UPDATE ON TIME AND FREQUENCY ACTIVITIES AT NIST

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Abstract

The mission and organization of the Time and Frequency Division of the National Institute of Standards and Technology (NIST) are reviewed and a discussion is presented of recent activities. Among the major recent milestones have been the development of cold-atom frequency standards, including the construction of a new cesium-fountain frequency standard and the design of a standard for operation on the International Space Station. In addition, the use of GPS carrier phase for frequency transfer at the $1x10^{-15}$ *level has been demonstrated, and the power radiated by WWVB has been increased to 50 kW. Other areas discussed include time scales, time transfer, optical frequency standards, and time and frequency dissemination services.*

MISSION

The mission of the Time and Frequency Division of the National Institute of Standards and Technology (NIST) is to support U.S. industry and science through provision of measurement services and research in time and frequency and related technology. To fulfill this mission the Division engages in:

- the development and operation of standards of time and frequency and coordination of them with other world standards;
- the development of optical frequency standards supporting wavelength and length metrology;
- the provision of time and frequency services to the United States;
- basic and applied research in support of future standards, dissemination services, and measurement methods.

The work supporting length metrology derives from the dependence of the definition of the meter on the realization of the second. This work contributes to a larger program in the NIST Precision Engineering Division, which has primary responsibility for length and its dissemination.

ORGANIZATION

The Time and Frequency Division is organized into eight technical Groups: Time & Frequency Services, Network Synchronization, Atomic Frequency Standards, Ion Storage, Phase Noise Measurements, Local Oscillators, Laser Frequency Spectroscopy, and Optical Frequency Measurements. The Groups are necessarily small, and the Group Leaders are thus able to function primarily as technical leaders within their areas. The unifying theme of time-and-frequency technology requires strong interactions among the Groups.

CURRENT DIRECTIONS

TIME AND FREQUENCY BROADCAST SERVICES

The Division provides time and frequency broadcasts from stations WWV and WWVB in Fort Collins, Colorado and from WWVH in Hawaii. The Division has just completed an upgrade of the equipment and power level for WWVB. At a higher output power, these LF broadcasts are substantially more useful for mobile and consumer applications, because the antenna/receiver cost and size is very small. A detailed discussion of this upgrade is presented in another paper in this symposium. The Division also operates a telephone time service, the Automated Computer Time Service (ACTS), designed for setting clocks in digital systems. The network (Internet) version of this service now receives more than 12 million requests per day. These broadcasts and services address applications in a broad range of systems in business, telecommunications, science, transportation, and radio/TV broadcasting. Industry calibration laboratories are served by the Division's Frequency Measurement Service, a system that provides these laboratories with continuous assurance of the accuracy of their frequency measurements [1].

TIME SCALES

The NIST Time Scale is a highly stable and reliable clock system that provides accurate time and frequency references for services and applications, and that serves as a reference for research on new standards and measurement methods. The reliability and stability of this time scale is based on the use of an ensemble of commercial cesium-beam standards and hydrogen masers combined under the control of a computer-implemented algorithm. The Division is working to advance the performance of the time scale through acquisition of more-stable clocks and improvement of electronic systems that read the clock outputs. These improvements are critical to the successful evaluation and use of the next generation of primary standards now being developed by the Division. An equivalence agreement exists between NIST and the U.S. Naval Observatory (USNO) stating that their two scales are equivalent to better than 100 ns.

FREQUENCY STANDARDS

The accuracy of the time scale is derived from primary frequency standards, which provide the practical realization of the definition of the second. The Division now operates two frequency standards. The first, NIST-7, went into operation in early 1993. This atomic-beam standard is based on optical pumping methods (using diode lasers) rather than the traditional magnetic methods used for state selection and detection. The uncertainty from known biases for this standard is on the order of 5×10^{-15}. More recently, the Division has constructed and evaluated a cesium-fountain frequency standard, NIST-F1, with an uncertainty substantially smaller than that of NIST-7. During the next year, these two standards will be operated in parallel to make sure that they are in full agreement before NIST-F1 takes over as the U.S. primary frequency standard. Looking toward still higher accuracy, the Division is studying standards based on trapped, laser-cooled atomic ions. Both microwave (40 GHz) and optical (1064 THz) ion standards have been demonstrated, and significant advances in performance should be made during the next few years. While the ion-storage program is already demonstrating prototype clocks, the work is generally treated as basic research providing the knowledge base needed for the development of future frequency standards.

METHODS OF TIME TRANSFER

Since the world operates on a unified time system, Coordinated Universal Time (UTC), highly accurate time transfer (to coordinate time internationally) is a critical ingredient in standards operations. The Division is working to further improve the GPS common-view time-transfer method that is the standard for international time coordination. The Division also continues to study two-way time transfer and has been studying GPS carrier-phase time transfer, a method that could become very important for comparisons of the next generation of frequency standards.

OPTICAL FREQUENCY SYNTHESIS

In collaboration with the Quantum Physics Division of NIST, the Time and Frequency Division is developing improved methods for optical frequency synthesis through frequency-comb generation with mode-locked lasers. The method appears to have the potential for large spectral coverage (> 100 THz) with low measurement uncertainty. The objective is to develop a low-uncertainty link between the frequency of optical standards, such as the mercury-ion and calcium standards, and frequency standards operating in the microwave region. Such synthesis will allow translation of the high performance of optical standards to the microwave region and will further support optical-wavelength measurements for improved length metrology.

OPTICAL FREQUENCY STANDARDS AND MEASUREMENTS

Current optical-frequency standards such as the carbon dioxide laser and the calcium-stabilized diode laser already serve as references for supporting accurate spectroscopic measurements for industrial and scientific applications; but as indicated above, optical frequency standards can have still broader impact. This is because higher-frequency transitions can lead to better fractional-frequency uncertainty. Aside from this work on optical standards, the Division is engaged in developing improved optical frequency measurements important for secondary wavelength standards based on atomic and molecular transitions, advanced optical communication, analytical instrumentation, and length measurement. An important part of this program involves the development of diode laser systems, which can have very high spectral purity, tunability, simplicity, and low cost.

SPECTRAL-PURITY MEASUREMENTS

The Division's development of spectral-purity measurements supports sound specifications for a range of aerospace and telecommunications systems. Systems capable of making highly accurate measurements of both phase-modulation (PM) and amplitude-modulation (AM) noise have been developed for carrier frequencies ranging from 5 MHz to 75 GHz. Portable systems covering this same range have also been developed, and these are being used to validate measurements made in industrial and government laboratories. More recently, systems have been developed for making pulsed measurements, which are important for high-power systems such as radars. Further work will broaden the spectral coverage and simplify comparison of measurement accuracy among standards laboratories.

SYNCHRONIZATION FOR TELECOMMUNICATIONS

The Division has been engaged with the telecommunications industry in issues relating to synchronization of advanced generations of telecommunications networks. NIST has made useful contributions to emerging telecommunications systems, but with expansion of effort by the Division, it is clear that NIST could contribute even more significantly to this industry. The industry has requested such expansion.

APPLICATION OF TIME AND FREQUENCY TECHNOLOGY

Finally, the Division is engaged in the application of time and frequency technology to important problems in high-resolution spectroscopy and quantum-limited measurements.

TECHNICAL HIGHLIGHTS

EVALUATION OF THE NIST CESIUM-FOUNTAIN FREQUENCY STANDARD, NIST-F1

Dawn Meekhof and Steve Jefferts of the Division have now completed four preliminary evaluations and one formal evaluation of NIST's newest atomic frequency standard, a cesium-fountain frequency standard [2]. The new standard, NIST-F1, uses laser-cooled atoms that are tossed vertically through the microwave cavity and return under the influence of gravity to a detector below the level of the cavity. Because the atoms move at much lower speed, this standard suffers much smaller systematic frequency shifts than are found in atomic-beam standards. The linewidth of the central Ramsey fringe can be as narrow as 1 Hz (see Figure 1). This is to be compared with a linewidth of approximately 60 Hz for NIST-7.

The lowest uncertainty from these evaluations was 1.8 parts in 10^{15}, about one third that of the best performance of NIST's atomic beam standard, NIST-7. This result is still dominated by measurement noise, which should be reduced through improvement of the signal-to-noise performance of the standard. The uncertainty associated with known systematic effects, particularly the collision shift, is estimated to be 0.8 parts in 10^{15}. It is these effects that are expected to limit the performance of the device.

OPTICAL FREQUENCY STANDARD BASED ON $^{199}HG^{+}$.

In a continuing effort toward development of an optical frequency standard based on mercury ions, Brent Young, Rob Rafac, and Jim Bergquist have improved both the laser local oscillator and the ion-trap system, bringing them very close to a full demonstration of a prototype of a new generation of frequency standards. The goal of this project is to lock the frequency of a narrow-linewidth laser to the S-D resonance in $^{199}Hg^{+}$ (wavelength of 282 nm and natural linewidth of 2 Hz). The optical output of this standard will be frequency-divided to the microwave region, where comparisons can be made with other microwave frequency standards [3-5].

Significant improvement has been made in the spectral purity of the laser oscillator and they have verified that light from the laser can be sent through 100 meters of optical fiber without compromising its frequency stability. In a recent experiment (see Figure 2), they have measured the beat frequency between the outputs of two independent laser systems to be 0.22 Hz, a factor of four smaller than the world record 0.8 Hz reported last year by this group [6]. To verify that the additive noise introduced by light transmission through a fiber could be stripped away, the radiation sent through the fiber was heterodyned with some of the light introduced into the fiber. In the absence of feedback and with the fiber in a noisy environment, the heterodyne signal revealed that the frequency of the light transmitted through the fiber was broadened to about 20 kHz. However, when the feedback servo was enabled the beat signal was only a few millihertz wide, indicating nearly complete elimination of the noise introduced by the fiber. Since the frequency instability of the laser is about 200 millihertz, the residual contamination by the fiber will not limit the performance of the clock.

In order to operate the standard with a single ion, the ion must be laser cooled and tightly confined so the amplitude of its motion is less than the wavelength of the light probing the optical transition (the so-called Lamb-Dicke regime). While the group had previously demonstrated Lamb-Dicke confinement of a single ion in a room temperature trap, chemical reactions with the background gas prevented long storage times. They have just recently observed Lamb-Dicke confinement in a linear Paul trap in a cryogenic environment where the storage time has been shown to be at least several days. Since all known systematic shifts for the mercury optical transition are expected to be very small, this new standard should perform better than all previous frequency standards.

PARCS PROGRESS

The Primary Atomic Reference Clock in Space (PARCS), a NASA-funded program to put a laser-cooled cesium atomic clock in space, has passed the first major NASA review, and system development has started. This collaborative program involves NIST, the Jet Propulsion Laboratory (JPL), the University of Colorado, the Harvard-Smithsonian Center for Astrophysics, and the University of Torino. The Science Concept Review by an external panel was satisfactorily completed in January of 1999, allowing the program to move to the next stage of development, where prototypes of the various system components are constructed and tested to demonstrate the feasibility of the concept. The majority of the space hardware will be developed and tested by JPL, but the entire team will collaboratively direct the development work. Don Sullivan of NIST and Neil Ashby of the University of Colorado are the principal investigators for the program.

Work within the Division that contributes to PARCS includes: (1) the development by Fred Walls and his collaborators of a space-qualified microwave frequency synthesizer; (2) an experimental study by Tom Heavner and Dawn Meekhof of the laser-power requirements and the atom-trapping parameters; (3) design of the microwave cavity by Steve Jefferts; (4) simulations of clock and microwave-cavity performance by Hugh Robinson,and (5) theoretical work on transverse laser-cooling schemes by guest researchers Aleksej Taichenaclev and Valery Udin of Novosibirsk State University in Russia. In addition, Steve Rolston, Bill Phillips, and Laura Lising of the Atomic Physics Division have been doing experimental work on transverse laser cooling. One significant result is the quantitative verification that the spin-exchange shift, a serious problem for fountain standards on earth, decreases with increasing Ramsey time (see Figure 3). This provides one of the motivations for operating such clocks in a microgravity environment.

INTERNATIONAL FREQUENCY COMPARISONS USING GPS CARRIER PHASE

Judah Levine and Lisa Nelson, in collaboration with Kristine Larson of the University of Colorado, have completed cross-country frequency comparisons using GPS carrier-phase methods [8] and have now initiated comparisons of NIST-7 and PTB's CS-2 (see paper in this conference). These feasibility tests have involved baselines from NIST to USNO and from USNO to Colorado Springs. The test have shown a time stability of 200 ps at one day and a frequency stability at one day of $2.5x10^{-15}$. This appears to be the most cost-effective way for decreasing the uncertainty in the comparison of primary frequency standards, a step that must be taken as the accuracy of these standards continues to improve. It is becoming increasingly difficult to effect these comparisons using the traditional method of GPS common-view time transfer.

IMPROVEMENTS IN TIME TRANSFER

Following the development last year of a model of multipath effects on time transfer with pseudo-random phase codes, Franklin Ascarrunz, Marc Weiss, and Tom Parker have implemented improvements (suggested by the model) in the NIST two-way satellite-time-transfer (TWSTT) and GPS common-view systems that have measurably improved performance. Recent comparisons between NIST and NPL now exhibit a time-transfer noise of only 700 ps at a few days, the lowest noise yet achieved using two-way time transfer over this particular transatlantic path.

The key changes (suggested by the model) that have been made involve measures that minimize signal reflections within cables in the system. This was achieved by replacing key cables with cables of high phase stability and by more carefully matching the impedances of all circuits to the system cables. While multipath effects at the antennas remain a concern, it is variations in these effects that give rise to time-transfer noise, so such effects can be minimized by maintaining careful control over the geometry of peripheral objects that scatter signals at the antenna locations.

TWO-WAY TIME TRANSFER LINK TO AUSTRALIA

Tom Parker is collaborating with Peter Fisk of the Commonwealth Scientific and Industrial Organization (CSIRO) in Australia in developing a satellite link between NIST and CSIRO to compare their time scales using two-way satellite time transfer. This C-band link between these widely separated laboratories provides a fully reciprocal path for comparisons. This means that receive and transmit footprints of the satellite cover both sites and that the phase-delay through the satellite is fixed and stable. In principle, this is an ideal type of link, since it is not subject to variation in delays associated with conversion from one spot beam to another, a difficulty that has been encountered using Intelsat for the two-way time transfer link between Boulder and Europe. The NIST satellite ground station for this link is located at the WWV radio-station site, so the signals must still be linked to the time scale in Boulder. This very short link is accomplished with very high precision using GPS common-view time transfer. The system has only recently been brought into operation, so present results are only preliminary.

PULSED MICROWAVE PM AND AM NOISE MEASUREMENT

Fred Walls and Craig Nelson, along with guest researcher Francisco Garcia of the Centro Nacional de Metrologia in Mexico, have developed a new approach to the measurement of PM and AM noise in pulsed amplifiers. There has long been a difficulty in characterizing the noise performance of high-power amplifiers used in systems such as radars, because such amplifiers cannot remain on in CW mode for very long or they will burn up. The new system dramatically improves the resolution, noise floor, and time required for making pulsed measurements of noise close to the carrier frequency. A significant aspect of this work is the reduction in measurement time by two orders of magnitude, but the order-of-magnitude improvement in resolution and three-orders-of-magnitude reduction in the noise floor are also noteworthy. The new system will allow manufacturers to directly evaluate the performance of pulsed amplifiers, rather than inferring amplifier performance from overall system performance.

The measurement system, based on a two-channel cross-correlation concept, uses special filters in the intermediate-frequency amplifiers to substantially reduce noise in the measurement process. Another important feature is the rapid (few seconds) in-situ calibration of the gain of the phase or amplitude detectors as a function of frequency offset from the carrier.

PM AND AM NOISE MEASUREMENT AT 100 GHZ.

Fred Walls has started development of a system for ultra-low noise measurement of PM and AM noise in amplifiers and oscillators at 100 GHz. The objective is to provide the measurement technology needed to support the development of high-speed gallium-arsenide amplifiers and oscillators to be used in digital and signal-processing applications. Such measurement technology is not now available. It is clear that, as signal processing moves to still higher frequencies, there will be a need to develop still higher-frequency noise-measurement systems.

The measurement system uses the two-channel cross-correlation method to reduce the noise contributed by the reference oscillators and measurement system. The reference oscillators, which must have exceptionally low noise, involve two 100 GHz oscillators, the phases of which are controlled by signals multiplied from two 10 GHz cooled-sapphire resonators.

SUMMARY

The Time and Frequency Division continues to provide critical services to US industry and science through the operation and dissemination of frequency and time standards. It also provides important contributions to fundamental science through the development of new standards, and research projects in basic physics.

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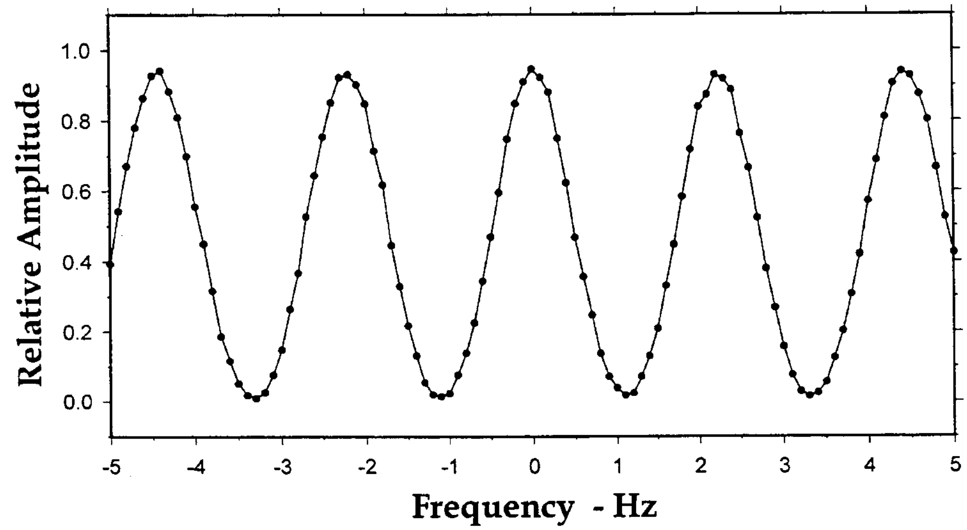

Figure 1. Central Ramsey fringe for NIST-F1. The central fringe in this pattern has a width just greater than 1 Hz. The narrow linewidth results in a smaller error from the servo system that locks the local oscillator to the center of the fringe. The large number of fringes reflects the narrow range of velocities of the tossed atoms. The low value of the velocity and the narrow velocity range dramatically reduce errors associated with the first-order and second-order Doppler shifts.

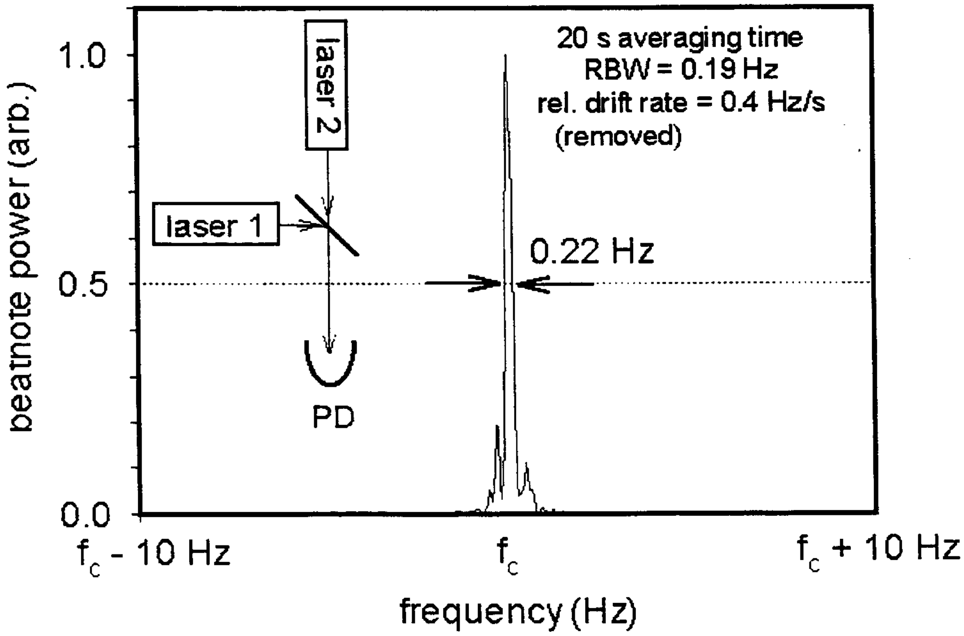

Figure 2. Beatnote observed in mixing the outputs of two 563 nm sources. The inset shows the simple experimental arrangement. The data are for a measurement time of 20 s. PD is a photodiode and RBW is resolution bandwidth.

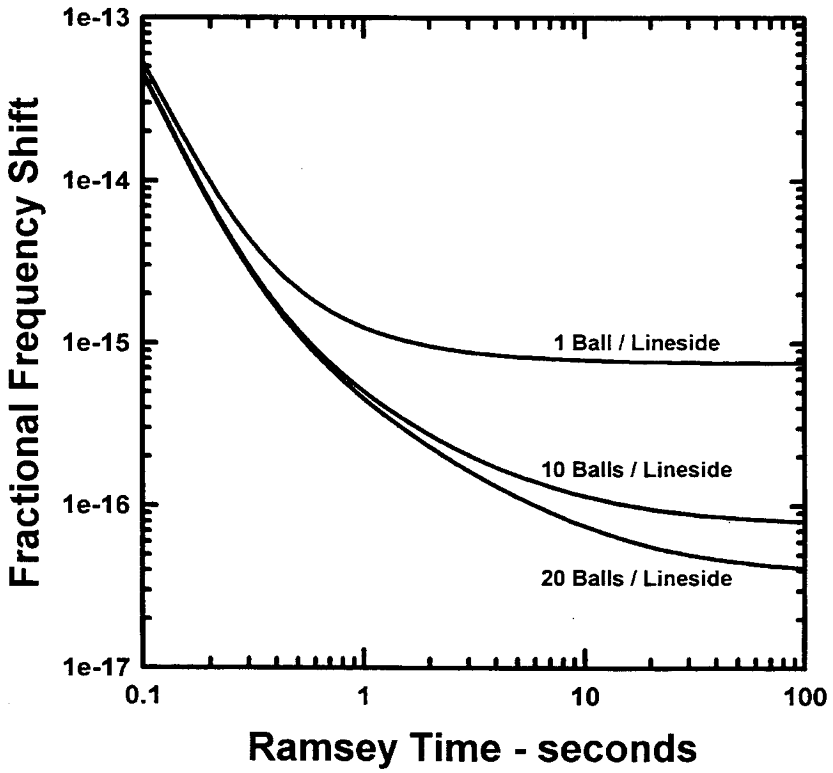

Figure 3. Fractional-frequency spin-exchange shift (for constant frequency stability) as a function of Ramsey time for several different launch parameters. The number of atom balls per lineside is a measure of how many balls pass through the system before moving to the other side of the central fringe so as to locate and servo-control the system to the center of the resonance.