CCTF white paper
Promoting the mutual benefit of UTC and GNSS

Feb 28, 2023

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Executive summary

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. In the past, it was noted at meetings of the Consultative Committee for Time and Frequency (CCTF) that UTC may not be fully compatible with the needs of some user communities, and that the access to UTC is not described well enough. On the other hand, reference to UTC is made in many normative documents and international standards issued by and applicable in practically all user groups that share an interest in timing. Often the word "traceability" is found in such documents but not used with the strict meaning applying in the metrology community. The reception of signals from Global Navigation Satellite Systems (GNSS) as source of time and frequency (synchronization and syntonization) has found widest use in virtually all sectors, including electrical power supply, telecommunications, and financial institutions. This White Paper has been written by the Task Group on "*Traceability to UTC from GNSS measurements*" which was created in 2021 and whose membership comprised GNSS experts and metrologists as explained in Annex 2. It reports on the concept of metrological traceability, the properties of GNSS signals, the requirements of different user communities as fixed in their respective normative documents, and practices common in the metrological community to support achieving traceability. The Task Group proposes practical steps to ensure traceability to UTC from GNSS measurements to a wide community of GNSS users, depending on the required uncertainty in time and frequency offset from UTC. Some practical measures are suggested that can be followed by users in addition to improvements to the services provided by National Metrology Institutes (NMIs). A shortened version of this White Paper was published [Defraigne et al., Metrologia 59 (2022) 064001] and feedback received during peer review as well as after the publication was very helpful in the final editing process.

Key Words

Time and frequency metrology, UTC, time dissemination, traceability, GNSS

1 Introduction and aim of the white paper

The CCTF noted that UTC, although recommended as the unique time scale for international reference and the basis of civil time by CGPM already in 1975 and lately confirmed in 2018, is not fully compatible with the needs of some user communities, and access to UTC is not described well enough. The CCTF thus considered three topics in the recent months to promote the high quality and acceptability of UTC as unique reference time scale. An online survey was organized by the CCTF between its two sessions of the 22nd edition (October 2020 – March 2021). It addressed members of the CCTF, laboratories cooperating with the BIPM (referred to as UTC(k) – labs), other timing institutes, liaisons to the CCTF, and representatives of various user groups, referred to as stakeholders. More than 200 answers were received, confirming the need to take actions on

1) amplifying the utility of UTC by making it a continuous time scale without leap seconds,
2) promoting the mutual benefits of UTC and GNSS, including community education on achieving traceability to UTC from GNSS measurement,
3) sharing resources to improve international timekeeping.

This White Paper has been written as part of the activities in support of item 2 above (see Annex 3 for an evaluation of the answers), undertaken by a joint Task Group on "*Traceability to UTC from GNSS measurements*" of the CCTF Working Group (WG) on GNSS Time Transfer and the WG on the CIPM Mutual Recognition Arrangement. It represents an extended version of the publication [1], and covers the following topics, taking into account feedback received during peer review as well as after the publication.

The Mutual Benefit of GNSS and UTC (Section 2)

> The current use of GNSS signals in the process of generating UTC is described, followed by an illustration of the collaboration of National Metrology Institutes (NMI) and time laboratories with GNSS providers, as well as of the possible role of UTC for GNSS interoperability,

Metrological traceability (Section 3)

> The concept of metrological traceability for time and frequency measurements is contrasted with the current needs of stakeholders as reported in respective requirements documents,

Prerequisites for the use of GNSS signals for time and frequency metrology (Section 4)

> The description of various methods to obtain delay determination ("calibration") is given, next to a short reflection on the vulnerability of GNSS reception,

Suggested actions to permit traceable measurements based on GNSS signal reception (Section 5)

> Building on the foregoing, in this central section suggestions to permit traceability of time and frequency references based on GNSS signal reception have been compiled. Separately, the requirements for calibration and for demonstration of the unbroken chain of calibrated measurements between user and UTC are detailed,

Overview on services offered by NMIs (Section 6)

> As followed from the results of the questionnaire, already today NMIs offer services to support claims of traceability of time and frequency outputs of GNSS devices.

Following the Conclusions which contain proposed actions to different addressees, a set of 5 Annexes completes the White Paper.

Annex 1: List of acronyms used

Annex 2: Explanations on the authorship of this White Paper and the role of the Working Groups engaged in its development.

Annex 3: Summary of the CCTF questionnaire

Annex 4: Detailed description of so-called GNSS Disciplined Oscillators (GNSS DO) and their performance

Annex 5: Facts on GNSS system times and navigation messages.

2 The Mutual Benefit of GNSS and UTC

Assured access to accurate time 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. At the same time, in some of the above sectors, the demand for demonstrating traceability to national or international standards has been imposed by legislation or regulation. As a basis for making suggestions on the appropriate use of GNSS signals, in this Section the current use of GNSS signals in the process of generating UTC is reviewed, including the status of GNSS delay calibrations.

2.1 GNSS time links and the realization of UTC

UTC is a paper time scale computed monthly by the BIPM from an ensemble of about 400 atomic standards distributed over the world in NMIs and other timing centres. The UTC(k)s generated by these time laboratories “k” are approximate realizations of UTC. The clocks operated at institute “k” are compared to the local UTC(k), and in turn the UTC(k) time scales are compared among each other. To date, all the time links between UTC(k) laboratories needed for the realization of UTC are based on GNSS, either GPS only, for 87% of the links, or combined with Two-Way Satellite Time and Frequency Transfer (TWSTFT) for the remaining ones. One exemption is the link OP-PTB which is established using TWSTFT only (status June 2022).

GPS has been used since the 1980s following the Common-View scheme (GPS CV) [2], or its later variant called GNSS All-In-View [3]. Currently the Precise Point Positioning (PPP) method, the best-performing GNSS-based approach [4] is widely used. Unlike GPS CV and AV which are based on code measurements only, PPP is based on a precise modeling 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.

The internal signal delays of a GNSS receiver are frequency and modulation dependent. Up to 2020, only GPS signal delays were determined. This de facto limited the use of GNSS signals to GPS for accurate time comparisons. In the past, GLONASS was used for more than 10 years. But as the GLONASS satellites do all emit on different carrier frequencies, there is in the clock solution an additional noise induced by the satellite-dependent hardware delays in the receiving equipment. The accurate calibration of these delays is still an issue. Galileo is now operational, and its performances are slightly better than GPS in terms of noise. The CCTF Working Group on GNSS started working on Galileo signal delay determinations in the recent years [5]. A BIPM-organized campaign in 2020, designated 1001-2020 [5], provided Galileo signal delays for the first time. The fourth and last currently operational global constellation of GNSS is BeiDou. A major transition from the second (BeiDou-2) to the third generation (BeiDou-3) occurred in 2020, characterized by the introduction of new signals and new frequencies, in the same frequency bands as GPS and Galileo. BeiDou introduction in the computation of UTC will follow in the coming years, once a sufficient number of receivers provide BeiDou-3 measurement results and the signal delays in the receivers can be determined on a regular basis. It has been announced that delays for BeiDou-3 signals will also be available from one of the next BIPM campaigns.

Because of the convenience and performance of the PPP analysis of GPS observations, the signals from the other GNSS have up to now been used by the BIPM only to establish back-up links.

To be used for the time links in UTC, 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 solutions. Technical solutions which also apply to user equipment will be discussed in Section 4.2. For what concerns the realization of UTC, 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 [7]. To improve the efficiency and reduce the administrative load, it was proposed that BIPM ensures the calibration of only a few laboratories, named Group 1 laboratories (G1), selected in each RMO. These G1 laboratories are then hosting several reference stations and are responsible for the calibration of the other laboratories of their RMO (Figure 1). 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 [8].

In late 2022, 73 % of the stations participating in UTC have been calibrated under this scheme. Some of the remaining stations have received a calibration of their equipment by the manufacturer before installation, and in such cases an uncertainty not lower than 5 ns is assigned in the computation of UTC. Finally, there are still some time laboratories that have never been calibrated. For these stations an uncertainty of 20 ns is currently assigned in the Circular T. In the future, this will be replaced by “not calibrated” as decided by BIPM after discussions in the CCTF WG on the CIPM Mutual Recognition Arrangement (CIPM MRA). In the Circular T, a note will explain that in this case traceability can only be guaranteed for frequency.

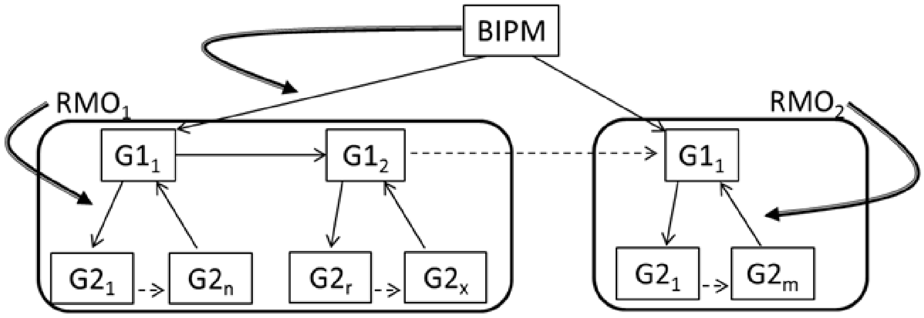


Figure 1: *BIPM-RMO collaboration for GNSS calibration*

The CCTF survey also collected feedback from UTC(k) laboratories regarding experience with the current practice and potential improvements. The following question was included in the CCTF survey: “*Are you satisfied with the current G1/G2 situation? Do you have requests or suggestions?”* Among the 67 answers received, about 75% expressed satisfaction. The major concern of those being dissatisfied is the significant waiting times for calibration in some RMOs, or the absence of G1 altogether in other RMOs. The answers clearly converged towards a need to reinforce the calibration effort. A dedicated meeting of the CCTF Working Group (WG) on GNSS time transfer was therefore organised in June 2021 to set up an improvement strategy.

The WG decided

- to reiterate and clarify the procedure to get calibration
- to repeat the invitation to RMOs to support calibration exercises
- to remind laboratories with calibration dates older than 4 years on that fact.

Items (1) and (3) have been completed in August 2021 by BIPM. The BIPM maintains a list of requested calibrations for laboratories without a direct access to G1 labs and will update the G1 labs about the requests.

2.2 Cooperation of metrological institutions and GNSS providers

2.2.1 The role of UTC(k) time laboratories

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 $\mathrm{bUTC}_{\mathrm{GNSS}}$.

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 [9]. GLONASS broadcasts a prediction of UTC based on UTC(SU) realized at the Russian metrology institute of technical physics and radio engineering (FSUE "VNIIFTRI") [10]. 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 [11]. BeiDou broadcasts a prediction of UTC built from UTC(NTSC) realized at the National Time Service Center of China and UTC(NIM) realized at the China National Institute of Metrology [12].

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 [13], and for the Navigation with Indian Constellation (NavIC) the reference is UTC(NPLI), realized at the National Physical Laboratory of India [14]. 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. More details on the specificities of each GNSS can be found in Annex 5.

The access to UTC from GNSS measurements is therefore provided thanks to the important contribution of time laboratories maintaining a realization UTC(k). Furthermore, as indicated in Figure 2, the time laboratories play an active role in the development, calibration, and steering of the GNSS time scales, as well as for the monitoring of the timing information broadcast by the systems.

Figure 2: *UTC(k) laboratories contributing to the Global Navigation Satellite systems (as of 2021)*

2.2.2 The role of the BIPM

BIPM is responsible for the generation of UTC and the publication of the differences between each UTC(k) and UTC. Furthermore, BIPM, in its Circular T (Section 4), documents a validation of the prediction of UTC provided by the GNSS. This section indeed presents "Relations of UTC and TAI with predictions of UTC(k) disseminated by GNSS", currently for GPS and GLONASS only. In late 2022, the information is based on measurements made at Observatoire de Paris for GPS and at Borowiec Astrogeodynamic Observatory (AOS) for GLONASS. BIPM announced to upgrade Section 4 to Galileo and BeiDou and possibly to the regional satellite navigation systems NavIC (India) and QZSS (Japan) at a later stage. Such publication had been recommended by the CCTF in 2015. These quantities will be computed from GNSS stations located in G1 laboratories, as these are regularly calibrated by the BIPM. Contrary to the time links used for the computation of UTC for which a relative calibration is sufficient, the clock solutions used for Circular T Section 4 need to be calibrated absolutely. Only a few time laboratories are currently equipped with the necessary equipment to perform absolute calibration of both antennas and receivers. With the advent of new GNSS and new signals, the CCTF recommends (Recommendation GNSS-2 of the 22nd session of the CCTF, 2021, "On absolute calibration of GNSS equipment for time transfer") that competent laboratories continue in their efforts in determining signal delays in GNSS receiver installations, including antenna, antenna cable and receiver electronics, providing so-called "absolute calibrations" for existing and emerging GNSS signals, and that BIPM maintains a list and a follow-up of the absolutely calibrated GNSS stations and their comparisons with the receiver systems operated in G1 laboratories.

2.2.3 Relating a user time scale to UTC via GNSS

The schematic in Figure 3 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 [$\mathrm{bUTC}_{\mathrm{GNSS}}$ – 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).

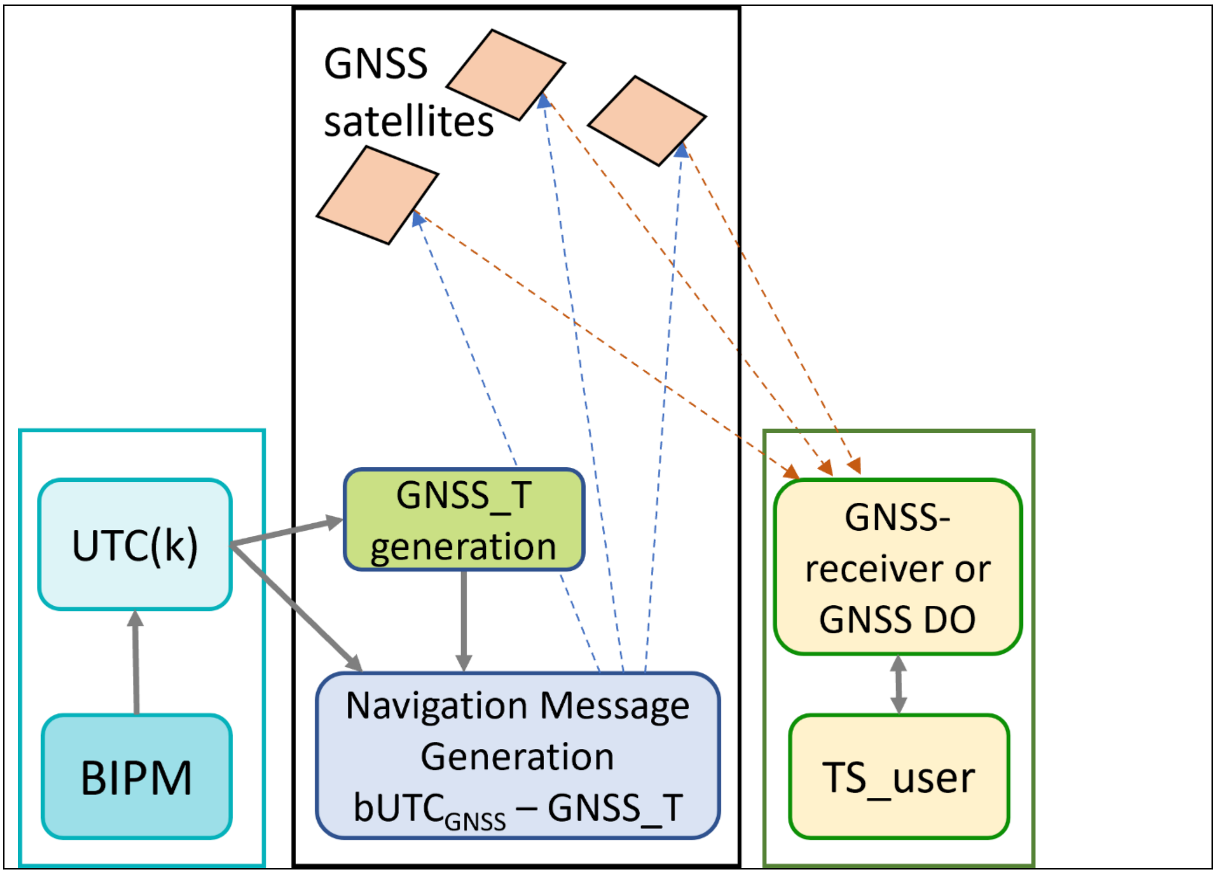


Figure 3: *Timing elements involved in relating UTC and TS_user via GNSS. The central block contains the elements under the responsibility of a GNSS provider, to the left the elements accessed from the metrological community and to the right the user part.*

For users who wish 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:

TS_user – UTC(k) = [TS_user – GNSS_T] – [UTC(k) –GNSS_T] (2.1)

In order to relate TS_user to UTC, the difference UTC – UTC(k) needs to be added. This latter quantity 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. A variant consists of a un-steered local oscillator followed by a direct digital synthesis engine, the outputs of which reflecting the steering via GNSS reception. Irrespective of the details, we speak of a GNSS Disciplined Oscillator (GNSS DO). Its output signals (standard frequency, e. g. 10 MHz, and 1 pulse per second, 1 PPS) represent TS_user. Both configurations 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 [$\mathrm{bUTC}_{\mathrm{GNSS}}$ – GNSS_T], the offset between the user time scale and UTC as predicted in the GNSS navigation message can be calculated as follows:

$$\begin{aligned}\mathrm{bUTC}_{\mathrm{GNSS}} - \mathrm{TS\_user} = \; & [\mathrm{GNSS\_T} - \mathrm{TS\_user}] \\ & + [\mathrm{bUTC}_{\mathrm{GNSS}} - \mathrm{GNSS\_T}]. \qquad (2.2)\end{aligned}$$

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 [15].

In a GNSS DO, the TS_user is typically realized in such a way that the time offset between TS_user and $\mathrm{bUTC}_{\mathrm{GNSS}}$ (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 – $\mathrm{bUTC}_{\mathrm{GNSS}}$ needs to be added. The latter can be obtained from the following relation

$$\begin{aligned}\mathrm{UTC} - \mathrm{bUTC}_{\mathrm{GNSS}} = \; & [\mathrm{UTC} - \mathrm{UTC(k)}] \\ & + [\mathrm{UTC(k)} - \mathrm{GNSS\_T}] \\ & - [\mathrm{bUTC}_{\mathrm{GNSS}} - \mathrm{GNSS\_T}], \qquad (2.3)\end{aligned}$$

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). As explained before, the BIPM publishes daily values of [UTC - $\mathrm{bUTC}_{\mathrm{GNSS}}$] 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.

2.3 UTC as reference for timing interoperability of GNSS constellations

The timing community is also contributing to the International Committee on GNSS (ICG), a sub-committee of the United Nations, and more specifically to the ICG Working Group on Reference Frames, Timing and Applications. One of the ICG's core missions is to encourage co-ordination among providers of GNSS to ensure greater compatibility, interoperability, and transparency. It has been demonstrated that combining GNSS signals from multiple constellations can significantly improve the positioning and timing performances at the user level, especially in situations of low visibility of Medium Earth Orbit (MEO) satellites. The multi-GNSS approach, however, requires the knowledge of the offsets between the different GNSS time scales, also called inter-system biases. These biases are at the level of several ns and vary with time [16]. Under the condition of good visibility, the inter-system biases can be determined directly from the GNSS measurements, while in other situations a broadcast value may be required. In the current navigation messages, the GNSS satellites broadcast or will broadcast all these inter-system time scale differences. This however leads to some complexity at the system level due to the high number of inter-system biases to be determined and broadcast (Figure 4, left hand side), even if report of all inter-system biases has not been implemented at the time of writing. At the user level this high number of biases coming from all the GNSS satellites can lead to confusion. It was therefore proposed at the ICG to use a common reference time scale and that each system broadcast only the time offset between its reference time scale and this common reference used as a pivot. (Figure 4, right hand side);

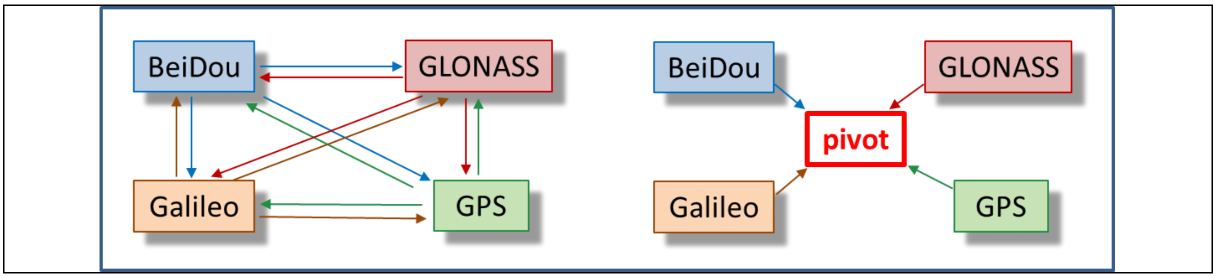


Figure 4: *Current approach (left) and proposed approach (right) for broadcasting inter-system biases*

In 2019, the CIPM decided (CIPM/108-41) "to support the International GNSS service (IGS) and the International GNSS Committee (ICG) in exploring the capacity of GNSS providers to ensure multi-GNSS interoperability, based on Coordinated Universal Time (UTC), with the final goal of avoiding the proliferation of international reference time scales."

The reference time scale used as pivot can in principle be the $\mathrm{bUTC}_{\mathrm{GNSS}}$, individually for each GNSS. But, as mentioned previously, these $\mathrm{bUTC}_{\mathrm{GNSS}}$ are based on different UTC(k) for different constellations and the pivot is therefore not identical. Recent studies have confirmed that with the current differences between the UTC terms in the broadcast predictions, a maximum error of 20 ns could affect the inter-system bias when the UTC term is used as pivot [16]. Such an error would have, however, no significant impact on positioning and timing in many situations, in particular in situations where mass-market receivers cannot determine the inter-system bias from the measurements due to a poor visibility [17].

The CCTF 2021 took note of the topic and recommended that

- "GNSS providers consider the benefit of using the predictions of (UTC - GNSS time) as reference for computing the inter-system biases, which avoids the need to create an ad-hoc common reference time scale,
- GNSS providers continue their efforts to improve the prediction of (UTC - GNSS time) with the help of time laboratories,

and furthermore that

- Multi-GNSS receiver manufacturers explore the possibility to obtain the GNSS inter-system biases from these predictions of (UTC - GNSS time),
- The International Committee on GNSS of the United Nations supports this recommendation."

This Recommendation will be further considered at the ICG-17 in 2023, after a workshop bringing together all actors and classes of users of multi-GNSS time interoperability.

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 [18, 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 [18, Section 2.40]. In the case when 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 [19]: “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”.

The International Laboratory Accreditation Conference (ILAC) [20] adopted the same definition as in the VIM and refers to both the VIM and the ISO/IEC 17025 standard [21]. 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 CIPM-MRA, ILAC and the joint BIPM, OIML, ILAC and ISO declaration on metrological traceability [22].

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 [23, 24]. 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 [20]. Note finally that the assessment of NMI/DI measurement capabilities might be based on different validation processes depending on different RMO rules.

Figure 5: *World map of RMO. From left to right: SIM for the Americas, EURAMET for Europe, AFRIMETS for Africa, GULFMET for Middle-East, COOMET for Eastern Europe, and APMP for the Asian Pacific region.*

The participants in the CIPM MRA are NMIs, DIs and international organizations [25]. This implies that these bodies have established a quality management system (QMS) around their declared CMCs according to a standard (e. g. ISO/IEC 17025 for calibration and testing) that requires the traceability of measurements to the SI, which is assessed by dedicated formal review and agreed at RMO level. Figure 5 provides a world map of the current RMOs. In addition, each NMI/DI must declare its CMCs, which are peer reviewed and approved before being included in the BIPM KCDB.

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 [26], 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. The degrees of equivalence [UTC – UTC(k)] are published retrospectively, so that one might argue that traceability to UTC can, strictly speaking, be attributed only to measurements made in the past. From this point of view, it would be safe to issue calibration reports only after publication of the respective Key Comparison results. As a way around this situation, the stated CMC may account for the prediction uncertainty of [UTC – UTC(k)].

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 management system, are technically 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" (Citations from [21]).

Furthermore, in Annex A1 of [21] 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

In the frame of the survey carried out by the CCTF after its 22nd meeting, several questions were proposed to stakeholders of time and frequency, concerning the current and future needs in terms of accuracy, stability, but also in terms of traceability. A detailed presentation of the answers is given in Annex 3. It was noted that the term traceability is used with different connotation in the various user groups. We present in this section regulatory and technical requirements related to accuracy and traceability of time and frequency signals in different industrial sectors, without pretending completeness.

The standard ISO/IEC 17025 [21] 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.

If the term "traceability" is used in this White Paper it refers to metrological traceability as defined before, unless it is used in a citation from such a document issued by or applicable in a user community. According to its definition, traceability is a qualitative and not a quantitative term. Traceability and accuracy should in principle not be confused. Unfortunately, such misconception can be occasionally found in third-party normative documents.

3.3.1 Electricity Sector

Electrical power grids require real-time capable control and monitoring systems to ensure stability under increasingly complex and challenging conditions [27]. The associated digital high voltage sensors and digital metering systems must be managed through accurate and reliable time synchronization in a wide area. The IEC 61850 suite of protocols [28] governs fast-acting protection, automation, and control applications of digital substations. In its section on Time Synchronization, we read

"UTC time is required for making synchrophasor measurements. Accuracy is dictated by the requirements specified in the IEEE Synchrophasor Measurement Standard, IEEE C37.118.1. The expected accuracy is 1 µs though the measurement can meet required accuracy with a timing error of 26 µs (at 60 Hz) if all other measurements are perfect. The measurement is made continuously, and a typical measurement system requires continuous time accuracy at 5 µs or better. Time can be provided by any source that can deliver UTC time at the required accuracy and reliability." This document does not refer to any specific source of time, e. g. GNSS signals.

From an IEEE guidance document [29] we read: "This guide covers the design, installation, and monitoring of time synchronization systems in power utility substations. This includes time sources such as Global Positioning Satellite (GPS), and time distribution systems such as Inter-Range Instrumentation Group Format B (IRIG-B), Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP), and IEEE Std C37.238™ plus IEC/IEEE 61850-9-3". The latter represents a specific PTP profile for power utility automation. In each domain, one clock is identified as the Grandmaster, whose local oscillator (clock) "is typically synchronized to an external source of time traceable to TAI and UTC such as the GPS system."

"It is strongly recommended to use public time reference sources that are traceable to the International Atomic Time (TAI, from the French name Temps Atomique International) and/or UTC. Both of these sources are coordinated by the International Bureau of Weights and Measures (BIPM, from the French name Bureau International des Poids et Mesures). (...) UTC and TAI are recommended as the time reference because electric utilities tend to cover large geographic areas. Further, it is often desirable to share time-correlated information between utility entities. This means that all entities must be synchronized to time reference sources that are traceable to a common source" (citations from [29] with omissions).

From the verbal citations one can conclude that "traceability" is understood here as "source well-defined and common for all".

3.3.2 Financial Sector

Business clocks that are used to record the date and time of any "reportable event" are in general part of a local synchronization network. The protocols used internally are NTP, PTP, or White Rabbit, depending on the sophistication and accuracy requirements. The network time itself comes from one or more master clocks that receive their timing information mostly via GPS, rarely via DCF77 in Europe or WWVB in the US.

In the European Regulation [30] we find

"Article 1 ***Reference time***
Operators of trading venues and their members or participants shall synchronise the business clocks they use to record the date and time of any reportable event with the Coordinated Universal Time (UTC) issued and maintained by the timing centres listed in the latest Bureau International des Poids et Mesures Annual Report on Time Activities. Operators of trading venues and their members or participants may also synchronise the business clocks they use to record the date and time of any reportable event with UTC disseminated by a satellite system, provided that any offset from UTC is accounted for and removed from the timestamp.

Article 4 ***Compliance with the maximum divergence requirements***
Operators of trading venues and their members or participants shall establish a system of traceability to UTC. They shall be able to demonstrate traceability to UTC by documenting the system design, functioning and specifications."

In the accompanying Guidelines [30b] we find

"7.3 Compliance with the maximum divergence requirements RTS 25 specifies two types of accuracy requirements: the maximum divergence from UTC and the timestamp granularity. This section of the guidelines only concerns the former requirement. Article 4 of RTS 25 states that 'Operators of Trading Venues and their members or participants should establish a system of traceability to UTC'. This includes ensuring that their systems operate within the granularity and a maximum tolerated divergence from UTC as per RTS 25. Furthermore, operators of Trading Venues and their members or participants should evidence that the crucial system components used meet the accuracy standard levels on granularity and maximum divergence of UTC as guaranteed and specified by the manufacturer of such system components (component specifications should meet the required accuracy levels) and that these system components are installed in compliance with the manufacturer's installation guidelines.

As per Article 1 of RTS 25, 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 in RTS 25."
We note that reference is made to [31] which list all institutes collaborating with BIPM irrespective of their status as NMI/DI. Following the interpretation given in Section 3.1, metrological traceability is thus not strictly required.

In the US Regulations [32, 33] we find equivalent statements, with slightly different numerical values for the resolution and accuracy of time stamps, but explicitly the US NMI NIST is referred to. In [32] we read "…shall synchronize its Business Clocks, (..) at a minimum to within a fifty (50) millisecond tolerance of the time maintained by the atomic clock of the National Institute of Standards and Technology ("NIST") and maintain such synchronization." The term traceability is not used in the document.

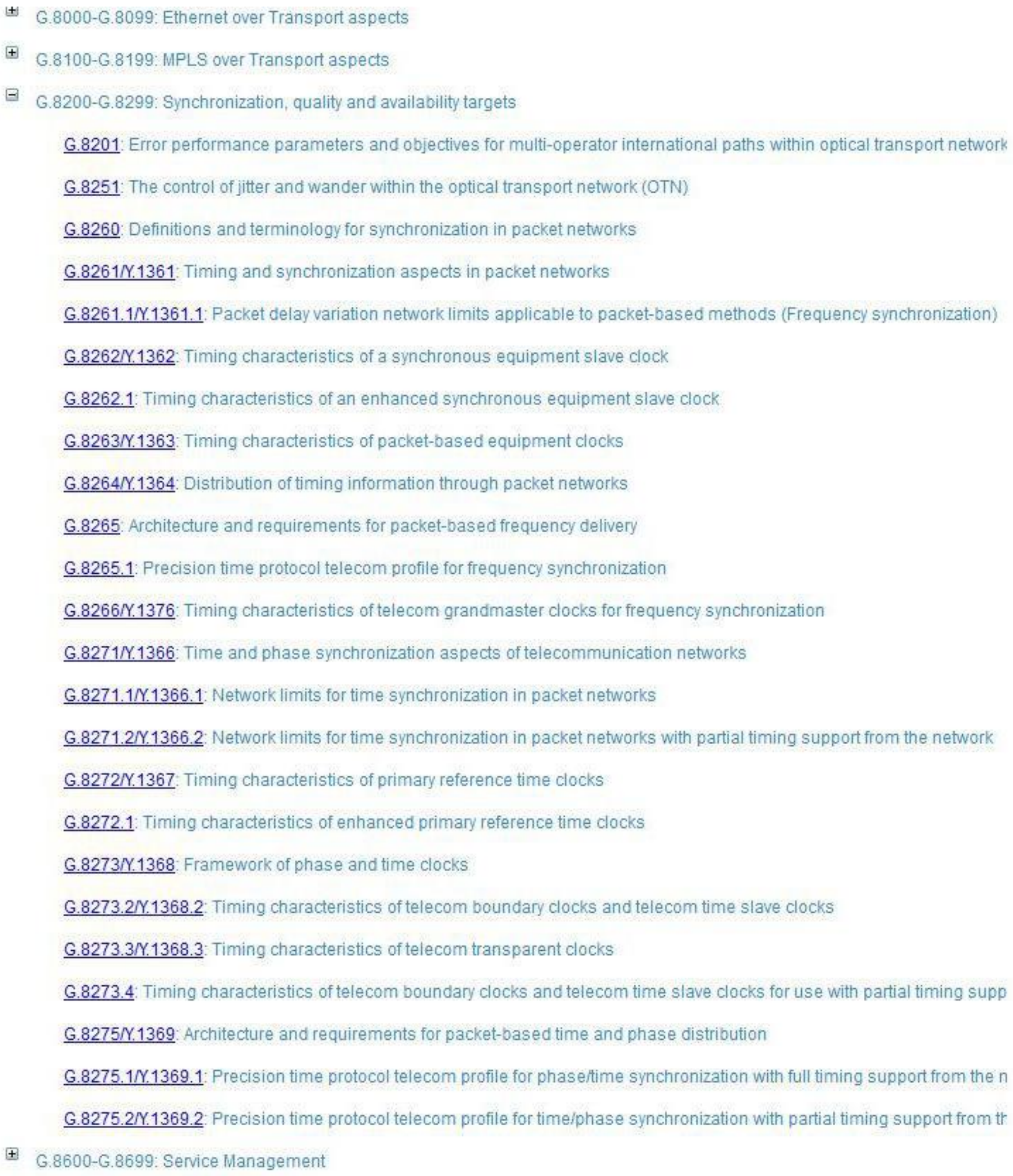
3.3.3 Telecommunication Sector /Communication in general

The International Telecommunication Union (ITU) is structured in three independent Sectors, namely the ITU Telecommunication Standardization Sector (ITU-T), the ITU Radiocommunication Sector (ITU-R), and the ITU Development Sector (ITU-D). Within ITU-R, the Working Party 7A with scope "Time signals and frequency standard emissions" develop and maintain ITU-R Recommendations (https://www.itu.int/rec/R-REC-TF/en) and Reports in the TF Series and Handbooks relevant to standard frequency and time-signal (SFTS) activities, covering the following topics: Terrestrial SFTS transmissions (including HF, VHF, UHF broadcasts), television broadcasts, microwave link, coaxial and optical cables; Space-based SFTS transmissions (including navigation satellites) and communication satellites and meteorological satellites; Time and frequency technology, (including frequency standards and clocks), measurement systems, performance characterization, time scales and time codes.

In the Radio Regulations (2020), the use of UTC in the realm of ITU activities is advocated:
"2.6 Whenever a specified time is used in international radiocommunication activities, UTC shall be applied, unless otherwise indicated, and it shall be presented as a four-digit group (0000-2359). The abbreviation UTC shall be used in all languages."

Within ITU-T, the Study Group 15 (SG15) with scope "Networks, Technologies and Infrastructures for Transport, Access and Home" performs standardization of clock characteristics and PTP-profiles for the telecommunication sector. The products of ITU-T standardization are ITU-T Recommendations (ITU-T Recs). They detail technical specifications giving shape to global communication infrastructure. The standards define technologies and architectures of optical transport networks enabling long-haul global information exchange; fibre- or copper-based access networks through which subscribers connect; and home networks connecting in-premises devices and interfacing with the outside world. In Table 3-1 the long list of pertinent ITU-T Recs with the titles of the Recommendations visible is compiled.

Table 3-1: List of ITU-T Recommendations in force on synchronization matters



- ⊞ G.8000-G.8099: Ethernet over Transport aspects
- ⊞ G.8100-G.8199: MPLS over Transport aspects
- ⊟ G.8200-G.8299: Synchronization, quality and availability targets
  - G.8201: Error performance parameters and objectives for multi-operator international paths within optical transport network
  - G.8251: The control of jitter and wander within the optical transport network (OTN)
  - G.8260: Definitions and terminology for synchronization in packet networks
  - G.8261/Y.1361: Timing and synchronization aspects in packet networks
  - G.8261.1/Y.1361.1: Packet delay variation network limits applicable to packet-based methods (Frequency synchronization)
  - G.8262/Y.1362: Timing characteristics of a synchronous equipment slave clock
  - G.8262.1: Timing characteristics of an enhanced synchronous equipment slave clock
  - G.8263/Y.1363: Timing characteristics of packet-based equipment clocks
  - G.8264/Y.1364: Distribution of timing information through packet networks
  - G.8265: Architecture and requirements for packet-based frequency delivery
  - G.8265.1: Precision time protocol telecom profile for frequency synchronization
  - G.8266/Y.1376: Timing characteristics of telecom grandmaster clocks for frequency synchronization
  - G.8271/Y.1366: Time and phase synchronization aspects of telecommunication networks
  - G.8271.1/Y.1366.1: Network limits for time synchronization in packet networks
  - G.8271.2/Y.1366.2: Network limits for time synchronization in packet networks with partial timing support from the network
  - G.8272/Y.1367: Timing characteristics of primary reference time clocks
  - G.8272.1: Timing characteristics of enhanced primary reference time clocks
  - G.8273/Y.1368: Framework of phase and time clocks
  - G.8273.2/Y.1368.2: Timing characteristics of telecom boundary clocks and telecom time slave clocks
  - G.8273.3/Y.1368.3: Timing characteristics of telecom transparent clocks
  - G.8273.4: Timing characteristics of telecom boundary clocks and telecom time slave clocks for use with partial timing supp
  - G.8275/Y.1369: Architecture and requirements for packet-based time and phase distribution
  - G.8275.1/Y.1369.1: Precision time protocol telecom profile for phase/time synchronization with full timing support from the n
  - G.8275.2/Y.1369.2: Precision time protocol telecom profile for time/phase synchronization with partial timing support from th
- ⊞ G.8600-G.8699: Service Management

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In the Standard G-8260 on definitions and terminology, we find

"**3.1.3 coherent time and frequency**: The condition where the timing signal-carrying frequency and the timing signal-carrying time-of-day or phase are traceable back to the same primary source."

“**3.1.17 primary reference time clock (PRTC)**: A reference time generator that provides a reference timing signal traceable to an internationally recognized time standard [e.g., Co-ordinated Universal Time (UTC)],” an expression that one should read with the following in mind:

“3.1.19 time synchronization: The distribution of a time reference to the real-time clocks of a telecommunication network. All the associated nodes have access to information about time (in other words, each period of the reference timing signal is marked and dated) and share a common time scale and related epoch… (omission)

Examples of time scales are:

- UTC
- International Atomic Time (TAI)
- UTC + offset (e.g., local time)
- Global Positioning System (GPS)
- PTP
- local arbitrary time”

It seems incorrect to interpret “traceable” in 3.1.3 and 3.1.17 as being used in the VIM sense, given also the unclear use of the expression “time scale” in general. When specifying the enhanced PRTC (ePRTC) the wording is similar as above. In several other of the above listed recommendations “traceable” is used with the meaning of “source of time (or frequency) known and common to all devices in a network”. In Rec. ITU-T G.8275.1 which specifies the PTP (IEEE 1588) profile for telecom application, the expression “ePRTC traceable to global navigation satellite system (GNSS)” can be found several times.

The 3rd Generation Partnership Project in its Technical Specification “Group Radio Access Network” defines the communication and synchronization standards between base station (here called Radio Head or gNB) and the end user device. (Note: ITU-T covers the communication and synchronization up to the base-station). In Release 16 one can read “Logical synchronization port for phase- and time-synchronization shall provide: continuous time without leap seconds traceable to common time reference for all gNBs in synchronized TDD-unicast area. In the case the TDD-unicast area is not isolated, the common time reference shall be traceable to the Coordinated Universal Time (UTC).”
TDD stands for Time Division Duplex. As before, “traceable” is apparently used in the meaning of “with known, unique source”, and UTC is considered as a specific source only in case when signals from different sources may reach the gNB.

3.4 Synopsis of traceability at user level

From the above survey it becomes clear that different user communities have developed normative documents which govern their rules of conduct and inter alia specify how time and frequency signals are to be employed in their realm.

Three use categories can be distinguished:

1. Use of GNSS signal-based information and data, including the control of a local oscillator, for internal applications;
2. Same as 1.) but explicit reference is made to “traceability to UTC”;

3. Calibration laboratories using GNSS signals as source of reference signals for their services offered to third parties

The standard ISO/IEC 17025 [21] is applicable for laboratories accredited for calibration and testing and thus undoubtedly for use 3). Activities falling under category 2) should also adhere to it. It is quite common that NMIs/DIs work under a self-declaration of their adherence to this standard (mutans mutandi) and under a compliant QMS which undergoes regular international review. Examples are NRC, Canada, and PTB, Germany. This practice is common in EURAMET, but e. g. not at all in APMP.

4 Prerequisites for the use of GNSS signals for time and frequency metrology

4.1 General remark

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 [34]. 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 White Paper, where we consider only the ideal situation in which the GNSS signals are received properly.

4.2 Technical methods for GNSS receiver calibration

Before it can be used for accurate frequency or accurate timing generation, the GNSS equipment must either be calibrated or be delivered by the manufacturer with a conformity certificate included. In Section 5, we introduce a tiered approach, depending on the user need (frequency or timing or both) and on the requested uncertainty of the output signals. Calibration, at manufacturer side or at user side, is often needed, and thus we detail here the technical methods for doing this. As the hardware can vary with environmental changes, or aging, periodic recalibrations are also suggested at regular intervals, depending on the required level of accuracy. For a long time, GNSS DOs on the market were de facto GPS DOs. In modern devices more than one GNSS could be tracked, but the output might depend still on one or an average of received GNSS signals. This may lead to significant differences in the output signals, particularly on the PPS epoch. The calibration certificate must thus include the GNSS DO configuration parameters.

4.2.1 Calibration for timing

To determine the uncertainty of the time output of a GNSS DO with respect to UTC, the simplest option is to take the manufacturer’s published specifications as the basis. These specifications should be based on a calibration of one example of a particular model of GNSS DO, with allowance being made for the variations between notionally identical receivers. When the required time uncertainty is larger than 1 μs ($k = 1$), determination of the uncertainty from the manufacturer’s specifications or type testing of the model of GNSS DO in use may be regarded as sufficient by some accreditation bodies. With some care, this approach would be covered by the requirements from ISO/IEC 17025 as detailed in Section 3.2. If superior accuracy is aimed for, various options for calibration have been developed and frequently used. The calibration will evaluate the time differences between the output one-pulse-per-second (1 PPS) epoch and an agreed international reference time scale, usually UTC or its national realization UTC(k). This calibration may be restricted to a time interval measurement between the GNSS DO PPS output and a PPS signal with calibrated offset from UTC(k). Only in special cases it will be technically feasible to determine the individual hardware delays as it is the practice for receivers used in NMIs/DIs as explained in Section 2.1. This is usually beyond the scope of the user. Both options are nevertheless discussed subsequently.

Option 1 is based on 1 PPS measurements only. It consists in sending the GNSS DO to the calibration laboratory with the antenna and cable that will be used during routine operation of the GNSS DO, so that the complete system can be evaluated. The 1 PPS output of the GNSS DO will then be measured using, e. g., a Time Interval Counter (TIC) with respect to the reference time scale of the calibration laboratory, which can be UTC(k) in case of an NMI or DI, or a time source traceable to UTC maintained by the calibration laboratory (Figure 6). The TIC measurements will contain both the GNSS DO hardware delays and the difference between the reference time scale of the calibration laboratory, which can be traced to UTC and $bUTC_{GNSS}$. (see Section 2.2.3 for explanations on $bUTC_{GNSS}$). This calibration technique should provide uncertainties of tens of ns.

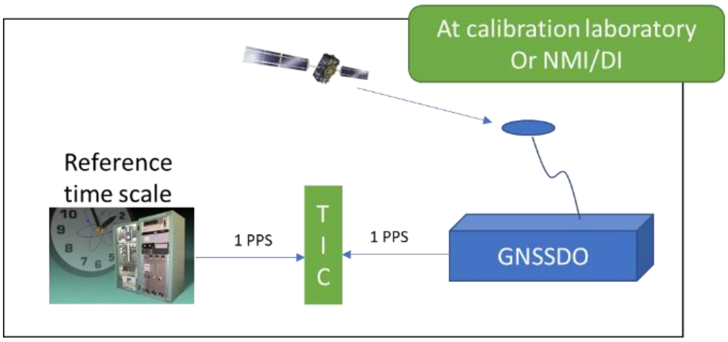


Figure 6: *Calibration for timing of a GNSS DO at the premises of a calibration laboratory*

Alternately, the same activity can be undertaken after the GNSS DO is installed in the environment in which it will operate routinely. This requires using a travelling clock, e. g., another GNSS DO firstly calibrated at the calibration laboratory against a reference time scale traceable to UTC (Figure 7). Use of a traveling GNSS DO would require installation of a GNSS antenna which is sometimes difficult at the customer premises. The 1 PPS output of the GNSS DO will then be measured using e. g. a TIC with respect to the 1 PPS output of the calibrated GNSS DO, provided by the calibration laboratory. This calibration technique should again provide uncertainties of tens of ns.

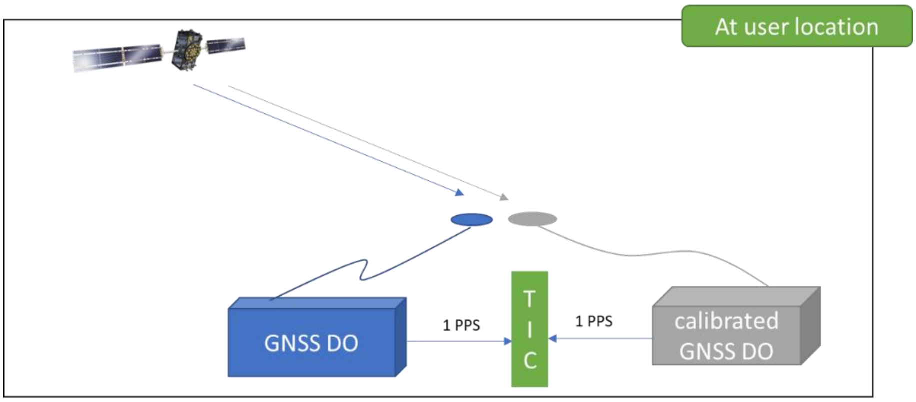


Figure 7: *Calibration of a GNSS DO at the user location*

Option 2 includes different levels of involvement of metrological practices, relying on standard data files in CGGTTS format (Common GNSS Generic Time Transfer Standard) [4.3]. A few GNSS DO models offer the possibility to deliver time measurement results in the CGGTTS format. They are often instrumental in services offered by NMIs which are described in Section 6.2.2. In addition, some GNSS DO provide access to raw GNSS measurements, but no CGGTTS files are generated. Software tools for data conversion from the raw measurements exist but require obviously additional processing steps.

If this has been achieved, the GNSS DO can be compared with the NMI/DI by GNSS CV. Differencing the measurements from the GNSS DO and a receiver at the NMI/DI provides the time offset between the GNSS DO at the calibration laboratory and the reference time scale maintained at the NMI/DI, with a standard uncertainty (k = 1) of typically 5 – 10 ns for the time offset. The advantage of this approach is that it can be continuously operated and hence provides a continuous monitoring of the GNSS DO timing. In addition to the GNSS CV comparison the offset between the GNSS DO 1 PPS out and its internal clock can be determined if the PPS output is compared to a reference as indicated in Figure 7.

Figure 8 illustrates the situation when such activity is done at the NMI/DI. The CGGTTS files of the GNSS DO indeed report the differences between the receiver clock and the GNSS time scale which are affected by the hardware delay (antenna, cable, and receiver). A time receiver at the NMI/DI provides also CGGTTS files, reporting the differences between UTC(k) and the GNSS time scale. The CV results from these two sets of CGGTTS files gives then

$$\mathrm{CV} = \mathrm{UTC}(k) - T_{\mathrm{DO}} + \delta, \qquad (4.1)$$

where T_{DO} is the internal clock of the GNSS DO and δ is the hardware delay of the latter. Let us assume that the GNSS DO reports the offset OPPS between the receiver clock and the 1 PPS output

$$\mathrm{OPPS} = \mathrm{PPS} - T_{\mathrm{DO}} \qquad (4.2).$$

In parallel, a direct time comparison of UTC(k) and the 1 PPS output obtained using a time interval counter provides the offset UTC(k) – 1 PPS. Combining these three sets of measurements gives access to the hardware delays of the GNSS DO. If information (4.2) is not available, the user can still obtain the quantity of interest, UTC(k) – 1 PPS.

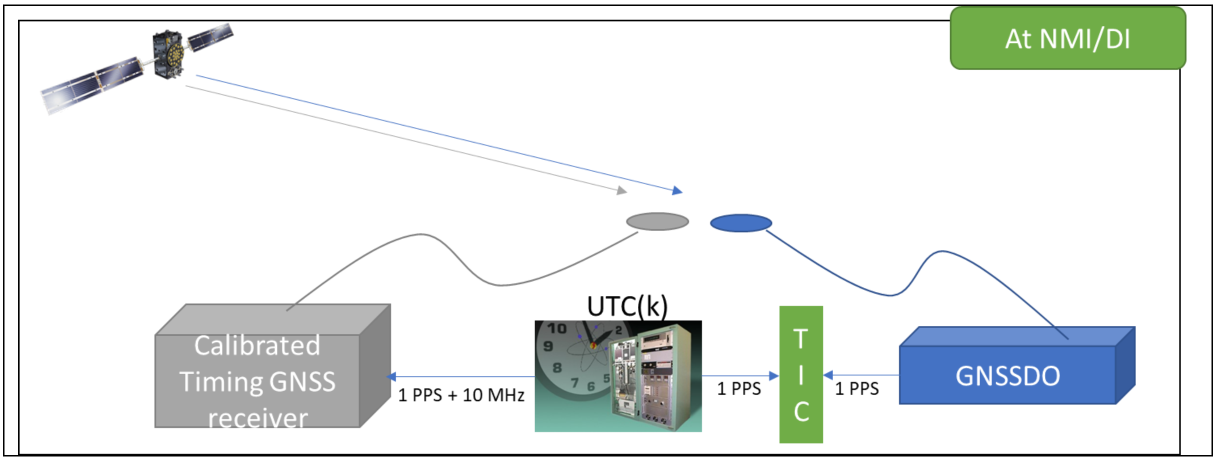


Figure 8: *Calibration of a GNSS DO at NMI/DI using CGGTTS files when operated at a NMI/DI*

An alternative, illustrated in Figure 9, consists in installing for a few days a calibrated timing receiver provided by the NMI/DI at the user location. The 1 PPS and frequency from the GNSS DO should then feed the timing receiver. The CGGTTS results from the calibrated timing receiver will provide the true value of the difference between GNSS_T and the PPS output of the GNSS DO. The CGGTTS results from the calibrated timing receiver at the NMI will provide the true value of the difference between GNSS_T and UTC(k). Combining both data sets provide the required measurement quantity.

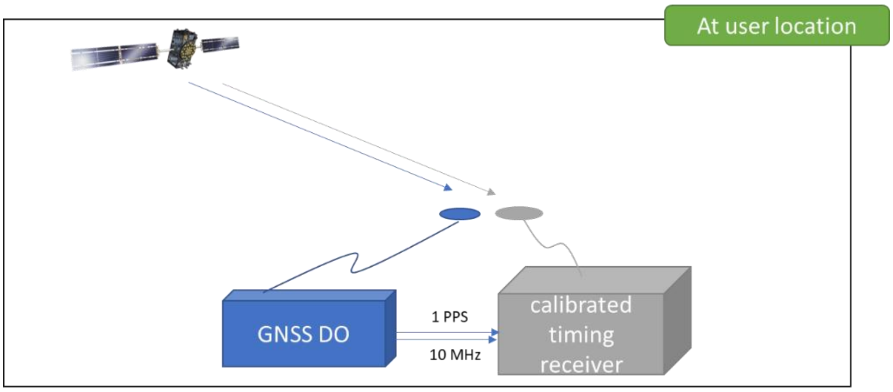


Figure 9: *Calibration of a GNSS DO at the user site, using CGGTTS files, including data exchange with the NMI/DI (not shown)*

Any calibration measurements that aim at the lowest uncertainty should be taken over a period of continuous operation of at least 2 days so that the possible diurnal hardware delay variations and multipath can be observed and considered in the uncertainty budget. Calibration of the GNSS DO by an NMI or an accredited laboratory (AL) will result in an uncertainty being assigned to the GNSS DO's time output signals. The uncertainty budget should contain the contribution of each measurement (TIC, associated cables delays) as well as the noise of the GNSS DO.

4.2.2 Calibration for frequency:

Frequency calibration requires a comparison of the GNSS DO and a reference frequency traceable to the SI second, maintained by an NMI/DI or an AL. All the techniques described previously for timing calibration can be used. The main difference here is that only the time evolution of the clock differences will be considered. For this reason, the knowledge of antenna, cable and receiver hardware delays is not needed.

The calibration will be based on either time (1 PPS) or frequency comparisons. Both the frequency accuracy and the frequency stability of the user GNSS DO outputs can be determined. For frequency calibration at the user site, the NMI/DI/AL should send to the user a traveling standard, which can be either an oscillator or a GNSS receiver. This traveling standard should be compared to the reference before shipping, and then to the user equipment. The comparisons can be carried out using either a frequency counter, a phase comparator, or a TIC (when using the 1 PPS outputs signals), respectively.

If the user GNSS receiver is providing clock solutions in the CGGTTS standard, then periodic calibration is also possible through the GNSS common-view method, providing a comparison between the frequency of the user equipment and the reference maintained by the NMI/DI/AL.

4.2.3 Further considerations on calibrations

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 behavior 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.

5 Suggested actions to permit traceable measurements based on GNSS signal reception

5.1 Differentiation between types of use

In Figure 10 we illustrate three usage classes (U1, U2 and U3) for time information obtained from GNSS signals. Later, we will detail for each class how traceability can be achieved and 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 [9 - 13]. 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 [36] 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 10**Erreur ! Source du renvoi introuvable.**. Specific suggestions for this type of use are given in Section 5.3.

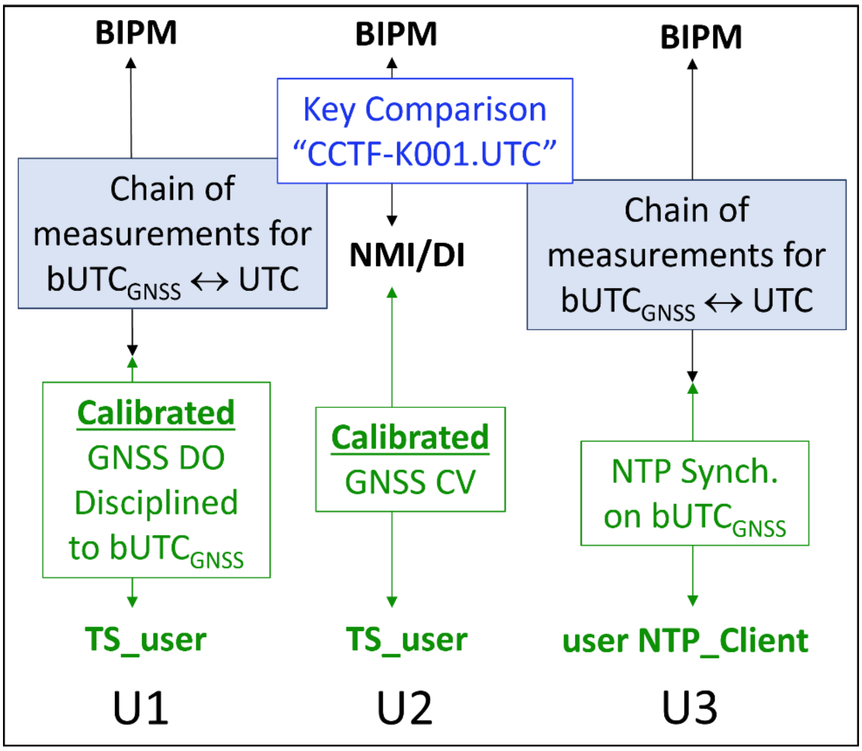


Figure 10: *General scheme for obtaining time traceability using GNSS signals, for 3 of the most common use cases (U1, U2 and U3)*

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 it requires the technical competency of the former to ensure traceability. Some services of this type are already offered by NMIs / DIs, and in Section 6.3 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 the following Section 5.2, and (2) the existence of a documented chain of comparisons between the user and the NMI / DI or UTC, detailed in Section 5.3.

5.2 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 behavior, the sources of uncertainty inherent in their practical operation, and typical specifications quoted for the instruments by the manufacturers.

5.2.1 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 [18], and illustrated in Figure 11.

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 [21], see Section 3.2.

b. *For uncertainties U between* $1x10^{-8}$ *and* $1x10^{-10}$ *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* $1x10^{-10}$ *and* $1x10^{-12}$ *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* $1x10^{-12}$ *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.

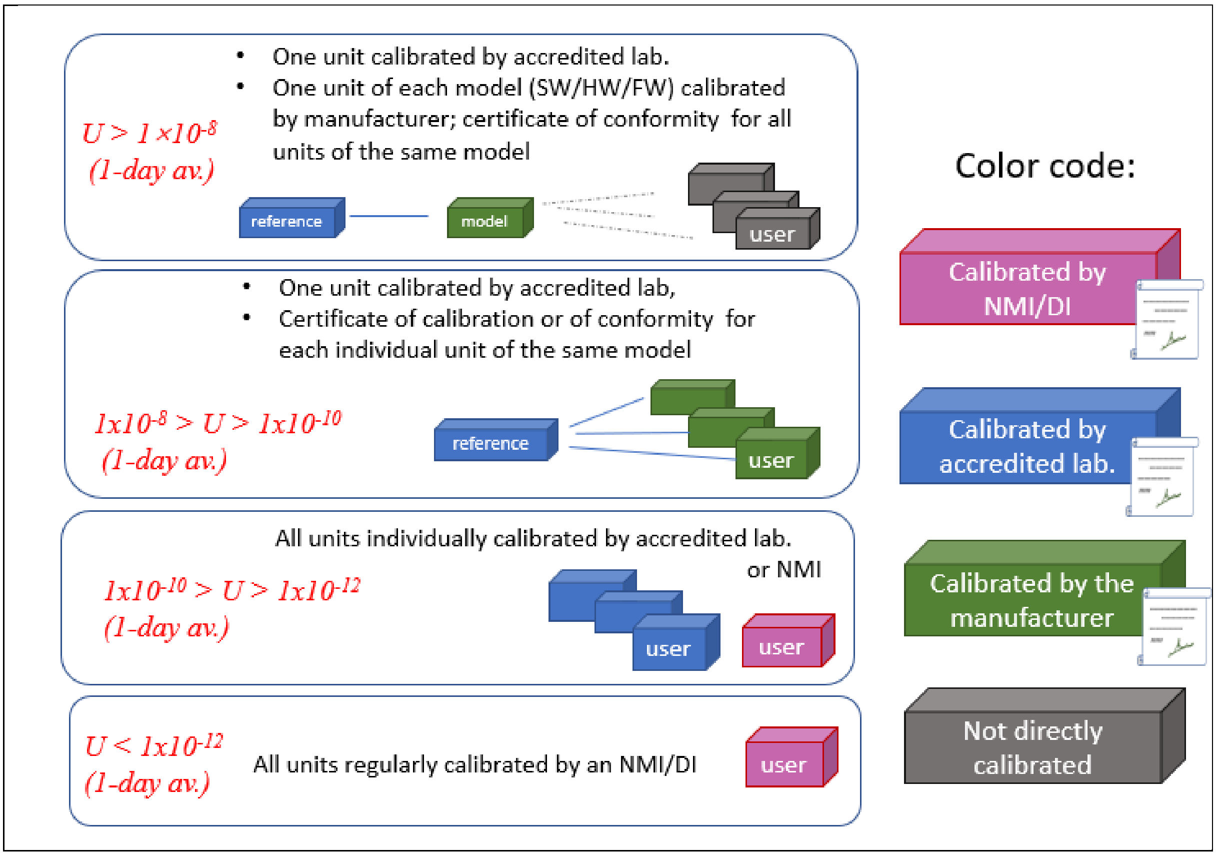


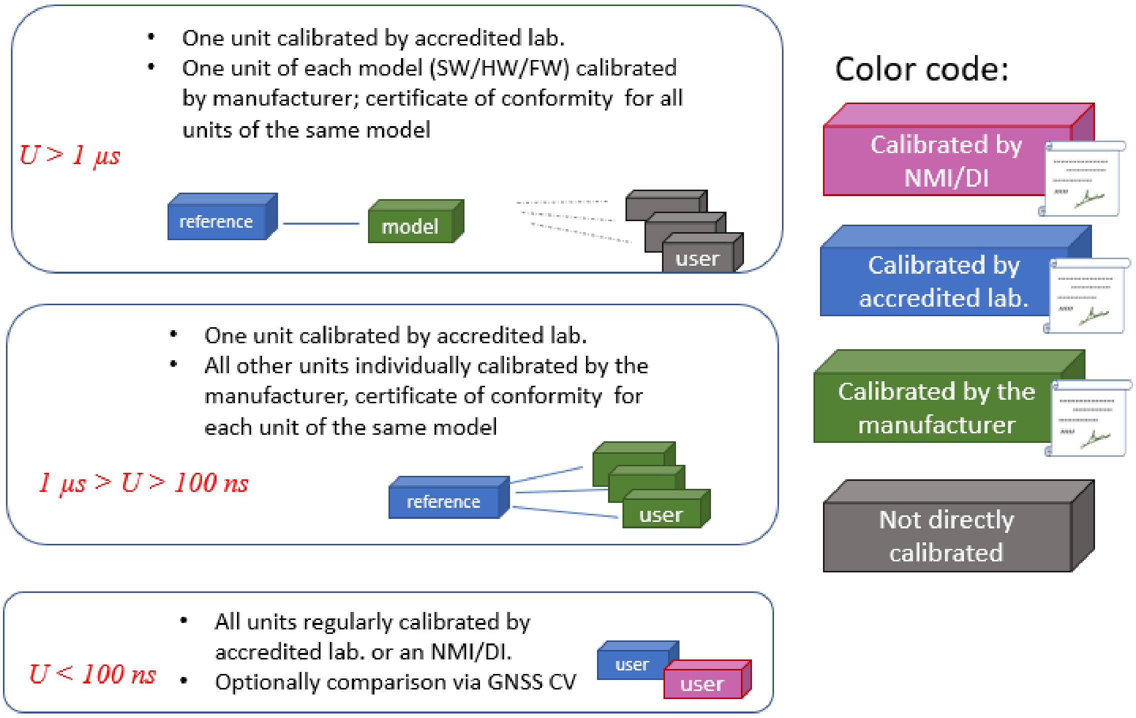
Figure 11: *Calibration needed to support traceable frequency measurements to be made at user level within a range of uncertainties*

5.2.2 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.

In some applications, there may be requirements on both relative synchronization within a network, and absolute synchronization to UTC. The guidelines we propose here only address the use of GNSS to satisfy the latter requirement; the means by which relative synchronization is assured are at the discretion of the operator.

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 12.



- One unit calibrated by accredited lab.
- One unit of each model (SW/HW/FW) calibrated by manufacturer; certificate of conformity for all units of the same model

- One unit calibrated by accredited lab.
- All other units individually calibrated by the manufacturer, certificate of conformity for each unit of the same model

- All units regularly calibrated by accredited lab. or an NMI/DI.
- Optionally comparison via GNSS CV

Figure 12: *Calibration needed to support traceable time determination to be made at user level within a range of uncertainties*

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 [21], 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 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.

Note that for a traceability to UTC with an uncertainty below 100 ns, in addition to the calibration, the specification of the GNSS signals used is particularly important, and the specified uncertainty for the $bUTC_{GNSS}$ information as in the ICDs [9-13] must not be neglected.

5.3 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 5.1. For each option considered, the uncertainty contributions are stated.

Usage Class U1 as illustrated in Figure 10 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 must 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 elaborate 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. In summary,

$$Uc = \mathrm{sqrt}\{ u_{cu}^2 + u_{cr}^2 \}. \qquad (5.1)$$

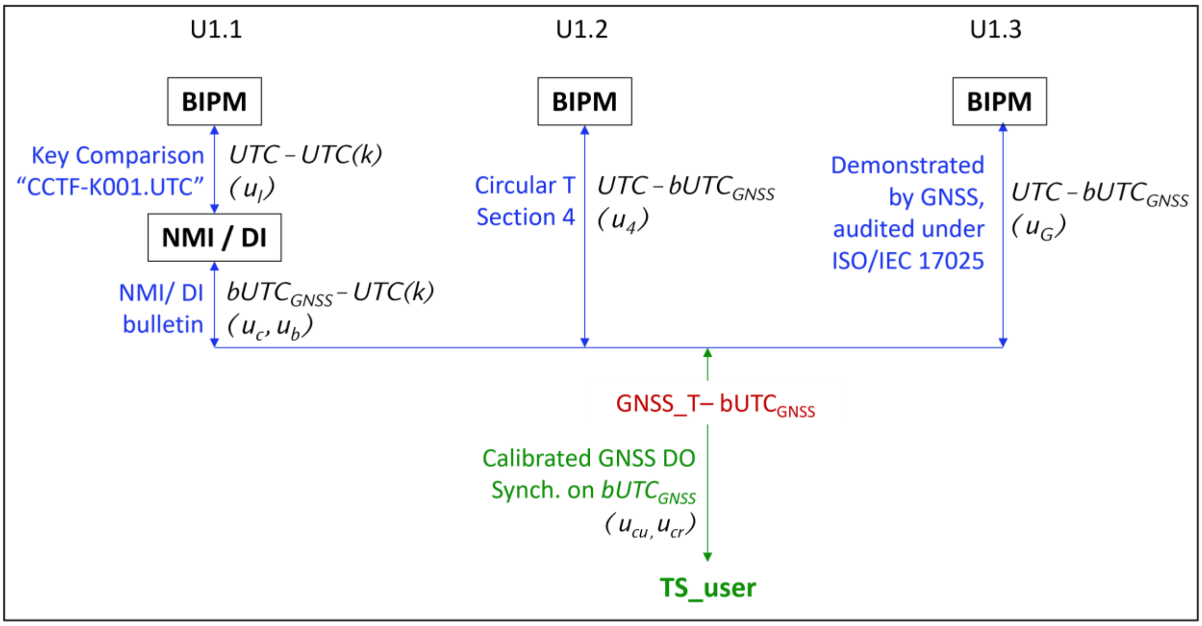


Figure 13: *Usage class U1, showing the three options to establish the traceability chain*

(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 13 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 (5.1) and a term u_b associated with the broadcast value and described in [15]. The latter 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 [15] 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. In summary, we get

$$U_{11} = \mathrm{sqrt}\{ u_c^2 + u_b^2 + u_l^2 \}. \qquad (5.2)$$

(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 and GLONASS. As of end-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 [7]. 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 to be 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. No numerical estimates can be given today.

Usage class U2 involves GNSS time transfer between a user and a UTC(k) at an NMI / DI and is illustrated in Figure 14.

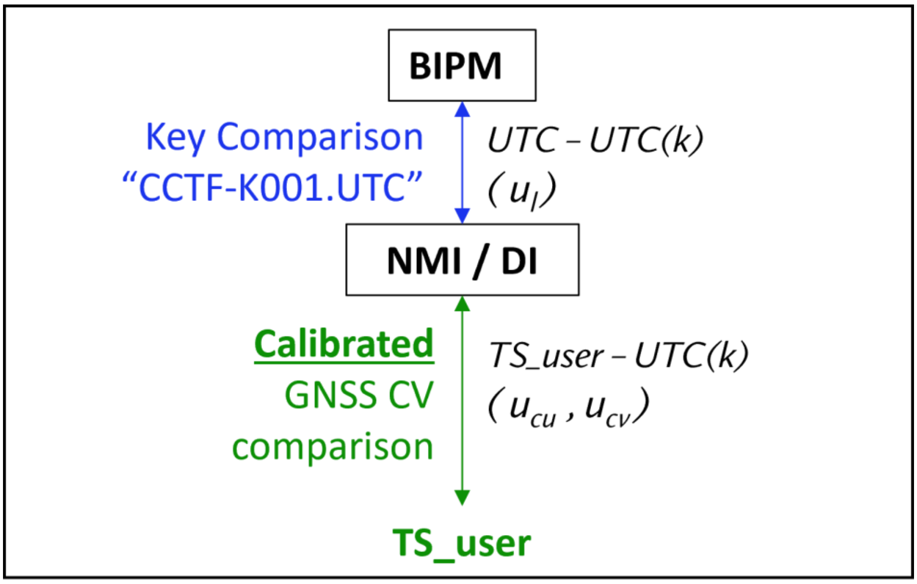


Figure 14 *Usage class U2, involving continuous exchanges between the user and an NMI/DI*

To that aim, some NMI / DI have already published CMCs for time comparisons with users based on GNSS CV time transfer [2], 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 considered, due to the noise, local multipath, and atmospheric perturbations. 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 from the NTP server hosted at user side, based on packet exchange using the NTP protocol as illustrated in Figure 15.

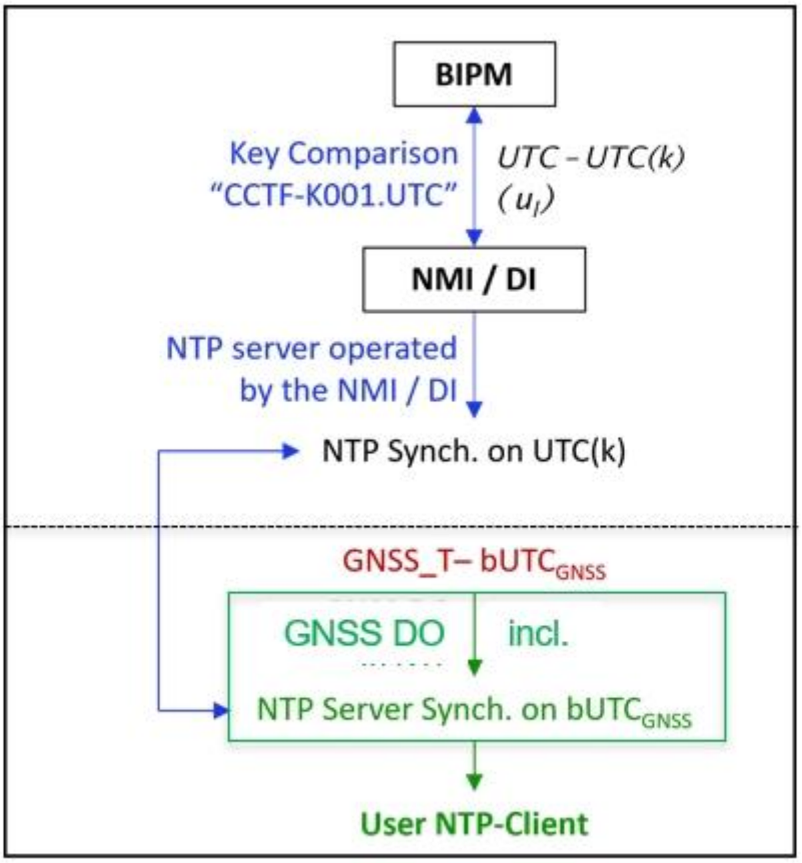


Figure 15 *Usage class U3, involving time dissemination in networks*

A variety of equipment exists that generates time protocols, in particular the Network Time Protocol (NTP) [36], using a GNSS receiver as the time reference. Other network-based time transfer protocols (e.g. PTP and White Rabbit [37]) exist but are less prevalent than NTP. 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 type of use. Establishing a link to an NTP server represents the most common method for synchronizing downstream computer clocks and devices over the public internet, designated as "User NTP-client" in Figure 15. 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, e. g., 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.

6 Overview on services offered by NMIs

Results of measurements of GNSS signals made by NMIs/DIs with respect to their UTC(k) may be used to support claims of traceability of GNSS device outputs to the UTC(k). The CCTF survey was also the occasion to get an overview of the services offered by the NMIs/DIs for the users supporting such claims. This section provides a summary of the answers and may assist NMIs/DIs to develop such services in the future.

6.1 Results from the questionnaire and provided by RMOs

Regarding services offered by NMIs to support traceability of GNSS devices, the CCTF survey asked:

1. Were services to calibrate and/or certify GNSS equipment offered?
2. What services were provided to users to allow them to obtain traceability to the local UTC(k)?

About two thirds of the 58 respondents said that they offered services to calibrate GNSS equipment. None offered certification of GNSS devices. The second question was not specific to GNSS equipment and so some responses are not relevant in the present case. The responses detailing the services provided were generally short, and sometimes ambiguous. There is an apparent disagreement between the answers to the two questions, since only 22 NMIs described services identifiable as related to GNSS equipment. Several NMIs planned to offer services in the future. Of the 7 NMIs not yet contributing to UTC who responded, none currently offer services supporting traceability of GNSS signals.

Table 6-1: Services offered by NMI/DIs to support traceability of GNSS devices (Spring 2022); Some of these services are inferred from CMCs published in the KCDB, + designates G1 laboratories in their respective RMOs, see Figure 1

.

Service	NMI
Conventional calibration of GNSS devices	DMDM (Serbia), METAS, MIRS (Slovenia), NMIA, NMIM, NPL, NTSC, PTB$^+$
Remote calibration via GNSS time-transfer$^+$	BEV, BelGIM, CENAM, FTMTC, GUM, IPE/ASCR, LNE-LTFB, LNE-SYRTE$^+$, INRIM, KazStandard, KRISS, METAS, NICT$^+$, NIM$^+$, NIMT, NIST$^+$, NMIA, NMIJ, NPL, NPLI, NRC, NTSC, PTB$^+$, RISE, ROA$^+$, TL, UME, VSL, VNIIFTRI$^+$
Remote calibration by NTP	NMIA, Norwegian Metrology Service, NRC
Publication of UTC(k) – GNSS measurements	NMIA, NMISA, NTSC, PTB, ROB, VNIIFTRI, VSL
Publication of time-transfer data	NMIA, PTB, TL
GNSS equipment delay determination	METAS, NMIA, RISE AB, VSL, NICT$^+$, NIM$^+$, NIST$^+$, LNE-SYRTE$^+$, PTB$^+$, ROA$^+$, VNIIFTRI$^+$

Several distinct services offered by NMIs to support traceability of GNSS devices have been identified, listed in Table 6-1, and are described in more detail below. To supplement information obtained from the survey, some respondents were contacted, and information was also collected from some NMI's websites and publications.

6.2 Detailed Description of the services

6.2.1 Conventional calibration of GNSS devices

"Conventional calibration" is taken to mean that the device is calibrated by direct comparison of its outputs with a reference standard. As detailed in Section 4.2, this can happen at the customer's premises in case that the provider of the calibration service sends a reference standard, which can be a calibrated mobile GNSS DO, a mobile time-transfer system, or a travelling atomic clock. Alternately, the Device Under Test can be sent to the calibration laboratory where the comparison takes place. The different cases were illustrated in Figure 6 to Figure 9.

GNSS speed measurement devices use the Doppler shift of the GNSS carrier signal to estimate speed. Calibration of these devices can be performed using a suitably referenced GNSS simulator and software. Several NMIs offer a calibration service using this technique.

6.2.2 Continuous monitoring through GNSS time transfer

GNSS time transfer [2, 3] is the 'gold standard' for establishing traceability of a remote standard to UTC(k) of a NMI/DI or UTC at present. Many NMIs have published CMCs for this capability in the KCBD. These CMCs refer to just a remote standard, and not to GNSS DOs specifically. For users, operating continuous time-transfer has the advantage of providing continuous traceability, uninterrupted access to their standard and high accuracy.

Several time-transfer systems suitable for the purpose are available commercially and a few NMIs also produce the specific devices to support their services [38 - 43]. For example, NMIA offers such a service and issues calibration reports for the user equipment. Since the remote calibration service is intrinsically continuous, these services tend to be offered by monthly subscription or yearly contract, for example. In some cases, NMIs make their time-transfer data files publicly available so that users can make the necessary calculations themselves.

6.2.3 Remote calibration by NTP

Autonomously operated Network Time Protocol (NTP) appliances with an internal source of time of day almost invariably use a GNSS receiver as the source of time-of-day. In most use cases that employ such equipment, the accuracy requirements are quite modest, and this opens other possibilities for establishing traceability. For example, point to point speed measurement systems used for enforcement of vehicle speed only need timestamps accurate to one second or so, but nevertheless traceable to a local UTC(k). To have a reliable, local source of time, these systems may incorporate a GPS-referenced NTP server. The system also has an external network connection for control and data upload. By sending NTP queries from a server connected to a traceable source of time to the remote NTP appliance the time offset between both can be checked. Even less demanding is to use the existing network connection (3G modem) and to act as a NTP client that sends queries to an NTP server operated at an NMI/DI. In more demanding applications it is important to evaluate and monitor with care the additional uncertainties introduced by the downstream distribution equipment which usually provides the timestamps whose accuracy is dictated by various regulations and standards.

6.2.4 Publication of UTC(k) – GNSS measurements

A simpler version of GNSS time-transfer can be realized by recording the time interval difference between the 1 PPS output of a user's local clock and the 1 PPS output of a receiver or GNSS DO. The latter is typically aligned to UTC, using the broadcast prediction $\mathrm{bUTC}_{\mathrm{GNSS}}$, with offsets that are time variable and dependent on the sophistication of the devices and their utilization (see Annex 4). In conjunction with data published by an NMI for a similar measurement and appropriate consideration of uncertainties, a user can then establish a link to its respective UTC(k). This is considered as sufficient to establish traceability for frequency of a GNSS device by at least one NMI [44]. As an example, NMISA (Pretoria, South Africa) publishes a monthly bulletin that gives the daily difference at 00:00 UTC between UTC(ZA) and UTC as predicted by GPS and GLONASS [45]. The data are intended to be used for frequency comparisons between a user's equipment and UTC(ZA) using simple GNSS time-transfer. The data are generated from a linear fit to 24 hours of CGGTTS data and corrected to UTC using the broadcast prediction. The uncertainty stated in the bulletin refers to the statistical uncertainty of the fit.

For Australian users NMIA reports data for three GPS receivers, with the mean frequency offset for each receiver estimated from a linear fit to two days of data, centered on 00:00 UTC of the second day. The mean frequency offset of the ensemble is also reported. This gives a more practical indication of the performance to be expected from a user receiver elsewhere. Similarly, data from a group of more advanced (multi) GNSS DOs could be used in the future. Reporting data measured with such equipment also mitigates a problem that arises now that multiple GNSS signals are available: the output of a receiver may be some weighted estimate of UTC obtained from multiple GNSS and the algorithm which the receiver uses is unavailable to the user.

As another example, VSL publishes a weekly bulletin that reports the differences UTC(VSL) - UTC and UTC(VSL) - $\mathrm{bUTC}_{\mathrm{GPS}}$. To claim traceability though there is a further requirement from VSL that the user's GNSS equipment has been calibrated. These calibration services are available from VSL to support use of its bulletin data.

PTB currently acts as a G1 laboratory and thus gets signal delays for GPS and Galileo calibrated by BIPM. Based on the observations with calibrated receivers, data are reported in PTB's weekly Time Service Bulletin [46], including an uncertainty estimate (as far as known). The user can find daily values for

- UTC - GPS time
- UTC(PTB) – $\mathrm{bUTC}_{\mathrm{GPS}}$
- UTC(PTB) – GST
- UTC(PTB) – $\mathrm{bUTC}_{\mathrm{GALILEO}}$
- GST – GPS time as predicted in the Galileo navigation message.

After publication of a new Circular T, the values which had been predicted for the past month are contrasted with the results contained in the Circular T.

A final consideration might be whether it is necessary to account for geographical variation in the received GNSS signals in case that the NMI/DI is located in a vast county. Some relevant effects are variations in the observed ionosphere through the day and that distant receivers will necessarily be seeing a different set of satellites at any given time. Averaging data over a suitable interval will remove some of this variation but not all.

6.2.5 Calibration of GNSS equipment delays

Most GNSS DOs do not provide access to raw data or to internal signal delays. So, this method is reserved to GNSS timing receivers as they are operated in NMIs/DIs and other dedicated timing laboratories. Calibration of delays is most easily done with a side-by-side comparison with a calibrated system (see section 4.2). The BIPM scheme, introduced in Section 2 is an example for a successful implementation of this method, but as seen in Table 6-1 also NMIs belonging to group G2 offer such services.

6.3 Existing and future NMI/DI services for the various use types of GNSS DO

The different CMCs that can be provided by an NMI/DI, realizing a time scale UTC(k) with degrees of equivalence reported in the KCDB, including four of them which are already identified in the Classification of Services in Time and Frequency (Version 1.1 (September 2013)) defined by the CCTF WG on MRA [47] and a new service to be proposed to the Group for adoption and inclusion, are the following:

- Frequency calibration by direct comparisons ("Local frequency standard" service under the "Frequency" branch)
- Frequency calibration via GNSS CV ("Remote frequency standard" service under the "Frequency" branch)
- Time comparison via GNSS CV ("Remote clock vs. UTC(NMI)" service under the "Time scale difference" branch)
- Calibration of GNSS equipment delays ("Delay meter" service under the "Time interval" branch)
- Regular publication of UTC(k) - $\mathrm{bUTC_{GNSS}}$ (a new service to create under the "Time scale difference" branch)

Concerning this last quantity, UTC(k) - $\mathrm{bUTC_{GNSS}}$, it is important to note that a UTC(k) laboratory included in the BIPM Circular T, but not NMI/DI and hence not reported in the KCDB, could also propose this service, but it would be considered as valid for the traceability to UTC only if this laboratory is covered by a QMS and accredited for such service provision.

7 Conclusions

Access to accurate time (in the widest sense) 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 a re-thinking started, asking for assured access to accurate time based on more than one source [34]. Even more, legal prescriptions or regulations issued by many user communities ask for traceability to national or international standards when measurements are made or when time stamps are issued. This trend is in line with general metrological requirements. International consistency and comparability of measurements are essential in international collaboration in many application fields as it ensures that measurement results can be universally accepted. This can only be guaranteed if measurement results are metrologically traceable to internationally recognized references. In the view of the Task Group that authors this White Paper, this required level of traceability is not attainable by blindly trusting the output of any GNSS device.

Considering answers received from a variety of involved institutions and stakeholders to the CCTF questionnaire (Annex 3), the timing properties of GNSS signals (Annex 5), the typical performance of GNSS DO (Annex 4) and the rules for getting (metrological) traceability to UTC (Section 3.1), the Task Group proposes

to users

- to carefully analyze 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 analyze 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 uncertainty requirements for time and frequency signals used within their realms, 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 signals accuracy as described in Section 4.2. Users are encouraged to make use of the services offered by NMIs (Section 6.2 and Section 6.3) and build on the expertise available there.

The traceability to UTC from $\mathrm{bUTC}_{\mathrm{GNSS}}$ 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 $\mathrm{bUTC}_{\mathrm{GNSS}}$ if these requirements are not met.

- to NMis/DIs

- 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 [48] or CGGTTS [35]), or in simplified formats, accompanied by documentation on their best usage and a statement of the measurement uncertainty.

- to GNSS DO equipment manufacturers

- to seek calibration of their GNSS DO models as proposed in Sections 5.2.1 and 5.2.2;
- to provide technical documentation of their devices including specifications on the parameters of time accuracy to UTC and frequency instability as function of averaging time etc. 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 $\mathrm{bUTC}_{\mathrm{GNSS}}$ 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.
-

- to GNSS providers

- to seek the collaboration with NMIs/DIs regarding GNSS system time realization and monitoring;
- to describe the realization of GNSS system times as well as the data contents in the navigation messages following metrological practice and vocabulary.

The Task Group encourages the use of UTC as the unique international reference time scale and as the basis of civil time in as many applications as possible. The Task Group encourages NMIs/DIs to provide additional services that the user groups are looking for and encourages the BIPM to provide appropriate documentation and explanation of the use of predictions of UTC in GNSS navigation messages. The Task Group encourages the CCTF WG on the CIPM MRA to consider the definition of a new service (on $\mathrm{bUTC}_{\mathrm{GNSS}}$ monitoring) by revising the current CCTF-MRA Guideline 1.

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Annexes

References, Figures and Tables contained within the Annexes only are numbered A.x, and references are listed separately at the end of the document.

Annex 1: List of Acronyms

ADEV	Allan deviation
AL	Accredited (calibration) laboratory
ALS162	Call sign of the French standard frequency and time signal emitter at 162 kHz
AOS	Borowiec Astrogeodynamic Observatory
BIPM	Bureau international des poids et mesures
BPC	Call sign of the Chinese standard frequency and time signal emitter at 68.5 kHz
BPL	Call sign of the Chinese standard frequency and time signal emitter at 100 kHz
BPM	Call sign of the Chinese standard frequency and time signal emitter at 2.5 MHz, 5 MHz,10 MHz and 15 MHz
CGPM	Conférence général des poids et mesures
CIPM	Comité international des poids et mesures
CMC	Calibration and measurement capability
DCF77	Call sign of the German standard frequency and time signal emitter at 77.5 kHz
DI	Designated institute
DO	Disciplined oscillator
DUT	Device under test
G1, G2	Group 1, group 2
GLONASS	Russian GNSS
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)
ICG	International committee on GNSS
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGS	International GNSS service
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
KCDB	Key comparison data base
MEO	Medium earth orbit
MRA	Mutual recognition arrangement
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
PPP	Precise point positioning
PRTC	Primary reference time clock
PTP	Precision time protocol
QMS	Quality management system
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 an NMI or DI, “k”
UTC(SU)	UTC realization generated in the Russian metrology institute FSUE VNIIFTRI
VIM	Vocabulaire international de métrologie
WWV	Call sign of the US standard frequency and time signal emitter at 2.5 MHz, 5MHz, 10 MHz, 15 MHz, 20 MHz and 25 MHz
WWVB	Call sign of the US standard frequency and time signal emitter at 60 kHz

The acronyms of NMIs and DIs collaborating with BIPM (including respective country and their location) can be found at https://webtai.bipm.org/database/showlab.html

Annex 2: The actors dealing with the topic “traceability to UTC from GNSS measurements”

The CCTF Task Group on “traceability to UTC from GNSS measurements” was created as a temporary working unit combining forces from the permanent CCTF Working Group on GNSS and the CCTF Working Group on the MRA. It got the mandate to develop guidelines explaining the different methods to relate the reading of a user clock to UTC via GNSS. It comprised the members as detailed in the following table and was chaired by Andreas Bauch (PTB). Gianna Panfilo of BIPM acted as Secretary.

Joseph Achkar (LNE-SYRTE)	LNE-SYRTE, Observatoire de Paris, PSL University, CNRS, Sorbonne University, France
Andreas Bauch (PTB)	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Michael Coleman (NRL)	Naval Research Laboratory, Space PNT Branch, Washington DC, USA
Pascale Defraigne (ORB)	Royal Observatory of Belgium, Brussels, Belgium
Jerome Delporte (CNES)	Centre National d'Etudes Spatiales, Toulouse, France
Erik Dierickx (VSL)	Van Swinden Laboratory, Delft, The Netherlands
Hector Esteban (ROA)	Real Instituto y Observatorio de la Armada, an Fernando, Spain
Marina Gertsvolf (NRC)	National Research Council, Ottawa, Canada
Ryuichi Ichikawa (NICT)	National Institute of Information and Communications Technology, Koganei, Tokyo, Japan

Artyom Karaush (VNIIFTRI)	Russian metrological institute of technical physics and radio engineering (FSUE "VNIIFTRI"), Moscow, Russian Federation
Paul Koppang (USNO)	United States Naval Obsrvatory, Washington DC, USA
Alexander Kuna (UFE)	Institute of Photonics and Electronics, Czech Academy of Sciences (IPE/ASCR), Prague, Czech Republic
Judah Levine (NIST)	National Institute of Standards and Technology, Time and Frequency Division, Boulder CO, USA
Calvin Lin (TL)	Telecommunications Laboratory, Chung-Li, Chinese Taipei
Huang-Tien Lin (TL)	Telecommunications Laboratory, Chung-Li, Chinese Taipei
Jerzy Nawrocki (AOS	Astrogeodynamical Observatory, Space Research Centre P.A.S., Borowiec, Poland
Gerard Petit (BIPM)	Bureau International des Poids et Mesures, Sèvres, France
Weijin Qin (NTSC)	National Time Service Center of China, Lintong, P.R. China
Ilaria Sesia (INRIM)	Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
Pierre Uhrich (LNE-SYRTE)	LNE-SYRTE, Observatoire de Paris, PSL University, CNRS, Sorbonne University, France
Pierre Waller (ESA)	European Space Agence, Noordwijk, The Netherlands
Yuzhuo Wang (NIM)	National Institute of Metrology. Beijing, P.R. China
Peter Whibberley (NPL)	National Physical Laboratory, Teddington, UK
Michael Wouters, (NMIA)	Electricity Section, National Measurement Institute, Lindfield NSW 2070, Australia
Wenjun Wu (NTSC)	National Time Service Center of China, Lintong, P.R. China

The CCTF-WGGNSS terms of reference are as follows [A.1]:

- to report to the CCTF on the state of the art in GNSS time and frequency transfer and to provide recommendations concerning receiving systems, calibration and data processing;
- in collaboration with the BIPM, to gather and share the information and the experience on available equipment, characterization of the hardware delays, data processing and scientific results;
- to maintain contacts with the receiver manufacturers in order to inform them about our needs;
- to stimulate the collection and analysis of code and carrier phase data from all GNSS constellations;
- to stimulate the development of calibration procedures in agreement with new GNSS receiving systems;
- to establish contacts with the parallel scientific communities working on the definition of the receiver output standards;
- to study the clock results formats in agreement with the user needs.

Among other work, the CCTF-WGGNSS contributed to the BIPM guidelines for GNSS calibration [7]. These guidelines describe in detail the way to achieve relative calibration of GNSS stations in the frame of the TAI network [5]).

The CCTF-WGMRA terms of reference are as follows [A.1]:

- to authorize on a provisional basis for any action needed between meetings of the CCTF as indicated by the CIPM MRA, in consultation with the CCTF President;
- to perform coordination activities relating to the CIPM MRA between RMOs;
- to act as point of contact for the BIPM and JCRB on CIPM MRA matters;
- to report actions to the next CCTF meeting, the CCTF revising the decisions as required;
- to identify areas where additional key comparisons and supplementary comparisons are needed, and develop the necessary guidelines and procedures;
- to provide guidance on the range of CMCs supported by particular key and supplementary comparisons;
- to establish and maintain a list of service categories, and where necessary rules for the preparation of CMC entries;
- to agree on detailed technical review criteria;
- to coordinate the review of existing CMCs in the context of new results of key and supplementary comparisons.

Among other documents, the WG on MRA edited the Guideline 9 [A.2]. This guideline provides the CCTF criteria for obtaining traceability in time and frequency and is addressed to the laboratories participating in the CIPM MRA. In this White Paper, possibilities for extending or adapting the prescribed procedures are developed, in order to meet the needs of all users more broadly.

At the time of writing, the CCTF WG on GNSS Time Transfer is chaired by Dr Pascale Defraigne (Royal Observatory of Belgium), with Dr Gérard Petit (BIPM) acting as Secretary, and the CCTF WG on MRA is chaired by Mr Chris Matthee (National metrology institute of South-Africa), with Dr Gianna Panfilo (BIPM) acting as Secretary.

Annex 3: Summary of the CCTF questionnaire

In preparation of CCTF2021, a questionnaire was developed and sent to representatives from four groups:

- CCTF members, observers, and other institutes contributing to the Coordinated Universal Time (UTC) (UTC Labs)
- CCTF liaisons (IAU, IGS, ITU, IUGG, URSI)
- NMIs not yet contributing to UTC
- Stakeholders: science, industry, international and national institutions / projects / services, space/defence agencies.

The questions were tailored to the specific group. The questions came under two overarching headlines:

- Roadmap towards the redefinition of the second
- Sustainability of UTC as a unique and high-quality reference time scale,

where the latter covered the topic – "Promotion of the mutual benefit of UTC and GNSS, specifically "Options on traceability for different levels of user needs". Section A.3.1 summarizes the distribution of addressees for questions related to the topic dealt with in this White Paper, originally designated as Hot Topic 3. The questions and answers / comments received are detailed in Section A.3.2.

A.3.1 Statistics of answers to Hot Topic 3

Answers to Hot Topic 3 were received with the distribution among the addressees as depicted in Figure A1. As the answers from stakeholders are of relevance for further work, the adherence to certain user communities is detailed in Figure A2. The total number of answers received was 75.

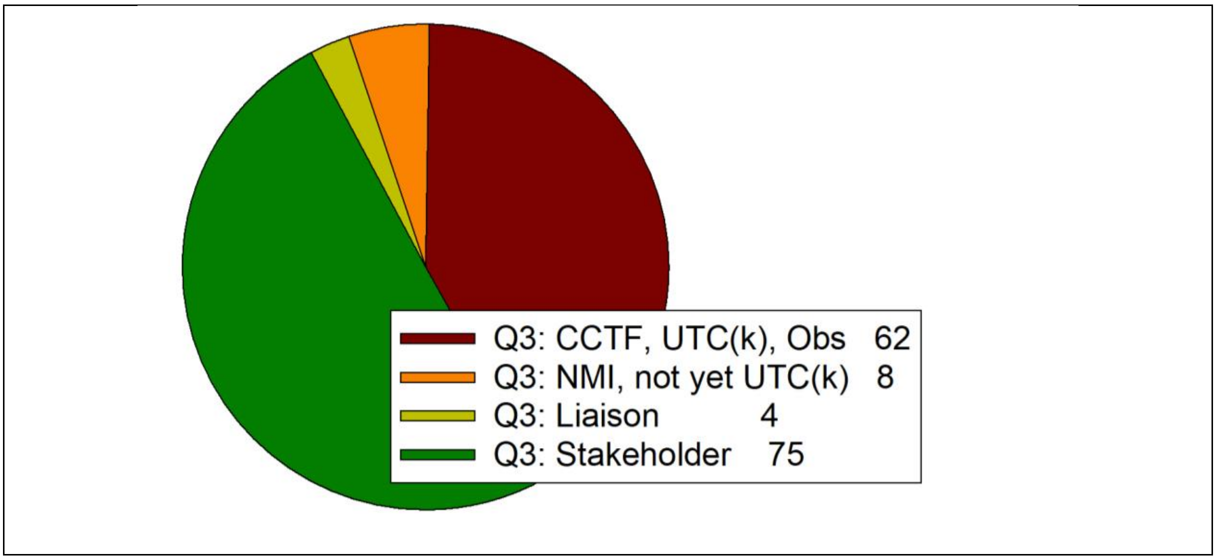

Figure A1: *Distribution of answers received on questions to Hot Topic 3*

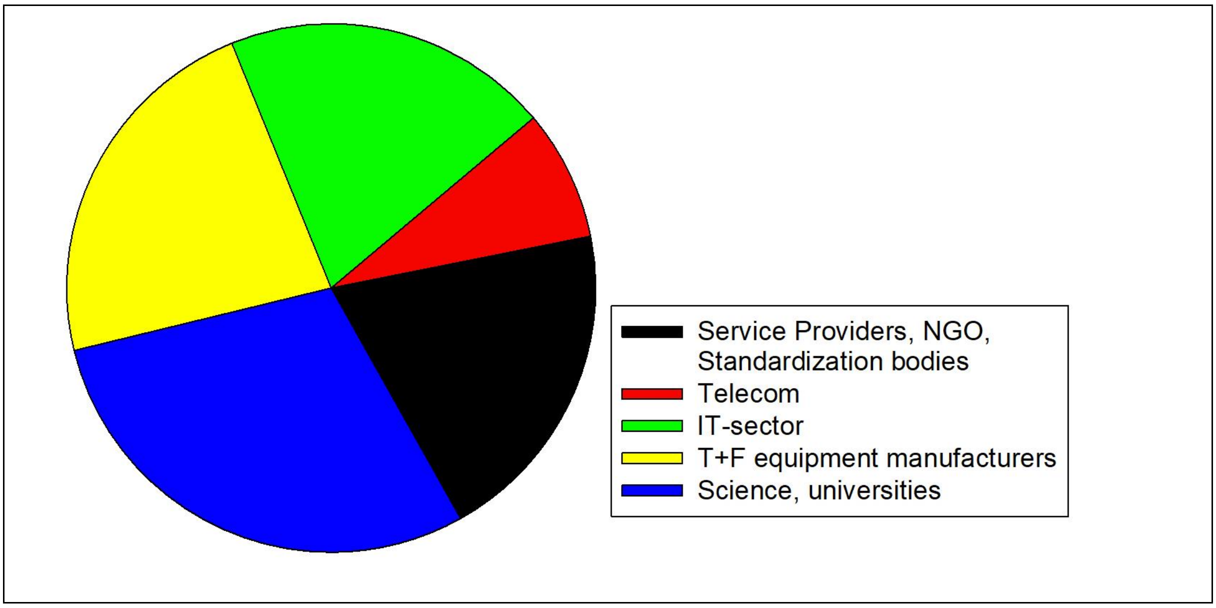

Figure A2: *Distribution of answers from specific user groups*

A.3.2. Questions regarding Hot Topic 3: traceability

Table A1 *Compilation of questions on Hot Topic 3 in the CCTF Questionnaire*

Text of question	Number of answers (not N/A)
Is there a service in your country to calibrate and certify GNSS-based timing equipment to support time and frequency traceability to international standards?	Yes=36 No=22
If there is such a program: Is it a direct collaboration with receiver manufacturers or is it supported by a calibration facility? What timing uncertainty is aimed at and how is traceability reported?	Comments 1
Are you in contact with users who report "time traceable to UTC" by operating a GNSS-clock?	Yes= 34 No= 33
Concerning the previous question: Do you or would you accept this wording? If not, what do you recommend that time acquired through a GNSS receiver be called?	Yes= 11 No= 14 Yes with comments= 20 Comments 2
Which services do you provide to customers, or the public in general, which allow them to obtain traceability to your UTC(k)? If you do not provide such services, are you planning to provide them in future?	comments 3
Which user communities have contacted your NMI/DI to get advice or support in issues of traceability when using GNSS?	Comments 4
Is your work governed by standards, regulations or laws that require "time traceable to UTC" ?	Yes 27 No= 24 Comments 5

if yes: How do you try to fulfill the requirement and how do you document it?	Comments 6
Do you get or expect to get traceability to your national UTC(k) or UTC in general by your local NMI?	Comments 7
Do you agree that the reception of GNSS time signals without further measures does not provide traceability to UTC in the metrological sense?	Comments 8
Do you have other comments or suggestions?	Comments 9

Comments 1:
A number of laboratories provide frequency calibrations with uncertainty in the fractional frequency of about 10^{-13}, with $k = 2$. The uncertainty in the time calibration is generally better than 10 ns and is 2 ns for some services. A few laboratories provide calibration certificates. A few laboratories reported a collaboration with receiver manufacturers. No laboratory reported a program to certify equipment.

Comments 2:
GNSS time not traceable to UTC by default. Would agree with statement if some or all of following was fulfilled:

1. Traceability was claimed with larger uncertainty calculated from receiver characteristics or other methods
2. Receiving equipment had been calibrated by calibration facility or NMI
3. Receiver operation is monitored continuously. Data are verified by common-view or equivalent method
4. Data are traceable only to GNSS system time or to a prediction UTC as transmitted by the GNSS satellite.

Comments 3:
1. Laboratories provide monthly bulletins, giving data on UTC(k)-UTC and sometimes UTC(k) – GNSS time. Some laboratories publish data on UTC(k)-GNSS time to facilitate common-view calibrations by users whose equipment supports the standard data format.
2. Laboratories provide network-based link to UTC(k) by hosting servers that support the NTP and PTP protocols and similar services, including digital time stamps that are derived from UTC(k).
3. Laboratories provide telephone-based servers such as a “talking clock” or modem-based access to UTC(k), such as the ACTS service of NIST.
4. Laboratories provide remote monitoring of user equipment by using GPS common-view and similar techniques. This is usually a paid service.
5. Laboratories disseminate UTC(k) via dedicated optical fiber circuits. This is usually a paid service.
6. Laboratories operate radio broadcasts linked to UTC(k). The broadcasts include short-wave services, such as NIST WWV and NTSC BPM, as well as low-frequency services such as NIST WWVB, French ALS162, German DCF77, Chinese BPL and BPC etc.

Comments 4:
1. Various user groups including telecommunications providers, operators of electrical power distribution systems and financial institutions that are required to establish traceability to UTC(k) to comply with regulations.

2. General users request assistance in establishing or operating user equipment, including network-based equipment to link to UTC(k) via NTP and PTP protocols.
3. Some of the smaller timing laboratories and NMIs request assistance in establishing a local UTC(k) and in transmitting data to the BIPM.
4. Calibration laboratories request assistance in establishing calibration procedures or certification by the local NMI.
5. Scientific organizations that need an accurate source of UTC(k). For example, observatories that characterize the signals from pulsars.

Comments 5:

1. MiFID regulations govern commercial and financial transactions in Europe [30, 30b]
2. Securities and Exchange Commission establishes rules in the US and also Online Auditing Transactions System (OATS) rules [32, 33]
3. In the telecommunication sector, work is governed by a large set of recommendations. In the comments received reference has been made to [A.3] which specifies packet-based time and phase distribution, but many others exist. This was referred to in Section 3.3.3 for further details.
4. Similarly, the IEEE-1588 profile for the power sector has been defined in [A.4]. This was referred to in Section 3.3.1.
5. Many countries require traceability to local UTC(k) for legal purposes [A.5]

Comments 6:

1. Portable rubidium clock synchronized to UTC(k) or disciplined to GNSS time
2. Test and calibration reports
3. Real-time monitoring of remote system
4. Log files at remote system

Comments 7:

1. Yes, but only if required by local laws or regulations.
2. No, if traceability is not required or not important
3. No, because traceability is too difficult or too expensive. GNSS data are good enough.

Comments 8:

1. Almost all responses agree with the statement without qualification.
2. Reasons for not agreeing with the statement:
    a. GNSS data are presumed to be traceable to UTC with an increased uncertainty. This is a common industrial practice and is often adequate in many applications.
    b. GNSS equipment can be calibrated and the various corrections (ionosphere, etc.) can be estimated. Data from manufacturer may provide adequate calibration with increased uncertainty
    c. Frequency traceability is less sensitive to calibration and requires only the stability of the equipment characteristics

Comments 9:

1. Increase support for smaller laboratories in developing countries
2. Increase communication among NMIs, especially in smaller countries

Annex 4 GNSS disciplined oscillators.

Annex 4.1 A brief description of a GNSS DO

De facto each GNSS receiver contains an internal quartz oscillator as signal source for the processing functions to track the received satellite signals. A dedicated GNSS disciplined oscillator (GNSS DO) combines a multi-channel OEM GNSS receiver with a voltage-controlled reference oscillator and a means of adjusting the oscillator to maintain its frequency and 1 PPS output aligned with the received GNSS signal. A variant consists of an un-steered local oscillator followed by a direct digital synthesis engine, the outputs of which reflecting the steering via GNSS reception. A typical block diagram of a GNSS DO of traditional design is depicted in Figure A3. The local oscillator can be a temperature-compensated quartz oscillator (TCXO), an oven-controlled quartz oscillator (OCXO), a small rubidium oscillator or even a caesium frequency standard. Additional information, such as whether the 1 PPS is aligned to bUTCGNSS or T_GNSS, the antenna coordinates, the local oscillator disciplining process, and the time tagging of external events can in some cases be obtained through a display or a computer interface.

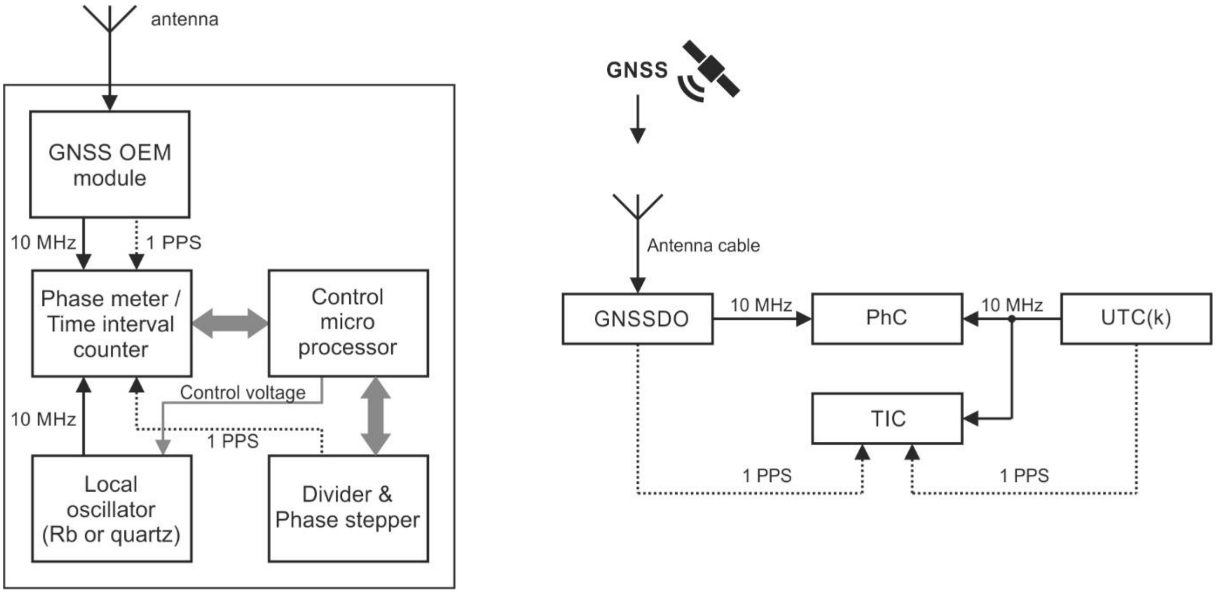

Figure A3: *Set-up example of a GNSS DO (left) and for the validation of precision and accuracy of its 10 MHz and 1 PPS output signals against UTC(k)) as the time and frequency reference (right); TIC = time interval counter, PhC = phase comparator*

The actual performance of a GNSS receiver (in general) depends on its local environment, including the antenna installation, multipath environment, and temperature fluctuations at the receiver and the antenna. In general, the accuracy and stability of the electrical output signals are limited by the uncertainties in the inputs needed by the receiver to perform its calculations, such as broadcast satellite orbits and clocks and the ionospheric delay along the satellite-to-ground signal path. The unpredictable delay caused by the ionosphere is particularly significant, amounting to tens of nanoseconds. As the ionosphere is a dispersive medium, GNSS address this by broadcasting signals at two or more separated frequencies (e. g, for legacy GPS at the L1 frequency 1.57542 GHz and at the L2 frequency 1.22760 GHz) that can be combined to remove the first order ionospheric delay, and broadcasting model parameters for single-frequency users. Dual frequency receivers are also capable of providing a very accurate position for the antenna by logging the receiver's measurements and post processing them and can be used to improve operation in the timing mode as well. For a long time, dual frequency operation has typically only been available in expensive geodetic-like receivers but is now becoming available in low-cost OEM devices as well. Nonetheless, it can be expected that single frequency receivers will continue to be used in GNSS DOs for some time to come.

A proper characterization of the function of a GNSS DO can favorably be undertaken after its installation in the environment in which it will operate routinely, using another well-characterized GNSS DO, a dedicated GNSS timing receiver or a portable frequency standard as a transfer standard, as explained later in this document. A test installation is depicted in Figure A3 as it was used to generate the example performance plots shown in the next section.

Annex 4.2 Examples of GNSS DO performance

A set-up as depicted in the right part of Figure A3 was used at PTB to characterize a variety of GNSS DO (in fact mostly using GPS up to now). In each case, the 1 PPS input representing UTC(PTB) had a known offset from the reference point in the laboratory, and the frequency instability of the 10 MHz reference signal was negligible compared to that of the devices under test.

The frequency instability of GNSS DOs varies considerably, depending on the sophistication and cost of the device. No general statement is possible, except of the fact that the uncertainty of the output frequency provided is dictated by the frequency instability achieved which depends on the selected model and – of course – on the averaging time. Any systematic frequency offset between GPS time and UTC(PTB) or UTC was negligible at the time of data taking.

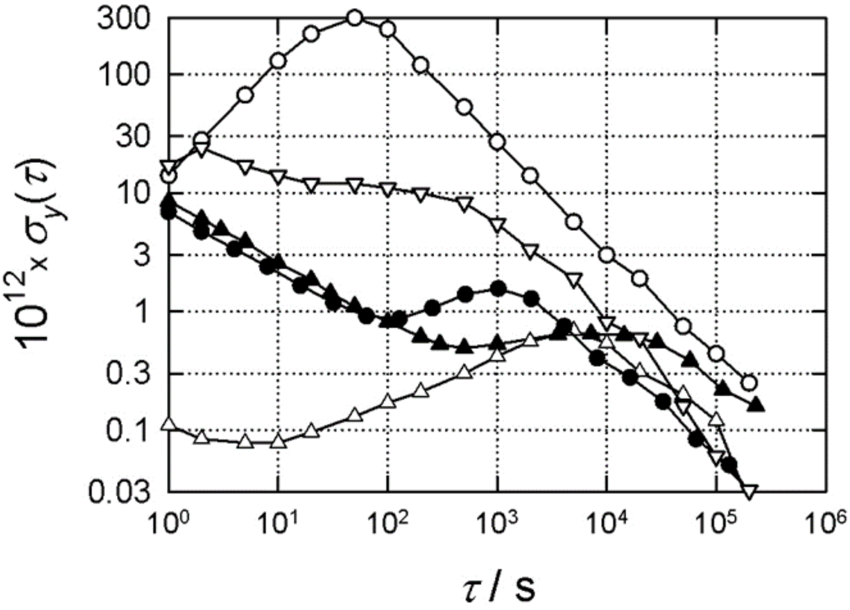

Figure A4: *Frequency instability of different GNSS DO 10 MHz outputs (see details in the text)*

In Figure A4, data represented with bold symbols are from two devices that comprise a rubidium atomic frequency standard as the local oscillator. A time constant of 10^3 s or even more is chosen for the control. Data represented with open symbols are from devices that employ a quartz oscillator. The highest instability is observed for a 500 € device, the lowest for a 20k € ultra-stable oscillator. Open triangle down is from the GNSS DO_2 that is referred to in Figure A5 as well.

The time offset of two GNSS DO PPS outputs was measured with respect to UTC(PTB) for extended periods. The two GNSS DO are quite different: GNSS DO_1 is a metrology-grade disciplined Rb frequency standard that is found in many AL. GNSS DO_2 with its local quartz oscillator is embedded in a multi-purpose time dissemination device that can act as NTP server, PTP Grandmaster, and that can optionally provide further time codes. The offset in time of both devices were recorded after careful determination of and correcting for antenna cable delay and delay of connecting cables. The offset between UTC(PTB) and $bUTC_{GPS}$ was below 10 ns during both periods.

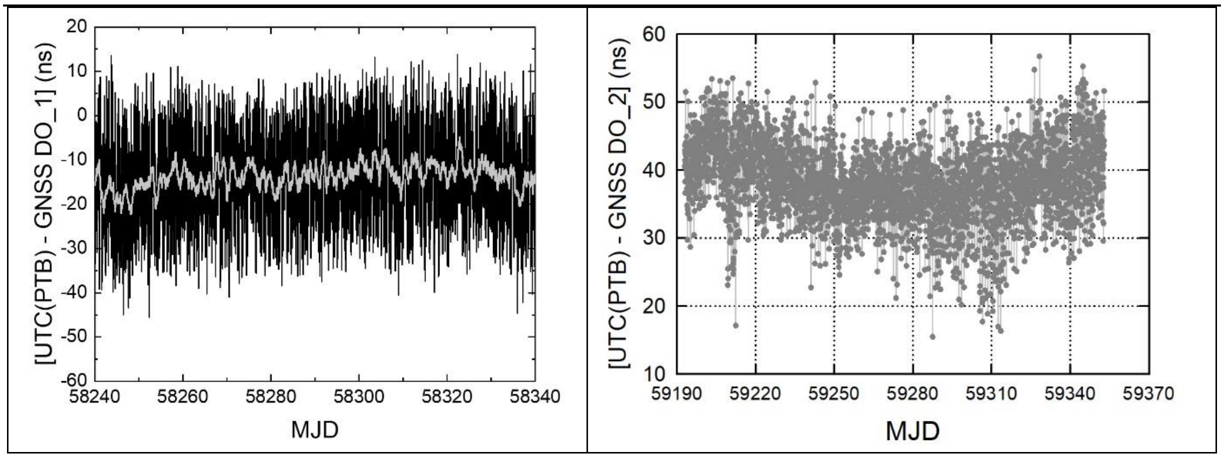

Figure A5: *Time comparison between GNSS DO and UTC(PTB) as local reference, hourly data (24-h sliding average added left)*

In many receiver models, the timing of this signal has a sawtooth variation of some tens of ns because of limitations in setting the delay of the output 1 PPS. It is also usually possible to select UTC as the reference time scale in which case the receiver considers the prediction of UTC broadcast by the GNSS, as explained in Section 2.2.3. A word of caution may be required here: In the past, the common product was a GPS DO and the time reference used was $bUTC_{GPS}$. A modern GNSS DO may process signals from more than one GNSS and it is potentially not transparent to the user whether an individual $bUTC_{GNSS}$ or an average is used.

Annex 4.3 Suggestions regarding documentation, specification, and operation of GNSS DOs

Irrespective of the future use, whether as a source of time or as a source of frequency only, a common requirement is to be stressed that complements the need for qualification as described in the next section: The GNSS station or GNSS DO should provide some log file with the information that the oscillator is locked to the GNSS signals. Furthermore, the reference GNSS(s) timescale for the receiver's output PPS should be specified, as this can be one of the $bUTC_{GNSS}$ or a combination. The minimum information required is the log status, even better is the recording of the control voltage to the internal oscillator, number of satellites tracked, events of loss of satellite signals, poor signal-to-noise ratio etc.. Users are invited to select models that provide such capabilities and include observance in their QMS.

Manufacturers should provide sufficient guidance regarding the installation and operation of GNSS receivers, including the following points – even if they may seem trivial. The GNSS antenna must be mounted externally in a location that has a clear view of the sky and is well away from potential sources of electrical or RF interference. It should be raised up above any nearby structures to reduce interference caused by multipath reflections of satellite signals into the antenna. The antenna cable should be positioned out of direct sunlight where possible, and any excess length of cable should be kept inside the laboratory rather than outdoors to minimize the effect of temperature changes on the delay.

Annex 5: Facts on GNSS system times and navigation messages

GPS

GPS System Time (GPST) is a continuous time scale generated from an ensemble of monitor stations and satellites clocks, as part of the overall clock and orbit estimation process. GPST is steered to UTC(USNO). While the maximum offset between the two time scales (modulo 1 s) is specified to be below 1 µs, it is typically within 10 ns.

A GPS signal's message contains information on both the originating vehicle's clock offset from GPS System Time (GPST), and GPST offsets from UTC(USNO) such that a user's receiver clock would have the ability to reasonably synchronize to UTC(USNO). The information presented here references the GPS Interface Specification (IS) Document IS-GPS-200L [A.6] which was approved and published on 14 May 2020. In particular, the paragraph numbers of the form 20.x.x.x.x and 30.x.x.x.x identify specific blocks of text within that document.SV Clock Correction

A GPS SV's message contains the coefficients of a quadratic polynomial to identify its clock's offset from GPST. In paragraph 20.3.3.3.3.1, these parameters are utilized in the correction equation

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$$\Delta t_{SV} = a_0 + a_1(t - t_{oc}) + a_2(t - t_{oc})^2 + \Delta t_r \qquad (1)$$

where a_0, a_1 and a_2 are the quadratic coefficients of the model offset between the SV clock and GPST, and t_{oc} is the reference time of clock. The final term Δt_r is the relativistic correction, details of which can be found in 20.3.3.3.3.1. An estimate of GPS Time, t is then attained by

$$t = t_{SV} - \Delta t_{SV}. \qquad (2)$$

In paragraph 20.3.3.5.2.3, information regarding these parameters in the GPS almanac are presented. While only a linear fit is provided there, and indeed the almanac typically provides a more coarse acquisition of position and time, it is stated that the time accuracy attained by this model yields GPST to within 2 µs. It is also mentioned that the user range error (URE) as provided by this component would be up to 135 meters (or 450.311 ns) for one sigma. The conversion between distance and time utilizes the speed of light value 299792458 m/s, which is official for the GPS reference frame, WGS 84; this is noted in 20.3.4.3. While no specific details are provided on the uncertainties of the SV clock correction Δt_{SV}, we might expect the finer model of Equation (1) to possess better precision than the almanac model most of the time.

Countless studies and the performance of GPS confirm this implicitly, but the IS document does not specifically guarantee it.

GPST offset from UTC(USNO)

According to paragraph 30.3.3.6.1, parameters contained in the GPS message that allow conversion to UTC(USNO) are provided and updated at least once every three days. The time data reference for this information is stamped with a GPS week number w_{ot} and time of week t_{ot}. In paragraph 30.3.3.6.2, the equation to determine UTC is presented as

$$\Delta t_{UTC}(t) = \Delta t_{LS} + A_0 + A_1(t - t_{ot} + 604800(w - w_{ot}) + A_2\big(t - t_{ot} + 604800(w - w_{ot})\big)^2 \qquad (3)$$

where w and t are the present estimate of GPS Time in week number of time of week, respectively; and Δt_{LS} accounts for leap seconds in UTC-GPST; and A_0, A_1, and A_2 are the estimates of the local quadratic between GPST and UTC(USNO).

Although the three quadratic coefficients are estimates, whose accuracy degrade over time, the variances of these statistics are not provided in the GPS message nor is a typical probability distribution for these provided in the IS. In [A.6] we find "*The LNAV/CNAV data contains the requisite data for relating GPS time to UTC. The accuracy of this data during the transmission interval shall be such that it relates GPS time (maintained by the MCS (*Master Control Station*) of the CS (*Control Segment*)) to UTC (USNO) within 20 nanoseconds (one sigma).*"

In paragraph 20.3.3.5.2.4, it is further clarified that

$$t_{UTC} = t_E - \Delta t_{UTC} \;\; [\,modulo\ 86400\ seconds\,]$$

where t_E is the estimated value of GPST after accounting for SV corrections and t_{UTC} is specifically the UTC that is generated by UTC(USNO). As with the SV correction, the UTC correction's level of accuracy and uncertainty remain unquantified in this IS Document.

Galileo

GST, the Galileo System Time is a continuous time scale based on the definition of the SI second whose origin epoch is defined as 13 s before Sunday 22 August 1999 00:00:00 UTC. It is generated by a clock ensemble at the Precise Time Facility, with an option to include ground station and satellite clocks. It is steered to a prediction of UTC that is provided by the Galileo Time Service Provider based on contributions from European UTC laboratories. The maximum offset between GST and UTC (modulo 1 s) is quite limited by design of the Galileo Ground Segment and the collaboration of the Galileo operator, Spaceopal GmbH, with European NMIs, however not specified in public documents. The Open Service Service Definition Document [A.7] specifies the uncertainty of the $\mathrm{bUTC}_{\mathrm{GALILEO}}$ to be less than 30 ns for 95% of any one-year period.

GST is represented by a 32-bit binary number composed of two parameters: the Week Number (WN) is an integer counter counting the number of weeks elapsed since the GST start epoch, and the Time of Week (ToW) is an integer counter counting the number of seconds elapsed since the transition from the previous week. The start of the week occurs at 00:00 during the night between Saturday and Sunday.

The Galileo system broadcasts, in its navigation message, the correction parameters to convert the GST to a prediction of UTC. This includes both an integer part (number of leap seconds between GST and UTC) and a fractional part based on a linear model. Those parameters are in page 4 of sub-frames 1 to 12 for F/NAV message (transmitted on E5a signal component) and Word Type 6 for I/NAV message (transmitted on E5b and E1b signal components). With these corrections, the accuracy of the UTC time and frequency dissemination are specified to be better than 30 ns (95%) and 3×10^{-13} (95%) respectively, excluding propagation and user contributions. The actual Galileo time and frequency dissemination accuracies are reported quarterly by the Galileo Service Centre [A.8] and are typically well below the specifications.

To account for user-dependant contributions, the user environment and equipment (antenna, receiver…) needs to be characterised and calibrated. In the best conditions (open sky, fixed professional receiver), this contribution can be estimated within an uncertainty of 2 ns to 3 ns (k = 1).

GLONASS

According to GLONASS ICD [A.9], GLONASS Time (GLOT) is based on the continuous time scale of System Central Synchronizer (CS). CS is equipped with Hydrogen Masers which have a daily relative frequency instability (Allan Deviation) around 2×10^{-15}. Unlike other GNSS time scales, GLOT itself is not continuous, it is corrected simultaneously with UTC(SU), which follows UTC. UTC(SU) is a reference time scale for GLOT, but there is a constant offset of 3 hours between them. Beside that constant offset there also exist some residual offset, called τ_c. So total deviation of GLOT with respect to UTC(SU) is as follows:

$$\mathrm{GLOT} = \mathrm{UTC(SU)} + 10800\ \mathrm{s} + \tau_c \qquad (4)$$

τ_c is determined once or twice a day and is broadcasted in navigation message. τ_c should not exceed 1 ms and the error of τ_c determination should not exceed 1 µs.

GLOT is obtained using SVs time scale with broadcasted corrections of satellite to GLOT, which are the coefficients of linear polynomial:

$$\mathrm{GLOT} = t + \tau_n - \gamma_n \cdot (t - t_b), \qquad (5)$$

Where t: SV time,
t_b: ephemeris reference time,
τ_n: SV time offset,
γ_n: SV relative frequency offset.

The newer CDMA GLONASS navigation message also includes derivative of τ_c in equation (4) and quadratic polynomial coefficient in equation (5). Unlike other GNSS, relativistic correction is already included in polynomial coefficients of (5) and should not be further estimated and corrected by the user.

BeiDou

The BeiDou navigation satellite system Time (BDT) is adopted by the BDS as time reference. BDT adopts the international system of units (SI) second as the base unit and accumulates continuously without leap seconds. The start epoch of BDT is 00:00:00 on January 1, 2006 of

Coordinated Universal Time (UTC). BDT connects with UTC via UTC (NTSC), and the deviation of BDT to UTC is maintained within 50 ns (modulo 1 second). The leap second information is broadcast in the navigation message.

BDT is generated by a composite clock based on a clock ensemble of master control station and monitor station. The maximum offset between BDT and UTC (modulo 1 second) is reported to be between 100 ns (ICG templates) and 50 ns [A.10].

The BeiDou system broadcasts, in its navigation message, the correction parameters to convert the BDT to UTC. This includes both an integer part (number of leap seconds between BDT and UTC) and a fractional part based on a polynomial. In the navigation message of BeiDou-2, transmitted on B1I, B2I and B3I, a first-order polynomial is used, and the parameters are broadcast in sub-frame 5, page 10 [A.10]. The relationship between UTC and BDT is then given by:

$$t_{UTC} = t_E - \Delta t_{UTC} \;\; [\, modulo\ 86400\ seconds\,]$$

$$\Delta t_{UTC} = \; \Delta t_{LS} + A_{0UTC} + A_{1UTC}\, t_E \quad \text{, seconds}$$

where, t_E is the second of week in BDT computed by user, and Δt_{LS} is the Delta time due to leap seconds. The specified accuracy of the corrections to UTC is 5 ns (95%).
In the more recent BeiDou-3 system, the relationship between UTC and BDT is then given by a second order polynomial:

$$\Delta t_{UTC}(t) = \; \Delta t_{LS} + A_{0UTC} + A_{1UTC}(t_E - t_{ot} + 604800(WN - WN_{ot}) + A_2\big(t - t_{ot} + 604800(WN - WN_{ot})\big)^2$$

The navigation message B-CNAV2 is modulating the B2a signal, and the parameters are broadcast in the Message Type 34 [A.11], while in the message B-CNAV1 modulating the B1C signal, the parameters are provided in the Page Type 1 of Subframe 3 [A.12]. Finally, the B-CNAV3 message transmitted on B2b contains the UTC parameters in the Message Type 30 [A.13].

NavIC

Navigation with Indian Constellation (NavIC) was earlier known as Indian Regional Navigation Satellite System (IRNSS). The IRNSS Network Timing Facility (IRNWT) is responsible for the realization, dissemination and maintenance of the NavIC System time, which acts as the reference for the entire NavIC network [A.14]. NavIC system time is generated through a carefully selected ensemble of atomic clocks, such as cesium atomic frequency standards, passive hydrogen masers and active hydrogen masers [A.15]. In addition, the IRNWT timescale is steered in such a way that its offset with UTC remains within 40 ns (2- sigma), while under nominal conditions, the time offset of IRNWT relative to UTC is smaller than 20 ns (2-sigma). [2.6]
The NavIC system time start epoch shall be 00:00:00 UT on Sunday August 22nd, 1999 (midnight between August 21st and 22nd). At the start epoch, IRNSS System Time shall be ahead of UTC by 13 leap seconds. (i.e. NavIC system time time, August 22nd 1999, 00:00:00 corresponds to UTC time August 21st 1999, 23:59:47). Message type 9 provides the NavIC time offset with respect to UTC and Message Type 26 provides the NavIC time offset with respect to both UTC and UTC(NPLI). Time transfer between IRNWT and UTC (NPLI), using

TWSTFT and GNSS CV, along with the offset of UTC (NPLI) relative to UTC, obtained from the Circular-T, are used to derive the broadcast information.
The relationship between UTC and NavIC Time is given by a second order polynomial [A.16]

$$t_{UTC} = (t_E - \Delta t_{UTC}) \ [modulo\ 86400\ seconds]\ seconds$$

with

$$\Delta t_{UTC}(t) = \Delta t_{LS} + A_{0UTC} + A_{1UTC}(t_E - t_{oUTC} + 604800(WN - WN_{oUTC})) + A_{2UTC}\big(t - t_{oUTC} + 604800(WN - WN_{oUTC})\big)^2\ seconds$$

where, t_E is the NavIC Time in seconds as estimated by the user after correcting t_{SV} (effective satellite PRN code phase time at message transmission time in seconds) and WN is the current week number (derived from subframe 1 of NavIC broadcast message), and Δt_{LS} is the Delta time due to leap seconds.

The relationship between UTC(NPLI) and NavIC Time is given by a second order polynomial [A.16]

$$t_{UTC(NPLI)} = (t_E - \Delta t_{UTC(NPLI)}) \ [modulo\ 86400\ seconds]\ seconds$$

with

$$\Delta t_{UTC(NPLI)}(t) = \Delta t_{LS} + A_0 + A_1(t_E - t_{oT} + 604800(WN - WN_{oT})) + A_2\big(t_E - t_{oT} + 604800(WN - WN_{oT})\big)^2\ seconds$$

where, t_E is the NavIC Time in seconds as estimated by the user after correcting t_{SV} (effective satellite PRN code phase time at message transmission time in seconds) and WN is the current week number (derived from subframe 1 of NavIC broadcast message), and Δt_{LS} is the Delta time due to leap seconds.

QZSS

The Cabinet Office, Government of Japan (CAO) and Quasi-Zenith Satellite System Services Inc. (QSS) are operationally performing the QZSS service [A.17]. The CAO has taken on direct responsibility for the QZSS operations, and the CAO entrust these operations to QSS Inc. The time difference between QZSST and UTC(NICT) is monitored using CGGTTS comparison by the QSS Inc. The time scale origin is aligned on GPS time origin, i. e. 0:00 am (UTC) on January 6, 1980, hence with a delay from TAI of 19 seconds. The difference between QZSST and UTC(NICT) is broadcast in the different navigation messages. It can be found in Subframe 4, on the QZSS L1C/A, legacy type message, in Message type 33 and 49 of the CNAV message broadcast on the QZSS L2C and L5 signals, and in Subframe 3, page 1 and 17 of the CNAV2 message broadcast on the QZSS L1C signal [A.17].

Documents referred to in the Annexes only

[A.1] URL: https://www.bipm.org/en/committees/cc/cctf/wg/cctf-wgmra

[A.2] CCTF WGMRA Guidelines 9 June 2017, CCTF criteria for obtaining traceability in time and frequency, cc-publication-ID-493

[A.3] International Telecommunication Union, Telecommunication Standardization Sector (2021) Architecture and requirements for packet-based time and phase distribution Recommendation ITU-T G.8275/Y.1369 (2020) – with two additional versions, including Amendment 1 for “full timing support from the network“ and Amendment 2 „with partial timing support from the network“

[A.4] IEC/ INTERNATIONAL ELECTROTECHNICAL COMMISSION IEEE 61850-9-3 Communication networks and systems for power utility automation – Part 9-3: Precision time protocol profile for power utility automation, Edition 1.0 , 2016-05

[A.5] Lapuh R (2011) EURAMET Countries' Legal Time Regulations and Practices, URL: https://www.euramet.org/technical-committees/tc-projects/details/project/survey-of-european-countries-legal-time-regulations-and-practices/?tx_eurametctcp_project%5Baction%5D=show&tx_eurametctcp_project%5Bcontroller%5D=Project&cHash=f9814a8a8b8ba7bac4d9e7687c3539b5

[A.6] GPS Interface Specification (IS) Document IS-GPS-200L, 14 May 2020

[A.7] Galileo Open Service Service Definition Document (OS SDD), EUSPA

[A.8] EUSPA, European GNSS Service Centre, Galileo quarterly performance reports https://www.gsc-europa.eu/electronic-library/galileo-service-performance-reports

[A.9] GLONASS Interface Control Document Navigational radiosignal in bands L1, L2 (Edition 5.1), 2008

[A.10] BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1I (Version 3.0), 2019

[A.11] BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B2a (Version 1.0) , 2017

[A.12] BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1C (Version 1.0), 2017

[A.13] BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B2b（Beta Version), 2019

[A.14] A.A. Bhardwajan, et al., Challenges in the system engineering of a precise timing facility for NavIC. INCOSE International Symposium, 29 (2019) 302–3138, 10.1002/j.2334-5837.2019.00687.x

[A.15] A. Arora et al., An in-house developed Timescale for NavIC PTF, 2019 European Navigation Conference (ENC), Warsaw, Poland, 2019, pp. 1-6, https://doi.org/10.1109/EURONAV. 2019.8714190

[A.16] IRNSS Signal In Space ICD for standard positioning service, Version 1.1, 2017

[A.17] Quasi-Zenith Satellite System Interface Specification Satellite Positioning, Navigation and Timing Service (IS-QZSS-PNT-004, January 25, 2021)