GPS RECEIVER RELATIVE CALIBRATION CAMPAIGN PREPARATION FOR GALILEO IN-ORBIT VALIDATION

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ABSTRACT

Among other tasks in the frame of the Galileo In-Orbit Validation (IOV) phase, the French National Metrology Laboratory (NML) LNE-SYRTE is engaged in the relative calibration of Global Positioning System (GPS) receiver delays: the GPS Common-Views (CV) using ionosphere free P3 technique is the time transfer backup mean for Two-Way satellite Time and Frequency Transfer (TWSTFT). The relative delay characterization of GPS equipment is scheduled today to be achieved by transport of a traveling equipment between Observatoire de Paris (OP) and another European NML, one Galileo Precise Timing Facility (PTF) and the United States Naval Observatory (USNO) successively. The goal here is to perform separate calibration of the P-Code delays as collected on either L1 (P1) or L2 (P2) GPS carriers, by applying an original processing developed by LNE-SYRTE and derived from the standard TAIP3 processing. We describe the process, the techniques involved, the traveling equipment, the data processing and the uncertainty budget computation, according to former results obtained in the frame of the Galileo Time Service Provider (GTSP) Prototype development. Two possible applications of such a GPS receiver relative calibration campaign might be first an initial synchronization of Galileo System Time (GST) to UTC via UTC(OP), and second an initial GPS CV connection between GST and UTC(USNO), the UTC prediction of United States Naval Observatory, as a first step for the future computation of Galileo GPS Time Offset (GGTO). Therefore, we also propose here to study some limits of two links: first over a European baseline link, namely between OP and the Physikalisch Technische Bundesanstalt (PTB) in Germany; and second between OP and USNO, a long baseline compared to European links. We use the GPS TAIP3 files without any additional products to build Common-Views (CV), and we assess the quality of the results with respect to TWSTFT, and with respect to the computations of UTC – UTC(k) released monthly by the Bureau International des Poids et Mesures (BIPM) in its Circular T. Provided the relative calibration of GPS receiver delays would be successful, we assess both potential initial synchronizations of GST to be possible within an expanded uncertainty below 10 ns (k = 2) over an averaging period of two days or more.

INTRODUCTION

Like other European National Metrology Laboratories (NML) for Time and Frequency units, the French NML LNE-SYRTE, in Observatoire de Paris (OP), has been contributing for more than twelve years to the development of the European global navigation satellite system Galileo. Among other tasks in the frame of the current Galileo In-Orbit Validation (IOV) phase, LNE-SYRTE is engaged in the relative characterization of Global Positioning System (GPS) receiver delays. For time transfer between remote Earth station clocks, the GPS Common-Views (CV) by ionosphere free P3 technique is the backup mean for Two-Way Satellite Time and Frequency Transfer (TWSTFT). Such a relative delay characterization relies on a traveling equipment made of a geodetic multi-channel GPS receiver main unit, a geodetic choke-ring antenna, an antenna cable and a laptop computer to drive the receiver and to collect the raw data to be converted into the geodetic standard Rinex format. The goal here is to perform separate calibration of the P-Code delays as collected on either L1 (P1) or L2 (P2) GPS carriers, by applying an original processing developed by LNE-SYRTE and derived from the standard TAIP3 processing of the Bureau International des Poids et Mesures (BIPM). The second Chapter reminds the technique for achieving such relative delay characterization. The third Chapter describes the equipment OP built up in 2008 for achieving such relative delay characterization campaigns. The fourth Chapter details the required data processing together with the proper validations to be undertaken, and the fifth Chapter provides an uncertainty budget analysis based on former OP work for Galileo.

In a second step, the sixth Chapter proposes to assess the performances to be expected from an initial synchronization of Galileo System Time (GST), as produced in a Precise Timing Facility (PTF) of the Galileo Mission Segment, towards UTC, via UTC(OP). GST is generated from an ensemble clock steering the output of an H-Maser, and the signal is called GST(MC), "MC" for Master Clock, another H-Maser playing the role of a Backup Clock. The initial synchronization of GST towards UTC would be achieved according to the following equation: GST(MC) – UTC = [GST(MC) – UTC(OP)] – [UTC – UTC(OP)]. GST(MC) might be considered here as equivalent to a UTC(k) time scale, the real time prediction of UTC achieved by the NML. Therefore, it is expected that an initial difference between GST(MC) and UTC(OP) would be similar to the comparison between UTC(OP) and any UTC(k) over a European baseline. We have chosen to use the link between OP and the Physikalisch Technische Bundesanstalt (PTB), the German NML, which is also the backup link chosen by the BIPM to relate OP to TAI. We compare the GPS CV between UTC(OP) and UTC(PTB) by using TAIP3 processing, and we assess the quality of this link by comparing to the TWSTFT technique, together with the output of UTC – UTC(k) for both NML as released monthly by the BIPM in its Circular T [1]. The seventh Chapter provides in a similar way an assessment of the quality of a GPS CV link between UTC(OP) and UTC(USNO), the UTC prediction of the United States Naval Observatory, by using TAIP3 as compared to TWSTFT together with Circular T data. This might be a first step of the future Galileo GPS Time Offset (GGTO) determination.

RELATIVE CHARACTERIZATION OF GPS RECEIVER DELAYS

The well-known principle of a relative characterization of remote GPS receiver delays relies on a campaign of measurements by using a similar traveling equipment [2, 3, 4]. The goal is to perform measurements between each local equipment and the traveling equipment in a common-clock implementation. Fig. 1 shows this set-up, where all the delays between the receiver main units and the reference clock signal have to be measured according to a given procedure and documented in each visited laboratory. The reference clock signal should be of 1 pps type, but can be different from the local UTC(k), or GST(MC) in the case of Galileo PTF, as long as the reference signal is the same for both units. These measurements have to be performed also at the start and at the end of each campaign with respect to the GPS receiver which is used as the reference for the campaign. The difference between the mean values of the measurements at the start and at the end of the campaign shows the deviation from closure of the ensemble [traveling + reference] equipment, which has to be taken into account for the computation of the uncertainty budgets.

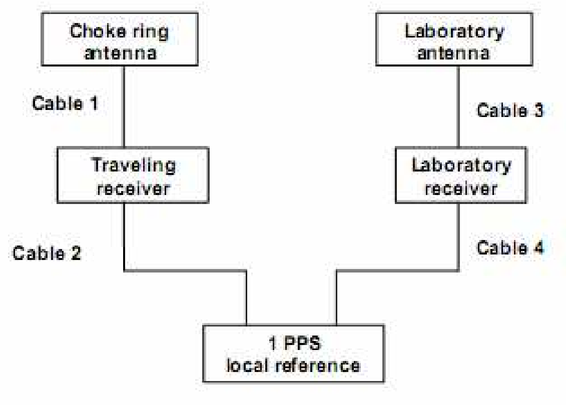

Fig. 1. The common-clock set-up between the traveling equipment and the local equipment for the relative characterization of GPS receiver delays.

TRAVELING EQUIPMENT AND MEASUREMENT

In the frame of the “Fidelity” consortium activities aiming at providing to the European GNSS Supervisory Authority (GSA) a prototype of the Galileo Time Service Provider [5], the LNE-SYRTE was in charge of the relative characterization of GPS receiver delays for the European NML involved. This activity led to the development of a traveling equipment ensemble inside a mobile box as shown in Fig. 2. The GPS receiver main unit is an Ashtech Z12-T [6] called OPM4. It travels along with a 50 m antenna low loss cable together with a geodetic choke-ring Ashtech antenna. A portable laptop PC is also included, in order to drive OPM4 and to collect and process the GPS Ashtech measurements. The results are 30 s sampled geodetic Rinex files, which contain among other data the P-Code on GPS L1 carrier (P1) and the same P-Code on GPS L2 carrier (P2) measurements for all visible GPS satellites above the Earth station. The appropriate local delays have also to be measured: the Ashtech Z12-T unit requires not only the 1 pps IN cable delay measurement with respect to the common clock reference, but also the measurement of the delay between the 1 pps IN signal and a given period of the 20 MHz signal IN to which all GPS signals generated by the receiver are related. LNE-SYRTE has written down a complete procedure describing the process and the control panels on the laptop screen, and provides a measurement sheet which has to be filled in by local operators.

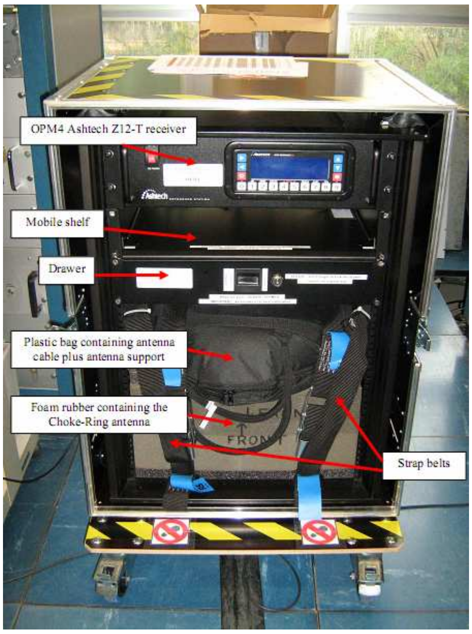

Fig. 2. The OP traveling equipment including OPM4 in its rolling box.

DATA PROCESSING AND VALIDATION

The data processing is performed by an original software developed by LNE-SYRTE on the basis of the BIPM standard TAIP3 processing originally written by Dr. P. Defraigne (Observatoire Royal de Belgique) [7]. The goal here is to compute the P1 and P2 delays of the visited laboratory equipment. In the case the Galileo PTF GPS receiver would not provide Rinex files consistent with the TAIP3 processing, it is expected that this receiver would provide P3 data, issued from some unknown proprietary software. But in that case only a characterization of the global P3 delays would be achieved by LNE-SYRTE.

In each location, with the start and the end of the campaign included, the receiver delays to be computed are set to 0 and the P1 and P2 differences between Rinex files are computed for each epoch and for all satellites in common-views. This leads for example to the left plot of Fig. 3 showing the initial computation of OPM4 delays with respect to the OP reference receiver OPMT, which has been relatively calibrated on a regular basis by the BIPM over the years. Average values of OPM4 P1 and P2 delays are computed, the noise affecting these averages being extrapolated from the Allan Time Deviation (TDEV) plotted on the right side of Fig. 3: here for example, the resulting noise on P1 and P2 can be taken as below 90 ps, by considering the upper limit of the 90 % chi-square distributed statistical noise on the TDEV values for an averaging period of about 2 d.

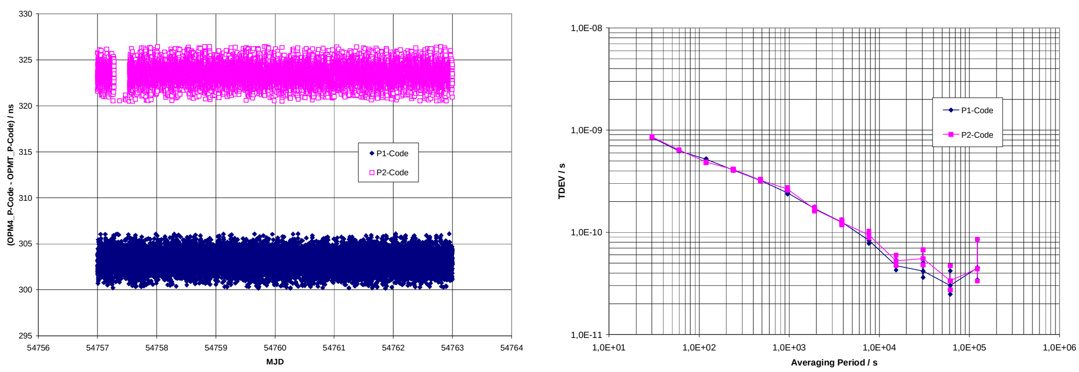

Fig. 3. Initial P1 and P2 delays computation of OPM4 at the start of the Fidelity campaign: on the left the P1 and P2 differences between OPM4 (delays set to 0) and OPMT, on the right the TDEV plots of these data.

Similar computations and plots have to be made for each visited laboratory, by setting to 0 the P1 and P2 delays of the local GPS equipment. At the end of the campaign, the traveling equipment OPM4 is again compared to OPMT, and a deviation from closure can be computed on OPM4 P1 and P2 delays. During the Fidelity campaign, the obtained deviations were: ΔP1_delay = + 0.22 ns, ΔP2_delay = - 0.34 ns. As explained below, this is an important part of the combined uncertainty budget. Of course, this aspect relies on the stability of the equipment used as fixed reference during the measurement campaign. One of the ways to evaluate this stability is to perform a continuous comparison of the campaign fixed reference with either locally implemented or remote receivers in CV. During the Fidelity campaign, there was a continuous comparison in LNE-SYRTE between OPMT and OPM2, another Ashtech Z12-T implemented in a common-clock common-antenna set-up with OPMT. In addition, we also looked at the OPMT stability by comparing the GPS CV to TWSTFT on the link OP – PTB. All this helped us to state that the OPMT delays remained close to initial values during all the Fidelity campaign. Thus, we only take into account the noise of the OPM2 – OPMT CV, which was 0.25 ns RMS over three months of data. Assuming an equal contribution from both receivers of similar type, this led to a additional noise of 0.17 ns for OPMT only.

The next step is then to compute the mean values of OPM4 P1 and P2 delays between the start and the end of the campaign, and to use these OPM4 delays as references for the computation of P1 and P2 delays of each equipment in the visited laboratories, by including the cable delays and other delays, depending on the receiver types, which have been measured by local operators.

Last but not least, an internal validation of the process has to be undertaken. It consists in using the computed delays to build GPS CV between the traveling and the local receiver side by side. This aims at two goals. On one hand, such CV would help to detect any potential bias due to a software computation error: the CV data set must be centered on 0 to be consistent. During the Fidelity campaign, a 1 ns bias was detected in the validation, which led to a correction of the software. On the other hand, the dispersion of the CV data around 0 might be a good indication about whether some delays were either constant or not during the campaign. In the case the mean value of these CV would not be 0, the difference to 0 should be taken into account accordingly in the uncertainty budget.

UNCERTAINTY BUDGET COMPUTATION

The uncertainty budget computation has to be made first for the traveling standard as compared to the campaign reference, considered as a fixed reference. Table 1 shows as an example the uncertainty budget of OPM4 as traveling equipment compared to OPMT considered as fixed. The uncertainties of the following measurements have been taken into account: the delay of the cable providing the 1 pps IN signal to OPM4; the phase delay between the 1 pps IN and a given period of the 20 MHz IN signal for OPM4 (Ashtech Z12-T specific configuration [6]); the delay of the OPM4 antenna cable measured by using a Time Interval Counter and a 1 pps signal; the resulting noise obtained from the TDEV in Fig. 3; and the noise affecting OPMT obtained from the noise of the CV between OPM2 and OPMT. The quadratic sum of all these terms lead to the combined uncertainty at k = 1, which characterized OPM4 delays for the Fidelity calibration campaign.

Table 1. Combined uncertainty budget (k = 1) of OPM4 with respect to OPMT considered as a fixed reference.

OPM4 to OPMT	**P1-Code (ns)**	**P2-Code (ns)**
1 pps IN cable delay (OPM4)	0.20	0.20
1 pps IN to 20 MHz IN (OPM4)	0.30	0.30
Antenna cable delay (OPM4)	0.20	0.20
Noise from TDEV	0.09	0.09
Noise affecting OPMT	0.17	0.17
Combined uncertainty (quadratic)	**0.45**	**0.45**

Second, the uncertainty budget of the delays of the visited laboratory equipment can be computed, and here follows in Table 2 an example taken from the results of the Fidelity campaign as obtained in PTB with the receiver PTBB (Ashtech Z12-T). In this case however, both complete equipment delays have to be considered as being affected by delay fluctuations, hence the list of uncertainties of related measurements to be taken into account is longer: the delay of the cable providing the 1 pps IN signal to PTBB; the delay of the cable providing the 1 pps IN signal to OPM4; the phase delay between the 1 pps IN and a given period of the 20 MHz IN signal for PTBB; the phase delay between the 1 pps IN and a given period of the 20 MHz IN signal for OPM4; the resulting noise obtained from the TDEV at an averaging period of 1 d, which was plotted in a similar way as in Fig. 3; and of course the uncertainty on the OPM4 delays used for the computation of PTBB delays, which include the ensemble receiver main unit + antenna + antenna cable. Moreover, this is where we proposed to add the OPM4 deviations from closure, in such a way that the whole deviations from closure are included in the expanded uncertainty for a coverage factor k = 2. To this aim, only half the deviations from closure are added as simple sum to the quadratic sum of all other effects for k = 1.

Table 2. Combined uncertainty budget (k = 1) of PTBB with respect to OPM4.

PTBB to OPM4	**P1-Code**	**P2-Code**
1 pps IN cable delay (PTBB)	0.10	0.10
1 pps IN cable delay (OPM4)	0.10	0.10
1 pps IN to 20 MHz IN (PTBB)	0.30	0.30
1 pps IN to 20 MHz IN (OPM4)	0.30	0.30
Noise from TDEV	0.05	0.08
Uncertainty of OPM4 delays	0.45	0.45
Quadratic sum	**0.64**	**0.64**
Half-deviation from closure	0.11	0.17
Combined uncertainty (simple sum)	**0.75**	**0.81**

And finally, the uncertainty on the ionosphere free linear combination P3 can be computed for PTBB simply by applying the well-known formulae (L1 = 1575.42 MHz, L2 = 1227.60 MHz):

$$P3 = (L1^2 / (L1^2 - L2^2)) \times P1 - (L2^2 / (L1^2 - L2^2)) \times P2$$

$$[u(P3)]^2 = (2.546)^2 \times [u(P1)]^2 + (1.546)^2 \times [u(P2)]^2$$

In our example from the Fidelity campaign, this led to the conservative expanded Type B uncertainty for the PTBB receiver with respect to OPMT considered here as a fixed reference: uB(TAIP3_PTBB) = 4.57 ns (k = 2). A similar result was obtained for OPMT receiver, based on former results from BIPM relative delay characterization campaigns, and from absolute calibration activities undertaken by the French Space Agency CNES [8]: uB(TAIP3_OPMT) = 4.60 ns (k = 2). When using those GPS receivers on the link OP-PTB, one obtains finally for the expanded Type B uncertainty:

uB(TAIP3_OPMT-PTBB) = 6.5 ns (k = 2)

INITIAL GST SYNCHRONIZATION TO UTC

To perform a relative characterization of PTF GPS receiver delays does not require that the PTF reference signal GST(MC) be synchronized to UTC or GPS Time in any ways: only a common reference is required. Provided such a campaign as described above would be successful, the results might be used to compute an initial synchronization of GST(MC) to UTC, via UTC(OP). The goal is to use the PTF receiver delays and the Rinex files to compute simple TAIP3 GPS Common-Views (CV) between the PTF and OP in order to provide the difference GST(MC) – UTC(OP).

In order to assess the quality of such a TAIP3 GPS CV computation we propose here to look at an equivalent TAIP3 CV link between laboratories over a European distance. The link OP – PTB has been chosen due to the fact that it is used as backup to TWSTFT by the BIPM for the computation of the Temps Atomique International (TAI), the first step of the UTC generation. In the Fig. 4 are provided as an example the differences UTC(OP) – UTC(PTB) as obtained by two different techniques: TWSTFT and TAIP3 GPS CV. In addition, the same differences issued from the UTC – UTC(k) data published in the BIPM Circular T are also plotted in the same figure, in that case sampled every 5 d. In Fig. 4 are also plotted the related TDEV.

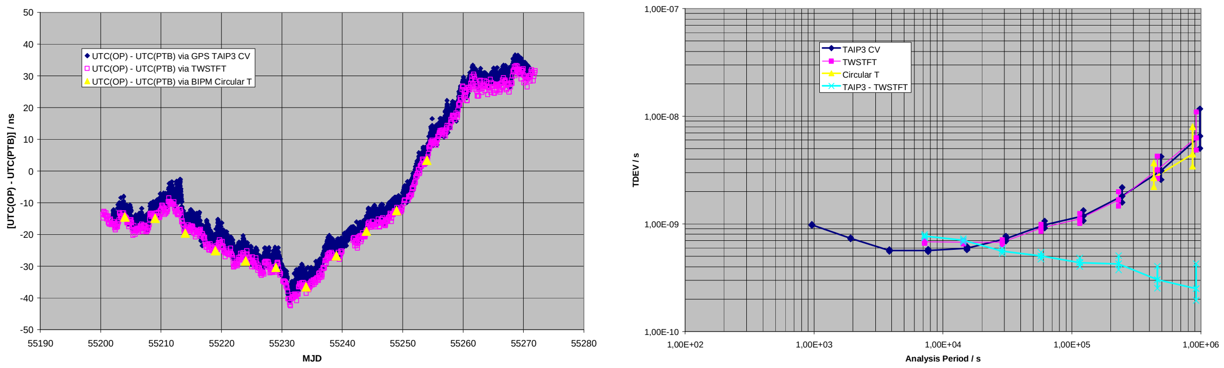

Fig. 4. UTC(OP) – UTC(PTB) by TAIP3 GPS CV and by TWSTFT, together with similar data computed from UTC – UTC(k) data published by the BIPM in its Circular T, from January 4 to March 16, 2010, together with the related TDEV. On the TDEV plot, the light blue * are obtained from a simple linear fit of GPS TAIP3 CV data inside windows of two hours centered on any TWSTFT data.

We have built a difference between TAIP3 GPS CV and TWSTFT, based on a simple linear fit of GPS data inside windows of two hour centered on any TWSTFT data, which are sampled by the usual two hour period. The TDEV of this difference in Fig. 4 shows that the noise estimate stays below 500 ps over an averaging period of two days or more: uA(TAIP3-TWSTFT_OPMT-PTBB) < 0.50 ns (k = 1). This result provides an upper limit of the resulting noise affecting a TAIP3 CV link between GST(MC) and UTC(OP), as it is foreseen that similar results might be obtained over any European baseline. Therefore, only a few days of data might lead to a synchronization of GST(MC) to UTC(OP) within an expanded uncertainty u(TAIP3) < 6.6 ns (k = 2) over an averaging period of 2 d or more. This result appears consistent with what can be derived from Fig. 4 by comparison between the different techniques.

To reach the synchronization of GST(MC) to UTC, one should in addition subtract UTC – UTC(OP) from GST(MC) – UTC(OP). This might be obtained either by an estimate of the UTC(OP) departure from UTC based on previous data published by the BIPM, or by waiting for the next Circular T release. UTC(OP) has been kept close to UTC inside the limits + 60 ns to – 80 ns during the last ten years, as can be seen in Fig. 5, and an upper limit of the difference UTC – UTC(OP) for the given epochs of the GST(MC) – UTC(OP) computation would be given.

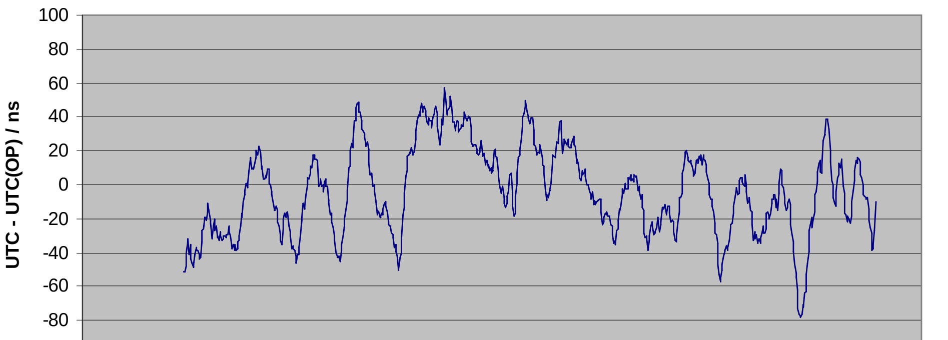

Fig. 5. UTC – UTC(OP) for the last ten years, as published in the BIPM Circular T.

INITIAL GST(MC) – UTC(USNO) COMPUTATION FOR GGTO

In a very similar way, an initial connection between GST(MC) and UTC(USNO) might be obtained by computing TAIP3 GPS CV. In this case however, it can be foreseen that the results might be either slightly noisier, due to the weak number of GPS Satellite CV between GST(MC) and UTC(USNO), or even biased. Fig. 6 shows an example in a similar way as above: UTC(OP) – UTC(USNO) is obtained by TAIP3 GPS CV and by TWSTFT together with similar data issued from a simple difference of relevant BIPM Circular T UTC – UTC(k) data. The related TDEV are also plotted in Fig. 6.

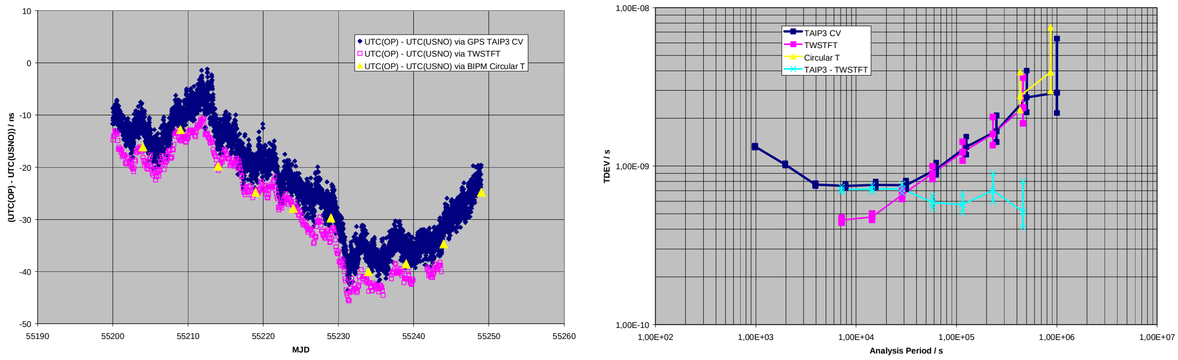

Fig. 6. UTC(OP) – UTC(USNO) obtained by TWSTFT and TAIP3 GPS CV together with the similar data issued from BIPM Circular T UTC – UTC(k), from January 4 to February 22, 2010, together with related TDEV. On the TDEV plot, the light blue * are obtained from a simple linear fit of GPS TAIP3 CV data inside windows of two hours centered on any TWSTFT data.

Again, we have built a difference between TAIP3 GPS CV and TWSTFT, based on a simple linear fit of GPS data inside windows of two hour centered on any TWSTFT data. The TDEV of this difference in Fig. 6 shows that the noise estimate stays below 1.0 ns over any averaging period: uA(TAIP3-TWSTFT_OPMT-USNO) < 1.00 ns (k = 1). This result provides an upper limit of the resulting noise affecting a TAIP3 CV link between GST(MC) and UTC(USNO). Therefore, only a few days of data might lead to a synchronization of GST(MC) to UTC(USNO) within an expanded uncertainty u(TAIP3) < 6.8 ns (k = 2). This result appears consistent with what can be derived from Fig. 6 by comparison between the different techniques, except that there remains apparently a small bias of a few ns between GPS CV and TWSTFT techniques. Most probably, this is coming from uncompensated bias in the GPS CV, like satellite ephemeris error or tropospheric delays, which are here not corrected. Nevertheless, provided the results of the relative characterization of the equipment delays be as expected, it might be possible to compute an initial connection between GST(MC) and UTC(USNO) within an expanded uncertainty below 10 ns (k = 2). This might lead to an initial synchronization between GST and GPS Time, which is planned to be delivered to Galileo users as the GGTO.

CONCLUSION

Provided all GPS equipment work nominally during the campaign of relative characterization of equipment delays, it might be possible for LNE-SYRTE to perform the Galileo required delay calibration largely below an expanded uncertainty of 10 ns (k = 2) with the technique described. Current developments of this technique call for the use of a Vector Network Analyser to perform the antenna cable delay measurement and to achieve the proper impedance adaptation between the antenna and the receiver main unit.

Once the PTF GPS equipment delays computed, an initial synchronization of GST(MC) with respect to UTC might be undertaken by LNE-SYRTE by computing GST(MC) – UTC(OP). This link should be equivalent to any other link between OP and any European NML generating a UTC(k) prediction of UTC. For the performance assessment, we have chosen the link between OP and PTB, which is also the backup link used by the BIPM for the TAI computation. A direct comparison between GPS CV by using TAIP3 processing and either TWSTFT or the difference between UTC – UTC(k) data published monthly by the BIPM in its Circular T shows that such an initial synchronization of GST(MC) to UTC(OP) might be feasible within an expanded uncertainty below 10 ns (k = 2), provided the relative delay characterization of GPS equipment would be successful. The other part of the link between GST and UTC would be UTC – UTC(OP). For the last few years, LNE-SYRTE has undertaken a modernization of UTC(OP) [9], and it is expected that the future UTC(OP) will be closer to UTC compared to the last years performances: this would help to achieve a better initial synchronization of GST(MC) to UTC, depending today on the respective planning of both activities.

The relative delay characterization of GPS equipment is scheduled today to be achieved by transport of a traveling equipment between LNE-SYRTE and another European NML, one Galileo PTF and the USNO successively. Provided the relative delay characterization of GPS equipment between PTF and USNO would be successful, LNE-SYRTE might in a very similar way compute GPS TAIP3 CV between GST(MC) and UTC(USNO). This might be a first step for the future computation of the GGTO. By comparing in a similar way the GPS TAIP3 CV between UTC(OP) and

UTC(USNO) with TWSTFT and Circular T data, we have shown that such a transatlantic link might be achieved within an expanded uncertainty below 10 ns (k = 2).

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