Practical Traceability to UTC(k) from a GNSS Timing Receiver

Ricardo Píriz, Pedro Roldán, Francisco Domingo, Esteban Garbin
GMV
Tres Cantos, Spain
rpiriz@gmv.com

Pascale Defraigne
Royal Observatory of Belgium (ROB)
Brussels, Belgium

Javier Díaz
University of Granada / Seven Solutions
Granada, Spain

***Abstract*— A GNSS timing receiver can generate a time pulse aligned to GNSS System Time (GNSST) or to the predicted UTC transmitted by GNSS. Using GNSST or its associated UTC realization is enough for many synchronization and time stamping applications, but in some cases (for example in the financial sector) it is necessary to trace the timing solution to the legal time scale of the user's country, which is normally a national UTC(k) laboratory as for example UTC(NIST) in the USA, UTC(PTB) in Germany, or UTC(ROA) in Spain. Traceability to a UTC(k) time scale can be achieved a-posteriori by means of Common-View (CV) time transfer between the receiver and the UTC(k) laboratory. This paper provides practical recommendations for CV traceability computations, focused on affordable, single-frequency timing receivers.**

***Keywords*— GNSS; receiver; timing; clock; synchronization; UTC; traceability; liability; ionosphere; calibration**

I. Introduction

The standard GNSS navigation solution (also called PVT, for Position, Velocity and Time) solves for the receiver position and for the receiver clock bias. In timing applications the antenna position is often known a-priori and therefore is "fixed" in the PVT solution. Since the broadcast satellite clocks are referred to GNSST, by default the receiver clock bias from PVT is referred to GNSST too. GPS and Galileo transmit also the predicted offset between their GNSST and UTC modulo one second (leap seconds are transmitted separately). By applying such offset after the PVT calculation, the receiver can obtain its clock bias referred to the predicted UTC instead of to GNSST. Thus, the output time pulse can be aligned either to GNSST or to UTC.

In the case of GPS, GNSST is GPS Time, and the predicted UTC is UTC(USNO). USNO is the United States Naval Observatory. In the case of Galileo, GNSST is Galileo System Time (GST), and the predicted UTC is the average of five European UTC(k) laboratories. The GPS and Galileo UTC realizations normally agree within a few ns, which guarantees inter-system compatibility.

The International Telecommunications Union (ITU) adopted the following definition of traceability in 2013: "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties" [1].

Many applications require an accurate and traceable time reference. For instance, in the electricity transmission domain, Phasor Measurement Units (PMUs) for Smart Grids require to have UTC delivered to them accurately and reliably [2]. Another example is the financial market: as from 2018, the European MiFID II regulation [3] requires that various types of events are time-stamped with a maximum divergence of 100 µs, traceable to UTC, without exception. Finally, in the evolution to 5G of mobile telecommunication networks [4], multiple operators need to share the spectrum, which requires putting in place a proper time traceability mechanism as a response to any liability issue between operators derived from possible cross-interferences. As a general rule, we will consider in this paper that the most stringent accuracy requirements nowadays for timing applications in different markets are of the order of one µs.

Traceability to a national UTC(k) time scale can be achieved a-posteriori by means of Common-View (CV) time transfer between the receiver and the UTC(k) laboratory, provided that the receiver complies with certain requirements [5]. The CV technique is explained in detail in [6]. The following sections deal with practical calculation of traceability when using commercially available timing receivers, in particular affordable, single-frequency ones.

II. Time Pulse Generation

A GNSS timing receiver estimates its clock bias with respect to a certain time reference, which can be GNSST or its associated UTC realization, as explained above. The 1PPS (One Pulse Per Second) time pulse is generated by means of correcting the physical clock with the estimated bias. Thus:

$$1PPS \approx CLK_{rx} - CLKB_{rx} \quad (1)$$

where CLK_{rx} is the receiver clock, and $CLKB_{rx}$ is the clock bias estimated by the receiver. The ≈ symbol denotes *aligned to*. On the other hand the estimated clock bias $CLKB_{rx}$ is the difference between the receiver clock CLK_{rx} and the estimated

time reference REF_{rx}. The estimated time reference REF_{rx} is affected by the receiver hardware delay DLY_{rx}. The receiver hardware delay DLY_{rx} is the total delay in the measured pseudorange measurements, including the GNSS antenna delay, the antenna cable delay, and the GNSS receiver internal delay. We will assume that there is no further delay between the internal measurement latching point and the output time pulse connector. Thus:

$$CLKB_{rx} = CLK_{rx} - (REF_{rx} + DLY_{rx}) \quad (2)$$

where, if the user selects GNSST as output:

$$REF_{rx} = GNSST_{rx} \quad (3)$$

and, if the user selects UTC as output:

$$REF_{rx} = UTC_{rx} = GNSST_{rx} + UTCO_{rx} \quad (4)$$

where $UTCO_{rx}$ is the broadcast predicted offset between GNSST and UTC.

And then, substituting (2) in (1):

$$1PPS \approx REF_{rx} + DLY_{rx} \quad (5)$$

Equation (5) indicates that the output time pulse is aligned to the time reference REF_{rx} (GNSST or its associated UTC realization), and is affected by the receiver hardware delay.

III. Traceability Using CGGTTS Files

In parallel to the routine time pulse generation, some timing receivers can record raw GNSS data (i.e., raw pseudorange measurements and navigation messages). This allows the user to generate, a-posteriori, a CGGTTS file [6]. CGGTTS is a standard format for CV time transfer between timing laboratories. CGGTTS files can be generated from raw measurements and navigation data provided by the receiver in the RINEX (Receiver INdependent EXchange) format [7]. The CGGTTS file provides in its REFSYS column the difference at each epoch between the receiver clock CLK_{rx} and the estimation of GNSST from each satellite in view ($GNSST_{sat\_i}$). $GNSST_{sat\_i}$ is also affected by the receiver hardware delay DLY_{rx}. Thus:

$$REFSYS_{rx} = CLK_{rx} - (GNSST_{sat\_i} + DLY_{rx}) \quad (6)$$

On the UTC(k) laboratory side, the CGGTTS file provides the difference between the UTC(k) time scale and the estimated GNSST from each satellite in view. Reference GNSS receivers at UTC(k) laboratories are normally calibrated, therefore their REFSYS values are free of delays. Thus:

$$REFSYS_{utc(k)} = UTC(k) - GNSST_{sat\_i} \quad (7)$$

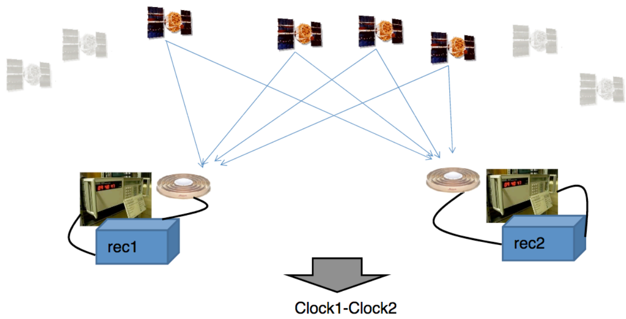

Fig. 1. Principle of GNSS Common-View (CV) time transfer.

The CV technique consists in differencing two CGGTTS files and averaging the REFSYS difference for all satellites in view at each epoch. The principle is depicted in Fig. 1.

By differencing the two CGGTTS files, the estimated GNSST from the satellites ($GNSST_{sat\_i}$) cancels out, and the CV difference of the two ground clocks is obtained:

$$CV_{rx\text{-}utc(k)} = REFSYS_{rx} - REFSYS_{utc(k)} \quad (8)$$

And then, substituting (6) and (7) in (8):

$$CV_{rx\text{-}utc(k)} = CLK_{rx} - UTC(k) - DLY_{rx} \quad (9)$$

The CV solution from (9) includes errors caused by differences between the two sites due to uncertainties in satellite orbit predictions and in the ionospheric and tropospheric delay corrections, errors from multipath signal reflections and local environmental conditions, and errors in the GNSS antenna coordinates. When the two sites are relatively close (a few hundred km separation) the CV error due to orbits and atmospheric corrections is strongly reduced, under the condition that the same modeling of these corrections has been used for both sites.

Let us assume that the receiver can also record its clock bias estimate $CLKB_{rx}$. By differencing (9) and (2) we obtain:

$$CV_{rx\text{-}utc(k)} - CLKB_{rx} = REF_{rx} - UTC(k) \quad (10)$$

Equation (10) is the final tool to obtain the difference between the receiver time pulse reference REF_{rx} and the UTC(k) time scale. Notice that the receiver hardware delay DLY_{rx} has vanished in (10). This means that the proposed traceability method cannot be used to measure or monitor the receiver hardware delay. Such delay must be calibrated separately.

When the receiver is configured to generate a time pulse aligned to the UTC realization from GNSS, the user should verify if the calculated receiver clock bias $CLKB_{rx}$ contains the full bias of the internal clock CLK_{rx} to UTC time, or only the bias to GNSST. In the second case, the applied offset between GNSST and the predicted UTC ($UTCO_{rx}$), if reported by the receiver, must be added explicitly to $CLKB_{rx}$ in (10).

CGGTTS is a format with low temporal resolution (nominally 16 min) optimized for time transfer between timing laboratories that operate very stable clocks. When applied to less-stable or rapidly drifting clocks, results show that CGGTTS usage can lead to an important loss of accuracy in the time transfer. To circumvent this fact we have chosen to subtract the receiver clock bias $CLKB_{rx}$ before doing the CV calculation in (10). In practice this is achieved correcting the pseudoranges in the RINEX file by subtracting the clock bias, before generating the CGGTTS file. In this way the resulting CGGTTS file is aligned directly to the receiver time reference REF_{rx} (GNSST or its associated UTC realization), which in general is a more stable time scale than the receiver internal clock.

In the following sections we present the application of the described CV technique to two different receiver models, each using a different internal clock control algorithm.

IV. Example 1: Steered Clock

The u-blox LEA-M8F is a single-frequency timing receiver including a low-noise VCTCXO (Voltage Controlled Temperature Compensated Crystal Oscillator). A M8F receiver has been installed at GMV's offices in Madrid, Spain, configured to use GPS-only, fixing an accurate antenna position calculated beforehand, and generating a time pulse aligned to GPS Time. The receiver antenna setup is shown in Fig. 2. The satellite visibility from the antenna location is very close to full-sky.

The receiver reports in the NAV-CLOCK message its estimated clock bias $CLKB_{rx}$. The receiver can also generate pseudorange (and carrier-phase) measurements, as well as navigation messages. One day of such data has been recorded (April 18, 2018, MJD 58226). The recorded clock bias $CLKB_{rx}$ from the NAV-CLOCK message is depicted in Fig. 3.

As can be seen, the estimated clock bias is basically a constant of around -0.129 ms, with a jitter of ± 2 ns around it. The constant behavior of $CLKB_{rx}$ comes from the fact that the internal clock frequency is constantly steered to follow GPS Time as determined by the receiver. Such bias is arbitrary (within 1 ms) and changes every time the receiver is powered off and on. The ± 2 ns jitter derives from the granularity in the applied steering, which prevents compensating the short-term instability of the internal clock. The observed jitter is in line with the M8F specifications [8].

Pseudorange measurements and navigation messages from the receiver in u-blox binary format have been converted to RINEX format using RTKLIB [9]. The resulting RINEX file has been manipulated to subtract the estimated clock bias $CLKB_{rx}$ from NAV-CLOCK, as explained at the end of Section III. A CGGTTS file has been generated from the RINEX file using GMV's proprietary software. The software was developed in the frame of the Galileo Time Validation Facility (TVF) [10].

Fig. 2. GNSS antenna on GMV's rooftop.

Another CGGTTS file has been generated from RINEX files of a calibrated receiver located at the Real Instituto y Observatorio de la Armada (ROA), the Spanish National Timing Laboratory located in Cádiz, around 500 km away from our timing receiver. In order to have the same modeling errors for the two sites, the CGGTTS file for ROA is also single-frequency, and the Klobuchar model broadcast by GPS [11] has been used to correct for the ionospheric delay on both sites.

By applying (10), we obtain the traceability results shown in Fig. 5 (blue line). Notice that although the CGGTTS standard dictates a 16-min resolution, our CV processing can provide data records every 5 min.

The results in Fig. 5 show a good agreement between the GPS Time estimated by the receiver and UTC(ROA), with a maximum difference of around 10 ns and a slow daily oscillation. This pattern is typical of the residual error due to the uncertainties on the ionospheric correction applied by the M8F's PVT, based on the Klobuchar model from GPS. Fig. 5 represents an estimation of the actual timing error in the output 1PPS signal from the M8F, measured a-posteriori against UTC(ROA), and except for receiver delays (which are discussed in Section VIII).

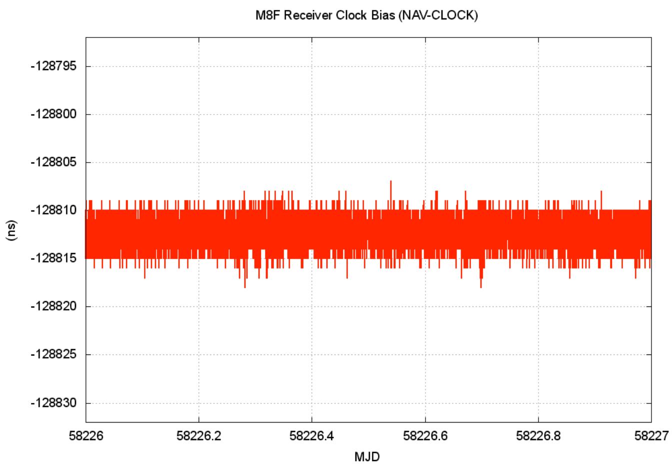

Fig. 3. M8F clock bias as estimated by the receiver.

V. Example 2: Free-Running Clock

The NEO-M8T is another single-frequency GNSS timing receiver from u-blox. The main difference with the M8F is that the M8T is driven by a less stable internal clock that operates free-running within 0.5 ms of GPS Time. The resulting 1PPS presents a jitter of ± 11 ns with respect to the reference, according to the M8T specifications [12].

A M8T receiver has been installed at GMV in common antenna with the M8F, using an antenna splitter. As in the case of the M8F, the M8T is configured to use GPS-only, fixing the same antenna position, and generating a 1PPS aligned to GPS Time.

The recorded clock bias $CLKB_{rx}$ is depicted in Fig. 4. The traceability results after applying (10) following the procedure described in Section IV are shown in Fig. 5 (magenta line). Notice the good agreement with the traceability results from the M8F, despite the very different internal clock behavior.

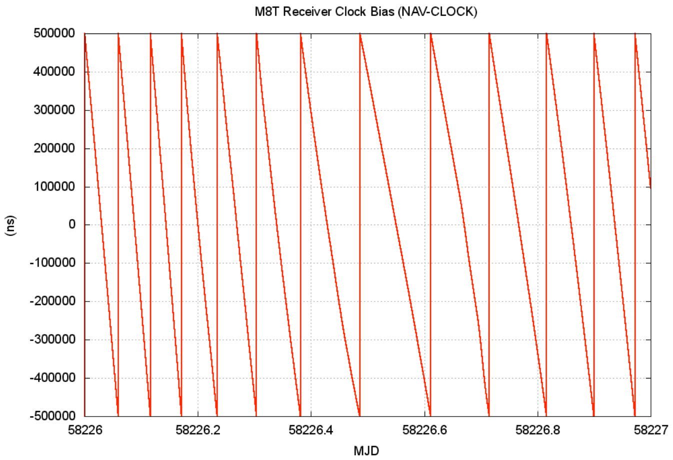

Fig. 4. M8T clock bias as estimated by the receiver.

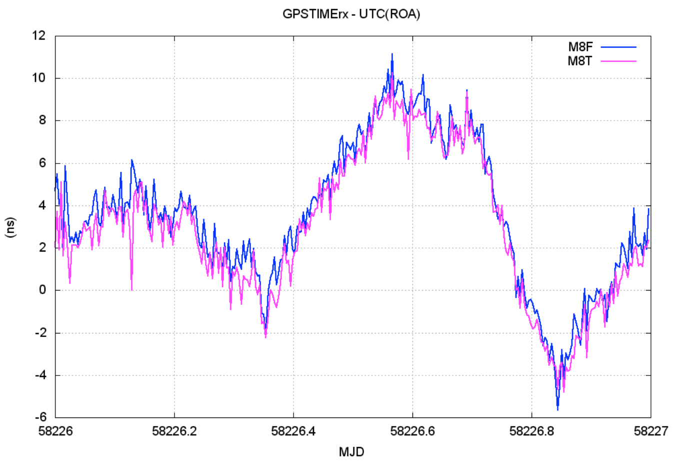

Fig. 5. Traceability of GPS Time from the M8F and M8T receivers to UTC(ROA).

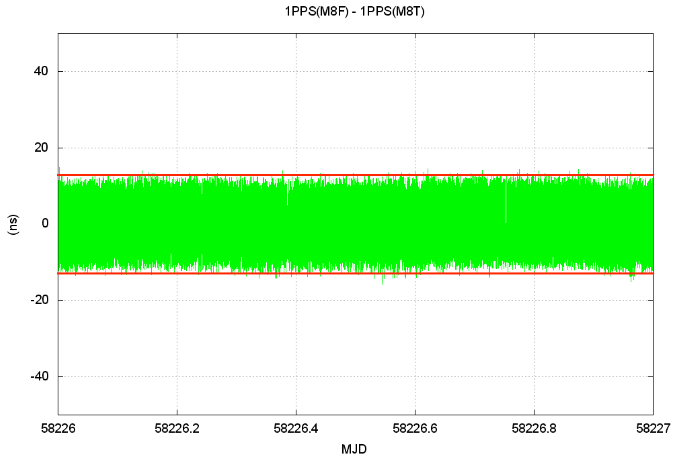

Fig. 6. Comparison between 1PPS signals from M8F and M8T.

VI. Verification of Results

Simultaneously to the collection of raw measurements from the two receivers, we have measured the difference between their 1PPS signals using a Time Interval Counter (TIC). The results are shown in Fig. 6. An average bias of 53 ns has been removed from the results. This bias corresponds to the difference between the internal delays of the two receivers (see Section VIII). The red lines are set at ± 13 ns around the zero mean, which corresponds to the combined 1PPS jitter of the M8F (± 2 ns) and the M8T (± 11 ns).

Fig. 6 shows that, except for a relative bias and jitter, the 1PPS signals from the two receivers are perfectly aligned, which confirms the agreement between the traceability results of the two receivers.

VII. CV Accuracy

Time transfer accuracy is determined by both the statistical uncertainties and the systematic uncertainties. The latter are related to the hardware delays in the receiving equipment and will be discussed in Section VIII. A detailed discussion about the time transfer performances that can be obtained from CV can be found in [13], covering dual-frequency and single-frequency GPS. Within 1000 km, there is no significant degradation of CV with the distance using dual-frequency GPS, and the statistical uncertainty is of the order of 1 ns at 1-sigma.

Single-frequency CV provides a similar performance, except in cases of high ionospheric activity. During the last ionospheric event, on April 20, deviations up to 2.5 ns between the single-frequency and dual-frequency CV solutions could be observed in links of about 1000 km in the E-W and N-S directions. Fig. 7 shows the results of time transfer between two European timing laboratories for such day.

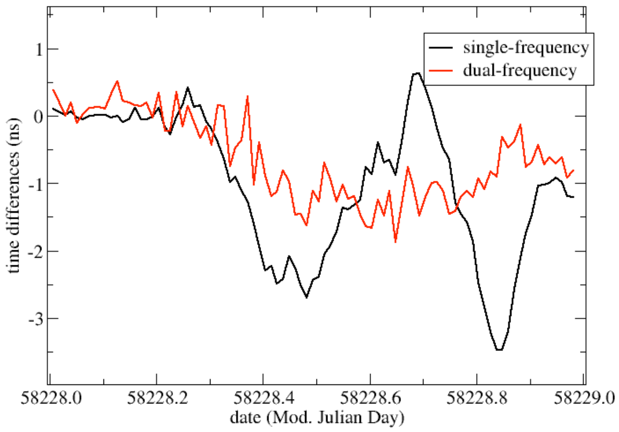

Fig. 7. Dual-frequency and single-frequency CV time transfer between ORB (Brussels) and CNES (Toulouse) during high ionospheric activity. The single-frequency solution applies the Klobuchar model on both sides.

VIII. Receiver Calibration

The receiver hardware delay DLY_{rx} can reach typically up to a few hundred ns, depending mainly on the length of the antenna cable. Following [14], the calibration of the delay shall be done shipping the receiver to a UTC(k) laboratory. The receiver is to be configured to output a 1PPS time pulse aligned to GNSST. The difference between the receiver 1PPS and the 1PPS from the UTC(k) time scale is measured in a TIC during at least one day. The average of the TIC measurements provides an estimation of the receiver hardware delay DLY_{rx}. A correction provided by the laboratory can be applied a posteriori to account for the difference between GNSST and UTC(k). A residual calibration error remains due to the possible non-zero average delay from the ionospheric model used in the receiver internal PVT computation (Klobuchar for GPS or NeQuick [15] for Galileo). The resulting calibration uncertainty can be at the level of 2-3 ns at 1-sigma.

Notice that the calibration method described above does not require any raw GNSS data from the user receiver. Furthermore, the calibration does not necessarily need to be carried out at the same UTC(k) laboratory as the one used for traceability. Once a user receiver has been calibrated at a UTC(k) laboratory, additional receivers can be easily calibrated in factory relative to the first one, measuring in a TIC the difference between the two 1PPS signals.

IX. Accurate Antenna Positioning

A precise antenna position can be calculated offline from raw GNSS data, if available. The most accurate technique using pseudorange and carrier-phase measurements is differential positioning relative to a base station nearby. This approach is known as Real Time Kinematics (RTK). The method can be applied in post-processing for non-real-time applications, for example using RTKLIB [9]. In relatively short distances (baselines of less than 10 km), RTK allows to resolve the carrier-phase ambiguity as an integer number, even in single-frequency GNSS, and using short observation times (10-15 minutes), and thus to achieve cm-level position accuracy.

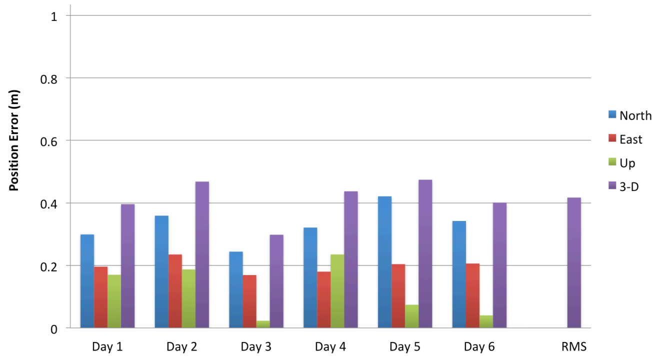

Fig. 8. Single-frequency PPP positioning error.

If a neighbouring GNSS base station is not available, an alternative approach is to use Precise Point Positioning (PPP) [16]. PPP is an absolute (non-differential) positioning technique that uses pseudorange and carrier-phase measurements, and precise orbit and clock “products” (instead of the navigation message). Unlike dual-frequency PPP, single-frequency PPP does not provide cm-level accuracy. Fig. 8 shows the error of single-frequency PPP positioning for six different data batches of a 24-hour duration each. The values indicate the difference with respect to the “true” antenna position computed using RTK. The online PPP service from Natural Resources Canada (NRCan) [17] has been used. The PPP report indicates that NRcan *rapid* orbit/clock products, and ionospheric grid maps have been applied. NRcan PPP does not process carrier-phase measurements in single-frequency, the positioning results are based on the pseudorange exclusively.

As can be seen in Fig. 8, single-frequency PPP can provide a positioning error of around 40 cm (3-D), which is equivalent to just above 1 ns in time.

X. Conclusions and Limitations

Standard GNSS timing receivers can provide a time pulse aligned either to GNSST or to the UTC realization derived from GNSST. Traceability of the selected output time pulse to a national UTC(k) time scale can be achieved a-posteriori by means of Common-View (CV) time transfer between the receiver and the UTC(k) laboratory, under the following conditions:

- The receiver provides its estimated clock bias at every epoch.
- The receiver provides raw pseudorange measurements and navigation messages.
- Software is available to convert the receiver raw format to RINEX format (for example RTKLIB for converting the u-blox native format).
- Software is available to modify the RINEX observation file to subtract the receiver estimated clock bias from the pseudoranges.

- Software is available to generate a CGGTTS file for the receiver from its raw pseudorange measurements and navigation messages in RINEX format (normally daily CGGTTS files are used). A software tool named R2CGGTTS has been developed at the Royal Observatory of Belgium (ROB). Its latest version (V8) supports multi-GNSS and 30-sec resolution in addition to the 16-min standard [18].

- A single-frequency CGGTTS file from a reference calibrated receiver at the UTC(k) laboratory is available for the same day, or otherwise pseudorange measurements and navigation in RINEX format are available to generate the required CGGTTS file. If RINEX files are used, calibration values for the UTC(k) receiver are also needed to generate the CGGTTS file.

- Software is available to combine two CGGTTS files in order to obtain the CV difference between the receiver time reference and the UTC(k) time scale, applying (10) and generating the final traceability results.

The method is subject to the following limitations:

- The receiver hardware delay DLY_{rx} cancels out in the processing and therefore is "invisible"; however, such delay does affect the output time pulse and must be calibrated separately. Traceability and calibration are complementary needs. A simple calibration method can be applied by shipping the user receiver to a UTC(k) laboratory and comparing its 1PPS with the 1PPS from the UTC(k) time scale. This method provides a calibration uncertainty of 2-3 ns and does not require raw GNSS data.

- The receiver 1PPS jitter is also invisible to the CV method, but such jitter is present in most timing receivers to a larger or smaller extent depending on the receiver model. Although the jitter has normally a zero average around the selected time reference, the instantaneous synchronization error between the 1PPS signals from different receivers could reach up to a couple 10s of ns, depending on the receiver models.

- Traceability can only be obtained a-posteriori, typically on a next-day basis, although hourly traceability could be possible subject to hourly file availability on both sites.

- The CV solution uncertainty depends mainly on the receiver-to-laboratory baseline length. In general it is recommended to select a UTC(k) laboratory as close to the user receiver as possible. The CV precision in baselines up to 1000 km can range from 1 ns to a few ns, depending on the ionospheric activity. The additional systematic uncertainty associated with calibration is 2-3 ns, as indicated above. If we consider timing applications with a typical accuracy requirement of 1 μs, we can conclude that the proposed traceability method is almost three orders of magnitude better.

- Accurate CV requires moreover the usage of precise antenna positions on both sites in the generation of CGGTTS files. A precise antenna position can be calculated offline from raw GNSS data using RTK or PPP.

- Time-of-Day (ToD) traceability is indirectly addressed through the combination of CGGTTS files, since they are time-stamped in UTC [6]. However ToD traceability can be easily achieved in real time by comparing the ToD from GNSS with the ToD from the NTP server of the UTC(k) laboratory, at every second.

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