Metrological and legal traceability of time signals

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ABSTRACT

Metrological traceability requires an unbroken chain of calibrations that relate to a reference, with each calibration having a documented measurement uncertainty. In the field of time and frequency metrology, the desired reference is usually Coordinated Universal Time (UTC), or one or more of its official realizations, termed UTC(*k*), and traceability to UTC is a legal requirement for many entities. Traceability to UTC can be established in three areas – frequency, time interval, and time-of-day synchronization, but this paper focuses solely on the traceability of time signals used for synchronization. We first examine the definition of traceability, then discuss how traceability can be established via the reception of time signals transmitted by satellites and network time servers, followed by a discussion of how these signals can meet the synchronization and traceability requirements of the financial and electric power industries. Not all of the available UTC time signals are considered in this paper, as we primarily focus on direct broadcast and common-view Global Positioning System (GPS) signals, with uncertainties measured in nanoseconds, and Network Time Protocol (NTP) signals, with uncertainties measured in microseconds and milliseconds.

I. INTRODUCTION

The International Vocabulary of Metrology (VIM) defines metrological traceability in section 2.41 (6.10) as “the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty” [1]. The VIM is endorsed by the International Bureau of Weights and Measures (BIPM), the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), the International Organization for Standardization (ISO), the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP), the International Organization of Legal Metrology (OIML), and the International Laboratory Accreditation Cooperation (ILAC). Of these ILAC has a more detailed definition, which includes traceability to an international or national measurement standard, a documented measurement uncertainty, a documented measurement procedure, accredited technical competence, and comparisons to the international system of units (SI) with calibrations at regular intervals. The International Telecommunications Union (ITU) adopted the following definition in 2013: “the property of the 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” [2]. The ITU definition is essentially the same definition found in previous editions of the VIM. The most noteworthy change in the current VIM definition is probably the use of the words “documented” and “calibrations” as opposed to “comparisons” in the earlier definition, but the meaning and intent remain the same.

Determining whether enough evidence exists to establish traceability is usually the role of an auditor or assessor who visits the laboratory or facility where the measurements are performed. These auditors or assessors are usually working on behalf of an accreditation body such as ILAC and/or a standards organization such as ISO. In some cases, however, the determination of whether measurements are traceable is made by a regulatory agency, such as, in the case of financial markets, the U. S. Securities & Exchange Commission (SEC). In cases where losses or damages are incurred, the final determination of whether traceability was properly established may be made in a court of law. Those charged with the responsibility of proving or disproving traceability often refer to the internationally accepted definition of metrological traceability provided in the VIM [1]. This definition consists of four key parts, as described and expanded upon in the following sections.

Part 1 - *Traceability is “the property of a measurement result”* **-** This means that the concept of traceability only applies to measurement results and not to other things. Therefore:

- Traceability is not a property of a system. For example, traceability is not a property of the Global Positioning System (GPS) but a traceable measurement that involves GPS can be made.

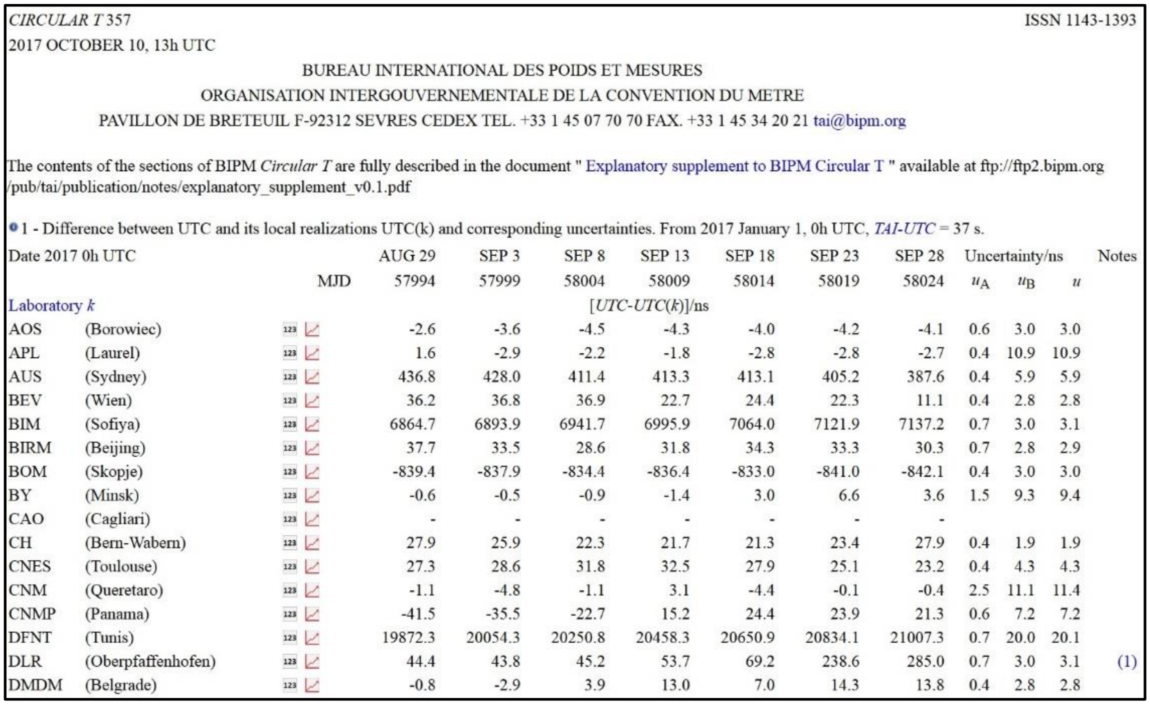
- Traceability is not a property of an instrument. For example, traceability is not a property of a time interval counter or even a cesium clock but a traceable measurement that involves these instruments can be made.

- Traceability is not a property of an organization or laboratory. For example, simply being the United States Naval Observatory (USNO) or the National Institute of Standards and Technology (NIST) does not guarantee that all measurements made at USNO or NIST are traceable, nor does it guarantee that all measurements referenced to USNO or NIST signals are traceable.

Part 2 – *A traceable measurement "can be related to a reference"* **–** For nearly all areas of metrology, including time and frequency, the ultimate measurement reference is the International System (SI) of units. The SI units are definitions of ideal values and as such have zero uncertainty. However, they are not physical standards, and establishing traceability requires a real measurement that involves a comparison against a physical standard.

Only two SI units apply to time and frequency, the second (s) and the hertz (Hz). The second is the standard unit for time interval, and one of the seven base units of the SI. Since 1967, it has been defined as "The duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom. [3]." The hertz is the standard unit for frequency. It represents events per second (the events are usually pulses or cycles in an electrical signal), and is defined as s^{-1} in SI parlance. The hertz is one of 21 named SI units that are derived from the base units.

The world's best approximation of the SI units for time and frequency, and thus the ultimate reference for establishing traceability, is Coordinated Universal Time (UTC), an atomic time scale based on the SI definition of the second. UTC is computed by the BIPM in France by performing a weighted average of data collected from local time scales located at more than 70 timing laboratories [4]. UTC itself exists only on paper, and is defined through its difference with the local time scales, known as UTC(k), of participating laboratories. It is published monthly in the BIPM *Circular T* (Figure 1). The *Circular T* is typically published around the tenth day of a month, and covers the previous month. Thus, the latency of the published measurement results typically ranges from 10 to 45 days.



CIRCULAR T 357 ISSN 1143-1393
2017 OCTOBER 10, 13h UTC
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The contents of the sections of BIPM *Circular T* are fully described in the document " Explanatory supplement to BIPM Circular T " available at ftp://ftp2.bipm.org /pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

● 1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties. From 2017 January 1, 0h UTC, *TAI-UTC* = 37 s.

Date 2017 0h UTC			AUG 29	SEP 3	SEP 8	SEP 13	SEP 18	SEP 23	SEP 28	Uncertainty/ns			Notes
		MJD	57994	57999	58004	58009	58014	58019	58024	u_A	u_B	u	
Laboratory *k*						[*UTC-UTC*(*k*)]/ns							
AOS	(Borowiec)	123 📈	-2.6	-3.6	-4.5	-4.3	-4.0	-4.2	-4.1	0.6	3.0	3.0	
APL	(Laurel)	123 📈	1.6	-2.9	-2.2	-1.8	-2.8	-2.8	-2.7	0.4	10.9	10.9	
AUS	(Sydney)	123 📈	436.8	428.0	411.4	413.3	413.1	405.2	387.6	0.4	5.9	5.9	
BEV	(Wien)	123 📈	36.2	36.8	36.9	22.7	24.4	22.3	11.1	0.4	2.8	2.8	
BIM	(Sofiya)	123 📈	6864.7	6893.9	6941.7	6995.9	7064.0	7121.9	7137.2	0.7	3.0	3.1	
BIRM	(Beijing)	123 📈	37.7	33.5	28.6	31.8	34.3	33.3	30.3	0.7	2.8	2.9	
BOM	(Skopje)	123 📈	-839.4	-837.9	-834.4	-836.4	-833.0	-841.0	-842.1	0.4	3.0	3.0	
BY	(Minsk)	123 📈	-0.6	-0.5	-0.9	-1.4	3.0	6.6	3.6	1.5	9.3	9.4	
CAO	(Cagliari)	123 📈	-	-	-	-	-	-	-				
CH	(Bern-Wabern)	123 📈	27.9	25.9	22.3	21.7	21.3	23.4	27.9	0.4	1.9	1.9	
CNES	(Toulouse)	123 📈	27.3	28.6	31.8	32.5	27.9	25.1	23.2	0.4	4.3	4.3	
CNM	(Queretaro)	123 📈	-1.1	-4.8	-1.1	3.1	-4.4	-0.1	-0.4	2.5	11.1	11.4	
CNMP	(Panama)	123 📈	-41.5	-35.5	-22.7	15.2	24.4	23.9	21.3	0.6	7.2	7.2	
DFNT	(Tunis)	123 📈	19872.3	20054.3	20250.8	20458.3	20650.9	20834.1	21007.3	0.7	20.0	20.1	
DLR	(Oberpfaffenhofen)	123 📈	44.4	43.8	45.2	53.7	69.2	238.6	285.0	0.7	3.0	3.1	(1)
DMDM	(Belgrade)	123 📈	-0.8	-2.9	3.9	13.0	7.0	14.3	13.8	0.4	2.8	2.8	

Figure 1. A portion of Section 1 of the BIPM's monthly *Circular T* document.

The UTC(k) are the outputs of physical standards that continuously realize the SI units of time and frequency, and can thus serve as the reference for real measurements. Section 1 of the *Circular T* shows UTC – UTC(k) for every contributing laboratory at 5-day intervals, allowing each participant to establish traceability to the SI. Three additional points should be noted about UTC:

- The measurements of the UTC(k) time scales never stop and thus traceability can be continuously established, not just at irregular intervals as is the case in other fields of metrology. These measurements constitute BIPM key comparison CCTF-K001.UTC which has been ongoing since 1977.

- UTC is the ultimate reference not only for frequency and time interval, but also for everyday time-of-day synchronization.

- UTC has been synchronized, since its inception, to stay within 0.9 seconds of the predicted value of UT1, the rotation angle of the Earth and effectively the successor to the no-longer existent Greenwich Mean Time. This synchronization involves the aperiodic insertion of leap seconds [5].

Part 3 - *Traceability requires "a documented unbroken chain of calibrations"* **–** This part of the definition tells us that claims of traceability must always be supported by actual measurements. It is incorrect, for example, to say that because a signal originates from NIST or USNO that it is therefore traceable without calibration. A calibration is a comparison between a reference and a device under test (DUT) that is conducted by collecting and analyzing measurements. In addition:

- The chain of calibrations must be documented. The amount of documentation will depend on the requirements of the organization or sector that needs to provide proof of traceability. In the United States, audit trail standards for the financial community are set using Rule 613 [6]. This documentation should cover the entire traceability chain; from the SI to the end-user.

- There is no restriction or limit on the number of calibration steps (or links in the traceability chain), but a simple traceability chain is easier to maintain and/or to demonstrate to auditors or assessors. The unbroken chain of calibrations must trace back from the measurement in question to a representation of the SI, which means that it will normally extend from the end user to a UTC(k) reference maintained by a laboratory such as NIST or the USNO.

Part 4 - *Each calibration in a traceability chain is "contributing to the measurement uncertainty"* **–** Traceability cannot exist without knowledge of the measurement uncertainty. Measurement uncertainty is defined in the VIM as "The parameter, associated with the result of a measurement, that characterizes the dispersion of values that could reasonably be attributed to the measurand." The measurand is the "particular quantity subject to measurement," [1] which in our case can be either time referenced to a UTC realization, time interval, or frequency.

Determining the uncertainty of a measurement result involves knowing the uncertainty of each calibration, or every link in the traceability chain, between UTC and the end user. The uncertainty of some links may be negligible and easy to document, for example the *Circular T* provides the uncertainty between UTC and UTC(k), but determining the uncertainty of the links that connect UTC(k) to the end user is often the most difficult part of establishing traceability. It requires knowledge of the uncertainty of the path delay between the time signal source and the user, as well as knowledge of the uncertainty of the calibration of the equipment used to receive the time signal, which could be, for example, a GPS receiver or a computer with network time protocol (NTP) client software.

The internationally recognized standards document for measurement uncertainty analysis is called the "Guide to expression of uncertainty in measurement," colloquially known as the GUM [7]. The GUM recommends that:

- Every parameter that contributes to the measurement uncertainty should be evaluated with either the Type A or the Type B method. Type A parameters are evaluated by the statistical analysis of a series of measurements, for example by use of the standard deviation, Allan deviation, or a similar statistic. Type B parameters are evaluated by non-statistical means. An example might be a single measurement of a cable delay that is applied as a constant in all subsequent uncertainty analysis.

- It is customary to combine the Type A and Type B parameters by taking the square root of the sum of the squares, and then multiplying the result by the coverage factor, k. The coverage factor relates to the range of the distribution and reflects the probability (which is approximately 68.3% for $k = 1$ or 95.5% for $k = 2$), that a given measurement result will fall within this range. This method for estimating the combined uncertainty is utilized on the *Circular T* (Figure 1) where $k = 1$ and all uncertainties are stated in units of nanoseconds. The Type A uncertainty, u_A, the Type B uncertainty, u_B, and the combined uncertainty, u, are listed in separate columns. The equation for determining u is

$$u = k\sqrt{{u_A}^2 + {u_B}^2}\,. \tag{1}$$

II. OFFICIAL TIME IN THE UNITED STATES

As discussed in Section I, international timekeeping is organized by a system in which individual timing laboratories can realize UTC in real time, and those realizations are termed UTC(k). The BIPM publishes its monthly *Circular T* which shows the time difference between UTC and its local realizations in the form of UTC – UTC(k).

Most nations have only one laboratory listed on the *Circular T*, but the United States has four. In addition to the USNO and NIST, the Naval Research Laboratory (NRL) and the Applied Physics Laboratory (APL) at John Hopkins University also contribute to UTC and, in theory, metrological traceability could also be established through either NRL or APL. However, the local UTC(k) time scales maintained by NRL and APL exist primarily for internal research purposes. Only the USNO and NIST distribute time and frequency signals in the United States, and jointly hold the responsibility of being the official U. S. timekeeper.

The America COMPETES Act of 2007 [8] specifies that the official time is UTC, as "interpreted or modified by the Secretary of Commerce, in coordination with the Secretary of the Navy." Ironically, until this bill was passed in 2007, official U. S. time was "mean solar time" as defined in the Calder Act of 1918. In practice, this means NIST (an agency of the U. S. Department of Commerce) is officially responsible for determining the UTC that is used for the financial and electric power sectors, while the USNO is the source of UTC for the Department of Defense and GPS, as specified in DoD Instruction 4650.06 [9]. Therefore, the legal traceability path for time measurements in the United States must involve either NIST or the USNO although, as noted above, establishing traceability to any UTC(k) can be used to establish metrological traceability to all of them, at the expense of increased complexity.

III. ESTABLISHING TRACEABILITY VIA THE DIRECT RECEPTION OF GPS TIME SIGNALS

The Global Positioning System (GPS) has its own time scale, known as GPS time, but the satellites broadcast parameters in subframe 4, page 18, of the GPS navigation message that receivers can apply to convert GPS time to a prediction of UTC(USNO). Although GPS time could in principle be used for traceability if the user were to carefully apply a considerable number of corrections, it is intended only for positioning and does not include leap seconds. It should not be used by time users, and nearly all GPS receivers apply the UTC corrections to their time determination by default. It is not even possible to disable the corrections for many receiver models. A receiver can obtain the UTC correction parameters from any satellite, but should use the satellite whose information was most recently refreshed. The UTC offset correction, Δt_{UTC}, is computed as [10]

$$\Delta t_{\mathrm{UTC}} = \Delta t_{\mathrm{LS}} + A_0 + A_1\,(t_{\mathrm{E}} - t_{\mathrm{ot}} + 604800(WN - WN_{\mathrm{t}})), \tag{2}$$

where

Δt_{LS} is the number of leap seconds introduced into UTC since GPS time began on January 6, 1980,

A_0 is the constant UTC offset parameter expressed in seconds,

A_1 is a dimensionless frequency offset value that allows the correction of the time error accumulated since the UTC reference time, t_{ot}, which is when A_0 was last determined,

t_{E} is GPS time (also known as the time of interest or the time being converted to UTC),

604800 is a constant that equals the number of seconds in one week.

t_{ot} is the reference time for UTC data,

WN is the GPS week number, and

WN_{t} is the UTC reference week number.

The first part of Eq. (2), $\Delta t_{LS} + A_0$, takes care of most of the UTC correction. The Δt_{LS} term is the large, integer second part of the correction, equal to the number of leap seconds that have occurred since the start of the GPS time scale. The A_0 term is the small, nanosecond part of the correction, equal to the difference between the GPS and UTC(USNO) second markers. It is broadcast in units of seconds, but is typically $< 1 \times 10^{-8}$ s, or < 10 ns in magnitude. The second part of Eq. (2) fine tunes the UTC output of a GPS clock by applying a dimensionless frequency offset, provided by A_1, as a drift correction for the interval between the time specified by t_{ot} and WN_t and the current time. This is normally a sub-nanosecond correction, because A_0 is normally updated in the GPS broadcast more than once per day and the drift correction supplied by A_1 is typically near 1 ns per day.

The UTC(USNO) prediction is based upon an extrapolation of the observed difference between GPS and UTC(USNO) from the start to the end of the previous day. The accuracy of that prediction, for the signal in space, is less than 1 ns in practice. To illustrate this, Figure 2 shows the differences between GPS time and UTC(USNO) modulo 1 s (to remove the leap second differential), as well as the difference between GPS predicted UTC and UTC(USNO) for the period from 2013 to the summer of 2017. More recent data can be obtained from the http://tycho.usno.navy.mil and ftp://tycho.usno.navy.mil/pub/gps. The procedures that GPS uses to deliver time are documented in the Interface Control Documents ICD202 and ICD200 [10, 11], where the official accuracy is currently (and very conservatively) listed as 90 ns. The actual data show that if we can accept a latency of up to two days, the time obtained from the GPS signal in space as transmitted by the satellite can be considered directly traceable to UTC(USNO), with an uncertainty of a few nanoseconds or less. Alternately, the real-time signal-in-space broadcast of UTC(USNO) can be considered to have negligible latency but with an additional uncertainty component of order 1 ns.

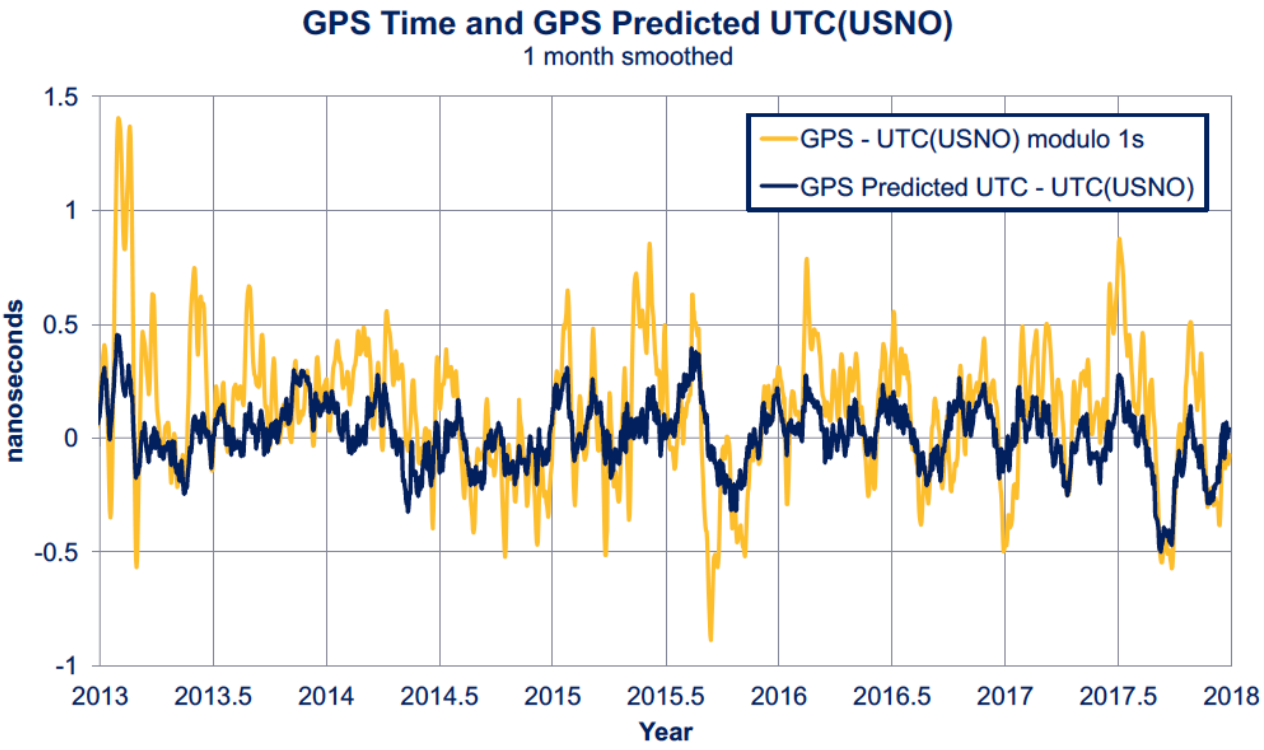

Figure 2. Time differences between GPS timing signals and UTC(USNO), from 2013 to 2017 as received at the USNO, courtesy Stephen Mitchell (USNO)

Section IV of the BIPM's *Circular T* document also publishes values for UTC – UTC(USNO via GPS) as well as UTC – UTC(SU via GLONASS), but with larger uncertainties. The *Circular T* does not currently include anything similar for the European Galileo satellites because Galileo's time is based on an average of UTC realizations. However, as described in the next section, a legal traceability chain that complies with the VIM definition could also be established by use of Global Navigation Satellite System (GNSS) signals as with GPS.

The uncertainty of the GPS signal in space with respect to UTC is ~1 ns, as shown in Figure 2, but will be considerably larger when received on Earth. This is due to many factors, including the quality and calibration of the user's receiving equipment, errors in the calibration of the user's antenna and antenna cable, antenna coordinate errors, environmental effects, ionospheric and tropospheric delays, multipath signal reflections, and other factors. For these reasons, the synchronization uncertainty of a GPS disciplined clocks ($k = 2$) will be ~10 ns in the best case and ~1 µs in the worst case. It is the responsibility of the user to provide enough documentation to support and if necessary, to defend, the uncertainty that they claim. Detailed methods for evaluating the uncertainty of GPS disciplined oscillators and clocks are provided in [12].

IV. ESTABLISHING TRACEABILITY VIA COMMON-VIEW GPS TIME SIGNALS

NIST and other national timing laboratories now distribute their UTC time scales to their customers by publishing the difference between UTC(k) and the prediction of UTC(USNO via GPS) for every satellite. These data can be used to compute the difference between a user's local clock and UTC(k) by observing the same satellite at the same time and subtracting the two measurements. However, the user is responsible for the calibration of their common-view equipment and needs also to consider the latency of the published data, which could be hours or days. A similar use could be made of any GNSS signal, provided that the reference laboratory makes the common-view information available.

When a common-view comparison is conducted with a UTC(k) laboratory (Figure 3), a reference system produces continuous measurements of *UTC(k) – GPS*. A system at the customer's site simultaneously produces continuous measurements of *Local Clock – GPS.* The measurements from the reference system and the customer's system are subtracted from each other, the time broadcast by GPS falls out of the equation, and the result is an estimate of *UTC(k) – Local Clock.* The GPS signals in this case are simply vehicles used to transfer or relay time from UTC(k) to the customer's site. The common-view equation for this example is

$$(UTC(k) - GPS) - (Local\ Clock - GPS) = (UTC(k) - Local\ Clock) + (e_{SA} - e_{SB}), \qquad (3)$$

where the components that make up the (e_{SA} – e_{SB}) error term include delay differences between the two sites caused by ionospheric and tropospheric delays, multipath signal reflections, environmental conditions, or errors in the GPS antenna coordinates. These factors are either measured or estimated and applied as a correction to the measurement of the local clock, with the uncorrected portions contributing to the uncertainty.

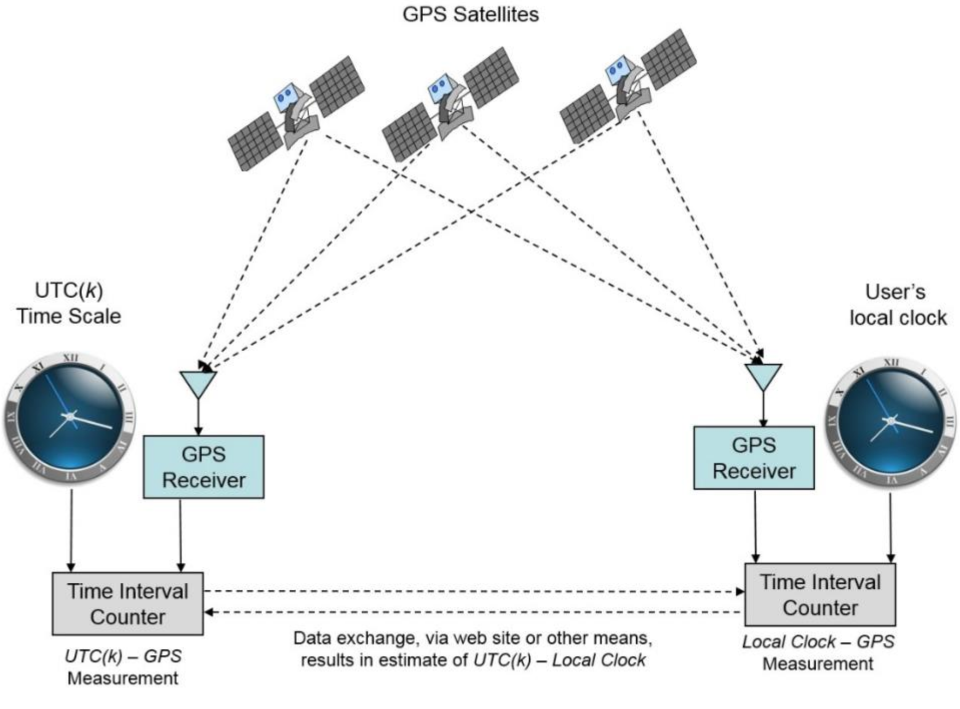

Figure 3. A common-view GPS comparison with a UTC(k) laboratory.

NIST and other national timing laboratories also offer formal common-view and all-in-view (described below) based services, in which each customer receives a common-view system whose receiver, antenna, and cable delays have all been calibrated prior to shipment. In the case of the NIST services, both NIST and the customer simultaneously upload their measurements to a data server every 10 minutes, the data processing is automated, and the results are published in near real-time. NIST also offers a disciplined clock (NISTDC) service (Figure 4) where the common-view measurement results are used to lock the customer's clock to UTC(NIST), just as a GPS disciplined clock is locked to UTC(USNO via GPS). The uncertainty of the NIST common-view services with respect to UTC(NIST) is reported monthly to each customer and is typically near 10 ns ($k = 2$) [13].

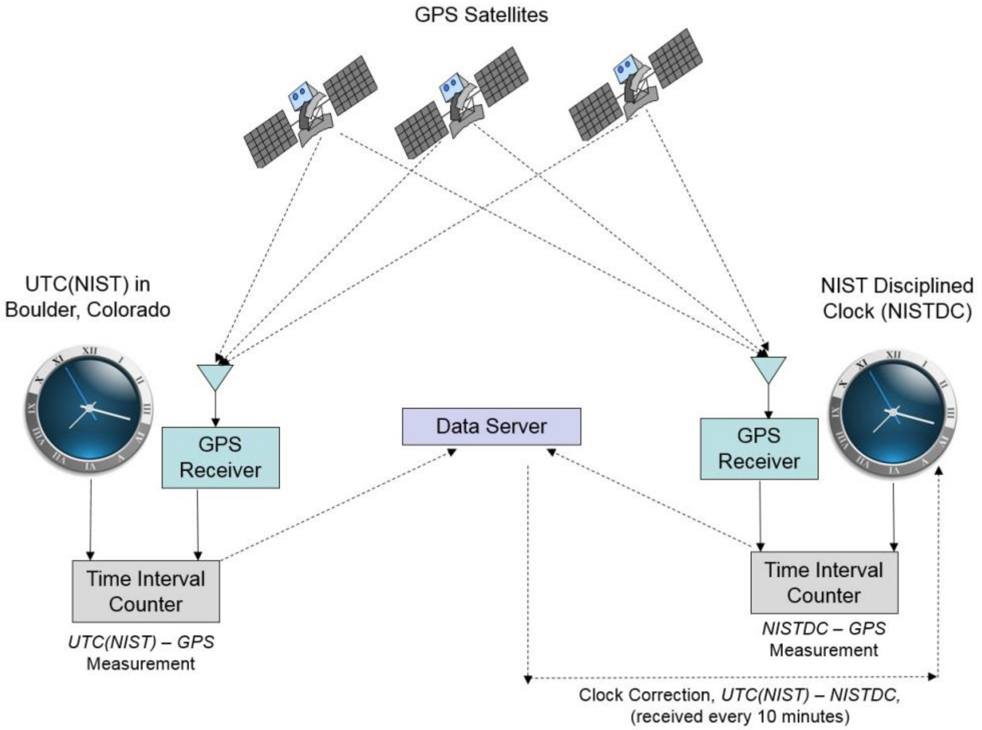

Figure 4. NIST disciplined clock system utilizing the common-view GPS method.

A measurement technique similar to common-view is known as all-in-view. For all-in-view, the time difference between the laboratory clock and all satellites in view is first averaged, and the timing difference is estimated from the difference between laboratory averages. This method has been adopted by the BIPM because it affords better signal to noise over long distances, when there may not be many satellites visible at both labs at the same time. Verifying all-in-view traceability is more complicated than in the common-view method because it requires adding a component to the error budget that accounts for the difference between the time as broadcast by the individual satellites. This is because errors in the broadcast ephemerides of the satellites, which are attenuated in common-view, must be allowed for and because the method depends on the availability of precise ephemerides and clock products. While these error sources can be estimated from past data, and measured after-the-fact, all-in-view would also remain sensitive to the same local station-errors that affect common-view.

V. THE TRACEABILITY OF NETWORK TIME PROTOCOL (NTP) SIGNALS

As discussed in Sections III and IV, GPS and other GNSS signals can provide traceability with uncertainties measured in nanoseconds. Another important and widely used source of traceable time signals are the NTP time servers that reside on the public Internet, albeit with much higher uncertainties measured in microseconds or milliseconds. The primary purpose of NTP is the synchronization of computer clocks and network appliances. The demand for these services is so high that many billions of NTP synchronization requests are currently received every day [14]. At this writing (November 2017) the average number of NTP requests received per second is about 460 000 at NIST and about 15 000 at the USNO.

The NTP services measure the round trip delay between the server and the client, assume that the one-way delay from the server to the client is equal to half of the round trip delay, and then correct the time received by the client by the one-way delay. This correction compensates for most, but not all, of the propagation delay between the server and the client. The standard NTP equation is

$$TD = \frac{((T_2 - T_1) + (T_3 - T_4))}{2}. \tag{4}$$

where *TD* is the time difference between the server and client clocks, T_1 is the time when the client made the request, T_2 is when the request was received by the server, T_3 is when the server transmitted its response, and T_4 is when the time packets transmitted by the server arrive at the client. Using these same four time stamps, the round trip delay between the client and server [15] is computed by the client as

$$RT_{Delay} = (T_4 - T_1) - (T_3 - T_2). \tag{5}$$

The division by two in Eq. (4) assumes that the delay from the server to the client is equal to one half of the round trip delay. If this assumption were true, the network would be symmetric, meaning that the path delays to and from the server would be equal and that dividing by two would compensate for all delays. In practice, however, networks are asymmetric. This means that the incoming and outgoing delays are not equal and that the difference in delays will contribute uncertainty to the time received by the client. The worst-case time uncertainty that can be added by network asymmetry is 50% of the round trip delay [15, 16], a situation that could, of course, only occur if 100% of the delay were in one direction.

An additional assumption in the use of Eqs. (4) and (5) is that the four time values are measured with negligible uncertainty. This assumption is questionable when the Network Time Protocol application runs as a normal user process on a system that supports a graphical user interface. The overhead in the communication between the user process and the clock of the operating system in this case may not be negligible, especially on a heavily-loaded system or one that is supporting web-based services. In addition, all of the time values are large quantities, and the potential loss of significance when the difference between two large quantities is very small is an important detail in the implementation of the software.

If the servers have been properly synchronized to a UTC(k) source such as UTC(NIST) or UTC(USNO), network asymmetry will probably dominate the uncertainty of NTP time transfer on a wide-area network. Because the maximum uncertainty cannot exceed 50% of the round trip delay, the uncertainty of NTP is likely to be much smaller on a local area network (LAN) than it is on a wide area network (WAN) such as the public Internet. On a WAN, care should be taken not to underestimate the uncertainty when establishing a traceability chain via NTP. A study of the USNO NTP service involving multiple servers and clients revealed semi-persistent systematic time errors as large as 100 ms, often due to the rerouting of packets and network congestion [16]. Even when Internet conditions are favorable, it is uncommon to have a network asymmetry smaller than a few percent of the round trip delay. Thus, if the round trip delay is 100 ms, it is reasonable to assume that the uncertainty is not less than a few milliseconds [17]. On a controlled LAN, uncertainties much smaller than 100 µs have been reported, but the remaining uncertainties may be difficult to characterize, including asymmetric delays in network interface cards and client and server instability [18]. To properly estimate the uncertainty of an NTP link, the received packets should be compared to a UTC(k) time source, such as UTC(NIST), UTC(USNO), or UTC(USNO via GPS). Finally, we note that, at best, the Network Time Protocol synchronizes the system clock, as seen by the NTP client software, to an external reference time scale. This may not be adequate to support end-to-end traceability as we discuss below.

VI. TRACEABILITY IN FINANCIAL MARKETS

Legal time traceability in financial markets has been a concern since about 1996, when the U. S. Securities and Exchange Commission (SEC) began investigating the practices of the National Association of Securities Dealers (NASD) and the NASDAQ stock market, and found that the methods that they used to execute trades were not always in the best interests of stock market investors. As a result of a legal settlement, the NASD was required to develop an order audit trail system (OATS) so that auditors could determine whether or not trades were executed in the same order that they were received. Developing a successful OATS required synchronizing every clock involved in a stock market transaction to a common time reference. The official time reference for U. S. stock market transactions was chosen to be NIST time, and the first synchronization requirement for financial markets, OATS Rule 6953 [19], went into effect in August 1998. Since then, all major U. S. financial markets require clocks to be referenced to UTC(NIST), and to provide evidence that traceability to NIST has been established [20]. The synchronization requirement was originally just 3 s [19, 21]. It was later reduced to 1 s (a requirement that is still in effect for manual orders) [22] and then to the current 50 ms synchronization requirement that applies to all computer clocks and all automated orders. The 50 ms requirement was approved by the SEC in 2016 and first implemented in February 2017 [23, 24]. Table 1 summarizes past and current synchronization requirements for U. S. financial markets.

Table 1. A summary of U. S. financial market synchronization requirements.

Rule Number	Author	Year of Origin	Current Status	Reference Time Source	Synchronization Requirements with Respect to Reference Time Source	
OATS Rule 6953 [19]	NASD	1998	Superseded by 7430	NIST	All clocks	3 s
NYSE Rule 132A [21]	NYSE	2003	Superseded by 7430	NIST	All clocks	3 s
OATS Rule 7430 [22]	FINRA	2008	In effect	NIST	All clocks	1 s
Regulatory Notice 16-23 [23]	FINRA	2016	In effect	NIST	Computer clocks	50 ms
					Mechanical clocks	1 s
Consolidated Audit Trail National Market Plan (CAT NMS) [24]	SEC	2016	In effect	NIST	Automated orders	50 ms
					Manual orders	1 s
					Time stamp resolution	1 ms

The current European standard is the MiFID II (Market in Financial Instruments Directive). The European Securities and Markets Authority (ESMA), who is empowered by MiFID to draft regulatory technical standards, has a role similar to that of the SEC in the United States. Except for manual orders, where the 1 s requirement is identical to that in the U. S., the proposed European synchronization requirements are far more stringent. Automated orders require 1 ms synchronization and high frequency trading (HFT) orders require 0.1 ms (100 μs) synchronization, where synchronization is defined as the maximum divergence from UTC. The required time stamp resolution, which does not exceed 1 ms in the U. S., is 1 μs in Europe for HFT orders. Table 2 summarizes the synchronization requirements for European financial markets that went into effect on January 3, 2018 [25].

Table 2. A summary of European financial market synchronization requirements.

Rule Number	Author	Year of Origin	Current Status	Reference Time Source	Synchronization Requirements with Respect to Reference Time Source	
MiFID II	ESMA	2015	In effect as of January 3, 2018	UTC	Manual orders	1 s
					Automated orders, non-HFT	1 ms
					HFT	0.1 ms
					HFT time stamp resolution	1 μs

Traceability to UTC is required, but any timing laboratory that contributes to UTC (the UTC(k) laboratories) can serve as the reference time source. According to the MiFID II clock synchronization guidelines published by ESMA,

> *"systems that provide direct traceability to the UTC time issued and maintained by a timing centre listed in the BIPM Annual Report on Time Activities are considered as acceptable to record reportable events. The use of the time source of the U.S. Global Positioning System (GPS) or any other global navigation satellite system such as the Russian GLONASS or European Galileo satellite system when it becomes operational is also acceptable to record reportable events provided that any offset from UTC is accounted for and removed from the timestamp. GPS time is different to UTC. However, the GPS time message also includes an offset from UTC (the leap seconds) and this offset should be combined with the GPS timestamp to provide a timestamp compliant with the maximum divergence requirements ….".* [26]

These guidelines indicate that UTC(NIST), UTC(USNO), or UTC(USNO via GPS) can all satisfy MiFID II requirements when the appropriate level of documentation is provided and serve as the reference time source for financial transactions in Europe. The guidelines do not distinguish between a real-time use of UTC(USNO via GPS), which is a prediction of UTC(USNO) and at best require an addition to the uncertainty budget, and after-the-fact use, which could be a measurement.

The stock market requirements for synchronization apply to all of the computer clocks that are involved in time stamping financial transactions, and it should be noted that it is typically easy to synchronize a GPS clock to within 1 μs, but keeping a group of computer clocks synchronized to within 100 μs is a more challenging problem. Computer clocks are normally referenced to inexpensive quartz oscillators with large instabilities and drift rates, and thus frequent synchronization to either a NTP or a Precision Time Protocol (PTP) server is required to ensure that the synchronization requirements are continuously met. The 50 ms requirement specified in the U. S. standards can still be met through periodic synchronization to NIST or USNO NTP servers via the public Internet (Section V), but the more stringent 100 µs requirement for HFT in Europe will require the continuous synchronization of NTP or PTP servers to a UTC source, and that these ideally will be located very close to the stock exchange, so that the round trip network delay between the time servers and the computers involved in stock transactions can be made as small as possible.

NIST is currently providing synchronization and establishing traceability for financial markets in the United States, Europe, and Asia with common-view GPS clocks that are disciplined to UTC(NIST), as described in Section IV. The NISTDC is located in the same data center as the stock exchange, and is used to synchronize NTP and PTP time servers that are also located in the data center. An additional service offered by NIST can now measure and verify the packets transmitted by the time servers by comparing them to the NISTDC [20].

All of the methods we have described can support the traceability of the system clock that is used to provide the time stamps for commercial or financial transactions to a UTC(*k*) time scale. However, completing the traceability chain requires assigning a measurement uncertainty to the time stamps received by the end user, which in turn requires knowledge of the latency in the link between the application that time stamps a transaction (often called the "matching engine") and the system time, which is being controlled by a separate process with its own latencies. These latencies are probably small enough to support traceability requirements at the millisecond-level, but could be too large to support microsecond-level uncertainties. Users are responsible for including the uncertainties of this final link in the traceability chain in their uncertainty analysis. These uncertainties can be especially large for applications that run in the "cloud" where there is generally a much weaker connection between the physical system clock and the time seen by an application.

VII. TRACEABILITY IN THE ELECTRIC POWER INDUSTRY

As electric power usage has increased, the electric power industry has become more and more dependent upon accurate time. Synchronized phasors, or synchrophasors, are referenced to an absolute point in time by using a common UTC time reference. The devices that perform the synchrophasor measurements are known as phasor measurement units (PMUs). A PMU measures positive sequence voltages and currents at power system substations, and time stamps each measurement. The measurement results are then sent through a network to a central site, where the time stamps are aligned, the measurements are processed, and real-time decisions are made about how to allocate power within the grid to prevent outages.

The *IEEE C37.118.1* document is the standard for synchrophasor measurements. Section 4.3 of the standard specifically mentions traceability to UTC in three places, beginning with the clause stating that "the PMU shall be capable of receiving time from a reliable and accurate source, such as the Global Positioning System (GPS), that can provide time traceable to UTC ….". Time synchronization of 26 µs corresponds to a phase angle error of 0.57 ° at the 60 Hz AC line frequency, which in turn corresponds to a 1% total vector error (TVE), as defined in the standard. However, the standard indicates that:

> *"A time source that reliably provides time, frequency, and frequency stability at least 10 times better than these values corresponding to 1% TVE is highly recommended. The time source shall also provide an indication of traceability to UTC and leap second changes.*
>
> *For each measurement, the PMU shall assign a time tag that includes the time and time quality at the time of measurement. The time tag shall accurately resolve time of measurement to at least 1 µs within a specified 100 year period. The time status shall include time quality that clearly indicates traceability to UTC, time accuracy, and leap second status."* [27]

The language calling for a source providing time "at least 10 times better" than 1% TVE indicates that at least 2.6 µs synchronization is recommended. The desired accuracy is usually given as 1 µs, which corresponds to a phase angle error of only 0.022° at 60 Hz, and the time tags also require 1 µs resolution. These requirements are difficult to meet at geographically dispersed locations without GPS clocks. Therefore, in practice the time source is nearly always a GPS clock, or a PTP system that is synchronized to a GPS clock and accessed by multiple PMUs over a LAN.

VIII. TRACEABILITY OVER LEAP SECONDS AND OTHER IRREGULARITIES

Leap seconds are integer seconds that are added to UTC to maintain the difference between UTC and UT1 less than ±0.9 s. They are always added as the last second of the last day of a month, with the last days of June and December preferred. The leap seconds can also be added at other times if needed. A leap second is inserted after 23:59:59 UTC, and its official name is 23:59:60. Since leap seconds are inserted in the UTC time scale, they occur late in the afternoon in the US Pacific time zone and near noon in Asia and Australia.

Digital clocks in general, and computer clocks in particular, cannot display a time corresponding to 23:59:60, and various ad-hoc techniques must be used to define a time stamp during a leap second. Many systems, including the NIST network time servers, effectively stop the clock during a leap second, and transmit a time corresponding to 23:59:59 a second time. A similar technique repeats the time stamp corresponding to 00:00:00 of the next day a second time. (This technique has the correct long-term behavior but puts the extra second in the wrong day.) Both of these techniques have an ambiguity in the time stamp transmitted in the NTP format, since the format cannot distinguish between the first and second time stamps with the same integer value. This problem introduces an ambiguity in the time-ordering of events in the vicinity of the leap second. (For example, the NIST time servers will receive about ~900 000 requests for time during the two seconds with identical time stamps of 23:59:59.) Some operating systems "solve" the leap second problem by ignoring them altogether, and all systems are susceptible to software bugs.

Leap seconds introduce a numerical discontinuity into a time interval that includes the leap second, so that real-time systems, such as GPS system time, do not use them. GPS (and other GNSS, with the exception of GLONASS) transmit the integer-second offset between system time and UTC as part of the navigation message, shown in Eq. (2). User equipment can use this parameter to translate between system time and UTC, but this does not solve the problem of the ambiguity in the name assigned to the leap second.

Some corporations, in an attempt to minimize the impact on their systems and eliminate the discontinuity, have implemented "smears", that slow down their clocks for a period around the time of the leap second insertion [28]. This method has the advantage that the time stamps are monotonically increasing even in the vicinity of the leap second, but it has an error of order ±0.5 s with respect to the definition of UTC during the interval of the frequency adjustment. In addition, there is no standard method for applying this frequency adjustment, so that different implementations may disagree among themselves in addition to the time error with respect to UTC. Metrological traceability can be maintained through a leap second only if the user is able to program the systems to keep track of the extra second, or the smear, and take it into account.

IX. TRACEABILITY AND LATENCY

The official definitions of traceability do not address the issue of the non-zero latency between the measurement and the determination of the uncertainty. This often-small latency can convert even a direct measurement into a prediction awaiting confirmation. In many cases the assumption that the difference between the actual value and the prediction of a UTC(k) is of zero mean and has a near-Gaussian distribution can be justified on the basis of past data. The assumption can also be verified after-the-fact, and any user whose traceability data are being carefully scrutinized would be well-advised to take the verification into consideration. For example, a user of GPS via direct access should confirm that the results shown in Figure 2 continue as shown.

X. SUMMARY

Time signals, including those transmitted by GPS satellites and network time servers, can be used to establish legal metrological traceability to UTC through a UTC(k) time scale. These signals have small enough uncertainties to meet industrial synchronization and traceability requirements, but users are responsible for having sufficient evidence to prove that their requirements are being met. A critical part of this evidence is the ability to demonstrate that an unbroken chain of calibrations back to UTC through a UTC(k) laboratory exists, and that each link of the traceability chain has a documented measurement uncertainty.

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