Traceability in Time and Frequency Metrology

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Abstract

This paper discusses the techniques and reference signals used to establish traceability to national and international standards when making time and frequency measurements. It explains how traceable time and frequency information is distributed by NIST and other national metrology institutes through radio, telephone, and Internet signals. It also describes how signals broadcast by the Global Positioning System (GPS) satellites can serve as a traceable time and frequency reference that is available worldwide.

1. Introduction

Traceability is a desired characteristic of every measurement. Traceability is defined as:

> *The property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. [1]*

Metrologists are required to complete the traceability chain by stating the uncertainty of their measurements with respect to a National Metrology Institute (NMI). The NMI is required to show traceability to the International System (SI) of units maintained by the Bureau International des Poids et Mesures (BIPM). Traceability is often a legal or contractual requirement, and its importance to quality control systems cannot be overstated. The International Organization for Standardization (ISO) Guide 25 lists the requirements for competence of calibration and testing laboratories. Section 9.2 of Guide 25 states:

> *The overall programme of calibration and/or verification and validation of equipment shall be designed and operated so as to ensure that, wherever applicable, measurements made by the laboratory are traceable to national standards of measurement, where available. Calibration certificates shall wherever applicable indicate the traceability to national standards of measurement and shall provide the measurement results and associated uncertainty of measurement and/or a statement of compliance with an identified metrological specification. [2]*

A pyramid (Figure 1) is often used to illustrate traceability. The pyramid's apex shows us that the traceability chain begins with the SI units maintained by the BIPM. The base unit for time and frequency metrology is the second (s). The second is one of seven base SI units and is defined as the duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the cesium atom. Frequency (expressed in hertz) is one of nineteen derived SI units, and is obtained by counting events over a 1 s interval. The pyramid extends to national standards maintained by the NMI, to regional standards, to working standards, and ultimately to measurements made by end users.

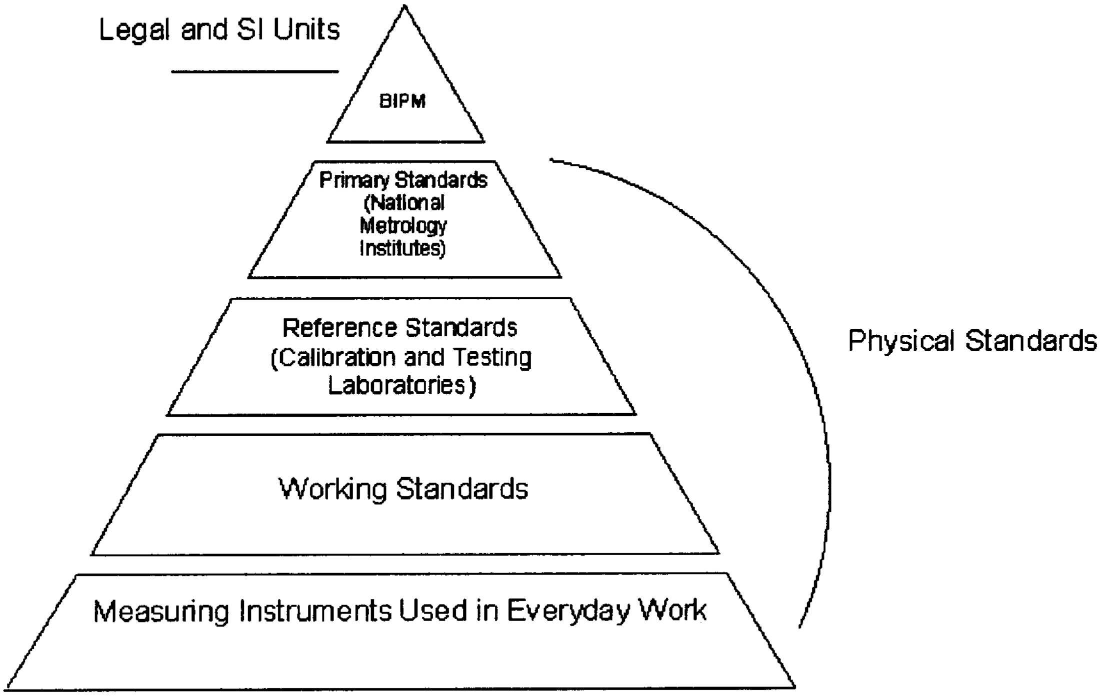


Figure 1 – The traceability pyramid

In some fields of metrology, traceability is established only at periodic intervals, since it involves shipping standards and devices from one location to another. However, time and frequency metrology offers many convenient ways to establish continuous, real time traceability to a NMI. Direct links to a NMI are available in the form of Coordinated Universal Time (UTC) signals broadcast over a radio, telephone, or network path.

2. The Coordinated Universal Time Scale (UTC)

The international standard for time and frequency metrology is the UTC time scale maintained by the BIPM in Paris, France. The task of the BIPM is to ensure international uniformity of measurements and traceability to the International System of Units (SI). It does this with the authority of the Convention du Metre, a diplomatic treaty between forty-eight nations that has been in existence since 1875. It operates through a series of Consultative Committees, whose members are the NMIs of the Member States of the Convention, and through its own laboratory work.

The BIPM maintains a time scale known as International Atomic Time (TAI) by including data from over 200 atomic oscillators located at about 50 NMIs. Most of the oscillators are cesium based, but some hydrogen masers also contribute to the calculation of TAI. Each contributing oscillator is assigned a weighting factor, with the best oscillators given the most weight in the calculation. However, no oscillator is currently given a weight of more than 0.7%. Data from each contributing oscillator is submitted to the BIPM through common-view observations of GPS satellites. The scale unit of TAI is kept as close as possible to the SI second.

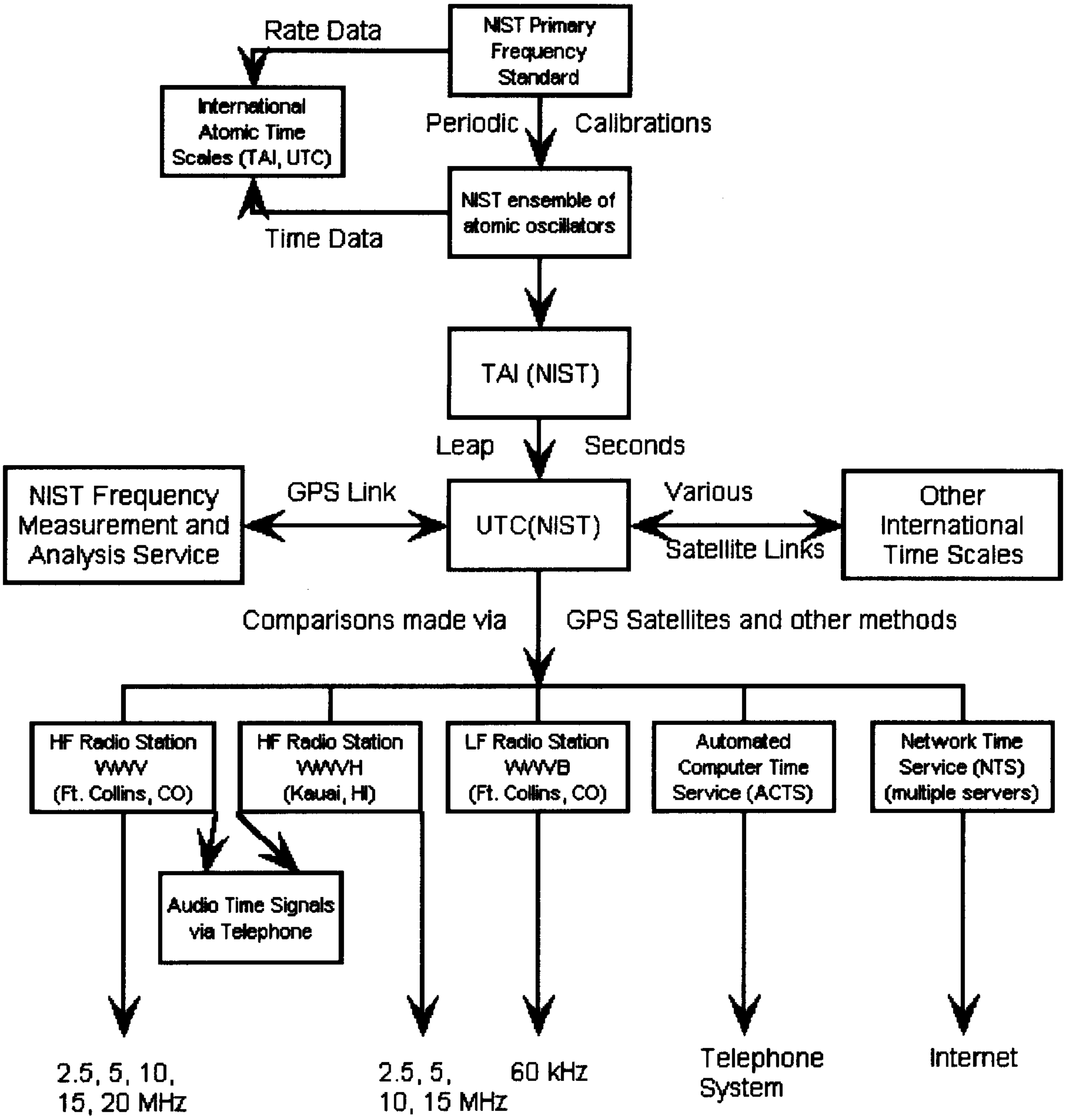


Figure 2 – The Distribution of UTC(NIST)

Since TAI is an atomic time scale it does not keep in step with the irregular rotation of the Earth and is fast with respect to the astronomical time scale (UT1) by about 3×10^{-8} per year. The UTC time scale is identical to TAI except that for practical reasons leap seconds are added to UTC when necessary to keep it within 0.9 s of UT1. [3,4]

UTC is a "paper" time scale, and it is computed by the BIPM at least several weeks after the fact. The time signals received by end users are referenced to real time versions of UTC that are maintained and distributed by the NMIs, such as UTC(NIST) in the United States. The real time versions of UTC are often equivalent or nearly equivalent to the paper version. Nearly all of the NMIs that send data to the BIPM keep time within 1 µs of UTC, and some are offset by <100 ns.

The BIPM publishes the current time offset between UTC and the version of UTC maintained by each contributing NMI in its monthly Circular T publication, which is available on the Internet at:

ftp://193.104.126.5/pub/tai/publication/

3. Establishing Traceability to a NMI

Typically, metrologists are required to make measurements traceable to a NMI located in their country. The reference for these measurements is a signal that is directly referenced or regularly compared to a real time version of UTC maintained by a NMI. If international traceability is required, the measurement must be traceable to a NMI that in turn is traceable to the BIPM.

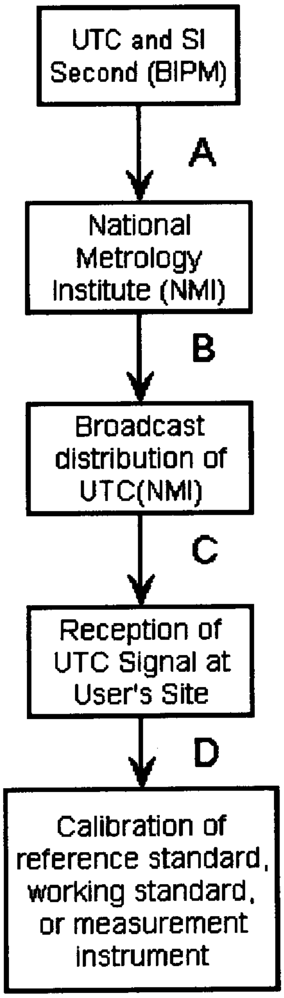


Figure 3 – The Traceability Chain for Signals Controlled by a NMI

As a service to end users, many NMIs distribute signals referenced to their UTC time scale. [5] These services allow the end user to directly link to a NMI and complete the traceability chain. Figure 2 shows how NIST distributes UTC(NIST) to its end users through a wide variety of time and frequency services.

When using a broadcast service controlled by a NMI, metrologists use the chain shown in Figure 3 to establish traceability. Link A connects the BIPM to the NMI. The uncertainty of link A can be obtained (after the fact) from the BIPM's Circular T. Link B is the control link between the NMI and the broadcast service. The uncertainty of link B can be obtained from the NMI. Some broadcast services are directly connected to the UTC time scale maintained by the NMI; others are located at remote locations and referenced to frequency standards that are regularly compared to UTC. Link C connects the broadcast service to the user. This uncertainty is due to the signal path between the NMI and the user. Typically, signals that travel over a low frequency (LF) radio or satellite path have smaller uncertainties than signals that travel over a high frequency (HF) radio path, or a telephone or Internet path. Link D is the link between the broadcast signal and the user's reference standard, working standard or measurement instrument. For example, the broadcast service may be used to calibrate a reference standard. The reference standard is now traceable to the NMI and is used for the calibration of working standards and measurement instruments. By definition, traceability is the result of a measurement. Therefore, everything that contributes to the measurement process can contribute uncertainty to link D, including receiving instruments, antenna systems, software, test equipment, calibration procedures, and human error. [6]

Obviously, the uncertainty of links C and D is much larger than the uncertainty of links A and B. For most measurements, the uncertainty of links A and B is indiscernible and can be ignored.

Traceability can also be established through signals not controlled by a NMI, provided that the NMI monitors and compares the signals to its UTC time scale. This traceability chain is shown in Figure 4. It is nearly identical to the chain shown in Figure 3, except that link B is not a control link, but a monitoring link. To keep the traceability chain intact, monitoring should be done continuously, without interruption. [6] This type of traceability chain can establish traceability through radio navigation systems like LORAN-C or GPS, and is discussed in more detail in the section on GPS traceability.

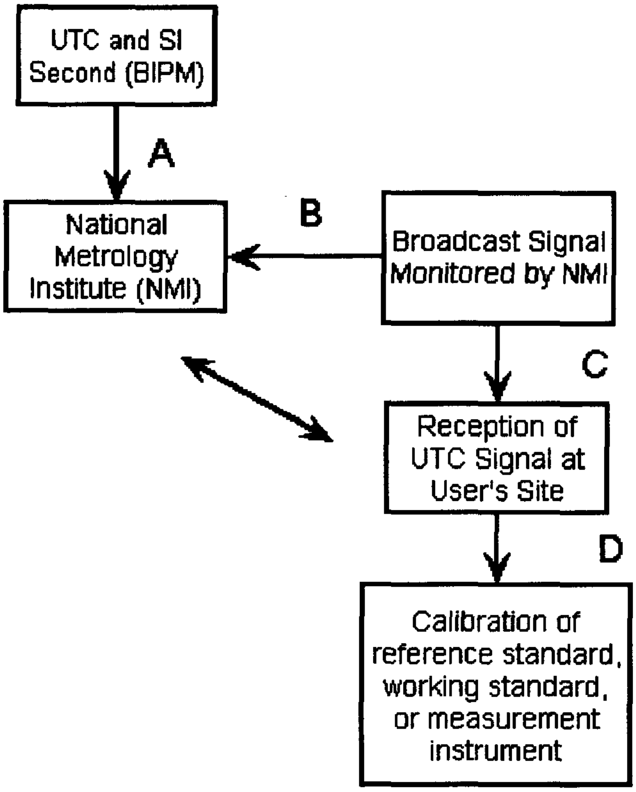


Figure 4 – The Traceability Chain for Signals Monitored by a NMI

Once traceability to a NMI is established, it might be accepted in other countries as well. A number of metrology cooperations and mutual recognition agreements between NMIs now exist. The purpose of these agreements is to support international trade. One example is the North American Metrology Cooperation (NORAMET) whose member countries are Canada, Mexico, and the United States. If a mutual recognition agreement exists, traceability to one NMI can be accepted as equivalent to traceability to another, although perhaps with a different uncertainty. [7]

4. Applications requiring Time and Frequency Traceability

Traceability to time and frequency standards is required for the calibration and testing of devices ranging from simple mechanical timers to state-of-the-art atomic oscillators. The following sections provide examples of applications. Table 1 is a summary of applications that lists the signal commonly used to link to a NMI to establish traceability, and the measurement uncertainty that is typically required.

4.1 Traceability Requirements for Measurements Made in Other Fields of Metrology

Since the second is one of the seven base SI units, it contributes to the derivation and measurement of other units. The meter and volt are two examples of units whose measurement requires frequency traceable to a NMI. However, since frequency is far from being the limiting factor in either measurement, the required frequency uncertainty is fairly modest, even for state-of-the-art results. For example, precision length measurements, with uncertainties of about 10^{-10}, require a frequency standard with an uncertainty of about 10^{-11}. [8] Voltage measurements based on the Josephson array intrinsic standard now have reached uncertainties as small as parts in 10^9 and require a frequency standard with an uncertainty of about 10^{-10}. [9] Other measurements have more modest frequency uncertainty requirements. One common example is the unit for angular frequency, the radian per second, which is required in ac electrical measurements. A frequency of 1592 Hz (± 1 Hz) is regarded as being sufficiently close to the desired angular frequency of 10^4 rad/s. The 1 Hz tolerance means that the required frequency uncertainty of the 1592 Hz source is just 6×10^{-4}. [10]

4.2 Traceability for Low Accuracy Measurements

Traceability is often legally required for low accuracy measurements where the acceptable uncertainties may be as large as parts per hundred. For example, the mechanical and electronic timers found in parking meters, coin-operated laundries, car washes, taxicab meters, and other devices where customers pay for "time" require traceability, but the acceptable uncertainty may be 5% or higher. [11] These devices are calibrated with field standard stopwatches or interval timers with an acceptable uncertainty of about 2×10^{-4}. [12] Law enforcement agencies use tuning forks to calibrate radar equipment used to measure vehicle speed. Maintaining traceability within 1×10^{-3} is adequate for measuring speed within 0.1 km/h. [13,14]

Traceability is also required in the radio and television broadcast industries. Commercial broadcast stations need to calibrate their transmission frequency to comply with federal regulations and to avoid interfering with other stations. The United States Federal Communications Commission (FCC) requires AM broadcast stations to stay within 20 Hz of their assigned frequency. FM broadcast stations are required to stay within 2000 Hz. In both cases, the required uncertainty equals parts in 10^5. [15]

The reference for these low accuracy measurements is often an audio time announcement distributed by either HF radio signals or by telephone. NIST operates two HF broadcast stations (WWV in Colorado and WWVH in Hawaii) [5, 16] and similar stations are operated by NMIs in other countries. [17] The audio time announcements broadcast by HF stations provide a convenient reference for calibrating stopwatches and interval timers. By far the largest cause of uncertainty in these measurements is human reaction time when starting and stopping the device under test. [13,14] The HF carrier may also be used as a measurement reference. Since the carrier is usually a standard frequency (like 5 or 10 MHz), it can provide traceability with an uncertainty of $\sim 1 \times 10^{-6}$ when calibrations are made using a beat frequency method or with an oscilloscope. [17]

One of the largest groups requiring traceability consists of users who synchronize computer and network clocks. NIST offers services that allow users to synchronize computer clocks over a telephone [18] or Internet [19] connection, and similar services are offered by a number of NMIs. With properly designed client software, these services can provide traceability to NIST with an uncertainty of a few milliseconds. The services are very popular, and NIST now handles millions of computer timing requests per day. While not all of these users require legal traceability, many do. For example, the National Association of Securities Dealers (NASD) requires its members to record stock market transactions with an uncertainty of 3 s relative to UTC(NIST). [20]

Nearly all low accuracy time and frequency measurements follow the traceability chain shown in Figure 3. Nearly all of the uncertainty in this traceability chain is introduced in the signal path between the NMI and the user (link C), or in the user's application of the received signal (link D). For practical purposes, the uncertainties between the BIPM and the NMI (link A) and the NMI and the broadcast signal (link B) can be regarded as 0 and ignored.

Table 1 - Summary of Time and Frequency Measurements That Require Traceability

Type of Measurement	**Link to NMI**	**Required Uncertainty**
Calibration of radar devices used in law enforcement	Audio time announcements (HF radio or telephone)	1×10^{-3}
AC electrical measurements	HF or LF radio signals	6×10^{-4}
Calibration of stopwatches and interval timers	Audio time announcements (HF radio or telephone)	2×10^{-4}
Calibration of transmitted frequencies used by commercial broadcast stations	HF or LF radio signals	1×10^{-5}
Calibration of low cost crystal oscillators used in electronic circuits	HF or LF radio signals	1×10^{-6}
Time synchronization of computers used in financial transactions	Telephone and Internet time setting signals, LF radio signals	1 s
Calibration of electronic test equipment	LF signal or GPS signal monitored by NMI	10^{-6} to 10^{-10}
Derivation of meter and volt	LF signal or GPS signal monitored by NMI	10^{-9} to 10^{-11}
Distribution of frequency for measurement and calibration purposes	LF signal or GPS signal monitored by NMI	10^{-8} to 10^{-12}
Primary reference frequency for synchronous digital networks	LF signal or GPS signal monitored by NMI	$< 1 \times 10^{-11}$
Fault location on electrical transmission lines	GPS signal monitored by NMI	1 μs
Comparisons between national laboratories, control of broadcast services, defense and space applications	Direct comparison to NMI through common view GPS measurements, two-way satellite measurements, or carrier phase GPS measurements	$< 1 \times 10^{-13}$

4.3 Traceability for High Accuracy Measurements

Traceability is often required for high accuracy measurements involving frequency calibration or time synchronization. For example, test equipment like frequency counters and signal generators often have internal oscillators than need calibration to uncertainties ranging from 10^{-6} to 10^{-10} to meet manufacturer's specifications. Organizations in both government and industry are sometimes contractually required to distribute frequency within their facility at uncertainties ranging from 10^{-7} to 10^{-12}. Digital telecommunication networks that carry voice, data, and facsimile information over DS1 or E1 lines require a primary reference source with an uncertainty of 10^{-11} or less. Higher data rate networks like the Synchronous Optical Network (SONET) require even less uncertainty. [21] High accuracy time synchronization is also a requirement of some industries. For example, the electric power industry requires 1 μs clock synchronization for fault location on transmission lines. [22]

Many high accuracy measurements are referenced to signals directly controlled by a NMI, using the traceability chain shown in Figure 3. Typically, low frequency (LF) and satellite signals are used as a reference to greatly reduce the uncertainty of the radio path (link C). For example, NIST operates radio station WWVB on a carrier frequency of 60 kHz. This LF signal can distribute frequency with an uncertainty of $< 1 \times 10^{-11}$ [5], and similar radio stations are operated by NMIs in other countries. [17]

Traceability can also be established using radio navigation systems like LORAN-C [23] and GPS using a traceability chain similar to Figure 4. Since the use of GPS signals is so prevalent, a separate section on GPS traceability is included below.

Some NMIs offer measurement services that provide high accuracy traceability. For example, the Frequency Measurement and Analysis Service (FMAS) allows users to lease a complete measurement system from NIST. The FMAS includes a GPS receiver, all necessary measurement hardware, and a data link back to NIST. It provides traceability with an uncertainty of about 5×10^{-13} over one day. This service essentially follows the same traceability chain shown in Figure 4, but NIST oversees the entire measurement process. The measurements and the uncertainty analysis are the responsibility of NIST and require no attention from the user. [24, 25]

Table 2 – Summary of Signals and Links Used to Establish Traceability to UTC(NIST)

Traceable Signal or Link	**Receiving Equipment**	**Timing Uncertainty**	**Frequency Uncertainty**
Audio Time Announcement	Telephone (303-499-7111)	< 30 ms	NA
Automated Computer Time Service (ACTS)	Computer, software, modem, and phone line (303-494-4774)	< 10 ms	NA
Network Time Service (NTS)	Computer, software, and Internet connection	< 1 s	NA
WWV and WWVH	HF Receiver (2.5, 5, 10, 15, or 20 MHz)	1 to 20 ms	10^{-5} to 10^{-8}
WWVB or LORAN-C	LF Receiver (60 or 100 kHz)	1 to 100 μs	10^{-10} to 10^{-12}
Global Positioning System (GPS)	GPS Receiver (1575.42 MHz)	< 500 ns	10^{-11} to 10^{-13}
GPS common-view, GPS carrier phase, and Two Way Satellite Time Transfer (TWSTT)	Receiving equipment, transmitting equipment (TWSTT only), tracking schedules, and data link with NIST	< 10 ns	$< 1 \times 10^{-13}$

The most sophisticated methods of measuring time and frequency are normally reserved for comparisons made between NMIs, to control broadcast services, or for advanced military or space applications. However, they can be applied to other users who need traceability with the smallest possible uncertainty. These methods include single channel GPS common view [26], multi channel GPS common view [27], multi channel GPS+GLONASS common view [28], two-way satellite time transfer [29], and GPS carrier phase measurements. [30] These methods require a data exchange with a NMI, so the measurement results are not known in real time. However, they make it possible to directly link to a NMI with uncertainties of $< 1 \times 10^{-13}$. The single channel GPS common view method is the most established technique. It uses standardized tracking schedules and a data format published by the BIPM, and as touched on earlier, is the method used by NMIs to contribute data for the computation of TAI and UTC. NIST also offers a Global Time Service that allows direct comparisons to UTC(NIST) through GPS common view measurements. [25]

Table 2 summarizes the signals and links that can be used to establish traceability to UTC(NIST) for both low and high accuracy measurements.

5. Traceability Using the Global Positioning System (GPS)

In the past decade, signals broadcast from GPS satellites have become the dominant reference source for high accuracy time and frequency measurements. GPS consists of an orbiting constellation of at least 24 satellites and at least four should be visible at all times from any location on Earth. Although some GPS signals are reserved for United States military use, the L1 carrier (1575.42 MHz) is available to all users.

GPS is a navigation and positioning service that produces time and frequency information as a byproduct. The time and frequency component of GPS is officially referenced to UTC(USNO), the time scale maintained by the United States Naval Observatory. However, there are at least two ways to establish traceability to a NMI (rather than to USNO) using GPS.

The first way uses the model shown earlier in Figure 4. It requires a NMI to continually measure signals from the GPS constellation, and compare GPS to their derivation of UTC. The resulting data must then be published and made available to users. As before, link A connects the BIPM to the NMI, and this uncertainty can be obtained from Circular T. Link B connects the NMI to GPS. This link is established through the NMI's measurements of the GPS signals, and the uncertainties are published and made available to users. Link C connects the NMI to the user. As before, link D is the uncertainty introduced by the user's measurement equipment. By comparing link B to their actual measurement results, users can determine if they are properly receiving and processing the GPS signals.

The second way is to use a calibration service provided by a NMI that uses GPS signals, such as the NIST Frequency Measurement and Analysis Service. This service follows the traceability model shown in Figure 4, but all aspects of the measurement process (including the measurement hardware and the uncertainty analysis) are supplied or controlled by NIST. [24, 25]

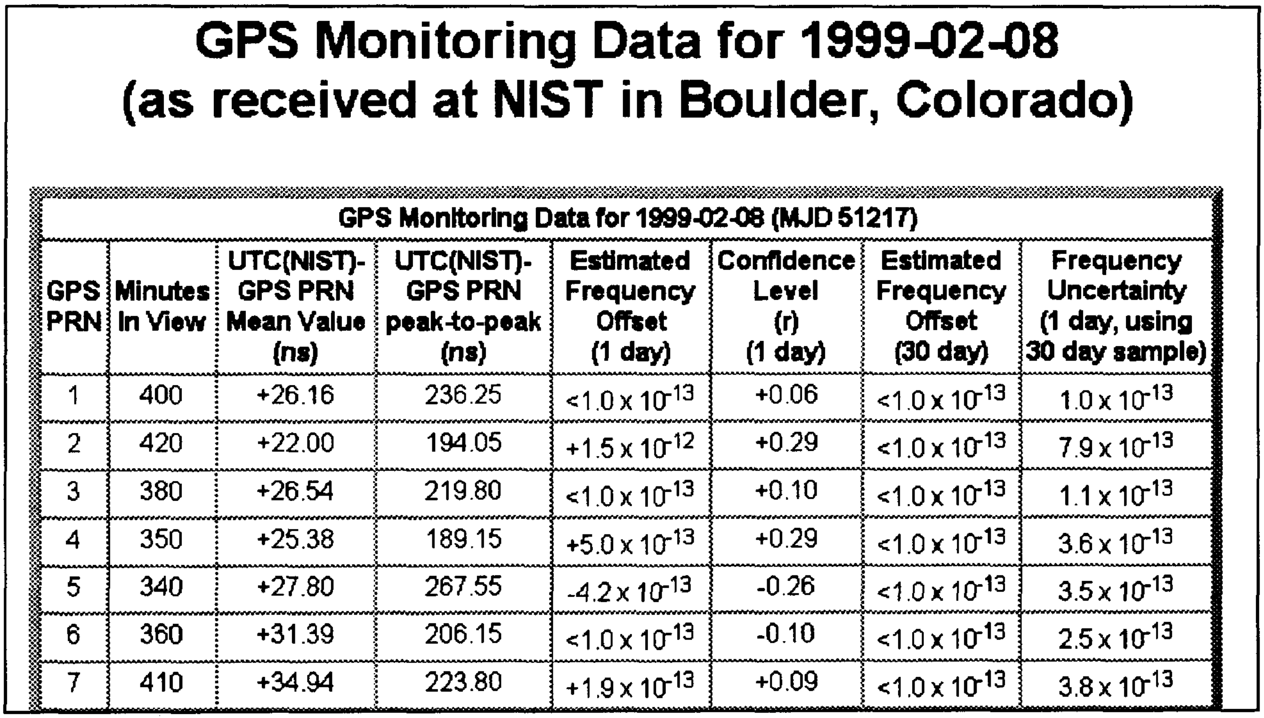
One limitation of GPS monitoring is that a single NMI cannot monitor all the satellites all the time. Unlike fixed position transmitters, signals from the orbiting GPS satellites can only be received as they fly over a NMI. Since the satellites have an orbital period of slightly less than 12 hours, they fly over twice in a 24 hour period. Several hours of data can be collected in each fly over.

Several NMIs now monitor GPS and publish data on the Internet. Some publish data from individual satellites, others publish a composite average of the entire constellation. NIST monitoring captures about 400 minutes of data from each satellite per day (Figure 5) and is available at:

http://gpsmonitor.timefreq.bldrdoc.gov/gpstrace.htm

Completing the traceability chain shown in Figure 4 requires analyzing the measurement uncertainty of links C and D. The uncertainty of link C is limited by the Selective Availability (SA) program initiated by the United States Department of Defense, which intentionally degrades the accuracy of GPS. Due to SA, the GPS specification lists the timing uncertainty as 340 ns. [31]

The uncertainty of link D is receiver dependent. Some receivers reduce the effects of SA, but others may perform worse than the GPS signal specification. While performance differences also exist with other types of time and frequency receivers, the differences between GPS receivers are more pronounced due to the increased complexity of the signal processing. A study conducted by the National Physical Laboratory (NPL) in the United Kingdom showed that the uncertainty of a GPS measurement varies widely depending upon the model of receiver used. [32]



GPS Monitoring Data for 1999-02-08 (as received at NIST in Boulder, Colorado)

GPS Monitoring Data for 1999-02-08 (MJD 51217)

GPS PRN	Minutes In View	UTC(NIST)-GPS PRN Mean Value (ns)	UTC(NIST)-GPS PRN peak-to-peak (ns)	Estimated Frequency Offset (1 day)	Confidence Level (r) (1 day)	Estimated Frequency Offset (30 day)	Frequency Uncertainty (1 day, using 30 day sample)
1	400	+26.16	236.25	$<1.0 \times 10^{-13}$	+0.06	$<1.0 \times 10^{-13}$	1.0×10^{-13}
2	420	+22.00	194.05	$+1.5 \times 10^{-12}$	+0.29	$<1.0 \times 10^{-13}$	7.9×10^{-13}
3	380	+26.54	219.80	$<1.0 \times 10^{-13}$	+0.10	$<1.0 \times 10^{-13}$	1.1×10^{-13}
4	350	+25.38	189.15	$+5.0 \times 10^{-13}$	+0.29	$<1.0 \times 10^{-13}$	3.6×10^{-13}
5	340	+27.80	267.55	-4.2×10^{-13}	-0.26	$<1.0 \times 10^{-13}$	3.5×10^{-13}
6	360	+31.39	206.15	$<1.0 \times 10^{-13}$	-0.10	$<1.0 \times 10^{-13}$	2.5×10^{-13}
7	410	+34.94	223.80	$+1.9 \times 10^{-13}$	+0.09	$<1.0 \times 10^{-13}$	3.8×10^{-13}

Figure 5 – The NIST GPS Data Archive

A GPS receiver that is properly designed and operated can establish traceability to a NMI with an uncertainty of $< 1 \times 10^{-12}$ when averaged for one day. However, users should carefully analyze the uncertainty of link D before claiming this level of performance. Two key factors that contribute to GPS receiver performance are the quality of the receiver's internal oscillator and the quality of the firmware algorithms that control the receiver. Receivers with oven controlled quartz or rubidium oscillators provide the best stability since the receiver can ignore most of the fluctuations caused by SA. High quality firmware can produce results that are better than the GPS specification by selecting the satellites that provide the best time and frequency reference, by filtering the effects of SA, by averaging data from multiple satellites to reduce the effect of SA, and by properly handling GPS broadcast errors.

6. Summary

Establishing traceability is often more convenient in time and frequency than in other fields of metrology. Direct links to a national metrology institute are often available in the form of signals broadcast over a radio, telephone, or network path. Traceability can also be established by receiving signals monitored by a NMI. Since traceability is required for both low and high accuracy applications, techniques exist to establish traceability at uncertainties ranging from parts in 10^3 to 10^{13}.

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