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Abstract

Coordinated universal time (UTC) is the international reference for time and frequency measurement, and the basis of civil timekeeping world-wide. The reception of signals from global navigation satellite systems (GNSS) as a source of time and frequency (synchronization and syntonization) has found widespread use in virtually all user sectors, including electrical power supply, telecommunications, and financial institutions. This paper summarizes the concept of metrological traceability and the practices employed in the time and frequency metrology community for achieving it. Practical steps are proposed to ensure that traceability to UTC from GNSS signal reception is available to a wide community of users, addressing different levels of required uncertainty in time and frequency offset from UTC. We suggest some practical measures that can be followed by users, and improvements to the services provided by National Metrology Institutes (NMIs).

Keywords: time and frequency metrology, UTC, time dissemination, traceability, GNSS

(Some figures may appear in colour only in the online journal)

1. Introduction

Assured access to accurate time and frequency has been identified as indispensable for the functioning of modern infrastructure world-wide. The reception of signals from global navigation satellite systems (GNSS) has found widest use in virtually all sectors, including electrical power supply, telecommunications, financial institutions, time and frequency metrology, and (quite naturally) positioning and navigation. In addition, in some of the above sectors a requirement to demonstrate traceability to national or international standards has been imposed by legislation or regulation. Coordinated universal time (UTC) has been recommended as the unique time scale for international reference and the basis of civil time by the general conference on weights and measures (CGPM) already in 1975 and this has been lately confirmed in 2018.

Triggered by these observations, the consultative committee for time and frequency (CCTF), the primary international

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technical body on time scales and the SI second, considered 'promoting the mutual benefits of UTC and GNSS', as one of the hot topics in time and frequency metrology during the last few years. An important aspect of this topic concerns the clarification of the achievement of traceability to UTC from GNSS measurement. This paper presents the outcomes of the work carried out by a joint task group of the CCTF working group (WG) on GNSS time transfer and the WG on the CIPM mutual recognition arrangement. We review in section 2 the current use of GNSS signals in the process of generating UTC, we then recall the concept of metrological traceability for time and frequency measurements in section 3. The proposed practical and technical aspects to allow traceability to UTC from GNSS measurements, for different categories of users, are then presented in section 4. Actions that can jointly support achieving traceability to UTC through GNSS measurements are proposed in section 5, and we conclude with some discussion in section 6.

2. Time comparisons and time dissemination services based on GNSS signals

2.1. Status of GNSS usage and of GNSS delay calibrations in the realization of UTC

UTC is a paper time scale computed monthly by the 'Bureau International des Poids et Mesures' (BIPM) from an ensemble of about 400 atomic frequency standards and operated in National Metrology Institutes (NMI) and other authorised timing centres distributed around the world. The UTC(k) time scales generated by these institutes are approximate realizations of UTC. The clocks operated at institute 'k' are compared to the local UTC(k), and the UTC(k) time scales are compared among each other. At present, almost all the time links between UTC(k) laboratories are based on GNSS, either GNSS only, for 87% of the links, or combined with two-way satellite time and frequency transfer (TWSTFT) for the remainder. One exception is the link OP-PTB, which is established using TWSTFT only (as of June 2022).

GPS has been used since the 1980s, initially following the common-view scheme (GPS CV) [1], or its later variant, GNSS all-in-view (GNSS AV) [2]. Currently the precise point positioning (PPP) method, the best-performing GNSS-based approach [3] is widely used. Unlike GPS CV and AV which are based on code measurements only, PPP is based on a precise modelling of both code and carrier phase measurements, allowing time comparisons to be made at the level of 1 ns, and frequency comparisons with a fractional frequency uncertainty of 10^{-16} for an averaging time of one day. Because of the convenience and performance of the PPP analysis, the signals from the other GNSS have been used by the BIPM only to establish back-up links. In general, any GNSS time comparison method can be employed to compare clocks of users within any nation to its UTC(k). Such comparison services have been established and are referred to in section 4.2. Most services employ the common-view scheme [1].

To be used for such applications, the GNSS stations must be calibrated, i.e. the signal delays in the receiving equipment (antenna, cable, and receiver) must be determined and removed from the clock difference solutions. The BIPM and various regional metrology organizations (RMOs) started a collaboration in 2014 to calibrate the GNSS equipment of each time laboratory participating in UTC. To improve the efficiency and reduce the administrative load, a hierarchical structure was adopted where the BIPM is responsible for the calibration of only a few laboratories, named group 1 laboratories (G1), selected in each RMO. These G1 laboratories are then responsible for the calibration of the other laboratories (group 2, or G2) within their RMO. The BIPM guidelines for GNSS calibration [4] describe the motivation, the process, and the detailed technical procedures for different types of GNSS timing receivers.

The internal signal delays of a GNSS receiver are frequency and modulation dependent. Up to 2020, only GPS signal delays were determined. A BIPM-organized campaign that year, designated 1001–2020 [5], provided Galileo signal delays for the first time. It is expected that delays for BeiDou-3 signals will also be available from the next campaign of this kind.

The status of calibrations, including results obtained in the past, can be found in [5]. Each campaign is documented in a short summary and a detailed report issued by the G1 laboratory involved. The different options for equipment calibration at time laboratories are summarized in a separate document [4]. As a result of the campaigns, the uncertainty of individual signal delays in calibrated receivers has been assessed to be typically of the order of 1 ns. UTC links between laboratories calibrated under this scheme are assigned a minimum calibration uncertainty of 1.5 ns for G1–G1 links and 2.5 ns for G1–G2 links as agreed by the CCTF WG on GNSS time transfer. The receiver calibration uncertainty includes an ageing component that increases with time passed since the last calibration.

The CCTF protocols for GNSS receiver calibrations, and for continuous measurements of GNSS data and laboratory clocks against UTC(k), together with regular participation in UTC, provide the basis for the timing laboratories to achieve traceability to UTC and the SI second that they can then use to provide calibration services to their clients.

2.2. Predictions of UTC broadcast by the GNSS

In addition to the broad use of GNSS for navigation, positioning and scientific applications, the GNSS also fulfil an effective time dissemination function. This is inherent in the basic technical functionality of a GNSS, and in the collaboration between GNSS operators and timing institutes. In the GNSS ground segment, the system time GNSS_T is generated from an ensemble of clocks located on the ground and might also include satellite clocks. A prediction of the difference between GNSS_T and a given realization of UTC, as explained below, is broadcast in the GNSS navigation messages. It contains a three-hour offset in the case of GLONASS, an integer number of seconds due to the insertion of leap seconds in UTC for the other GNSS, and in all cases a fractional-second part. This message allows any user to synchronize their clock to the broadcast prediction of UTC, conventionally named $bUTC_{GNSS}$.

For each GNSS the offset in the broadcast message corresponds to the predicted difference between that GNSS time scale and either a specific UTC(k) or a combination of several UTC(k) time scales. GPS broadcasts a prediction of UTC based on UTC(USNO) realized at the United States Naval Observatory [6]. GLONASS broadcasts a prediction of UTC based on UTC(SU) realized at the Russian metrology institute of technical physics and radio engineering (FSUE 'VNIIFTRI') [7]. Galileo relies on a contractual collaboration with 5 European NMIs and broadcasts a prediction of UTC without specifying the particular UTC(k) that it is based on [8]. BeiDou broadcasts a prediction of UTC built from UTC(NTSC) realized at the National Time Service Center of China [9] and UTC(NIM) realized at the China National Institute of Metrology [10].

Regional systems also broadcast similar messages. For the Quasi-Zenith Satellite System (QZSS) the UTC prediction is based on UTC(NICT), realized at the National Institute of Information and Communications Technology [11], and for the Navigation with Indian Constellation (NavIC) the reference is UTC(NPLI), realized at the National Physical Laboratory of India [12]. NavIC also provides in parallel a prediction of the offset between NavIC time and UTC. The formats of the respective messages are GNSS-specific and are documented in the respective Interface Control Documents.

2.3. Relating a user time scale to UTC via GNSS

The schematic in figure 1 illustrates the parties involved in obtaining time and frequency from GNSS signals and their general relationship. The BIPM and the UTC(k) laboratories, which provide signals representing approximations of UTC, support the GNSS operators represented in the middle box. The realization of GNSS_T and of the signals in the navigation messages by the GNSS operators is in general not fully transparent to the user. Different algorithms are in use to determine the offset between the specific UTC(k) and the respective GNSS_T, and to predict its evolution into the future. This step of 'UTC prediction' needs to be conceptually distinguished from the [$bUTC_{GNSS}$ − GNSS_T] value which is reported in the navigation message as a set of the parameters, such as time offset and rate, that are valid only for a certain duration (typically one day).

For a user who wishes to relate their local time scale, TS_user, to UTC(k) or UTC, two possible configurations are available. One is where the TS_user is generated from a suitable (atomic) clock and is connected to a GNSS timing receiver of the type typically in use in metrological timing centres (section 2.1). From the GNSS measurements collected at the user side and in the National Metrology Institute, the offset between the user time scale and UTC(k) is calculated as follows:

$$\mathrm{TS\_user} - \mathrm{UTC(k)} = [\mathrm{TS\_user} - \mathrm{GNSS\_T}] - [\mathrm{UTC(k)} - \mathrm{GNSS\_T}]. \quad (2.1)$$

In order to relate TS_user to UTC, the difference UTC − UTC(k) needs to be added. This latter is published monthly by the BIPM in the Circular T.

The second configuration, and by far the most common one, is where the output signals of an oscillator (quartz or atomic frequency standard) are disciplined with the help of the received GNSS signals. This configuration is called a GNSS disciplined oscillator (GNSS DO), and its output signals (standard frequency, e.g. 10 MHz, and 1 pulse per second, 1 PPS) represent TS_user. Both options allow TS_user to be related to the time scale GNSS_T derived from the pseudorange measurements made by the receiver using the received satellite signals. By adding the broadcast quantity [$bUTC_{GNSS}$ − GNSS_T], the offset between the user time scale and UTC as predicted in the GNSS navigation message can be calculated as follows:

$$\mathrm{bUTC_{GNSS}} - \mathrm{TS\_user} = [\mathrm{GNSS\_T} - \mathrm{TS\_user}] + [\mathrm{bUTC_{GNSS}} - \mathrm{GNSS\_T}]. \quad (2.2)$$

The users' receiver software can calculate the predicted offset at the moment of reception of the signal. The individual satellites of a particular GNSS might broadcast different information at the same time, but the differences are usually within a few nanoseconds [13].

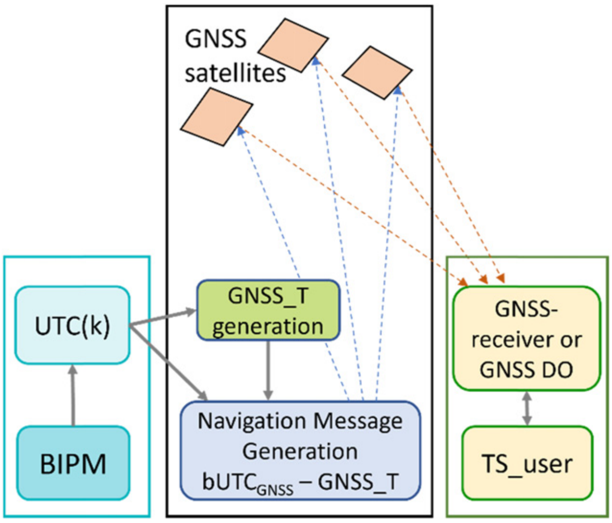

Figure 1. Timing elements involved in relating UTC and TS_user via GNSS. The central block contains the elements under the responsibility of a GNSS provider, to the left the elements accessed from the metrological community and to the right the user part.

In a GNSS DO, the TS_user is typically realized in such a way that the time offset between TS_user and $bUTC_{GNSS}$ (as in equation (2.2)) is close to zero (for timing applications) or kept constant on average (for frequency applications).

In order to relate TS_user to UTC, the difference UTC − $bUTC_{GNSS}$ needs to be added. The latter can be obtained from the following relation

$$\begin{aligned} \mathrm{UTC} - \mathrm{bUTC_{GNSS}} = {} & [\mathrm{UTC} - \mathrm{UTC(k)}] \\ & + [\mathrm{UTC(k)} - \mathrm{GNSS\_T}] \\ & - [\mathrm{bUTC_{GNSS}} - \mathrm{GNSS\_T}] \quad (2.3) \end{aligned}$$

where UTC − UTC(k) is provided by BIPM in Circular T, the second term is available at a UTC(k) timing laboratory operating a calibrated receiver, and the third term is the same as in (2.1). In addition, the BIPM publishes daily values of [UTC − $bUTC_{GNSS}$] in section 4 of Circular T. The different potential scenarios for ensuring metrological traceability to UTC through the configuration given by equation (2.1) or through the combination of (2.1) and (2.2) are discussed in detail in section 4, including a discussion of the associated uncertainties.

3. On traceability

3.1. Metrological traceability

The international vocabulary of metrology (VIM) reference document provides a definition of 'metrological traceability' to a given reference [14, section 2.41]: it is 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'. Here the 'reference' can be a measurement unit through its practical realization, and the computation of a chain of calibrations might require a calibration hierarchy [14, section 2.40]. Where more than one input quantity is included in the measurement model, each of the input quantity values should itself be metrologically traceable. The International Telecommunication Union-Radiocommunication sector (ITU-R)—adopted an almost identical definition in its glossary [15].

The International Laboratory Accreditation Cooperation (ILAC) [16] adopted the same definition as in the VIM and refers to both the VIM and the ISO/IEC 17025 standard [17]. The latter has been developed by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) and gives detailed information on establishing and demonstrating metrological traceability, while referring to the International Committee for Weights and Measures (CIPM) Mutual Recognition Arrangement (MRA), ILAC and the joint BIPM, OIML, ILAC and ISO declaration on metrological traceability [18].

In addition, recommendations have been made by the following organizations involved in metrology, standards, and accreditation: the BIPM, the International Organization of Legal Metrology (OIML) and several accreditation bodies. These additional recommendations specify that the required calibrations should be performed by NMIs or Designated Institutes (DI) participating in the CIPM-MRA and having their calibration and measurement capabilities (CMC) published in the relevant area of the key comparison database (KCDB) maintained by the BIPM [19, 20]. It is important to point out here that measurements traceable to the SI can also be made by an accredited laboratory (AL) whose calibration and testing capabilities were formally approved by an accreditation body [16]. Note finally that the assessment of NMI/DI measurement capabilities might be based on different validation processes depending on different RMO rules.

Key comparisons (KC) underpin the equivalency of CMCs between different NMI and DI. In the time metrology domain, there is only one CCTF key comparison: CCTF-K001.UTC [21], and UTC is defined as the KC reference value. In this frame, the metrological traceability to UTC is ensured for UTC(k) time scales generated by NMIs or DIs participating in the CIPM MRA, having degrees of equivalence [UTC − UTC(k)] and/or CMCs published in the BIPM KCDB. However, the degrees of equivalence [UTC − UTC(k)] are published retrospectively, so that traceability to UTC can, strictly speaking, be attributed only to measurements made in the past.

The reader will find throughout this document wording like 'traceability of an output signal' or 'traceability of a local reference frequency'. This should be understood to imply that measurements made using the respective signals are considered as traceable.

3.2. General remarks related to the standard ISO/IEC 17025

The standard ISO/IEC 17025 contains requirements that testing and calibration laboratories have to meet if they wish to demonstrate that they operate a quality management system, are professionally competent, and are able to generate technically valid results. This international standard is applicable to all organizations performing tests and/or calibrations. These include, for example, first-, second- and third-party laboratories, and laboratories where testing and/or calibration forms part of inspection and product certification. All equipment used for tests and/or calibrations, including equipment for subsidiary measurements (e.g. for environmental conditions) having a significant effect on the accuracy or validity of the result of the test, calibration or sampling shall be calibrated before being put into service. The laboratory shall have an established programme and procedure for the calibration of its equipment' (citation from [17]). The calibration for time and frequency equipment receiving GNSS signals will be discussed in section 4.

Furthermore, in Annex A1 of [17] we read: 'Measurement standards that have reported information from a competent laboratory that includes only a statement of conformity to a specification (omitting the measurement results and associated uncertainties) are sometimes used to disseminate metrological traceability. This approach, in which the specification limits are imported as the source of uncertainty, is dependent upon:

- The use of an appropriate decision rule to establish conformity;

- The specification limits subsequently being treated in a technically appropriate way in the uncertainty budget.

The technical basis for this approach is that the declared conformance to a specification defines a range of measurement values, within which the true value is expected to lie, at a specified level of confidence, which considers both any bias from the true value, as well as the measurement uncertainty'. This implies that both calibration and conformity should be considered when discussing the traceability to UTC of GNSS signals.

3.3. Stakeholder regulatory and technical requirements for traceability to UTC

Different user communities have developed normative documents which govern their rules of conduct, and among other things these documents specify how time and frequency signals are to be employed in their community. The term traceability is used with different connotations in the various normative documents. Where the term 'traceability' is used in this paper it refers to metrological traceability as defined above. It is a qualitative and not a quantitative term and should not be confused with accuracy, a misconception that can be found occasionally.

The standard ISO/IEC 17025 [17] is applicable for the use of GNSS signals as a source of reference signals for services offered to third parties. The same holds when explicit reference is made to 'traceability to UTC'. Strict adherence can be waived if GNSS-derived signals are used for internal purposes only.

4. Suggested actions to permit traceable measurements based on GNSS signal reception

4.1. A word of caution

The widespread use of GNSS in many user communities has spurred concerns about the vulnerability of a GNSS-based service because of the weakness of the received signals and the proliferation of electronic equipment suitable for jamming and spoofing GNSS signals [22]. From a practical point of view, jamming and spoofing present different problems. A jamming event is a denial of service. It can cause significant perturbations, but it is usually easy to detect and should normally be identified through the obligatory process of verifying correct operation. On the other hand, a spoofing event corrupts the data, but the effect may not be detected by the receiver itself. It can often be detected by comparison with data from other sources or by comparing the received data with the expectation based on the stability of the receiver clock. Detection and/or mitigation of spoofing is, however, out of the scope of this paper, where we consider only the ideal situation in which the GNSS signals are received properly.

4.2. Differentiation between types of use

In figure 2 we introduce three usage classes (U1, U2 and U3) for time information obtained from GNSS signals. Later, we detail for each class how traceability can be achieved and

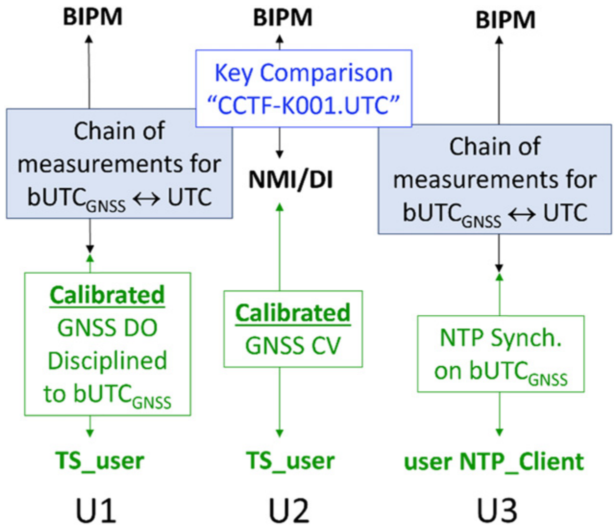

Figure 2. General scheme for obtaining time traceability using GNSS signals, for 3 of the most common use cases (U1, U2 and U3).

> the factors that dictate the uncertainty with which [UTC − TS_user] can be obtained.

In addition to disciplining the internal oscillator of the GNSS DO, decoding of the navigation message allows the receiver to obtain the calendar date and time-of day. The encoding of the required information is described in the GNSS ICDs [6–11]. Retrieval and dissemination of this data content is the most basic use of GNSS signals for timing, that many low-cost timing receivers employ to provide a source of time. Many GNSS OEM modules are therefore embedded in servers intended to distribute time information in local area networks (LANs) or over the public internet. Packet exchange using the NTP protocol [23] represents the most common method for synchronizing computer clocks and devices over the internet or in LANs. This usage is designated as U3 in figure 2. Other network-based time transfer protocols (e.g. PTP and White Rabbit [24]) exist but are less prevalent than NTP. Specific suggestions for NTP case are given in section 4.4.

Another type of use (U2) involves the continuous or periodic comparison of TS_user to an NMI/DI using GNSS time transfer as described in section 2.1. This method typically involves a tight collaboration or contractual relation between the NMI/DI and the user, and requires the technical competency of the former to ensure traceability. Some services of this type are already offered by NMIs/DIs, and in section 5 we propose to expand these activities and include them formally in the CMC list of the organization.

The type of use (U1) that deserves greatest attention is the stand-alone operation of a GNSS DO to provide high-accuracy reference signals, either as a source of time (1 PPS) signals, or as a source of standard frequency only.

For all these cases, two building blocks have been identified to ensure that traceability of the measurements can be achieved: (1) 'appropriate' calibration of the output signals (1 PPS or standard frequency), detailed in section 4.3, and (2) the existence of a documented chain of comparisons between the user and the NMI/DI or UTC, detailed in section 4.4.

4.3. Calibration requirements

According to its definition, traceability is a qualitative and not a quantitative term. To simplify the classification of metrological requirements and guide the adoption of the appropriate operating practices, we propose a tiered approach, depending on the user need (frequency or timing or both) and on the requested uncertainty of the output signals. Thus, we have defined a hierarchy of accuracy levels for time and frequency signals, with the requirements to establish traceability of a GNSS device specified for each level. This has been guided by the typical accuracies of the reference oscillators (crystal oscillator, rubidium oscillator or caesium atomic frequency standard) that a GNSS DO would replace at the user side. In particular, it draws upon the authors' substantial experience with such devices, their behaviour, the sources of uncertainty inherent in their practical operation, and typical specifications quoted for the instruments by the manufacturers.

4.3.1. Calibration requirements for measurements of frequency. We consider the situation where a GNSS DO is employed by a calibration laboratory as a frequency standard. A typical example is the use of the 5 MHz or 10 MHz output signal from a GNSS DO acting as the laboratory reference standard. The output of the GNSS DO can be made traceable to UTC by performing a comparison to evaluate the accuracy and the stability of the standard-frequency output. The calibration can take several forms depending on the required level of uncertainty, expressed below in standard-type uncertainty, U [14], and illustrated in figure 3.

a. *For uncertainties U above* 1×10^{-8} *at an averaging time of one day*: the GNSS DO could represent the external frequency reference for counters, synthesizers and general signal generators. The manufacturer should seek a calibration, preferentially by an AL or an NMI/DI, of at least one unit of a given model and repeat the calibration for each update (firmware or hardware) of this model. Then all units of this model could be used when accompanied by a calibration certificate or a certificate of conformity issued by the manufacturer and bearing its logo, valid for the respective model. Each certificate must refer to the manufacturer's reference unit. A similar practice is known as 'type approval' in legal metrology. To the best of our knowledge, such practice is supported by [17], see section 3.2.

b. *For uncertainties U between* 1×10^{-8} *and* 1×10^{-10} *at an averaging time of one day*: the GNSS DO could act as a substitute for a high-quality temperature-compensated or ovenized crystal oscillator. The manufacturer should organize a calibration by an AL or NMI/DI of at least one unit of a given model and repeat this calibration for each update (firmware or hardware) of this model. This unit is then used by the manufacturer to individually calibrate units of the same type. They could then be used when accompanied by a calibration certificate or a certificate of conformity issued by the manufacturer and bearing its logo for each individual device delivered to the customer. Each certificate must refer to the manufacturer's reference unit. The manufacturer should seek approval of an accreditation body of its calibration capabilities.

c. *For uncertainties U between* 1×10^{-10} *and* 1×10^{-12} *at an averaging time of one day:* the GNSS DO could easily substitute for a free-running rubidium atomic frequency standard. In this case the GNSS DO should be directly calibrated by either an NMI/DI or an AL.

d. *For uncertainties U below* 1×10^{-12} *at an averaging time of one day*: the GNSS DO could substitute for a commercial caesium atomic frequency standard. The frequency from the GNSS DO should be calibrated regularly against a standard frequency maintained by an NMI/DI. To that aim, some NMI/DIs have already published CMCs for frequency comparisons, based on GNSS common view time transfer, which allows the frequency offset between the GNSS DO and the UTC(k) at the NMI/DI to be determined together with its associated uncertainty. This procedure will likely require the operation of a dedicated GNSS timing receiver at the user site.

4.3.2. Calibration requirements for measurements of time. The 1 PPS output of a GNSS DO is affected by GNSS signal delays in the antenna, the antenna cable, and internal cabling and processing. The user therefore needs an initial calibration of their GNSS equipment for hardware time delays. In many cases this will be replaced by a calibration of the 1 PPS output with respect to an external reference with a known, calibrated offset from a UTC(k) or UTC.

Here we can distinguish different types of users and the required level of uncertainty U of the 1 PPS output with respect to UTC, illustrated in figure 4.

a. *For uncertainties U greater than 1* μs*:* based on the authors' experience in the operation of GNSS DOs, offsets exceeding 1 μs are rare and not related to signal delays. The manufacturer should seek a calibration by an AL or NMI/DI of at least one unit of a given model and repeat this calibration for each update (firmware or hardware) of this model. The calibration should specify the maximum offset of the 1 PPS output from UTC, with stated uncertainty for a given configuration of antenna, antenna cable and receiver. Then all units of this model could be used for traceable measurements when accompanied by a calibration certificate or a certificate of conformity issued by the manufacturer and bearing its logo, valid for the respective model. Each certificate must refer to the manufacturer's reference unit. Devices used exclusively as a source of time information for dissemination via NTP may require no calibration. A similar practice is known as 'type approval' in legal metrology. To the best of our knowledge such practice is supported by [17], see section 3.2.

b. *For uncertainties U between 100 ns and 1* μs: time offsets from UTC exceeding 100 ns have been observed in some units, and these offsets sometimes were in contradiction to the manufacturer's specifications. The authors therefore propose that manufacturers should organize a calibration by an AL or NMI/DI of at least one unit of a given model and repeat the calibration after each hardware or firmware update for this model. This unit is then used by the manufacturer to individually calibrate units of the same type. They could then be used for traceable measurements when accompanied by a calibration certificate or a certificate of conformity issued

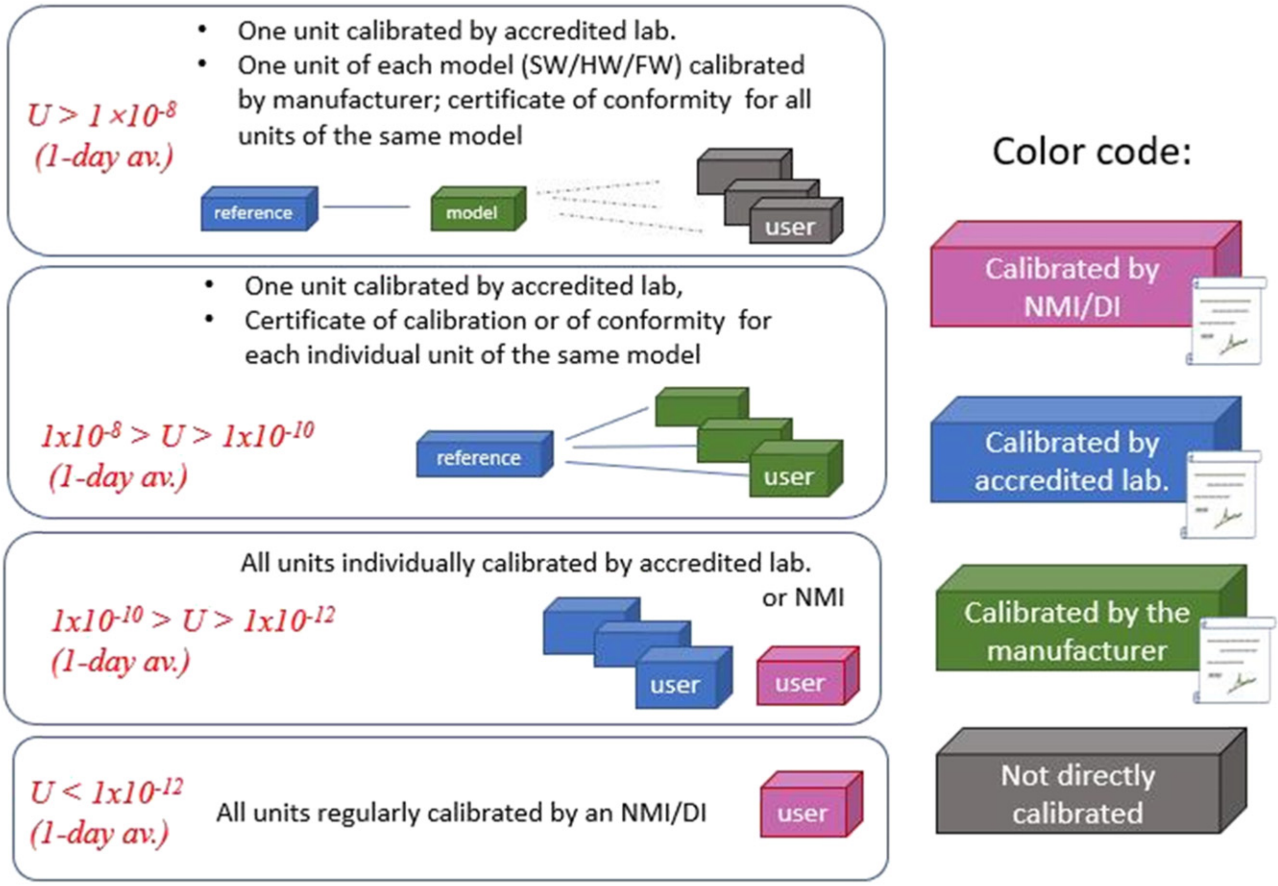

Figure 3. Calibrations needed to enable traceable frequency measurements to be made by a user within specified ranges of uncertainty.

by the manufacturer and bearing its logo for each individual device delivered to the customer. Each certificate must refer to the manufacturer's reference unit. The manufacturer should seek approval of an accreditation body of its calibration capabilities.

c. *For uncertainties below 100 ns*: applications requiring measurements of the offset between TS_user and UTC or a UTC(k) with an uncertainty below 100 ns call for a more elaborate procedure. Many different physical effects have indeed to be considered in the measurements, depending on the final uncertainty target. In these situations, the GNSS station should be calibrated at regular intervals by either an NMI/DI or an AL, which would provide good advice on what effects should be considered.

4.3.3. General considerations on calibrations. Different technical options are available for performing the required calibrations. As the GNSS hardware delays can vary with environmental changes, or ageing, periodic recalibrations are suggested at regular intervals, depending on the required level of accuracy. For a long time, GNSS DOs on the market were in fact GPS DOs. Modern devices are able to track signals from more than one GNSS, but the output might still depend on GPS alone, or another GNSS alone, or an average of all received GNSS signals. This may lead to significant differences in the output signals, in particular the timing of the 1 PPS signal. The calibration certificate must therefore include the GNSS DO configuration parameters, comprising the GNSS used for the output 1 PPS synchronization.

The calibration measurement only evaluates the performance of the GNSS DO at the time of the calibration, so the possibility of a fault developing later remains possible. Other means must therefore be used to verify that the device is operating correctly between calibrations. It is important to monitor the GNSS DO parameters, in particular its lock onto the GNSS signals and its oscillator control voltage variations. An additional comparison with another local time or frequency standard is also an effective means of monitoring a GNSS DO. If the second standard is also a GNSS DO then it should be from a different manufacturer to remove the possibility of both receivers displaying similar anomalous behaviour at the same time, which would not be detected by the comparison. Users are also advised to verify that the GNSS system in use by the GNSS DO is operating correctly. Relevant information is available from websites maintained by the GNSS operators, and some NMIs report their GNSS signal reception results.

It should be noted that the approaches described above for GNSS DO calibrations in time and frequency apply only to the output 1 PPS and standard frequency signals from the GNSS DO. If the GNSS DO is embedded in another appliance or system, the approach needs to be specifically adapted to the situation.

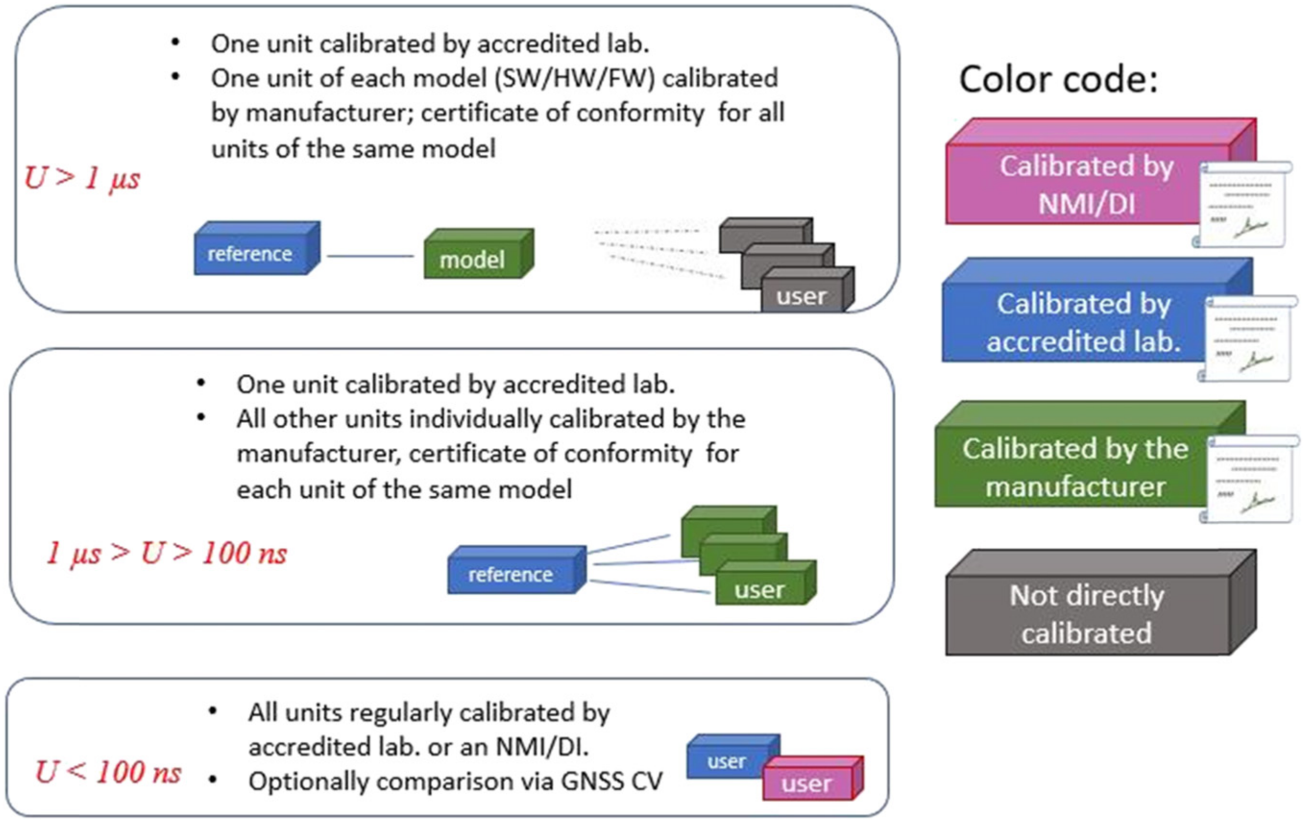

Figure 4. Calibrations needed to enable traceable time determination to be made by a user within specified ranges of uncertainty.

4.4. Options for a calibrated chain of measurements between bUTC$_{GNSS}$ and UTC

This section contains a more detailed analysis of the usage classes defined in section 4.2. For each option considered, the uncertainty contributions are stated.

Usage class U1 as illustrated in figure 5 involves no continuous link between the user and an NMI/DI. The most common method of using a GNSS DO falls in this category. The GNSS DO outputs are aligned on the bUTC$_{GNSS}$ as determined from the pseudorange measurements and the navigation message as given by equation (2.2). The authors identified three options for establishing a calibrated chain of measurements between bUTC$_{GNSS}$ and UTC. To make any of these approaches easily and continuously available, additional services have to be established. As detailed below, one option (U1.1) requires some services from an NMI/DI; a second option (U1.2) requires some additional service from the BIPM, while a third option (U1.3) would require an action at the GNSS provider level.

Since all U1 usage path calibrations depend on the GNSS DO calibration, we compute the uncertainty in that first. Two components have to be considered: u_{cu}, for the relative calibration of the GNSS DO against a reference signal at the NMI/DI, and u_{cr} related to the calibration of the NMI/DI or AL reference against UTC.

(U1.1) The calibrated chain of measurements between bUTC$_{GNSS}$ and UTC is given by equation (2.3). The 'NMI/DI bulletin' mentioned in figure 5 reports the difference between the local UTC(k) and the bUTC$_{GNSS}$ included in the navigation message. This new service to be provided by an NMI/DI should be defined in a new CMC, which will require joint effort from the CCTF WGs on GNSS and on the MRA, respectively. The NMI/DI should publish the results in a 'bulletin', with its format, medium and periodicity chosen to best meet its users' needs, and possibly according to recommendations from the two WGs. The user can combine this information with his local measurements based on the GNSS DO output signals to obtain traceability to UTC. The bulletin of any NMI can be used for this purpose as the geographical effect on the observed [UTC(k) − bUTC$_{GNSS}$] difference caused by signal reception at different sites is negligible compared with the calibration uncertainties.

The NMI/DI must develop the related uncertainty budget. The combined uncertainty comprises the term u_c (see above), and a term u_b associated with the broadcast value and described in [13]. It is related to the fact that at a given point in time different navigation messages may be transmitted from the satellites of a GNSS. The study [13] showed that the magnitude of u_b is dependent on the GNSS. Another uncertainty contribution is u_l for the link between UTC and UTC(k), which is reported in the BIPM Circular T, section 1. Strictly speaking, the required link should be established using the monthly publication of the degrees of equivalence—including uncertainty U_k (95% confidence value) in the BIPM KCDB.

(U1.2) The BIPM, in its Circular T (section 4), at present documents 'relations of UTC and TAI with predictions of UTC(k) disseminated by GNSS', currently only for GPS

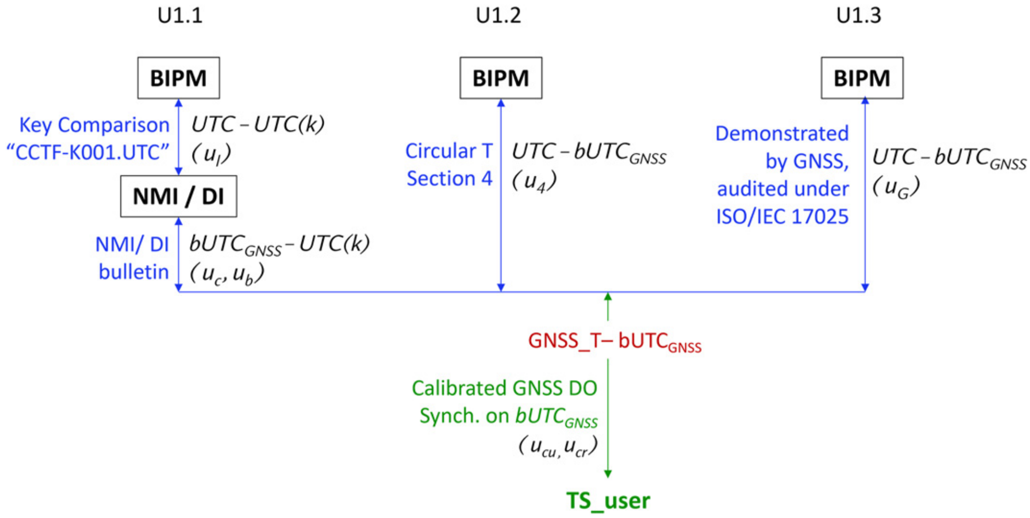

Figure 5. Use case U1, showing the three options to establish the traceability chain.

and GLONASS. As of mid-2022, the information is based on measurements made at Observatoire de Paris for GPS and at Borowiec Astrogeodynamic Observatory (AOS) for GLONASS. In the near future section 4 will be extended to include measurements of Galileo and BeiDou in addition, as recommended by the CCTF in 2015. The required multi-GNSS observation data will be collected from a group of G1 laboratories, distributed across the globe, as these are regularly calibrated by the BIPM [4]. A reference to Circular T section 4 would then be an option to ensure traceability for internal services for a user. The combined uncertainty for the link from TS_user to UTC comprises the terms u_{cu} for the calibration of the local user equipment and u_4 as reported in the BIPM Circular T section 4. The term u_4 will include an u_b-value as described before.

(U1.3) The calibrated chain of measurements between $bUTC_{GNSS}$ and UTC could also be demonstrated by the GNSS provider. This would require that the GNSS provider maintains documents showing a validated traceability of $bUTC_{GNSS}$ to UTC with an associated uncertainty u_G. The elements needed to validate the traceability of $bUTC_{GNSS}$ to UTC should be audited according to the ISO/IEC 17025 standard. It is not essential that the GNSS provider itself is accredited according to ISO/IEC 17025. The combined uncertainty for the link from TS_user to UTC comprises the terms u_{cu} for the calibration of the local equipment and u_G as reported (in the future) by the GNSS provider.

Type of use U2 involves GNSS time transfer between a user and a UTC(k) at an NMI/DI, and is shown in figure 6.

To that aim, some NMI/DI have already published CMCs for time comparisons with users based on GNSS CV time transfer [1], which allow the time offset between the user clock and the UTC(k) at the NMI/DI to be determined along with its associated uncertainty. Establishing a permanent link to an NMI/DI is in principle straightforward but requires operation of a dedicated timing receiver at the user site, which must be calibrated with associated uncertainty u_{cu} by a competent institute. Uncertainties of the CV links (u_{cv}) must also be

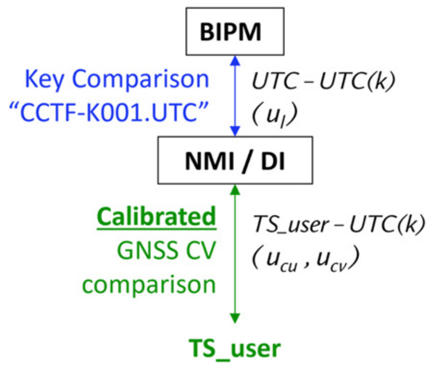

Figure 6. Use case U2, involving continuous exchanges between the user and an NMI/DI.

considered, due to the noise, local multipath, and atmospheric perturbations. Rather than a CV link, a difference of PPP solutions computed at the user side and at the NMI/DI side can also be used, which can improve the statistical uncertainty but not the contribution from the time delay calibration. Uncertainties in the time comparison lower than 100 ns, even below 10 ns, can be achieved in this way, but the uncertainty for the time difference [TS_user − UTC(k)] may be compromised by the instability of TS_user. Traceability to UTC involves the link between BIPM and the NMI/DI with the associated uncertainty u_l (see above).

Type of use U3 represents the dissemination of time information based on packet exchange using the NTP protocol and is illustrated in figure 7.

A variety of equipment exists that generates time protocols, in particular the network time protocol (NTP) [23], using a GNSS receiver as the time reference. The oscillator inside the GNSS receiver is disciplined as in any GNSS DO, and the navigation message is decoded to generate a representation of time-of-day. The NTP time stamp expresses the UTC time as the number of seconds and fractions of a second that have elapsed since 1 January 1900. The 1 PPS or standard frequency output signals representing TS_user are not relevant in this

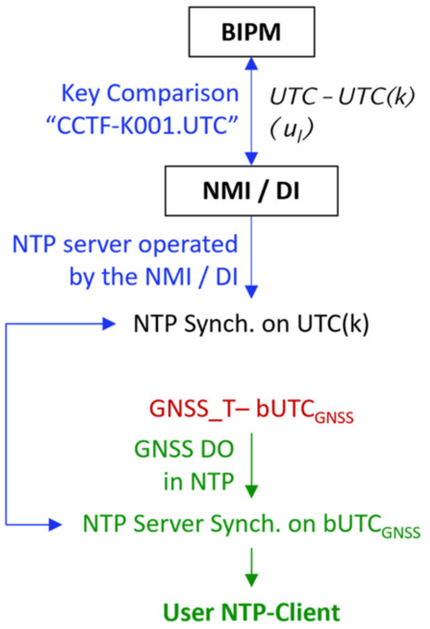

Figure 7. Use case U3, involving time dissemination in networks.

type of use. Establishing a link to an NTP server represents the most common method for synchronizing computer clocks and devices over the public internet, designated as 'User NTP-client' in figure 7. Although the technique is in principle capable of providing time accurate to 10 µs, in a general use case involving the public internet it may only be necessary to prove traceability at the level of 100 ms. Discussion of the achievable accuracy of time transfer between NTP server and client in the public internet is beyond the scope of this paper. In the general case, comparison with a second NTP server (or more), which is operated by, for example, an NMI/DI and is therefore independent of GNSS, is considered as sufficient to verify the proper function of the user NTP server. The options listed for type of use U1 would also work, but as a break of the medium is involved, they will seem less attractive to users. For higher accuracy, PTP and White Rabbit protocols that aim at uncertainties below 1 µs, the methods described in U1 and U2 cases, as well as calibration of the network equipment delays, would be required.

5. Proposed actions

Considering suggestions received from a variety of interested parties, the timing properties of GNSS signals, the typical performance of GNSS DOs, and the rules for obtaining metrological traceability to UTC (section 3.1), the authors propose the following, backed by a CCTF 2022 Recommendation [25].

The proposed actions to users are:

- To carefully analyse their respective needs and improve the wording and communication on 'traceability' in their publications so that it conforms with the established meaning of this term in metrology;
- To analyse their needs regarding the uncertainty for the time and/or frequency offset of their clocks from UTC or its national realizations UTC(k) and to follow the corresponding advice regarding calibration of their GNSS disciplined oscillators;
- To maintain log files and other documentation that are adequate to satisfy any statutory or regulatory requirements, especially for verifying the proper performance of the equipment in the past. These records may supplement the log files that may be provided by the equipment manufacturer, as discussed below.

As a general guidance, the tighter the user's uncertainty requirements for time and frequency signals, the more care in calibration and monitoring is required. For timing uncertainties below 1 µs and frequency uncertainties below 1×10^{-12}, metrological traceability should be established as the best way to assure the validity of the uncertainty budget and the signal accuracy. Users are encouraged to make use of the services offered by NMIs/DIs and to build on the expertise available there.

The traceability to UTC from bUTC$_{GNSS}$ for any user is limited to their own internal use. The user can provide similar services to third-party users and thereby guarantee metrological traceability of third-party users' reference signals to UTC if these services are covered by a QMS compliant with the ISO/IEC 17025 standard. This may constitute a limitation on a general use of bUTC$_{GNSS}$ if these requirements are not met.

The proposed actions to NMIs/DIs are:

- To support the establishment of 'the unbroken chain of calibrations' by offering services to calibrate GNSS receiving equipment at their premises or remotely, documented in the appropriate CMCs in the BIPM KCDB;
- To publish results on the performance (stability and offset from the local UTC(k)) of received GNSS signals, including an uncertainty estimate, and seek approval of such capabilities as a new CMC;
- To publish GNSS observation data in standard formats (RINEX [26] or CGGTTS [27]), or in simplified formats, accompanied by documentation on their best usage and a statement of the measurement uncertainty.

From a formal point of view, it is important to note that a UTC(k) laboratory included in the BIPM Circular T, but not having the status of a NMI/DI and hence not reported in the KCDB, could also propose this service, but it would be considered as valid for traceability to UTC only if this laboratory is covered by a QMS and accredited for such service provision.

The proposed actions to GNSS DO equipment manufacturers are:

- To seek calibration of their GNSS DO models as proposed in sections 4.3.1 and 4.3.2;
- To provide technical documentation of their devices, including specifications for the parameters of time accuracy to UTC and frequency instability as a function of averaging time, according to metrological rules and adapted to the users' needs;
- To include functions in their devices that allow the user to verify correct operation, for example by monitoring

and keeping records of its internal control parameters. To this end, the GNSS DO should provide a log file that includes information about the status of the oscillator lock to the GNSS signals. The reference GNSS(s) time scale for the receiver's output 1 PPS signal should be specified, as this can be one of the $bUTC_{GNSS}$ or a combination. The minimum information required is the lock status, but other desirable information includes the recording of the control voltage to the internal oscillator, number of satellites tracked, events such as loss of satellite signals, poor signal-to-noise ratio etc. Users are invited to select models that provide such capabilities and to include observance in their QMS.

The proposed actions to GNSS providers are:

- To seek collaboration with NMIs/DIs regarding GNSS system time realization and monitoring;
- To describe the realization of GNSS system times and the information contained in the navigation messages following metrological practice and vocabulary.

6. Conclusions

Access to accurate time is crucial for many applications in industry and technology. The free availability of GNSS signals of excellent quality and reliability has spurred the extensive reliance on GNSS as a single source of time and the neglect of other sources. In recent years the proliferation of equipment to disrupt reception of GNSS signals and concern about the vulnerability of services has led to a re-think, with requests from users for assured access to accurate time based on more than one source [22]. Furthermore, legal requirements or regulations issued by many user communities specify traceability to national or international standards when measurements are made and time stamps are issued. This trend is consistent with general metrological requirements. International consistency and comparability of measurements are essential for international collaborations in many application fields to ensure that measurement results can be universally accepted. This aim can only be guaranteed if measurement results are metrologically traceable to internationally recognized references. In the authors' view the required level of traceability is not attainable by blindly trusting the output of any GNSS device.

The authors encourage the use of UTC as the unique international reference time scale and as the basis of civil time in as many applications as possible. They also welcome the ongoing activity of BIPM to improve the documentation and explanation of the use of predictions of UTC in GNSS navigation messages. The CCTF WG on the CIPM MRA is invited to consider the definition of two new services, one on the calibration of GNSS equipment delays and the other on $bUTC_{GNSS}$ monitoring, by revising the current CCTF-MRA guideline 1. The NMIs/DIs are encouraged to provide the additional services that user groups may need in pursuit of attaining traceability to UTC with their GNSS equipment.

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List of Acronyms

AL	Accredited (calibration) laboratory
AOS	Astrogeodynamical Observatory, Space Research Centre P.A.S., Poland
AV	All-in-view, method for evaluating GNSS time comparisons
BDT	BeiDou system time
BIPM	Bureau international des poids et mesures
$bUTC_{GNSS}$	Broadcast prediction of UTC in GNSS navigation messages
CCTF	Comité consultatif du temps et fréquences
CGPM	Conférence général des poids et mesures
CIPM	Comité international des poids et mesures
CMC	Calibration and measurement capability
CV	Common view, legacy method for evaluation of GNSS time comparisons
DI	Designated institute
DO	Disciplined oscillator
DUT	Device under test
FSUE 'VNIIFTRI'	Russian metrology institute of technical physics and radio engineering
G1, G2	Group 1, group 2
GLONASS	Global Navigation Satellite System (Russian)
GNSS	Global navigation satellite system
GNSS_T	GNSS system time
GPS	Global positioning system
ICD	Interface control document (issued for each GNSS by the operator)
IEC	International Electrotechnical Commission

IGS	International GNSS service
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
ITU-R	International Telecommunication Union, Radiocommunication sector
KCDB	Key comparison data base
MRA	Mutual recognition arrangement
NavIC	Navigation with Indian Constellation
NICT	National Institute of Information and Communications Technology, Japan
NMI	National Metrology Institute
NPLI	National Metrology Institute of India
NTSC	National Time Service Center of China
OIML	Organisation internationale de métrologie légale
OP	Observatoire de Paris, France
PPP	Precise point positioning
PTB	Physikalisch-Technische Bundesanstalt, Germany
QMS	Quality management system
QZSS	Quasi Zenith Satellite System (Japan)
RMO	Regional metrology organization
SI	Système international, International system of units
TAI	Temps atomique international
TS-user	Time scale (PPS and/or standard frequency) realized at user site
TWSTFT	Two-way satellite time and frequency transfer
USNO	United States Naval Observatory
UTC	Coordinated universal time
UTC(k)	Real-time realization of UTC by a timing institute 'k'
UTC(SU)	UTC realization generated in the Russian metrology institute FSUE VNIIFTRI
VIM	Vocabulaire international de métrologie
WG	Working group

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