# The NIST Time Measurement and Analysis Service

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## Abstract

NIST now offers a new remote calibration service designed to assist laboratories that maintain an accurate local time standard. The service monitors the local time standard by continuously comparing it to the national time standard, and reports the comparison results to the customer in near real-time. This new service, called the NIST Time Measurement and Analysis Service, or TMAS, works by making simultaneous common-view measurements at NIST and at the customer's laboratory with up to eight Global Positioning System (GPS) satellites. 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 standard's performance with respect to NIST in near real-time, using an ordinary web browser. Time is measured with a combined standard uncertainty of less than 15 nanoseconds, and frequency is measured with an uncertainty of less than $1 \times 10^{-13}$ after 1 day of averaging. This paper describes the multi–channel GPS common–view technique used by the service and the measurement system sent to each customer. It also explains how NIST calibrates each measurement system prior to shipment, how measurement results are reported to the customer, and how the measurement uncertainties are estimated.

## 1. Introduction

There is a small but growing demand for calibration laboratories and research facilities to maintain a high accuracy time standard. This requires the laboratory to continuously generate a 1 pulse per second (pps) on-time signal, and for laboratories in the United States, to be able to state the uncertainty of that signal with respect to the Coordinated Universal Time (UTC) scale maintained at NIST, known as UTC(NIST). Once the uncertainty of the 1 pps signal is known, it can then be used as a standard for traceable measurements of time interval and/or frequency, or as a synchronization source for other timing systems. Generating a high accuracy 1 pps signal is normally done using either a cesium oscillator or a Global Positioning System disciplined oscillator (GPSDO). Cesium oscillators are primary laboratory standards that physically realize the base unit of time interval (the second) as defined by the International System (SI). However, they still need to be synchronized before serving as a time standard. GPSDOs are devices that usually contain a quartz or rubidium oscillator whose outputs are continuously steered to agree with signals from the GPS satellites. In contrast to a cesium oscillator, a GPSDO is inherently on-time, and can produce a 1 pps signal that is usually well within 1 μs of UTC. However, because it is not usually possible to measure the time offset of a GPSDO with respect to

UTC(NIST), laboratories are often limited to using and trusting the number quoted on the manufacturer's specification sheet as an uncertainty figure.

Laboratories that want their time standards calibrated against UTC(NIST) to accuracies better than 1 µs have historically had several options, all of which have some shortcomings. Customers sometimes ask to send their cesium oscillator to NIST for calibration, but this is normally not a good solution, nor is it practical. NIST offers several frequency calibration services for cesium oscillators that are sent to Boulder (Service IDs 77100C, 77110C, and 77120C), but time information is lost during the shipment to NIST and the return shipment to the customer, and the cesium would need to be resynchronized when it returns to the customer's lab. In fact, when the device returns to the customer, even the frequency of the device might be substantially different from what it was during the calibration. A GPSDO can be sent to NIST for delay calibrations (Service ID 76120S) [1]. This works well if the antenna and cable are calibrated along with the receiver. However, due to local reception conditions, the device might perform differently at the customer's site than it did at NIST, and the customer will be without a time reference during the interval when the unit is gone from their laboratory.

The NIST services described in the above paragraph follow the traditional model, common in most fields of metrology, where the device under test (DUT) is sent to another laboratory for calibration. In these cases, the DUT is sent to NIST, where it is calibrated and then returned to the customer along with a report containing the measurement results and an uncertainty statement. This calibration is typically repeated at an interval determined by the customer, for example, once every year. The field of time and frequency typically uses a different model, based upon remote calibration. Unlike the traditional model, a remote calibration does not require the customer to send their DUT to NIST. Instead, the DUT remains in place at the customer's site, and NIST sends a measurement system to the customer. The measurement system then collects data that are sent back to NIST for processing, and the calibration can last for as long as the customer wants it to last. Laboratories that want their standard to be continuously monitored by NIST can do so by subscribing to a remote calibration service, and have their standard continuously compared to UTC(NIST) every day of the year.

NIST has offered remote frequency and time calibration services since 1983 [2]. The original remote time calibration service, called the Global Time Service (GTS), was launched that year and continues to serve a number of customers. However, its technology is now outdated in some respects. For example, there are gaps in the measurement data because the satellites are not continuously tracked. Instead, satellite data are recorded during a series of scheduled tracks that last for 13 minutes each, and the single-channel receivers supplied to some GTS customers track just one satellite at a time. Perhaps more importantly, the GTS does not allow customers a convenient way to view their measurement results until they receive their monthly reports in the mail. With today's technology, it seems the ultimate solution to a customer's time measurement problem would be to have their standard compared to UTC(NIST), 24 hours a day, 7 days a week, with the results continuously updated via the Internet so that they can easily be accessed from anywhere. This is the solution provided by the new NIST Time Measurement and Analysis Service (TMAS), the subject of this paper. The TMAS offers measurement uncertainties that are essentially equivalent to the GTS, but it costs significantly less, and has the advantage of making its measurement results available to customers in near real-time via the Internet.

## 2. Physical description of the TMAS measurement system

The TMAS was announced in late 2005 and assigned a Service ID of 76101S by the NIST calibration office [1]. The service shares hardware technology previously developed for the NIST Frequency Measurement and Analysis Service (FMAS) [3], and software technology previously developed for the Interamerican Metrology System (SIM) time and frequency comparison network. Thus, the same technology delivered to TMAS customers has been proven by continuously comparing the national time scales of the National Research Council in Canada, UTC(NRC), and the Centro Nacional de Metrologia (CENAM) in Mexico, UTC(CNM), to each other and to UTC(NIST), with excellent results [4].


*Figure 1. The TMAS measurement system.*

Customers who subscribe to the TMAS receive a measurement system consisting of an industrial rack-mount computer, an LCD monitor, and a keyboard with an integrated trackball (Figure 1). A time interval counter with a single shot resolution of about 30 ps and an eight-channel GPS receiver are embedded inside the computer case [3]. The system is assembled by NIST prior to shipment and is easy to install. The customer is required only to connect four cables to the back panel of the system, as listed in Table 1. When signals are connected and the unit is powered on, it will begin taking measurements and sending data back to NIST.

*Table 1. TMAS input signals.*

| Input Signal | Connector Type | Description |
|---|---|---|
| Counter Time Base | BNC | The time interval counter requires either a 5 or 10 MHz sine wave signal as its external time base. This can often be obtained from the same DUT that provides the time standard. This connection is made with coaxial cable (typically RG-58). |
| Time Standard | BNC | The customer's 1 pps time standard is connected to the measurement unit using a coaxial cable (typically RG-58). The delay of this cable must be measured by the customer and entered into the system software. |
| GPS Antenna | TNC | The GPS antenna and cable are included with the system and calibrated at NIST prior to shipment, and a delay value is already entered into the system (Section 4). The length of the antenna cable is specified by the customer before the calibration is started. After the system arrives at the customer's site, the customer is responsible for mounting the antenna on a rooftop location with a clear view of the sky on all sides. The cone-shaped antenna is small (163 mm in height and 90 mm in diameter) and easy to mount. |
| Network | Ethernet | An Ethernet interface is used to connect the system to the Internet. The customer is required to provide an always-on Internet connection with a dedicated IP address. The system transmits measurement data using the file transfer protocol (FTP), and TCP ports 20 and 21 must be left open if the system resides behind a firewall. |

## 3. The common-view measurement technique

The TMAS employs the common-view measurement technique to compare time standards located at remote locations from each other. Ideally, a comparison between two time standards would be made by bringing them into the same laboratory and connecting them both to some type of phase comparator, usually a time interval counter. If bringing the time standards together into the same lab is not practical or desirable, the difference between the two time standards can still be measured by simultaneously comparing both standards to a common reference signal that can be received at both sites. Both sites record their measurements and exchange their results, and the results are subtracted from each other to obtain the time difference between the two standards. The common-view signal can be thought of as a transfer standard, and its value drops out of the final measurement result.

To visualize how the common-view technique works, imagine two people living at opposite ends of a small town who want to compare the time displayed by the grandfather clocks in their living rooms. This would be an easy problem to solve if they could get the clocks together in the same place and compare them side by side. However, moving the clocks would be difficult and is not practical or desirable. Therefore, each person agrees to write down the time displayed by their clock when a fire whistle (located midway between them) blows in their town, an event that happens periodically. After writing down the readings, they call or email each other and exchange the time readings. If the first clock read 12:01:35 and the second clock read 12:01:47, then simple subtraction tells them that the second clock was 12 seconds ahead of the first clock when the fire whistle blew. The time when the fire whistle blew is unimportant. It only matters that it was heard at the same time, and that a simultaneous measurement was made at both houses. If so, the measurement reveals the time difference between the two grandfather clocks and the comparison was successful [5].

The common-view technique has been used in the time measurement world for many decades, with a number of different types of signals used as transfer standards. One notable common-view measurement involved radio station WWV. From 1955 to 1958, the United States Naval Observatory (USNO) in Washington, D.C. and the National Physical Laboratory (NPL) in Teddington, United Kingdom made simultaneous common-view measurements of the signals broadcast from WWV, which was then located in the Washington area. The USNO compared WWV to an astronomical time scale (UT2), and NPL compared WWV to the new cesium standard they had just developed. The resulting measurement helped the USNO and NPL equate the length of the astronomical second to the atomic second, eventually leading to the atomic second being defined as the duration of 9,192,631,770 energy transitions of the cesium atom [6]. In later years, common-view measurements were made with a variety of signals serving as transfer standards, including LORAN-C and television broadcasts, 60 Hz power line signals, and even pulses from optical pulsars [7].

Major advances in accurate common-view measurements began after the first GPS satellite was launched in 1978. Signals from the GPS satellites were a nearly ideal common-view reference because there was a clear path between the transmitter and receiver, and because the lengths of the two paths between the transmitter and receivers were nearly equal. Common-view GPS measurements began at NIST (then known as NBS) shortly after the first GPS satellite was launched [8], and as previously mentioned, a common-view service was in place by 1983 [2]. The performance of common-view GPS measurements was some 20 to 30 times better than results previously obtained using LORAN-C as a transfer standard [9], and the common-view GPS technique soon played a central role in the international calculation of UTC performed by the International Bureau of Weights and Measures (BIPM), as it does to this day [10].

Common-view GPS comparisons use one or more GPS satellites as the common-view reference (Figure 2). There are several variations of the technique, but all have the same objective, to compare time or frequency standards located at remote locations. The common-view method involves a GPS satellite (*S*), and two receiving sites (*A* and *B*), each containing a GPS receiver, a time interval counter, and a local time standard. The satellite transmits a time signal that is nearly simultaneously received at *A* and *B*, and a measurement is made at both *A* and *B* that compares the received GPS signal to the local time standard. Thus, the measurement at site *A* compares the GPS signal received over the path $d_{SA}$ to the local clock, *S - Clock A*. Site *B* receives GPS over the path $d_{SB}$ and measures *S - Clock B*. The two receivers then exchange and difference the data. Delays that are common to both paths $d_{SA}$ and $d_{SB}$ cancel out, but delays that aren't common to both paths contribute uncertainty to the measurement. The result of the measurement is (*Clock A - Clock B*) with an error term of $d_{SA} - d_{SB}$. Thus, the basic equation for common-view GPS measurements is:

$$(Clock_A - GPS) - (Clock_B - GPS) = Clock_A - Clock_B + (d_{SA} - d_{SB})\ . \qquad (1)$$

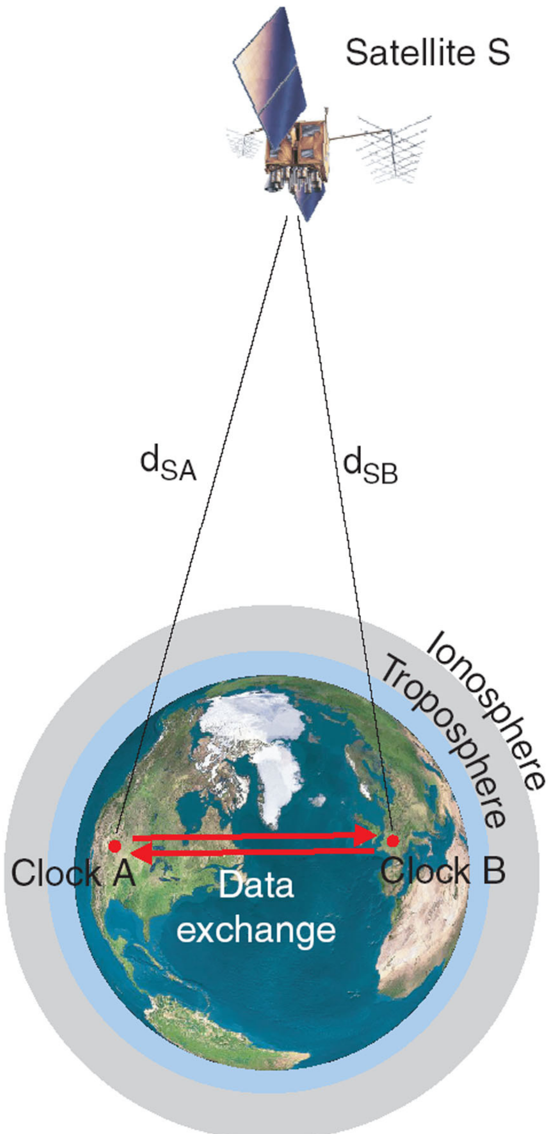



*Figure 2. Common-View GPS.*

The components that make up the $d_{SA} - d_{SB}$ error term can be measured or estimated (Section 8) and applied as a correction to the measurement and/or be accounted for in the uncertainty analysis. The $d_{SA} - d_{SB}$ error term includes not only delays from the satellite to the receiving antennas, but also delays that take place after the signal is received. Therefore, a key to a successful measurement is to have equal delays at each site. This means that the common-view systems must be calibrated so that their relative delays are as close to zero as possible. The calibration of TMAS units is done at NIST prior to shipment to the customer, and is discussed in Section 4.

### 3.1 Common-view and traceability

For obvious reasons, the common-view technique simplifies a laboratory's task of establishing traceability to the SI. Calibration laboratories are generally required to establish traceability of their own measurement standards and measuring instruments to the SI by means of an unbroken chain of calibrations or comparisons. The link back to the SI is normally achieved through measurements that can be traced to the measurement standards maintained by a national metrology institute (NMI), the role filled by NIST in the United States. Therefore, laboratories can establish traceability to the SI by sending their standard to NIST for calibration, or to another laboratory that has had its standard calibrated by NIST (which of course introduces another "link" in the traceability chain). Even then, however, traceability is established only at a given point in time, and needs to be periodically reestablished [11]. For example, if a standard had been calibrated by NIST ten years ago, a laboratory auditor or assessor would probably not consider that to be sufficient evidence to establish traceability today.

The TMAS completely solves the traceability problem. If we equate the TMAS to the model described in Section 3 above, *Clock A* is the time standard maintained at the customer's site, and *Clock B* is the national time standard maintained by NIST. Thus, the TMAS makes it possible to continuously establish traceability by making continuous, direct comparisons against the national standard. This means that the traceability chain back to the NMI contains only one link [12], which is the optimal situation for obtaining the best measurement results.

## 4. Calibration of measurement systems prior to shipment from NIST

Each measurement system is calibrated at the NIST Boulder laboratories prior to being shipped to the customer. The calibration is done by the common-clock method, where the system under test and the reference system at NIST are both measuring the same clock, a 1 pps signal from the UTC(NIST) time scale (Figure 3). The customer's system is installed at NIST using the same antenna and cable that will be shipped to the customer. The antenna is attached to a previous surveyed mounting pole whose coordinates are known to within an uncertainty of less than 20 cm. The length of the baseline between the customer's antenna and the reference antenna at NIST is about 6 m. The calibration lasts for 10 days, and results in an average delay number, $D_{Rx}$, that is entered into the TMAS system prior to shipment to the customer.

The time stability, $\sigma_x(\tau)$ [13], of the common-clock calibrations is typically 0.2 ns or less at an averaging period of 1 day. Figure 4 shows results for a recent (March 2006) system calibration, where the peak-to-peak variation of the 10 minute averages was less than 10 ns, the average delay $D_{Rx}$ was equal to 41.1 ns, and the time deviation, $\sigma_x(\tau)$ was equal to 0.16 ns at an averaging time of 1 day. There are some outliers in the data, but there appears to be no significant slope or trend. However, the results of a common-view, common-clock calibration will vary slightly when repeated multiple times, introducing a systematic error that must be accounted for in the uncertainty analysis. This will be discussed further in Section 8.

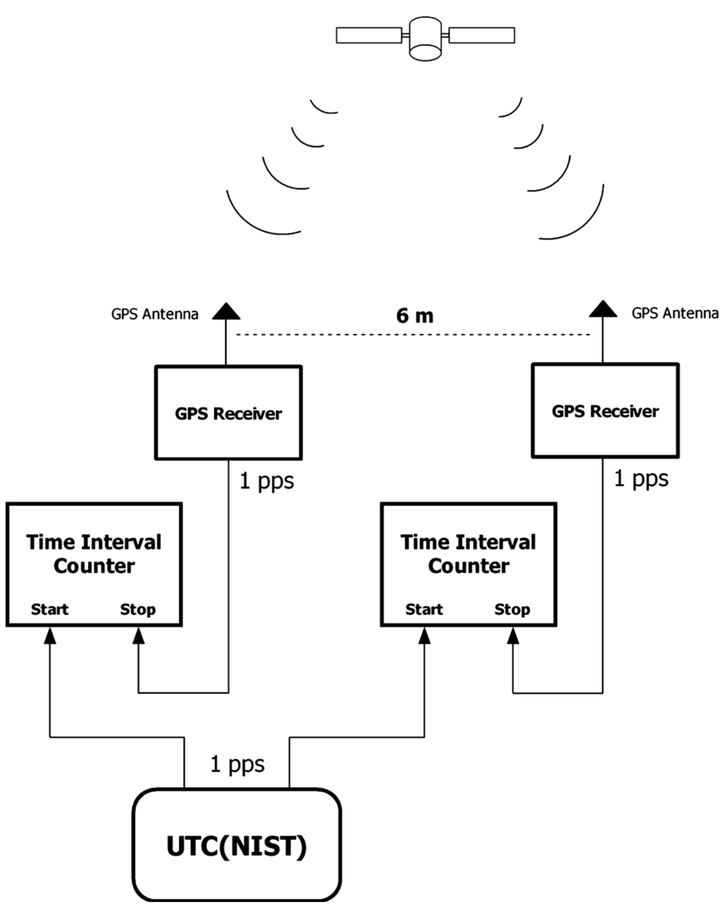



*Figure 3. A common-view common-clock calibration of a TMAS measurement system.*

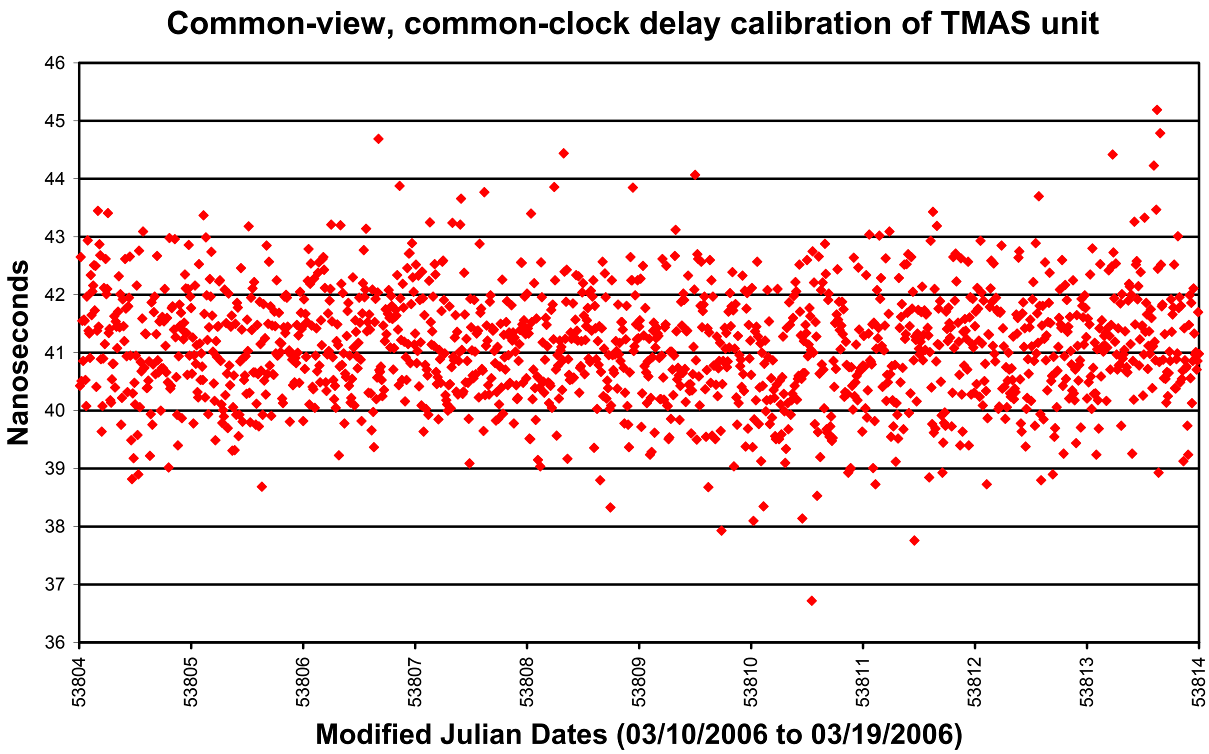



*Figure 4. Results of a 10-day TMAS measurement system calibration.*

## 5. Technical details of the TMAS software and hardware

The GPS receiver used by the TMAS simultaneously tracks up to eight GPS satellites, and outputs a 1 pps signal that is compared to customer's time standard with a time interval counter. The receiver also provides data used to produce a time offset reading for each individual satellite, and these readings are displayed on the system monitor (Figure 5). Data are stored in a file containing a header with the current system settings, and GPS data contained in a 32 × 144 matrix. The 32 columns represent the GPS satellites, with each satellite's data stored in the column whose number equals its pseudo-random noise (PRN) code. The 144 rows represent the number of 10 minute segments in 1 day. At the end of each 10 minute segment, the averaged data are sent via the file transfer protocol (FTP) to a NIST web server, where they are reduced and displayed on-the-fly (Section 6) when requested by a customer. As many as 11 520 minutes of data (144 segments × 10 minute tracks × 8 satellites) can be collected per day, with no dead time or gaps between measurements. This exceeds the maximum amount of data collectable by the GTS with a single-channel receiver by a factor of about 18.

Note that the software installed on the customer's measurement system only collects data and sends it to NIST; it does not perform the common-view data reduction. This is done by web-based analysis software developed at NIST as a group of common gateway interface (CGI) applications written with a combination of a compiled BASIC scripting language and a Java graphics library. The software can process up to 200 days of data (28 800 10-minute segments) and display them on one graph. It quickly aligns the common-view tracks where both NIST and customer viewed the same satellite at the same time and performs the common-view subtraction for each aligned track. A time difference, *TD*, for a single 10 min track is computed as

$$TD = \frac{\sum_{i=1}^{8} (SatA_i - SatB_i)}{CV} , \qquad (2)$$

where $SatA_i$ is the series of individual satellite tracks recorded at site A, $SatB_i$ is the series of tracks recorded at site B, and $CV$ is the number of satellite tracks common to both sites.

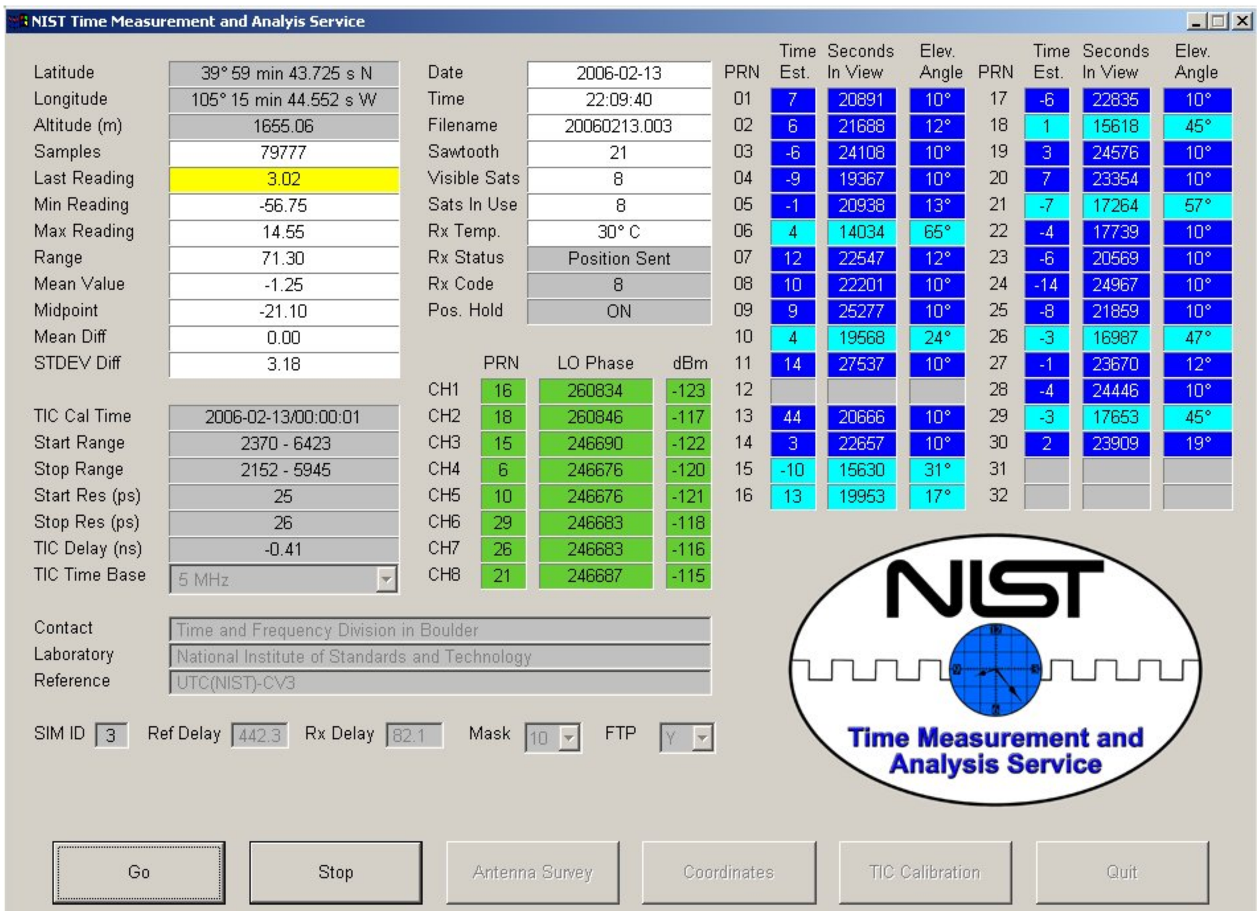
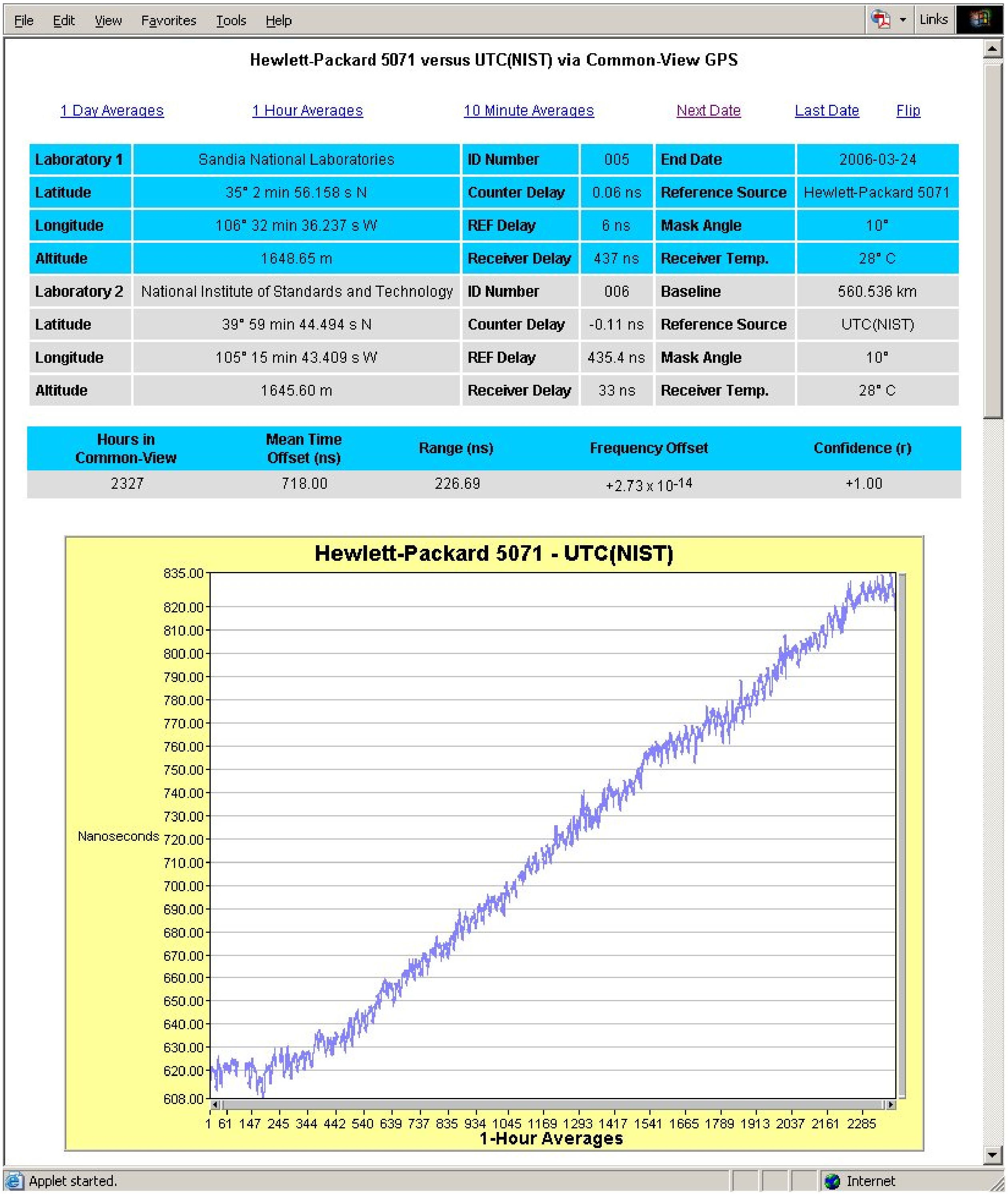



*Figure 5. The TMAS measurement system displays the collected GPS readings.*

## 6. Reporting results to the customer

Because all of the data collected by TMAS customers are uploaded to a NIST server, customers can request and view the data whenever they wish. Requests are normally processed within a fraction of a second, and can be made using any Java-enabled web browser from any Internet connection, through a password protected web site. The data are graphed as either 1 hour (Figure 6) or 1 day averages, and the web-based software computes both the time deviation, $\sigma_x(\tau)$, and Allan deviation, $\sigma_y(\tau)$ [13], of the entire data set. In addition, 10 minute, 1 hour, or 1 day averages can be copied from the web browser and pasted into a spreadsheet or other application if the customer wants to perform further analysis. At the laboratory's request, NIST can also provide signed paper copies of TMAS reports. These reports are issued monthly, but contain essentially the same information that is available on-line.




| Laboratory 1 | Sandia National Laboratories | ID Number | 005 | End Date | 2006-03-24 |
|---|---|---|---|---|---|
| Latitude | 35° 2 min 56.158 s N | Counter Delay | 0.06 ns | Reference Source | Hewlett-Packard 5071 |
| Longitude | 106° 32 min 36.237 s W | REF Delay | 6 ns | Mask Angle | 10° |
| Altitude | 1648.65 m | Receiver Delay | 437 ns | Receiver Temp. | 28° C |
| Laboratory 2 | National Institute of Standards and Technology | ID Number | 006 | Baseline | 560.536 km |
| Latitude | 39° 59 min 44.494 s N | Counter Delay | -0.11 ns | Reference Source | UTC(NIST) |
| Longitude | 105° 15 min 43.409 s W | REF Delay | 435.4 ns | Mask Angle | 10° |
| Altitude | 1645.60 m | Receiver Delay | 33 ns | Receiver Temp. | 28° C |

| Hours in Common-View | Mean Time Offset (ns) | Range (ns) | Frequency Offset | Confidence (r) |
|---|---|---|---|---|
| 2327 | 718.00 | 226.69 | $+2.73 \times 10^{-14}$ | +1.00 |

*Figure 6. Viewing TMAS data using a web browser.*

The TMAS is a near real-time common-view system, which is a tremendous benefit to the customer. During normal operation, the data will be updated every 10 minutes, meaning that customers can view their time difference with respect to UTC(NIST) within minutes after the measurement was made. Near real-time common-view systems have been implemented previously in Asia [14] and in the SIM region [4], but they are still the exception rather than the rule. Some common-view services do not reports results to the customer for days or weeks after the measurements were made.

## 7. Field Tests

Figure 7 shows the results of a six month comparison (September 2005 to March 2006) between the Sandia National Laboratories primary time standard and the UTC(NIST) time scale. The Sandia standard is a cesium oscillator located in Albuquerque, New Mexico, a distance of about 561 km from the NIST laboratories in Boulder, Colorado. The red line shows the actual measurement data, and the blue line is a linear least squares fit. The slope of the least squares line is about 1.7 ns per day. This indicates that the Sandia standard has a mean frequency offset of $1.9 \times 10^{-14}$ with respect to UTC(NIST).

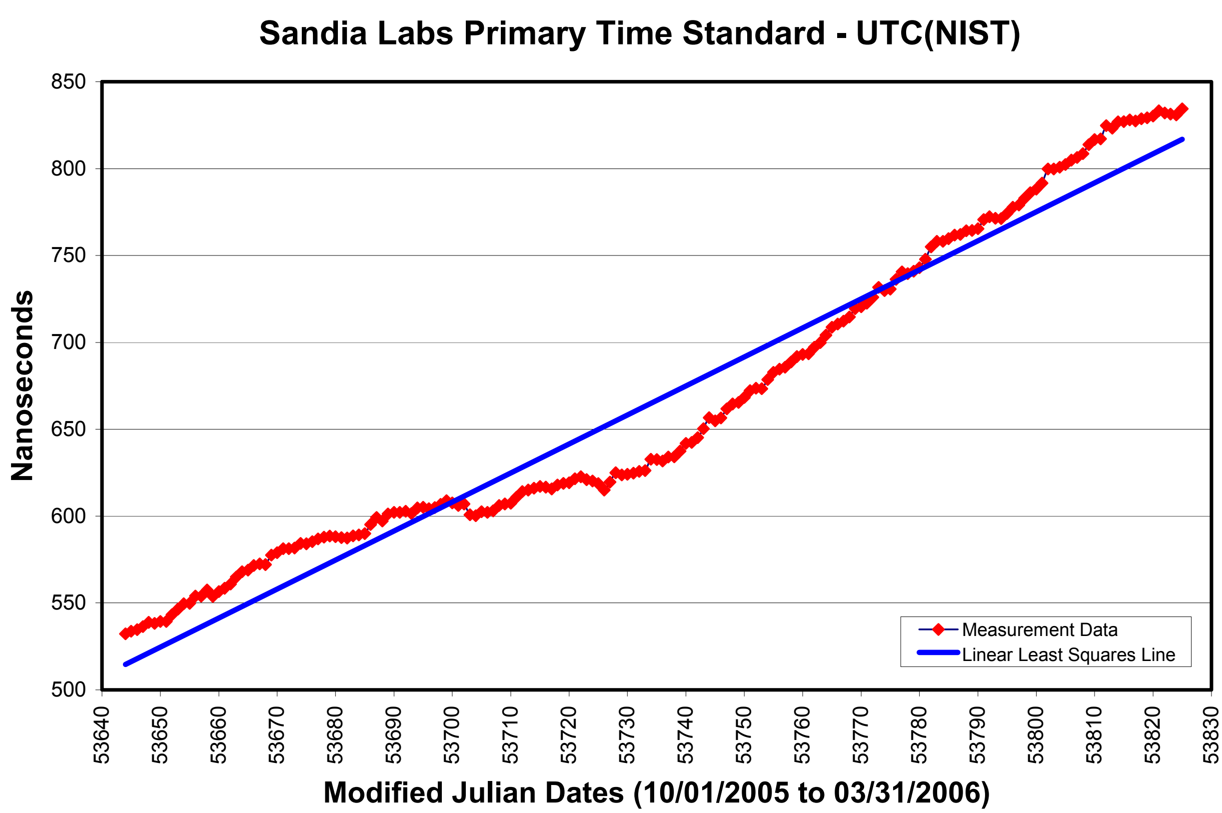



*Figure 7. TMAS comparison between the time standard at Sandia and UTC(NIST).*

As described earlier, the TMAS technology has also been field tested by comparing UTC(NIST) to the time scales of other NMIs in the SIM region [4]. Figure 8 shows the result of a 41 day comparison between UTC(NIST) and UTC(NRC), the Canadian national standard, over the 2471 km baseline between Boulder and Ottawa, Canada. NIST and NRC each contribute data to the BIPM that are used to help derive the international UTC time scale. The BIPM publishes these data monthly in their *Circular-T* document [15]. Figure 8 shows the results of the daily comparisons made with the TMAS technology in blue, and the "official" numbers from the BIPM *Circular-T* reported at five-day intervals in red. The *Circular-T* values are obtained with common-view GPS, but are made by different receivers and with the benefit of some extensive post processing, with results reported anywhere from two to eight weeks after the measurements are made. The blue values have error bars reflecting the estimated 15 ns uncertainty of the TMAS (analysis is provided in the next section). The *Circular-T* values are well within the coverage area of this estimated uncertainty, typically within 5 ns, which helps to validate the TMAS performance.

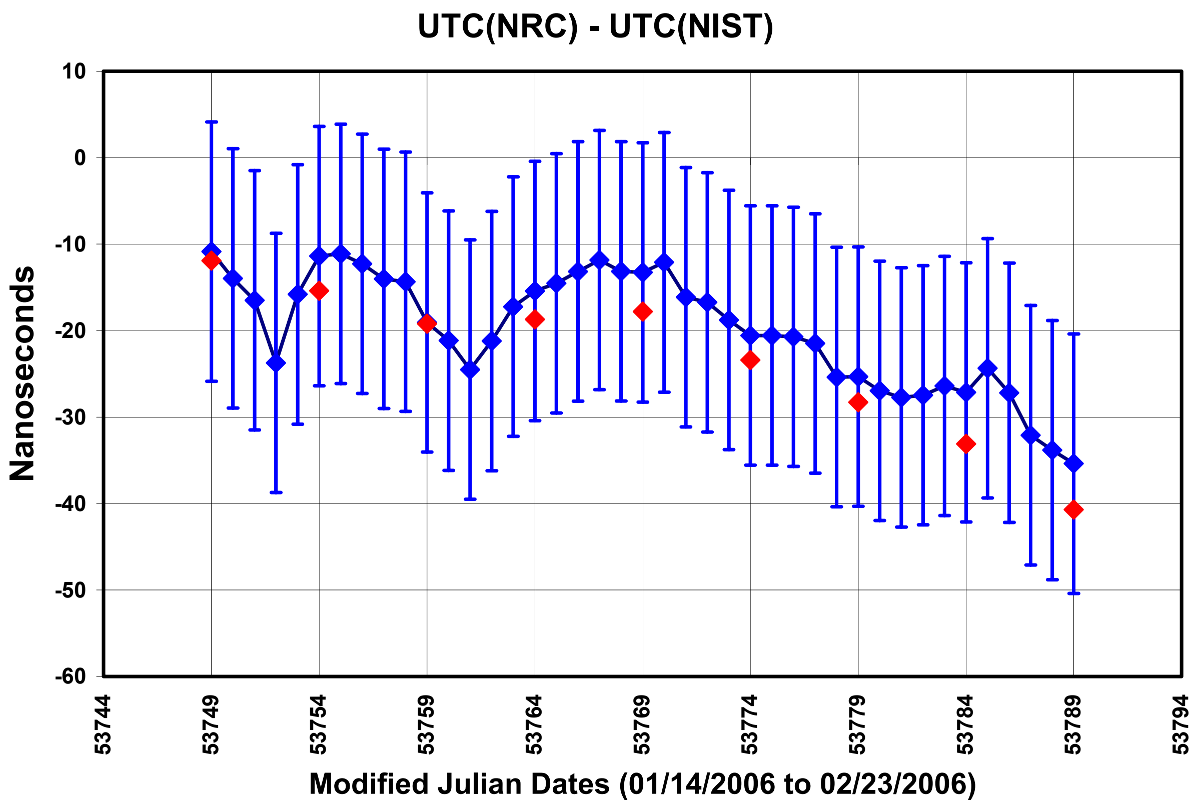



*Figure 8. Comparison between UTC(NRC) and UTC(NIST).*

## 8. TMAS uncertainty analysis

Estimating the uncertainty of the TMAS involves evaluating both the Type A and Type B uncertainties as described in the ISO standard [16]. Brief examples are given here for both time and frequency.

## 8.1 Analysis of time uncertainty

To evaluate the Type A time uncertainty, we use the time deviation statistic, $\sigma_x(\tau)$, at an averaging time of 1 day. The time deviation is an industry standard [13] that is calculated automatically by our web-based software. Using the data displayed in Figure 7, we obtain a Type A uncertainty of 1.2 ns between NIST and Sandia, over a baseline of 561 km. This uncertainty will increase over longer baselines, but is typically about 1.5 ns for the 2471 km baseline between NIST and NRC. As a result, we expect the Type A time uncertainty to be less than 2 ns for all TMAS customers in the continental United States.

The Type B evaluation is more difficult, but we have identified seven components that can potentially introduce systematic errors that are summarized in Table 2 and discussed in more detail in sections 8.11 through 8.17. Some Type B uncertainties can also get larger as a function of the length of the baseline, but the estimates provided here should be applicable for all TMAS customers in the continental United States, where the baseline length should not exceed 3000 km. Due to the nature of common-view measurements, any systematic error that is common to both sites will cancel out, so the Type B components listed here all relate to uncertainties that affect one site differently than the other. With the exception of the antenna position, all of these uncertainty components have a uniform distribution that we expect to cover all cases. However, in the case of antenna coordinates, we assume in Table 2 that the customer will be able to survey their antenna's position to within an uncertainty of 1 m. If this is not true, the combined time uncertainty of the TMAS will increase, as explained in section 8.12.

*Table 2. TMAS estimated Type B uncertainties.*

| Description | Uncertainty (nanoseconds) |
|---|---|
| Calibration of TMAS measurement unit at NIST | 4 |
| GPS antenna coordinates error | 3 |
| TMAS equipment delay changes due to environmental factors | 3 |
| Propagation delay changes due to multipath | 2 |
| Propagation delay changes due to ionospheric conditions | 2 |
| Cable delay measurements made at customer's site | 2 |
| Resolution uncertainty of software and instrumentation | 0.05 |

### 8.1.1 Calibration of TMAS measurement unit at NIST

As described in Section 4, the 10-day common-clock calibrations of TMAS units are typically stable to 0.2 ns or less, but the results are not necessarily repeatable at different times of the year. For example, if a common-clock calibration were continuously repeated, the resulting estimate of $D_{Rx}$ would vary by at least several nanoseconds depending upon which 10-day segment was chosen [17]. This is illustrated in Figure 9, which shows the results of a unit that was continuously calibrated at NIST over a 190-day interval spanning from September 2005 to March 2006, producing 181 overlapping 10-day segments. During this interval, the peak-to-peak variation is nearly 4 ns, and a unit could be shipped with a $D_{Rx}$ value from anywhere within this range. Thus we assign a Type B uncertainty of 4 ns to our delay calibrations, with a uniform distribution that should cover all cases.

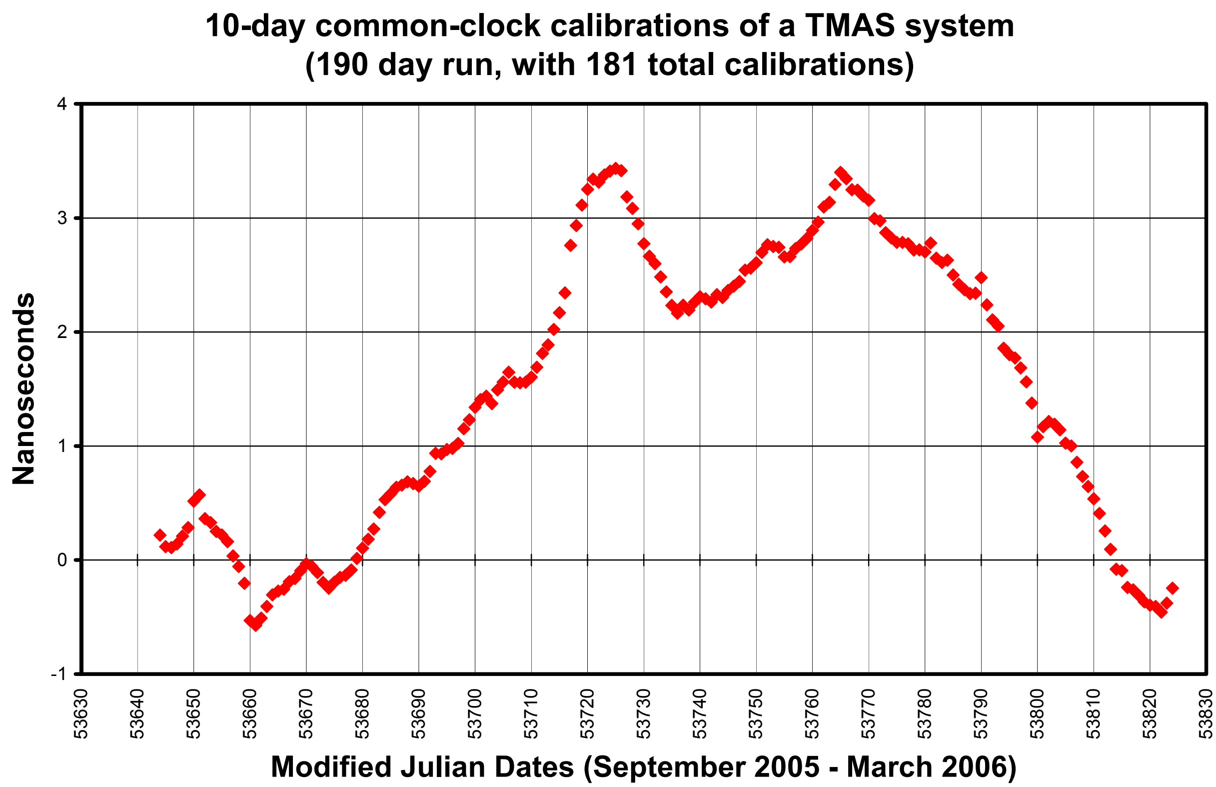



*Figure 9. Results of consecutive 10-day common-clock calibrations made over a 190 day interval.*

### 8.1.2 GPS antenna coordinates error

The customer is required to obtain coordinates for the GPS antenna prior to starting the TMAS measurements. If the customer has a way to independently survey the antenna, the resulting coordinates can be typed in to the TMAS software. If not, the TMAS system can survey the antenna position by averaging position fixes for 24 hours, a method that does an excellent job of determining the antenna's horizontal position (latitude and longitude) to within less than 1 m. However, GPS does a comparatively poor job of surveying vertical position (elevation), and the vertical position error is usually at least several times larger than the horizontal position error. This is because GPS provides earth-centered coordinates and measures the distance between the center of the earth and the satellite. Vertical position is obtained with the radius of a model of the earth's surface. There is nearly always some bias in the estimated vertical position due to local terrain that differs from the model.

We assign a Type B uncertainty of 3 ns to the GPS antenna coordinates, which assumes that the customer survey is within 1 m (the approximate distance that light travels in 3 ns). However, if the TMAS self survey is used, this uncertainly will probably be larger, as large as 3 ns per meter for some satellites, but closer to 2 ns per meter of position error, on average. Figure 10 shows the result of 20 TMAS antenna surveys conducted at NIST in Boulder, Colorado, each lasting for 24 hours. Each survey was done with the same receiver and an antenna that had been independently surveyed to an estimated uncertainty of less than 20 cm. The blue line in the figure shows the total position error in the X, Y, Z coordinates based on the distance from the known coordinates, and the red line shows the error in the vertical position for each of the 20 surveys.

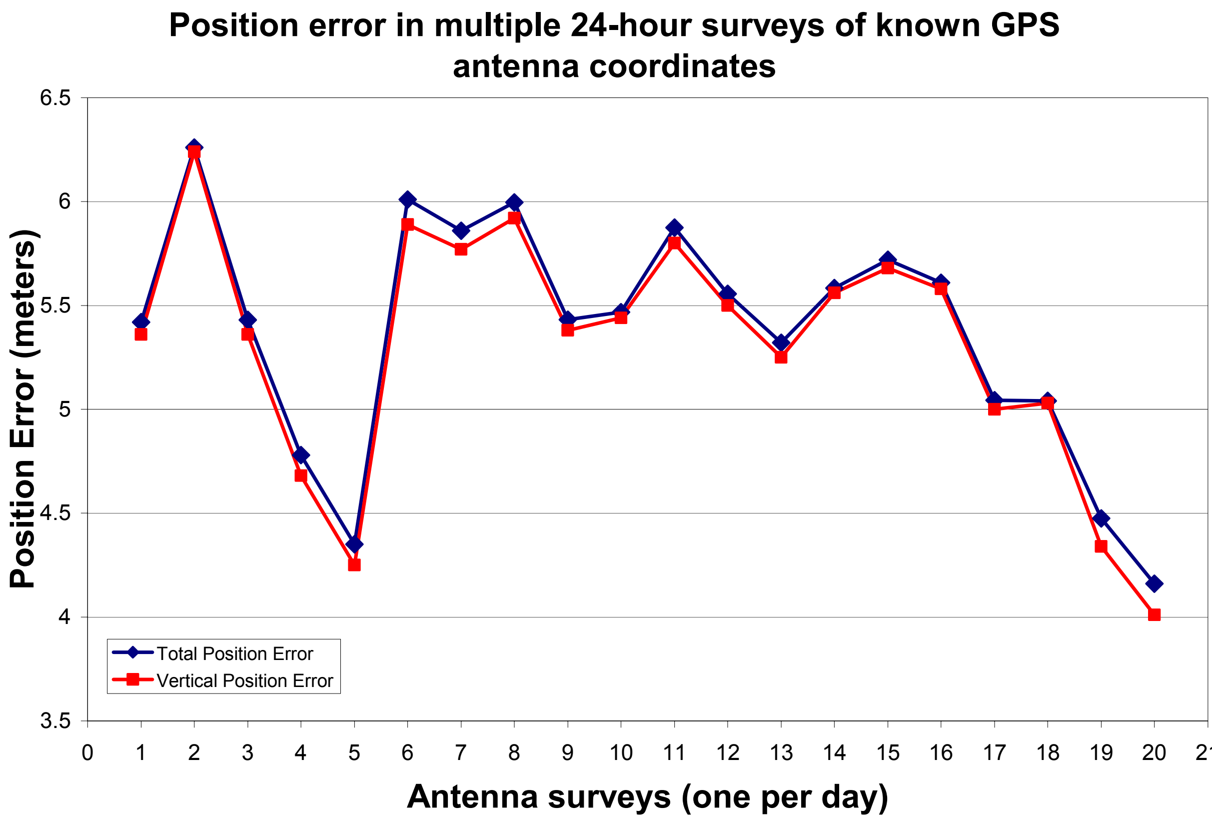



*Figure 10. Position errors (with respect to known coordinates) from 20 TMAS antenna surveys.*

As shown in Figure 10, the average position error was 5.37 m, with nearly all of this error due to error in the vertical position, which was 5.30 m. The estimated vertical positions were biased about 4 to 6 m above the actual elevation, resulting in a Type B uncertainty due to antenna coordinates error that would typically exceed 10 ns, much larger than our 3 ns allowance. This might be an acceptable uncertainty for many customers, but for the best results, TMAS customers should have their antenna elevation independently surveyed to within an uncertainty of 1 m.

### 8.1.3 TMAS equipment delay changes due to environmental factors

Due to environmental factors, particularly due to temperature, GPS receiver, antenna, and antenna cable delays can change over the course of time. As a result, we assign a Type B uncertainty of 3 ns with a uniform distribution to account for receiver/antenna delay changes due to the environment. Equipment delays change for various reasons. The GPS receiver delay is sensitive to temperature changes, but the TMAS tries to minimize this by keeping the receiver inside the rack-mount computer case, where the temperature is typically just a few degrees Celsius higher than the laboratory temperature, with a similar range. However, the receiver delay can still change slowly over time for reasons that are not completely understood. These delay changes might be caused by environmental factors other than temperature, including fluctuations in power supply voltages, vibration, or humidity.

The GPS antenna and part of the cable are outdoors, and are thus subjected to large annual variations in temperature (the peak-to-peak annual temperature variation can exceed 60 °C in Boulder, Colorado). The actual changes in the electrical delay of the cable due to temperature are insignificant, but can still cause the receiver tracking point to change, introducing phase steps in the data [18]. The TMAS attempts to compensate for this by using a high quality antenna cable with a low temperature coefficient.

### 8.1.4 Propagation delay changes due to multipath

Errors due to multipath are caused by GPS signals being reflected from surfaces near the antenna. These reflected signals can then either interfere with, or be mistaken for, the signals that follow a straight line path from the satellite. TMAS customers are instructed to mount their antennas in an area with a clear, unobstructed view of the sky on all sides. If this is possible, the uncertainty due to multipath is usually very small. However, because some errors due to multipath are difficult to detect and avoid, we assign a Type B uncertainty of 2 ns [19].

### 8.1.5 Propagation delay changes due to ionospheric conditions

The GPS signals are line of sight, and the path delay between the satellites and the receiver can be accurately estimated from the distance and the speed of light. However, the signals are bent slightly as they pass through the ionosphere and troposphere, which changes their delay. The delay changes are largest for satellites at low elevation angles. The GPS satellites broadcast a modeled ionospheric delay correction that is automatically applied by the TMAS to the measurements made at both sites. However, ionospheric conditions are not identical at both sites (particularly when it is dark at one site and daylight at the other), and some common-view GPS systems apply ionospheric corrections as measured at each site, instead of using the broadcast corrections [19]. This delays the processing of the measurement results by at least one day, but reduces the measurement uncertainty. Because the TMAS uses modeled ionospheric corrections as opposed to measured corrections, we assign a Type B uncertainty of 2 ns for ionospheric delay with a uniform distribution that should cover all customers in the continental United States.

### 8.1.6 Cable delay measurements made at customer's site

When the TMAS unit is installed, the customer is responsible for measuring the reference delay, or $D_{REF}$, and entering this value into the system software. The reference delay represents the delay from the local time standard to the end of the cable that connects to the TMAS system. This is typically a one-time measurement made by the customer with a time interval counter, with a Type B uncertainty that will normally not exceed 2 ns.

### 8.1.7 Resolution uncertainty of software and instrumentation

The TMAS software limits the resolution of the entered delay values to 0.1 ns, contributing an insignificant resolution uncertainty of 0.05 ns.

### 8.1.8 Combined time uncertainty

The combined Type B uncertainty, $U_b$, is obtained by taking the square root of the sum of the squares of the estimated uncertainties listed in Table 2, and is calculated as 6.8 ns. The combined expanded uncertainty $U_c$ is obtained by this equation, where $k$ is the coverage factor:

$$U_c = k\sqrt{U_a^2 + U_b^2} \; . \tag{3}$$

If we use a coverage factor, $k$, of 2 and a Type A uncertainty of 2 ns, then $U_c$ is equal to 14.1 ns, rounded up to a service specification of 15 ns. In the case of the 2471 km baseline between NIST and NRC, these results have been validated with independent measurements published by the BIPM [15] that fall well within the TMAS coverage area (Figure 8).

## 8.2 Analysis of frequency uncertainty

Frequency uncertainty can be estimated by fitting a least squares linear line to the data to obtain a mean frequency offset, $Y$, and then using $2\sigma_y(\tau)$ [13] as the Type A uncertainty $U_a$ ($k = 2$ coverage). Since there is no significant Type B component for frequency, the combined uncertainty $U_c$ can be considered as the Type A uncertainty. The upper and lower bounds of the coverage area are represented by $Y + U_c$ and $Y - U_c$, respectively. For the 6-month data run shown in Figure 7, the mean frequency offset is $1.9 \times 10^{-14}$, with a $k = 2$ uncertainty of approximately $1.3 \times 10^{-14}$ after one month of averaging. The lower and upper bounds of the coverage area over a one month interval would be $0.6 \times 10^{-14}$ and $3.2 \times 10^{-14}$, respectively, with respect to UTC(NIST). Note that the frequency uncertainty decreases as the averaging time increases. The estimated uncertainty after 1 day of averaging is near $5 \times 10^{-14}$.

## 9. Summary

The NIST Time and Measurement and Analysis service makes the measurement techniques used for international comparisons between the world's best timing laboratories available to any calibration lab or research facility. The TMAS offers a combined standard uncertainty ($k = 2$ coverage factor) of less than 15 nanoseconds for time, and less than $1 \times 10^{-13}$ for frequency after 1 day of averaging. The service is available though NIST as service number 76101S at a cost of $750 per month, with a one-time startup fee of $1500 [1].

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