NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Report to the 19th Meeting of the CCTF
Activities of the NIST Time and Frequency Division
September 2012

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 three 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. Primary Frequency Standard and Time Scale

1.1 NIST-F1 primary frequency standard

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 55 formal evaluations to BIPM, with uncertainties generally decreasing as improvements are made to the standard and its operational reliability improved. Eighteen formal evaluations were reported since the last CCTF meeting in May 2009. A NIST-F1 formal evaluation consists of measuring the frequency of one of the seven hydrogen masers at NIST compared to NIST-F1 and reporting the results and uncertainties to BIPM. [2, 3] The NIST ensemble of seven 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.

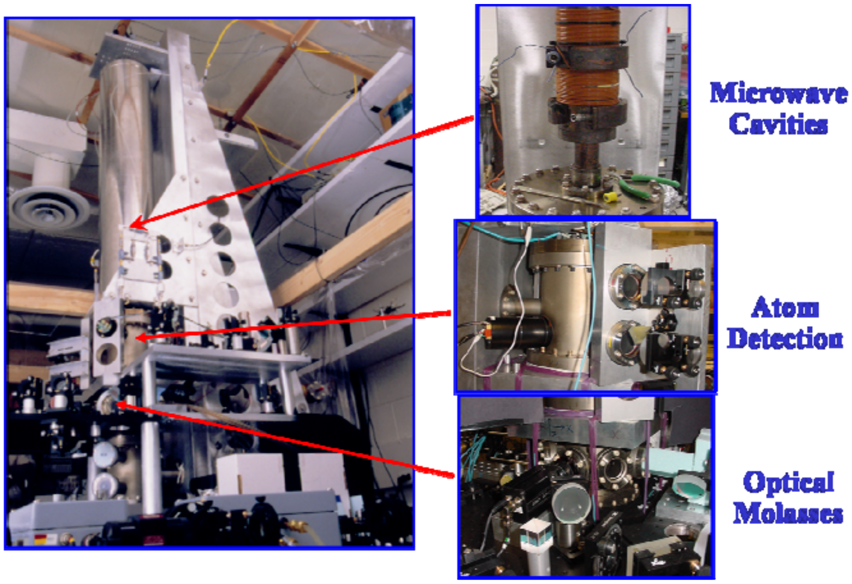


Figure 1. NIST-F1 primary frequency standard.

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. [1, 4]

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}).

Over the past two years, "in-house" uncertainties (u_A and u_B) have remained essentially constant for a given evaluation period. It is likely that NIST-F1 has reached the practical lower limit of its uncertainties. Further improvements will come with the full commissioning of the NIST-F2 second generation primary frequency standard.

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. [1, 5]

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., [6] will permit the reduction of atom densities by about an order of magnitude with a comparable reduction in the frequency shift uncertainty.

Several initial internal comparisons of NIST-F1 and NIST-F2 have been conducted over the past two years. A formal evaluation of NIST-F2 is expected around the beginning of 2013, including a comparison of NIST-F2 and NIST-F1 performance. The NIST-F1/F2 comparison will also provide an improved

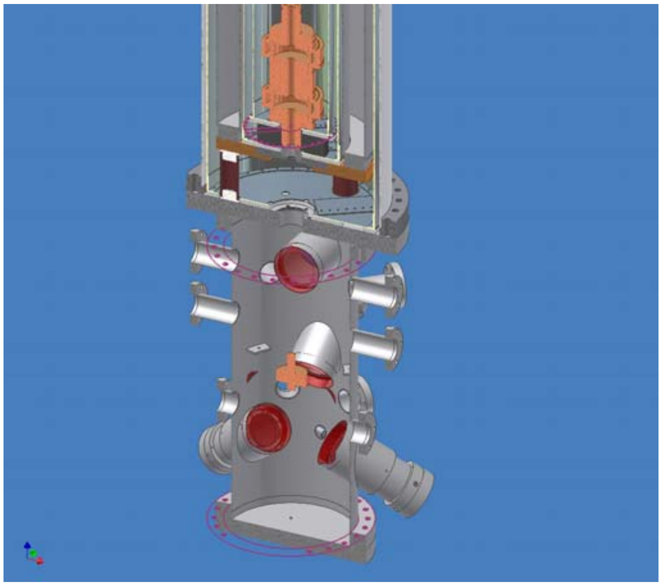


Figure 2. Schematic of NIST-F2 molasses, detection, and microwave cavity areas.

estimate of the cesium blackbody radiation shift.

1.3 NIST-Time Scale

The primary NIST Time Scale comprises seven active hydrogen masers and four high performance cesium beam standards located at NIST in Boulder, Colorado. [7] A secondary time scale comprising four high performance cesium beam standards is located at the site of NIST time and frequency radio stations WWV and WWVB approximately 100 km from Boulder. The two time scales are coordinated through common-view GPS. [8]

NIST is in the early stages of a multiyear project to expand and improve the NIST Time Scale through the addition of nine new active hydrogen masers, several new high performance cesium beam standards, and new digital measurement systems. [9] Several existing masers and cesium beam standards are nearing the end of their useful lives and will be retired as new clocks are introduced. When the Time Scale upgrade is completed in approximately 2015, NIST expects to have at least 10 active hydrogen masers and at least 10 high performance cesium beam standards regularly contributing to TAI.

2. Optical frequency standards

2.1 Aluminum ion“logic clock” optical frequency standards

The NIST Time and Frequency Division has constructed, tested, and continues to improve two experimental optical frequency standards based on the ${}^1S_0 \leftrightarrow {}^3P_0$ transition in a single trapped ${}^{27}Al^+$ ion (approximately 1.12 x 10^{15} Hz or approximately 267 nm). The most recent frequency standard demonstrated a fractional frequency uncertainty of 8.6 x 10^{-18} in 2010. [10]

The “logic clocks” are so named because they rely on some of the techniques developed as part of NIST’s research program on quantum information processing, including entanglement, superposition, and sympathetic laser cooling. Each of the two “logic clocks” uses relatively simple electromagnetic trap and laser cooling and excitation processes on a “logic ion” to indirectly excite and interrogate atomic states in the “clock ion.” This procedure permits the use of the excellent clock transition in the ${}^{27}Al^+$ ion, which has an excellent clock transition (${}^1S_0 \leftrightarrow {}^3P_0$, ~1.12 THz) with a long lifetime (~30 seconds), low sensitivity to magnetic fields, and no electric quadrupole shift – but which cannot be directly laser cooled or interrogated because of the deep ultraviolet radiation required (~167 nm). This limitation is overcome by simultaneously loading single logic ion (${}^9Be^+$ or ${}^{25}Mg^+$) and ${}^{27}Al^+$ clock ion into a linear Paul electromagnetic 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 logic ion, 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 logic ion for efficient detection. [11]

The first demonstration logic clock used ^{9}Be$^+$ as the logic ion, since NIST has extensive experience with this ion from quantum information processing research. The second frequency standard uses ^{25}Mg$^+$ as the logic ion, which is much closer in mass to the ^{27}Al$^+$ clock ion, and thus reduces some uncertainties due to asymmetric motions of the electromagnetically coupled logic and clock ions. [10]

The logic clock technology evolved directly from the NIST Time and Frequency Division programs in quantum information processing using laser-cooled, trapped ions. Developing quantum computing and quantum communications technologies 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. [12]

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

The two logic clock frequency standards have been intercompared with a relative stability of $2.8 \times 10^{-15}\ \tau^{-1/2}$. The two frequency standards have also permitted the most sensitive laboratory scale measurements of general and special relativistic effects on clocks, measuring clock shifts due to different elevations of a few centimeters near the surface of the earth, and due to relative motion of the ions different clocks by a few meters per second. [13] These measurements, coupled with expected improvement of the logic clock fractional frequency uncertainty to around 1×10^{-18}, emphasize the growing potential of optical frequency

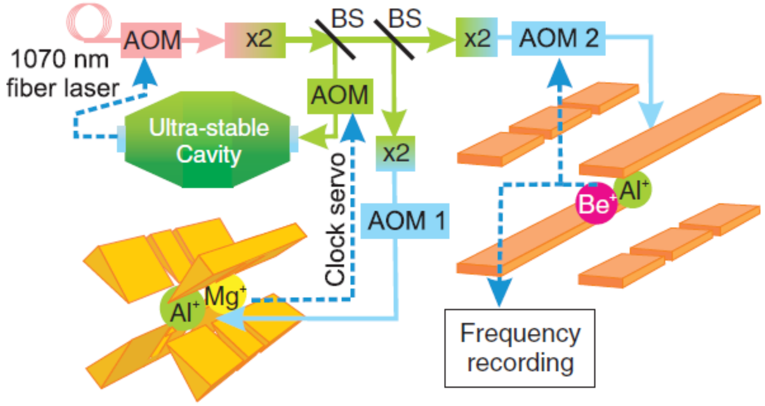


Figure 3. Schematic of intercomparison of two Al$^+$ "logic clocks."

standards as exquisite sensors of a variety of parameters, such as gravitational potential, magnetic field, motion and other quantities.

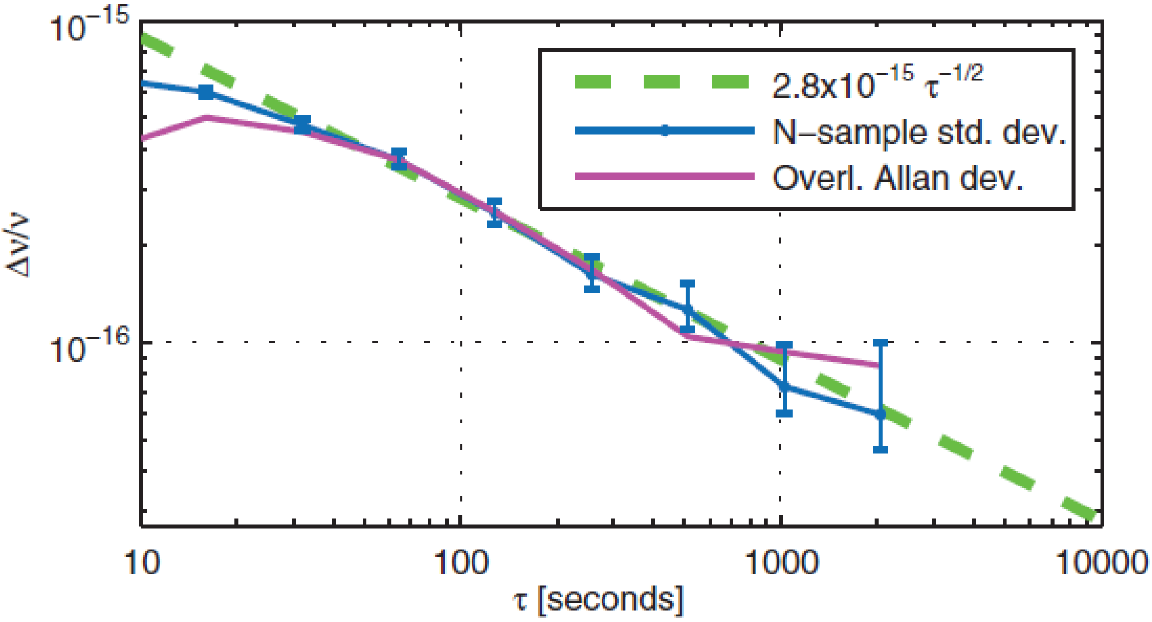


Figure 4. Stability of intercomparison between two Al$^+$ "logic clocks."

2.2 Single mercury ion optical frequency standard

NIST has continued development and systematic evaluation of optical frequency standards 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.

Figure 5. Jim Bergquist with mercury ion optical frequency standard.

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}. [14] A second mercury ion optical frequency standard is under development.

The long-term intercomparisons of the mercury ion frequency standard, the aluminum 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 five years placed an upper limit on any time variation in α of about 1.6 x 10^{-17} per year, a significantly reduced upper limit compared to previous measurements. [15]

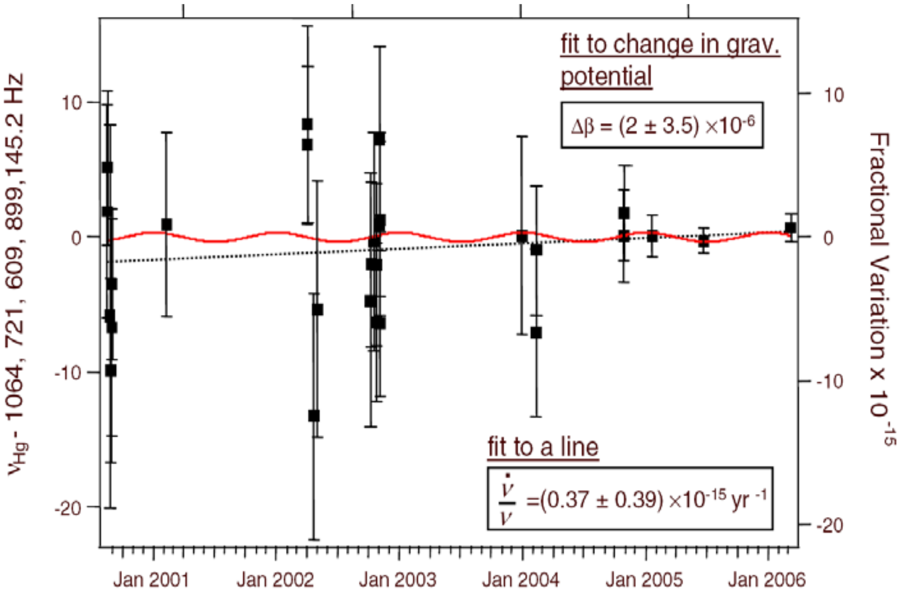


Figure 6. Comparisons of mercury ion optical frequency standard with NIST-F1 primary frequency standard, demonstrating significant reductions in uncertainties of the mercury ion frequency measurement in recent years.

2.3 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 x 10^{-15}). The calcium optical frequency standard continues to be an invaluable reference for extensive work using optical frequency combs, described below. [16]

NIST scientists have also begun developing a compact thermal calcium beam standard with an initial fractional frequency uncertainty better than 10^{-14} and a stability of better than 6 x 10^{-15} at one second of averaging. Still in the early stages of development and testing, this system has the potential to be a very useful compact frequency reference and flywheel for modest accuracy requirements. [17]

2.4 Neutral ytterbium lattice optical frequency standard

NIST continues research and development on optical frequency standards based on the $^1S_0 \leftrightarrow {}^3P_0$ clock transition (~579 nm) in ^{171}Yb atoms confined in optical lattices. 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. [18]

Informal measurements of Yb lattice clock performance demonstrate fractional frequency uncertainties in the high 10^{-17} range, with significant performance improvements continuing. Recent advances have included demonstrating unexpected p-wave ultracold collisions, which can lead to strong interaction suppression of collisional frequency shifts in two and three dimensional lattices [19], and precision measurement of the polarizability of lattice-confined Yb atoms reducing the blackbody frequency shift uncertainty to 3 x 10^{-17} near 300 K. [20]

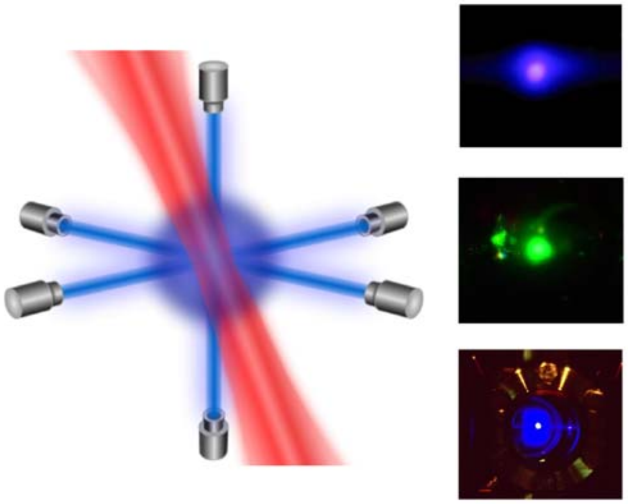


Figure 7. Photos and schematic of the NIST Yb lattice clock.

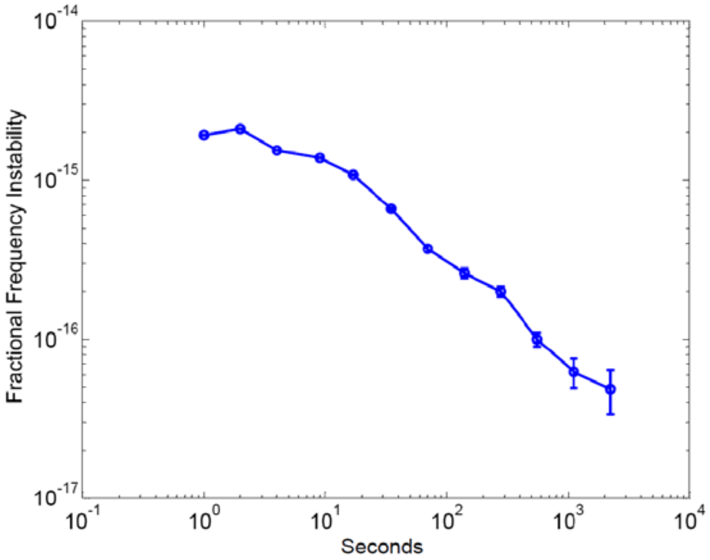


Figure 8. Fractional frequency instability of comparison between NIST Yb lattice clock and JILA Sr lattice clock. The two clocks are located about 1 km apart, and the comparison is mediated through a dedicated optical fiber linking the two sites.

2.5 Frequency combs

Substantial progress continues in the development and applications of femtosecond laser frequency combs, including expansion of spectral ranges into the ultraviolet and mid-infrared, expansion of repetition rates to the tens of GHz range [21], and demonstration of microscale frequency comb technologies [22]. Some of the growing range of applications beyond optical frequency standards include arbitrary optical waveform generation [21], trace gas analysis [23], high-stability wavelength reference for calibration of optical spectrographs used in exoplanet detection [24], and generation of ultralow noise radiofrequency and microwave signals based on optical frequency division [25].

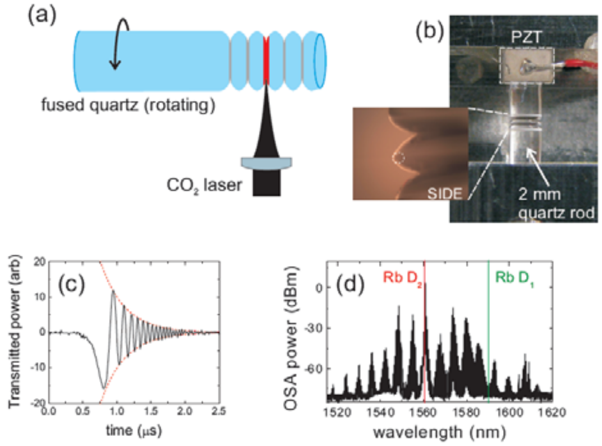


Fig. 9. (a) Schematic of our CO_2-laser machining system for creating ultrahigh Q microrod resonators for fused quartz. (b) Microrod resonator created with the setup in (a). The inset shows the profile of the 2 mm diameter resonator. The microrod is clamped with a PZT, which enables mechanical control the of the device's optical mode spectrum. (c) Ringdown measurement of the microrod optical Q. (d) Frequency-comb spectrum generated by way of nonlinear parametric oscillation and four-wave mixing in the microrod. The comb spectrum covers $\sim$ 100 nm about 1560 nm, and provides access to the D1 and D2 transitions of rubidium by way of second harmonic generation.

New microresonator techniques for frequency comb generation have the potential to lead to highly-miniaturized frequency combs that could be incorporated into complex instruments and devices providing a broad range of sensing, measurement and standards capabilities, such as combination with chip-scale atomic clocks, magnetometers and other sensors. These developments could lead to versatile new "laboratory on a chip" technologies for precision measurement of a broad range of quantities such as frequency, electric and magnetic fields, electrical quantities, length, temperature and other quantities.

Generation of microwaves and RF signals with extremely low phase noise (high spectral purity, low timing jitter) is becoming increasingly important in optical frequency standards and in a growing range of technology applications including remote sensing and surveillance, communications, and many other areas. Generation of low phase noise signals based on optical frequency combs combined with electronic sensing is already outperforming the best ultralow noise cryogenic microwave generation sources in many spectral ranges. NIST recently demonstrated 10 GHz signals generated from optical frequency comb dividers with timing jitter on the 400 attosecond level (4 x 10^{-16} second). [26]

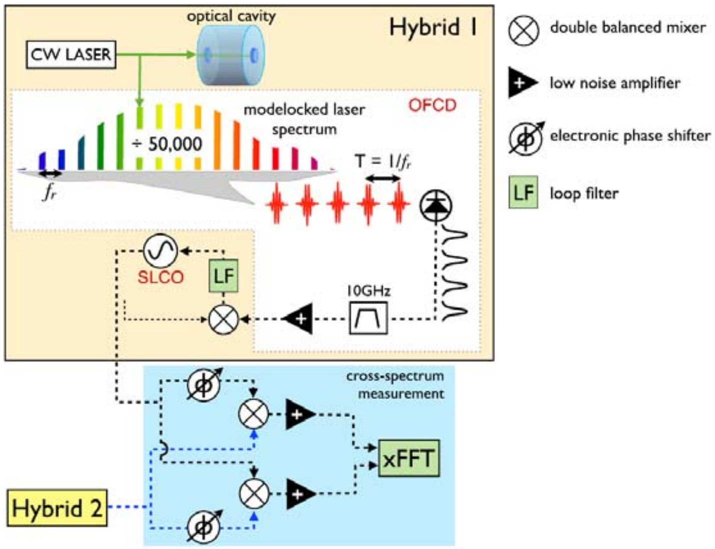


Fig. 10. Generation and characterization of 10 GHz signals from hybrid oscillators. Each hybrid oscillator is formed from the combination of laser-based and sapphire dielectric microwave oscillators. The optical frequency of the stable laser is divided down to the microwave domain with an OFCD. Photodetection of the laser pulse train results in a train of electronic pulses. The 10th harmonic of the laser repetition rate at 10 GHz is filtered with a bandpass filter and amplified. The 10 GHz microwave signal from an SLCO is phase locked to this electronic signal with a loop bandwidth of 5 kHz. Phase noise characterization of two independent, but similar, hybrid oscillators is accomplished via a cross spectrum measurement.

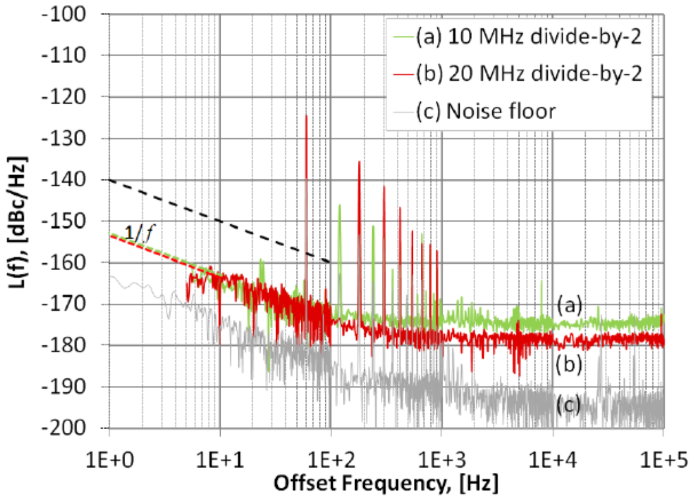
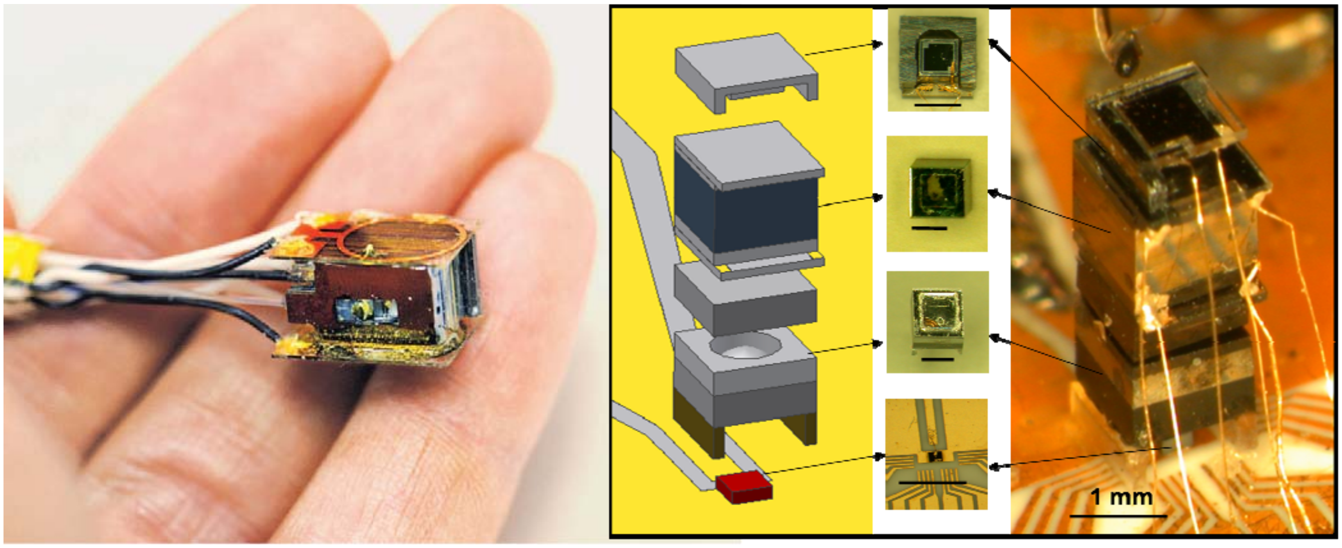


Figure 11. Single-sideband output referred phase noise of a NIST regenerative frequency divider.

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 devices based directly or indirectly on frequency measurements. [27] These devices include chip-scale atomic clocks – now being commercialized by at least three companies – magnetometers, gyroscopes, and related devices. Most NIST research in chip-scale atomic sensors exploits optical coherent population trapping approaches to probe microwave transitions without the need for relatively large cavities to directly generate microwaves. These devices include physics package sizes on the order of 10 mm^3, total device volume on the order 10 cm^3, total power consumption on the order of 100 mW, and frequency stability on the order of 10^{-10} / $\tau^{1/2}$. These ultraminiature atom- based sensors have the potential to greatly expand the nascent “laboratory on a chip” technology for a broad range of high accuracy and precision measurements. Combined with ultraminiature frequency combs (described earlier) and MEMS technology, these “laboratory on a chip” devices could provide easily transportable, SI-traceable measurements of frequency, length, electrical quantities, magnetic fields, temperature, pressure, and many other quantities.

Some recent NIST advances include the development and application of high-precision chip-scale atomic magnetometers for femtotesla-order measurements, including measurements of the extremely small magnetic fields generated by biological activity in heart, brain, and muscle tissue. [28] The NIST chip-scale atomic magnetometers operating at ambient temperature perform comparable to super-conducting quantum interference devices (SQuIDs) requiring cryogenic cooling and large-scale sensors and electronics.



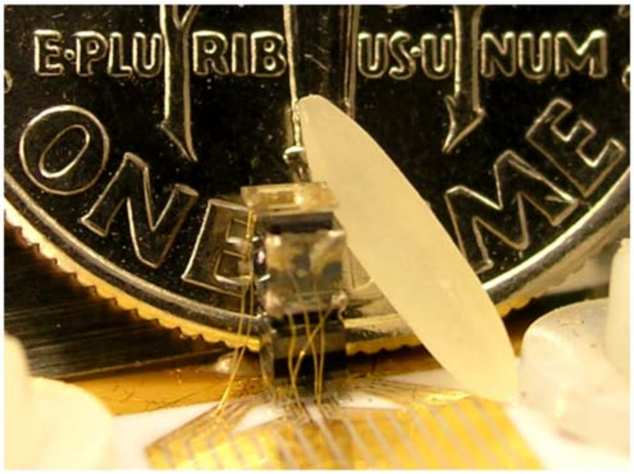


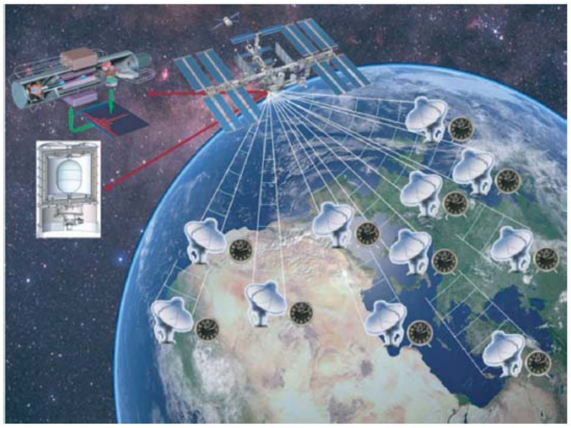
Figure 12. NIST chip-scale atomic magnetometer sensor package (top left) used in biomagnetic measurements. NIST chip-scale atomic clock (above and left) physics package. The magnetometer physics package is very similar in size and constructioh.

NIST is also pursuing ultraminiature cold-atom atomic sensors using coherent population trapping in laser-cooled systems, with the potential for $10^{-11} / \tau^{1/2}$ stability and 10^{-13} accuracy in a 10 cm^3 package. Preliminary results are highly encouraging. [29]

3. Time and Frequency Dissemination

3.1 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). As part of the longer-term upgrade of the NIST Time Scale and distribution systems, NIST plans to install a new high performance Ku-band ground station by 2015.



NIST is also partnering with the European Space Agency (ESA) and NASA to host a Microwave Link Ground Terminal (MWL GT) as part of the Atomic Clock Ensemble in Space (ACES) program, expected to fly on the International Space Station in 2015. NIST will be able to participate in significantly improved international time and frequency transfer mediated through the ACES project, including intercomparisons of NIST's primary frequency standards and multiple optical frequency standards.

Figure 13. Schematic of ACES-mediated time and frequency transfer from the International Space Station. (ESA figure.)

3.3 Internet Time Service

Use of the NIST Internet Time Service (ITS) to automatically synchronize computer clocks continues to grow, averaging more than 13 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.

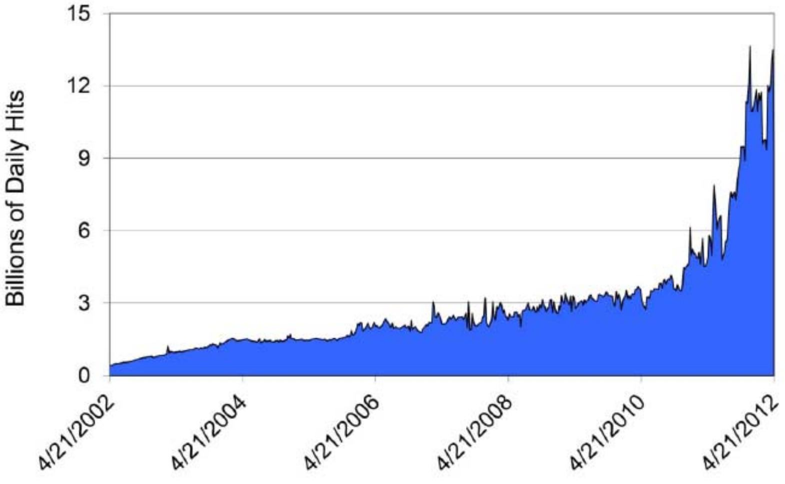


Figure 14. Trends in utilization of NIST Internet Time Service.

To meet this demand, NIST continues to expand the number of servers, now totaling 29 servers at 25 locations throughout the United States. NIST also continues to upgrade the servers. [30] NIST also offers an authenticated NTP service that includes additional messages to registered clients assuring that the timing message was generated from a NIST time server and was not maliciously or inadvertently altered in transmission. [31]

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. A major upgrade is being planned. 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 most electronic transactions, such as those on the New York and NASDAQ stock exchanges, to NIST time, and ACTS is one convenient method of establishing such traceability.

3.6 Radio stations

NIST broadcasts low frequency (60 kHz) digital 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 70 kW, nearly all parts of the 48 contiguous United States receive sufficiently strong radio signals to permit synchronization of commercial timepieces at night. However, 60 kHz radio frequency interference is becoming stronger in many areas, especially urban areas, making it difficult for the receivers to obtain the WWVB signal against the increasing background noise.

NIST has partnered with a US company to experiment with the addition of binary phase shift keying modulation to the existing amplitude modulated digital time codes. [32] This addition of phase modulation will enable a new type of receiver to have much better discrimination of the WWVB signal against background noise, effectively increasing the signal strength by about 10 dB. The new time code system remains compatible with existing time code receivers. The new protocol does prevent the use of the WWVB 60 kHz carrier signal as a reference frequency in phase locked loop receivers, but this application is quite limited and substitute systems are available. NIST has conducted several periods of test broadcasts of a few days each using the new broadcast protocol, with no significant problems encountered. After further successful tests and management approval, the new broadcast protocol will be permanently implemented.

NIST published a recommended practice guide (updated in 2009) for manufacturers and users of radio-controlled timepieces to optimize performance and usability. The pdf version of this guide been downloaded more than 3 million times so far from the freely available Time and Frequency Division publication database [33]:
http://tf.boulder.nist.gov/general/pdf/2422.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 completion of a major antenna replacement program at WWVH and significant automation improvements at WWV to 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 $2x10^{-13}$ per day, customers receive monthly written calibration reports compliant with ISO Guides 25 and 17025 and the ANSI Z-540 standard. [34]

3.8 NIST Time Measurement and Analysis Service

The NIST Time Measurement and Analysis Service provides 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. [35]

Figure 15. Measurement system provided to customers of NIST Time Measurement and Analysis Service. Very similar systems are used for the SIM Time Network described below.

3.9 SIM Time Network

Seventeen laboratories representing nations of Systema Interamericano de Metrologia (SIM) are currently participating in coordination of time and frequency through the SIM Time Network, with 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). [36]

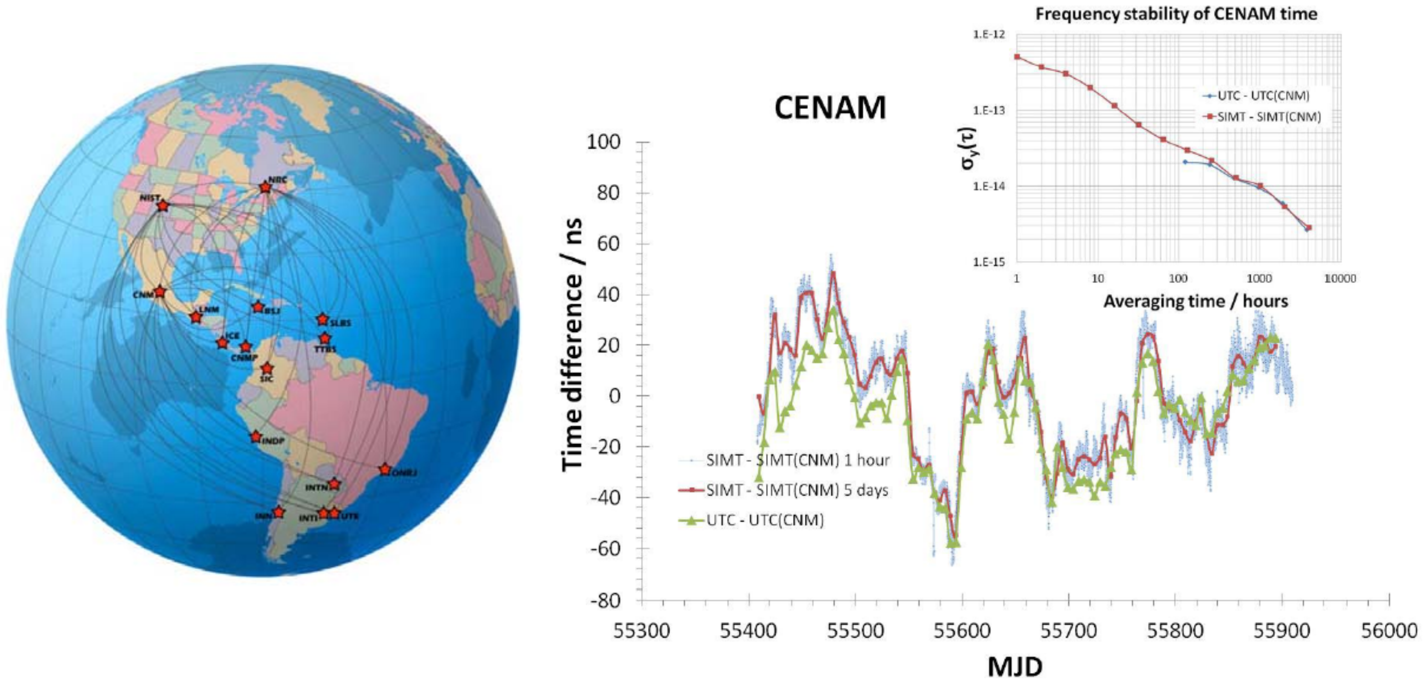


Figure 16. SIM Time Network. As an example of SIM Time Network performance, comparison of CENAM time with UTC and with SIM Time over a period of about 500 days.

4. Additional Information

4.1 Quantum Information Processing and Quantum Simulation Research

The NIST Time and Frequency Division conducts a vigorous program in quantum computing and quantum simulation using arrays of trapped ions. [37] These programs will not be directly discussed here, but more information is available at: http://www.nist.gov/pml/div688/grp10/index.cfm

The Time and Frequency quantum computing program is relevant to time and frequency activities since the program evolved directly from quantum state engineering research as part of developing trapped ion frequency standards, and since the technologies developed in the quantum computing program have directly enabled the aluminum ion “logic clock” frequency standards.

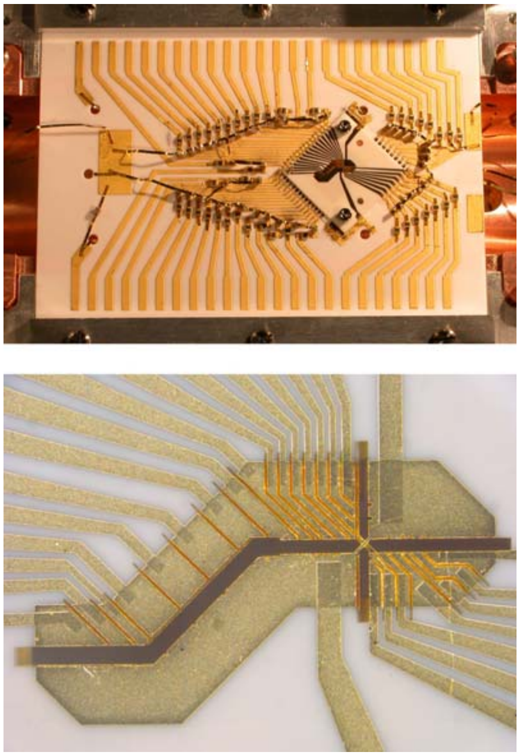


Figure 17. Example of multizone ion trap used in NIST quantum computing research. The multiple zones represent independent electromagnetic trapping regions. Beryllium ions used as qubits can be efficiently transferred among the different zones to accomplish various quantum logic operations. The gap in the lower photo (enlarged version of the top photo) is on the order of 1 mm.

4.2 New Facilities for NIST Time and Frequency Division

In 2012 a new advanced NIST laboratory was completed at NIST in Boulder, Colorado. [38] The US$120 million Precision Measurement Laboratory (PML) includes approximately 5,000 net assignable square meters of advanced laboratory space with tight control of temperature, vibration, humidity and air quality. Before the PML was completed, most laboratory space at NIST Boulder was in buildings nearly 60 years old, and not able to provide the stringent environmental control needed for the most advanced research and metrology.

Programs of the Time and Frequency Division will occupy approximately 2,000 square meters (40%) of the new laboratory, representing an approximately 30% increase in total space for Division activities. But the primary benefit of the PML is the much higher performing laboratory space compared to the older facilities. Time and Frequency programs that do not require the stringent environmental control will remain in the existing facilities.

As of summer 2012, about half of the new Time and Frequency Laboratories have been occupied. The remaining programs will migrate to the new PML over the next several months.

Figure 18. New Precision Measurement Laboratory (PML) at NIST in Boulder, Colorado, USA. The PML provides high performance laboratory space with tight control of temperature, vibration, humidity and air quality to facilitate the most demanding metrology and research. The PML was dedicated in April 2012 and will house many of the NIST Time and Frequency activities.

The aerial photo at left shows the new PML (under construction) adjacent to the previous main NIST Boulder laboratory facilities. The older facilities were constructed in 1954.

References

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:
http://tf.nist.gov/general/publications.htm

1. T. Heavner, T. Parker, J. Shirley, P. Kunz, and S. Jefferts, *NIST F1 and F2*, Proc. 2010 PTTI Mtg., 457-463 (2010).

2. T.E. Parker, S.R. Jefferts, T.P. Heavner, and E.A. Donley, *Operation of the NIST-F1 caesium fountain primary frequency standard with a maser ensemble, including the impact of frequency transfer noise,* Metrologia **42**, pp. 423-430 (2005).

3. T.E. Parker and S.R. Jefferts, *Operation of a Primary Frequency Standard in the Real World*, IEEE CPEM 2012 Conf. Dig., 180-181 (2012).

4. S.R. Jefferts, T.P. Heavner, T.E. Parker, and J.H. Shirley, *NIST Cesium Fountains - Current Status and Future Prospects,* Proc. 2007 SPIE Conf. **6673**, 667309-1 – 667309-9 (2007).

5. T.P. Heavner, T.E. Parker, J.H. Shirley, L. Donley, S.R. Jefferts, F. Levi, D. Calonico, C. Calosso, G. Costanzo, and B. Mongino, *Comparing Room Temperature and Cryogenic Cesium Fountains,* Proc. 2011 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 48-50 (2011).

6. F. Levi, A. Godone, L. Lorini, *Reduction of the Cold Collision Frequency Shift in a Multiple Velocity Fountain: A New Proposal*, IEEE Trans. Ultrason. Ferr, **48**, pp 847-853 (2001).

7. T.E. Parker, The uncertainty in the realization and dissemination of the SI second from a systems point of view, Rev. Sci. Instrum., **83**, 021102-7 (2012).

8. J. Levine, *Realizing UTC(NIST) at a remote location*, Metrologia 45, S23-S33 (2008).

9. S. Romisch, S.R. Jefferts, and T.E. Parker, *Towards an All-digital Time Scale,* Proc. 2011 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf. 685-689 (2011).

10. C.W Chou, D. Hume, J.C.J. Koelemeij, D.J. Wineland, and T. Rosenband, *Frequency Comparison of Two High-Accuracy Al+ Optical Clocks*, Phys. Rev. Lett. **104**, 070802-4 (2010).

11. T. Rosenband, P.O. Schmidt, D. Hume, W.M. Itano, T. Fortier, J. Stalnaker, K. Kim, S.A. Diddams, J. Koelemeij, J.C. Bergquist, and D.J. Wineland, *Observation of the ^1S_0-^3P_0 Clock Transition in ^27Al^+*, Phys. Rev. Lett. **98**, 220801-4 (2007).

12. D.J. Wineland and D. Leibfried, *Quantum information processing and metrology with trapped ions*, Laser Phys. Lett. **8**, 175-188 (2011).

13. C.W. Chou, D. Hume, T. Rosenband, and D.J. Wineland, *Optical Clocks and Relativity*, Science **329**, 1630-1633 (2010).

14. T. Rosenband, D.B. Hume, P.O. Schmidt, C.W. Chou, A. Brusch, L. Lorini, W.H. Oskay, R.E. Drullinger, T.M. Fortier, J.E. Stalnaker, S.A. Diddams, W.C. Swann, N.R. Newbury, W.M. Itano, D.J. Wineland, and J.C. Bergquist, *Frequency Ratio of Al+ and Hg+ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place*, Science **319**, 1808-1812 (2008).

15. T. Fortier, N. Ashby, J.C. Bergquist, M.J. Delaney, S.A. Diddams, T.P. Heavner, L. Hollberg, W.M. Itano, S.R. Jefferts, K. Kim, F. Levi, L. Lorini, W.H. Oskay, T.E. Parker, J.H. Shirley, and J.E. Stalnaker, *Precision Atomic Spectroscopy for Improved Limits on Variation of the Fine Structure Constant and Local Position Invariance,* Phys. Rev. Lett. **98**, 070801-4 (2007).

16. G. Wilpers, C.W. Oates, S.A. Diddams, A. Bartels, W.H. Oskay, J.C. Bergquist and L. Hollberg, *Ultra-high Stability Optical Frequency Standard Based on Laser-Cooled Neutral Calcium*, Proc. 2005 Conf. Lasers and Electro-Optics, pp. 1405-1407 (2005).

17. R.W. Fox, J.A. Sherman, W. Douglas, J.B. Olson, A.D. Ludlow, and C.W. Oates, *A high stability optical frequency reference based on thermal calcium atoms*, Proc. 2012 IEEE Intl. Freq. Cont. Symp. 404-406 (2012).

18. N. Lemke, A.D. Ludlow, Z. Barber, T. Fortier, S.A. Diddams, Y. Jiang, S.R. Jefferts, T.P. Heavner, T.E. Parker, and C.W. Oates, *A Spin-1/2 Optical Lattice Clock*, Phys. Rev. Lett. **103**, 063001-4 (2009).

19. N.D. Lemke, J. von Stecher, J.A. Sherman, A.M. Rey, C.W. Oates, and A.D. Ludlow, *p-Wave Cold Collisions in an Optical Lattice Clock*, Phys. Rev. Lett. **107**, 103902-5 (2011).

20. J.A. Sherman, N.D. Lemke, N. Hinkley, M. Pizzocaro, R.W. Fox, A.D. Ludlow, and C.W. Oates, *High-Accuracy Measurement of Atomic Polarizability in an Optical Lattice Clock,* Phys. Rev. Lett. **108**, 153002-5 (2012).

21. S.A. Diddams, *The evolving optical frequency comb,* J. Opt. Soc. Am. **B27**, B51-B62 (2011).

22. S.B. Papp, P. Del'Haye, and S.A. Diddams, *Mechanical stabilization of a microrod-resonator optical frequency comb,* Proc. 2012 IEEE Intl. Freq. Cont. Symp. 765-767 (2012).

23. L. Nugent-Glandorf, T. Neely, F. Adler, A.J. Fleisher, K.C. Cossel, B. Bjork, T. Dinneen, C. Wood, J. Ye, and S.A. Diddams, *Mid-infrared virtually imaged phased array spectrometer for rapid and broadband trace gas detection,* Opt. Lett. **37**, 3285-3287 (2012).

24. G.G. Ycas, F. Quinlan, S.A. Diddams, S. Osterman, s. Mahadevan, S. Redman, R. Terrien, L. Ramsey, C.F. Bender, B. Botzer, and S. Sigurdsson, *Demonstration of on-sky calibration of astronomical spectra using a 25 GHz near-IR laser frequency comb*, Opt. Express **20**, 6631-6643 (2012).

25. Hati, C.W. Nelson, C. Barnes, D. Lirette, J. A. DeSalvo, T. Fortier, F. Quinlan, A. Ludlow, T. Rosenband, S.A. Diddams, and D.A. Howe, *Ultra-low-noise Regenerative Frequency Divider for High Spectral Purity RF Signal Generation,* Proc. 2012 IEEE Intl. Freq. Cont. Symp. 625-628 (2012).

26. T.M. Fortier, C.W. Nelson, A. Hati, F. Quinlan, J. Taylor, H. Jiang, C.W. Chou, T. Rosenband, N. Lemke, A. Ludlow, D. Howe, C.W. Oates and S.A. Diddams, *Sub-femtosecond absolute timing jutter with a 10 GHz hybrid photonic-microwave oscillator,* Appl. Phys. Lett. **100**, 231111-3 (2012).

27. J. Kitching, S. Knappe, and E. Donley, *Atomic Sensors - A Review*, IEEE Sens. J. **11**, 1749-1758 (2011).

28. T.H. Sander, J. Preusser, R. Mhaskar, J. Kitching, L. Trahms, and S. Knappe, *Magnetoencephalography with a chip-scale atomic magnetometer*, Biomed. Opt. Express **3**, 981-990 (2012).

29. F.-X. Esnault, J. Kitching, and E.A. Donley, *A Compact Cold-Atom Frequency Standard Based on Coherent Population Trapping,* Proc. 2012 IEEE Intl. Freq. Cont. Symp., 697-699 (2012).

30. J. Levine, *Improvements to the NIST network time protocol servers,* Metrologia **45**, S12-S22 (2008).

31. http://www.nist.gov/pml/div688/grp40/auth-ntp.cfm

32. J. Lowe, M. Deutch, G. Nelson, D. Sutton, W. Yates, P. Hansen, O. Eliezer, T. Jung, S. Morrison, Y. Liang, D. Rajan, S. Balasubramanian, A. Ramasami, and W. Khalil, *New Improved System for WWVB Broadcast*, Proc. 2011 PTTI Mtg., 163-184 (2012).

33. M.A. Lombardi, A.N. Novick, J.P. Lowe, M.J. Deutch, G.K. Nelson, D.D. Sutton, W.C. Yates, and D.W. Hanson, *WWVB Radio Controlled Clocks: Recommended Practices for Manufacturers and Consumers (2009 edition)*, NIST Spec. Publ. 960-14, 68 p. (2009).

34. M.A. Lombardi, *Remote Frequency Calibrations: The NIST Frequency Measurement and Analysis Service,* NIST Spec. Publ. 250-29 90 p. (2004).

35. M.A. Lombardi and A.N. Novick, *The NIST Time Measurement and Analysis Service*, Proc. 2006 NCSLI Conf. 18 p. (2006).

36. M. A. Lombardi, A.N. Novick, J.M. Lopez-Romero, F. Jimenez, E. de Carlos-Lopez, J.S. Boulanger, R. Pelletier, R. de Carvalho, R. Solis, H. Sanchez, C.A. Quevedo, G. Pascoe, D. Perez, E. Bances, L. Trigo, V. Masi, H. Postigo, A. Questelles, and A. Gittens, *The SIM Time Network*, J. Res. Natl. Inst. Stan. **116**, 557-572 (2011).

37. D.J. Wineland and D. Leibfried, *Quantum information processing and metrology with trapped ions,* Laser Phys. Lett.**8**, 175-188 (2011).

38. http://www.nist.gov/public_affairs/factsheet/pmlboulder-brochure.cfm