NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Report to the 21st Meeting of the CCTF
Activities of the NIST Time and Frequency Division
June 2017

This 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 2-3 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

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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 65 formal evaluations to BIPM, with uncertainties generally decreasing as improvements are made to the standard and its operational reliability improved. 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.

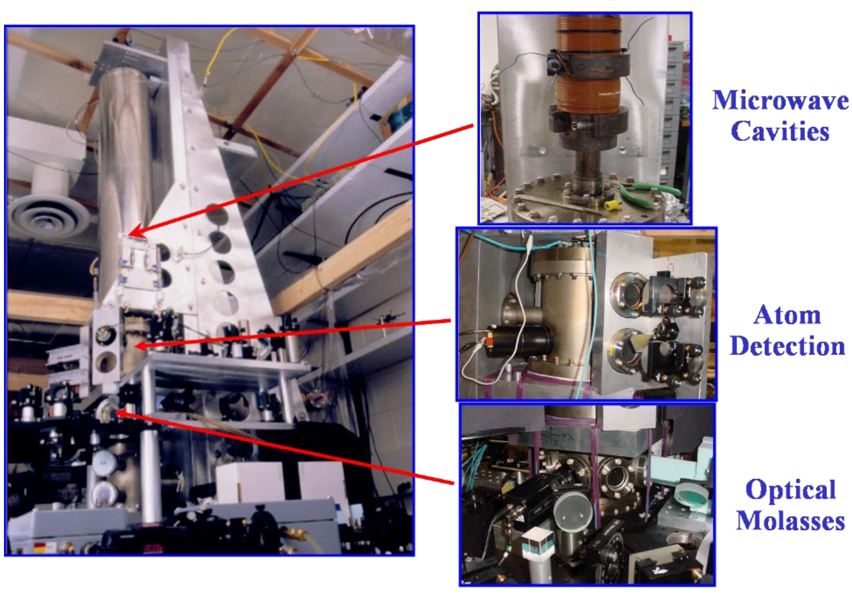

Figure 1. NIST-F1 primary frequency standard.

Recently NIST-F1 has been undergoing a relocation and reconstruction which has resulted in the need to reperform many of the tests validating its performance in its new location. It is believed that this process is essentially complete and that NIST-F1 will be submitting new evaluations on a regular basis in the near future.

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 80 K to about 320 K. [1,4-5]

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.

Since the last NIST formal report to the CCTF, NIST-F2 has been approved by the Working Group on Primary and Secondary Frequency Standards and has submitted 5 formal frequency evaluations for inclusion into TAI.

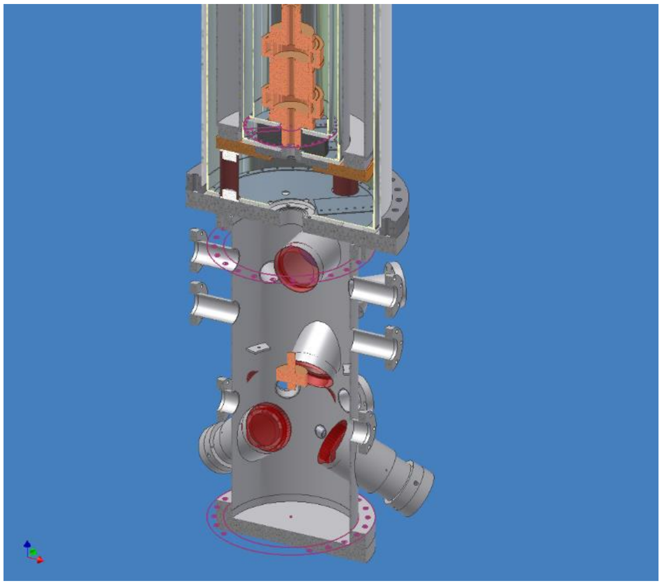

Figure 2. Schematic of NIST-F2 molasses, detection, and microwave cavity areas.

1.3 NIST-Time Scale

The primary NIST Time Scale comprises eight active hydrogen masers and six 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] The number of clocks regularly contributing to TAI has increased to 17 (8 active hydrogen masers and 9 high performance Cesium beam standards) and will continue to increase as the last of the most recently acquired active hydrogen masers will be included.

A new set of laboratories has been activated in a new building on campus offering much improved environmental conditions for the instrumentation and the clocks. The transfer of the generation of UTC(NIST) to the new laboratories hasn't been completed yet, but a core number of active hydrogen masers is already installed, together with the necessary measurement and monitoring infrastructure. A continuously-running cold-atom fountain is under construction and when completed in 2018, will be the foundation of the new NIST time scale, significantly improving its performance.

Recent improvements in the reliability of the optical standards under development at NIST are enabling a significant effort towards the inclusion of their frequency information into the generation of the future NIST time scale as well.

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2. Optical frequency standards

2.1 Aluminum ion "quantum-logic clock" optical frequency standard

NIST has continued the development of experimental optical frequency standards based on the $^1S_0 \leftrightarrow {}^3P_0$ transition of single, trapped $^{27}Al^+$ ions at 1.12×10^{15} Hz (267 nm).

The "quantum-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 quantum-logic clocks uses relatively simple electromagnetic trapping and laser cooling/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 a long lifetime (20 s), low sensitivity to electric and magnetic fields, and a vanishingly small 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 a single logic ion ($^9Be^+$, $^{25}Mg^+$, or $^{40}Ca^+$) and a single $^{27}Al^+$ clock ion into a linear Paul electromagnetic trap. The two ions form a stable crystal, and the motional modes can be 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 (267 nm), and the quantum state of the $^{27}Al^+$ ion can be transferred to the logic ion for efficient detection [9].

The first-generation $^{27}Al^+$ frequency standard used $^9Be^+$ as the logic ion and reached a systematic fractional frequency uncertainty of 2.3×10^{-17} in 2008 [10], while the second-generation $^{27}Al^+$ frequency standard used $^{25}Mg^+$ as the logic ion and reached a systematic fractional frequency uncertainty of 8.6×10^{-18} in 2010 [11]. The dominant source of uncertainty in both frequency standards was second-order time dilation shifts due to imperfections and noise in the electric field of the ion trap.

Currently, a third-generation $^{27}Al^+$ quantum-logic clock is under development with the goal of reduced systematic uncertainty due to motional time dilation shifts. As in the second-generation system, $^{25}Mg^+$ is used as the logic ion. The third-generation frequency standard is based on a new ion trap design with improved control of the electric field geometry and reduced electric field noise. The associated lower motional heating rates have made it possible to operate the frequency standard with the motion cooled to near the quantum mechanical ground state, resulting in a reduction of the secular motion time dilation shift to $(-1.9 \pm 0.1) \times 10^{-18}$. This shift is dominated by the quantum mechanical zero-point energy of the ions' motion, and its uncertainty is a factor of 50 lower than that of the second-generation frequency standard [12]. Work is ongoing to complete the uncertainty evaluation of the remaining systematic frequency shifts.

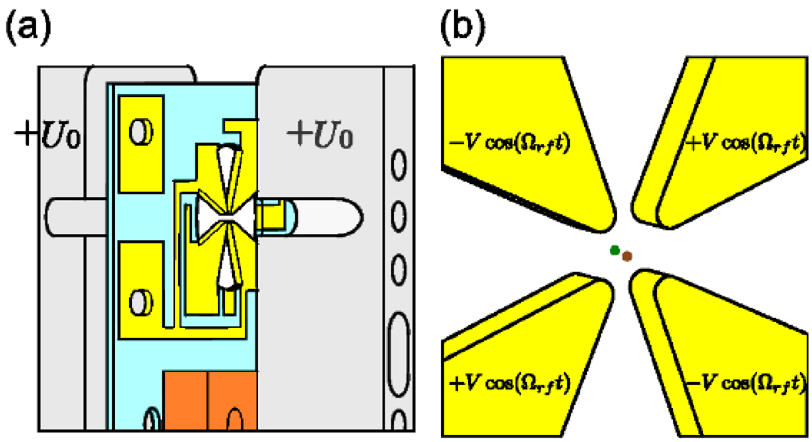


Figure 3. New ion trap used in the third-generation $^{27}Al^+$ frequency standard. (a) Drawing of the trap electrodes. (b) Enlarged view of the four rf electrodes with the clock and logic ions shown as green and brown dots. Reproduced from [12].

Comparison measurements have demonstrated the potential of these frequency standards as exquisite sensors of a variety of parameters, such as time variations of the strengths of the fundamental physical interactions [10] as well as gravitational potentials and motion [13]. Improved sensitivity to these and other quantities will require lower systematic uncertainties as discussed above as well as improved clock comparison measurement stabilities. While the stability of single ion frequency standards is fundamentally limited by quantum projection noise, NIST has designed measurement protocols that will allow the probe time to be extended beyond the laser coherence time and ultimately to the excited state lifetime, thereby reducing the contribution of quantum projection noise to comparison measurement instability [14].

2.2 Mercury ion optical frequency standard

NIST continues to work on optical frequency standards based on the 1.06×10^{15} Hz (282 nm) electric quadrupole transition of single trapped $^{199}Hg^+$ ions. The standards use cryogenic spherical Paul electromagnetic traps to enable storage of single, trapped ions for up to 100 days. The $^{199}Hg^+$ frequency standard reached a systematic fractional frequency uncertainty of 1.7×10^{-17} in 2008 [10], and has been involved in several comparison measurements with the aluminum ion frequency standards and the NIST-F1 cesium frequency standard since 2001. Future comparison measurements involving the $^{199}Hg^+$ frequency standard would be invaluable both as a test of the long-term reproducibility of optical frequency standards and to improve constraints on the possible time variation of the fine structure constant, which is predicted by models of dark matter and physics beyond the standard model, and to which the clock transition of $^{199}Hg^{+}$ is highly sensitive.

2.3 Neutral calcium optical frequency standard

Over the last several years, NIST scientists have continued development of a compact optical frequency standard based on a thermal calcium beam in a Ramsey-Borde interferometer. Despite the apparatus' simplicity, including no need of laser cooling, this optical frequency standard has exhibited a short-term instability as low as 2 x 10^{-16} at 10 seconds, remaining at or below 5 x 10^{-16} from 1 to 1000 seconds. Experimental analysis of the frequency stabilization signal-to-noise ratio suggest that ten times improvement in short-term instability should be possible. While still under development, this system has the potential to be a very useful compact frequency reference and flywheel for applications requiring excellent frequency stability at short and intermediate times.

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 (578 nm) in ^{171}Yb atoms confined in optical lattices. As with all lattice clocks, large numbers of neutral atoms are trapped in far off-resonance optical lattices designed to realize quasi-zero light shift of the clock transition. Doing so enables the combination of high signal-to-noise ratio with long interaction times and Doppler-free spectroscopy.

Recent efforts at NIST have focused on pushing both the instability and systematic uncertainty of the ytterbium optical lattice clock to new levels. The instability of most optical clocks has been limited by the Dick effect: aliasing of frequency noise on the laser used to interrogate the clock transition [15,16]. By working to minimize Dick noise contributions, the NIST ytterbium lattice clock has demonstrated a fractional frequency measurement instability of 1.4 x 10^{-16} in just one second ([17], see figure). Indeed, by merging two ytterbium lattice clocks systems into a single, hybrid 'zero-dead-time' clock, the Dick effect can be virtually eliminated. In this case, the NIST ytterbium zero-dead-time clock can realize a measurement instability of 6 x 10^{-17} at one second [17]. The frequency instability continues to average down as white frequency noise, reaching a level of nearly 1 x 10^{-18} in just a few thousand seconds of measurement [15,16].

In order to achieve systematic frequency uncertainty of the NIST Yb lattice clock at the same level as its demonstrated frequency instability, NIST has carried out an updated and detailed systematic uncertainty evaluation. Efforts first focused on the largest systematic frequency shift, the blackbody Stark effect. This included a high-accuracy measurement of the differential static polarizability for the Yb clock transition [18] and a precise determination of the dynamic correction to the blackbody shift [19]. It further included the design and construction of a thermal radiative enclosure that enables the precise determination of the blackbody environment bathing the lattice-trapped ytterbium atoms [20]. Taken together, the room-temperature blackbody Stark shift could be determined at a level corresponding to 1 x10^{-18} clock uncertainty [20].

Subsequent efforts in the uncertainty evaluation focused on the lattice light shifts. While most light shifts are eliminated by operating the optical lattice at the so-called magic wavelength, higher-order Stark effects are not eliminated, causing a breakdown of the magic wavelength concept. Some of these higher-order effects include hyperpolarizability and higher multi- polarizabilities. To add further complexity, the magnitude of these higher-order light shifts depends on finite temperature effects of the lattice-trapped atoms. These effects were precisely characterized, enabling all lattice light shifts to be determined at the 1×10^{-18} clock uncertainty level [21]. Combined with a range of other systematic shifts investigated, the total systematic uncertainty of the NIST Yb lattice clock now lies in the low 10^{-18} level, a result currently being prepared for publication.

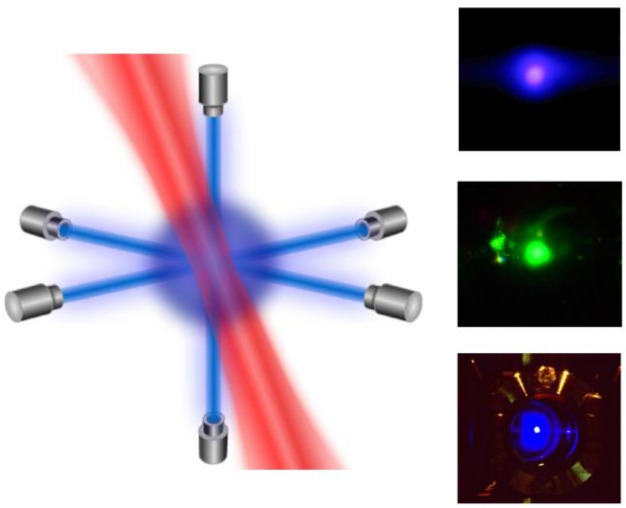


Figure 4. Photos and schematic of the NIST Yb lattice clock.

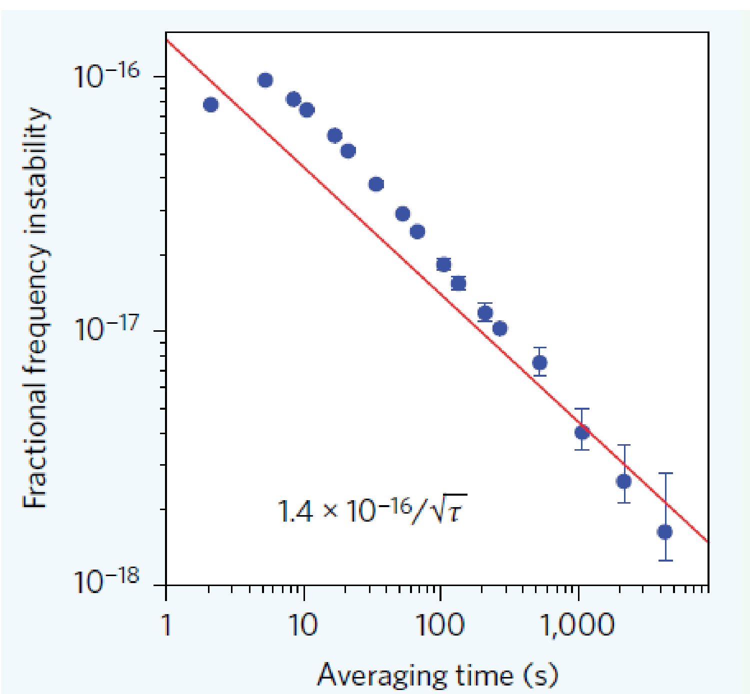


Figure 5. Fractional frequency instability of Yb lattice clock at NIST, measured by direct comparison between two distinct Yb clocks.

2.5 **Frequency combs**

Substantial progress continues in the development and applications of laser frequency combs. Primary activities include: (1) the continued development of laser frequency combs for precision clock comparison and frequency synthesis [22,23]; (2) the extension and application of frequency combs across the visible, infrared and terahertz regions for direct frequency comb spectroscopy and trace gas sensing [24-28]; (3) the investigation of a new type of frequency comb based on parametric oscillation in micro-resonators [29-31]; and (4) the development and application of 10+ GHz frequency combs for astronomical spectrograph calibration aimed at exoplanet searches [32-34]. Here we highlight just a few of the many advances in these areas.

New techniques for frequency comb generation in micro-resonators 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 in combination with chip-scale atomic clocks, magnetometers and other sensors. Such developments will 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. Some examples of devices and micro resonator frequency combs are shown in **Figure 6.**

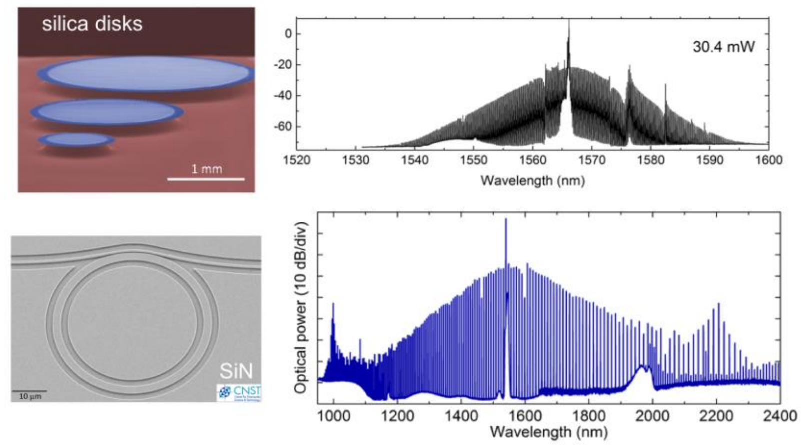


Fig. 6. Examples of microresonator frequency combs. (top left) Silica disk resonators on a silicon substrate, and (upper right) typical 22 GHz soliton microcomb generated with a CW pump laser at 1560 nm. (bottom left) Silicon nitride microring resonator on silicon, and (bottom right) octave span comb with 1 THz mode spacing.

Generation of optical, microwave and RF signals with extremely low phase noise (high spectral purity, low timing jitter) is becoming increasingly important for research in 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 the extension of these techniques up to 100 GHz, with W-band signals having absolute instability at the 10^{-15} level [22]. **Figure 7** shows the system and representative data.

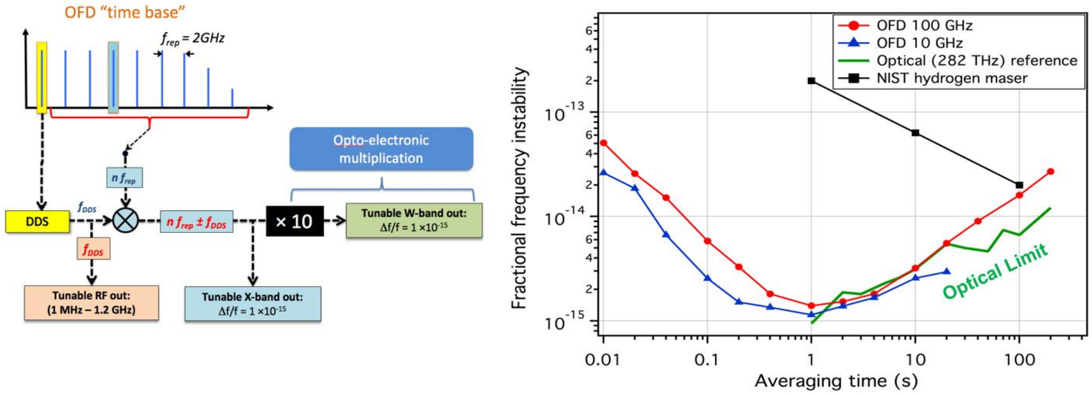
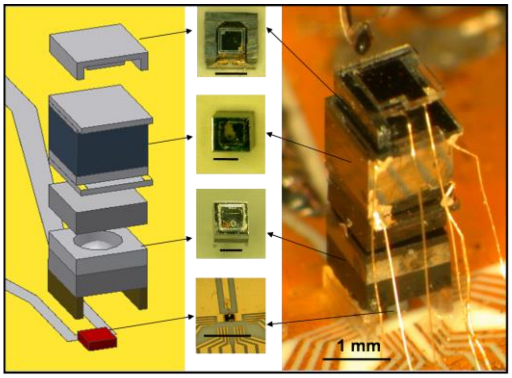


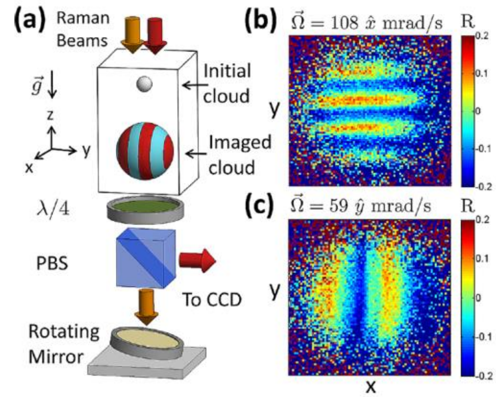
Fig. 7. (left) Frequency comb based system for digital photonic synthesis. (right) Measured instabilities of tunable 10 and 100 GHz signals. These measurements were performed with two independent systems. The longer-term drift (labeled optical limit) arises from the slow drift of the laser that serves as the optical reference of the system.

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 and microfabricated alkali vapor cells [35]. These devices include chip-scale atomic clocks [36] and magnetometers [37] – now being commercialized by at least three companies – gyroscopes, and, most recently, chip-scale length standards and compact cold atom instruments. 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 instruments 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 ultra-miniature 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 [38].

Recent NIST advances include the development of novel atom interferometry techniques based on expanding clouds of laser-cooled atoms [39]. This technique promises to enable a new generation of compact, multi-axis atom interferometer inertial sensors. In addition, the integration of microfabricated alkali atom vapor cells with single-mode SiN photonics chips has been demonstrated and a chip-scale optical frequency reference constructed.





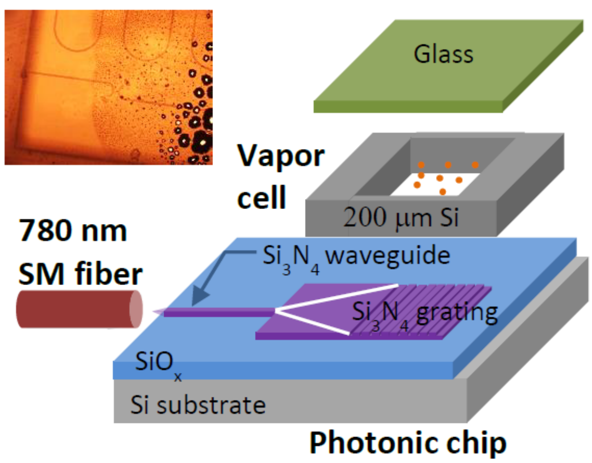


Figure 8. NIST chip-scale atomic clock physics package (top left), and fringes from a compact point-source atom interferometer (top right). An illustration and photograph showing alkali vapor cells integrated with a single-mode SiN photonic chip.

3. Time and Frequency Dissemination

3.1 Time Transfer

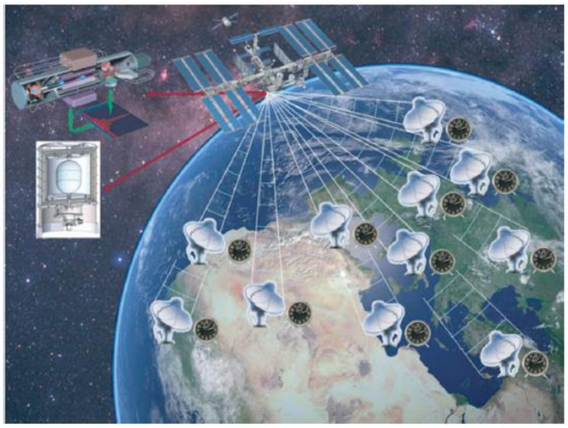
NIST participates in two-way satellite time and frequency transfer (TWSTFT) to Europe daily through a Ku-band link, achieving approximately 100 ps time transfer stability at one day of averaging.

The installation of a second Ku-band station is under way and will be completed in 2018, allowing NIST to add a direct TWSTFT link with the United States Naval Observatory (USNO). This link will, in turn, enable the calibration of the transcontinental TWSTFT link to Europe in a manner independent from the GNSS-based time transfer. NIST has also installed the recently developed SDR modem, improving the short-term (2-4 hours) performance of the TWSFT link to Europe.

In accordance with the most recent recommendation for redundant time transfer. NIST is now ready to start reporting three independent multichannel, dual-frequency receivers (two

Novatel and one Septentrio) for GPS common-view time transfer, attaining approximately 300 ps stability at one day of averaging.

NIST has now participated in two GNSS calibration campaigns coordinated by BIPM reducing the time uncertainty of UTC(NIST) from 5 to 1.7 nanoseconds [40]. Following the recommendations outlined in the Guidelines issued by BIPM, NIST is also coordinating the GNSS calibrations for the National Metrology Institutes of the Sistema Interamericano de Metrologia (SIM – Inter-American Metrology System) using a NIST-developed travelling GPS system.



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, now expected to fly on the International Space Station in 2018. 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 9. Schematic of ACES-mediated time and frequency transfer from the International Space Station. (ESA figure.)

3.2 Internet Time Service

Use of the NIST Internet Time Service (ITS) to automatically synchronize computer clocks continues to grow, averaging more than 20 billion requests for service each day at the time of this report [41]. 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 is in the process of upgrading the service by consolidating the servers on three NIST sites with expanded bandwidth on each site. Included in this consolidation is the upgrade of the servers themselves. 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.

3.3 Web clock

NIST and USNO jointly operate a Javascript web clock, www.time.gov, which provides users with a ticking display of the current official U.S. time, usually accurate within 0.1 second (an estimate of the network delay is removed from the time displayed). The clock displays a live indication of daylight saving time and leap seconds. This service receives about 2 million time requests per day on average. The time widget, which is a flash application that users can embed in their own web pages, averages approximately 300,000 hits per day.

3.4 Automated Computer Time Service (ACTS)

This modem-based time-of-day service continues to receive an average of about 3,000 requests for service per day, a number that has dropped about 80% since the year 2000, largely due to the increasing popularity of the Internet Time Service (ITS), but also because few if any computers are now sold with telephone modems. The service continues to be offered for legacy users that are prevented by firewalls or by security policies from accessing the ITS. For those users, ACTS continues to be a convenient method for establishing traceability to UTC(NIST).

3.5 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 millions of radio-controlled timepieces across the country. 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 added a binary phase shift keying modulation to the existing amplitude modulated digital time codes. [42] 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 14 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 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 [43]:
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.

3.6 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 tracing the device under test to NIST standards at an uncertainty of 2×10^{-13} ($k = 2$) per day, customers receive monthly written calibration reports compliant with *ISO Guide 17025*. [44]

3.7 NIST Time Measurement and Analysis Service

The NIST Time Measurement and Analysis Service (TMAS) provides automated traceability to NIST time through common-view GPS with a combined uncertainty of 15 ns or better and a frequency uncertainty of $\sim 5 \times 10^{-14}$ after one day of averaging. All customers can review their measurement results in near real-time via the Internet, and receive monthly written calibration reports compliant with *ISO Guide 17025*. [45] The NIST disciplined oscillator/clock service, a service option to the TMAS, synchronizes and syntonizes a

Figure 10. Measurement system provided to customers of NIST Time Measurement and Analysis Service. Very similar systems are used for the SIM Time Network described below.

rubidium or cesium standard to UTC(NIST), typically to within a few parts in 10^{14} in frequency and within 10 ns in time. [46] This service is essential for providing high accuracy NIST time to a wide range of industries; including telecommunications, aerospace, defense, instrument manufacturers, and world financial markets. [47]

3.9 SIM Time Network

Twenty-five 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 expected to join (SIM includes the 34 nations located in North, Central, and South America, as well as the Caribbean Islands). The technology developed at NIST for the SIM Time Network (SIMTN) led to the NIST TMAS service described in Section 3.8. 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). [48] The SIM Time Scale (SIMT), the world's first multi-national time scale computed in near real-time (every hour), originated in 2008 and has been in continuous operation since 2010. [49]. Results obtained via the SIMTN and SIMT are available at http://tf.nist.gov/sim.

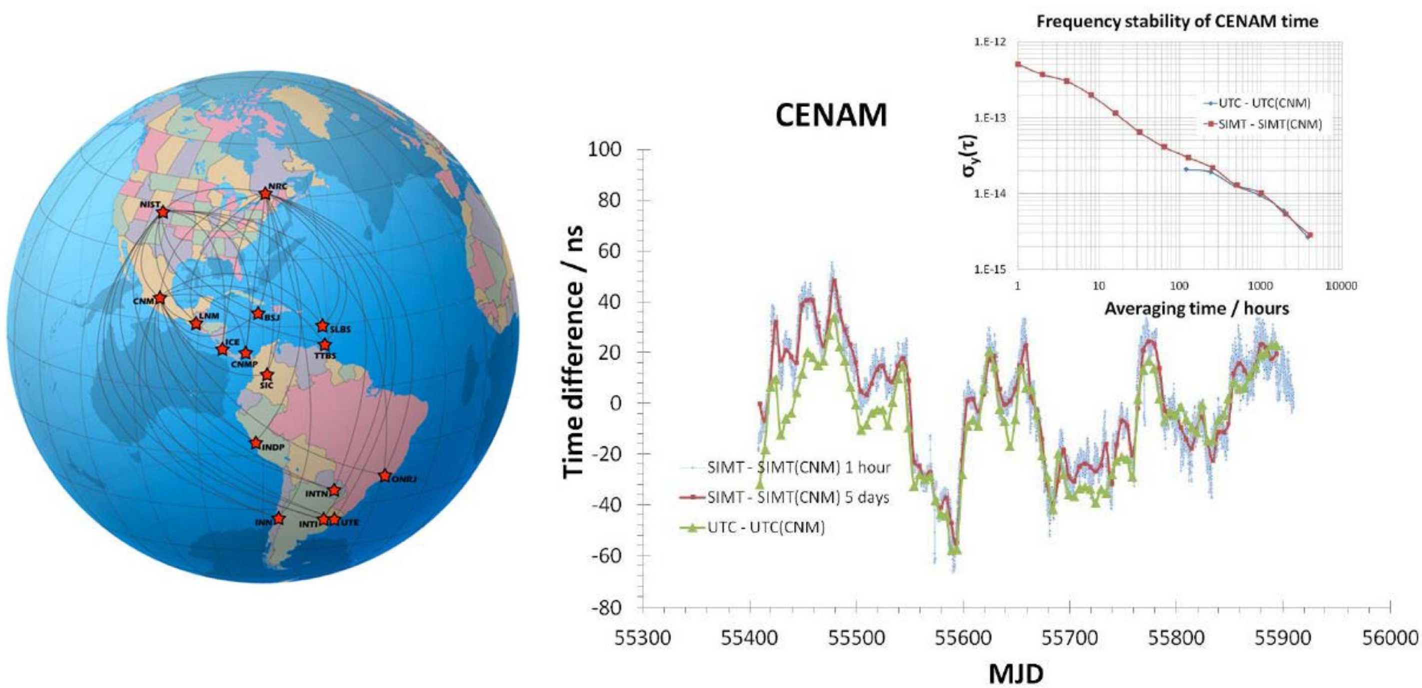


Figure 11. SIM Time Network. As an example of SIM Time Network performance, comparison of CENAM time with UTC and with SIM Time over a period of about 500 days.

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. [50] 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. More recently, NIST has demonstrated the trapping and full quantum control over molecular ions, which could one day play an important role in frequency metrology and frequency tests of fundamental physics. [51]

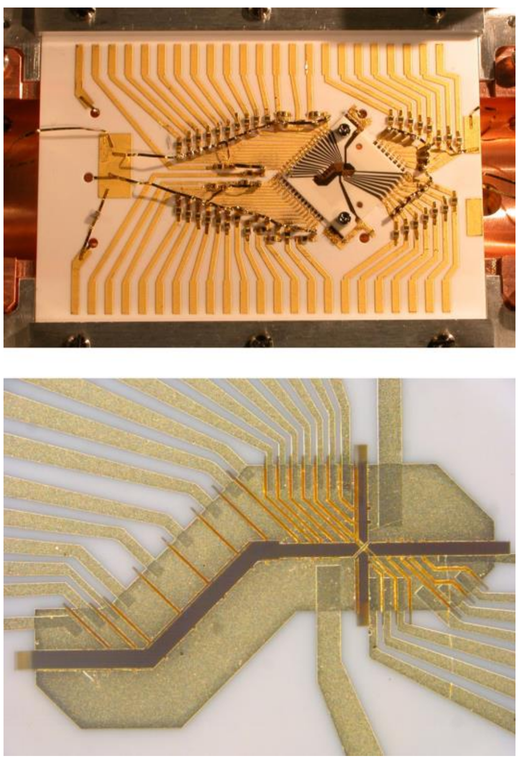


Figure 12. Example of multizone ion trap used in NIST quantum computing research. The multiple zones represent independent electromagnetic trapping regions. Beryllium ions used as qubits can be efficiently transferred among the different zones to accomplish various quantum logic operations. The gap in the lower photo (enlarged version of the top photo) is on the order of 1 mm.

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. 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).

5. S.R. Jefferts, T.P. Heavner, T.E. Parker, J. Shirley, E.A. Donely, N.Ashby, F. Levi, D. Calonico, G. Costanzo, *High-accuracy measurement of the black-body radiation frequency shift of the ground-state hyperfine transition in ^{133}Cs*, Phys Rev Lett **112** 050801-4.

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. P.O. Schmidt, T. Rosenband, C. Langer, W.M. Itano, J.C. Bergquist, and D.J. Wineland, *Spectroscopy using quantum logic*, Science **309**, 749 (2005).

10. 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).

11. 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).

12. J.-S. Chen, S.M. Brewer, C.W. Chou, D.J. Wineland, D.R. Leibrandt, and D.B. Hume, *Sympathetic Ground State Cooling and Time-Dilation Shifts in an $^{27}Al^{+}$ Optical Clock*, Phys. Rev. Lett. **118**, 053002 (2017).

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

14. D.B. Hume and D.R. Leibrandt, *Probing beyond the laser coherence time in optical clock comparisons*, Phys. Rev. A **93**, 032138 (2016).

15. Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, R. W. Fox, J. A. Sherman, L.-S. Ma, C. W. Oates, *Making optical atomic clocks more stable with 10^{-16} level laser stabilization*, Nature Photonics **5** 158-161 (2011).

16. N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke, K. Beloy, M. Pizzocaro, C. W. Oates, and A. D. Ludlow, *An atomic clock with 10^{-18} instability*, Science **341** 1215-1218 (2013).

17. M. Schioppo, R. C. Brown, W. F. McGrew, N. Hinkley, R. J. Fasano, K. Beloy, T. H. Yoon, G. Milani, D. Nicolodi, J. A. Sherman, N. B. Phillips, C. W. Oates and A. D. Ludlow, *Ultrastable optical clock with two cold-atom ensembles*, Nature Photonics **11** 48–52 (2017)

18. 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 (2011).

19. K. Beloy, J. A. Sherman, N. D. Lemke, N. Hinkley, C. W. Oates, and A. D. Ludlow, *Determination of the 5d6s 3D1 state lifetime and blackbody radiation clock shift in Yb*, Phys. Rev. A Rapid Communications **86** 051404 (2012).

20. K. Beloy, N. Hinkley, N. B. Phillips, J. A. Sherman, M. Schioppo, J. Lehman, A. Feldman, L. M. Hanssen, C. W. Oates, A. D. Ludlow, *Atomic Clock with $1x10^{-18}$ Room-Temperature Blackbody Stark Uncertainty*, Phys. Rev. Lett. **113** 260801 (2014).

21. R. C. Brown, N. B. Phillips, K. Beloy, W. F. McGrew, M. Schioppo, R. J. Fasano, G. Milani, N. Hinkley, T. Yoon, H. Leopardi, T. M. Fortier, and A. D. Ludlow, *High-order light shifts and operational magic wavelength behavior in lattice clocks*, submitted (2017).

22. T.M. Fortier, A. Rolland, F. Quinlan, F.N. Baynes, A.J. Metcalf, A. Hati, A.D. Ludlow, N. Hinkley, M. Shimizu, T. Ishibashi, J.C. Campbell, and S.A. Diddams, *Optically referenced broadband electronic synthesizer with 15 digits of resolution*, Laser Photonics Rev. **10**, 780-790 (2016).

23. H. Leopardi, J. Davila-Rodriguez, F. Quinlan, J. Olson, S. Diddams, and T. Fortier, *Single-branch Ef:fiber frequency comb for optical synthesis at the* 10^{-18} *level*, arXiv:1611.02259.

24. Dong Yoon Oh, Ki Youl Yang, Connor Fredrick2, Gabriel Ycas, Scott A. Diddams & Kerry J. Vahala, *Coherent ultra-violet to near-infrared generation in silica ridge waveguides*, Nature Communications **8**, 13922 (2017).

25. F. C. Cruz, D. L. Maser, T. Johnson, G. Ycas, A. Klose, F. R. Giorgetta, I. Coddington, and S. A. Diddams, *Mid-infrared optical frequency combs based on difference frequency generation for molecular spectroscopy*, Opt. Express **23**, 26815 (2015).

26. A. Klose, G. Ycas, F. C. Cruz, D. L. Maser, S. A. Diddams, *Rapid, broadband spectroscopic temperature measurement of* CO^2 *using VIPA spectroscopy*, Appl. Phys B , (2016).

27. Francisco S. Vieira, Flavio C. Cruz, David F. Plusquellic, Scott A. Diddams, *Tunable resolution terahertz dual frequency comb spectrometer*, Optics Express **24**, 30100 (2016).

28. L. Nugent-Glandorf, F. Giorgetta, S. A. Diddams, *Open-air, broad-bandwidth trace gas sensing with a mid-infrared optical frequency comb*, Appl. Phys. B **119**, 327 (2015).

29. P. Del'Haye, A. Coillet, T. Fortier, K. Beha, D. C. Cole, H. Lee, K. J. Vahala, S. B. Papp, and S. A. Diddams, *Phase Coherent Link of an Atomic Clock to a Self-Referenced Microresonator Frequency Comb*, Nature Photonics **10**, 516–520 (2016)

30. K. Y. Yang, X. Yi, K. Beha, D. Cole, X. Yi, P. Del'Haye, H. Lee, J. Li, D. Oh, S. A. Diddams, S. B. Papp, K. J. Vahala, *Broadband dispersion engineered microresonator on-a-chip*, Nature Photonics **10**, 316–320 (2016)

31. Q. Li, T. C. Briles, D. A. Westly, T. E. Drake, J. R. Stone, B.R. Ilic, S.A. Diddams, S.B. Papp, K. Srinivasan, *Stably accessing octave-spanning microresonator frequency combs in the soliton regime*, Optica **4**, 193-203 (2017).

32. Debra A. Fischer, et al., *State of the Field: Extreme Precision Radial Velocities*, Publications of the Astronomical Society of the *Pacific* **128**, 066001 (2016)

33. Katja Beha, Daniel C. Cole, Pascal Del'Haye, Aurélien Coillet, Scott A. Diddams, and Scott B. Papp, *Electronic synthesis of light*, Optica **4**, 406-411 (2017).

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

35. L. A. Liew et al., Appl. Phys. Lett. **84**, 2694-2696 (2004).

36. S. Knappe et al., Appl. Phys. Lett. **85**, 1460-1462 (2004).

37. P. D. Schwindt et al., Appl. Phys. Lett. **85**, 6409-6411 (2004).

38. J. Kitching et al., Journal of Physics: Conference Series **723**, 012056 (2016).

39. Gregory W. Hoth et al., Appl. Phys. Lett. **109**, 071113 (2016).

40. **BIPM TM 243** "Determination of reference GPS "INTDLY" values of Group 1 geodetic receivers in the initial Group 1 trip (Cal_Id = 1001-2014)".

41. J. Sherman and J. Levine, *Usage Analysis of the NIST Internet Time Service*, J. Res. Natl. Inst. Stan. **121**, 33-46 (2016).

42. 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).

43. 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).

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

45. M. A. Lombardi and A. N. Novick, *Remote Time Calibrations via the NIST Time Measurement and Analysis Service*, NCSLI Measure: The Journal of Measurement Science **1,** 50-59 (2006).

46. M. A. Lombardi, *A NIST Disciplined Oscillator: Delivering UTC(NIST) to the Calibration Laboratory*, NCSLI Measure: The Journal of Measurement Science **5**, 46-54 (2010).

47. M. A. Lombardi, A. N. Novick, G. Neville-Neill, and B. Cooke, *Accurate, Traceable, and Verifiable Time Synchronization for World Financial Markets*, NIST Journal of Research **121**, 436-463 (2016).

48. 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).

49. J. M. López-Romero, M. A. Lombardi, N. Díaz-Muñoz, and E. de Carlos-Lopez, *SIM Time Scale*, IEEE Transactions on Instrumentation and Measurement **62**, 3343-3350 (2013).

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

51. C. Chou, C. Kurz, D. B. Hume, P. N. Plessow, D. R. Leibrandt, and D. Leibfried, *Preparation and coherent manipulation of pure quantum states of a single molecular ion*, Nature **545**, 203-207 (2017).