REEVALUATION OF THE MEASUREMENT UNCERTAINTY OF UTC TIME TRANSFER

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Abstract

The uncertainty u_A of clock comparisons as reported in the* BIPM Circular T *is defined as the statistical uncertainty evaluated by taking into account the level of phase noise in the raw data, the interpolation interval, and effects with typical duration between 5 days and 30 days.

The first global evaluation of u_A was performed in 2002. Since then time-transfer techniques have improved significantly. New techniques have been introduced at different periods and the methods used to estimate their uncertainty u_A were not necessarily consistent.

In this paper, we propose a revised definition of u_A and recalculate its value for all 67 links used in UTC.

NOTATION AND ABBREVIATIONS

d_{Link} Link difference: d_{Link} = Link1 – Link2
u_A Standard uncertainty as defined in Section 6 of the *BIPM Circular T* **[1]**.
u_A' Estimation of u_A in this study
u_A'' Standard uncertainty of d_{Link} defined as $u_A''=\sqrt{[u_A^2(\text{link1}) + u_A^2(\text{link2})]}$
σ Standard deviation of the d_{Link}
$\underline{\sigma}$ Standard deviation of the Vondrak smoothing residuals of a link
TDev/τ Time Deviation corresponding to the averaging time τ indicating the flicker PM segment **[2,3]**
YYMM Year and month of a particular UTC computation; e.g., 1101 is for January 2011.
AV All in View time transfer **[4,5]**
CP Carrier phase. Used to obtain the GPS PPP result
CV Common View time transfer
GPS US Global Positioning System
GLN GLONASS, Russian Global Navigation Satellite System
GPSGLN Combination of GPS C/A and GLN L1C codes **[6]**
MC Multi-channel GPS or GLN receiver
P3 Ionosphere-free code obtained with the linear combination of the two precise codes P1 and P2 **[7]**
PPP Time and frequency transfer using the Precise Point Positioning method **[8]**
SC Single channel GPS
TW TWSTFT
TWPPP Combination of TW and PPP **[9]**

1. INTRODUCTION

The dominating part of the total uncertainty in [*UTC* - *UTC*(*k*)] is the uncertainty of the time transfer **[10]**. The first estimation of the values of u_A for all time links (hereafter referred to as “global estimation”) was presented in December 2002 **[11]**. The values were updated and officially introduced in *Circular T 194* (March 2004). Since then, the uncertainty of each UTC link is published each month in Section 6 of *BIPM Circular T*. This Section 6 was created specially to provide the uncertainty of the links used in the calculation of UTC **[1]**.

Since then, time-transfer techniques in the generation of UTC have evolved with the introduction of P3 CV (2004) **[7]**, GPS All in View (2006) **[4,5]**, PPP (2008) **[8,12]**, TWPPP (2010) **[9]** as well as GLN (2009) **[13]** and GPSGLN (2010) **[6]**. Considering this significant improvement in time-transfer techniques and the possibility to intercompare independent techniques, we propose in this paper a new definition and a global reevaluation of u_A.

The uncertainty u_A of clock comparisons, as reported in the *BIPM Circular T*, is defined as the statistical uncertainty evaluated by taking into account the level of phase noise in the raw data, the interpolation interval, and the effects with typical duration between 5 days and 30 days.

The definition of u_A in the new evaluation is "u_A *is the standard uncertainty accounting for measurement noise and random effects with typical duration between 1 day and 30 days*". For example the diurnals in TW and the daily and monthly discontinuities in GPSPPP are effects that cannot be clearly seen in the averaged or smoothed results, but they can be observed when analyzing the time deviations TDev or by comparing TW and GPSPPP data.

2. METHOD

The basic idea is similar to that of the 2002 evaluation; we first classify the links into four categories according to their measurement quality (Table 1) and then study the relationship between the link uncertainty and its TDev on some selected baselines where all the types and the categories of the links are available.

Table 1. The four qualities of link, grouped according to their present values of u_A which are considered as the *a priori* values for this evaluation.

Category	Type of link	u_A / ns
Ia	TW, GPSPPP, TWPPP	0.3 to 0.6
Ib	TW	0.6 to 1.0
II	P3	0.7 to 1.0
III	GPSGLN, GPSMC	1.2 to 1.5
IV	GPSMC, GPSSC	> 1.5

TWPPP and PPP are the most precise techniques and can be used to estimate the u_A of the less stable categories. The u_A of the PPP links has been estimated previously through geodesic and time-transfer experiments **[12]**. To better characterize the uncertainty of a link and its components, we select two baselines – one short and one long **-** between laboratories where all the time-link techniques are available. We then estimate the u_A' of a link, e.g. a P3 link, by comparing it to the TWPPP link, and consider its relation to the TDev. In turn we can use this relation to estimate the u_A' for other links where TWPPP data are not available. In this study, we analyze all UTC links for which data are available for at least 9 months. If necessary, we consult the historical data kept in the BIPM ftp server **[14]**.

The reevaluation is realized by following steps:

- The present values of u_A are used as the *à priori* u_A' (Table 1);

- The u_A' of TW, GPSPPP and TWPPP links are established first, by analyzing the NIST-PTB baseline for 15 months (1007-1109);
- The baseline OP-PTB, where all the techniques are available (GPS SC, MC, P3, PPP, GLN MC, TW and the combined solution GPSGLN), is analyzed using u_A' for TWPPP as a reference;
- The relationship between the TDev of the raw data and the standard deviation (σ) of the difference of each type of link is established with respect to that from TWPPP (d_{Link}). Here we take the slope change, termed TDev/$\underline{\tau}$, between Flicker PM and White FM as the reference point for the estimation of u_A'. In the following, TDev/$\underline{\tau}$ is used for the estimation of the less stable categories. The value will be first confirmed by the comparison to the TWPPP or GPSPPP in the selected test baselines. 15 months data (1007-1109) were used for this detailed numerical analysis;
- The 67 UTC links were reevaluated based on the TDev analysis on raw link data. At least 9 months of data (1101-1109) were used;
- For the inter-technique link comparisons, smoothed data were considered, using the standard Vondrak parameters for the UTC link computations. Raw link data were used for TDev.

3. STATISTICAL ANALYSIS BASED ON THE UTC TIME LINK DATA

3.1 THE DATA

Two sets of the UTC time links have been exhaustively analyzed. The 15 months' data set between 1007-1109 is available for a dozen of baselines of the most stable category. The 9 months' data set between 1101-1109 were used for less stable category time links. All the results are given in the *Rapport BIPM* **[15]**. Many analyses have been performed, that cannot be all presented in this paper. Therefore, we present the example of two typical long and short links NIST-PTB and OP-PTB to show the application of the method the reevaluation.

3.2 THE CASE OF THE BASELINE NIST-PTB

NIST-PTB is a maser-maser baseline operating TW and GPSCP. TWPPP is used for the UTC computation since 1101. The present values u_A for TW, GPSPPP and TWPPP are respectively 0.5 ns, 0.3 ns and 0.3 ns. We should prove in this section if the above u_A a priori given in Table 1 is correct. The NIST-PTB baseline is one of the longest baselines and hence the conclusions draw here and used for shorter baselines of same category should be conservative.

Table 2 reports results of the comparison between different types of time links over the baseline NIST-PTB over 15 months between 1007-1109. Here the statistics were made over the 15 continued months combined into a unique time series instead of 15 months separately. As can be seen in the table the value of $\sigma < u_A$". The biggest σ value is 0.580 ns for the comparison TW-GPSPPP. This σ masks also the middle-term (up to 30 days) and long-term (over 1 year) variations (or biases) between TW and GPSPPP.

Table 2. Comparisons of the time links over the baseline NIST-PTB during 15 months between 1007-1109.

Link1−Link2	**N**	**Mean** /ns	**σ** /ns	**u_A''** /ns
TW−GPSPPP	4815	-2.424	0.580	0.6
TW−(TWPPP)	4815	-0.009	0.281	0.6
(TWPPP)−GPSPPP	4336	-2.437	0.484	0.6

Figure 1 plots the TDev of the three time links TW, GPSPPP and TWPPP over a data set of 15 months, between 1007 and 1109. The diurnal signal in the TW can be seen clearly. The combined link TWPPP is the most stable; in this case, the calibration is given by the TW and the diurnals have disappeared. Starting from 1 day the TDev of the three links start to converge. The masers are quite stable and the time transfer stabilities are well below their conventional u_A values.

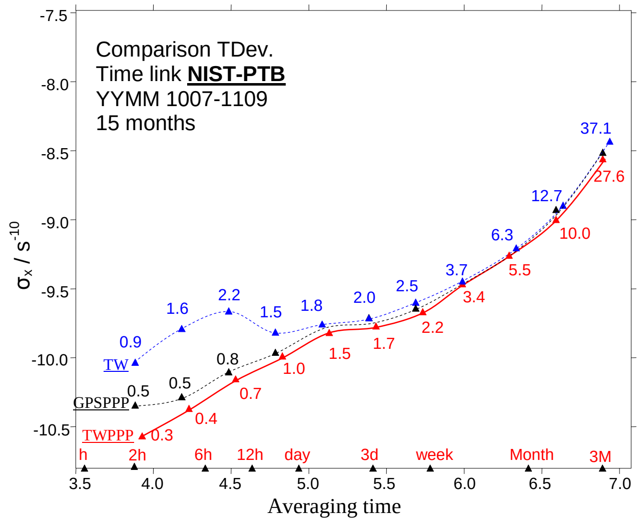

Figure 1. TDev of the three time links TW, GPSPPP and TWPPP. The diurnals in the TW can be seen. The combined link TWPPP is of the most stable.

We conclude that both the σ of the inter-technique comparisons and the TDev are inferior to the present u_A''. Considering that u_A of the three types of link is 0.3 ns for GPSPPP and TWPPP, 0.5 ns for TW, we can safely consider $u_A' = u_A$ in the normal operation condition. As mentioned above, the baseline is the longest TW baseline in Europe and America, this evaluation is conservative.

3.3 The Case of the Baseline OP-PTB

This baseline is chosen as the example because it can be solved by all types of times links used at present for UTC computation. The result will serve as a reference to estimate the u_A' of the same link or those of less stable category. We first compare the TDev of the links of the most stable category (TW, GPSPPP and TWPPP) and then that of the less stable categories to find the adequate averaging duration given by the TDev/$\underline{\tau}$. However this agreement between TDev/$\underline{\tau}$ and σ (of d_{Link}) may not be enough and we should further refer to the $\underline{\sigma}$ (of the Vondrak smoothing residuals); cf. Notation for their meaning. All these statistical results are considered together in the evaluation the u_A' for all types of links on this baseline by considering the values of u_A''/u_A, $\sigma/\underline{\sigma}$ and TDev/$\underline{\tau}$. The result will be finally used to estimate the u_A' for all other UTC links.

Figure 2 shows the TDev of TW, GPSPPP and TWPPP on the baseline OP-PTB during 15 months between 1007-1109. The TW link is rather noisy than the usual case. This can be seen also by the link comparisons. Therefore we suggest u_A'(TW) = 0.6 ns instead of the present conventional value 0.5 ns. The TWPPP is the most stable one and is used as the official UTC link.

Figure 3 presents the TDev of GLN/L1C, GPS C/A, and GPSGLN over the baseline OP-PTB during 15 months between 1007-1109. As can be seen, the GPSGLN is the most stable one; it is the official UTC link for the baselines SU-PTB and UME-PTB since January 2011; we plan to use this combination soon for other baselines (CAO-PTB, KZ-PTB).

Figure 4 plots the TDev of GPSMC C/A, GPS P3, and TWPPP over the baseline OP-PTB during 15 months between 1007-1109. The P3 link is more stable than the MC one. The TDev of the three links converge after 1 day.

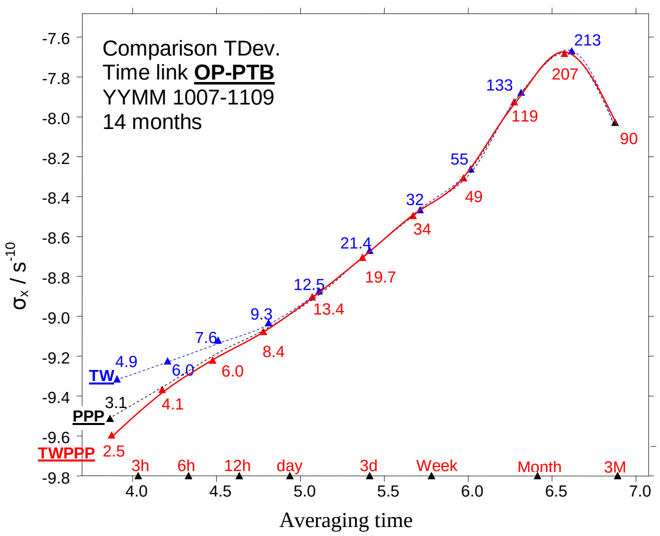

Figure 2. TDev of TW, GPSPPP and TWPPP over the baseline OP-PTB evaluated during 15 months between 1007-1109. The TWPPP is the most stable one and is used as the official UTC link, it is chosen as the reference scale to study the instability of other links.

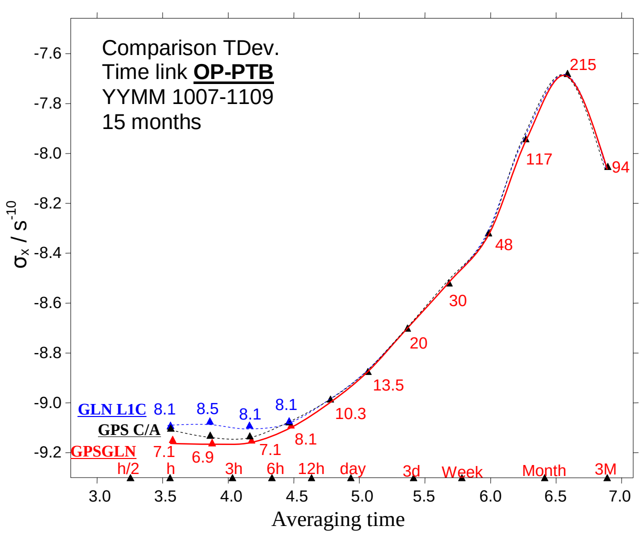

Figure 3. TDev of GLN/L1C, GPS C/A and GPSGLN over the baseline OP-PTB evaluated over 15 months between 1007-1109.

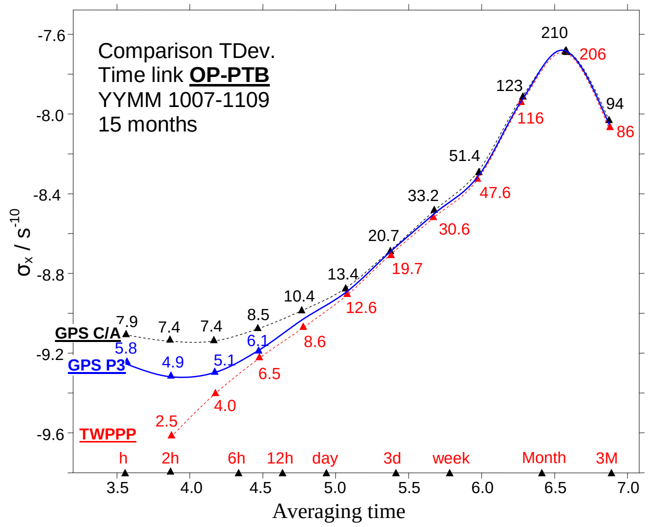

Figure 4. TDev of GPSMC C/A, GPS P3 and TWPPP over the baseline OP-PTB evaluated over 15 months between 1007-1109.

4. REEVALUATION OF ALL THE UTC LINKS UNCERTAINTIES

Multiple indicators are used to estimate the u_A' as discussed in Sections 2 and 3.3; for $\underline{\sigma}$, σ and TDev/$\underline{\tau}$, cf. the Notation for their meaning.

Here, TDev/$\underline{\tau}$ is the conventional value of time deviation in nanosecond for averaging time $\underline{\tau}$ in hour. The minimum value is 0.1 ns even if the true value is less than that. In the TDev/$\underline{\tau}$ column, * stands for a TDev value dominated by clock noise and not applicable for u_A'.

We also investigated the relationship between these indicators. This is particularly useful for the baselines where the σ, i.e. the most stable category link, is not available. The present values of u_A and the observation for one decade of the behavior of the UTC links are important to be considered.

Numerical analysis and statistics were based on long-term data at least 9 months from 1101 to 1109. A bad historical record in a link in this period may degrade its u_A estimation.

The difficulty remains of separating the instabilities of the clock in the Lab(k) from those of the measurements linking Lab(k) to another one. The instability of the hydrogen maser at the PTB, for example, can be considered as negligible, at least for the less stable categories. Even in this case, it is not straightforward to exactly distinguish the Flicker PM belonging to a time link and the White FM of a clock. The values of u_A' given in Table 3 mask partially the clock instability. Anyway, if the TDEV contains some clock instability, it is not critical, since we prefer to give a u_A' value that is conservative rather than optimistic.

Table 3 lists the u_A values of the UTC time links as given in the Section 6 of the *BIPM Circular T* **[1]** and the u_A' values obtained from the new evaluation.

Table 3. Uncertainty in the UTC time links in the Section 6 on the *BIPM Circular T* (c.f. the Notation for the meaning of the terms).

Link	Type	u_A /ns	TDev/τ /ns	τ /h	u_A' /ns
AOS -PTB	TWPPP	0.4	0.1	4	0.3
APL -PTB	GPS MC	1.5	0.7	24	1.0
AUS -PTB	GPSPPP	0.3	0.5*	4	0.3
BEV -PTB	GPS MC	1.5	1.0	24	1.5
BIM -PTB	GPS MC	2.0	1.1	4	1.5
BIRM-PTB	GPS MC	2.0	1.0	7	1.5
BY -PTB	GPS MC	2.0	0.8	24	1.5
CAO -PTB	GPS MC	1.5	1.2	6	1.5
CH -PTB	TWPPP	0.3	0.1	2	0.3
CNM -PTB	GPS MC	2.5	2.0	24	2.5
CNMP-PTB	GPS MC	3.0	1.0	24	2.0
DLR -PTB	GPSPPP	0.4	0.5*	3	0.4
DMDM-PTB	GPS MC	2.0	1.6	24	2.0
DTAG-PTB	GPSPPP	0.3	0.3*	2	0.3
EIM -PTB	GPS MC	5.0	4.0	24	5.0
HKO -PTB	GPS MC	2.5	1.5	24	2.5
IFAG-PTB	GPSPPP	0.3	0.4*	24	0.3
IGNA-PTB	GPS MC	2.5	1.1	24	1.5
INPL-PTB	GPS MC	1.5	0.8	24	1.5
INTI-PTB	GPS MC	4.0	2.0	24	3.0
IPQ -PTB	GPSPPP	0.4	0.3*	2	0.4
IT -PTB	TWPPP	0.3	0.1	2	0.3
JATC/NTSC	INT LK	0.2	-		0.2
JV -PTB	GPS GT	5.0	-		5.0
KIM -PTB	GPS MC	3.0	1.7	3	2.0
KRIS-PTB	GPSPPP	0.3	0.1	2	0.3
KZ -PTB	GPS MC	2.0	1.0	8	1.5
LT -PTB	GPS MC	2.0	1.5	6	2.0
MIKE-PTB	GPSPPP	0.3	0.1	2	0.3
MKEH-PTB	GPS MC	2.0	2.3	24	2.5
MSL -PTB	GPS P3	1.5	1.2	6	1.5
NAO -PTB	GPS MC	3.0	1.6	24	2.0
NICT-PTB	GPSPPP	0.3	0.1	6	0.3
NIM -PTB	GPS P3	0.7	0.4	24	0.7
NIMB-PTB	GPSPPP	0.3	0.9*	2	0.3
NIMT-PTB	GPS P3	1.0	0.7	8	1.0
NIS -PTB	GPS P3	0.8	0.6	8	0.8
NIST-PTB	TWPPP	0.3	0.1	2	0.3
NMIJ-PTB	GPSPPP	0.3	0.1	2	0.3
NMLS-PTB	GPS MC	2.0	1.2	24	1.5
NPL -PTB	TWPPP	0.3	0.1	2	0.3
NPLI-PTB	GPS MC	2.5	1.7	24	2.0
NRC -PTB	GPSPPP	0.3	1.2*	2	0.3
NRL -PTB	GPSPPP	0.3	0.1	2	0.3
NTSC-PTB	GPS MC	1.5	0.8	24	1.5
ONBA-PTB	GPS MC	7.0	4.0	3	6.0
ONRJ-PTB	GPS MC	4.0	1.3	24	2.0
OP -PTB	TWPPP	0.3	0.3*	2	0.3
ORB -PTB	GPSPPP	0.3	0.9*	2	0.3
PL -PTB	GPS MC	1.5	1.1	8	1.5
ROA -PTB	TWPPP	0.4	0.3	2	0.3
SCL -PTB	GPS MC	3.0	2.2	24	2.5
SG -PTB	GPSPPP	0.3	0.2	2	0.3
SIQ -PTB	GPS SC	5.0	2.4	12	4.0
SMD -PTB	GPS MC	1.5	0.9	24	1.5
SMU -PTB	GPS MC	1.5	0.9	8	1.5
SP -PTB	TWPPP	0.3	0.1	2	0.3
SU -PTB	GPSGLN	1.2	0.5	48	1.0
TCC -PTB	GPSPPP	0.3	0.1	2	0.3
TL -PTB	GPSPPP	0.3	0.1	2	0.3
TP -PTB	GPSPPP	0.3	0.3*	2	0.3
UA -PTB	GPS MC	1.5	1.1	48	1.5
UME -PTB	GPSGLN	1.3	0.8	8	1.0
USNO-PTB	GPSPPP	0.3	0.1	2	0.3
VMI -PTB	GPSPPP	0.3	0.6*	6	0.3
VSL -PTB	TWPPP	0.3	0.2	2	0.3
ZA -PTB	GPS P3	1.5	1.0	8	1.5

5. CONCLUSION

The first global evaluation of u_A was made in 2002 **[11]** on the basis of the type of time links used for UTC at that epoch. Based on this method of evaluation, the first values of u_A were published in Section 6 of *Circular T* in 2004. Based on these link uncertainties, the uncertainty of [UTC-UTC(k)] is evaluated each month, and published in Section 1 of *Circular T*.

During the last decade, new time transfer techniques have been incorporated into the calculation of the links for UTC. In this paper, we present a revision of the method used in 2002 for the calculation of $u_{A,}$ taking into account the evolution of techniques and methods of clock comparison for UTC, and we propose new values all the 67 UTC links. One of the advantages of this work compared to the 2002 one is that we use new precise methods, e.g. TWPPP, that can supply a reliable indicator for the estimate of u_A through inter-technique comparisons.

Other the individual revision of u_A values for some links, which has been made whenever necessary, we suggest a complete revision every few years for taking into account of the progress in the time transfer techniques and methods.

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