NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Report to the 15th Meeting of the CCTF
On the Activities of the NIST Time and Frequency Division
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1. Cesium Frequency Standards and Comparisons

Recent work in this area involves an older optically pumped cesium-beam frequency standard, the newer cesium-fountain frequency standard, comparisons between these two standards, comparisons between the fountain standards at NIST and PTB, preliminary development work on a laser-cooled space clock, and development of a miniature cesium standard.

1.1 Improved Evaluation of NIST-F1

For the most recent evaluation, the combined uncertainty of NIST-F1 was 1.7×10^{-15}. An important aspect of evaluation of the standard is the measurement of the spin-exchange frequency shift. This shift was determined by extrapolating the relative frequency shift as a function of the clock signal, which is proportional to the density of atoms launched through the clock, to zero density. In this linear extrapolation, which covered densities approximately 5 times higher than the normal operating conditions (where the shift is approximately -2×10^{-15}), the uncertainty in the shift was found to be 1.4×10^{-15}. While it is understood that a linear extrapolation may not be fully justified, this procedure produces an estimate that is not much smaller in absolute value than the total estimated shift. It is clear that additional work must be done to fully understand and better evaluate this shift. The performance of the standard is now limited by noise in the quartz local oscillator, and improvement should be achieved with the acquisition of a better oscillator. A report on the evaluation of NIST-F1 has been submitted to Metrologia [1] and 4 formal evaluations of the standard have been submitted to the BIPM.

1.2 Comparison of NIST-7 and NIST-F1 Using a Special Time Scale

A post-processed time scale [2], involving an ensemble of 5 hydrogen masers, has been developed to serve as reference for comparing primary frequency standards. During the last 2 years, this time scale has been used to evaluate the relative frequencies of NIST-7, an optically pumped cesium-beam standard, and NIST-F1, the newer cesium-fountain frequency standard. It is particularly important to note that this scale allows comparison of frequency standards not operated at exactly the same time. The stability of this post-processed scale, called AT1E, is less than $\sigma_y(\tau) = 1 \times 10^{-15}$ for averaging times from 1 to 100 days, with a minimum near 3×10^{-16} at about 20 days.

Comparisons of the uncertainties of NIST-7 and NIST-F1 were made against this scale (and thus with each other) over a period of > 2 years. These comparisons show that the standards have maintained agreement within their uncertainties over this period, thus adding confidence to the methods used for evaluation of the uncertainties. Having completed this overlap of operation with good results, NIST-7 will now be taken out of operation.

1.3 Comparison of Fountain Standards at NIST and PTB

Using the post-processed time scale described above, a frequency comparison of the cesium-fountain primary frequency standards at NIST and PTB has been made [3]. Two-way and GPS-carrier-phase time transfer were the principal methods used to make this long-distance comparison. For the 15 day interval in which both fountains were in operation with significant overlap, the frequency comparison was made with an additional uncertainty due to the comparison process of only 5.8 x 10^{-16}. The two standards agree within their 1σ uncertainties of ~ 1.7 x 10^{-15}.

The results of this comparison indicate approximately the same frequency comparison noise for the two-way and the GPS carrier-phase methods. The measurements also show that comparison errors can be minimized by coordinating the evaluation periods of the standards, since this eliminates the error associated with the extrapolation where the measurements do not overlap substantially. The measurements also show that, for standards having uncertainties on the order of 1×10^{-15}, the uncertainties of the comparison process can be reduced to a nearly negligible level if the comparison duration is 15 or more days.

1.4 Determination of the Relativistic Red Shift in Boulder

In a collaboration involving Nikolaos Pavlis of Raytheon Corporation, the relativistic red-shift correction (in Boulder) due to gravity has been evaluated [4] with an uncertainty of 2 parts in 10^{17}. An accurate estimate of this shift is an important item in the list of systematic frequency shifts that must be determined to evaluate NIST-F1. In fact, this is the largest frequency bias for this standard. This shift will become even more important as yet more accurate frequency standards are developed.

Three different methods were used to arrive at their estimate. These were (1) a 1998 global gravitational model produced by NASA and the National Imagery and Mapping Agency; (2) a 1999 regional, high-resolution geoid model generated by Smith and Milbert; and (3) recent measurements made by the National Geodetic Survey of a reference marker on the NIST site. Through a critical analysis of these three methods the estimate of the frequency correction for NIST-F1 in its current location was found to be -1798.93×10^{-16}, with an estimated uncertainty of 0.2×10^{-16}. This is well below the NIST-F1 uncertainty of 1.7×10^{-15}, so at this time the red-shift correction is not of particular concern. It is worth noting that when the Division moves this standard to a different floor of the building, which should happen in about a year, the correction would have to be changed.

1.5 Transverse Cooling for Fountain Frequency Standards

In a collaborative theoretical effort, A.V. Taichenachev, A.M. Tumaikin and V.I. Yudin of Novosibirsk State University and Leo Hollberg of the Division have developed a concept for two-dimensional sideband cooling and Zeeman state preparation in an optical lattice [5]. The development of this concept was driven by the need to reduce transverse velocities of laser-cooled atoms in primary cesium-fountain frequency standards. The approach suggested appears to be both simpler and more effective than previously proposed methods and has two significant advantages: the method only requires laser beams transverse to the atomic fountain axis, and the cooling process simultaneously pumps atoms into the desired ($m=0$) ground-state energy level. The theory predicts that 95% of the atoms can be cooled to transverse temperatures of about 100 nK. An experimental apparatus designed to test the effectiveness of this cooling method is now under development.

Further transverse cooling could provide for significant reduction in the uncertainty of the cesium-fountain frequency standard. The largest uncertainty in this standard is the spin-exchange frequency shift, the magnitude of which depends on the density of atoms averaged over the fountain trajectory. In the present standard, the magnitude of the transverse velocities of the launched atoms (cooled to about 1.5 μK) results in a loss of approximately 90% of the atoms before they reach the detection region. This means that most of these atoms contribute to an increased spin-exchange frequency shift without contributing to the output signal. With better transverse cooling, a larger fraction of the atoms will reach the detection region and the launch density can be decreased leading to a lower spin-exchange shift while retaining a good signal-to-noise ratio.

1.6 Atomic Clock for the International Space Station

NIST is collaborating with the Jet Propulsion Laboratory, the University of Colorado, the Harvard-Smithsonian Center for Astrophysics, and the Politecnico di Torino in developing a Primary Atomic Reference Clock in Space (PARCS), a NASA-funded program to put a laser-cooled cesium atomic clock in space [6]. Following successful NASA program reviews in January 1999 and December 2000, this group initiated development of components and fabrication of prototypes for some of the components. The objectives of the PARCS mission, scheduled to fly in early 2005, are (1) to test relativity theory by measuring the net (Doppler-plus-gravitational) frequency shift of the cesium clock, (2) to perform a test of local position invariance by comparing the frequency of the cesium clock with that of a hydrogen maser that is part of the PARCS package, (3) to improve upon the realization of the second by taking advantage of the long atom-observation times provided by the microgravity environment, and (4) to study the performance of GPS satellites through comparison of the received GPS clock signals with the PARCS clock.

Staff members at NIST and the University of Colorado are serving as the Co-Principal Investigators for the experiment, and the Project Scientist and Project Manager are from the Jet Propulsion Laboratory where the space hardware is being developed. A hydrogen maser, originally developed (but not flown) for an earlier space mission by the Harvard-Smithsonian Center for Astrophysics, will serve as both the local oscillator for the cesium clock and reference for the test of local position invariance. The Politecnico di Torino is providing input to the design of the cesium clock.

1.7 Compact Cesium Frequency Standard Driven by a Diode Laser

NIST staff members, in collaboration with guest researchers Robert Wynands and Svenja Knappe, have developed a small, 4.6 GHz frequency standard using a vertical-cavity surface-emitting laser (VCSEL) that pumps a cesium atomic vapor in a small cell structure [7]. Design information developed in this program indicates that the package for the standard can be as small as 10 mm × 10 mm × 20 mm, and that the system might operate with an input power as low as 100 mW. This standard has potential applications in areas such as wireless telecommunications where good synchronization is needed to assure efficient data transfer between network nodes. In these systems, it is particularly important to maintain reference timing at each node, even when external synchronization is lost. Thus, the industry is searching for compact, high-stability oscillators that can meet this ‘holdover’ requirement. The timing uncertainty of these devices is currently better than 10μs over 1 day, which meets the industry requirements. Current research efforts are aimed at understanding the fundamental physics of operation of these standards and further improvement of their performance.

2. Optical Frequency Standards and Measurements

The work described here supports the development of both optical frequency standards and the measurement of length. Of particular interest is the recent development of optical-frequency combs based on femtosecond lasers. These not only allow for optical-frequency measurements that are limited solely by the uncertainty of the microwave primary standard, but also provide the basis for the development of a new generation of frequency standards of exceptional merit.

2.1 Ultra-Narrow-Linewidth Optical Frequency Standard Based on Mercury Ions

Staff in the Division have frequency locked an ultra-narrow-linewidth laser to an ultraviolet transition in a single $^{199}\text{Hg}^+$ ion to produce the highest-Q, narrowest-linewidth optical-frequency standard ever demonstrated [8]. The uncertainties for such standards should approach 1×10^{-18}, orders of magnitude better than the best present microwave standards.

The laser linewidth is initially narrowed by frequency locking its output to a Fabry-Pérot étalon of high-finesse, and high stability is achieved through exceptionally good isolation of the cavity from building vibrations and acoustic noise [9]. This line-narrowed (linewidth of ~ 0.2 Hz) laser is frequency doubled and then used to probe the 282 nm (1.06×10^{15} Hz) electric-quadrupole transition in a single $^{199}\mathrm{Hg}^{+}$ ion stored in a cryogenic radio-frequency ion trap. The measured linewidth is 6.7 Hz resulting in a $Q \approx 1.6 \times 10^{14}$.

Systems with such exceptional Qs are extremely attractive as frequency standards, since large Q translates to small uncertainty in locating the line center of the resonance. Of course, systematic frequency shifts caused by non-ideal experimental conditions must be considered, but while these limit the performance in the present experiments to an uncertainty of order 10^{-14}, they appear to be controllable at much lower levels.

2.2 Improved Calcium Optical Frequency Standard

Substantial improvements in the performance of NIST's calcium optical-frequency standard have recently been made [10]. In particular, the stability of the standard has been improved to $\sigma_y(\tau) = 4 \times 10^{-15}$ at 1 s. This is the best short-term stability reported to date for an atomic frequency standards. This standard has played a key role in recent optical-frequency measurements using frequency combs (described below), since without this standard, the stability performance of the mercury-ion standard could not have been measured, and the ability of the combs to translate high stability in the optical region to lower frequency could not have been evaluated.

Calcium continues to be an attractive optical frequency standard at many laboratories in the world, since the 657 nm transition is relatively insensitive to external electric and magnetic fields, and because the entire system (trapping, laser cooling, and state probing) is operated with diode lasers. While the system is already laser cooled, the temperature of the atoms might be further reduced using second-stage cooling schemes to a stability as low as $\sigma_y(\tau) = 2 \times 10^{-16}\tau^{-1/2}$. Recent frequency measurements of the 657 nm transition have been performed relative to the cesium atomic fountain with an uncertainty of $6 \text{ x } 10^{-14}$. The measurements agree well with previous measurements made at PTB.

2.3 Connecting Optical Frequency Standards to the Microwave Region

In collaboration with Thomas Udem of the Max Planck Institute, staff members in the Division have built a high-repetition-rate mode-locked laser that has been used to produce evenly spaced optical-frequency combs. The comb spacing corresponds to the laser's pulse repetition rate that is then used to provide a microwave-frequency output from optical-frequency standards [11]. The output of the laser, operating at a repetition rate of 1 GHz, is fed to highly nonlinear microstructure optical fiber that substantially broadens the frequency comb to cover more than an octave spanning the visible portion of the spectrum. The comb extends from less than 300 THz (1000 nm) to more than 600 THz (500 nm). To demonstrate the generation of a microwave output from an optical standard, a line in the comb was stabilized to the Hg^{+} optical frequency standard described above. Frequency measurements were then made at the 1 GHz repetition frequency as well as at other optical frequencies spanned by the comb. The stability of the microwave output was compared to a signal from a hydrogen maser and was consistent with that of the maser (an therefore limited by the maser). However, measurements could be made against the very-high-stability calcium frequency standard (described in the item above) operating at 657 nm. The relative fractional-frequency stability observed in these experiments was $\sigma_y(\tau) = 7 \times 10^{-15}\tau^{-1/2}$ (for short times), an order of magnitude better than the stability of the best quartz oscillators.

While this same system was also referenced to a microwave frequency to make the best-ever measurements of both the calcium and mercury-ion frequencies relative to the frequency of cesium-fountain standard, it is the generation of a microwave output that is so significant to the future of primary frequency standards. It has long been recognized that line Q is a good figure of merit for assessing the performance of frequency standards, and that optical standards, having such high Qs (better than 10^{14} for the Hg^+), should outperform their microwave counterparts (best Q of ~10^{10}) by a wide margin. What has been missing until now is a means for counting cycles and making measurements at lower frequencies. Now that the extraordinary performance of the optical frequency standards can be translated to lower frequency, they can be seen as a new generation of frequency standards that should substantially outperform even the cesium-fountain frequency standard.

2.4 Comparing Frequency Standards Through an Optical-Fiber Network

In a joint program among the City of Boulder, NIST, the University of Colorado, and the National Center for Atmospheric Research, an optical-fiber network has been installed connecting various organizations dispersed throughout the city. The network acronym is BRAN, meaning Boulder Research and Administrative Network. A number of network fibers have been assigned to NIST. Of particular relevance is the assignment of a dark pair (no included optoelectronic interfaces) of fibers connecting optical systems in the Time and Frequency Division to systems within the NIST Quantum Physics Division on the University campus. The distance (along the fiber) between these two sites is approximately 3.5 km. Exceptional microwave and optical frequency standards are located in these two Divisions providing the opportunity to study the performance of this fiber connection. The list of potential studies that can be done using this network includes: (1) comparison of microwave frequency standards and transfer of absolute time, (2) transfer of optical atomic-clock signals at optical frequencies, (3) accurate transfer of microwave frequencies, (4) calibration and transfer of laser wavelengths important to wave-division multiplexing, (5) dissemination of optical frequencies used as references for measuring length, and (6) distribution of high-accuracy pulse trains used for time-domain measurements.

In preliminary experiments, very high short-term-stability transfer of frequency across the network has been demonstrated. The output of a 1.3 μm laser was first modulated at 2.3 GHz using a source locked to a hydrogen maser in the NIST time scale. This was transferred to the University over BRAN and then back to the Division. The measurement-system noise floor limited the results of the measurements to $\sigma_y(\tau) = 10^{-12}\tau^{-1/2}$, so it is clear that the fiber is not limiting the performance at this level. The uncompensated diurnal variations of the time delay between the two sites were about 140 ps, and these can be controlled well below this level.

3. Entangled States in Trapped Ions

While the work described here is not targeted explicitly at frequency standards, the entangled states used for achieving quantum-logic operations and tests of fundamental theory are of practical interest for future frequency standards, since entangled states represent a means for changing the way in which frequency noise scales with the number of atoms (ions) involved.

3.1 Quantum Entanglement of Four Particles

In the cover story for the March 16, 2000 issue of Nature magazine [12], NIST staff describe the first successful quantum entanglement of four particles, an important step in demonstrating a quantum-processing system that possesses the requisite characteristics for scal ing to larger computing systems. Such entangled states explicitly demonstrate the non-local character of quantum theory, and have been suggested for use in high-resolution spectroscopy, quantum communication, cryptography, and computation.

The entanglement uses a recently proposed technique applicable to trapped ions. Coupling between the ions, stored in a lithographically fabricated trap, is provided by the Coulomb interaction through their collective motional degrees of freedom, but actual motional excitation is minimized. Entanglement was achieved using a single laser pulse, and the same one-step method can in principle be applied to any number of ions.

3.2 Quantum Memory Using Trapped Ions

Division staff have also recently demonstrated operation of a decoherence-free quantum memory using trapped ions [13]. A quantum memory stores information in superposition states of a collection of two-level systems called qubits. Quantum computation works by operating on information in the form of such superpositions, and robust quantum memories are therefore essential to realizing the potentials gains of quantum computing. However, interaction of a quantum memory with its environment destroys the stored information, a process called decoherence. Many proposed quantum memories decohere via an environment that has the same coupling to each qubit. In the trapped-ion demonstration, information from an arbitrary qubit stored in a single ion is encoded into a decoherence-free subspace of two ions. The decoherence-free subspace states are invariant under the coupling to the environment, protecting the encoded information. The experiments on this memory concept involved measurement of the storage time under both ambient conditions and under interaction with an engineered noisy environment. They found that encoding the qubit information into the decoherence-free subspace increases the storage time by up to an order of magnitude.

3.3 Decoherence Studies of Motional States of Trapped Ions

Quantum-state-engineering of trapped atomic ions relies on using motional states entangled with the internal states of the ions. Since trapped ions form a charged oscillator, the motion of this oscillator is very susceptible to external fluctuating electric fields. Currently, such fields limit the fidelity of engineered states; this has prompted a study of various forms of motional decoherence.

Certain superpositions of motional states, commonly called Schrödinger cats, are especially sensitive to the strength and nature of the fluctuating fields. The decoherence of these states has been studied under different kinds of impressed noise as well as that from ambient fields [14]. These studies indicate the ambient fields are uniform and stochastic with a relatively large bandwidth. Additional studies correlating the magnitude of these fields with the trap electrode dimensions indicate that the noise is not due to thermal electronic processes (e.g., Johnson noise), but is consistent with fluctuating patch fields on the electrode surfaces. Such studies will be used to identify and eliminate this source of decoherence. On a fundamental level, for the first time, the group has shown experimentally that the rate of decoherence scales exponentially with the "size" of the cat state.

3.4 Test of Bell’s Inequalities Using Trapped Ions

In experiments using trapped ions, Division staff members have demonstrated violation of Bell’s inequalities [15]. These mathematical inequalities provide a basis for experimental tests whose results can distinguish between quantum mechanics and local realistic theories. Many experiments have been done that are consistent with quantum mechanics and inconsistent with local realism. Because these conclusions have generated considerable debate, experiments are still being refined in order to overcome “loopholes” that might affect the results. This is the first violation of Bell's inequalities with massive particles ($^9Be^+$ ions) obtained by use of a complete set of Bell measurements. In addition, the high detection efficiency of the experiments eliminates the detection loophole for the first time. All previous experiments have had detection efficiencies low enough to allow the possibility for the subensemble of detected events to agree with quantum mechanics even though the entire ensemble satisfies Bell's inequalities.

The experiment prepares a pair of two-level atomic ions in a repeatable configuration. Next, a laser field is applied to the particles; the classical manipulation variables are the phases of this field at each ion's position. Finally, upon application of a detection laser beam, the classical property measured is the number of scattered photons emanating from the particles. The Bell signal B was constructed using the results for four sets of phase parameters. Analyses of the photon count distributions indicate that the Bell's signal was $B = 2.25 \pm 0.03$, a result that clearly exceeds 2, the maximum value allowed by local realistic theories of nature.

4. Time and Frequency Comparisons

4.1 Improvements in Time Transfer

Following the development of a model of multipath effects on time transfer with pseudorandom phase codes, NIST has implemented improvements (suggested by the model) in its two-way satellite-time-transfer (TWSTT) and GPS common-view systems that have measurably improved performance [16]. Similar improvements of the TWSTT systems have been made at stations in Europe and comparisons between NIST, NPL, and PTB now exhibit a time transfer noise as low as 300 ps, the lowest noise yet achieved using two-way time transfer over this particular trans-Atlantic path.

The changes suggested by the model involve measures that minimize signal reflections within cables in the system. This was achieved by replacing key cables with high-phase-stability cables and by carefully matching the impedance 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.

4.2 Two-Way Time Transfer Link to Australia

NIST is collaborating with the Commonwealth Scientific and Industrial Organization (CSIRO) in Australia in developing a satellite link between NIST and CSIRO to compare time scales using the two-way method. The 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 should be 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 preliminary.

4.3 Improvements in GPS Carrier-Phase Time Transfer

Frequency comparisons between primary standards at NIST and PTB have been made using both the two-way method and the GPS carrier-phase method [17]. The results indicate a substantial improvement in reliability and noise level for the GPS method. They further showed that the methods agree to about 3×10^{-15} (for several days of averaging).

The present analysis of the GPS carrier-phase data is limited by frequency steps, which must be carefully reconnected to form the desired time series. Furthermore, there are gaps in the data from the GPS reference stations that limit the length of the time series that can be processed at one time. Thus, elimination or reduction of these problems could further improve the performance of the system. The analysis limitation could be removed through better analysis methods, and studies are now being done using a new analysis package from the University of Berne.

4.4 Time-Scale Improvements

The Division has initiated a series of upgrades to the NIST time scale. The first improvement is the addition of a low-noise synthesizer that is used to generate an improved real-time output of UTC(NIST). The synthesizer, controlled by the time-scale computer, transforms the output of a selected hydrogen maser to UTC(NIST) with substantially less short-term noise (50 times less) than that exhibited by the previous system.

The next phase of improvement involves the replacement of the time-scale measurement system with a more-reliable, lower-noise system. The current measurement system is so old that replacement parts are hard to find, so long-term reliability is becoming a concern. Furthermore, measurement noise is starting to become a factor in the performance of the time scale. Following a careful study of upgrade options, specifications were developed for a new measurement system, which operates at 100 MHz rather than 5 MHz. A contract for the system has been let and delivery of components is anticipated by the end of the year.

5. Noise Measurement

5.1 PM and AM Noise Measurement at 100 GHz

NIST has developed a system for ultra-low noise measurement of PM and AM noise in amplifiers and oscillators at 100 GHz. The goal 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 sources, which must have exceptionally low noise, are two 100 GHz oscillators, the phases of which are controlled by signals multiplied from two 10 GHz sapphire-loaded oscillators.

5.2 Pulsed Microwave PM and AM Noise Measurement

The Division has 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 (operate cw) 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. Significant aspects of this work are (1) the reduction in measurement time by two orders of magnitude, (2) an order-of-magnitude improvement in resolution, and (3) a three order-of-magnitude reduction in the noise floor. The new system allows direct evaluation of the performance of pulsed amplifiers rather than reliance on characteristics inferred from the overall performance of a full system.

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. 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.

5.3 Phase and Amplitude Noise Measurements Between 10 GHz and 100 GHz

A new system has been developed for making high-resolution phase-and-amplitude-noise measurements in the frequency range from 10 GHz to 100 GHz to support the characterization of high-performance radars, which use digital methods for processing return radar signals. The performance of these radar systems is critically dependent on noise in the systems. The new measurement system uses the two-channel cross-correlation method. The system reference for the measurements is provided by any of the lines in a comb of extremely stable reference frequencies produced by the combination of an ultra-stable, sapphire-loaded oscillator and a set of low-noise regenerative dividers. The stability of the reference signals is in fact the key to making these measurements. To date there have been no high-stability reference sources for measurements across this frequency region.

6. Time and Frequency Dissemination

Of particular note in this section is the very rapid growth in use of the Internet time service and the completion of a major upgrade of LF station WWVB providing for full coverage of the continental United States. These services are having a substantial impact on the way in which less demanding applications receive timing information in the United States.

6.1 Further Growth and Expansion of the Network Time Service

The Division has been managing ever-increasing activity with its Network Time Service [18]. The volume of daily hits on this time service is increasing by 7-8% per month and is now at a level of nearly 7×10^7 per day. During the short period of Y2K rollover, the service level was nearly 2.4×10^8 requests (often many requests from the same user). To meet this increasing demand, new servers have been installed in Virginia and California to complement the 12 servers already in the system. There has been a rapid rise in commercial interest in this type of service. Two companies have established cooperative arrangements with NIST and interactions with a third are being discussed. Six servers have been configured by NIST and delivered to one of these companies to become part of a commercial authenticated time service. In cooperation with another of these companies, real-time tests between Boulder and San Jose were conducted of remote synchronization of a time server. The third interaction, still in the negotiation stage, involves yet another network for authenticated-time delivery.

6.2 A New Web Site for Official U.S. Time

With assistance from an independent contractor, the Division has developed a web site (time.gov), which provides official United States time usually within 1 second in a format that can be widely appreciated by non-technical users. The time distributed by this site is considered traceable to both NIST and the U.S. Naval Observatory, although NIST operates the site for both agencies. The format allows the user to select any U.S. time zone from a map and then initiate operation of a Java clock that runs in the local time zone. Site usage, which grew by a factor of 5 last year is approximately 5 million hits per month.

6.3 Completion of the Upgrade of WWVB

The multi-year program to upgrade and increase the output power of WWVB was completed in December 1999 [19]. WWVB time-signal broadcasts at 60 kHz are now delivered at a power of 50 kW using two separate in-phase transmitter-antenna systems. Since antenna impedance can vary substantially under windy conditions, the system design involves servo tuning of the antenna-impedance-matching networks to the impedance of the coaxial transmission lines. A third backup transmitter can be switched into service should either of the primary transmitters fail. A new generator capable of operation at full power was also installed to assure broadcast continuity. Since completion of this project, a large number of companies have developed commercial products that use the broadcast signal.

6.4 Enhancements to the NIST Frequency Measurement Service

NIST has completed a set of enhancements to the Frequency Measurement Service resulting in substantial improvement in measurement uncertainty and flexibility [20]. The measurement uncertainty has been reduced to 2×10^{-13} (2σ) for a 24 hour averaging period, and the system can now measure any frequency from 1 Hz to 120 MHz in 1 Hz increments. Up to 5 devices can be calibrated simultaneously. Subscribers to the service receive monthly calibration reports compliant with ISO Guides 25 and 17025 and the ANSI Z-540 standard. A wide range of high-level calibration laboratories in industrial and government organizations use this service, which provides continuous frequency traceability to NIST.

To further simplify the problem of achieving frequency traceability, a database of frequency comparisons between the NIST time scale and individual GPS satellites has been developed and is updated daily on the Division web site. While it is generally acknowledged that the frequency delivered by these satellites is quite accurate, the mode of operation of GPS does not allow for a clear specification of frequency accuracy that can be used for legal traceability. This database provides the means for achieving this traceability.

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