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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Report to the 18th Meeting of the CCTF
Activities of the NIST Time and Frequency Division
May 2009

This brief summary is not intended as a comprehensive report of all the activities of the NIST Time and Frequency Division, but serves to highlight some of the Division's accomplishments and some changes in Division activities over the past two years. For more information on any of the topics outlined in this report, please see the NIST Time and Frequency Division website: http://tf.nist.gov

All publications from the NIST Time and Frequency Division are available for free download from a searchable web database: http://tf.nist.gov/timefreq/general/publications.htm

1. Cesium primary frequency standards

1.1 NIST-F1 frequency evaluations

The NIST-F1 cesium fountain primary frequency standard has been in operation since November 1998 with the first formal report to BIPM made in November 1999. [1] NIST-F1 has reported approximately 35 formal evaluations to BIPM, with uncertainties generally decreasing as improvements are made to the standard and its operational reliability improved. Seventeen formal evaluations were reported since the last CCTF meeting. A NIST-F1 formal evaluation consists of measuring the frequency of one of the six hydrogen masers at NIST compared to NIST-F1 and reporting the results and uncertainties to BIPM. [2] The NIST ensemble of six active, cavity-tuned hydrogen masers provides a very stable frequency reference to characterize the performance of the reference maser. The NIST-F1 frequency at zero atom density is determined by performing frequency measurements over a range of atom densities and conducting a linear least squares fit extrapolation to zero atom density.

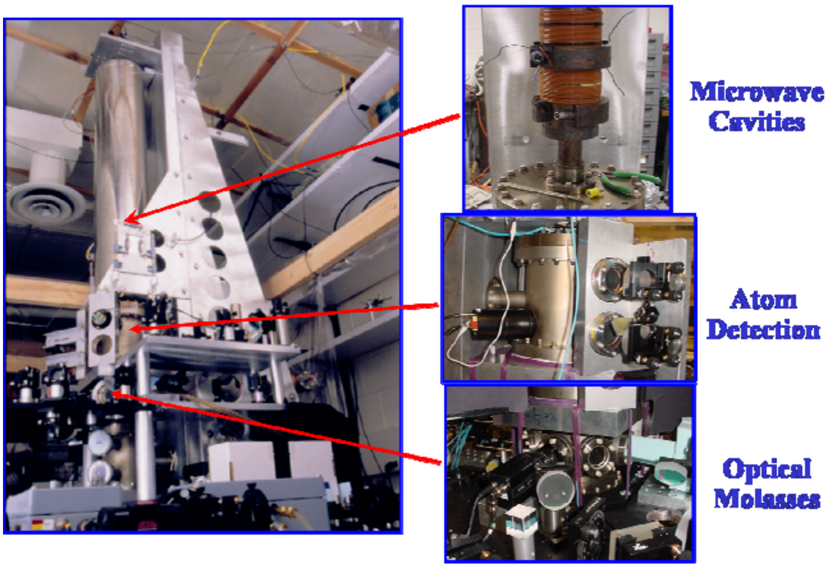

Figure 1. NIST-F1 primary frequency standard.

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Some recent improvements in NIST-F1 include extensive cleaning and improvements to the vacuum system, improved temperature control and instrumentation, improved magnetic field control, improvements to the shutter and fiber optics systems, and improvements in the molasses optics. These improvements helped reduce the light shift uncertainty, improved general reliability reducing dead time during evaluations, and a larger molasses with about twice the number of atoms but only a small increase in atom density. [3]

Recently, NIST has been conducting more frequent by shorter evaluations, typically representing 10 days to 15 days of averaging, interspersed with longer full evaluations representing 25 days to 40 days of averaging. Recent “in-house” uncertainties (u_A and u_B) have been on the order of 0.3 x 10^{-15} for both shorter and full evaluations. Time transfer uncertainties (u_{TAI}) are of course greater for shorter evaluations (order of 0.9 x 10^{-15}) than for longer evaluations (order of 0.6 x 10^{-15})

1.2 NIST-F2 next generation cesium primary frequency standard

Construction and initial testing for the second generation NIST fountain, NIST-F2, has been completed with the principal goal of introducing a cryogenic drift tube to substantially reduce the blackbody shift uncertainty, as well as permit more sensitive tests of the magnitude of the blackbody shift by measuring the fountain frequency at drift tube temperatures between about 50 K to about 320 K.

NIST-F2 was constructed to permit upgrades to a multiple launch velocity fountain system that will permit the launching of some 10 balls of atoms to different heights that return simultaneously to the detection region. This approach, first proposed and investigated by Levi et al., will permit the reduction of atom densities by about an order of magnitude with a comparable reduction in the frequency shift uncertainty. [4]

Initial frequency evaluation of NIST-F2 operated at cryogenic temperatures is expected in late 2009 or early 2010.

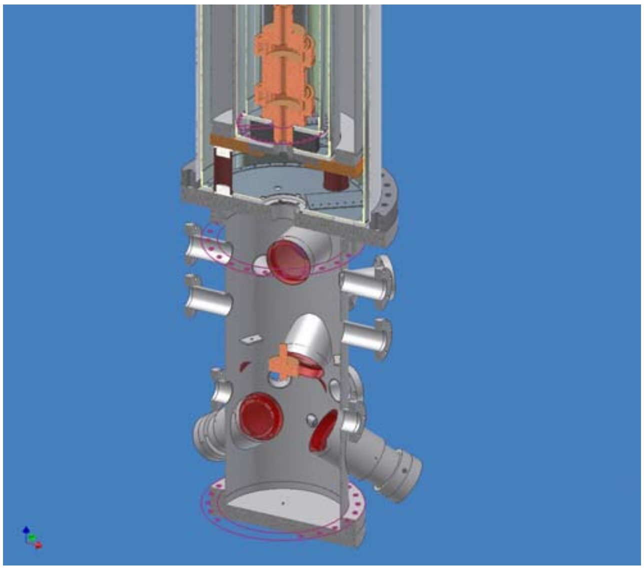

Figure 2. CAD of NIST-F2, showing details of optical molasses region and microwave cavity.

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2. Optical frequency standards

2.1 Single mercury ion optical frequency standard

NIST has continued development and systematic evaluation of an optical frequency standard based on the 1.06 x 10^{15} Hz (282 nm) electric quadrupole transition in a single trapped $^{199}Hg^{+}$ ion. The mercury ion standard demonstrates measured fractional frequency instabilities of about 1.7 x 10^{-17}, and a theoretical quantum-limited fractional frequency uncertainty approaching 10^{-18}. The standard uses a cryogenic spherical Paul electromagnetic traps to enable storage of a single trapped ion for as long as 100 days, and uses a laser locked to a high-finesse Fabry-Perot cavity with stringent temperature control and vibration isolation, providing laser linewidths below 0.2 Hz for averaging periods of about 1 second to 10 seconds. Over a period of more than eight years, several intercomparisons have been conducted between the mercury ion standard and the NIST-F1 cesium primary frequency standard, using the NIST optical frequency comb.

Recent improvements include a new system to compensate for electric field gradients by making measurements along three different axes. This new approach yielded an accurate measurement of the electric quadrupole moment and a constraint on the electric quadrupole shift, resulting in a recent reported fractional frequency uncertainty of 1.7 x 10^{-17}. [5]

The long-term intercomparisons of the mercury ion frequency standard and the NIST-F1 cesium frequency standard have also permitted sensitive testing of possible time variation in the fine structure constant, α. Such measurements conducted at NIST over a period of more than two years placed an upper limit on any time variation in α of about 1.6×10^{-17} per year, substantially smaller than possible time variations in α suggested by certain quasar spectra. [6, 7]

Figure 3. Jim Bergquist with mercury ion frequency standard.

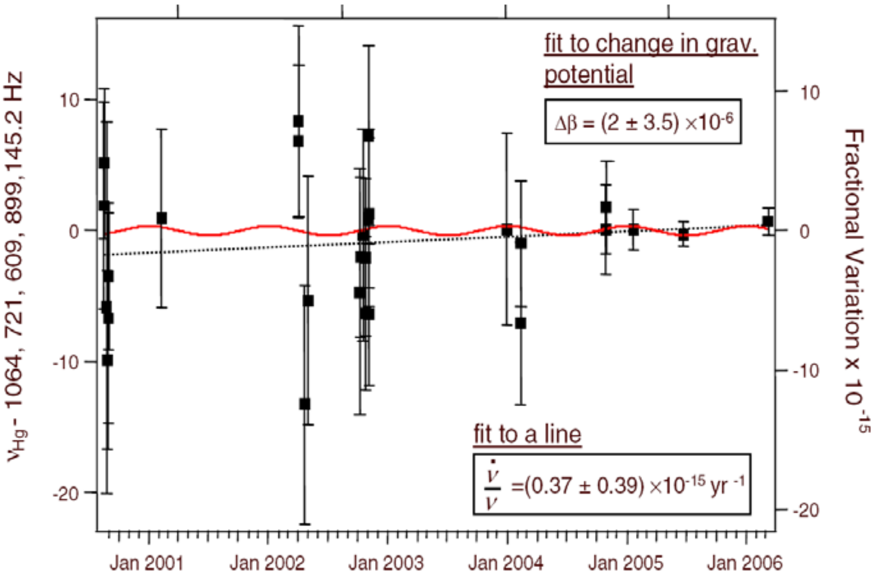


Figure 4. Comparisons of mercury ion optical frequency standard with NIST-F1 primary frequency standard, demonstrating significant reductions in uncertainties of the mercury ion frequency measurement in recent years.

2.2 "Logic clock" optical frequency standard [5, 7, 8]

The NIST Time and Frequency Division has a highly productive program in quantum computing using laser-cooled, trapped ions. Developing quantum computing and quantum communications is an area of intense research across the world, including a large effort at NIST involving the Time and Frequency Division and several other NIST laboratories. The primary goal of the Time and Frequency Division's world-class program is to conduct the fundamental research needed to demonstrate a small-scale working quantum computer with about 10 quantum bits (qubits). Such research is being intensively pursued across the world using a wide variety of schemes including ions, neutral atoms, and various solid state technologies. The Time and Frequency Division's program using laser-cooled trapped ions is demonstrably a world-leader, with several significant research breakthroughs reported in recent years, and with the trapped ion approach being the only one to have successfully demonstrated all of the so-called DiVincenzo criteria necessary to the development of a working, scalable quantum computer.

Because most of the extensive quantum computing achievements in the Time and Frequency Division are not directly related to time and frequency metrology, they will not be detailed here. Interested persons can find extensive references to quantum information activities in the Time and Frequency Division and at NIST overall at http://qubit.nist.gov/ and at the Time and Frequency Division's publications database at:
http://tf.nist.gov/general/publications.htm

Using techniques developed in research on quantum computing with laser-cooled trapped ions, NIST scientists demonstrated a prototype "logic clock" based on a single $^{27}Al^+$ ion entangled with a $^{9}Be^+$ ion. Single ion optical frequency standards, such as the $^{199}Hg^+$ clock described above, have been limited to atomic species with suitable transitions for laser cooling, state preparation and detection, in addition to a stable clock transition. But many other potential clock species exist which do not fulfill all these criteria. For example, the $^{27}Al^+$ ion has an excellent clock transition ($^1S_0 \leftrightarrow {}^3P_0$, ~267 nm) with a long lifetime (~30 seconds), low sensitivity to magnetic fields, and no electric quadrupole shift. However, the only suitable transition for laser cooling and state detection is at approximately 167 nm, which is significantly beyond current technology for stable, narrow-band cw lasers.

This limitation is overcome by simultaneously loading single $^9Be^+$ and $^{27}Al^+$ ions into a linear Paul trap. The two ions form a stable crystal, and the motional modes can be easily cooled to near the ground state through direct laser cooling of the $^9Be^+$ ion at ~313 nm, which sympathetically cools the $^{27}Al^+$ ion. The $^{27}Al^+$ ion can be placed in a superposition of the ground $^1S_0$ and excited $^3P_0$ states of the clock transition with an appropriate laser pulse (~276 nm), and the quantum state of the $^{27}Al^+$ ion can be transferred to the $^9Be^+$ ion for efficient detection.

Current experiments demonstrate a fractional frequency uncertainty on the order of 2×10^{-17} and an Allan variance of $\sim 7 \times 10^{-15} / \tau^{1/2}$. This approach appears particularly promising since nearly any "clock" ion can be coupled with a convenient "logic" ion such as $^9Be^+$.

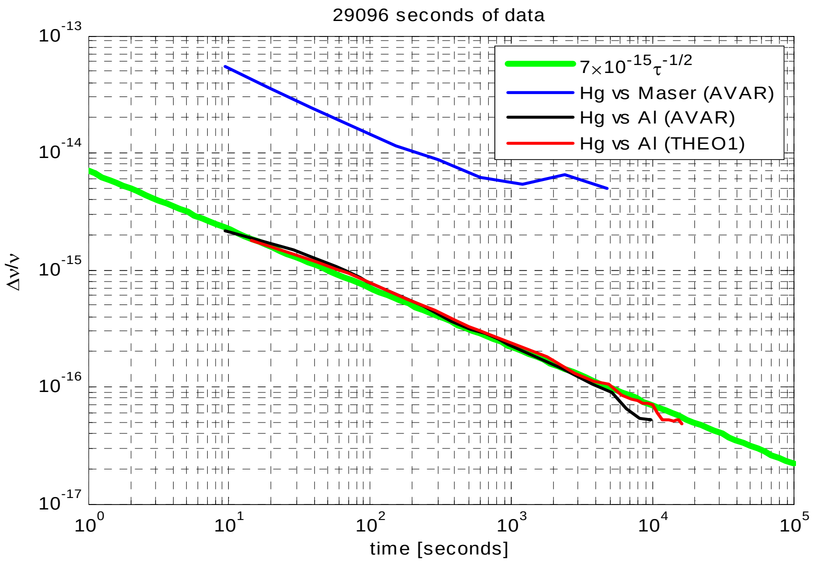


Figure 5. Frequency stability of the Al^+/Be^+ "logic clock" in preliminary measurements.

2.3 Neutral calcium optical frequency standard

Significant progress continues in the neutral ^{40}Ca optical frequency standard. Among recent developments are the demonstration of quenched narrow-line second and third stage laser cooling of ^{40}Ca to reach atom to about 10 µK, an improvement of more than 2 orders of magnitude, with the potential to reduce systematic frequency uncertainties in the calcium standard to better than 1 Hz (about 3×10^{-15}). The calcium optical frequency standard continues to be an invaluable reference for extensive work using optical frequency combs, described below. [9]

2.4 Neutral ytterbium lattice optical frequency standard

NIST demonstrated direct laser excitation of the strictly forbidden $^1S_0 \leftrightarrow {}^3P_0$ clock transition (~578.42 nm) in ^{174}Yb atoms confined in a one-dimensional lattice. Lattice clocks based on large numbers of neutral atoms trapped in far off-resonance optical lattices can be designed for zero net ac Stark shift, combining the strong signal-to-noise of large collections of atoms with the long interaction times and Doppler-free spectroscopy of single-ion standards. Lattice clock experiments have focused on the $^1S_0 \leftrightarrow {}^3P_0$ clock transition in odd isotopes of alkaline-earth-like atoms such as Sr and Yb. This transition is weakly allowed in odd isotopes due to hyperfine mixing, but the non-zero nuclear spin introduces problems such as residual lattice polarization sensitivity, optical pumping issues, and linear magnetic-field sensitivity.

The use of even-isotope (zero nuclear spin) ^{174}Yb essentially eliminates these difficulties – but had remained out of reach because direct optical excitation is strictly forbidden in the absence of hyperfine mixing. However, the addition of a small magnetic field (~1.2 mT) mixes a fraction of a nearby state into the upper clock state ($^3P_0$) creating a weakly allowed electric dipole transition which can be directly excited at ~578.42 nm. The applied magnetic field must be carefully stabilized if this approach will be successful for a frequency standard, but the simplicity of the approach provides many benefits over odd-isotope lattices. [10, 11]

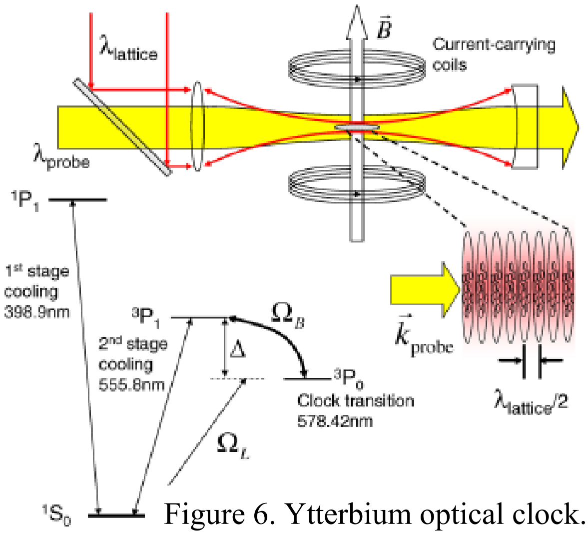
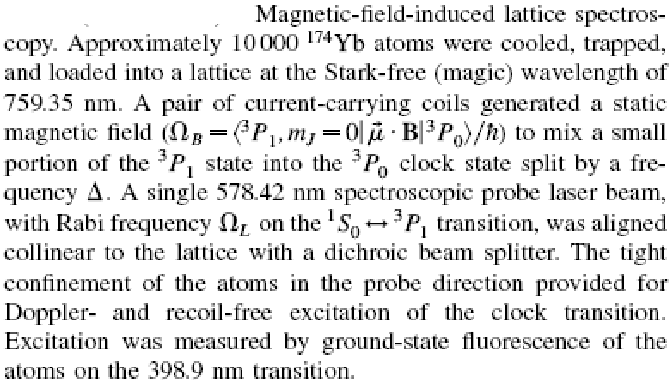


Figure 6. Ytterbium optical clock.


Magnetic-field-induced lattice spectroscopy. Approximately 10 000 ^{174}Yb atoms were cooled, trapped, and loaded into a lattice at the Stark-free (magic) wavelength of 759.35 nm. A pair of current-carrying coils generated a static magnetic field ($\Omega_B = \langle {}^3P_1, m_J = 0 | \vec{\mu} \cdot \mathbf{B} | {}^3P_0 \rangle / \hbar$) to mix a small portion of the $^3P_1$ state into the $^3P_0$ clock state split by a frequency Δ. A single 578.42 nm spectroscopic probe laser beam, with Rabi frequency Ω_L on the $^1S_0 \leftrightarrow {}^3P_1$ transition, was aligned collinear to the lattice with a dichroic beam splitter. The tight confinement of the atoms in the probe direction provided for Doppler- and recoil-free excitation of the clock transition. Excitation was measured by ground-state fluorescence of the atoms on the 398.9 nm transition.

2.5 Frequency combs

Substantial progress continues in the development and applications of high-repetition-rate mode-locked lasers to develop optical frequency combs. NIST recently demonstrated a self-referenced, octave-spanning, mode-locked Ti:sapphire laser with a scalable repetition rate (550 MHz to 1.35 GHz). The frequency comb output of the laser, without additional broadening in optical fiber, was for simultaneous measurements against atomic optical standards at 534 nm, 578 nm, 563 nm, and 657 nm and to stabilize the laser offset frequency.

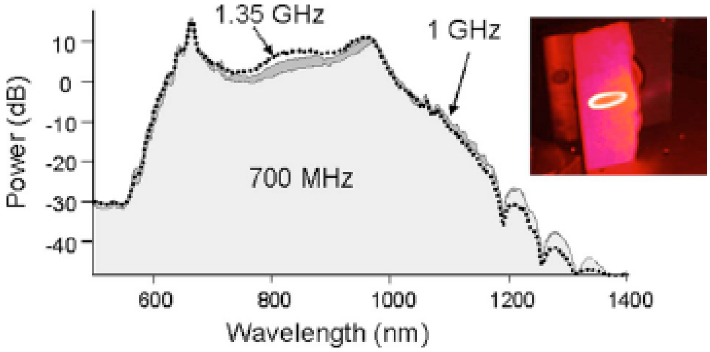


Figure 7. Left, laser output spectrum as a function of repetition rate, f_{rep}. The dark gray shading shows the spectrum at f_{rep} = 1 GHz. The dotted curve shows the laser spectrum for f_{rep} = 1.35 GHz. Right, mode profile for light in the green portion of the spectrum as taken at the output of M1 (Fig. 1). The spatial profile appears elliptical because the incident beam is at an angle to the camera.

Most frequency comb research involved with optical frequency standards has focused on the 400 nm to 1100 nm spectral range, typically using fiber-broadened Ti:Sapphire lasers. To extend this spectral range further into the infrared, particularly the 1300 nm to 1700 nm spectral range so important for telecommunications and remote sensing, NIST has developed a frequency comb generated with a Cr:forsterite femtosecond laser, spectrally broadened through a highly onlinear optical fiber to span from 1000 nm to 2200 nm, and stabilized using the *f*-to-2*f* self-referencing technique. The repetition rate and the carrier-envelope offset frequency are stabilized to a hydrogen maser, calibrated by a cesium atomic fountain clock. Simultaneous frequency measurement of a 657-nm cw laser by use of the stabilized frequency combs from this Cr:forsterite system and a Ti:sapphire laser agree at the 10^{-13} level. The frequency noise of the comb components is observed at 1064 nm, 1314 nm, and 1550 nm by comparing the measured beat frequencies between cw lasers and the

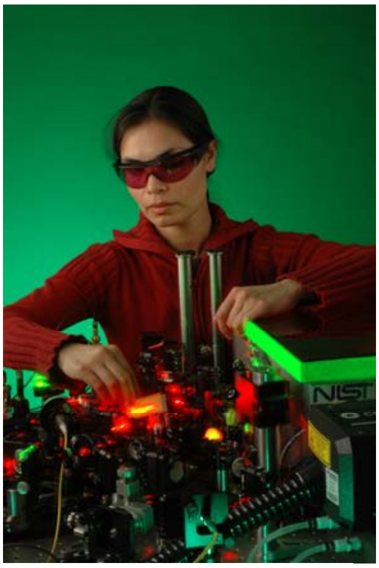


Figure 9. NIST optical frequency comb.

supercontinuum frequency combs.

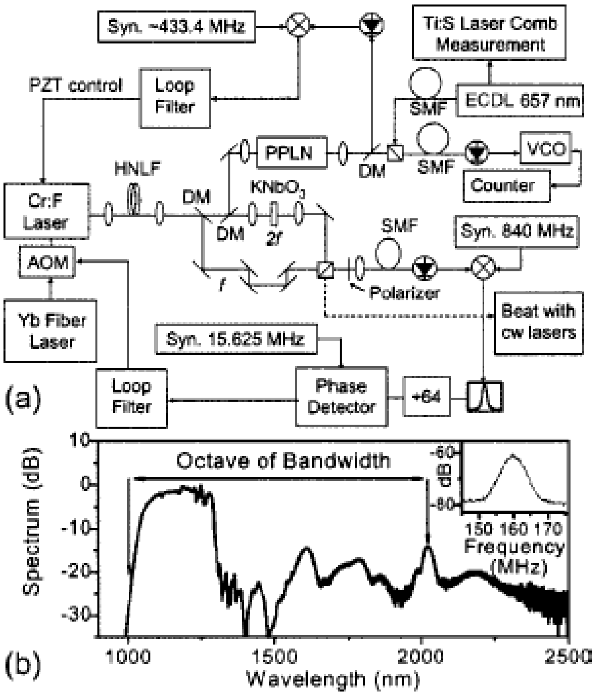


Figure 8. (a) Schematic of the experimental setup. DMs, dichroic mirrors, Syns; maser-referenced synthesizers; PZT, piezoelectric transducer; Ti:S, Ti:sapphire; SMF, single-mode fiber; ECDL, external cavity laser diode; PPLN, periodically poled lithium niobate; AOM, acousto-optic modulator. (b) Supercontinuum generated through a 2-m-long HNLF. The inset graph is the f_0 beat note measured with a 300-kHz RBW.

In addition to direct time and frequency intercomparisons, NIST is actively developing frequency combs for applications such as arbitrary optical waveform generation, remote sensing, precision astrophysical measurements, and many other applications. [12, 13, 14]

2.6 Chip-scale atomic clocks and other devices

NIST continues to make significant progress in developing the science and technology to support chip-scale atomic clocks and related devices such as chip-scale atomic magnetometers and ultraminiature gyroscopes. Such devices will be very valuable in portable electronic applications, bringing atomic accuracy with very small size, low power consumption, and the potential for relatively low-cost mass production using standard MEMS technology.

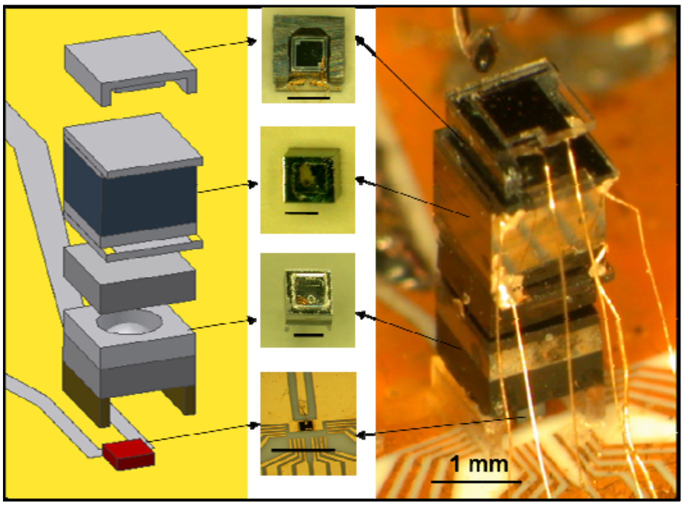


Figure 9. Schematic diagram and photomicrograph of NIST chip-scale atomic clock

NIST has demonstrated rubidium chip-scale atomic frequency references based on coherent population trapping with a physics package volume less than 10 mm^3, a total device volume less than 10 cm^3 including all electronics, a total power consumption of about 200 mW, and a frequency stability better than 6 x 10^{-10} / $\tau^{1/2}$. Based on NIST demonstrations, companies are commercializing chip-scale atomic clocks, and it seems likely that chip-scale atomic clocks can be developed with a total device volume on order of 1 cm^3, a total power consumption of about 30 mW, and a fractional frequency instability on order of 10^{-11} at one hour of integration. [15]

The chip-scale atomic clock can be adapted to a precision atomic magnetometer by probing magnetically sensitive transitions. Early versions of the NIST chip-scale magnetometer demonstrate sensitivity of 10 fT / Hz$^{1/2}$ at 125 Hz, a performance comparable to the best magnetometers that are much larger in size and may require cryogenic operation. [16]

3. Time and Frequency Dissemination

3.1 NIST Time Scale

NIST has integrated a new hydrogen maser into its primary time scale, now comprising six active hydrogen masers and four high performance cesium beam standards. NIST has also upgraded its time scale measurement system, and implemented a backup time scale at a remote location comprising four high performance cesium beam standards. All the clocks in the primary and backup time scales routinely report to BIPM for UTC realization.

3.2 Time Transfer

NIST participates in two-way satellite time and frequency transfer to Europe daily through a Ku-band link, achieving approximately 100 ps time transfer stability at one day of averaging. NIST is now using a Novatel multichannel two frequency receiver as the main receiver for

GPS common-view time transfer, attaining approximately 300 ps stability at one day of averaging between NIST and USNO (using IGS ionospheric corrections).

3.3 Internet Time Service

Use of the NIST Internet Time Service (ITS) to automatically synchronize computer clocks continues to grow, averaging more than 3 billion requests for service each day at the time of this report. Part of the growth in use results from ITS being one of the default sources of network time built into newer popular computer operating systems such as Microsoft Windows and Apple operating systems. To meet this demand, NIST continues to expand the number of servers, now totaling 22 servers at 18 locations throughout the United States. NIST also continues to upgrade the servers. [17]

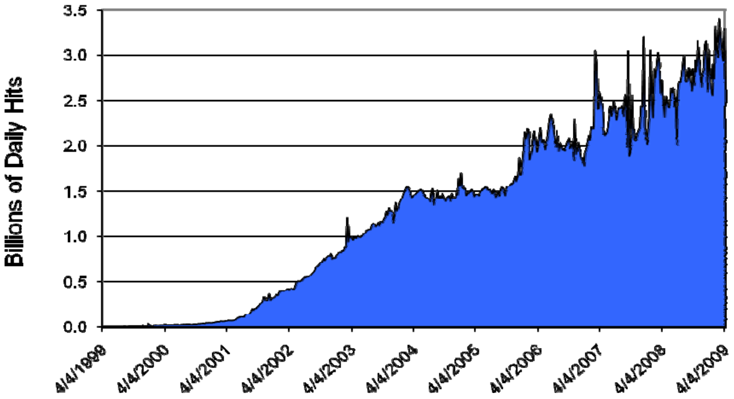


Figure 10. Daily service requests to NIST Internet Time Service.

3.4 Web clock

NIST and USNO jointly operate a Java web clock, www.time.gov , which provides users with a ticking display of the current official U.S. time, usually accurate to a few tenths of a second. (The current accuracy is displayed with the clock.) This service receives about 400,000 hits per day on average. A parallel service operated only by NIST, nist.time.gov , averages approximately 100,000 hits per day. These services will receive a major upgrade in 2009-2010. While the current pages allow the user to only select United States time zones, the new version will include an interactive map to select the current time anywhere in the world, including the wide range of different observances of daylight or summer time.

3.5 Automated Computer Time Service (ACTS)

This modem-based time-of-day service continues to receive an average of about 10,000 requests for service per day, although its historically high usage has dropped with the increasing popularity of the Internet Time Service. While NIST does not track individual users of ACTS, anecdotal evidence suggests a significant portion of the users are in the U.S. financial markets. U.S. regulations require the traceability of some electronic transactions, such as those on the NASDAQ stock exchange, to NIST time, and ACTS is one convenient method of establishing such traceability.

3.6 Radio stations

NIST broadcasts low frequency (60 kHz) time code signals from station WWVB near Ft. Collins, Colorado (about 100 km from the main NIST laboratories in Boulder, Colorado), to automatically set radio-controlled timepieces. At the current broadcast power level of approximately 50 kW, nearly all parts of the 48 contiguous United States receive sufficiently strong radio signals to permit synchronization of commercial timepieces at night, and U.S.

sales of radio-controlled timepieces are accelerating. NIST continues to implement a number of improvements in WWVB to increase reliability, improve broadcast efficiency, and ensure the greatest possible synchronization of the on-time marker to UTC(NIST).

NIST published in 2005 a recommended practice guide for manufacturers and users of radio-controlled timepieces to optimize performance and usability. The pdf version of this guide been downloaded more than 1 million times so far from the freely available Time and Frequency Division publication database:
http://tf.nist.gov/timefreq/general/pdf/1976.pdf

NIST also broadcasts high frequency (2.5 MHz to 20 MHz) time and frequency information from radio stations WWV near Ft. Collins, Colorado and WWVH on the Hawaiian island of Kauai. NIST continues to upgrade the infrastructure for stations WWV and WWVH to improve reliability of broadcasts, including a major antenna replacement program at WWVH and significant automation improvements at WWV to enable ensure backup transmitters appropriately take over upon loss of primary transmitters.

3.7 NIST Frequency Measurement Service

NIST continues to improve its Frequency Measurement and Analysis Service which provides automated traceability to NIST through common-view GPS for measuring any frequency from 1 Hz to 120 MHz in 1 Hz increments, and accommodating up to five different customer devices simultaneously. In addition to the real time data tracing the device under test to NIST standards at an uncertainty of 2×10^{-13} per day, customers receive monthly written calibration reports compliant with ISO Guides 25 and 17025 and the ANSI Z-540 standard. [18]

3.8 NIST Time Measurement and Analysis Service

In 2006, NIST initiated a new companion service, the Time Measurement and Analysis Service providing automated traceability to NIST time through common-view GPS with a combined uncertainty of 15 ns or better and a frequency uncertainty of 1×10^{-13} after one day of averaging. Customers receive monthly written calibration reports compliant with ISO Guides 25 and 17025 and the ANSI Z-540 standard. [19]

Figure 11. Measurement system provided to customers of new NIST Time Measurement and Analysis Service. Very similar systems are used for the SIM Time Network described below.

3.9 SIM Time and Frequency Comparison Network

Twelve laboratories representing nations of Systema Interamericano de Metrologia (SIM) are currently participating in coordination of time and frequency through the SIM Time Network, with several more member nations planning to join soon. The network uses technology initially developed at NIST for the Frequency Measurement and Analysis Service and Time Measurement and Analysis Service. The time uncertainty between any two laboratories and any set of comparisons is typically less than 15 ns (k = 2) and the frequency uncertainty is typically about 5 x 10^{-14} after 1 day of averaging (k = 2). [20]

Figure 12. A SIM map showing locations of the current (light circles) and future (dark circles) members of the SIM Time Network.

4. Noise metrology

4.1 Ultra-low noise microwaves synthesized from optical frequency signals

Demand for ultralow noise microwave sources and metrology is growing to support applications in communications, surveillance, navigation, and other areas. Recently, NIST has demonstrated generation of ultralow noise microwaves from femtosecond frequency combs. This approach exploits the exceptional stability and low-noise characteristics of optical cavities to generate microwaves with close-to-carrier phase noise 40 dB or more lower than possible with the best sapphire microwave oscillators. At frequencies on order of 1 KHz or larger from the carrier, sapphire microwave synthesizers will probably remain superior. But a complete phase noise characterization or synthesis system should rely on a combination of microwaves generated by femtosecond frequency combs and sapphire synthesizers for best phase-noise performance across the entire spectral range. [21, 22]

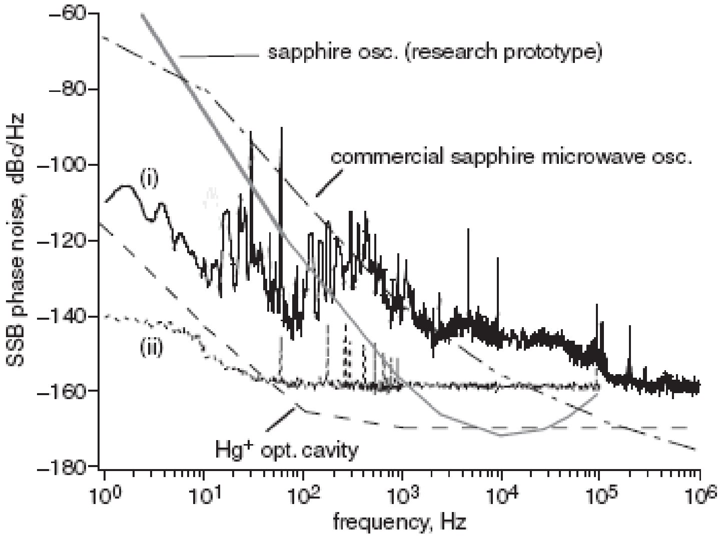


Figure 13. *Residual phase noise on 10 GHz harmonic of phase stabilised femtosecond laser frequency comb (curve (i)) compared to other low phase noise microwave sources*

Curve (ii) is noise floor of measurement system

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Below is the list of publications cited in this report. Reprints (pdf) of all publications of the NIST Time and Frequency Division, including the NIST publications listed below, are publicly and freely available on a searchable database:
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