TIME AND FREQUENCY TRANSFER ACTIVITIES AT NIST

Victor Zhang and Michael A. Lombardi
Time and Frequency Division
National Institute of Standards and Technology (NIST)
Boulder, CO 80305, USA
vzhang@boulder.nist.gov
lombardi@nist.gov

Abstract

The National Institute of Standards and Technology (NIST) maintains one of the world's most accurate and stable time scales, and also developed and maintains the primary frequency standard for the United States. Various techniques are used to compare the NIST time scale, UTC (NIST), and the NIST primary frequency standard to other standards located around the world. These techniques include two-way satellite time and frequency transfer (TWSTFT), code-based GPS common-view, and GPS carrier-phase comparisons. NIST provides remote time and frequency calibration services to industries and research institutes using GPS time transfer technologies. We disseminate UTC (NIST) through signals broadcast by our radio stations WWV/WWVH and WWVB, the Internet Time Service (ITS), and the Automated Computer Time Service (ACTS). NIST also conducts research intended to develop new time transfer techniques and to improve the performance of existing methods.

I. INTRODUCTION

NIST engages in a wide variety of time transfer activities. These activities range from international comparisons conducted at state-of-the-art accuracy levels, to the operation of free broadcast services that directly benefit the American public by synchronizing many millions of clocks every day. In addition, NIST offers remote calibration services to paying customers in both the public and private sectors, and conducts time transfer research intended to advance the state of the art in time transfer and to improve existing services.

This paper is an overview of NIST time transfer activities. Section II covers international comparisons, and Section III describes the remote calibration services. Radio and network broadcast services are discussed in Sections IV and V, and Section VI describes some of the time transfer research that is currently ongoing at NIST.

II. INTERNATIONAL COMPARISONS OF UTC (NIST)

NIST uses the techniques of two-way satellite time and frequency transfer (TWSTFT), GPS code-based and carrier-phase time and frequency transfer for international time and frequency comparisons, including contribution of the NIST time scale, UTC (NIST), to the computation of International Atomic Time (TAI) and Coordinated Universal Time (UTC), as described in the following sections.

II.A. Two-Way Satellite Time and Frequency Transfer (TWSTFT)

TWSTFT **[1]** has become an important technique used internationally for comparing time and frequency standards over long distances. NIST was actively involved in the development of the TWSTFT technique, and has made large contributions to TWSTFT since the early 1980s. Currently, NIST participates in the transatlantic TWSTFT operation together with the United States Naval Observatory (USNO) on the United States side and up to 12 national timing laboratories on the European side. The NIST earth station consists of a 3.7-m motorized dish antenna with K_u band radio frequency (RF) equipment. The NIST system uses RF equipment and cables with small temperature coefficients **[2]**. A thermostat-controlled heater and fan are installed to minimize temperature variation in the RF equipment hub. The best stability of our transatlantic TWSTFT comparisons is less than 100 ps at τ = 1 day, when estimated with the Time deviation (TDEV).

The TWSTFT measurements are made daily (on even-numbered hours) with a dual-receive-channel two-way modem. The NIST TWSTFT operation is software driven and fully automated. The software controls the TWSTFT measurements, monitors environmental sensor readings and transmit/receive power levels, and generates and uploads the TWSTFT data in standard format for remote clock comparisons. The operation also includes the process of collecting the remote TWSTFT data and computing the TWSTFT differences to monitor the TWSTFT performance. Figure 1 shows a screen shot of the NIST TWSTFT software.

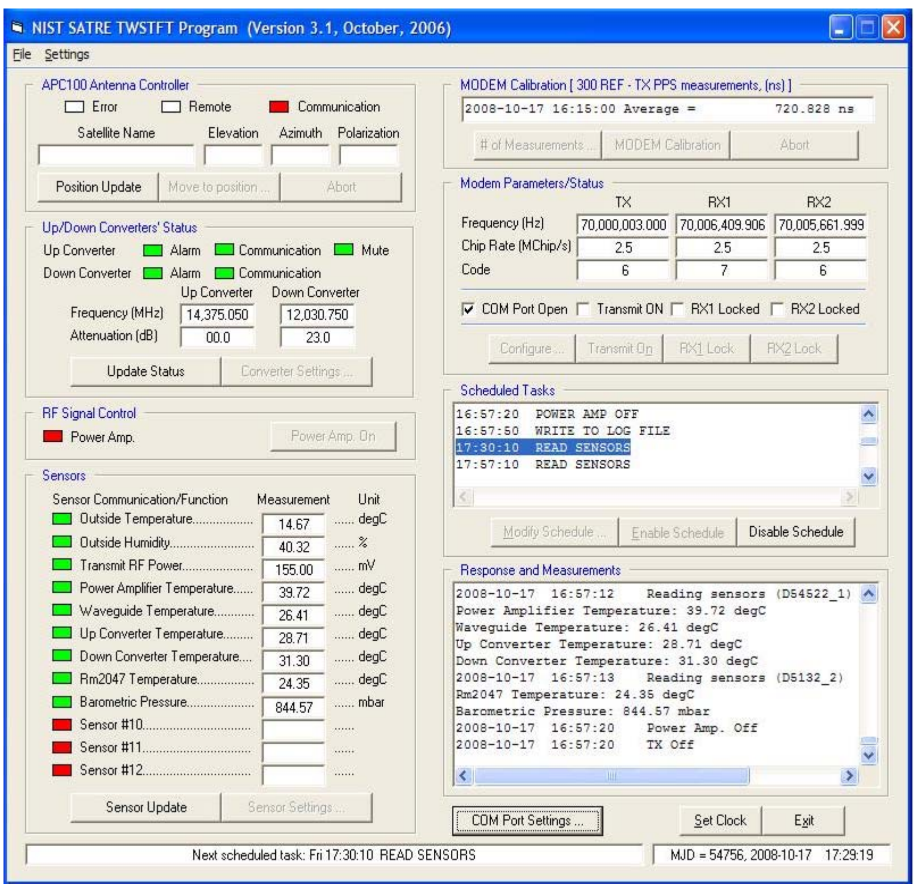

Figure 1. Screen shot of the NIST TWSTFT software.

II.B. GPS Code-Based Time Transfer

The coarse acquisition (C/A) code-based GPS common-view (CV) method has been used since about 1980 **[3]**, when NIST (then known as the National Bureau of Standards, or NBS) developed the first operational single-channel CV receiver. This type of receiver is still used around the world today. Over the years, however, the GPS CV technique has matured and the performance has been greatly improved. Now, NIST operates several different types of CV receivers, including single-channel, multi-channel, and geodetic receivers for different applications. The primary CV receiver at NIST was upgraded from a single-channel receiver, named *NBS10*, to a dual-frequency multi-channel geodetic type of receiver, named *NIST*, in July 2006.

NIST has developed the capability of postprocessing the CV data with the International Global Navigation Satellite System (GNSS) Service (IGS) measured ionospheric delay correction (MSIO) and precise ephemeris correction. NIST also generates the ionosphere-free code (P3) **[4]** CV data from our geodetic type of receivers. The performance of CV is dependent on the distance between the two receivers. The TDEVs of the CV differences obtained using the IGS MSIO correction are similar to those obtained using the P3 method. Table 1 shows TDEV at $\tau = 1$ day for GPS CV between NIST and USNO and between NIST and the *Physikalisch-Technische Bundesanstalt* (PTB) in Braunschweig, Germany. Note that the NIST CV and P3 CV data are both generated by the *NIST* receiver, but the USNO and PTB use separate receivers for each type of data.

Table 1. Time Deviations of NIST/USNO and NIST/PTB CV links. The time deviations are computed with data from MJD 54466 to MJD 54757 (January 1 to October 18, 2008).

Link	Distance (km)	TDEV at $\tau = 1$ day	
		MSIO CV (ps)	P3 CV (ps)
NIST/USNO	2,400	250	300
NIST/PTB	7,530	600	530

II.C. GPS Carrier-Phase Time and Frequency Transfer

NIST operates several geodetic receivers for the purposes of GPS carrier-phase (CP) **[5]** remote clock comparison and IGS applications. Two of them, named *NISU* and *NIST* (our primary GPS timing receiver), are in the IGS tracking network. At this time, we do not directly process the CP observations ourselves due to the lack of resources. However, we use the IGS clock products (IGSCLK) **[6]** and the International Atomic Time Precise Point Positioning (TAIPPP) **[7]** results produced by the *Bureau International des Poids et Mesures* (BIPM) for comparing our time scale to remote clocks around the world. None of our geodetic receivers have been calibrated at this writing (November 2008) with respect to the geodetic receivers operated in other timing laboratories. Thus, the CP observations from our geodetic receivers are currently used only for frequency comparisons.

Figure 2 shows the TDEV for the NIST/USNO and NIST/PTB CP comparisons. The TDEV of the CP comparisons are smaller than the TDEV of the corresponding code-based CV comparisons. For example, the TDEV for the NIST/USNO TAIPPP is about 50 ps at $\tau = 1$ day, which is about five or six times smaller than that of the NIST/USNO code-based CV. The TDEV for the NIST/PTB CP comparisons at $\tau = 1$ day show very little improvement over the code-based CV. We believe that the TDEVs of the NIST/PTB CP comparisons are dominated by the PTB reference clock noise. The difference of the

TDEVs between the IGSCLK and TAIPPP results for the NIST/USNO comparisons is due to the different processing methods.

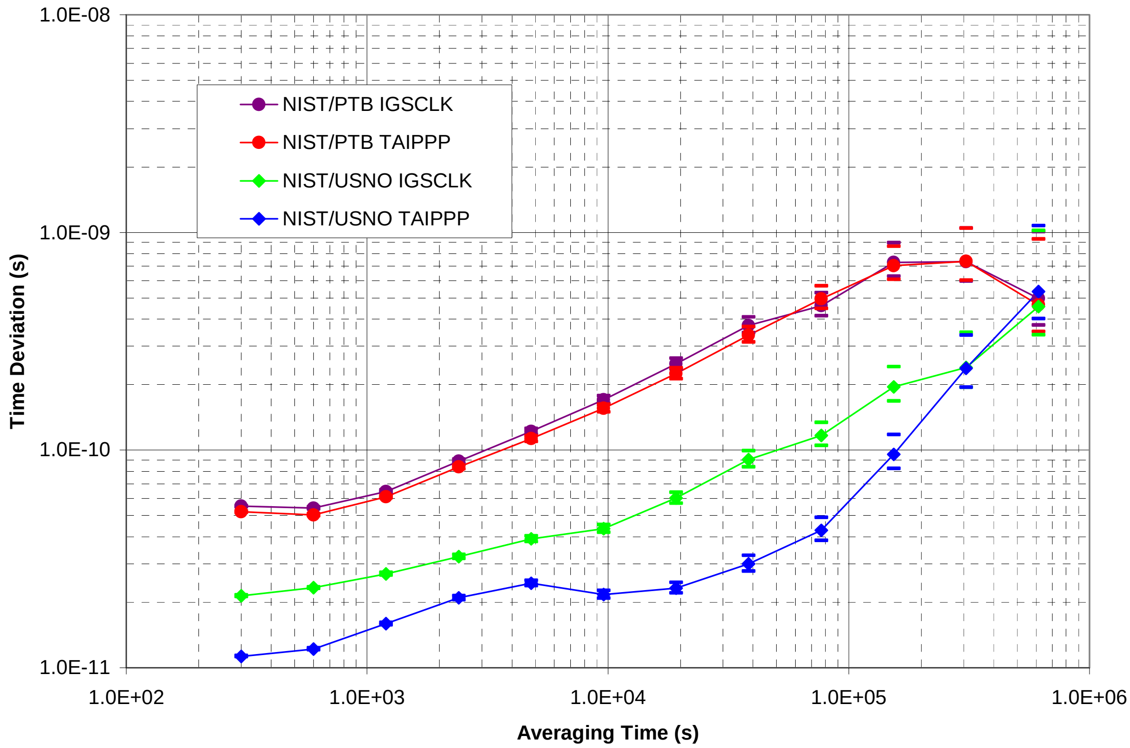

Figure 2. TDEV of NIST/USNO, NIST/PTB CP comparisons using the IGSCLK and using the BIPM TAIPPP results. TDEV are computed with data from MJD 54642 to MJD 54676.

II.D. Contributions of UTC (NIST) to International Atomic Time (TAI)

The NIST/PTB TWSTFT is the primary link for contributing the NIST time scale and primary frequency standard to the computation of TAI and UTC generated by the BIPM. The combined Type A and Type B uncertainty of the NIST/PTB TWSTFT link is 5 ns, as reported by the BIPM publication *Circular-T* **[8]**. The combined uncertainty is dominated by a Type B uncertainty of about 5 ns. This is due to the fact that the NIST/PTB TWSTFT link was calibrated in 2003 with code-based GPS CV when the link was switched from CV to TWSTFT in 2003. The CV data from our primary GPS timing receiver are used as the secondary link for the TAI and UTC computation.

Figure 3 shows the double difference, $[UTC(NIST) - UTC(PTB)]_{TWSTFT} - [UTC(NIST) - UTC(PTB)]_{CV}$, of the NIST/PTB links. The difference is computed with the daily averaged TWSTFT and GPS MSIO CV differences. There is a 2.1-ns offset between the TWSTFT and the GPS CV links. The difference contains several spikes on the order of a few nanoseconds, such as the 3.5 ns spike that occurred on MJD 54526. These spikes were mainly introduced by the GPS CV difference. The BIPM uses the all-in-view method **[9]** with the CV data when computing the difference for GPS links, so the BIPM result may be different from our GPS CV difference result.

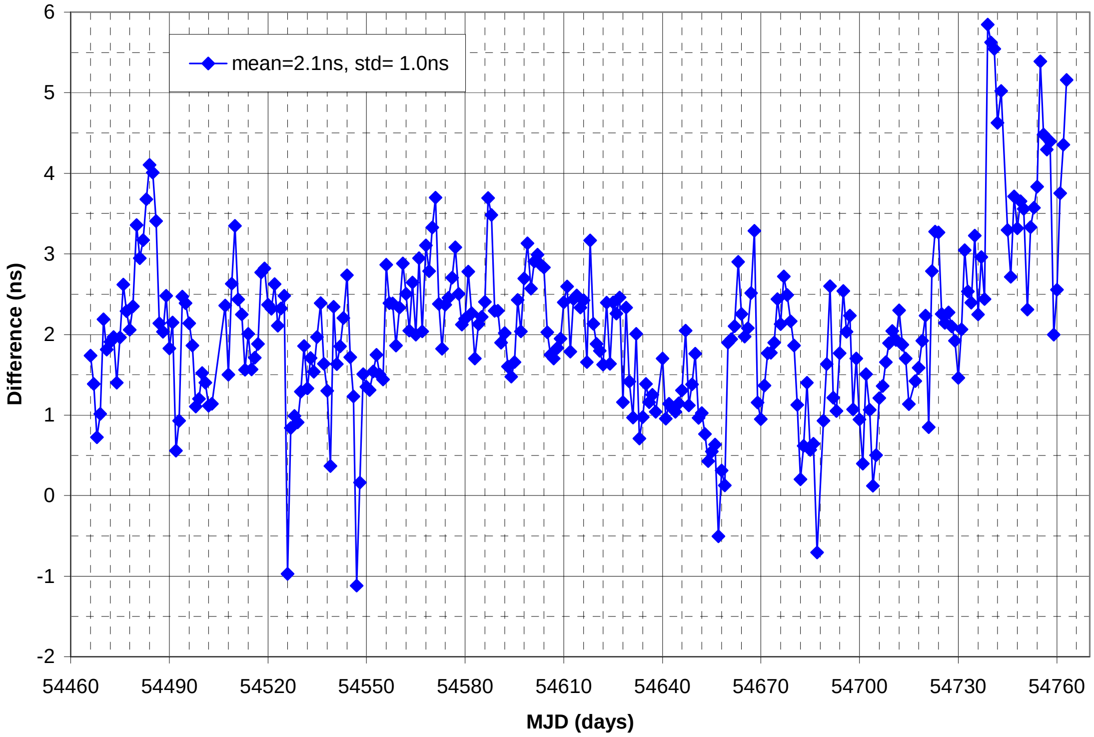

Figure 3. [UTC (NIST) – UTC (PTB)]$_{TWSTFT}$ – [UTC (NIST) – UTC (PTB)]$_{CV}$. The double differences are computed with daily TWSTFT and GPS MSIO CV differences. The graph shows data from MJD 54466 to MJD 54763 (January 1, 2008 to October 24, 2008).

II.E. The Sistema Interamericano de Metrologia (SIM) Time Network

The *Sistema Interamericano de Metrologia* (SIM) consists of national metrology institutes (NMIs) located in the 34 member nations of the Organization of American States (OAS), which extends throughout North, Central, and South America, and the Caribbean region. SIM is one of the world's five major regional metrology organizations (RMOs) recognized by the BIPM. NIST has led the development of the SIM Time network, a system designed to coordinate timing in the SIM region by allowing all SIM NMIs to participate in international comparisons.

The SIM Time network provides continuous, near-real-time comparisons between the national time and frequency standards located throughout the SIM region, by utilizing the technology of both the Internet and GPS C/A code common-view measurements. The network began operation in May 2005, with three countries participating (Canada, Mexico, and

Figure 4. Current (light) and future (dark) SIM network members.

the United States). As of November 2008, NMIs in 12 different nations are members of the network (Figure 4), and at least four more nations are expected to be added in the future.

Each member of the SIM Time network continuously operates a measurement system that was calibrated at NIST prior to shipment. Each system includes an eight-channel common-view GPS receiver, a time-interval counter, and an antenna designed to mitigate multipath signals. All SIM systems are connected to the Internet and upload their measurement results to Internet Web servers every 10 minutes, so that measurement results (either common-view or all-in-view) can be processed in near real time. Figure 5 shows the real-time SIM measurement grid that can be viewed at *tf.nist.gov/sim.*

The measurement uncertainty of the SIM network depends upon a number of factors, including the accuracy of the antenna coordinates, the environmental and multipath conditions, and the length of the baseline between laboratories. The combined time uncertainty ($k = 2$) is typically about 11.5 ns, and the frequency uncertainty ($k = 2$) is typically about 5×10^{-14} at $\tau = 1$ day **[10].**

SIM Time Network

(real-time measurement results for the 10-minute period ending on 10-29-2008 at 2320 UTC)

SIM SISTEMA INTERAMERICANO DE METROLOGIA	United States UTC(NIST)	Mexico UTC(CNM)	Canada UTC(NRC)	Panama UTC(CNMP)	Brazil UTC(ONRJ)	Costa Rica UTC(ICE)	Colombia UTC(SIC)	Argentina UTC(INTI)	Guatemala UTC(LNM)	Jamaica UTC(BSJ)	Uruguay UTC(UTE)	Paraguay UTC(INTN)
United States UTC(NIST)		-20.2	-23.4	20.1	0.1	772.2	-29.5	195.4		-22.1		
Mexico UTC(CNM)	20.2		-2.6	41.2	23.3	792.5	-9.1	218.6		-1.1		
Canada UTC(NRC)	23.4	2.6		43.4	25.2	796.2	-4.5	225.1		0.7		
Panama UTC(CNMP)	-20.1	-41.2	-43.4		-24.7	752.8	-52.3	180.7		-45.2		
Brazil UTC(ONRJ)	-0.1	-23.3	-25.2	24.7		775.8	-26.7	205.2		-22.8		
Costa Rica UTC(ICE)	-772.2	-792.5	-796.2	-752.8	-775.8		-802.3	-576.0		-795.5		
Colombia UTC(SIC)	29.5	9.1	4.5	52.3	26.7	802.3		233.3		6.0		
Argentina UTC(INTI)	-195.4	-218.6	-225.1	-180.7	-205.2	576.0	-233.3			-227.3		
Guatemala UTC(LNM)												
Jamaica UTC(BSJ)	22.1	1.1	-0.7	45.2	22.8	795.5	-6.0	227.3				
Uruguay UTC(UTE)												
Paraguay UTC(INTN)												
Last Update (HHMM UTC)	2320	2320	2320	2320	2320	2320	2320	2320		2320		2100

Figure 5. The real-time SIM measurement grid can be viewed on the Internet.

III. REMOTE CALIBRATION SERVICES

Remote calibrations differ from in-house calibrations in one very important aspect: the customer does not send the device under test to NIST. Instead, NIST sends a measurement system to the customer. This system automates remote calibrations of time and/or frequency. NIST offers three remote calibration services to customers that pay a monthly subscription fee, and each service is described in this section. In addition, this section describes the GPS Timing Receiver Calibration service offered by NIST.

III.A. Frequency Measurement and Analysis Service (FMAS)

The NIST Frequency Measurement and Analysis Service (FMAS) has served calibration and testing laboratories since 1984 by providing them with a convenient way to establish traceability for their frequency measurements. FMAS subscribers receive a five-channel measurement system that includes a time-interval counter, a GPS receiver, and programmable frequency dividers that allows the measurement of any frequency from 1 Hz to 120 MHz. The FMAS measurement uncertainty ($k = 2$) is about 1×10^{-15} at $\tau = 1$ day for direct comparisons between two oscillators and about 2×10^{-13} at $\tau = 1$ day for oscillator to GPS comparisons **[11]**.

FMAS customers receive daily phase plots showing the performance of each oscillator connected to the unit, and a monthly calibration report that shows the measurement uncertainty of their house standard with respect to UTC (NIST). NIST personnel monitor the measurements through a modem connection, and all parts that fail are immediately replaced via an overnight delivery service. The service has 33 customers as of November 2008, and FMAS units are also installed at NIST radio stations WWV and WWVH, and at several other facilities. The FMAS is described in detail at *tf.nist.gov/service/fms.htm*.

III.B. Time Measurement and Analysis Service (TMAS)

The NIST time Measurement and Analysis Service (TMAS) is based on the technology developed for the SIM Time network (Section II.2.E). The service was announced in late 2006, and has six subscribers as of November 2008. The TMAS display is shown in Figure 6.

The TMAS allows any subscribing laboratory or research facility to continuously compare their local time standard to UTC (NIST) and to view the comparison results in near real time via the Internet. Each customer receives a time measurement system that performs the measurements and sends the results to NIST via the Internet for instant processing. Customers can then view their own standard's performance with respect to NIST in near real time, with an ordinary Web browser **[12]**. The TMAS measurement uncertainties are essentially identical to those of the SIM Time network. The combined time uncertainty ($k = 2$) is typically about 11.5 ns, and the frequency uncertainty ($k = 2$) is typically about 5×10^{-14} at $\tau = 1$ day. The TMAS is described in detail at *tf.nist.gov/service/tms.htm*.

III.C. Global Time Service

This NIST service also uses the GPS CV to compare a remote clock to UTC (NIST). Receivers used in this service generate the data in the format recommended by the CCTF Group on GNSS Time Transfer Standards (CGGTTS) **[13]**. The service started in the early 1980s and currently has eight customers.

Data from a receiver located at the customer's facility are automatically downloaded (by phone or Internet FTP) to a NIST computer. The computer stores the data, determines which data are suitable for time transfer calculations, and provides optimally filtered values for the time and frequency of the user's clock relative to UTC (NIST). Monthly reports are sent to the user, and users also receive an account on a NIST computer that allows them to access a daily, preliminary analysis. To improve the performance of the Global Time Service, we apply the IGS measured ionospheric delay correction to the data used in the monthly report. The standard uncertainties for time comparisons are typically less than 10 ns, and less than 1×10^{-13} for frequency comparisons at $\tau = 1$ day.

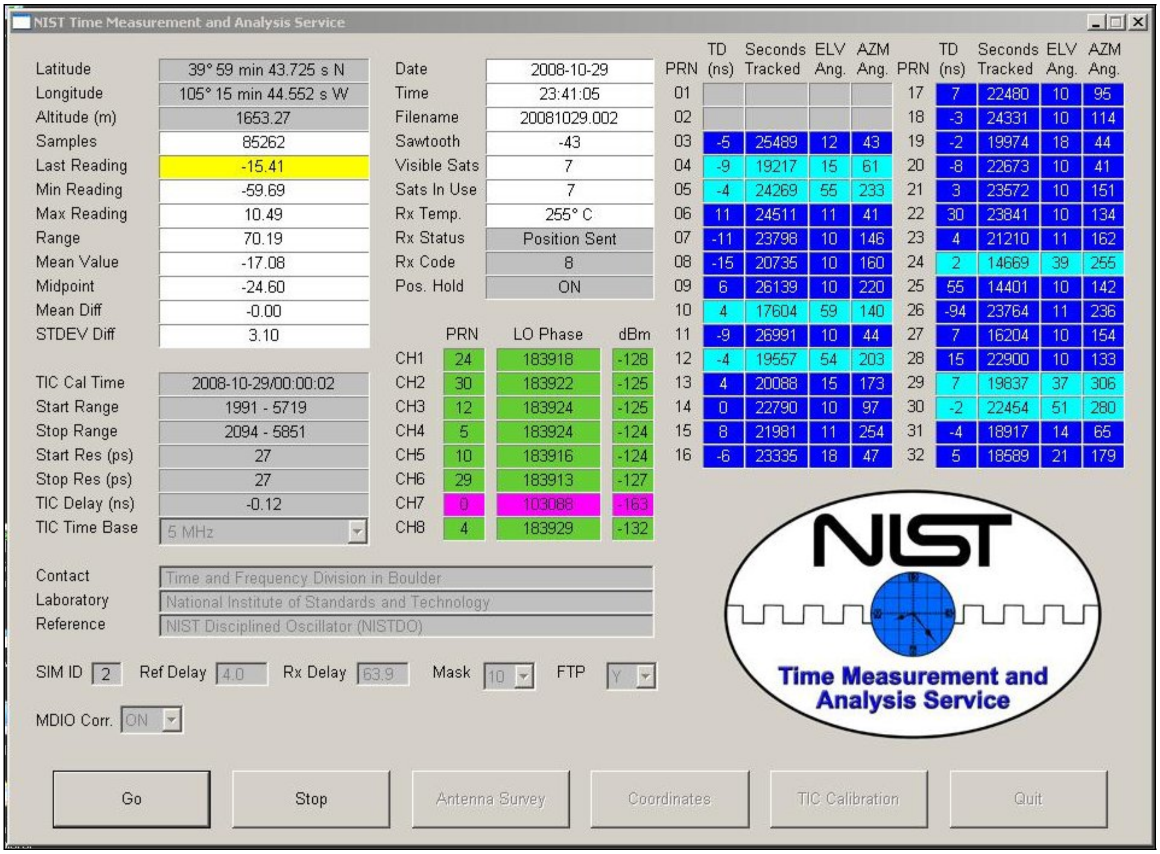

Figure 6. The TMAS display screen.

III.D. GPS Timing Receiver Calibration Service

GPS-disciplined oscillators and GPS receivers that are designed to deliver accurate time and/or frequency outputs can be characterized by using UTC (NIST) as a reference. The stability and accuracy of the signals delivered by the receiver can be determined. NIST has the capability to measure the accuracy of a one pulse per second (1 pps) signal relative to UTC (NIST) at a level of at least ±1 ns. The stability of the 1 pps signal can be measured as either a time deviation at better than 0.1 n from 1 s to 10^4 s, or as an Allan deviation (ADEV) at better than $1 \times 10^{-10}/\tau$ level (τ in seconds). The frequency accuracy of 5 MHz and 10 MHz frequency outputs from the receiver can be determined to within 5×10^{-15} for a 1-day average, and ADEV can be measured at the $1 \times 10^{-13}/\tau$ level.

IV. RADIO BROADCAST SERVICES

NIST operates three dedicated time signal stations, the low frequency (LF) station WWVB, and two shortwave stations, WWV and WWVH. Each station is described in the following sections.

IV.A. Radio Station WWVB (60 kHz)

WWVB, located in Fort Collins, Colorado, broadcasts a digital time code on 60 kHz at an output power of more than 50 kW. This time code serves as the synchronization source for radio-controlled clocks (RCCs) throughout the United States, and parts of Canada and Mexico [**14**,**15**]. A photograph of the station site is shown in Figure 7.

Figure 7. Radio station WWVB.

WWVB RCCs **[15]** have become a common consumer electronics item, and are sold at nearly every major department store in the United States with wall and alarm clocks sometimes costing less than $10 USD. As a result, the WWVB clocks and wristwatches in operation are now believed to number in the tens of millions. The sales figures have continued to increase, and the quality of the RCCs has continued to improve.

The proliferation of WWVB wristwatches is particularly noteworthy. Casio*, a major watch manufacturer, estimates that 1.5 million watches capable of receiving WWVB will be sold in 2008, with sales expected to increase to 2 million units in 2009. A major new development in the RCC arena are multiband devices that can receive signals from LF time signal stations located in China (68.5 kHz), England (60 kHz), Germany (77.5 kHz), and Japan (40 and 60 kHz), in addition to WWVB. Figure 8 is a photograph of a Casio* multiband watch with six-station capability.

Figure 8. A multiband radio-controlled wristwatch.

IV.B. Shortwave Radio Station WWV

WWV, located on the WWVB site in Fort Collins, Colorado, is one of the world's oldest radio stations, having begun experimental broadcasts in 1920 and the transmission of standard frequency signals in 1923. Today, the station is best known for its audio announcements of UTC (NIST), which occur every minute and are simulcast on five frequencies, 2.5, 5, 10, 15, and 20 MHz. The station is also used for the manual synchronization of clocks and watches, for the time interval calibrations of stopwatches and timers **[17]**, for frequency calibrations at modest accuracy levels, and for its digital time code that can be used to synchronize a time display **[14,15]**.

Figure 9. WWV transmitter (FRT-96).

Recent developments at WWV include the installation of replacement transmitters for the 2.5- and 20-MHz broadcasts in 2008. The new 2.5-MHz transmitter was placed in service on May 6, 2008; the 20-MHz transmitter was brought on line on August 11th. These transmitters replaced existing units that had been in service since 1966, the year when the station moved from Maryland to Colorado. The original transmitters had become difficult to repair and maintain.

The replacement transmitters should provide reliable service for years to come. They were transferred to NIST from the United States Navy where they had been placed in service in the mid-1980s, and are known by their military designation as the FRT-96* (Figure 9). They can be used for transmissions in the 2.0-MHz to 29.9999-MHz range, and provide the normal 2.5-KW output power for the 2.5- and 20-MHz broadcasts. They have several advantages over the original transmitters, including fewer vacuum tubes and more advanced tuning and overload circuitry, and these features have improved the quality of the WWV broadcasts.

Figure 10. WWVH 10-MHz antenna.

IV.C. Shortwave Radio Station WWVH

Located on the island of Kauai in the state of Hawaii, NIST radio station WWVH provides services nearly identical to those of WWV, and continuously broadcasts on 2.5, 5, 10, and 15 MHz. WWVH began operation on the island of Maui in 1948, and moved to its present location in Kauai in 1971. WWVH officially serves the state of Hawaii, the Pacific Ocean, and the Pacific Rim, but confirmation of reception has been received from as far away as South Africa, a distance of 19,300 km from Hawaii **[14,15]**.

NIST completed the installation of a new WWVH antenna system in October 2007. In a 7-year project to adopt a technology used on Navy ships, NIST has installed new antennas encased in fiberglass (the 10-MHz antenna is shown in Figure 10) rather than traditional steel supports, to resist corrosion from the salty ocean air. The fiberglass design will reduce maintenance and repair costs and increase the station's reliability. The new design also enables the flexible, lightweight antennas to be easily lowered to the ground for maintenance, reducing safety hazards to staff members who previously had to climb the towers, which are up to 30 meters tall. Because each of the four frequencies requires both a primary and a backup antenna, the station has a total of eight antennas, seven of which are now made of fiberglass. WWVH is believed to be the first station to utilize high-powered, high-frequency fiberglass antennas on land.

V. NETWORK BROADCAST SERVICES

NIST offers four network broadcast services, led by the phenomenally popular Internet Time Service (ITS). Two of the four services send time via the Internet; the other two send time via telephone. Each service is described below.

V.A. Internet Time Service (ITS)

The ITS is one of the world's most widely used time distribution systems, handling over three billion (3×10^9) timing requests per day on peak traffic days, as shown in Figure 11. Since its introduction in 1993, the usage of the service has grown steadily, and the ITS now utilizes 19 time servers located in eight different states. The server names, IP addresses, and locations, as well as the current status of each server, can be obtained from *tf.nist.gov/tf-cgi/servers.cgi*.

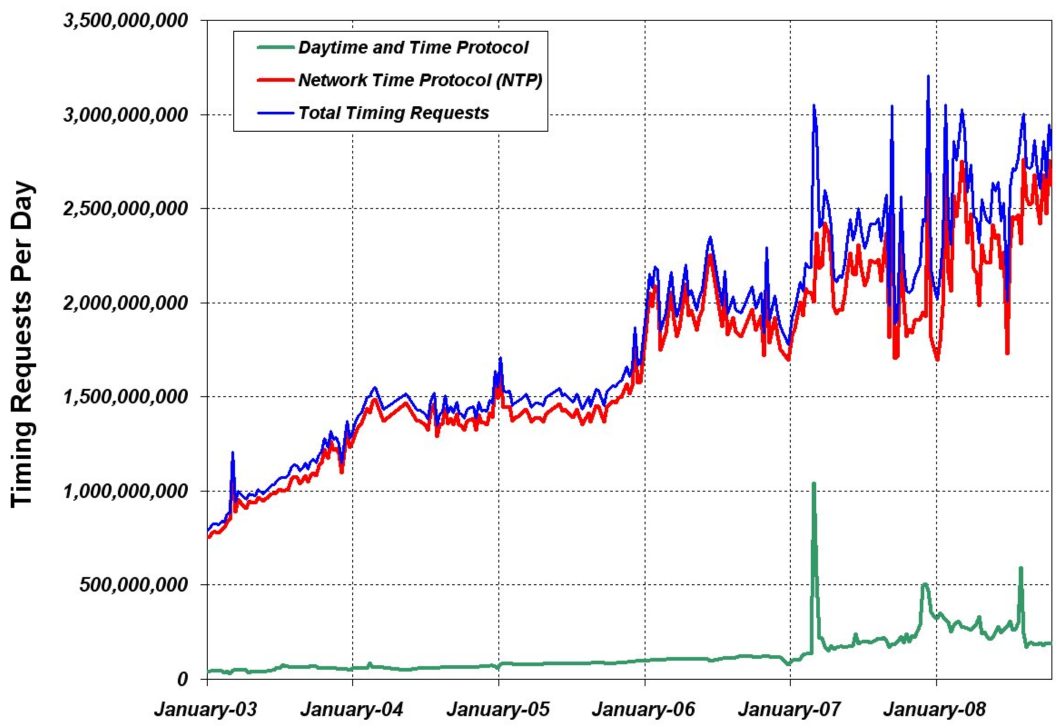

Figure 11. NIST ITS timing requests (January 2003 through October 2008).

The ITS responds to timing requests using three different protocols: the Network Time Protocol (NTP), the Daytime Protocol, and the Time Protocol. However, as illustrated in Figure 11, about 92.6% have been in NTP format since 2003. Most of the remaining requests use the Daytime Protocol. For more information about each of the timing protocols and to download ITS software, visit *tf.nist.gov/service/its.htm*.

Many commercial products and computer operating systems have built-in utilities that rely on the ITS for time synchronization, making it an essential part of the nation's time keeping infrastructure. Most clients are interested only in synchronizing their clocks to the nearest second, but with the appropriate client software, clock hardware, and network, the actual uncertainty can be less than 10 ms **[18].**

V.B. Time.gov Web Clock

The *time.gov* Web site (also available at *nist.time.gov*) serves as the national Web clock for the United States. The site allows any user with a web browser to view the current time in any United States time zone, and also provides an estimate of the accuracy of the received time with a resolution of 0.1 s **[18]**. According to the Web information site *Alexa.com*, *time.gov* ranked in the top 4,000 most visited Web sites in the United States as of November 2008, and in the top 15,000 most visited sites worldwide. An estimated 65 % of *time.gov* users reside in the United States.

The site is hosted at NIST, but is a joint undertaking of NIST and the USNO. The appearance of *time.gov* hasn't changed since its debut in 1999, but a redesigned version with additional features is planned **[19].**

V.C. Automated Computer Time Service (ACTS)

The Automated Computer Time Service (ACTS) distributes UTC (NIST) to computer systems that dial in via analog modems over ordinary telephone lines. NIST has operated ACTS since March 1988. The ACTS system operated from Boulder, Colorado has 24 incoming telephone lines that can be reached by dialing (303) 494-4774. A smaller four-line system is operated at radio station WWVH in Hawaii and can be reached by dialing (808) 335-4721.

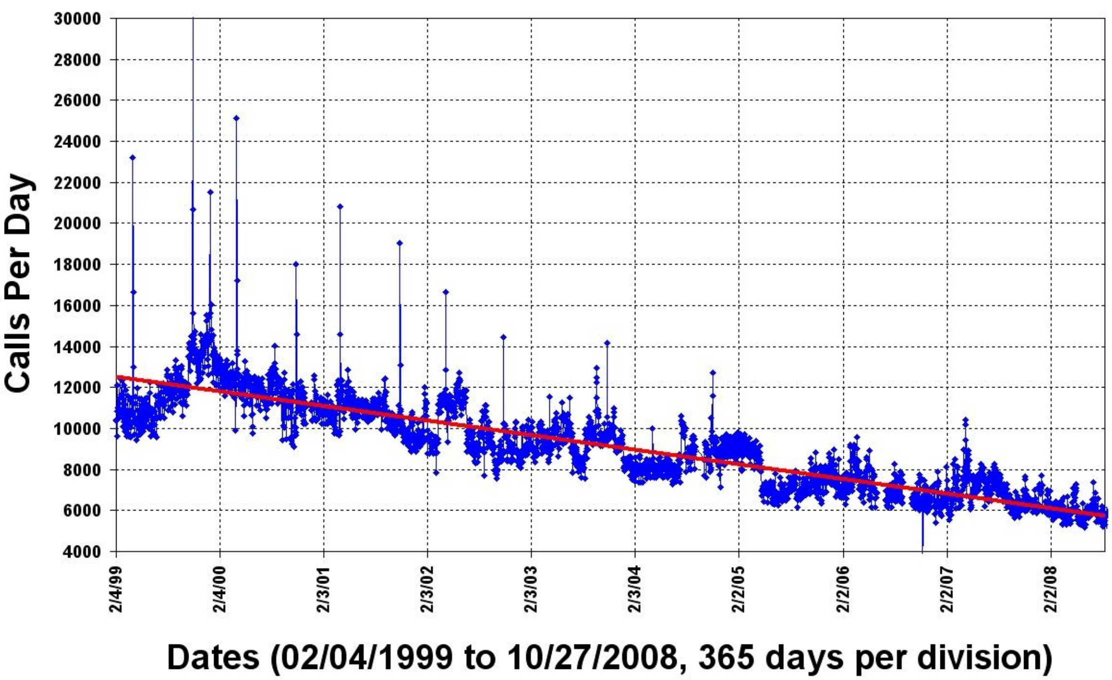

Figure 12. ACTS timing requests over an interval of nearly 10 years.

The uncertainty of ACTS typically ranges from about 5 to 20 ms. The uncertainty depends upon the type of modem and operating system used by the client, the resolution of the client's clock hardware, and the speed of the telephone connection **[18]**.

ACTS receives an average of more than 5,000 calls per day, but the calls have dwindled recently due to two factors: (1) a large number of ACTS clients have switched to the ITS (previous section) which provides free access without telephone tolls; (2) analog modems have become rare and are now included with only a small percentage of new computer systems. Many of the current ACTS calls originate from financial institutions seeking compliance with the National Association of Securities Dealers (NASD) Rule 6357, which requires all computer clocks and time stamping devices to be synchronized to within 3 seconds of UTC(NIST) **[20]**. Some ACTS calls also originate from non-networked computers, or from networked computers behind firewalls that block access to the NTP port.

Figure 12 shows that the number of ACTS calls has declined by about 50% over an interval of nearly 10 years (February 1999 through October 2008). The large spikes on the early part of the graph normally occurred on transition days to or from Daylight Saving Time.

V.D. Telephone Time-of-Day Service (TTDS)

The NIST Telephone Time-of-Day Service (TTDS) allows customers to listen to audio simulcasts of WWV and WWVH by telephone. The WWV audio signal can be heard by dialing (303) 499-7111, and WWVH can be heard by dialing (808) 335-4363. Calls are limited to about 3 minutes. The WWV service can handle 15 calls simultaneously, or at least 300 calls per hour. The WWVH service can handle at least 20 calls per hour **[15]**.

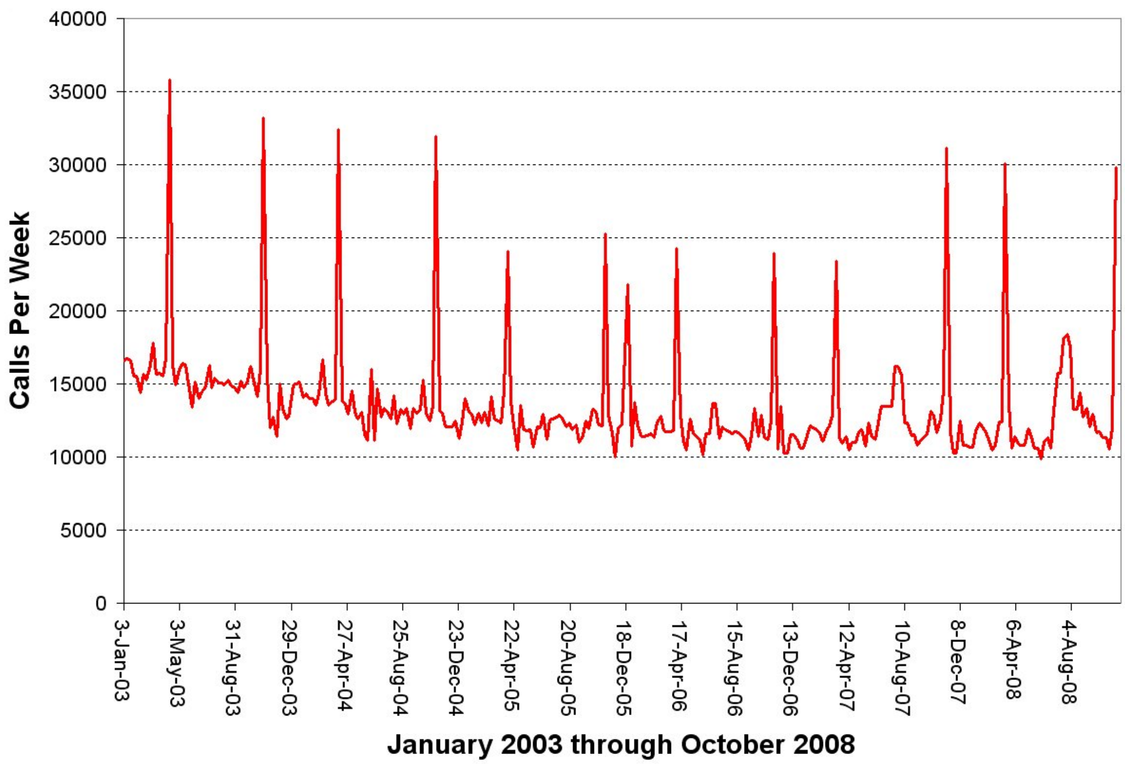

Figure 13. WWV TTDS timing requests over an interval of nearly 6 years.

The TTDS is used primarily for the manual synchronization of clocks, and for the time interval calibrations of stopwatches and timers **[17]**. The uncertainty of the time-of-day message is essentially equal to the delay through the telephone circuits (Type B uncertainty) and the variation in the delay during the call (Type A uncertainty). Delays can vary significantly depending upon the type of telephone network used for the call, but should not exceed 150 ms based on International Telecommunication Union (ITU) recommendations **[21]**. The delay variation during a call is typically much less than 1 ms.

The TTDS simulcast of WWV originated in 1971 and at WWVH about 2 years later. At its peak, the service received about 2 million calls per year, but usage has declined, due to the many alternative methods now available of obtaining the time. Even so, the WWV service still handles an average of nearly 13,000 calls per week (~675,000 calls per year), as shown in Figure 13.

VI. TIME TRANSFER RESEARCH

NIST continuously engages in time transfer research designed to improve its time transfer capability and the quality of services provided to customers. Some current projects are described in this section.

VI.A. Common-View Disciplined Oscillator Prototype (CVDO)

NIST is currently experimenting with a new type of device, a common-view disciplined oscillator. This device obtains near-real-time common-view GPS data from the Internet and uses a Proportional-Integral-Derivative (PID) controller to tightly lock a rubidium oscillator to UTC (NIST) (Figure 14). The result is a NIST disciplined oscillator (NISTDO) that can be installed at remote locations, such as calibration and metrology laboratories **[22]**. The NISTDO might eventually become an optional add-on to the TMAS (Section III.3.b), providing both syntonized 10-MHz frequency outputs and synchronized 1-pps timing outputs to NIST customers.

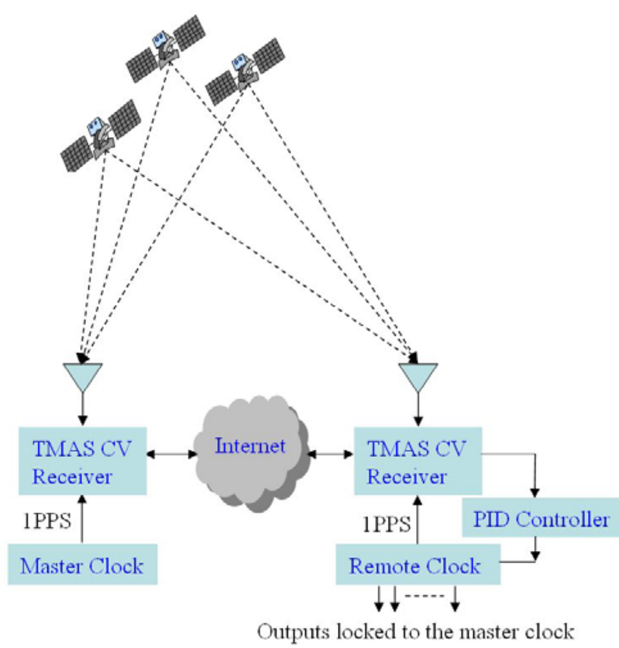

Figure 14. A common-view disciplined oscillator.

VI.B. WAAS Time and Frequency Transfer

NIST has worked with the USNO, the National Research Council (NRC) of Canada and Novatel, Inc.* on the project of using a Wide Area Augmentation System (WAAS) satellite for time and frequency comparison **[23]**.

Two geostationary WAAS satellites now transmit the standard GPS L1 and L5 codes and carriers. This makes it possible to make ionosphere-free remote clock comparisons. Using parabolic dish antennas, we can receive WAAS signals with high signal-to-noise ratios and very little multi-path interference. Over long observation intervals, WAAS time transfer can potentially provide better performance than the time transfer techniques based on the GPS satellites. However, the NIST/USNO/NRC experiment **[23]** showed that the frequency stability of the WAAS remote clock comparisons was not as good as hoped. The instability of the technique was dominated by errors in the broadcast WAAS ephemeris.

VI.C. LORAN Time and Frequency Transfer

NIST has monitored the 100-kHz LORAN (LOng RAnge Navigation) broadcasts for many years, comparing the signals received from several stations to UTC (NIST). Currently, NIST monitors the received phase of the LORAN stations located in Baudette, Minnesota (8970-Y), Boise City, Oklahoma (9610-M), and Gillette, Wyoming (8290-X). The results are updated monthly and made available at *tf.nist.gov/service/lorantrace.htm*.

NIST is now operating a prototype eLORAN (eLORAN) receiver that demodulates the LORAN Data Channel (LDC). The LDC contains a time code and other information that was lacking in legacy LORAN. With the appropriate software, this new receiver should eventually allow NIST to simultaneously monitor the phase of all LORAN stations within receiving distance and to make the results available via the Internet **[24]**.

VII. SUMMARY AND CONCLUSIONS

As demonstrated in this discussion, NIST participates in a broad spectrum of time and frequency transfer activities. These activities support many existing customers and applications as they have for many years, and are continually being enhanced to meet the future technology needs of the United States.

** Commercial products and companies are identified for technical completeness only, and no endorsement by NIST is implied.*

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