. The cooling transition was kept in resonance with the laser through a spatially varying magnetic field, which provided a changing Zeeman shift to compensate for the changing Doppler shift as the atoms decelerated. Simpler laser-cooling methods, developed subsequently, provided the basis for realization of the fountain frequency standard originally conceived by Zacharias.

4. The Speed of Light and the Meter

This is yet another digression, inserted at this point because NIST work in this area required accurate measurement of optical frequencies, and this represents an extension of primary frequency standards to the optical region (see especially the last paragraphs of Section 2).

NBS has had a long history of interest in the speed of light, and no doubt this interest contributed to the measurements described here [36]. As early as 1907, Rosa and Dorsey [37] determined the speed of light by measuring the ratio of the electrostatic to the electromagnetic capacity of a condenser. Over the ensuing years NBS developed still other methods to improve upon the accuracy of this important physical constant.

By the late 1960s, lasers stabilized in frequency to atomic and molecular resonances were becoming reliable research tools. These could be viewed as providing stable reference for either optical frequency or wavelength. This duality of frequency and length produced the suggestion that a simultaneous measurement of frequency and wavelength for the same laser would yield a very good measurement of the speed of light. At that time the wavelength of visible radiation could be measured fairly well, but no accurate methods for measuring visible frequencies were available. Conversely, where frequency could be measured quite well in the microwave to millimeter-wave region, wavelength measurements were problematic.

The measurement of the speed of light by NBS involved the development of a new method. The approach taken was to synthesize signals at progressively higher and higher fre-