Research Article

Accurate GLONASS Time Transfer for the Generation of the Coordinated Universal Time

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The spatial techniques currently used in accurate time transfer are based on GPS, TWSTFT, and GLONASS. The International Bureau of Weights and Measures (BIPM) is mandated for the generation of Coordinated Universal Time (UTC) which is published monthly in the BIPM *Circular T*. In 2009, the international Consultative Committee for Time and Frequency (CCTF) recommended the use of multitechniques in time transfer to ensure precision, accuracy, and robustness in UTC. To complement the existing GPS and TWSTFT time links, in November 2009 the first two GLONASS time links were introduced into the UTC worldwide time link network. By November 2011, 6 GLONASS time links are used in the UTC computation. In the frame of the application in the UTC computation, we establish the technical features of GLONASS time transfer: the short- and long-term stabilities, the calibration process, and in particular the impact of the multiple GLONASS frequency biases. We then outline various considerations for future developments, including the uses of P-codes and carrier-phase information.

1. Introduction

GLONASS (from GLObal NAvigation Satellite System, GLN for short) is a radio-based satellite navigation system operated by the Russian Space Forces with the aim of providing real-time, all-weather, three-dimensional positioning, velocity measuring, and timing with a worldwide coverage. The completely deployed GLN constellation is composed of 24 satellites in three orbital planes of which the ascending nodes are 120° apart. Eight satellites are equally distributed in each plane. The first satellite was launched on 12 October 1982, and the constellation was completed in 1995, although until recent years it has not always been well maintained.

With respect to present and future techniques for accurate time transfers, GLN is comparable to other global navigation satellite systems (GNSSs): the United States' Global Positioning System (GPS), the upcoming Chinese Compass navigation system, and the Galileo positioning system of the European Union.

To guarantee the accuracy and robustness of UTC generation, a multitechnique strategy for UTC time transfer is indispensable. Over the last two decades much effort has been devoted to introducing GLN in UTC. However, earlier GLN studies [1–9] remained at an experimental stage because there were only a few operational GLN timing receivers, the GLN constellation was incomplete, and there were unsolved technical issues; among them the major difficulty was of the multiple GLN frequency biases.

The situation has greatly improved in recent years. As of 2008, there were 15 GLN timing receivers operating at UTC laboratories (see Table 9), and these were used to back up the regular GPS and TWSTFT links. Recent studies [10–12] have fixed the last remaining problems, and the first two GLN time links to be included in the generation of UTC were SU-PTB and UME-PTB, which were introduced in November 2009 (*Circular T* 263) [10–15]. Figure 1 shows the status of the time-transfer techniques used in UTC in November 2011 (*Circular T* 287). Here GLN&GPS stands for the combination of GLN and GPS code measurement data.

In this study, we investigate the receivers available at present in the UTC time transfer. The data in the numerical tests were collected mainly using the 3S Navigation and the AOS TTS GPS/GLN receivers. The conclusion obtained in this study is applicable in these two types of receivers. The
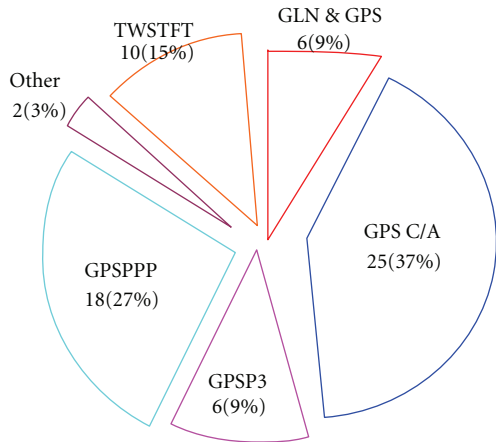
FIGURE 1: Status in November. 2011 (*Circular T* 287) of the 67 time transfer links used in UTC generation.

numerical analysis was carried out using the BIPM UTC/TAI software package Tsoft, with the usual monthly procedure. When the study was initialed, there were no TTS4 receiver data in the UTC databank. We have a couple of TTS4 receiver data recently and start to study them. As for Septentrio receivers, there is no software currently available to convert the receiver measurements to the CCTF CGGTS format used in UTC code time transfer. TTS-4 and Septentrio receivers are not investigated in this study.

In the following section we describe the technical features for the use of GLN in UTC, and then in Section 3 we present various ongoing studies at the BIPM and finally the conclusion.

In an earlier publication [16], we briefly reported the application of the GLN in UTC/TAI time and frequency transfers. In this paper, however, we present detailed considerations on this issue; in particular we discuss the impact of the GLN frequency biases in the UTC/TAI time links. For the readers who are not familiar with the concept of the accurate GNSS time transfer techniques, please refer to [16] that gives a simple explanation about GNSS CV and AV time transfers and to [17] where the AV is discussed in detail.

2. Use of GLN for UTC Time Transfer

GLN distributes three codes that can be used for time transfer: L1C, L1P, and L2P. The L1C code is authorized for civil applications in GLONASS ICD [18]. Although measurements are typically provided by the receivers, the P1 and P2 codes are primarily not intended for civil use [18]. A fourth code, L3P, free of ionospheric delays, is formed from a linear combination of L1P and L2P. The P-codes are of higher quality than the C-code, and logically one would thus expect them to have obvious advantages in time transfer. However, this was not observed in our previous investigations using the 3S Navigation receivers [6] nor in recent evaluations using the latest TTS-3 receivers [19]. We do not know the exact reason at present. Figure 2 illustrates a comparison of the

standard deviation of the smoothing residuals (σ) of the CV time links using GLN codes over different distances between 1200 and 9200 km. Here all the measurement data L1C, L1P, and L2P were corrected using the IGS precise orbit and ionosphere information. The CGGTTS data were collected in 2004 from the 3S receivers located at AOS (Poland), VSL (Netherlands), and CSIR (South Africa). It is seen that the mean values in the table obtained using the L1C and L1P data agree well with each other within the σ, implying that the same calibration applies across the same frequency band. The standard deviation obtained with the L1C code is statistically no bigger than that using the P-codes, and indeed for long distances, the L1C code results are slightly better than those of the P-codes. Similar results were obtained in more recent tests using TTS receivers [19].

The IGS analysis centres did not supply precise corrections for GLN satellite clocks (the IGS analysis center CODE recently announced the availability of the GLN clock product that we need to validate before using for UTC computation). hence the All in View (AV) technique [17] is not applicable for GLN at present. In GLN time transfer today: (1) Common View (CV) is still advantageous in cancelling the influence of the satellite clock and reducing the orbit and atmosphere delay uncertainties; (2) the state of the art of using the P-codes shows no obvious advantages over that of the L1C code, as unexpected biases and noises would degrade the quality of the P-code data. Further study is required.

The present study is therefore concentrated on L1C code CV time transfer and its application in UTC. In the following discussions, because the short-term measurement noise of the L1C time link is about 0.7 to 1.5 ns, as given in Tables 2–8 and Figures 3–7 in the following sections, the disturbing effects including that of the frequency biases with a magnitude well less than the measurement noise, saying 0.3 ns or less, will be considered negligible in the study.

Before GLN can be used in UTC, the following points need to be clarified:

(1) use of precise orbit and ionosphere corrections,

(2) biases due to the multiple GLN PRN and/or frequencies,

(3) short- and long-term stabilities,

(4) calibration and its long-term variation.

The first point has been fully discussed in earlier studies, such as [4–6]. Several analysis centres, including those of the IGS, ESA (European Space Agency), and IAC (Information Analysis Centre, Russian Federation), provide regular updates of the precise ephemerides of GLN satellites [14]. We currently use the IAC ephemeride products and the IGS ionosphere maps to compute the precise orbit and ionosphere corrections.

In the following sections, we discuss the three remaining points, based on test CGGTTS L1C data from UTC 1005 to UTC 1110 (May 2010 to October 2011), assuming that all the raw measurements have been corrected for precise orbits and atmosphere delays.
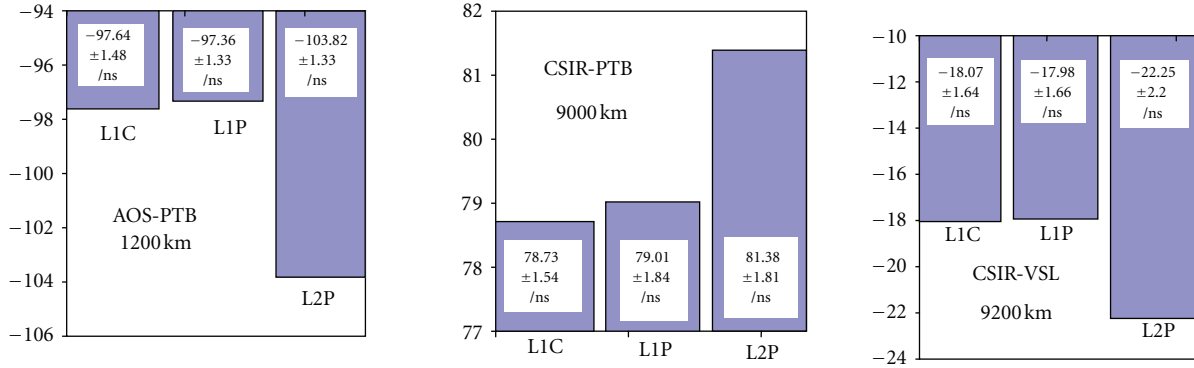
FIGURE 2: Histograms of the monthly mean value (Mean) of the CV clock differences and the standard deviations of the smoothing residuals ($\pm\sigma$) obtained using different GLN codes over different baselines. The values are given in form of Mean $\pm\ \sigma$ in ns. Data were collected from 3S receivers in 2004.
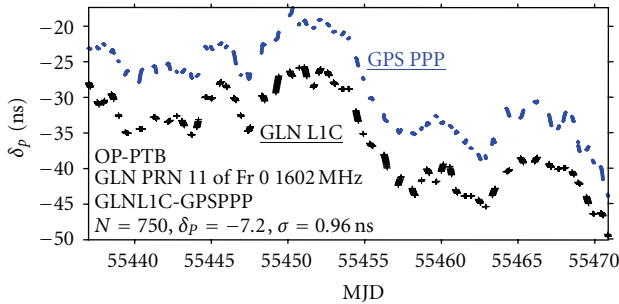

FIGURE 3: Bias of the GLN PRN 11 L1C link (+) relative to the GPS PPP link (•) for the data set UTC 1009. Here $\sigma = 0.96$ ns is the standard deviation of the difference of GLNL1C-GPSPPP but that of the mean of the difference. The same definition is given to the σ throughout the paper.
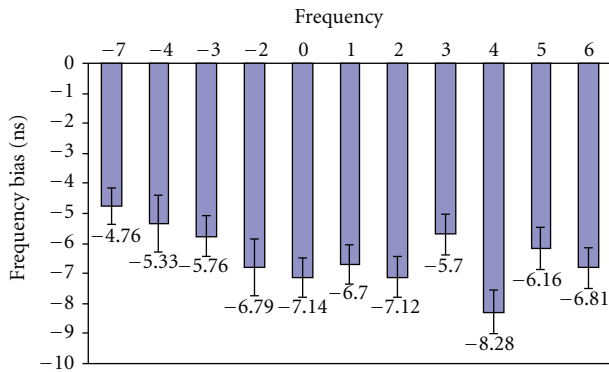

FIGURE 4: GLN Frequency L1C biases in order of the nominal frequencies corresponding to Table 2(b).

2.1. The PRN and Frequency Biases in the CV Time Links.

Unlike GPS, the satellites of GLN is divided into groups according to the frequencies used. Early studies based on certain physical considerations and on first-generation GLN receivers, for example, 3S Navigation, addressed the question of so-called frequency biases disturbing the CV time transfer

[3, 4] and suggested a precorrection to each GLN frequency for the data to be used for UTC computation. A later study in 2005 based also on the 3S receivers [5, 6] however and a recent study in 2009 based on a new generation of GLN receivers, for example, TTS3 [10, 12], have found, though the detailed results have not been published, that the influence of the biases is negligible compared to the measurement noise (1 ns to 1.5 ns). This conclusion meant that in principle the GLN CV time transfer technique could be used directly as GPS without the need of the frequency bias corrections for the computation of UTC; that is, comparing the gain and the complexity of the computation, it is not worth to make the frequency bias corrections in the monthly UTC computation. Further investigations corresponding to the P-codes of both GLN and GPS can be found in [11].

We estimate PRN and/or frequency biases, based on the most acceptable hypothesis, for example, [3], that different frequencies emitted by different satellites through different channels of a receiver causes different biases, which perturb the GLN CV time transfer. It is important to establish whether the biases are well below the measurement noise and are therefore negligible, or alternatively if a calibration or correction is needed for each frequency in a GLN CV time link.

2.1.1. PRNs and Frequencies of GLN.

As of mid-2010, the GLN system comprises 20 satellites operating the L1C code. Table 1 lists the operational GLN PRNs observed using receivers TTS-2 and TTS-3. A total of 20 operational PRNs are recorded using TTS-3 receivers and only 11 PRNs using TTS-2 receivers. A further PRN, 09, is listed in the official catalogue [18] as operating only in L1C but is not observed by the TTS receivers. Table 1 listed the satellites in order of the frequency codes. In total 11 coded frequencies are emitted by 1 or 2 satellites each. Excluding PRN 03, there are on average about 900 L1C observations in a typical UTC monthly data file using a TTS-3 receiver.

2.1.2. Biases of PRNs and Frequencies.

Our main interest is the influence of the so-called frequency biases on the CV time links. According to previous studies, we assume first that
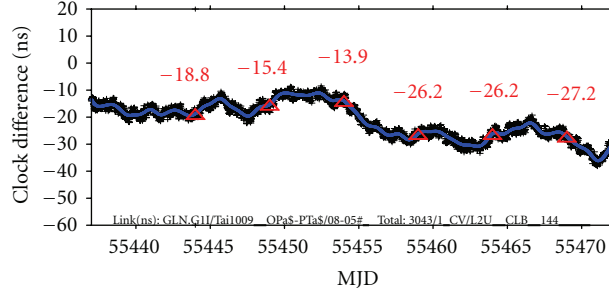
(a) GLN L1C time link OP-PTB 1009 where all the frequency biases have been corrected
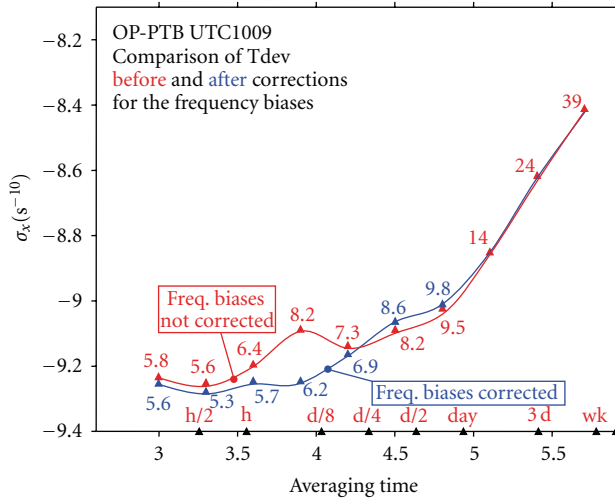
(b) Comparison of the time deviations σ_x of the same data as in Figure 5(a) before and after correction for all the frequency biases. Here h stands for hour, d for day, $d/2$ for half day, 3d for three days, and wk for a week. The x and y axis are labeled with log numbers and those in the graph are the real numbers. The same notations are used in all the TDev plots below
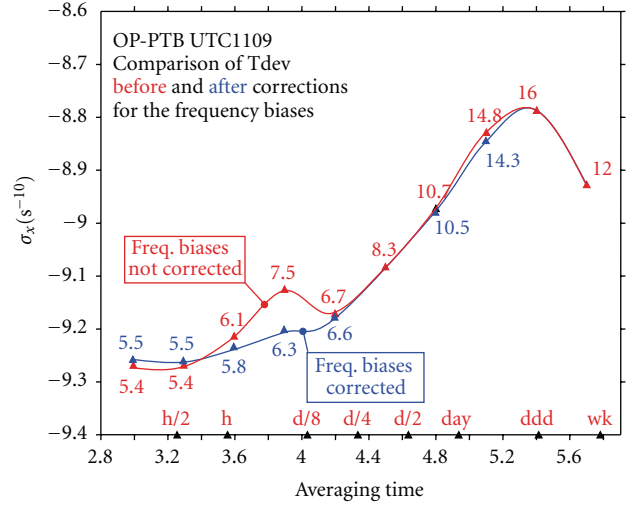
(c) Comparison of the Time deviations σ_x of the same baseline before and after correction for all the frequency biases (here 1109 is one year after 1009 as shown in Figure 5(b))

FIGURE 5: GLN L1C time links OP-PTB and Time deviations for UTC 1009 and 1109.

the frequency biases exist and are physically caused by the GLN frequencies, significantly receiver dependent, and are constant. The frequency biases should therefore be universal and could be corrected for in the UTC time transfer. We focus our analysis on the SU-PTB and OP-PTB baselines because both are UTC links, and for the latter we also have GPS PPP and TW links, which are more precise and provide good references for the evaluation of the GLN links. All three laboratories are equipped with TTS-3 receivers. To study the physical cause(s) of the frequency biases, we proceeded as follows:

(i) we first split the raw data file containing all the PRNs into subfiles for each PRN and then compute the one-PRN links;

(ii) we then compare the one-PRN links to the GPS PPP link to compute the frequency biases and use them to calibrate the raw link data;

(iii) we study if there are gains by comparing the time deviations and the differences versus GPS PPP and TW;

(iv) finally, we apply the "frequency biases" obtained from a month of a baseline to "calibrate" the raw data from other months and other baselines to see if the biases are "universal" (independent of receivers, months, and locations).

Figure 3 illustrates the bias of GLN PRN 11 L1C computed by comparing the OP-PTB CV link to that of GPS PPP for the data set UTC 1009. The bias of the PRN 11 is −7.20 ns

(a) The GLN L1C UTC time link SU-PTB 1109 after correction for the frequency biases

(b) Comparison of time deviations of the time link SU-PTB 1009 with and without correction for frequency biases

(c) Comparison of time deviations of the time link SU-PTB 1109 with and without correction for frequency biases (here 1109 is one year after 1009 in Figure 6(b))
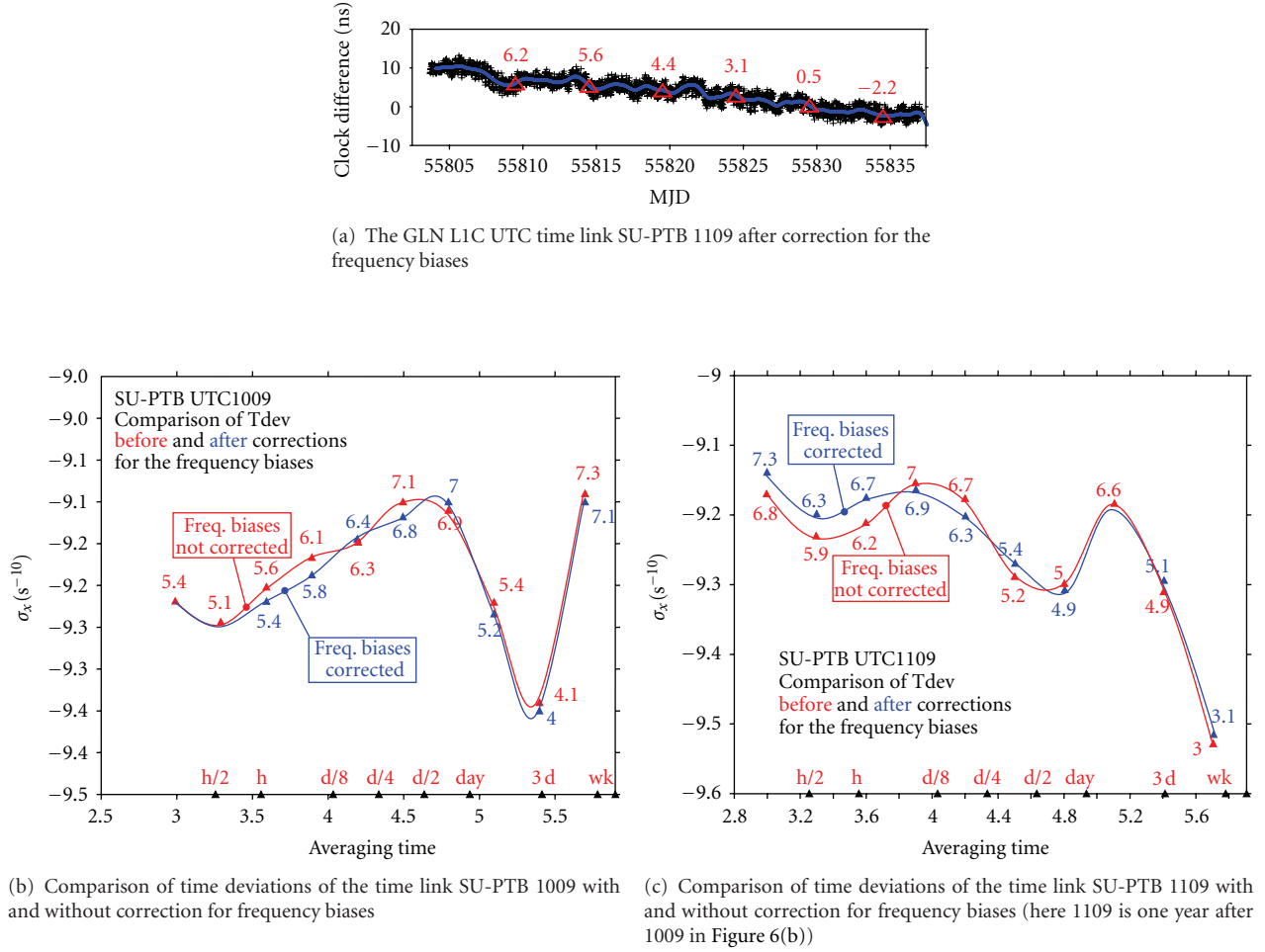
Figure 6: GLN L1C time links SU-PTB and Time deviations for UTC 1009 and 1109.
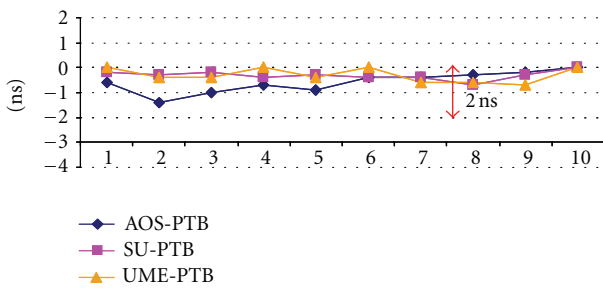
Figure 7: Consistency of UTC links between GPS C/A and GLN L1C (10-month comparison corresponding to Table 8).

±0.96 ns, including the calibration difference between GPS PPP and GLN L1C. What is important is not the size of the bias but whether or not it depends significantly on the GLN frequency, the receiver, and time.

Table 2(a) lists the PRN biases in the CV links with respect to the GPS PPP for the baseline OP-PTB (data set 1009). Observing the relation between the biases and the frequencies, Table 2(b) and the corresponding Figure 4 show the values in the increasing order of the nominal frequencies. The number of common points of the comparison (N) is typically about 750, with the exception of 220 for PRN 03. The standard deviation, (σ_P), of the bias determined for each PRN is slightly smaller than the measurement noise in the GLN L1C code (typically 1 ns to 1.5 ns as mentioned previously).

In Tables 2(a) and 2(b) and Figure 4, it is seen that the standard deviation σ_F of the frequency bias δ_F (cf. the caption of the Figure 3) is about 0.7 ns, while the maximum difference between the δ_F is 3.5 ns, bigger than the measurement noise. On the other side, the differences between the PRNs using the same frequency are mostly less than 0.3 ns, much smaller than the measurement noise. This would indicate that the biases vary with the frequency codes but the satellites.

TABLE 1: Operational GLN PRNs recorded using TTS-2 and TTS-3 time receivers (N is the number of observations by TTS3).

PRN	Fr. code	N	Receiver
GLN 11	0	904	TTS-3
GLN 15	0	915	TTS-3
GLN 01	1	900	TTS-3/TTS-2
GLN 05	1	906	TTS-3/TTS-2
GLN 20	2	901	TTS-3/TTS-2
GLN 24	2	912	TTS-3/TTS-2
GLN 13	−2	944	TTS-3
GLN 19	3	921	TTS-3/TTS-2
GLN 23	3	903	TTS-3
GLN 18	−3	920	TTS-3
GLN 22	−3	892	TTS-3
GLN 17	4	895	TTS-3/TTS-2
GLN 21	4	905	TTS-3/TTS-2
GLN 02	−4	893	TTS-3
GLN 03	5	251	TTS-3/TTS-2
GLN 07	5	885	TTS-3/TTS-2
GLN 04	6	851	TTS-3/TTS-2
GLN 08	6	902	TTS-3/TTS2
GLN 10	−7	915	TTS-3
GLN 14	−7	912	TTS-3

We also estimated the so-called frequency biases using other references such as P3 and TW, and the results are almost the same as those listed in Table 2; that is, the standard deviation is mainly due to the noise in L1C. There seems to be no obvious correlation between the amplitudes of the biases and the nominal frequencies.

2.1.3. Corrections for Frequency Biases in GLN CV Time Transfer. It is expected that application of the frequency bias corrections to the raw GLN measurements should lead to a significant reduction in noise level and improvement in the short-term stability of the link. In Figure 5, Figure 5(a) shows the GLN L1C link of OP-PTB 1009 where all the frequency biases have been corrected; Figure 5(b) shows a comparison of the time deviations of the time links before and after correction for the frequency biases calculated for the UTC months of 1009.

Figure 5(c) is the comparison of the time deviations of the data 1109 (one year after 1009) with and without the bias corrections. Similar to Figure 5(b), an improvement in the time transfer stability is observed for the averaging time of 2 to 3 hours. The time deviation is an indicator of the time stability in a link. Comparing the time deviations estimated before and after the bias corrections, it is seen in Figures 5(b) and 5(c) that after correction the little knolls at about 2-3 hour averaging time in the uncorrected plot disappear. Assuming the trajectory of the GLN satellite is on average symmetric around the observers, 2-3 hours correspond to the half-time of the observable passage of the satellite. The results show a gain in time transfer quality for an averaging time of 2-3 hours. In consequence, the time deviation of the

TABLE 2: (a) GLN PRN/Fr L1C biases relative to GPS PPP for the link OP-PTB 1009. (b) GLN Frequency L1C biases in increasing order of the nominal frequencies.

(a)

PRN	Fr	f/MHz	N	δ_P/ns	σ_P/ns
11	0	1602.0	750	−7.204	0.963
15	0		744	−7.083	0.920
01	1	1602.5625	727	−6.882	0.995
05	1		733	−6.518	0.896
20	2	1603.125	740	−7.071	0.968
24	2		745	−7.175	1.016
13	−2	1600.8750	757	−6.793	0.975
19	3	1603.6875	754	−5.559	0.928
23	3		730	−5.851	1.077
18	−3	1600.3125	759	−5.724	0.906
22	−3		732	−5.800	1.034
17	4	1604.25	745	−8.287	1.031
21	4		736	−8.277	1.070
02	−4	1599.7500	751	−5.328	0.983
03	5	1604.8125	220	−6.206	1.081
07	5		722	−6.120	1.017
04	6	1605.375	710	−6.727	0.931
08	6		720	−6.907	1.069
10	−7	1598.0625	753	−4.706	0.888
14	−7		748	−4.823	0.966

(b)

Fr	Fr′/MHz	N	δ_F/ns	σ_F/ns
−7	1598.0625	753	−4.76	0.65
−4	1599.7500	751	−5.33	0.98
−3	1600.3125	759	−5.76	0.69
−2	1600.8750	757	−6.79	0.98
0	1602.0	750	−7.14	0.66
1	1602.5625	727	−6.70	0.67
2	1603.125	740	−7.12	0.70
3	1603.6875	754	−5.70	0.70
4	1604.25	745	−8.28	0.74
5	1604.8125	220	−6.16	0.74
6	1605.375	710	−6.81	0.71

TABLE 3: Gains in the standard deviation of the smoothing residuals for the GLN L1C baseline OP-PTB after correction for the frequency biases calculated for the period 1009 (comparison over 18 months).

Period yymm	σ/ns raw link	$\underline{\sigma}$/ns bias calibrated	Gain
1005	1.199	1.073	11%
1008	1.199	1.110	7%
1009	**1.260**	**1.150**	**9%**
1109	1.180	1.134	4%

one month data set is slightly improved for averaging times within one day.

TABLE 4: Gains in standard deviation of the smoothing residuals after correction for the frequency biases calculated for the OP-PTB UTC 1009.

Baseline	Distance/km	σ/ns raw link	$\underline{\sigma}$/ns bias calibrated	Gain
AOS-PTB	500	1.721	1.381	20%
NIS-PTB	3000	1.338	1.276	5%
OP-PTB	**700**	**1.260**	**1.150**	**9%**
SG-PTB	6300	2.500	2.557	−2%
UME-PTB	1900	1.398	1.403	0

TABLE 5: GLN PRN/Fr L1C biases computed with SU-PTB 1009 versus GPS C/A (a constant of −200 ns is subtracted from the δ).

PRN	Fr.	N	δ_P/ns	σ_P/ns
11	0	700	−8.699	0.639
15	0	697	−8.331	0.649
01	1	683	−8.809	0.743
05	1	693	−8.507	0.684
20	2	691	−8.673	0.691
24	2	696	−8.578	0.760
13	−2	711	−8.857	0.711
19	3	701	−8.833	0.627
23	3	685	−8.700	0.751
18	−3	703	−9.988	0.690
22	−3	684	−9.730	0.698
17	4	703	−10.495	0.756
21	4	678	−10.365	0.701
02	−4	692	−8.927	0.674
03	5	200	−8.871	0.613
07	5	663	−8.811	0.686
04	6	663	−9.895	0.673
08	6	689	−9.880	0.735
10	−7	708	−9.329	0.744
14	−7	713	−9.078	0.763

TABLE 6: Gains in standard deviation of the smoothing residuals before and after corrections for the frequency biases calculated for the SU-PTB link for the period 1009.

Period yymm	σ/ns raw link	$\underline{\sigma}$/ns bias calibrated	Gain
1005	1.252	1.254	0%
1008	1.068	1.043	2%
1009	**1.066**	**1.022**	**4%**
1109	1.150	1.177	−2%

The standard deviation of the smoothing residuals is also an index of the gains. If the frequency biases are constant for that baseline, they should be applicable to the raw data of other periods. We used the frequency bias corrections listed in Table 2(a), based on the 1009 data, to correct the raw data of 1005, 1008, and 1109 for the same baseline, OP-PTB. The result is given in Table 3. A considerable gain of 7% to 11%

is seen within 4 months from 1005 to 1009. The gain seems reduced with time if we compare the σ of 9% in 1009 and 4% in 1109, one year after 1009. This 4% is probably the physical gain due to the hardware delay between different frequencies, which impact the CV time links. Given the σ of 1.2 ns, 4% of the σ is 48 ps. Obviously 48 ps is numerically negligible for the GNSS code time transfer.

Because the same type of the receiver TTS3 is used (hence the hardware delay for same frequency is similar if not equal) we may further assume that the frequency corrections obtained from OP-PTB can be used for other receivers at AOS, NIS, SU, UME, and SG. We may expect a global gain of about 9%. Table 4 lists the results obtained for the five baselines of different distances. Two of the links show no improvement after correction: SG-PTB (−2%) and UME-PTB (0%), while three of the links (AOS-PTB, OP-PTB, and NIS-PTB) show a marked decrease in the standard deviations of the smoothing residuals, of 11% on average. We may have two explanations for this conflicted result. (1) A set of bias corrections is applicable only for a particular pair of receivers, that is, baseline dependent. The 11% gain is accident. (2) The frequency biases are not receiver only dependent but affected by some unknown factor which is common for AOS, OP, and NIS but not for SG and UME. The ionosphere influence is location, direction, and frequency dependent. The residual influence of the IGS ionosphere correction used in this study might be one of such factors. However further investigation is required.

2.1.4. Case of the UTC Link SU-PTB.
We can use the same method to study the GLN UTC link SU-PTB. Because neither GPS PPP nor TW data exist for this baseline, we have to use GPS C/A as the reference to compute the so-called frequency biases.

Table 5 lists the frequency biases computed for GLN SU-PTB 1009 referenced to GPS C/A. As we assume the frequency biases are receiver dependent hence constant with time, we can apply these values obtained from the SU-PTB GLN data for the period 1009 to correct the corresponding data for 1008 and 1005 as well 1109.

Figure 6(a) shows the time link SU-PTB 1109, and Figure 6(b) illustrates the time deviations before and after correction for the frequency biases on the same baseline on 1009. Figure 6(c) shows that of 1109, one year after 1009. Not as seen for the baseline OP-PTB, Figures 6(b) and 6(c) show no obvious improvement in the time deviation for averaging time of 2-3 hours.

The standard deviations of the smoothing residuals for the months 1005, 1008, 1009, and 1109 are listed in Table 6. There is a slight, statistically not meaningful, variation in the standard deviations, 1% on average. Taking the value $\sigma = 1.2$ ns, 1% means 12 ps. The 1005 and 1009 data are separated by 4 months and 1009 and 1109 by 12 months. The gains of the application of the biases to the 1005 and 1109 data are 0% and −2%, that is, no gain in applying the so-called frequency-bias corrections. The frequency-bias corrections obtained from 1009 might not be really or completely caused by the frequency-bias but, at least partially, by some other frequency dependent biases. For this

TABLE 7: Comparing GLN PRN biases computed using OP-PTB and SU-PTB 1009.

PRN	Fr	$d\delta_{P1}$	σ_1	$d\delta_{P2}$	σ_2	Mean$_1$	Mean$_2$
11	0	0	0.963	0	0.639	0.0	0.0
15	0	0	0.920	0	0.649		
01	1	0.322	0.995	−0.110	0.743	0.4	−0.1
05	1	0.565	0.896	−0.176	0.684		
20	2	0.133	0.968	0.026	0.691	0.0	−0.1
24	2	−0.092	1.016	−0.247	0.760		
13	−2	0.411	0.975	−0.158	0.711	0.4	−0.2
19	3	1.524	0.928	−0.502	0.627	1.4	−0.3
23	3	1.353	1.077	−0.001	0.751		
18	−3	1.359	0.906	−1.657	0.690	1.4	−1.3
22	−3	1.404	1.034	−1.031	0.698		
17	4	−1.204	1.031	−2.164	0.756	−1.1	−1.9
21	4	−1.073	1.070	−1.666	0.701		
02	−4	1.755	0.983	−0.596	0.674	1.8	−0.6
03	5	0.998	1.081	−0.172	0.613	1.0	−0.3
07	5	0.963	1.017	−0.480	0.686		
04	6	0.477	0.931	−1.196	0.673	0.3	−1.4
08	6	0.176	1.069	−1.549	0.735		
10	−7	2.498	0.888	−0.630	0.744	2.4	−0.7
14	−7	2.260	0.966	−0.747	0.763		

baseline, it seems the frequency biases are statistically not baseline dependent.

According to Tables 3 and 6, the gains on average are about 0–4% or 0–50 ps for OP-PTB and for SU-PTB correspondingly. Even if we apply them to correct the frequency biases, such small values will be masked by the measurement noise and other frequency dependant biases.

2.1.5. Discussion. The previous results do not fully support the previous studies summarized in the beginning of Section 2.1 that the frequency biases should be precorrected for UTC time transfer within the L1C uncertainty. Would there exist other frequency dependent (or independent) factors, in addition to the receiver only dependent ones, that affect the frequency biases? Let us by the way point out that receiver dependent must lead to baseline dependent because the baseline is composed of a pair of receivers.

Let us use the exclusion method to examine a seemed impossible possibility.

If the biases are physically caused by the GLN signal frequencies alone, they should be constant with time, isotropically equivalent, and independent of receivers and baselines. As we now have two sets of frequency biases, obtained from the baselines OP-PTB and SU-PTB (Tables 2 and 5), both computed using the same data set UTC 1009, we can examine this hypothesis. In Table 7, $d\delta_P$ is obtained by subtracting the bias of the frequency "0" (PRN 11 and 15): $d\delta_{P1}$ is from the baseline OP-PTB (Table 2(a)) and $d\delta_{P2}$ from SU-PTB (Table 5). The Mean is the mean value of the $d\delta_P$ of the different PRNs using the same frequency. To hold the assumption, the values of Mean$_1$ and Mean$_2$ should agree

with each other within measurement noise (1 ns). As seen in Table 7, for more than half of the frequencies coded (Fr 3, −3, 4, −4, 5, 6, and −7) the same values are not found for the two baselines. For example, for the Frequency (−7), the difference of Mean$_1$ and Mean$_2$ is 3.1 ns which is much bigger than measurement noise.

This numerical evaluation based on two CV links does not prove the existence of the impact of the biases which are bigger than the measurement noise and depend on the GLN frequencies. Again, we cannot exclude the effects of other frequency-dependent factor(s) including the impact of the temperature variations. Considering the gain in applying the frequency bias corrections is not significant and the complexity of the computation is, it has been decided [12] not to use these corrections in the computation of UTC.

2.2. Calibration and Long-Term Stability of the GLN Time Links. A time link technique can be used in UTC only when it is calibrated, and its short- and long-term stabilities are proven. In the following study we use GPS as reference.

Table 8 and Figure 7 present the results of a ten-month comparison and list the differences between the GPS AV C/A links and GLN CV L1C links on the three UTC baselines AOS-PTB, SU-PTB, and UME-PTB between May 2009 and February 2010. All the data were collected using the same type of receivers (TTS-3). The GLN and the GPS raw data were corrected using the IGS/ESA precise ephemeride and ionosphere maps. The GLN links were calibrated and aligned to GPS in May 2009 [10, 12]. The calibrations of GPS and GLN links are stable and perfectly consistent. The mean values of the differences are −0.3 ns and −0.6 ns with

TABLE 8: Calibration consistency of GPS C/A versus GLN L1C links over 10 months (values given in the table are the mean of the differences between GPS and GLN links and its standard deviation).

YYMM	AOS-PTB/ns	SU-PTB/ns	UME-PTB/ns
1002	-0.6 ± 1.6	-0.2 ± 1.4	0.0 ± 1.4
1001	-1.4 ± 1.6	-0.3 ± 1.6	-0.4 ± 1.4
0912	-1.0 ± 1.5	-0.2 ± 1.6	-0.4 ± 1.4
0911	-0.7 ± 1.6	-0.4 ± 1.6	
0910	-0.9 ± 1.4	-0.3 ± 1.6	-0.4 ± 1.3
0909	-0.4 ± 1.6	-0.4 ± 1.6	-0.0 ± 1.4
0908	-0.4 ± 1.6	-0.4 ± 1.6	-0.6 ± 1.4
0907	-0.3 ± 1.6	-0.7 ± 1.6	-0.6 ± 1.4
0906	-0.2 ± 1.6	-0.3 ± 1.6	-0.7 ± 1.4
0905	-0.0 ± 1.6	-0.0 ± 1.6	-0.0 ± 1.4
Mean	-0.6	-0.3	-0.3
σ	0.4	0.2	0.3

TABLE 9: UTC laboratories operating two or three time and frequency transfer facilities as of 2008 [20].

Lab	GPS	GLN	TW
AOS	√	√	√
AUS	√		√
CH	√		√
IT	√	√	√
KRIS	√	√	√
LDS	√	√	
MIKE	√	√	
NICT	√		√
NIM	√		√
NIS	√	√	
NIST	√	√	√
NMIJ	√		√
NPL	√		√
NPLI	√	√	
NTSC	√		√
OP	√		√
PTB	√	√	√
ROA	√		√
SG	√	√	√
SP	√		√
SU	√	√	√
TL	√		√
UME	√	√	
USNO	√	√	√
VSL	√	√	√
ZA	√	√	

standard deviations between 0.2 ns and 0.4 ns and the RMS 0.4 and 0.7 ns. The GPS and GLN data are well consistent within their measurement uncertainties.

As the short- and long-term stabilities of GPS are well proven and GPS and GLN are completely independent

systems, this close consistency between the data sets demonstrates that the GLN time transfer technique is as stable as GPS in both the short and long terms. The same conclusion holds for the long-term variations in their calibrations (cf. [10, 12]).

*2.3. Combination of GLN and GPS for UTC Time Transfer.* Since January 2011, a combination of the GLN L1C and GPS C/A code time links has been used for SU-PTB and UME-PTB in UTC time transfer [21]. This is the first time that data from different GNSS have been combined for a UTC time link. By the end of 2011, 6 combined links are used for UTC computation. The discussion in the following focuses on introducing the weighted combination.

The UTC time transfer strategy until the end of 2010 was the so-called *primary* UTC *time transfer technique*, meaning that only the "best" techniques are used for UTC generation and others are kept as backup. Thus TWSTFT links are used in preference to GNSS links, and GPS links in preference to GLN links, and so forth. The coexisting multitechniques strategy has led to a rapid increase in the level of redundancy in the UTC data bank, with new techniques being added all the time. The tendency to use multitechniques for UTC time transfer is unavoidable. As of 2008 there were 26 UTC laboratories operating multifacilities of time transfer [20]; among them 15 were equipped with both GPS and GLN receivers. Table 9 summarizes the availability of the GNSS and TW facilities at some of the national laboratories contributing to UTC, where at least two time and frequency transfer techniques are equipped.

As discussed previously, (cf. Table 8 and Figure 7), the calibrations of GPS and GLN links agree well with each other and are stable with time. We can therefore take the mean values of sets of GLN L1C code CV and GPS C/A code AV data as (GPS C/A+GLN L1C)/2 or depending on the measurement quality of GPS and GLN, take the weighted combination as $[n \times (\text{GPS C/A}) + m \times (\text{GLN L1C})]/(n + m)$, namely, GLN&GPS standing for the time link combination using GLN and GPS data. Here n and m are the weights of the GPS and GLN.

In the numerical tests, we use the more precise TW and GPS PPP links as references to estimate the gains. Both are available for the baseline OP-PTB. In March 2010, the measurement uncertainty u_A of the GPS PPP and TW links for this baseline are, respectively, 0.3 ns and 0.7 ns (TW degraded somewhat since the beginning of 2010 from its previous conventional value, 0.5 ns). It should be pointed out that taking GPS PPP as reference may somewhat disfavour the GLN L1C CV links because GPS and GLN are independent systems while the GPS C/A and GPS PPP are not completely independent. We use the data sets of UTC 1002, 1005, and 1009 as well as a-15 month long-term data set 1007–1109. We test also the UTC baselines SU-PTB and INPL-PTB using the arbitrarily selected data sets of UTC 1102 and 1110.

Table 10 shows the standard deviations of the GPS-only, the GLN-only, and the combination GLN&GPS links against TW and GPS PPP. Here σ is the standard deviation of a single technique and $\underline{\sigma}$ is that of the GLN&GPS. The
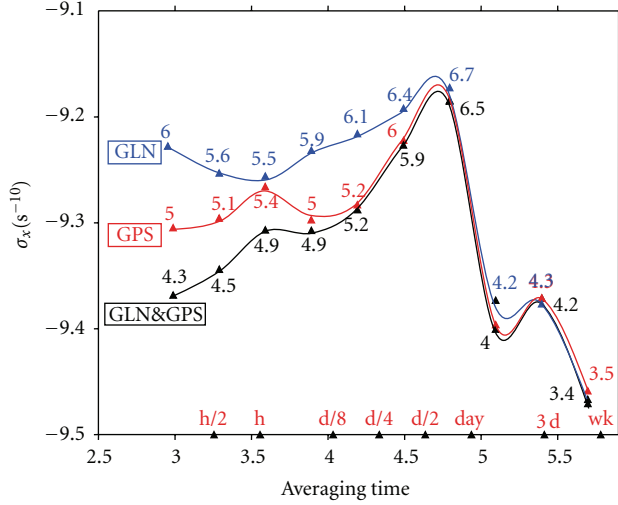
(a) The baseline SU-PTB for the time links of UTC1102
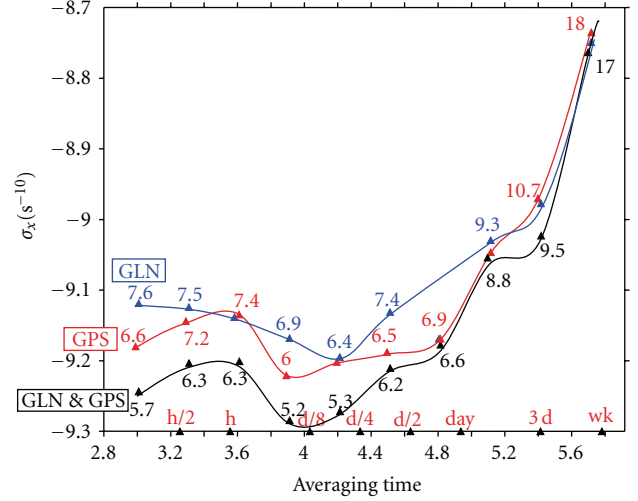
(b) The baseline INPL-PTB for the time links of UTC1110

FIGURE 8: Comparison of the time deviations between the GPS-only, GLN-only, and GLN&GPS links for the baselines SU-PTB (Figure 8(a)) and INPL-PTB (Figure 8(b)). Both are the UTC time links.

TABLE 10: Comparison of the standard deviations of the clock differences for the GPS-only, GLN-only, and GLN&GPS links for the baseline OP-PTB 1005 (MJD 55313 to 55346).

Compared to	GPS-only σ/ns	GLN-only σ/ns	(GLN&GPS) $\underline{\sigma}$/ns	Gains $(\sigma - \underline{\sigma})/\sigma$
TW	1.240	1.369	1.215	6.5%
PPP	1.182	1.285	1.149	7%

gain is computed by the equation $(\sigma - \underline{\sigma})/\sigma$. The standard deviations of the differences of the GPS-only, GLN-only, and GLN&GPS time links relative to TW are 1.240 ns, 1.369 ns, and 1.215 ns, respectively. The averaged gain in GLN&GPS versus GLN-only and GPS-only with respect to TW is 6.5%. Similarly, taking PPP as reference, the standard deviations are 1.182 ns, 1.285 ns, and 1.149 ns, respectively. The gain with respect to PPP is 7%. The combination thus confers an average gain of 7%. Knowing the measurement uncertainties of TW and of GPS PPP and the simplicity of the combination computation, the gain here is hence conservative and the operation is worthy.

Figures 8(a) and 8(b) illustrate the time deviation of the time links of GPS-only, GLN-only, and the combination GLN&GPS for the baseline SU-PTB 1102 and INPL-PTB 1110. The short-term stability of the GPS-only link is slightly better than that of the GLN-only, probably as a result of the advantage of the AV technique against the CV. The stability of the combined solution GLN&GPS is better in the short term than that of the GPS-only and the GLN-only. For averaging times of beyond 20 hours, the three time deviation curves converge.

Figure 9(a) shows the (GLN&GPS) data for the UTC baseline OP-PTB for the period UTC 1009 (corresponding to MJD 55437 to 55472). Figure 9(b) compares the time

deviations between the corresponding GPS-only, GLN-only, and GLN&GPS links. The comparison shows that for averaging times of up to half day the combined (GLN&GPS) link is much more stable than the data from either of the single techniques: less noisy and less biased.

To compare the long-term stabilities, we look at the GPS-only, GLN-only, and GLN&GPS data over a 15-month period (1007–1109: MJD 55378–55834) for the UTC baseline OP-PTB. Figure 10 shows the comparisons of the corresponding time deviations. After the better averaging based on the increased number of data points, we see here more clearly that the stability of the combined link GLN&GPS is better than the single techniques, at least for averaging times of up to 1 day.

The combination thus leads to an improvement in the short-term stability for averaging times of up to 1 day. Since January 2011 combined solutions have therefore been applied in UTC generation. We gave some examples of the links based on a combination of two fully independent techniques to be used in UTC time transfer [21].

3. Future Development in GLN Time Transfer

The possible use of P3-code clearly merits further investigation. Other open issues are the use of the carrier phase, the calibrations, and the raw data recording. We briefly outline our considerations for the coming future studies at the BIPM.

3.1. Use of the GLN Carrier Phase. Given the success of GPS PPP [22], GLN PPP is certainly worthy of study. At present few authors work on this topic [23] and as yet there is not a good enough solution to be able to use in UTC time transfer. In GNSS PPP, the P-codes and the carrier-phase (CP) data are dealt with together. In contrast to PPP, we are investigating a different approach, namely, the postcombination. We first

(a) Time link OP-PTB of the combination (GLN&GPS) for UTC 1009

(b) Comparison of the Time Deviations for the GPS-only, GLN-only, and combined link GLN&GPS for OP-PTB 1005
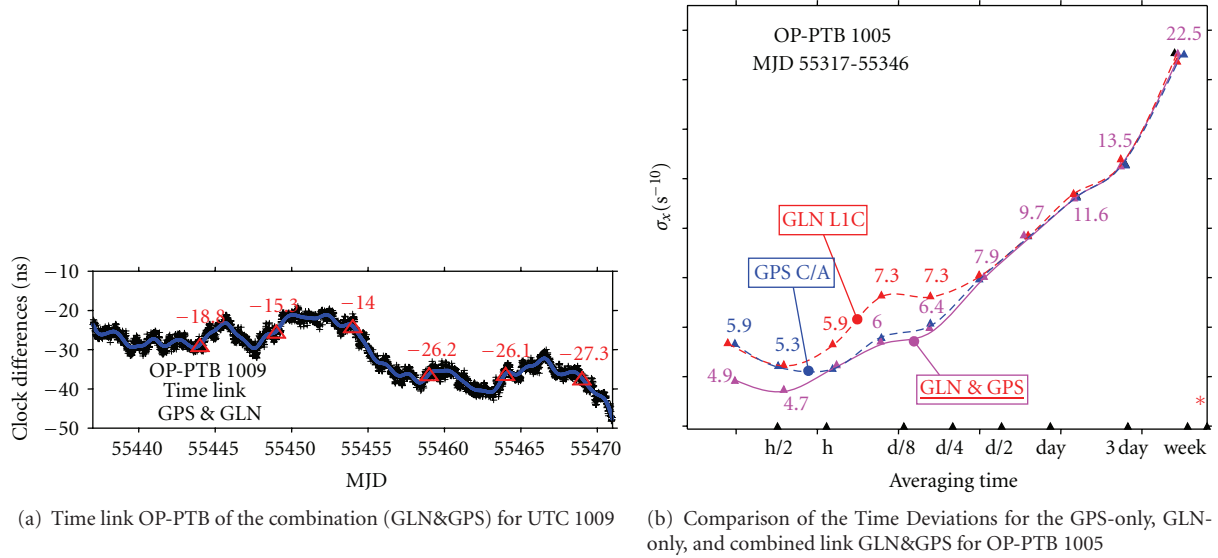
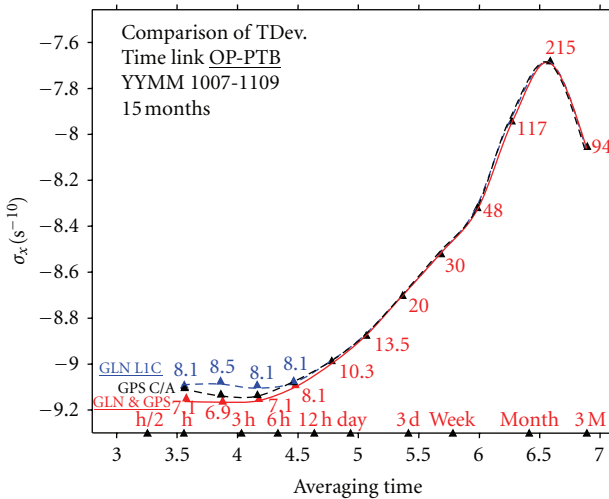FIGURE 9: The GLN&GPS time transfer baseline OP-PTB.

FIGURE 10: 15-month long-term comparison of the TDev of GLN/L1C, GPS C/A, and GLN&GPS over the baseline OP-PTB between 1007 and 1109. The GLN&GPS is the most stable one and is used as the official UTC link. The TDev of the three links converges up to 1 day.

compute the code and CP separately and then to combine the code and CP solutions.

One difficulty with the PPP is the ambiguity of the carrier-phase information. In addition, PPP relies on the Earth geocentric reference and related quantities, such as the geocentric coordinates of the satellites in space and of the antenna centres of the receivers on the ground, and the processing is complex.

The result of a time link is the *clock difference* (CD) between the two master clocks on the two ends of a baseline. In a clock comparison, the CD is given by the code data. If we can generate a carrier-phase solution that gives the

rates of the CD(RCD), we can use these rates to smooth the code solution CD. The advantage of this approach is that the carrier phase is two orders more precise than the code which generates the clock difference. This method of smoothing is not only precise but also easy. Further, the ambiguity in the simple difference of the CP solution, that is, in the RCD, is cancelled, and the absolutely determined geocentric terms required in the PPP/CP solution are simplified. Mathematically, the problem is to smooth a series of measurements using its derivatives. As the method (namely, combined smoothing) and its application in time transfer have been fully discussed in [24], we will not repeat them here.

Study of the GLN RCD option is an ongoing activity at the BIPM. One way to generate the difference in rates between two clocks is to differentiate the PPP data [25]. Our interest hereafter is not in combining GLN code and GPS CP data but lies in the method of the combination of the GLN L1C code and the GLN CP information (or RCD exactly) which is not available. As a simulation test, we use the GPS CP to replace the GLN CP. In the following discussion we examine the method of smoothing GLN code with the RCD and estimate the potential gains and the achievable uncertainty, assuming that the GLN CP is as precise as GPS CP. We then present the result of the combined smoothing of the GLN L1C and the RCD, namely, GLN RCD, which has the advantage of maintaining the calibration defined by the GLN L1C and the short-term stability assigned by the CP. It should be pointed out that the instabilities of the P-codes and the coarse code L1C are of the same order of magnitude, while the CP is two orders of magnitude more precisely. Earlier studies using GPS data proved that using the RCD to smooth either the coarse codes or the precise P-codes gives the same result in terms of stability. The following numerical test shows the same for GLN data. More details can be found in [25].
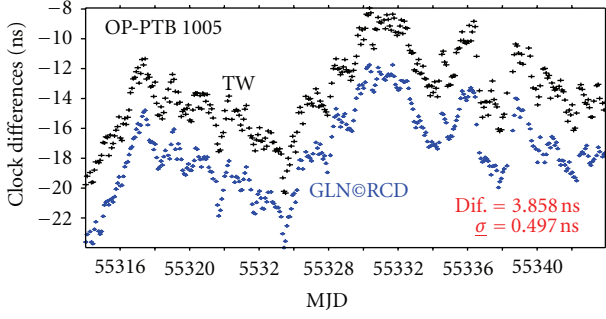
FIGURE 11: Comparison between the TW (+) and GLN©RCD (•) time links for the baseline OP-PTB.

TABLE 11: Comparison of the TW, GLN-only, GPS PPP, and GLN©RCD time links for OP-PTB 1005.

Link differences	N	Mean/ns	$\underline{\sigma}$/ns
TW-(GLN-only)	324	3.873	1.346
TW-GLN RCD	324	3.858	0.497
GPSPPP-GLN RCD	2870	−0.921	0.100

Table 11 compares the time links using TW, GLN-only, GPS PPP, and the combined smoothing GLN©RCD for the baseline OP-PTB using the data set UTC1005 (MJD 55313–55345). The mean values obtained for (TW-(GLN-only)) and (TW-GLN©RCD) are 3.873 ns and 3.858 ns, respectively. The difference between these two results, 0.015 ns, is well below the measurement noise in GLN L1C, confirming that the GLN RCD method keeps the calibration of the GLN L1C. The respective standard deviations are 1.346 ns and 0.497 ns; that is, the measurement noise is well reduced. This is also supported by the standard deviation of the difference (GPSPPP-GLN©RCD) which is only 0.1 ns. Figure 11 shows a comparison between the TW and GLN©RCD time links for the baseline OP-PTB.

Figure 12 shows the corresponding time deviations for the links based on GLN-only, GPS PPP, and GLN©RCD for the same baseline and period. The stability of the GLN©RCD and GPS PPP links is almost identical. In general, the characteristics of the combined smoothing data are dominated in the long term by that of the code used, and the CP dominates the short terms.

3.2. Improvement of the Calibration Uncertainty. The total uncertainty in (UTC-UTC(k)) is dominated by the uncertainty of the time-transfer calibration. Currently, the best calibration uncertainties in GNSS time transfer are 5 ns [15, 21]. Hence a key factor in the reduction of the uncertainty in UTC products is to improve the GNSS calibrations. A BIPM calibration scheme has been proposed, aiming to achieve a calibration uncertainty of less than 2 ns [26]. A pilot project improving the Asian links organized by the BIPM is ongoing, and a significant improvement in GLN calibrations is expected.
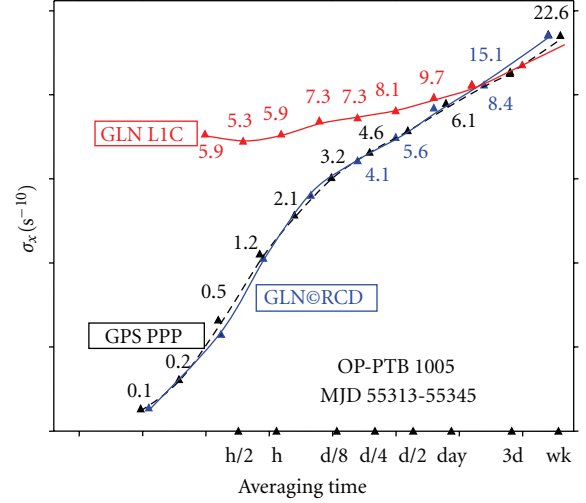

FIGURE 12: Time deviations of the GLN-only, GPS PPP, and the combined GLN©RCD links for OP-PTB 1005.

3.3. Raw Data Recording in the CCTF GGTTS Format. The CCTF GGTTS data format was designed in the early 1980s when GPS was introduced into time transfer using the receivers available at the time. The format has since been updated to accept GLN data as well but its basic specifications remain unchanged, and it is still used to facilitate the computation of UTC/TAI. However, some conventions defined in the GGTTS are now outdated due to the ever-progressing technology in GNSS receiver manufacturing and the introduction of new time-transfer techniques.

For example, one of the major outdated points in the GGTTS convention is that for a tracking arc of 16 minutes of data collection only 13 minutes of them are recorded and 3 minutes of data are wasted. In addition, the time tagging with a fixed interval of 780s and a lag of about 4 minutes every day is impractical for most users. The data are round off at 0.1 ns and only code data without CP information are recorded. The BIPM therefore envisages a reform of the raw data collection conventions and an update of the GGTTS format [27] to take account of current and future improvements in GLN time and frequency transfer.

4. Conclusion

To guarantee the precision, the accuracy, and the robustness of UTC generation, the multitechnique strategy for UTC time transfer is indispensable. Efforts towards introducing GLN to complement GPS and TW in the generation of UTC began in the early 1990s, and in November 2009 the first two GLN time links were introduced into the UTC worldwide time link network.

In this paper we present the technical features of GLN time transfer as important for UTC production: a study of the so-called frequency biases, the short- and long-term stabilities, the calibration process, and the advantages of combining GLN and GPS. We also describe various ongoing projects at the BIPM, particularly concerning the use of carrier-phase data.

The present study is focused on the application of GLN L1C code in the generation of UTC, which yields a short-term stability of 1 ns to 1.5 ns. The calibration uncertainty is 5 ns, and the long-term stability is about the same as for GPS. The combination of the GLN L1C and GPS C/A codes makes sense in reducing the short-term stability and particularly in increasing the accuracy and the robustness in the UTC links.

The cause of the so-called frequency biases remains unclear for the authors. Although correction for estimated frequency biases leads to some slight gains for certain baselines, these gains are not seen ubiquitously, and, pending further research, it has been decided not to apply such corrections for GLN links used in the computation of UTC.

Notation

UTC:	Coordinated Universal Time
BIPM:	International Bureau of Weights and Measures
GLN:	GLONASS (GLObal Navigation Satellite System) [18]
GPS:	Global Positioning System
GNSS:	Global Navigation Satellite Systems
IGS:	International GNSS Service
TW:	TWSTFT (Two-Way Satellite Time and Frequency Transfers)
PRN:	PseudoRandom Noise code signal. Each GPS satellite transmits a unique code sequence (Code Division Multiple Access) and may be identified according to its PRN number. All GLN satellites transmit the same PRN signals using different frequencies (Frequency Division Multiple Access). In the UTC/TAI data format (CGGTTS), PRN is the nominal number of a GLN satellite
Fr:	Frequency or frequency code
δ_P:	Bias in time delay of a GLN PRN
δ_F:	Bias in time delay of a GLN frequency
CV:	Code-based common view time transfer
AV:	Code-based and/or carrier phase all in view time transfer [17]
P3:	Time transfer (CV and/or AV) using the linear combination of L1 and L2 measurements to achieve ionosphere-free code measurements
PPP:	Time transfer using carrier-phase precise point positioning technique [22]
GLN&GPS:	Time transfer combining GPS C/A and GLN L1C codes
Gain:	In percentage to indicate the improvement in time transfer quality. The gain in σ versus σ is computed by the equation $(\sigma - \underline{\sigma})/\sigma$
CP:	Carrier phase
CD:	Clock difference
RCD:	Rate of CD
yymm:	Year and month (an UTC computation month), for example, 0910 for 2009 October and 1005 for 2010 May.

Acronyms Used for the National UTC Laboratories

AOS:	Astrogeodynamical Observatory, Borowiec (Poland)
CSIR:	National Metrology Institute of South Africa (NMISA, South Africa)
INPL:	National Physical Laboratory, Jerusalem (Israel)
NIS:	National Institute for Standards, Cairo (Egypt)
OP:	Observatoire de Paris (France)
PTB:	Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin (Germany)
SG:	Agency for Science Technology and Research (A*STAR) (Singapore)
SU:	Institute for Physical-Technical and Radiotechnical Measurements, Rostekhregulirovaniye of Russia (VNIIFTRI), Moscow, (Russian Federation)
UME:	Ulusal Metroloji Enstitüsü/National Metrology Institute, Gebze-Kocaeli (Turkey)
VSL:	Dutch Metrology Institute, Delft (Netherlands).

Acknowledgment

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