Time and Frequency Division

Goal

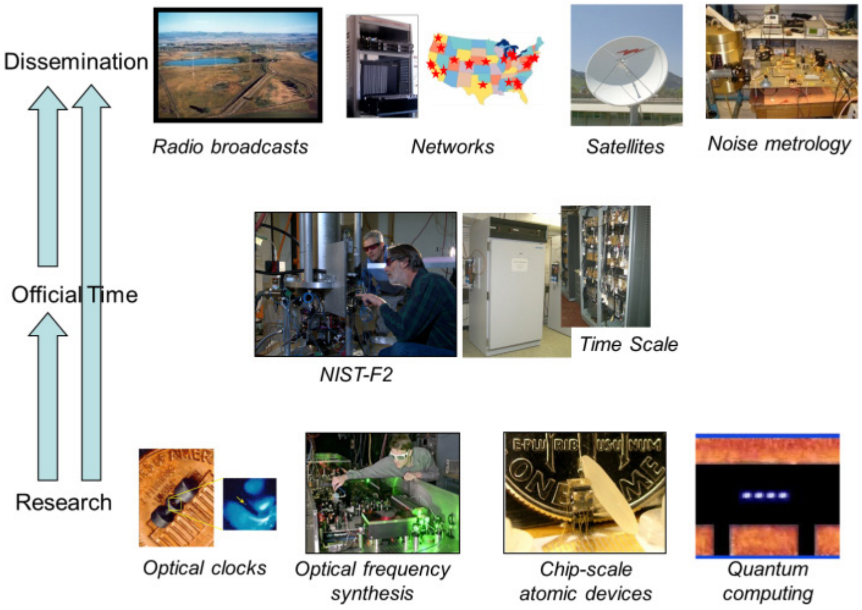
The broad mission of the Time and Frequency Division is to provide official U.S. time and related quantities to support a wide range of uses in industry, national infrastructure, research, and among the general public.

DIVISION STRATEGY

The division's research and metrology activities comprise three vertically integrated components, each of which constitutes a strategic element:

1. *Official time:* Accurate and precise realization of official U.S. time (UTC) and frequency.
2. *Dissemination:* A wide range of measurement services to efficiently and effectively distribute U.S. time and frequency and related quantities – primarily through free broadcast services available to any user 24/7/365.
3. *Research:* Research and technology development to improve time and frequency standards and dissemination. Part of this research includes high-impact programs in areas such as quantum information processing, atom-based sensors, and laser development and applications, which evolved directly from research to make better frequency standards (atomic clocks).

Time and Frequency Programs



Overview

These three components – official time, dissemination, and research – are closely integrated. For example, all Division dissemination services tie directly to the Division's realization of official time (UTC), and much of the Division's research is enabled by the continual availability of precision UTC.

Our modern technology and economy depend critically on the broad availability of precision timing, frequency, and synchronization. NIST realization and dissemination of time and frequency – continually improved by NIST research and development – is a crucial part of a series of informal national timing infrastructures that enable such essential technologies as:

- Telecommunications and computer networks
- Utility distribution
- GPS, widely available in every cell phone and smartphone as well as GPS receivers
- Electronic financial transactions

- National security and intelligence applications
- Research

Strategic Goal: Official Time

Intended Outcome and Background

U.S. Federal law (Public Law 110-69) defines official U.S. time as Coordinated Universal Time (UTC) and assigns responsibility for realization of UTC to NIST and the U.S. Naval Observatory (USNO), delegated from the Secretaries of Commerce and the Navy. Through a recently renewed, long-standing Memorandum of Understanding between NIST and USNO, NIST has primary responsibility for U.S. realization of the SI second, the underpinning standard for UTC and all timing-related measurements. NIST and USNO share responsibility for realizing UTC for the United States, with NIST primarily responsible for civilian applications and USNO primarily responsible for military applications. Both NIST and USNO contribute to the realization of international UTC through the International Bureau of Weights and Measures (BIPM), which determines UTC based on input from about 70 timing laboratories across the world.

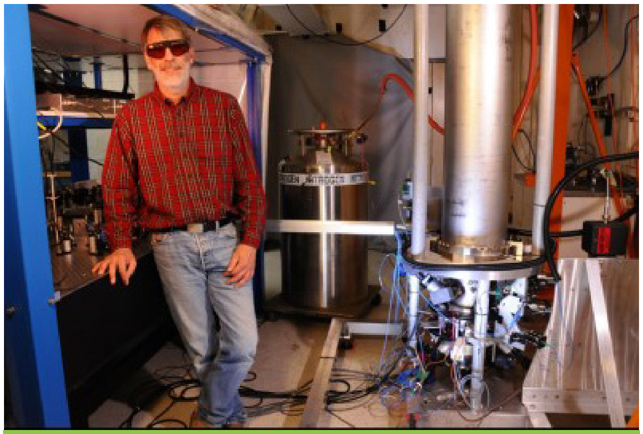
NIST's version of UTC – UTC(NIST) – is the basis of all NIST time and frequency measurement services, and related measurements such as phase noise. UTC(NIST) is realized through:

(1) Primary frequency standards which realize the SI second

(2) NIST time scale: An ensemble of commercial atomic clocks, primarily hydrogen masers

(1) NIST-F1 and NIST-F2 primary frequency standards

NIST realizes UTC through the NIST time scale periodically calibrated by the NIST-F1 and NIST-F2 primary frequency standards.


NIST-F2 laser-cooled fountain atomic frequency standard

The NIST primary frequency standards measure the SI second for the United States, and are among about 15 primary frequency standards across the world that regularly report to BIPM to realize the international SI second. The NIST primary frequency standards are laser-cooled atomic fountain frequency standards, measuring the ground state hyperfine transition in cesium-133 (9,192,631,770 Hz). NIST-F1, NIST's first laser-cooled fountain standard, was formally commissioned in 1999 with an initial fractional frequency uncertainty ($\Delta f/f$) of about 17×10^{-16}, and was systematically improved over time to a current uncertainty of about 3×10^{-16}. The largest residual uncertainty in NIST-F1 is the blackbody frequency shift – the tiny splitting of cesium energy levels due to background infrared radiation.

NIST-F2 dramatically reduces the background infrared radiation by using cryogenic (liquid nitrogen) components. NIST-F2 was formally commissioned in 2013 with a fractional frequency uncertainty of about 1×10^{-16}, largely through reduction of the blackbody radiation shift, but with other evolutionary improvements based on experience with NIST-F1.

NIST-F1 and F2 are used to periodically calibrate the NIST time scale, a process that typically requires about 20 days of operation of the primary frequency standard(s). The Division also reports these results directly to BIPM, which uses input from about 15 primary frequency standards across the world to determine the best estimate of "standard frequency" or the rate of UTC.

NIST-F1 was the world's most accurate primary frequency standard, or tied for best, during nearly all of the period from its 1999 commissioning. NIST-F2 is now the world's most accurate primary frequency standard, closely followed by a copy of NIST-F2 built by NIST for INRIM, Italy's National Metrology Laboratory. The NIST primary frequency standards team also trained key INRIM scientists, and NIST and INRIM teams continue to closely collaborate. Being able to intercompare essentially two NIST-F2 standards in different locations increases confidence that the uncertainties have been accurately evaluated.

Operating both NIST-F1 (thermal background near 300 K) and NIST-F2 (thermal background near 80 K) enabled NIST scientists to make the world's best measurement of the blackbody radiation shift in the cesium hyperfine transition. Since this shift is generally the largest uncertainty in non-cryogenic primary frequency standards, the measurement helped nearly all primary standards across the world to reduce their uncertainties, as well as directly improving NIST-F1 and NIST-F2.

NBS (NIST's predecessor) invented the atomic clock in 1949, and since then there has been a steady improvement in NBS/NIST primary frequency standard performance of approximately a factor of 10 per decade, with NIST-F2 continuing this trend. We expect there may be additional modest improvements in NIST-F2 performance over time, to fractional frequency uncertainties in the high 10^{-17} range. But we do not expect future "factor of 10 per decade" improvements – NIST-F2 likely represents the near-peak performance obtainable with cesium microwave transitions. It is likely that future primary frequency standards will use optical transitions, as discussed below.

Nonetheless, we continue a vigorous research program on microwave cesium frequency standards, with two main goals:

- Develop cesium fountain frequency standards that can be operated near continuously, enabling the realization of UTC and thus all Division measurement services with improved accuracy and stability compared to the current time scale, while also reducing complexity and capital equipment costs – better performance at less expense.
- Develop miniature cold-atom microwave frequency standards (cesium and/or rubidium) for a broad range of practical applications, including potential future GPS clocks to improve GPS stability and performance.

(2) NIST Time Scale

The time scale comprises an ensemble of about 10 commercial atomic clocks (primarily hydrogen masers) and a measurement system delivering NIST's best estimate of UTC and standard frequency. The measurement system continually performs a complex weighted ensemble average of signals from the atomic clocks, with occasional steering adjustments based on deviations of NIST's version of UTC from international UTC realized by BIPM. UTC and the standard frequency produced by the time scale are the basis of all NIST time and frequency measurement services, and are also used throughout the Division to support research and metrology.

Time Scale

NIST coordinates UTC and standard frequency through satellite-mediated international time and frequency transfer every two hours. The BIPM analyzes the input from NIST and about 70 timing laboratories across the world, and periodically publishes the deviations of each lab's results (including NIST's) from the BIPM weighted average UTC and related quantities. NIST uses these deviations to determine steering corrections to the NIST time scale as noted above.

Hydrogen maser ensemble time scales had been the best approach to UTC realization for many years, but are complex and expensive. Each hydrogen maser costs about $300,000 and has a limited lifetime; but the stability of a time scale is a function of the square root of the number of clocks, meaning that a large number of masers is required to modestly improve performance.

The Division is developing a new approach based on a near-continuously operating primary frequency standard (cesium fountain) directly steering a single hydrogen maser. Research has shown that this approach can lead to significantly improved performance with much reduced costs and complexity. In practice, additional masers must be available to mitigate potential maser failure, but the overall capital equipment investment is still much lower than a large maser ensemble.

A maser ensemble time scale is just sufficiently stable and accurate to take advantage of the performance of intermittently operating primary frequency standards such as NIST-F1 and F2. A continuously operating primary standard directly steering a maser should improve performance modestly with strong advantages in simplicity and cost.

The longer-term step is to develop a new type of time scale that can fully exploit the much greater stability and accuracy of optical frequency standards, which can be 100 times more accurate than microwave primary frequency standards, and an order of 106 more stable. No maser ensemble could come close to that performance level. The Division is exploring innovative ideas for a highly flexible new time scale that can take input from a variety of sources – microwave frequency standards, optical frequency standards, stabilized lasers, etc. – and produce a highly stable and accurate output of any desired optical or microwave frequency using frequency combs. This approach eliminates the need for a single optical frequency standard to continuously operate, which is currently not possible.

Recent Accomplishments

NIST-F2 Comes Online

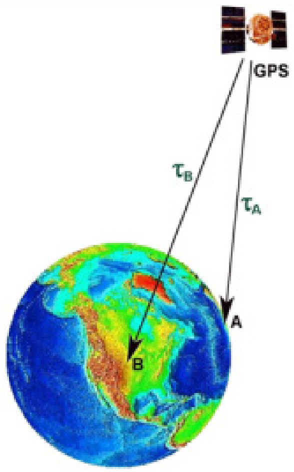
In April, 2014, NIST officially launched a new atomic clock, called NIST-F2, to serve as a new U.S. civilian time and frequency standard, along with the current NIST-F1 standard. NIST-F2 would neither gain nor lose one second in about 300 million years, making it about three times as accurate as NIST-F1.

NIST scientists reported the first official performance data for NIST-F2, which has been under development for a decade, to BIPM. According to BIPM data, NIST-F2 is now the world's most accurate time standard.

CONTACT: Steve Jefferts (303-497-7377), PML

Strategic Goal: Dissemination

Intended Outcome and Background



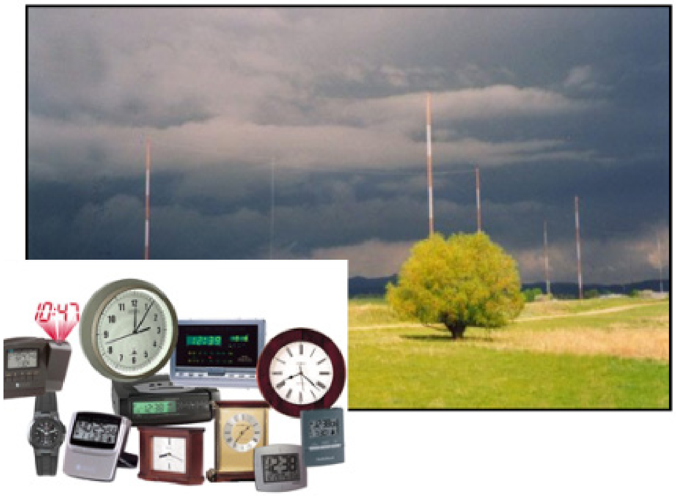
GPS common-view time & frequency transfer

Dissemination of UTC is different from any other NIST measurement service in that time is continuously varying, and to be useful the current precise and accurate time must be delivered efficiently and effectively across the nation (and the world) in real time. All other NIST measurement services rely on exchange of an artifact (device, material, etc.) which is measured in a NIST metrology lab and later provided to the user with calibration or measurement information. In contrast, NIST time and frequency information is continuously broadcast through multiple means to serve the varying needs of different users. Some examples include:

- *Satellite broadcasts*, using telecommunications satellites and GPS satellites as the relay system, for the most demanding applications (frequency stability on order 10^{-15}, timing on order of 1 nanosecond).
- *Radio broadcasts* from NIST time and frequency radio stations in Colorado and Hawaii, including low-frequency time-code broadcasts that automatically synchronize tens of millions of consumer radio-controlled timepieces to NIST time. Frequency stability of about 10^{-11} and timing to about

one microsecond (with compensation for propagation delays), but primarily used by general public at the one second uncertainty level.

- *The Internet*, automatically synchronizing clocks in computers and network devices to NIST time some 10 billion times every day. Typical accuracy of about one millisecond. Used by general public and in commercial applications such as timestamping hundreds of billions of dollars in electronic financial transactions each day.


NIST time code station WWVB

Most of these services are provided at no cost to anonymous users, with the NIST time and frequency information available to anyone 24/7/365. NIST typically does not know who the users are unless they identify themselves.

In addition to broadcast time and frequency services, the Division provides a small number of “traditional” calibrations each year, as described later. However, the overwhelming majority of Division time and frequency dissemination activities are through free, broadcast services to anonymous users.

The Division also operates a vigorous metrology and research program on noise metrology, including world-leading measurement capabilities in phase noise (timing jitter), spectral purity, and related quantities. Division noise metrology is generally disseminated through special tests similar to traditional NIST measurement services.

The Division provides a broad range of measurement services spanning a range of 10^{15} in accuracy and precision, tailored to the needs of widely varying users. Division measurement services fall into three broad classes:

(1) **Remote measurement services**, making NIST time and frequency information available 24/7/365 at the user’s location.

(2) **Traditional calibration services**, whereby a device or system is characterized in Division laboratories and returned to the user with a calibration certificate.

(3) **Special measurements** and tests performed through contracts, not through formal measurement services.

(1) Remote measurement services

These services leverage the natural encoding of precision time and frequency information on electromagnetic signals to broadcast NIST time and frequency information directly to the user’s lab, with 24/7/365 availability.


Remote time & frequency measurements in user’s lab. $\Delta f/f \sim 2 \times 10^{-13}$ $\Delta t \sim 1$ ns

Remote Time and Frequency Services

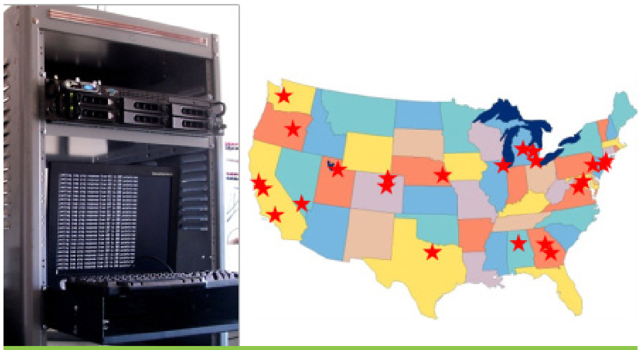
The Division operates a series of time and frequency remote measurement services where a NIST “black box” about the size of a microwave oven is placed in the user’s laboratory. The user simply plugs in the devices to be tested, and receives 24/7/365 NIST frequency information accurate to the 10^{-13} level and time accurate to the 1 nanosecond level (compared to NIST’s version of UTC). These measurements support users with the most stringent demands in such technology areas as telecommunications, aerospace, remote sensing, utility distribution, precision instruments, and even high-frequency electronic financial trading. The Division serves about 50 high-tech companies and organizations through these services. NIST uses GPS satellites to broadcast NIST time and frequency information (not GPS information) to the “black boxes” in the customer labs. These are the only such remote precision time and frequency measurement services in the world.

NIST Radio Broadcasts

Users with somewhat less stringent requirements can use broadcasts from NIST standard time and frequency radio stations, in both high-frequency (5 MHz to 20 MHz) and low-frequency (60 kHz) spectral ranges, typically providing 10^{-12} frequency stability and microsecond-level timing when corrected for propagation delays. The low-frequency broadcast includes a digital time code which automatically synchronizes tens of millions of radio-controlled timepieces to NIST time, primarily for consumer use at the one second accuracy level.

The NIST Internet Time Service (ITS)

The ITS automatically synchronizes clocks in computers and network devices to NIST time some 10 billion times per day – the most heavily used NIST measurement service by orders of magnitude. The service provides accuracy on the order of one millisecond, for both general public use and to support high-value applications such as time stamping of hundreds of billions of dollars of electronic financial transactions each day. NIST ITS is built in to all major computer operating systems (Windows, Mac, commercial Linux, etc.). ITS provides time through several standard formats, but Network Time Protocol (NTP) is the most heavily used. ITS is the most heavily used network time service in the world.


ITS provided from servers at about 15 locations across the U.S.

- The Division recently initiated as an experiment an authenticated version of ITS using public key encryption with more than 500 users with virtually no advertising or outreach.
- The Division recently initiated a specialized version of ITS providing UT1, which is UTC without leap second corrections, and DUT1, which is the current deviation between UTC and UT1. This information is primarily of interest to the astronomical and space science community.
- The Division is exploring innovative ways to partner with the private sector to ensure continued free public ITS while enabling companies to build innovative premium timing and synchronization services referenced to NIST official time.

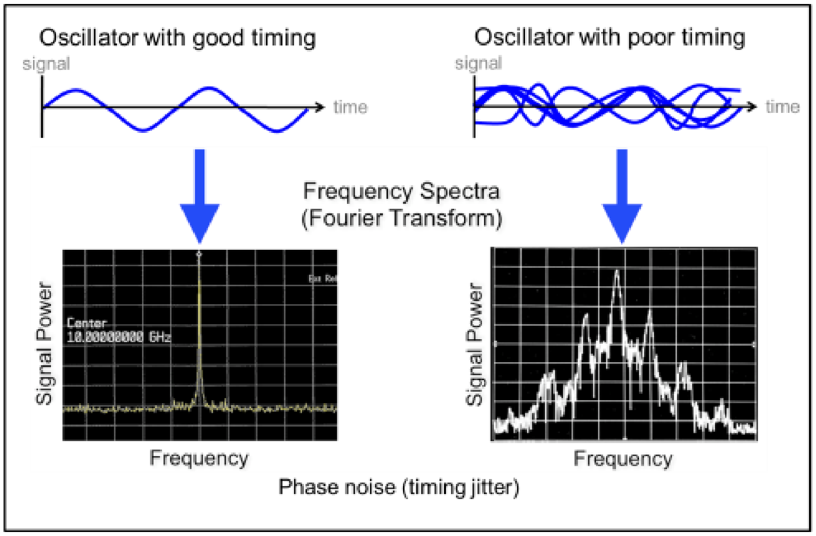
Additional Remote Services

The Division operates some additional services such as widgets users can install on web pages to display current NIST time, web-based NIST clocks, and other services. These services are primarily intended as conveniences for the general public interested in accurate time of day. The Division also operates a modem-based network time system of higher accuracy for specialized applications.

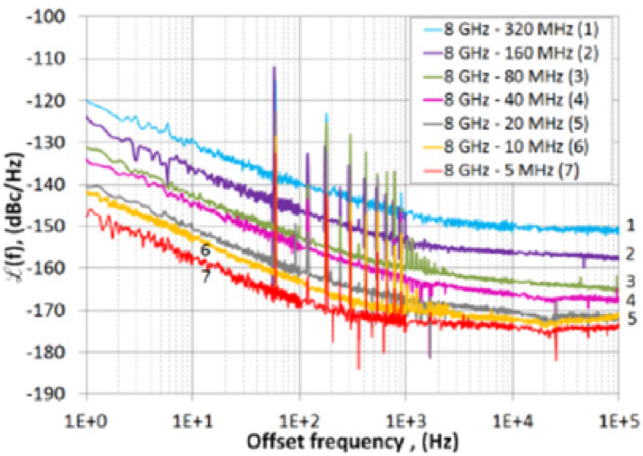
(2) Traditional calibration services

The Division provides precision measurements and calibrations for oscillators, commercial atomic clocks, and GPS receivers, and also provides standard calibrations for phase noise and spectral purity. Only a handful of such traditional calibrations are performed each year, largely replaced by the more flexible remote services with comparable accuracy. The Division expects to continue to transition traditional calibration services to remote services as much as possible, providing better service and flexibility to customers while freeing up Division resources for research on new measurement capabilities.

(3) Special measurements of phase noise, spectral purity and related quantities



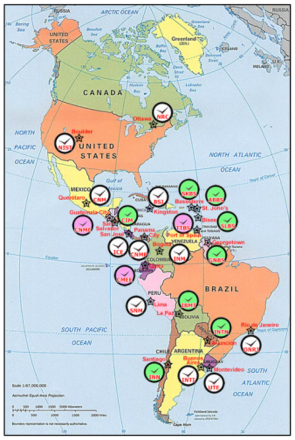
The Division provides unique, best-in-the-world measurements of precision electromagnetic signals in the radiofrequency, microwave and optical range. These measurements include phase noise (timing jitter), spectral purity, and perturbations due to acceleration/vibration and temperature. The Division can provide ultra-precise measurements as stringent as noise at the level of 10^{-17} compared to the carrier, about 100 times better than any other laboratory in the world. Such precision measurements support high-value applications such as telecommunications, high-speed computing, remote sensing, radar, surveillance, secure communications, GPS, atomic clocks, and many other applications. These measurements tend to be "one of a kind" on unique instruments or systems, and are best addressed through unique contracts with the customer rather than traditional measurement services. The demand for such ultra-precise measurements is rapidly growing and stimulating new research on precision signal generation and detection, as described below.

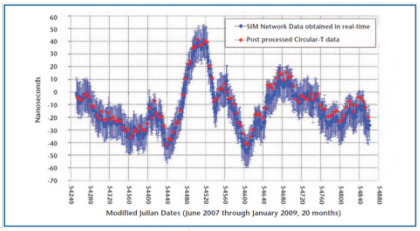


Example precision phase noise measurements

Recent Accomplishments

SIM Time Network: World's First Real-Time International Time Scale Leveraging NIST Remote Time and Frequency Innovations





SIM Time Network currently in 23 SIM nations. SIM Time closely follows BIPM's UTC

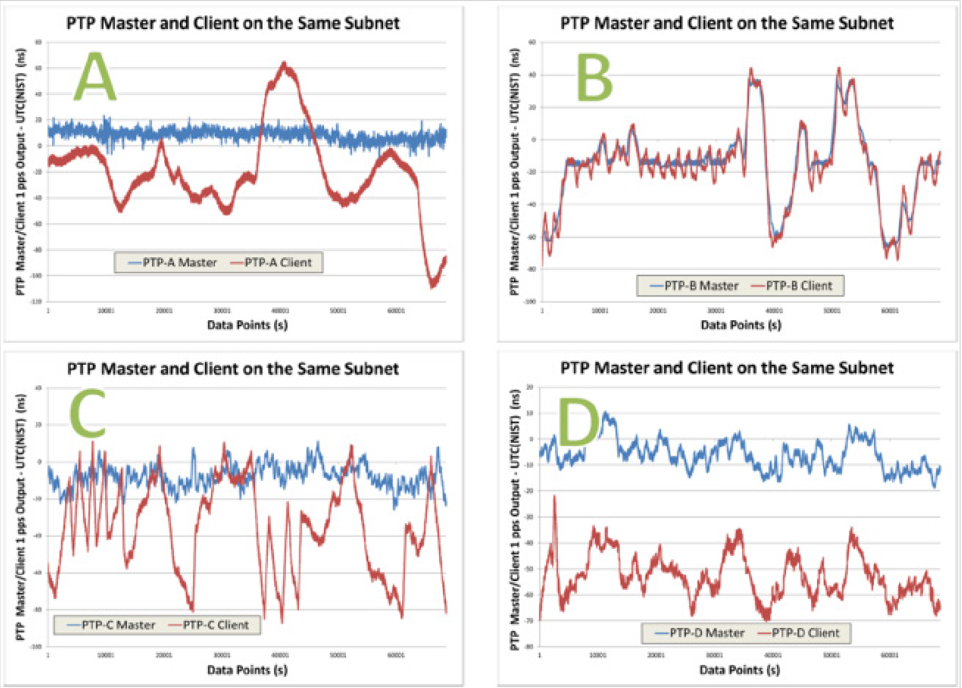
Division metrologists/researchers adapted their success with the remote time and frequency services to install and coordinate "black boxes" in the national timing labs of 23 countries in South, Central, and North America, representing the majority of nations in the Inter-American Metrology System (SIM). This system generates a real-time international time scale (SIM version of UTC) based on weighted averages of all the 23 participants, and this information is freely available in real time through multiple websites and other venues. In contrast, official global UTC realized by BIPM is a "paper scale" providing official time two weeks to six weeks in the past. SIM's UTC tracks official BIPM UTC extremely closely, although it is slightly noisier. NIST produced the SIM hardware and software and the architecture for the system of continuous real-time comparisons, but all SIM participants share in the operations of the network. The SIM network has enabled very resource-limited timing laboratories in developing South and Central American countries to participate in international timekeeping for the first time, and to support their national industries and infrastructures for the first time, all at very modest cost. NIST plans to continue to expand the SIM network to all willing nations. This program is an innovative, low-cost demonstration of new ways of conducting international precision metrology.

CONTACT: Mike Lombardi (303-497-3212), PML

New Network Time Services

The Division in partnership with industry and other Federal agencies is exploring ways to improve distribution of time and frequency over public networks by a factor of 1,000 or better.

The ITS has been highly successful since its 1991 introduction. But continually evolving technologies require more stringent timing and synchronization performance than the approximately 1 millisecond timing (or approximately 10^{-8} frequency stability) that ITS can provide on public networks. A key benchmark for precision network timing is the Stratum 1 metric of approximately 1 microsecond timing and 10^{-11} frequency stability on public networks – 1,000 times more stable than NTP. Key infrastructural technologies such as telecommunications networks, utility distribution, and high-speed electronic transactions currently rely on GPS for Stratum 1 time and frequency, but the very weak GPS signals are highly vulnerable to intentional and accidental jamming. NIST is partnering with industry and other agencies to make Stratum 1 performance ubiquitously available in public networks using Precision Time Protocol (PTP). Initial tests in operating public networks have been very promising, but much research and development is needed.



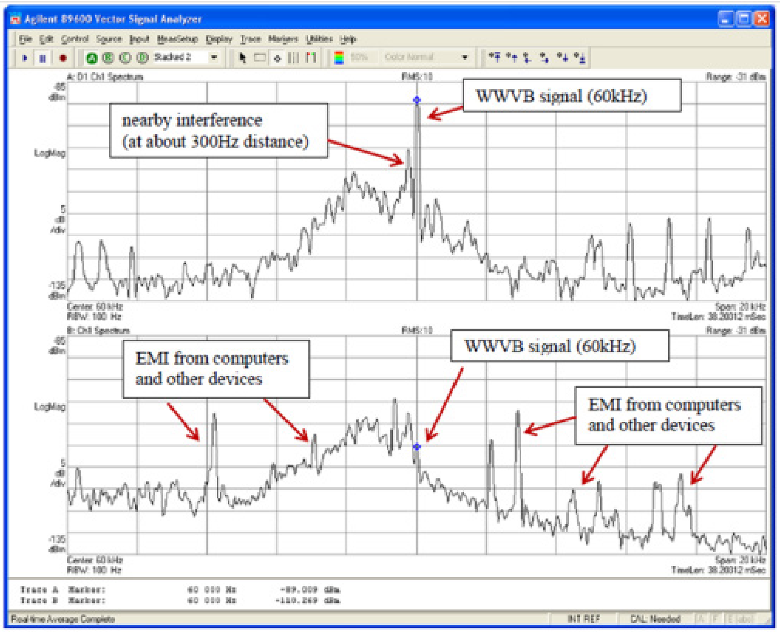
Commercial PTP equipment not yet meeting performance specifications

A national-level commitment will also be needed for full implementation, and we hope that strong test results from NIST and partners will facilitate that commitment. We expect NTP to remain important and heavily used for some time, but the Division intends to focus on developing new PTP-mediated network time and frequency services, and largely transfer NTP to private-sector partners.

CONTACT: Andrew Novick (303-497-3378), PML

Enhanced NIST Time Code Radio Broadcasts

NIST radio station WWVB broadcasts digital timecodes on a low-frequency carrier (60 kHz) that travels far beyond line of sight and penetrates much further than high-frequency signals; 60 kHz is in the range used to communicate with submerged submarines. In partnership with industry, the Division recently implemented a new approach to the broadcast of low-frequency digital time code signals from WWVB used to synchronize commercial radio-controlled timepieces. The new format uses binary phase shift keying to dramatically improve reception in commercial WWVB-controlled timepieces, especially in increasingly noisy environments. New receivers optimized for the phase shift keying signals behave as if WWVB broadcast power had increased by a factor of 20 or more in terms of noise rejection, with no actual increased broadcast power. The new time code is fully backwards-compatible with the installed base of tens of millions of WWVB-controlled timepieces, but will open up many new consumer applications. The substantially greater practical availability of WWVB signals is also making it attractive as part of a national system for GPS backup. This advance was facilitated by a NIST Small Business Innovation Research grant to a company partnering with the Division.



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Trace A  Marker:        60 000 Hz      -89.009 dBm
Trace B  Marker:        60 000 Hz     -110.269 dBm
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Typical interference near WWVB 60 kHz signal. New modulation scheme improves reception by factor of 20 or better in noisy environments.

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Strategic Goal: Research

Intended Outcome and Background

The primary focus of Time and Frequency Division research programs is to improve realization of official time and to develop new and better ways to distribute official time and related measurements for evolving needs. Examples include development of improved frequency standards (atomic clocks) using optical or microwave transitions, dramatically improved phase noise and spectral purity measurements, research on new time and frequency transfer techniques, and continuing development of new remote measurement services.

In researching improvements in official time and dissemination, Division scientists have often developed new technologies with substantial impact on the broad NIST measurement science and metrology mission, even if not appearing directly related to official time and dissemination. Examples include trapped-ion quantum information processing, development and applications of femtosecond laser frequency combs, and development and applications of chip-scale, atom-based sensors.

Described below are some recent developments resulting from Division research in four areas:

(1) *Official Time: [A] Improved Frequency Standards and [B] Time Scales*

(2) *Satellite Time and Frequency Transfer*

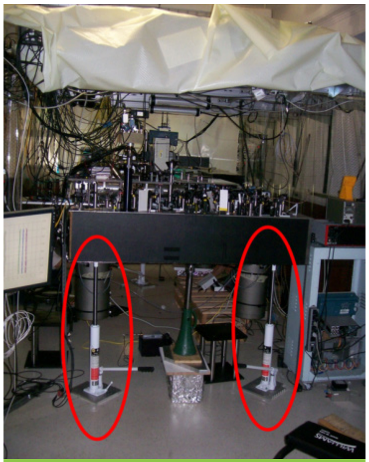
(3) *Network Time Distribution*

(4) *Research and Innovations Evolving Directly from Time and Frequency Research*

(1) Official Time: Improved Frequency Standards

The Division develops new microwave and optical frequency standards to address continually evolving technology needs. Better clocks can lead to improved telecommunications, better GPS performance, enhanced remote sensing and surveillance, new communications security, improved deep space exploration, and many other applications that depend on precision timing and synchronization. The general Division strategy is to develop new frequency standards with as much accuracy and stability as possible. The current best Division optical frequency standards are approaching 1 x 10^{-18} accuracy and stability level – best in the world and about 100 times better than the NIST-F2 microwave primary frequency standard – and continuing to rapidly improve.

But there are new, rapidly developing opportunities for “post-timing” applications of extremely accurate and stable frequency standards. The atomic transition frequency is perturbed by a host of environmental effects such as gravity, magnetic fields, motion, temperature, acceleration/vibration and many others. For frequency standards such as NIST-F2 with 10^{-16} order accuracy, these effects are relatively minor “nuisance” perturbations to be controlled to optimize accuracy.



Raising aluminum ion logic clock by a few centimeters shifts frequency commensurate with tiny gravity changes.

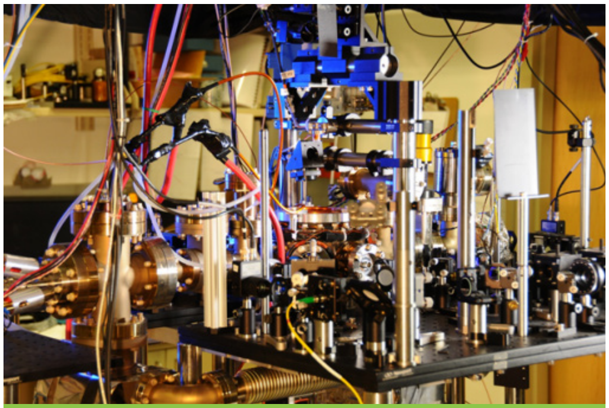
However, a frequency standard with 10^{-18} accuracy can become an exquisite sensor of gravity, magnetic fields, temperature, motion, vibration, and many other quantities. For example, near the earth's surface a 1 cm change in elevation generates an approximately 1×10^{-18} gravitational redshift in a frequency standard, so optical frequency standards can become precision gravimeters. Appropriately chosen frequency standards can even more precisely and accurately measure magnetic fields, temperature, electrical quantities, motion/acceleration, and many other quantities. The Division is vigorously pursuing developing ultra-high-performance frequency standards for these "post-timing" applications as well as for "traditional timing" applications, and we think it likely "post-timing" applications may have the greater impact in the next several years.

Recent Accomplishments

Cold Atom Optical Lattice Standards

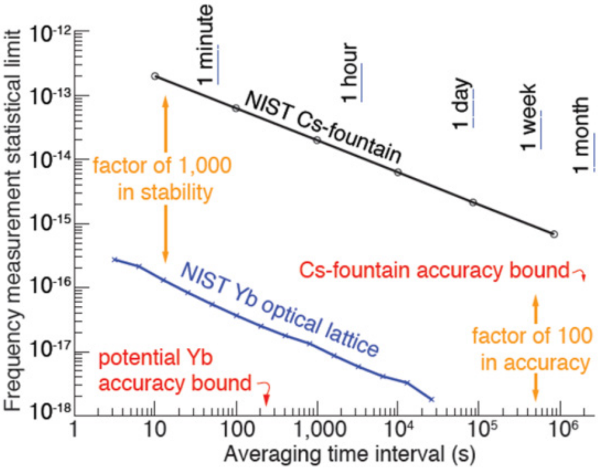
The two Division ytterbium lattice optical clocks demonstrated a world-record for stability of better than 2×10^{-18} over about seven hours of averaging. For comparison, the stability of NIST-F2 currently reaches a limit of about 1×10^{-16}. But if NIST-F2 could somehow continue to improve with further averaging, it would take more than 200 years of continuous averaging to reach the 2×10^{-18} stability of the ytterbium lattice optical clocks.

This enormous improvement represents another great impact on technology. For many applications, stability is more important than absolute accuracy. Even "traditional" timing applications such as telecommunications and GPS rely more on stability than absolute accuracy, and "post-timing" applications such as gravimetry, magnetometry, thermometry, etc. are also generally more sensitive to stability than absolute accuracy. The dramatically improved stability of the Division's optical frequency standards represents a critical enabling technology for a broad range of applications.



Yb lattice optical clock

The Division collaborates closely with the JILA program on the very similar strontium lattice optical frequency standard, comparing results and regularly exchanging personnel and ideas. The Yb and Sr optical lattice clocks effectively represent a coordinated program.



Both the accuracy and stability of optical frequency standards continue to rapidly improve. At the time of this writing, the Sr optical lattice clock is most accurate in the world (2×10^{-18} frequency uncertainty) while the Yb optical lattice clock is most stable in the world (1.7×10^{-18} stability). But these are among the most rapidly-improving metrology records in the world, and both accuracy and stability will almost certainly be significantly better within one year, and will continue to improve.

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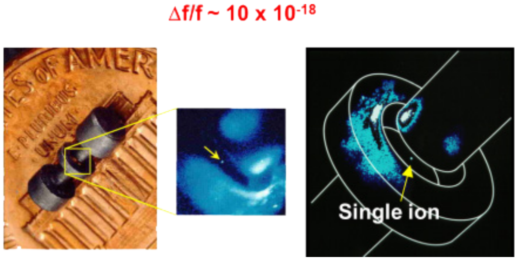
Single-Ion Optical Standards

The Division develops optical frequency standards based on single ions trapped in electromagnetic fields. Two general approaches are used:



Single mercury ion frequency standard

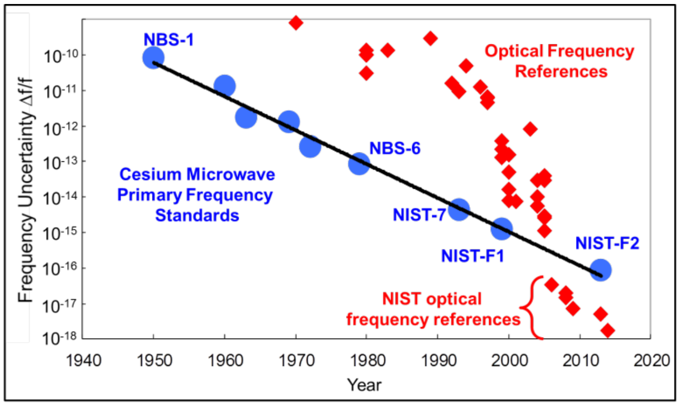
- The mercury-ion optical frequency standard uses lasers to directly interrogate an extremely narrow atomic transition in a single ion of ^{199}Hg+ confined in a miniature electromagnetic trap and laser-cooled. This standard currently has an accuracy of about 10 x 10^{-18}.
- The aluminum-ion logic clock uses techniques NIST pioneered for trapped-ion quantum computing to indirectly interrogate an extremely narrow transition in the ^{27}Al^{+} ion. The laser cooling transition for the aluminum ion is too far in the vacuum ultraviolet to be practicable. So a single aluminum ion (serving as the “clock” ion) is electromagnetically trapped with a single “logic” ion. (Beryllium, magnesium, or calcium ions are used, each with certain advantages). The “logic” ion can be directly laser cooled and sympathetically cools the aluminum “clock” ion through the Coulomb interaction. The “clock” and “logic” ion are entangled, and the atomic state of the “clock” ion is probed by operations on the “logic” ion. This approach minimizes the perturbations on the “clock” ion. The aluminum-ion logic frequency standard currently has an accuracy of about 8 x 10^{-18}, with significantly improvements expected.

Aluminum ion logic clock

Exploring Multiple Frequency Standards

Developing only one optical frequency standard would dramatically weaken the NIST/Division official time research program.

Recent progress in optical frequency standards has been explosive and unpredictable. Until about the year 2000, the best optical frequency standards were about 1,000 times less accurate than the best microwave frequency standards at that time. In the past 15 years, the best microwave standards have improved by about a factor of 15. But the best optical frequency standards have improved by more than a factor of 1,000,000 in the same time. And over the past several years, both different kinds of single-ion standards and different kinds of cold atom lattice standards have traded places as “best in the world.” It is simply not possible to predict which optical frequency standard will be the “best,” and choosing only one approach represents a significant risk of being locked into a relative “dead end.”



The best possible accuracy and stability address only part of the needs. Maximizing the practical impact of frequency standards requires ease of use, manufacturability for reasonable price, robustness when deployed in rugged environments (clocks on GPS satellites, clocks used in seismic exploration, etc.), and many other considerations. There are about 15 total cesium fountain primary frequency standards in the world today, but many millions of other kinds of atomic clocks broadly deployed on nearly every cellular communications base station, in most radio and TV broadcast centers, etc. The Division purposely chooses to explore not only the absolute best performance, but also to develop frequency standards with the biggest practical impacts – as described below.

Deployable Frequency Standards

Improving official time ("better" clocks) does not mean only focusing on accuracy and stability. The Division also conducts vigorous research and technology development on frequency standards that are potentially deployable for dramatically improving performance in field applications. The best-in-the-world performance of the Yb and Sr optical lattice frequency standards can only be realized in an advanced metrology lab, with high temperature stability, minimal vibrations, etc. Some of the Division's work on high-performance fieldable frequency standards includes:

Recent Accomplishments

Miniaturized and Rugged High Performance Optical Frequency Standards

The Division's single-ion optical frequency standards are currently slightly less accurate than the Yb or Sr optical lattice standards. But ion standards are generally more amenable to miniaturization (less complex laser and optical system requirements). And since the ion is trapped in a rather strong electromagnetic field, it is generally much less susceptible to external environmental perturbations. Currently, the ion frequency standard technology shows greater promise for a miniaturized, ruggedized deployable high performance standard, and the Division has successfully demonstrated a portable, rugged aluminum ion logic clock.

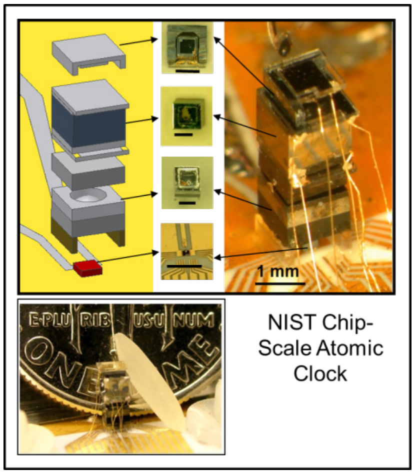
Miniaturized portable aluminum ion logic clock, operating in moving vehicle

CONTACT: David Leibrandt (303-497-7292), PML

Ultra-stable Thermal Beam Optical Frequency Standard

The highest-performance optical frequency standards rely on laser cooling of atoms or ions to improve accuracy by reducing Doppler shifts, minimizing collisions, etc. Now the Division has developed an optical thermal beam frequency standard using calcium atoms with the surprising potential for stability as stringent as 5×10^{-17} at one second, significantly better stability than the laser-cooled Yb or Sr optical lattice standards. The calcium thermal beam standard does not have good accuracy. But as described above, stability is arguably more important for many applications than absolute accuracy. A thermal beam standard is much less complex and more rugged than a cold atom or ion standard, and can be made into a small size, so there is exciting potential for strong practical impact for such a standard. Division scientists are working to achieve the promise of 5×10^{-17} stability at one second, and appear to have a good chance for success.

CONTACT: Chris Oates (303-497-7654), PML



NIST Chip-Scale Atomic Clock

Potential for Ubiquitous Moderate-Performance Atomic Clocks

Many "traditional" timing applications such as telecommunications, positioning, and remote sensing can be well served by "modestly" performing frequency standards, in the 10^{-11} to 10^{-14} stability range. GPS signals meet this performance requirement, but GPS is extremely vulnerable to intentional or accidental jamming, and GPS is available only with a direct, mostly unobstructed sky view (not available inside buildings, often not available outside at street level in a city with tall buildings). To address this need, the Division invented the world's first chip-scale atomic clock (CSAC). The NIST CSAC operates at room temperature, uses a few dozen milliwatts of power (can be supplied by AA battery), and uses standard MEMS microfabrication techniques enabling low cost mass production in principle. The original NIST version had a stability on order 10^{-12}, and Division scientists are researching a laser-cooled version with potential for 10^{-14} stability. The CSAC was first commercialized by the U.S. company Symmetricom (now Microsemi), and other companies are now introducing commercial versions. Commercial CSACs are being used in telecommunications systems, to improve GPS receiver performance, in seismic exploration, and many other applications. A laser-cooled version with 100 times better performance (now under development in the Division) would open up even more high value applications.

Symmetricom CSAC (now Microsemi)

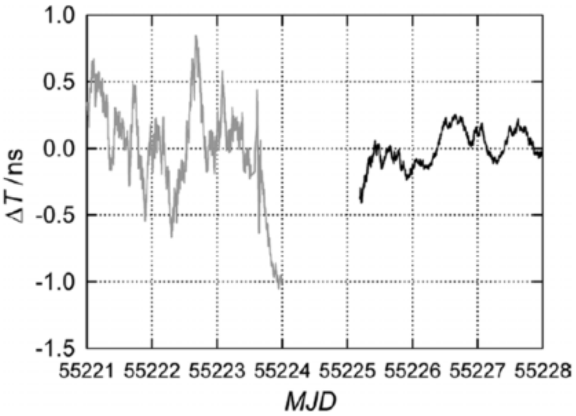
CONTACT: John Kitching (303-497-4083), PML

(1) B. Official time: Improving time scales

As described above, UTC (official time) directly results from the NIST time scale ensemble of commercial masers and complex measurement system, periodically calibrated by NIST-F1/F2. The time scale is the direct source of UTC and of signals for all NIST measurement services. This maser ensemble approach has nearly reached its fundamental physical limits, roughly commensurate with NIST-F2 accuracy and stability of 10^{-16}. Spending millions of dollars for dozens of additional masers could in principle improve performance by 20% or so. But a maser-ensemble time scale will never be able to leverage the 10^{-18} performance of optical frequency standards.

The Division is developing two parallel new time scale approaches to address both near-term and longer-term opportunities.

Near-term: Time Scale Based on Maser Directly Steered by Near-Continuous Fountain Standard



Experiment showing performance of ensemble time scale (left) compared to master steered directly by primary standard

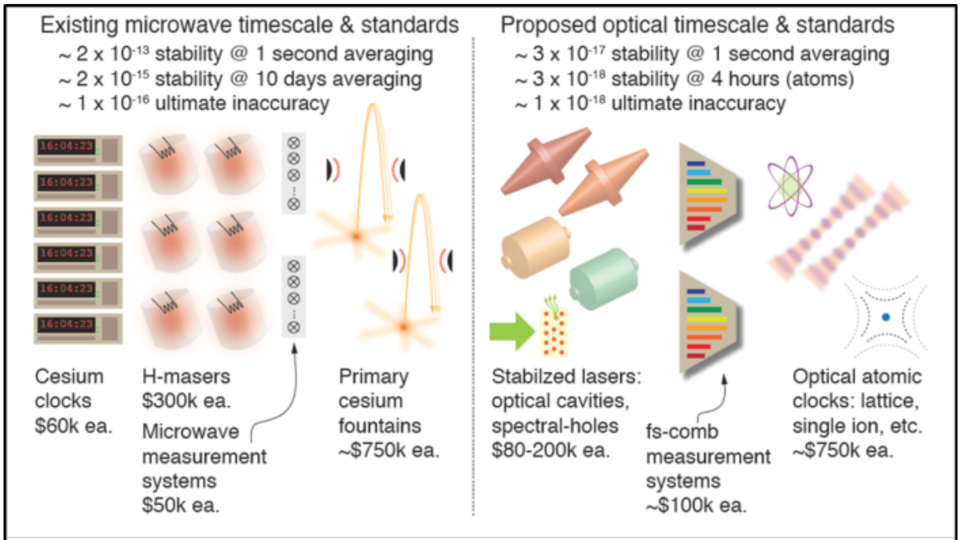
Time scale ensembles with large numbers of masers were necessities when cesium fountain primary frequency standards could be operated only intermittently, which was true from their introduction in the late 1990s until recently. Thanks to numerous technical advances, it is now possible to build fountain primary standards that can operate nearly continuously. Research has shown that directly steering a single maser with a fountain standard that operates for only a couple of hours each day results in substantially more stable UTC than even a large maser ensemble only calibrated every couple of months by the primary frequency standard (current procedure). Such a system is also dramatically less expensive (each maser costs about $300,000 and has a limited lifetime) and much less complex (reducing failure modes). If the primary standard can operate even more continuously, UTC performance is even further enhanced. The Division is currently constructing a continuously operating fountain standard to implement this directly steered maser approach.

- While only a single maser is needed, of course a small ensemble must be maintained to cope with inevitable maser failures. However, the overall investment and complexity is reduced by about an order of magnitude.
- The directly-steered maser UTC realization is a transitional approach. While it provides some performance improvements compared to the maser ensemble approach and is much more economical, it will not support the accuracy and stability of optical frequency standards.

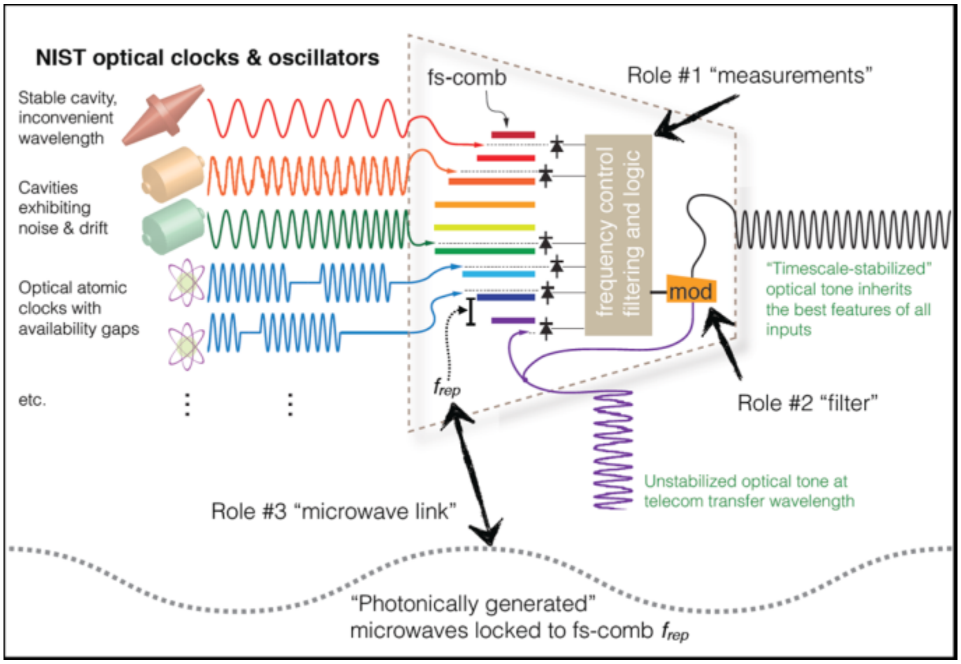
Longer-term: Optical Time Scale

Optical frequency standards such as single-ion standards and optical lattice standards are already accurate and stable to order 10^{-18}, and are continuing to improve. It is currently not possible to continuously operate optical frequency standards at that performance level, and as was true for microwave fountain standards it will likely require many years of research and development until continuous or nearly continuous performance is possible, enabling an optical frequency standard to directly provide UTC. For at least several years, it is highly likely an optical analogue of the current maser ensemble time scale will be needed – a system that operates continuously with high stability with little intervention, and obtains its accuracy reference from non-continuous calibrations by optical frequency standards.

The Division is conducting early-stage research on a potential highly flexible, high-performance optical time scale. This system will use frequency combs to acquire inputs at any time from a broad range of frequency references, including but not limited to microwave frequency standards, optical frequency standards, and stabilized lasers. The system will have on order of 10 inputs across these classes of references, although most or all of the references will likely be intermittently available. The system will use whatever references are available at any time for frequency calibration, and a very stable frequency comb system will provide long-term stability holdover even if no frequency reference is available. A frequency comb output will provide highly accurate and stable reference signals in the optical, microwave, and radiofrequency range for different applications.



General idea for optical time scale replacing maser ensemble



(2) Satellite Time and Frequency Transfer

The Division uses two-way satellite time and frequency transfer (TWSFTF) and GPS common-view time and frequency transfer to coordinate UTC through BIPM and other timing laboratories across the world. GPS common-view is also the basis for the Division's remote time and frequency measurement services, the SIM Time Network, synchronization of UTC with NIST time, and frequency radio stations in Colorado and Hawaii, along with other purposes. All these processes use microwave signals.

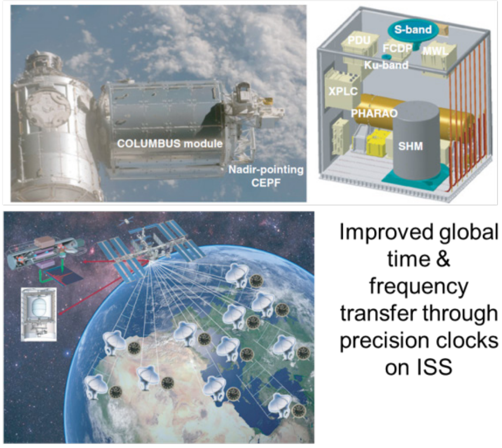
Microwave satellite-based time and frequency transfer has been highly effective in enabling global distribution of time and frequency information commensurate with the performance of the best microwave primary frequency standards, such as NIST-F1 and F2. But in analogy to maser ensemble time scales, microwave satellite-based time and frequency transfer has essentially reached its technical limitations for accuracy and stability. The Division conducts research to tease out the last performance improvements possible with microwave satellite systems, examine interim solutions, and build for the longer-term future leading to global transfer of optical time and frequency standards.

Shorter-Term: Incremental Improvements in Microwave Satellite Time and Frequency Transfer

GPS-mediated time and frequency transfer primarily relies on the GPS code – the signal indicating a reference time. The phase of the GPS carrier signals can actually serve as a more precise time and frequency source, but only if an observer can ensure that: no cycle is ever missed in the approximately 1.2 GHz to 1.6 GHz carrier signals; or that missed cycles can be unambiguously detected and appropriately corrected. The Division has had significant success in demonstrating effective GPS carrier-phase time and frequency transfer, and uses this approach to augment its TWSFTF and GPS code transfer.

Experiment and Interim Solution: Partnership with ESA/NASA Time Transfer Research Program

The European Space Agency (ESA) and NASA are partnering to fly a specialized hydrogen maser and a cold- atom cesium microwave frequency standard on the International Space Station, with launch currently planned for 2016. The Division will serve as one of a handful of ground stations across the globe using a special microwave link to communicate precision time and frequency information between frequency standards at NIST and on the ISS. The on-board presence of the high-performance frequency standards should improve international time and frequency transfer by about a factor of 10 beyond current capabilities. This is an experiment and an interim solution to improve international time and frequency transfer since the mission lifetime is approximately one year.



Improved global time & frequency transfer through precision clocks on ISS

ESA and NASA are tentatively planning a follow up mission several years later with a higher- performance system using on-board optical clocks. The Division is participating in the development of those on-board optical clocks. Both projects are demonstrations of technology, and will not represent long-term improved international time and frequency capabilities.

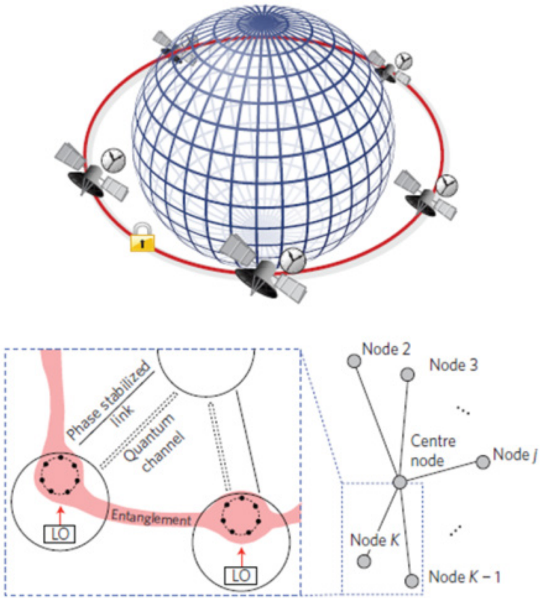
Longer-Term Solution: Fiber and Free-Space Optical Time and Frequency Transfer

The Division conducts successful research and metrology on precision time and frequency transfer through optical fibers, both through dark-fiber systems and systems with standard telecommunications traffic. Frequency stability and accuracy into the low 10^{-19} range has been demonstrated, more than sufficient to support current 10^{-18} optical frequency standards. Colleagues in PML's Applied Physics Division have partnered with Division scientists on demonstrations of free-space optical time and frequency transfer mediated through eye-safe lasers. These experiments have been very successful, even compensating effectively for turbulence and occasional beam disruptions. The obvious limitation for both fiber and laser-based free-space optical transfer is that the transfer is only point-to-point (location served by fiber or directly receiving the laser beam) rather than the multidirectional broadcast of microwaves. While not an insurmountable problem, a point-to-point system requires significant additional complexity and expense to ensure broad dissemination.

Speculative: Future Optical Time and Frequency Transfer

The combination of global telecommunications satellites and GPS created a global infrastructure for easy, inexpensive precision time and frequency transfer, in essence making precision timing a ubiquitously available infrastructure. Of course, these satellite systems were not implemented for time distribution; that was a secondary (or lower-order) benefit with wonderful consequences for global time and frequency. To enable global distribution of high performance optical frequency standards at the 10^{-18} or better level, some new global infrastructure will need to be implemented. A new satellite system enabling global optical signal relay will cost hundreds of billions of dollars. It will almost certainly not be implemented with optical time and frequency transfer as a major goal, but as with telecommunications and GPS satellites there could be an opportunity for optical time and frequency transfer to piggyback on systems with different primary purposes such as optical communications, optical defense/intelligence applications, etc. These types of decisions and investments are obviously completely out of the sphere of the Division or NIST. But the Division conducts general research and studies, and participates on national and international committees, to try to circulate these ideas for possible future use.

There will be a period where the performance of optical frequency standards will significantly surpass the ability to broadly distribute the standards. This period essentially recapitulates the period when microwave frequency standards outperformed earlier distribution technologies, before telecommunications satellites and GPS. As in that earlier era, one solution for distributing highest-accuracy time and frequency information will be "clock trips," where optical frequency standards are physically moved to different locations to directly intercompare the highest performance standards. The Division is performing research to develop high-performance portable optical frequency standards, as noted above.



Speculative plan for global quantum clock network

(3) Network time distribution

The Division's network time distribution programs have been highly successful and are by orders of magnitude the most heavily used NIST measurement services (Internet Time Service primarily using NTP for approximately 1 millisecond accuracy and 10^{-8} stability). But there are needs and opportunities for substantially improved network time and frequency transfer, both to meet current demands and to provide an infrastructure for future innovations.

Recent Accomplishments

Practical Use of PTP For 1,000-fold Improvement in Network Time Distribution

The Division performs research and measurements to support the use of Precise Time Protocol (PTP) as a 1,000 times (or better) improvement in network time and stability compared to NTP. While the PTP standards are well-established, Division measurements have clearly demonstrated that most commercial PTP equipment is not yet meeting PTP performance requirements in practice. Working with industry and other Federal agencies, the Division is trying to develop the metrology and technology to implement PTP for both improved network time transfer for more stringent uses (such as time-stamping high-frequency electronic financial transactions) and as a backup for GPS timing. The Division has demonstrated that PTP can exceed the one microsecond/10-11 stability requirements for GPS backup and other high-value applications, but significant work remains to translate this potential into practice.

CONTACT: Marc Weiss (303-497-3261), PML

(4) Research and innovations evolving directly from time and frequency research

As noted above, in researching improvements in official time and dissemination, Division scientists have often developed new technologies with substantial impact on the broad NIST measurement science and metrology mission, even if not appearing directly related to official time and dissemination. Examples include trapped-ion quantum information processing, development and applications of femtosecond laser frequency combs, and development and applications of chip-scale, atom-based sensors.

These all represent areas in which Division scientists conduct world-leading research and measurement programs that directly advance broad NIST measurement science and metrology goals. All these programs have some direct connection to official time and dissemination, although Division activities in these areas typically extend far beyond timing alone. The Division vigorously pursues these complementary research areas when:

- the research and measurement programs broadly address NIST, PML, and national priorities; and/or
- Division scientists bring unique expertise and innovations to make the program best-in-the-world in ways that could not be easily duplicated elsewhere; and/or
- the complementary programs support to a reasonable degree the core official timing and dissemination activities of the Division.

Some of this research is described below.

Trapped-ion Quantum Information Processing and Quantum Simulation

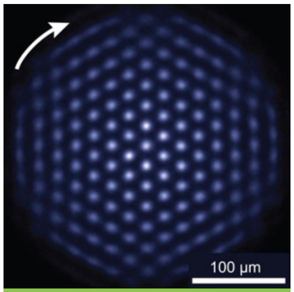
Trapped ion quantum computing

Division scientists led by Dr. David Wineland explored fundamental quantum mechanics in the quest to make better atomic frequency standards based on electromagnetically trapped ions. In the early 1990s, parts of this work were recognized as being very similar to logic operations, but using the “strange” logic of quantum mechanics. Theoretical exploration by leaders outside NIST, coupled with on-going experiments in the Division, soon established the field of quantum computing, in the case of the Division using trapped ions as the qubits. The Division programs progressed rapidly under Wineland’s leadership, with a long list of first and best-in-the-world results, including (a very small sample):

- the first demonstration of a quantum logic gate with controllable inputs
- the first observation of entangled superposition of states at the single-particle level – the so-called Schrödinger cat state
- the first observation of deterministic entanglement, a prerequisite for quantum computing
- the first implementation of a quantum Fourier transform operation in a scalable system
- the first demonstration of quantum error correction in a scalable system
- the first demonstration in a single experiment of all the criteria required for scalable, fault-tolerant quantum computing (DiVincenzo criteria)
- the first demonstration of an arbitrarily programmable “universal” quantum computer, capable in principle of simulating any physical system

These and many other breakthrough accomplishments led to the 2012 Nobel Physics Prize being awarded to Wineland and Serge Haroche. The Division quantum computing program continues to be a world leader (arguably *the* world leader). The Division has more recently expanded into quantum simulation employing large-scale arrays of trapped ions with many additional accomplishments, including the first demonstration of a googol-sized quantum memory.

Practical quantum computing and/or quantum simulation are of course completely disruptive technologies with the potential for enormous impacts on technology, the economy, national security, and many other areas. The pursuit of trapped-ion quantum computing has also directly advanced the “limited” Division mission of developing time and frequency standards by directly leading to the aluminum-ion quantum logic clock described above, one of the world's most accurate optical frequency standards with strong potential for miniaturization and portability. In addition, the Division's quantum computing program has led directly to: new methods for characterizing the chemistry and physics of surfaces at the microscopic level; new simple and cheap technologies to prevent optical fibers from solarizing (becoming opaque) when exposed to UV light; new ways to measure tiny forces at the 10^{-22} newton level; and many other accomplishments that directly advance the "standard" mission of the Division and of NIST.



Array of trapped ions for quantum simulation

While quantum computing may not immediately appear related to time and frequency metrology, it would have been an enormous loss to the Division, to NIST, to national priorities and to science to not pursue this completely disruptive science and technology simply because it did not appear to fit into a mission statement.

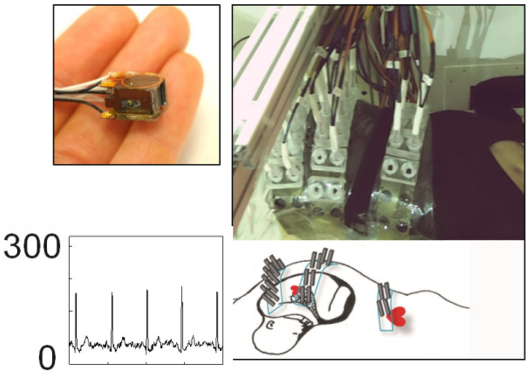
Chip-scale Atomic Devices (Sensors) and The "NIST on A Chip" Program

As described above, Division scientists pioneered the first chip-scale atomic clock (CSAC) for clearly-defined timing dissemination goals, such as improving GPS receivers and telecommunications systems. As CSAC commercialization began, Division scientists recognized that the technology of precision atomic frequency measurements in miniaturized vapor cells could be used for a broad range of measurements.

Recent Accomplishments

Chip-scale Atomic Magnetometer

First, the Division demonstrated the world's first chip-scale atomic magnetometer (CSAM), the size of a sugar cube and operating at ambient temperature. Division scientists soon improved its performance to equivalence with superconducting quantum interference devices (SQUIDs) requiring cooling to 0.1 K in large dewars and large racks of electronics. Division scientists in partnership with medical researchers showed that NIST CSAMs can be used to duplicate the best previous measurements of biomagentic fields generated by heart, brain, and muscle activity, providing new diagnostic and research capabilities. Division scientists and partners also demonstrated such advances as the world's first detection of certain epileptic signatures without having to implant electrodes in the brain, and the world's first precision measurements of fetal heart activity without having to implant electrodes in the uterus/fetus. Because the CSAMs are so small, Division scientists also demonstrated the first precision 3D spatial imaging of biomagnetic fields with millimeter-scale spatial resolution and millisecond-level timing resolution. In addition to biomagnetic fields, Division scientists working with external partners demonstrated such things as zero-field chip-scale NMR. The Division is collaborating with partners on commercialization of CSAMs.



First non-invasive fetal magnetcardiography with NIST chip-scale atomic magnetometers.

CONTACT: Svenja Knappe (303-497-3334), PML

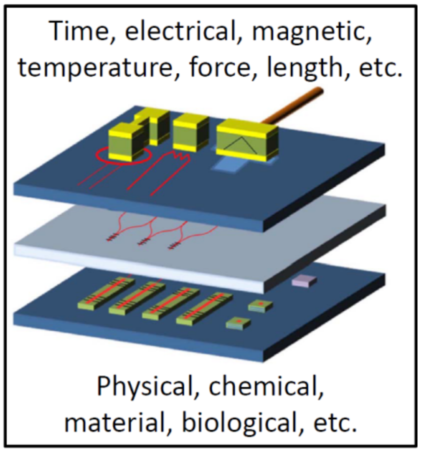
Other Chip-Scale Atomic Devices/Sensors

Division scientists extended the chip-scale device technology to demonstrations of precision gyroscopes, spectrometers, and other technologies. Division scientists are currently researching laser-cooled chip-scale atomic devices which could improve performance by factors of 1,000 or more in many different applications including timing, magnetometry, gyroscopic/acceleration measurements, and more.

CONTACT: John Kitching (303-497-4083), PML

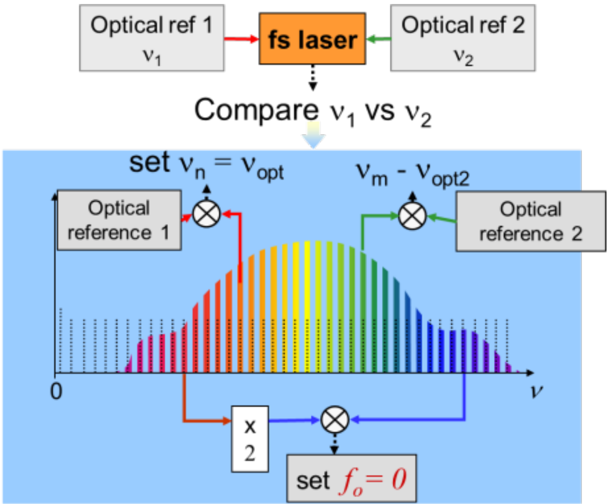
“NIST on a Chip” Program

The great success of chip-scale atomic devices in making a broad range of measurements led Division scientists to consider what other types of measurements might be possible using the vapor cell/atomic transition technology, and then more broadly to what type of precision measurements in general might be possible in chip-scale formats. Over time, these considerations led to the NIST-wide “NIST on a Chip” program to develop precision, NIST-traceable measurement technologies that are:



- Deployable – for use anywhere, such as the manufacturing floor, in operating aircraft or motor vehicles, etc.
- Usable – typically very small size, weight, power.
- Flexible – providing a range of measurements in one small device.
- Manufacturable – with potential for low cost mass production.

The NIST on a Chip program currently spans several Laboratories, Divisions and technologies across NIST. More information available in other PML documents.



Laser frequency comb comparing optical frequencies

Laser frequency comb development and applications

NIST scientists led by Dr. John Hall of PML’s Quantum Physics Division (JILA) pioneered the self-referenced femtosecond laser frequency comb around the year 2000, resulting in Hall’s Nobel Physics Prize in 2005 with Ted Hansch. One of the major motivations for exploring the frequency comb was to provide for the first time a way to directly measure optical frequencies and thus facilitate the development of optical frequency standards. This goal was wildly successful as noted above, with optical frequency standards improving by more than a factor of one million in the 15 years since the first demonstration of the self-referenced frequency comb.

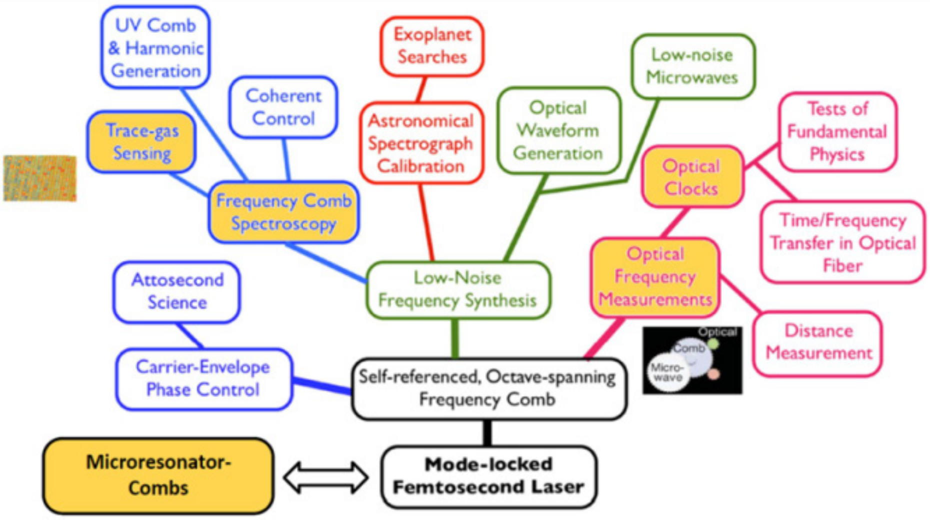
But to the surprise of even the frequency comb pioneers, frequency combs rapidly became one of the most powerful, flexible, and important precision-measurement technologies since the 1960 invention of the laser itself. Division scientists (including key scientists from the original NIST/JILA invention) used the frequency comb to vastly accelerate development of Division optical frequency standards.

But they are also pioneering many other applications, including (only a small sample):

- Development of massively parallel precision laser spectroscopy to “fingerprint” chemicals almost instantaneously.
- Moving toward optical frequency synthesis with as much flexibility and precision as current RF/microwave frequency synthesis, where any arbitrary optical waveform can be simply generated.
- Development of portable systems for remote sensing and quantification of chemicals such as greenhouse gases in the environment, threat chemicals (explosives and the like) for security applications, etc.
- Direct frequency intercomparisons between multiple microwave and optical frequency standards. These intercomparisons ensure accuracy of the standards, but also enable such things as exploring possible time variations of fundamental constants – for example, the fine-structure constant.

- Stable multi-wavelength reference sources supporting the identification and characterization of exoplanets through the "wobble" of stars.

Division scientists pursue fundamental developments in frequency combs, such as extending the spectral range into the deep ultraviolet and far infrared, extending the range of repetition rates into the 100 GHz range and beyond, performing fundamental studies of the tiny amounts of frequency noise on the combs (10^{-21} level and below), and other efforts to continue to expand the range of applications for frequency combs.

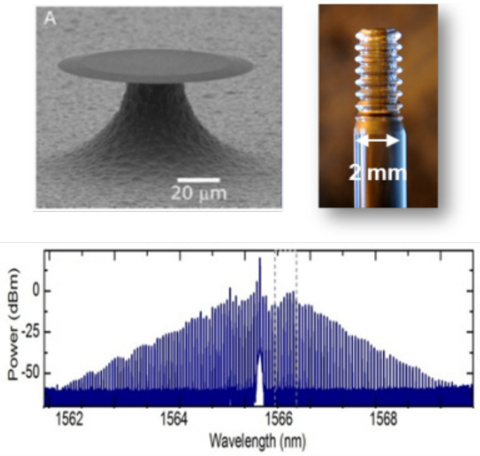


Example frequency comb applications

Recent Accomplishments

Microresonator Frequency Combs

One of the most important recent developments has been pioneering microresonator frequency combs based on silicon nitride microstructures or on microscale silica structures. This work, partly with external partners, has the potential to transform frequency combs from optical-table sized devices to chip-scale devices, thus even further extending the already impressive range of applications and impacts. Division scientists have even demonstrated how a microresonator frequency comb can be fabricated from a cheap silica rod using a commercial off-the-shelf CO2 laser in less than one minute at a cost of a few cents. The silicon nitride microresonators can be fabricated with standard microfab techniques. It seems likely that microscale frequency combs could become ubiquitous, low-cost, high- performance tools in the future, including crucial elements of integrated photonic/electronic circuits. Microscale frequency combs are also crucial components for the "NIST on a Chip" program. In just one example, the Division demonstrated the world's first chip-scale optical atomic clock (in contrast to the original microwave chip-scale atomic clock), with the potential for much greater stability and accuracy than the "standard" chip-scale clock even without laser cooling.



Microresonator frequency combs

CONTACT: Scott Diddams (303-497-7459), PML

Precision Measurement and Generation of Electromagnetic Waves

The Division performs research to develop world-leading capability in the measurement and generation of ultra-precise electromagnetic signals in the radiofrequency, microwave and optical range. Ultra-precise signals are increasingly important in high-value applications such as telecommunications, high-speed computing, remote sensing, GPS, radar, atomic clocks, and many other applications. Division advances in precision measurements such as phase noise (timing jitter), spectral purity, and vibration/acceleration sensitivity have dramatically advanced the use of precision signals and enabled technology producers and users for the first time to specify meaningful performance metrics in phase noise, spectral purity and related quantities. This "virtuous cycle" has led to continually improving systems and technologies.

Recent Accomplishments

Commercialization of Digital Phase-Noise Measurement Technology

Until recently, the precision measurement of phase noise, spectral purity, and related quantities had been a challenging process, with only a relative handful of experts in the world. The Division partnered with the company Microsemi (previously known as Symmetricom) through a NIST Small Business Innovation Research grant to develop the world's first digital phase-noise measurement system. This advance transformed phase-noise metrology to a “plug and play” measurement that can be mastered by any reasonable electronics lab, and resulted in one of the top-selling product lines for Microsemi. More importantly, the easy availability of precision phase-noise measurements in a company's or organization's own metrology lab led to an explosion in the use of phase noise, spectral purity and related quantities, directly leading to better-performing products and systems, and to many innovations. A few years ago phase noise specifications for components and products were rare because it was too hard and costly to measure. Now phase noise specifications are nearly ubiquitous for high-performance systems using RF and microwave signals.

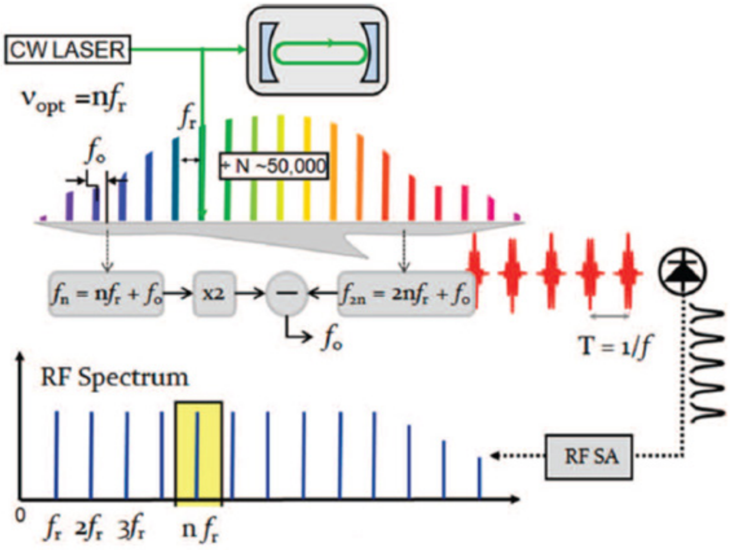
Microsemi digital phase noise metrology system

CONTACT: Dave Howe (303-497-3277), PML

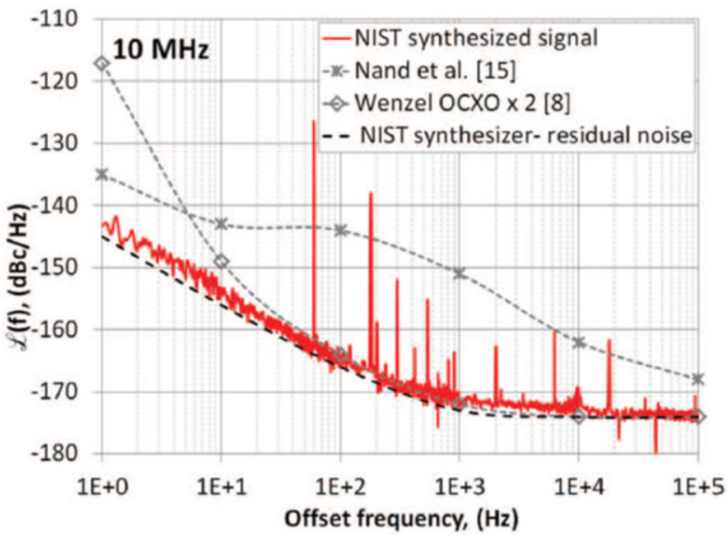
World's Most Stable RF/Microwave Signals from Laser Frequency Combs

One of the Division's most important advances has been mastering frequency division of femtosecond laser comb signals, translating the intrinsic stability of laser optical signals into RF and microwave signals 100 to 10,000 times more stable (lower noise) than possible through other generation means. The frequency-comb generated RF/microwave signals are especially more stable close to the carrier frequency, which is the region of greatest interest for most applications.

This work has led to new Division measurement capabilities and technologies (patents applied for), and partnerships with industry to develop new ultra-stable RF/microwave sources from frequency combs. A key part of this Division research has been intensive study of the ultra-fast noise processes of photodetectors used to convert the high repetition rate, femtosecond optical pulses into RF/microwave signals. This work has garnered substantial recognition from industry and the international scientific/metrology community, including a recent IEEE “Best Paper” award for a description of the Division's work, selected from among 300 international submissions.



Generation of ultralow noise microwaves from frequency comb



NIST ultralow noise microwaves compared to other leading technologies

The Division continues to advance the generation and measurement of ultra-stable signals, expanding into the terahertz range, and continuing to improve overall RF/microwave stability, and continuing to reduce noise further from the carrier frequency. A particularly intriguing area of research is using the Division’s microscale laser frequency combs to produce chip-scale systems that generate and measure ultra-stable RF/microwave signals. The Division expects the demand for and applications of ultra-stable RF/microwave/THz signals to continue to rapidly expand.

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Time and Frequency Division Supplemental

Division Partnerships and Technology Transfer

The Division transfers the results of its research, measurements and technology development through many means:

- **Publications:** Over the past five years, the Division has published an average of 58 articles per year in archival scientific journals and peer-reviewed conference proceedings. The Division's very diverse mission – from calibrations and Internet Time Service, to research on quantum computing and frequency combs, to measurements of human biomagnetic fields – results in a articles in a particularly broad range of technical disciplines and a wide variety of journals. About 20% of the publications on average are in the top international physics research journals relevant to much of the Division's work, such as *Science*, *Nature*, *Physical Review Letters*, and *Optics Letters*.
- **Training:** Exchange of highly trained people with unique knowledge is probably the most effective form of tech transfer. Of the approximately 100 scientific and technical staff in the Division, approximately 55% are trainees or scientific visitors at any time: Graduate students performing PhD thesis work in the Division, postdoctoral fellows, and guest researchers from across the world (universities, companies, national labs). These trainees advance the work of the Division and directly transfer their knowledge to companies, national labs, and industry when they move to new positions after NIST. The Division's network of knowledgeable scientific contacts also continually expands.
- **Inventions:** Division scientists regularly produce new high-impact technology innovations. Recent examples include: chip-scale atomic devices, microscale laser frequency combs, new ultra-precision oscillators, digital phase noise measurement systems, new radio time code systems, solarization-resistant optical fibers, and many more. When it appears that seeking patent protection will accelerate the development of these inventions, the Division/NIST pursue patents and licensing. In most cases, the inventions are publicly shared, through publications, movement of non-employee inventors to companies, and direct consultations with interested parties. Division scientists have patented (or have pending applications for) more than a dozen technologies in the past few years, but most inventions are publically shared.
- **Workshops/Seminars:** Division scientists host regular workshops and seminars to share knowledge and provide hands-on training from leading experts in the Division and from outside NIST. One regular training event is the Annual Time and Frequency Metrology Seminar, a four-day intense program of lectures, problem-solving and hands-on laboratory experience as a "boot camp" introduction to time and frequency metrology and applications. The Seminar typically includes about 60 participants from industry, other federal agencies, metrology labs and universities. In just one example, the company Microsemi (largest producer of time and frequency products) sends all its new managers and technical leaders to the Annual Seminar as the best available introduction to the topic.

Most of the Division's activities are conducted in partnership with industry, other Federal agencies, universities, and international metrology organizations. Approximately 40% of the Division's operating budget is received as contracts from other Federal agencies to provide research, metrology, and technology development supporting broad national priorities. As noted, precision timing and synchronization are crucial to a broad range of national technology infrastructures, and much of the external funding focuses on continued development of those infrastructures. Other Federal agencies also strongly support such Division programs as quantum computing, chip-scale atomic sensors, microscale frequency combs and ultra-stable signal generation and measurement, all of which advance national goals in defense, security and intelligence.

The Division is particularly closely connected to the international metrology community. A partial list of these on-going international metrology efforts includes:

- The Division reports its estimates of UTC to the BIPM and to a large number of international metrology institutes every two hours of every day, providing on-going direct international comparisons.
- Frequency evaluations of NIST-F1 and F2 are also directly reported to both BIPM and to the approximately dozen other national metrology labs operating primary frequency standards across the world.
- The Division coordinates closely with the US Naval Observatory to effectively and efficiently share the national responsibilities for realization and distribution of official US time.
- The Division is the primary host and leader of the SIM Time Network providing the only real-time international time scale in the world.
- The Division regularly hosts scientific visitors from across the world. In the past few years, the Division has made a special effort to host scientists from smaller South and Central American timing laboratories to help expand and strengthen metrology activities in developing nations.

Recognition for Division Scientists and Metrologists

One way of measuring the Division's impact is through major scientific awards presented to Division staff. Below is a partial, representative list of awards received by Division staff in the past few years (a full list is available elsewhere). All awards are from external organizations unless specified as a NIST or Department of Commerce (DoC) award.

- Benjamin Franklin Medal in Physics, for leadership quantum-based measurements.
- Arthur S. Flemming Award for excellence among early career Federal employees. Four awards, recognizing advanced frequency standards, quantum computing, and chip-scale atomic devices.
- NIST Fellow, outstanding scientific leadership limited to 40 total positions across NIST. Two new Fellows, bringing total number of Division Fellows to four.
- IEEE Cady Award for excellence in noise metrology.
- Rank Foundation Prize (UK), for chip-scale atomic device development (two winners).
- Condon Award (NIST), recognizing excellence in NIST scientific publications.
- Presidential Rank Award, recognizing career achievement in the top 1% of all Federal employees (two winners).
- DoC Bronze Medal, for pioneering new phase noise and spectral purity research and measurement programs.
- NCSLI Wildhack Award, for outstanding leadership in international time and frequency coordination.
- Rabinow Award (NIST), for pioneering new technologies for laser frequency combs and applications.
- National Association of Inventors, for new atomic clock technologies.
- DoC Silver Medal, for innovation in microscale laser frequency combs.
- IEEE Rabi Award, for excellence in network precision timing research and services.
- Slichter Award (NIST), for coordinating with industry on precision time and frequency metrology.
- IEEE/European Time and Frequency Forum Young Scientist Award, two awards, recognizing advances in optical lattice frequency standards, and generation of ultra-stable RF/microwave signals from laser frequency combs.

- Judson French Award (NIST), for excellence in remote time and frequency measurement services.
- IEEE Outstanding Paper Award, for generation and measurement of ultra-stable RF/microwave signals from laser frequency combs.
- Astin Award (NIST), for pioneering ultra-stable signal measurement technologies.
- IEEE Sensors Society Technical Achievement Award, for development of chip-scale atomic sensors.
- DoC Bronze Medal, for developing innovative time-code radio broadcast technologies in partnership with industry.
- Nobel Prize in Physics (2012), “for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems.”