Time and Frequency Measurements Using the Global Positioning System

Michael A. Lombardi, Lisa M. Nelson, Andrew N. Novick,
Victor S. Zhang
National Institute of Standards and Technology
Time and Frequency Division

This paper describes how Global Positioning System (GPS) satellite signals are used in time and frequency metrology. It discusses how a GPS receiver can provide a reference signal for frequency calibrations and time synchronization. It also explains the several types of time and frequency measurements that utilize GPS signals. These include one-way or direct reception measurements, single and multi-channel common-view measurements, and carrier phase measurements. A discussion of how GPS signals can provide traceability to national and international standards is also provided.

Introduction to GPS

GPS, well known as a versatile, global tool for positioning, has also become the primary system for distributing time and frequency. GPS receivers are fixtures in telecommunication networks, and calibration and testing laboratories. They make it possible to synchronize clocks and calibrate and control oscillators in any facility that can place an antenna outdoors for line-of-sight reception of the GPS satellites.

The GPS satellites are controlled and operated by the United States Department of Defense (USDOD). The constellation includes at least 24 satellites that orbit the earth at a height of 20,200 km in six fixed planes inclined 55° from the equator. The orbital period is 11 h 58 min, which means that a satellite will orbit the earth twice per day. By processing signals received from the satellites, a GPS receiver can determine its position with an uncertainty of < 10 m.

The GPS satellites broadcast on two carrier frequencies: L1 at 1575.42 MHz, and L2 at 1227.6 MHz. Each satellite broadcasts a spread-spectrum waveform, called a pseudo-random noise (PRN) code on L1 and L2, and each satellite is identified by the PRN code it transmits. There are two types of PRN codes. The first type is a coarse acquisition (C/A) code with a chip rate of 1023 chips per millisecond. The second type is a precision (P) code with a chip rate of 10230 chips per millisecond. The C/A code is broadcast on L1, and the P code is broadcast on both L1 and L2. GPS reception is line-of-sight, which means that the antenna must have a clear view of the sky. If a clear sky view is available, the signals can be received nearly anywhere on earth.

Each satellite carries either rubidium or cesium oscillators, or a combination of both. The on-board oscillators provide the reference for both the carrier and code broadcasts. They are steered from USDOD ground stations and are referenced to Coordinated Universal Time (UTC) maintained by the United States Naval Observatory (USNO). By mutual agreement UTC (USNO) and UTC (NIST) are maintained within 100 ns of each other, and the frequency offset between the two time scales is $< 1 \times 10^{-13}$.

GPS Receiving Equipment

There are several types of GPS receivers used in time and frequency metrology. The cost, size, and design of a GPS timing receiver varies significantly from model to model, but most share several common features. Most receivers use the C/A code broadcast on the L1 frequency as their time and frequency reference. Most can simultaneously track from 8 to 12 satellites, and can provide time and frequency signals derived from an average of all satellites in view. Most provide time-of-day and date information in a computer readable format, typically via RS-232 or a similar interface. Most provide a 1 pulse per second (pps) electrical output. The 1 pps output can easily be synchronized to within 100 ns of UTC by entering a delay constant (through the front panel or via a computer interface) that compensates for the antenna, antenna cable and receiver delays. Some receivers have a time-of-day clock displayed on their front panel, and some even include time code outputs that allow them to drive larger time-of-day displays located elsewhere in a facility.

The potential number of time and frequency applications for GPS timing receivers is nearly limitless. Their on-time 1 pps outputs can provide time synchronization at locations anywhere on earth or provide the timing reference for a telecommunications network or an Internet time server. Their time-of-day information can be used to time stamp any type of data collected and stored by a computer.

Another type of GPS receiver provides standard frequencies in addition to providing an on-time pulse and time-of-day information. Known as GPS disciplined oscillators (GPSDO), these devices typically provide outputs at 5 MHz and/or 10 MHz, and sometimes also produce frequencies used in telecommunications, such as 1.544 or 2.048 MHz. They contain a high-quality local oscillator, usually an oven controlled quartz crystal (OCXO) or rubidium oscillator. The local oscillator is continually disciplined or steered to agree with the on-board oscillators on the satellites. The result is a frequency standard that calibrates itself using GPS.

GPSDOs have many applications. For example, they can serve as references for frequency calibrations. They can be used to distribute frequency throughout a facility, or as an external time base oscillator for test equipment such as frequency counters and signal generators. They are also used in telecommunications applications where the use of free running oscillators is impractical. For example, consider an application that requires all nodes in a telecommunications network to maintain frequency within 1×10^{-11} of each other at all times. Due to the frequency drift and aging problem, this requirement is impossible to meet with quartz oscillators, and difficult to meet with rubidium oscillators, since they require periodic adjustment. Cesium oscillators would easily meet the requirement, but their high cost makes it impractical to buy multiple units. It is easy to see that a GPSDO is a good solution to the telecommunications network problem.

Two other types of GPS receivers are used for the more specialized measurements described in this paper. Common-view GPS receivers are actually integrated systems that combine a standard GPS timing receiver with measurement hardware and software. This hardware and software enables the system to make measurements from individual satellites and to store the results so they can be processed later.

Carrier-phase GPS receivers are designed for geodetic and surveying applications. Usually more expensive than traditional time and frequency receivers, they track and measure the L1 or L2 carrier frequencies. Their potential positioning performance is exceptional; the L1 carrier has a wavelength of just 19 cm and the positioning uncertainty is often measured in centimeters or even millimeters. When used for time and frequency measurements, the collected data must be stored so it can be processed later.

The GPS antennas used with most of the receivers described here are small, often < 100 mm in diameter. They typically have built-in amplifiers powered through the antenna cable, and more gain than antennas used for navigation. The use of high-gain antennas makes it possible to use long antenna cables, as long as 100 m in some instances. Unlike GPS receivers used for navigation, time and frequency receivers are located indoors in a room or laboratory and a long antenna cable is often necessary.

GPS Measurement Techniques

As implied by the different types of receivers described in the last section, there are several different types of GPS measurements used in time and frequency metrology. These measurements can be divided into three general categories: one-way, common-view, and carrier-phase. The majority of GPS measurements made in calibration and testing laboratories are one-way measurements. One-way measurements are easy to make and their uncertainties are small enough to meet the requirements of nearly any calibration or testing laboratory. Common-view and carrier-phase measurements require more effort, including post-processing of the measurement data. For this reason, they are usually reserved for international comparisons between metrology laboratories when the measurement uncertainties must be as small as possible. Table 1 compares the GPS measurement techniques.

Table 1. Typical Uncertainties of GPS Measurement Techniques.

Technique	Timing Uncertainty 24 h, 2σ	Frequency Uncertainty 24 h, 2σ
One-Way	< 20 ns	$< 2 \times 10^{-13}$
Single-Channel Common-View	≈10 ns	$\approx 1 \times 10^{-13}$
Multi-Channel Common-View	< 5 ns	$< 5 \times 10^{-14}$
Carrier-Phase Common-view	< 500 ps	$< 5 \times 10^{-15}$

One-Way GPS Measurements

The one-way GPS technique uses the signals obtained from a GPS receiver as the reference for a calibration. The GPS signals are used in real time, and no post processing of the measurement results is required. The purpose of the measurement is usually either to synchronize an on-time pulse, or to calibrate a frequency source.

Before a receiver is used for measurements, it must complete its signal acquisition process. Part of the acquisition process involves surveying the antenna position. Unlike GPS navigation receivers, which compute position fixes while moving (often at a rate faster than one position fix per second), GPS time and frequency receivers normally do not move at all and do not need to compute position fixes once the survey is completed.

Therefore, time and frequency receivers generally store a single position fix, and use that same position from then on. Many receivers automatically start a survey when they are turned on. When the process is finished, a front panel indicator tells the operator that the receiver is ready to use.

Once the signal acquisition is completed, an output signal from the receiver is connected to a measurement system. For time synchronization measurements, a 1 pps signal from the receiver is generally used as an input to a time interval counter. For frequency measurements, a frequency output (10 MHz, for example) from a GPSDO is used as an input to a phase comparator, or used as the external time base for a frequency counter.

One-Way Performance

Since the GPS satellites transmit signals that are steered to agree with UTC, the long-term accuracy of a GPS receiver has always been excellent. The performance of C/A code receivers became even better on May 2, 2000 (MJD 51666) when the USDOD set selective availability (SA) to zero. SA is a USDOD directive that can be used to intentionally introduce noise on the GPS signal to reduce its positioning and timing accuracy. Figure 1 is a phase plot showing data from a typical GPS receiver, recorded in the days immediately before and after SA was set to zero.

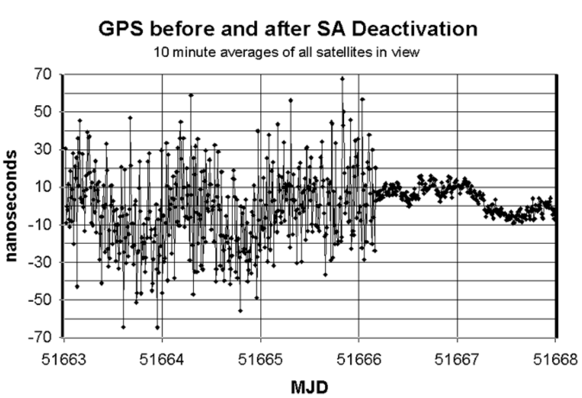

Figure 1. Phase plot showing GPS performance before and after SA was set to zero.

The data points shown in Figure 1 are 10-minute averages of the received signal obtained by comparing the 1 pps output from a typical GPS timing receiver to UTC (NIST) using a time interval counter. Figure 2 shows the received phase for the 15-day period immediately following May 2, 2000. During this period, the peak-to-peak variation in the received phase data was < 50 ns.

The phase plot shows that the GPS broadcasts are tightly controlled, since the amplitude of the phase measurement is similar from day to day. This leads to excellent accuracy and stability when an averaging period of 1 day or longer is used. However, phase noise on the signal limits the short-term stability, as shown in the Allan deviation ($\sigma_y(\tau)$) plot (Figure 3).

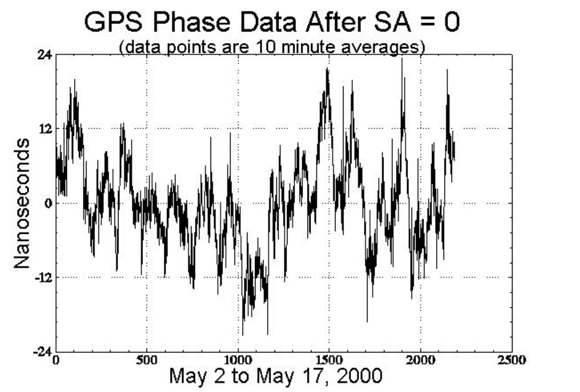

Figure 2. GPS Receiver versus UTC (NIST) during 15-day interval after SA was set to 0.

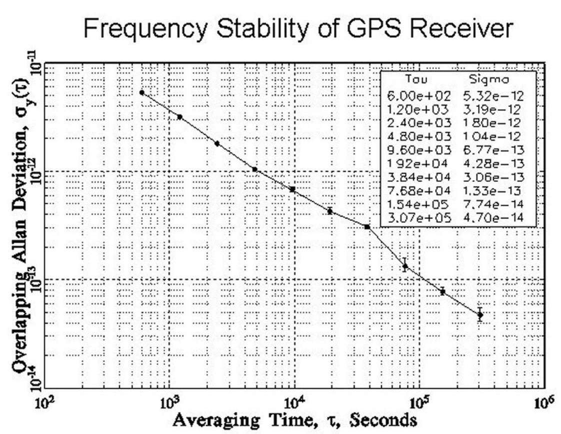

Figure 3. Frequency stability (Allan deviation) of GPS receiver after SA was set to 0.

Figure 3 shows that the stability of the receiver is near 1×10^{-13} at 1 day, and the phase noise continues to average down until stabilities reach parts in 10^{14}. Although not shown in Figure 3, the phase noise limits the short-term stability of this receiver to parts in 10^{9} at 1 s. If you elect to distribute frequency obtained from a GPSDO, or use it as reference for a measurement system, make sure that its short-term stability meets your requirements. While GPSDOs can calibrate nearly any frequency standard over a measurement period of 1 day or longer, they are usually not suitable for measuring oscillator stability at averaging periods of < 1000 s.

Establishing Traceability with One-Way GPS

The definition of traceability tells us that a traceable measurement requires an "unbroken chain of comparisons all having stated uncertainties." This chain usually originates with international and/or national standards. [1] In order to show traceability to NIST through GPS, the unbroken chain must extend from the GPS measurement back to NIST.

We provide two examples (Tables 2 and 3) of how to document a traceability chain. Both chains show traceability back to UTC (NIST), and back to the International System of units (SI) maintained by the Bureau International des Poids et Mesures (BIPM). Keep in mind that every link of a traceability chain involves a comparison between a reference and a device or signal under test.

Table 2. A sample traceability chain established through GPS measurements (Model A).

Link	Reference	Compared To:
A	SI units	UTC (NIST)
B	UTC (NIST)	UTC (USNO)
C	UTC (USNO)	GPS Signals
D	GPS Broadcast Signals	GPS Received Signals
E	GPS Received Signals	Users Device Under Test

The uncertainties of links A, B, and C are very small, and of little or no consequence for most measurements. However, they must be documented when establishing the traceability chain. The uncertainty of links A and B can be computed from the BIPM's Circular-T, which is published bimonthly and is available at:

www.bipm.fr/enus/5_Scientific/c_time/time.html

An alternate site for establishing Link B can be found on NIST's Time and Frequency Division's web site:

www.boulder.nist.gov/timefreq/pubs/bulletin/nistusno.htm

Link C can be established from data published by the USNO at:

tycho.usno.navy.mil/gps_datafiles.html

The uncertainty of Link D is receiver dependent. Not all GPS receivers are created equal, and some models introduce more uncertainty than others. Two factors that contribute to receiver performance are the quality of the receiver's local oscillator and the quality of the software algorithms that process data acquired from the satellites.

Establishing the uncertainty of Link D requires stating a specification that the receiver will meet or exceed when properly operated. The manufacturer's specification is a good starting point. However, if your requirements are high, it is usually possible to have NIST or another national laboratory evaluate a particular GPS receiver for a predetermined fee. Once a specification is stated, a set of criteria required to meet the specification should be established. For example, these criteria might include checks that determine if the receiver is locked to the satellites, if the receiver is in static position mode, and if the antenna position is known within 10 meters or less. Measurements should be made only if all indications show that the receiver is operating properly.

The uncertainty of Link E is the uncertainty of the calibration procedure. Any part of the measurement process can contribute uncertainty to Link E, including improperly operated receiving instruments and antenna systems, software errors, instrumentation errors, calibration procedure errors, and human error.

A second, slightly simpler traceability chain involves a direct comparison of GPS to the NIST frequency standard. This model is shown in Table 3.

Table 3. A sample traceability chain established through GPS measurements (Model B).

Link	Reference	Compared To:
A	SI units	UTC (NIST)
B	UTC (NIST)	GPS Broadcast Signals
C	GPS Broadcast Signals	GPS Received Signals
D	GPS Received Signals	Users Device Under Test

This chain has one less link than the earlier example. Link A in this example is equivalent to the Link A shown in Table 2, and Links C and D are equivalent to Links D and E in the previous example. Link B, however, is established by continuous NIST comparisons with every GPS satellite. The signal broadcast from each satellite is monitored for the entire time that the satellite is visible from the NIST laboratories in Boulder, Colorado. The results of these comparisons are published (updated daily) in the NIST GPS data archive at:

www.boulder.nist.gov/timefreq/service/gpstrace.htm

The archive lists daily time and frequency offsets for each GPS satellite. Data for the previous UTC day are made available at about 1600 UTC. The archived data are obtained by comparing a "typical" GPS receiver to the NIST frequency standard. [2, 3]

Common-View GPS Measurements

The common-view method is a simple but elegant way to compare two clocks or oscillators located in different places. Unlike one-way measurements that compare a clock or oscillator to GPS, a common-view measurement compares two clocks or oscillators to each other.

Figure 4 shows how the common-view technique works. A GPS satellite (S) serves as a single reference transmitter. The two clocks or oscillators being compared (A and B) are measured against two GPS receivers. The satellite is in common view of both receivers, and its signals are simultaneously received by both. Each receiver compares the received signal to its local clock and records the data. Receiver A receives the signal over the path τ_{SA} and compares the reference to the local clock (S - Clock A). Receiver B receives the signal over the path τ_{SB} and records (S - Clock B). The two receivers then exchange and difference the data.

Common-view directly compares two time and frequency standards. Errors from the two paths (τ_{SA} and τ_{SB}) that are common to the reference cancel out, including the performance of the satellite clock. The final measurement result is (Clock A - Clock B) - (τ_{SA} - τ_{SB}).

The common-view technique has long been used for international comparisons of time and frequency standards. The international time scales — International Atomic Time (TAI) and Coordinated Universal Time (UTC) — are created by averaging data collected from more than 200 atomic clocks located in about 50 laboratories. Most of these data are collected using common-view GPS measurements. Once the data are sent to the BIPM, the TAI and UTC time scales are computed using a weighted average of all the oscillators. The stability of TAI and UTC is currently about 1 part in 10^{15} over a period of a few weeks.

The two types of GPS common-view measurements: single-channel and multi-channel, are discussed in the following sections. The BIPM conventions for recording data are also discussed. However, it is not necessary to use the BIPM format to make common-view measurements. Any data format can be used if all participants in a common-view comparison record and process their data in the same way. [5, 6, 7, 8]

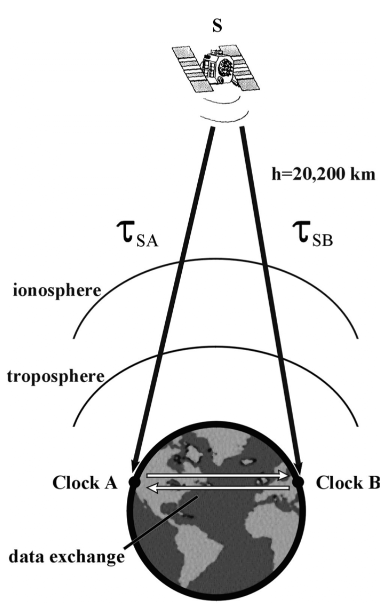

Figure 4. The common-view measurement technique.

Single-Channel Common-View

Single-channel common-view requires a GPS receiver that can read a tracking schedule. This schedule tells the receiver when to start making measurements and which satellite to track. A receiver at another location makes measurements from the same satellite at the same time. The data collected at both sites are then exchanged and compared. Single-channel common-view GPS receivers were first developed at NIST (then the National Bureau of Standards) in 1980. [4] Several companies soon developed similar products based on the NBS/NIST design. Only a few GPS satellites were in orbit during the early 1980's, and early receivers could track only one satellite at a time. Even though today's receivers can simultaneously track multiple satellites, the single-channel technique is still widely used for international comparisons.

The BIPM publishes a tracking schedule for single-channel common-view every 6 months. The schedule calls for data to be recorded in 13-minute tracks. The 13-minute track length resulted from the GPS navigation message's transmission speed. It takes 12.5 minutes for a satellite to send a complete almanac message. Collecting data for more than 12.5 minutes ensured that all common-view participants had the same data. The schedule limits the maximum number of 13-minute tracks to 48 per day, although in practice the number of tracks recorded might be smaller. [4, 5]

Multi-Channel Common-View

Multi-channel common-view does not use a schedule. The receiver simply records data from all satellites in view. Although there is more data to process, the multi-channel technique has some obvious advantages. For example, the limited number of tracks makes it impossible for two single-channel users to continuously compare their standards; there will always be gaps in their measurement data. However, if two multi-channel users are located within a reasonable distance of each other (on the same continent, for example), there should always be at least 1 satellite in common-view between them. Therefore, it is often possible for multi-channel users to continuously compare standards with no gaps in their measurement data.

Multi-channel common-view data is also accepted by the BIPM for contribution to TAI. The multi-channel receivers collect data from all satellites in view. Even though no tracking schedule is necessary, the BIPM multi-channel format still calls for data to be stored in 13 minute tracks. This makes it possible to extract the single-channel tracks from a multi-channel data file, and maintains compatibility with the older single-channel receivers. Data is collected every 16 minutes at the predetermined times referenced to October 1, 1997 (a date chosen by consensus), and are displaced each day by 4 minutes to follow the GPS sidereal orbits. The 16 minute period was convenient because it is the closest multiple of 4 minutes that exceeds the original 13 minute track. It allows 2 minutes for receivers to lock onto satellites, 13 minutes of regular tracking, and 1 minute of separation between tracks.

Obviously, multi-channel receivers collect more data than single-channel receivers. In theory, as many as 12 GPS satellites can be observed simultaneously, but typically only 5 or 6 are above a 15° elevation angle and useful for time and frequency transfer. If data from 5 satellites is collected in each of the available 16 minute segments, about 450 tracks can be recorded in one day using the BIPM format, or about 10 times the number of tracks recorded with the single-channel method. [5, 6, 7]

Common-View Measurements in Near Real-Time

One disadvantage of the common-view technique is that the measurement results are not known until after the data is exchanged and processed. In some cases, results might not be known for days or weeks. By combining the common-view technique with the Internet, however, it is possible to build a common-view network that processes data in near real-time.

To illustrate this, a prototype system built at NIST uses a multi-channel common-view receiver integrated with a personal computer connected to the Internet. A similar system could be sent to a customer's location and connected to their frequency standard. Each customer would be given a log-in account on a central web server. The receiver collects 10-minute averages from all GPS satellites in view and uploads data using the File Transfer Protocol (FTP) to the central web server. The web server simultaneously receives common-view measurements made at the NIST laboratories using UTC (NIST) as the reference. Software on the web server automatically processes each customer's data when requested. At any time, any customer could see the current uncertainty of their frequency standard relative to UTC (NIST) by accessing their account using a standard web browser.

This type of system can send data to the web server as soon as a measurement sample is collected. For example, if 10 minute averages are used, data can be sent to the web server every 10 minutes. If a customer ran their system continuously, they would know the uncertainty of their frequency standard relative to UTC (NIST) around the clock, with data that is never more than 10 minutes old.

Common-View Performance

Common-view comparisons produce the best results when the distance between the two receiving sites, called the baseline, is relatively short (a few thousand kilometers or less). A short baseline means that the satellite is visible to both sites at about the same elevation angle, and that the receiving conditions tend to be similar at both locations. If the sites are separated by a long baseline, receiving conditions tend to be different at each site, and fewer errors cancel out when the data are subtracted. In some cases, there might be little or no cancellation of errors, and measurement uncertainties will be equivalent to those obtained using the one-way technique. To get the best results, it is also desirable to use identical receiving equipment and antennas at both sites, and to survey the antenna positions as accurately as possible.

When used between two stations in the continental United States, the timing uncertainty (2σ) of the single-channel common-view technique should be < 10 ns at one day, and the frequency uncertainty should be ~1 x 10^{-13}. The Allan deviation ($\sigma_y(\tau)$) plot in Figure 5 shows the results of a single-channel comparison between NIST and the USNO over a baseline of 2405 km. The stability of the common-view link is about 1 x 10^{-13} at 1 day, and near 1 x 10^{-14} at one week. The multi-channel common-view technique should improve the 1-day results by about a factor of 2.

As discussed, the common-view technique completely removes measurement errors that are common to both receiver locations. However, errors not common to each location are only partially cancelled out and limit the measurement uncertainty. These limiting factors include ephemeris errors, ionospheric and tropospheric delay correction errors, receiver coordinate errors, multi-path variations in the received satellite signals, variations in receiver delays, and variations in antenna-cable delays due to multi-path reflections and temperature changes. [5, 6, 8]

Establishing Traceability with Common-View GPS

As shown, the measurement uncertainty of the common-view technique might be only slightly better than the one-way technique now that SA is set to zero. However, since a common-view comparison with NIST directly compares the device under test to the national standard, the traceability chain to NIST has just one link. Therefore, NIST and other laboratories use variations of the common-view technique to calibrate devices at remote locations. Remote calibration services can calibrate any time and frequency standard on-site, sparing the customer

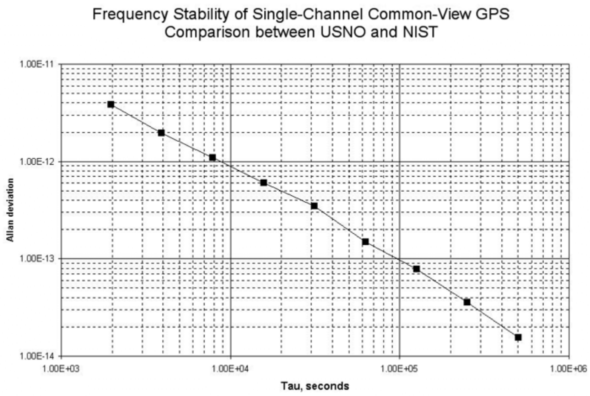

Figure 5. Frequency stability (Allan deviation) of single-channel common-view comparison between USNO and NIST.

the expense, labor, and lost time associated with shipping the device to the NIST laboratories.

NIST offers two GPS-based calibration services that provide a one-link traceability chain to the national standard. The NIST Global Time Service (service ID number 76110S) is intended primarily for time synchronization to UTC (NIST). The NIST Frequency Measurement Service (service ID Number 76100S) provides on-site frequency calibrations of up to 5 oscillators at once. For more information, see this link:

www.boulder.nist.gov/timefreq/service/fms.htm

Carrier Phase GPS Measurements

Primarily used for frequency transfer, this technique uses both the L1 and L2 carrier frequencies instead of the codes transmitted by the satellites. It is important to note that carrier phase measurements can be one-way measurements made in real-time or post-processed common-view measurements. Since the carrier frequency is more than 1000 times higher than the C/A code frequency, the potential resolution is much higher. However, taking advantage of the increased resolution requires making corrections to the measurements using orbital data and models of the ionosphere and troposphere. It also requires correcting for cycle slips that introduce phase shifts equal to multiples of the carrier period (635 ps in the case of L1).

Since the carrier-phase GPS technique requires extensive post-processing of the collected data, it is not practical to use for everyday measurements. However, the technique is used for international comparisons between primary frequency standards when the goal is to reduce the measurement uncertainty as much as possible.

International comparisons are usually made using the common-view carrier-phase technique. A dual frequency, geodetic quality GPS receiver is required at each laboratory involved in the comparison. The signals obtained from this receiver are compared to signals obtained from the local primary frequency standard. Before the measurement results are exchanged with another laboratory, they are translated from their native format to a standardized format called RINEX (Receiver Independent Exchange) format).

Ideally, the comparison requires only one receiver at each location. However, because of large differences in atmospheric delay between stations separated by a long baseline, a network of receivers is used to improve the measurement results. Each receiver collects data that is used to help estimate atmospheric delay differences and to help solve the cycle ambiguity problem. Comparisons made between NIST and Physikalisch Technischen Bundesanstalt (PTB) in Braunschweig, Germany currently use a network of 6 receivers. One receiver is located at each laboratory, one is located near each laboratory, and two are located in the middle of the baseline between the laboratories. Some carrier-phase networks are more extensive, and might include as many as 100 receivers.

The collected data are analyzed and processed using precise satellite orbit information and detailed models of the ionosphere and troposphere. The precise orbit information and other calculated parameters are made available from the International GPS Service for Geodynamics (IGS). Software analysis packages compatible with the RINEX format are available to help simplify the data processing.

The basic carrier-phase equation (Equation 1) shows the parameters that must be determined in the analysis. The analysis software makes it possible to make a good estimate of most parameters. Generally, the number of cycle slips and the atmospheric delays are the most difficult parameters to determine.

$$\lambda\phi_R^S = \rho_g + c\delta^S - c\delta_R + \rho_{trop} - \rho_{ion} + \rho_{mult} + \varepsilon_{cp} + N_R^S\lambda \quad (1)$$

where,

λ = carrier wavelength, *c/f*,
ϕ_R^S = carrier phase observable for satellite S and receiver R,
ρ_g = geometric range, $\sqrt{((X^S-X_R)^2+(Y^S-Y_R)^2+(Z^S-Z_R)^2}$,
δ^S = satellite clock error
δ_R = receiver clock error
ρ_{trop} = propagation delay due to troposphere,
ρ_{ion} = propagation delay due to ionosphere,
ρ_{mult} = multipath error,
ε_{cp} = unmodelled errors and receiver noise,
$N_R^S\lambda$ = carrier phase ambiguity or bias.

Measurements made between the primary frequency standards of NIST and PTB have shown that the uncertainty of the measurement technique after one day of averaging is smaller than the combined uncertainty of the two primary standards. To illustrate this, Figure 6 is a phase plot showing a peak-to-peak difference of about 70 ns over a 30 day interval. This represents a frequency

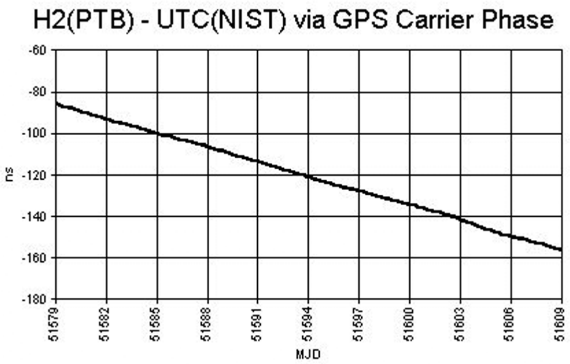

Figure 6. Comparison between PTB and NIST Frequency Standards using the GPS Carrier-Phase technique.

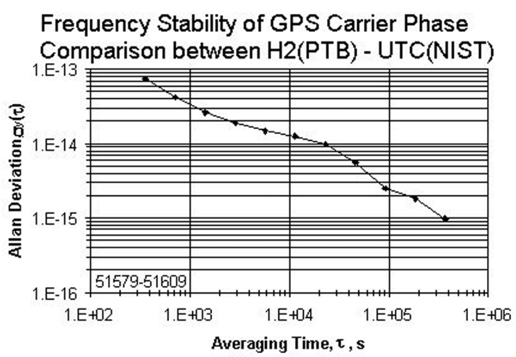

Figure 7. Frequency stability of carrier-phase comparison between PTB and NIST frequency standards.

offset between the two standards of about 2×10^{-14}. Figure 7 shows that the uncertainty of the measurement (estimated with the Allan deviation, ($\sigma_y(\tau)$) is about 2×10^{-15} at one day.

Research at NIST suggests that the measurement uncertainty can be made even smaller by reducing the measurement noise at each reference station, by improving cycle slip detection, and by using improved models of the ionosphere and troposphere. [9, 10, 11]

Summary and Conclusions

GPS has become the primary system for distributing time and frequency. The signals are available nearly anywhere on earth, and provide a convenient link for establishing traceability to national and international standards. The several types of GPS measurements provide enough versatility to meet the requirements of telecommunication networks, calibration and testing laboratories, and national measurement laboratories involved in the computation of TAI and UTC. Measurement uncertainties range from parts in 10^{13} to parts in 10^{15} (2σ, 1 day average), depending upon the technique used.

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Michael A. Lombardi, Lisa M. Nelson, Andrew N. Novick, Victor S. Zhang. National Institute of Standards and Technology, Time and Frequency Division, 325 Broadway Boulder, CO 80305. Contact: Michael Lombardi, tel 303-497-3212, lombardi@boulder.nist.gov.

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