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- Evolution and Reevaluation of Measurement Uncertainty in $[UTC - UTC(k)]$

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Abstract

Coordinated Universal Time (UTC) is computed at the International Bureau of Weights and Measures (BIPM) in Sèvres, France. The calculation is derived using data from about four hundred atomic clocks located in contributor laboratories worldwide. Numerically it is represented by the differences between UTC and the UTC realization of a contributing laboratory *k*, $[UTC - UTC(k)]$; the Type A standard uncertainties of these differences, denoted u_A in BIPM Circular T, are dominated by the uncertainty in time-transfer measurements accounting for measurement noise and random effects with a typical duration between 1 day and 30 days.

The first global evaluation of the Type A uncertainty of time links was published in 2002 and introduced into *Circular T* 194 in 2004. Since then time-transfer techniques have improved significantly, with the introduction into the calculation of UTC of new links based on GPS P3, All in View, PPP (Precise Point Positioning), a combination of the TW (Two-Way Satellite Time and Frequency Transfer) and GPS carrier phase (TWPPP), GLONASS and a combination of GPS and GLONASS. With these additions the configuration of the UTC time-transfer network has been transformed to adapt these new developments.

In this paper, we first review the Type A uncertainty of time links evaluation undertaken in 2002 and then the Type A uncertainty of TWPPP links, which are currently the most precise type of link available. By selecting one short and one long baseline where all the link types are available, we can estimate the u_A of the other links relative to the TWPPP link and study the relationship between these u_A and the time deviation of the links. From this relationship we can estimate u_A for other baselines where no TWPPP link is available. Finally, we carry out a global re-evaluation of u_A using a method that is consistent for all 67 UTC time links.

The results obtained were introduced into the generation of UTC in December 2011, with the publication of *Circular T* 287. We recommend that such a global re-evaluation of u_A should be carried out regularly – at least every four years – for the calculation of UTC.

Notation AND ABBREVIATIONS:

GUM[1]: 'Evaluation of measurement data - Guide to the expression of uncertainty in measurement', JCGM (Joint Committee for Guides in Metrology) 100:2008 [3]
Link: Time-transfer link. The result is the clock comparison between two laboratories
$\boldsymbol{d}_{\mathbf{L}}$: Time link difference between two Links 1 and 2 of a common clock baseline: d_L = Link1 – Link2
$\boldsymbol{u}_{\mathbf{A}}$: The Type A standard uncertainty in a 'link' as defined between February 2004 and November 2011 and evaluated in Section 6 of BIPM *Circular T* 194-286 [1]. Because it dominates the Type A uncertainty in [*UTC*-*UTC*(k)] and is therefore the key concept discussed in this paper
$\boldsymbol{u}_{\mathbf{A}}'$: The present estimation of u_A as defined and evaluated in Section 6 of *Circular T* 287 and since December 2011 [20]
$\boldsymbol{u}_{\mathbf{A}}''$: Standard uncertainty of d_L defined as $u_A''=\sqrt{[u_A^2(\text{Link1}) + u_A^2(\text{Link2})]}$. It serves in this paper as a criterion of the tolerance for the outliers in the d_L
$\boldsymbol{\sigma}$: Standard deviation of the d_L
$\underline{\boldsymbol{\sigma}}$: Standard deviation of the Vondrak smoothing residuals of a link
TDev/$\boldsymbol{\tau}$: Time Deviation corresponding to the averaging time τ indicating the flicker PM segment [9,10]
YYMM: Year and month of a particular UTC computation month, e.g. 1101 stands for January 2011.
TW: TWSTFT, Two-Way Satellite Time and Frequency Transfer
AV: All in View time transfer [13,14]
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]
SC: Single channel GPS
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]
CP: Carrier phase. Used to obtain the GPS PPP
TWPPP: Combination of TW and CP [5]
HM: Hydrogen-Maser

1. Introduction

According to the report from JCGM 100:2008 [3], the total uncertainty in a measurand can be considered to consist of two parts [11,12]: the Type A component (u_A) which is estimated by statistical means, and the Type B component (u_B) estimated by other methods.

In the case of UTC, the dominant contributions to both the Type A and Type B uncertainties of [*UTC*-*UTC*(*k*)] relate to the time links [*UTC*(*k*)–*UTC*(*PTB*)][2]. The evolution, and therefore the evaluation, of the uncertainty in [*UTC*-*UTC*(*k*)] corresponds almost exactly to that in the time-transfer techniques, although the clock weighting strategy in the algorithm of UTC generation also has some limited impact on uncertainty propagation [12]. Taking examples from *Circular T* 287 [20], the Type A uncertainties of [*UTC*-*UTC*(*k*)] and of the links [*UTC*(*k*)–*UTC*(*PTB*)] differ by no more than 0.1 ns (see Table 1). The same is true for u_B. u_B is not discussed in this paper.

[1] GUM 1993, GUM 1995 and JCGM 100:2008 are different editions of the same document [4].
[2] After the introduction of the AV in 2006, all UTC(*k*) are linked directly with PTB (Physikalisch-Technische Bundesanstalt), i.e. [*UTC*(k)–*UTC*(*PTB*)], cf. the Annex.

Table 1 Examples of the Type A uncertainties (u_A) in $[UTC - UTC(k)]$ and in the link $[UTC(k) - UTC(PTB)]$

k	Link type	u_A in $[UTC - UTC(k)]$ /ns	u_A in link $[UTC(k) - UTC(PTB)]$. / ns
USNO	PPP	0.3	0.3
NICT	TWPPP	0.3	0.3
NIS	P3	0.8	0.8
SU	GPSGLN	1.0	1.0
NPLI	MC	2.0	2.0
ORB	PPP	0.4	0.3
NTSC	MC	1.5	1.4

Our study therefore focuses on the determination of the Type A uncertainty for different types of time link. It is based on a previous global study of the uncertainties [11], undertaken in conformity with GUM [3].

1.1 Background

The BIPM has the mandate to compute the international time scale Coordinated Universal Time (UTC) in the form of $[UTC - UTC(k)]$ and its uncertainty [1,20].
The first global estimation of the uncertainty of the time links was published in December 2002 [11] based on a GUM-type analysis [2]). This 2002 evaluation was officially adopted in *Circular T* 194 of February 2004 [1]. At that time there were 53 time links in total: 44 GPS CV links and 9 TW links. The UTC time-transfer network was structured around four pivotal laboratories: USNO (United States Naval Observatory), NIST (National Institute of Standards and Technology), CRL (now NICT, National Institute of Information and Communications Technology) and PTB, cf. the Annex. The links were classified into four categories according to the type of link: (1) TW, (2) GPS CV MC operated under normal conditions, (3) GPS CV SC operated under normal conditions and (4) GPS links in poor conditions [11]. The number of TW measurement points was low, with only 2 or 3 points per week, making it difficult to estimate the short-term uncertainty of TW links. Furthermore, the TW link measurement noise was masked by the clock noise so that the only indicator, TDev, could be interpreted as the maximum u_A of the TW links. Hence, the 2002 evaluation was based on the TDev over the least noisy hydrogen maser–hydrogen maser baseline available in each category.

Since the 2002 evaluation, time-transfer techniques in the generation of UTC have evolved significantly with the introduction of P3 CV (2004) [7], GPS All in View (2006) [13,14], PPP (2008) [8,16], TWPPP (2010) [5] as well as GLN (2009) and GPSGLN (2011) [6,15]. The conventional Type A uncertainties of these new techniques are listed in Table 2. Considering this significant improvement in time-transfer techniques and the possibility of directly comparing independent techniques, a new global re-evaluation of u_A is timely.

Table 2 The Type A standard uncertainties of the time-transfer techniques introduced since 2005 in UTC time links

Type of link	u_A / ns	Introduced in
P3 CV/AV	0.7	2004/2006
GPSPPP	0.3	2008
TWPPP	0.3	2011
GLN	1.5	2009
GPSGLN	1.2	2011

1.2 Component of u_A

At present, there are a total of 68 laboratories contributing to UTC (67 operational links).

Until BIPM *Circular T* 286 (October 2011), u_A was defined in Section 6 [1] as u_A is the statistical uncertainty evaluated by taking into account: (1) *the level of phase noise in the raw data,* (2) *the interpolation interval between data points, and* (3) *effects with typical duration between 5 and 30 days*.

In view of the currently available short measurement intervals, item (2) is insignificant: the TW measurement interval has been reduced from typically 2 to 4 days (in 2002) to 1 to 2 hours [19]; the interval for GPS and GLN codes in CGGTTS format is 16 minutes, and for GPSPPP it is 5 minutes. The interpolation uncertainties are hence negligible. The third item has generally been determined first through a qualitative analysis of the main effects for each technique, and secondly through the comparisons of the independent link technique as well as the time series statistics and analysis. As an example, to estimate u_A for GPS single frequency code measurements, we estimate first the possible magnitude of ionospheric and tropospheric mismodelling and of multipaths with the help of the geodetic experiences. This result is then confirmed by the comparison of the link in question to that of a higher category. These are completed by the information given by the TDev and the smoothing residual analysis. In this paper, we base our estimates on inter-technique common clock comparisons, which provide a more objective method of estimating the u_A for a given technique, e.g., short-term comparisons for the measurement noise and long-term comparisons for effects with typical duration up to 30 days.

Our new evaluation is therefore: "*u_A is the standard uncertainty accounting for measurement noise and random effects with a typical duration between 1 day and 30 days*". Examples of random effects include the diurnals in TW and the daily and monthly discontinuities in GPSPPP, which cannot easily be seen in the averaged or smoothed results, but which can be observed when analyzing the time deviations TDev or by comparing TW and GPSPPP data.

Although UTC time links are computed using the smoothed data, the estimate of u_A is based on the raw measurement data so our evaluation still has a margin or acceptable error.

In Section 2the method used for the re-evaluation is presented. In Section 3 the numerical analysis and the statistical results for two selected baselines is given, while in Section 4 the u_A' evaluation for all the UTC links is provided and finally we draw our conclusions.

2. Method

The method to evaluate u_A under the new definition by using a consistent method is presented. The major difficulty remains the same as in 2002, that is that the instabilities of the linked clocks may affect the estimation of u_A of the links. However, compared to the 2002 evaluation, the situation has improved significantly:

1) As shown in Table 2, the precision of the GPS CP solution PPP has improved by one order of magnitude, and the number of TW measurements has increased thirty-fold. As the highest category, these two techniques supply a good scale to evaluate each other and the lower categories by analyzing d_L; this occurs because more than one third of the UTC laboratories operate at least one backup time transfer technique. This rich redundant data allows us to study the measurement uncertainty through a comparison of the independent time links;
2) Long-term link comparisons have being computed since 2005 on a monthly basis and since 2008 statistically analyzed. The results, including the plots and the ASCII data of the official UTC and certain back-up links, link differences (d_L), Modified Allan Deviation and Time Deviation are published monthly on the BIPM ftp site: ftp://tai.bipm.org/TimeLink/LkC/ and ftp://tai.bipm.org/TimeLink/LkC/LongTerm/ [18]. This gives an easy and precise way to assess the quality of the time links and the related clocks based on their historical behaviors;
3) The number of laboratories equipped with masers has been greatly increased. Following the introduction of the AV [13, 14] in 2006, PTB was the only pivotal laboratory in the UTC world-wide time transfer network, and since 2011 its master clock has been a very stable hydrogen maser (HM). This suggests that only the Lab(*k*) clock, if it is unstable, may impact the u_A' evaluation. Through the accuracy and number of masers used by contributing laboratories any clock instability affects the u_A less than it did previously as demonstrated by the 2002 calculation.

The 2002 evaluation scheme consisted firstly of classifying the links into four categories according to their measurement quality (Table 3) and then studying the relationship between the link uncertainty and its TDev through some selected baselines where all the types and the categories of the links are available. The master clocks are stable to identify the white noise and the biases in link measurements. The classical statistical information, such as the standard deviation of the smoothing residuals etc., is also shown.

Table 3 The four categories of links, grouped according to their 'old' u_A values which are considered as the *a priori* values for the new 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 each other and of the less stable categories. The u_A of the PPP links has been estimated previously through geodetic and time-transfer experiments [16]. To better characterize the uncertainty of a link and its components, we select two baselines – one short and one long - between laboratories NIST, OP (Observatoire de Paris) and PTB where all the link types and stable maser clocks are available. We then estimate the u_A' of a link, e.g. a P3 link, by comparing it to the TWPPP link, and considering its relationship to the TDev obtained using only the P3 raw measurement data. In turn we can use this relationship to estimate the u_A' for other P3 links where TWPPP data are not available. That is, the TDev is first validated by the d_L analysis of the selected baselines and then used as a general case. In this study, we analyze all UTC links for which continued data are available for at least nine months. If necessary, we consulted the historical behaviors of the link, using data held on the BIPM ftp server [18].

The re-evaluation is realized through the following steps:

- The old estimation values of u_A are used as the *a priori* u_A' (Table 3);
- The u_A' of TW, GPSPPP and TWPPP links are established first, by analyzing the NIST-PTB baseline for fifteen months (1007 to 1109);
- The baseline OP-PTB, where all the techniques are available (GPS SC, MC, P3, PPP, GLN MC, TW and the combined solutions TWPPP and GPSGLN), is analyzed using the u_A' of TWPPP as a reference;
- The relationship between the TDev of the raw data and the σ of d_L vs. TWPPP is investigated. Here we take the slope change in Figure 1, termed TDev/$\underline{\tau}$, between Flicker PM and White FM as the reference point for the estimation of u_A'. TDev/$\underline{\tau}$ is used for the estimation of u_A' of the less stable categories. The values will be confirmed initially by comparison with the TWPPP or GPSPPP in the selected test baselines. Fifteen months data (1007-1109) were used for this detailed numerical analysis;
- The 67 UTC links were re-evaluated based on the TDev analysis with the raw link data. At least nine months of data (1101 to 1109) were used;

For d_L analysis (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.

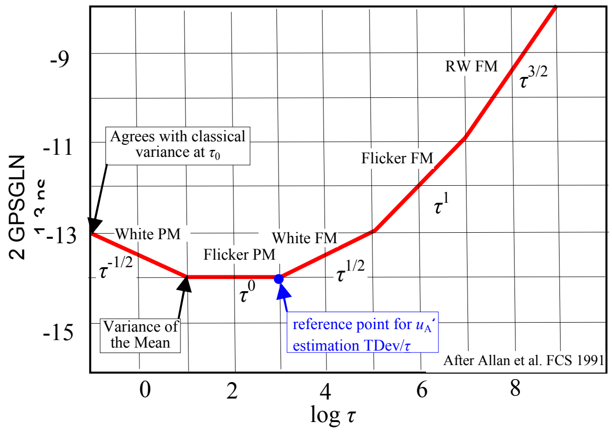

Figure 1 TVar optimally estimates time instability with White PM and distinguishes other noise types

Finally, we consider the basic tool we used. The TDev, square root of the Time Allan Variation (TVar), is particularly useful for measuring the stability of a time distribution network. Time transfer systems, such as GNSS codes used in the CV or AV modes, are well modeled using white-noises PM [9]. As illustrated in Figure 1, the bottom end of the variance ranges show those points where these variances are no longer convergent. It allows the white phase, flicker phase and random walk phase to be distinguished. These three noise processes are particularly useful models for systems where time measurements are important. Here we take the slope change, termed TDev/$\underline{\tau}$, between Flicker PM and White FM as the reference point for the u_A' estimation. In the following, TDev/$\underline{\tau}$ is used for the estimation of the low categories. The TDev suggested estimates should first be validated by the comparison to the TWPPP or GPSPPP in the selected test baselines before using in general cases.

3. Statistic analysis based on UTC data

3.1 The data

Two sets of the UTC time links have been exhaustively analyzed. The 15 months' data set between 1007 and 1109 is available for a dozen of baselines of the most stable category. The nine months' data set between 1101 and 1109 were used for lower category time links. All the results are given in the *Rapport BIPM* [17]. Many analyses have been performed and they cannot be all presented in this paper. We discuss therefore the examples of two typical long and short baselines NIST-PTB and OP-PTB to show the application of the method in the re-evaluation.

3.2 Case of the baseline NIST-PTB

NIST-PTB is a HM to HM baseline operating TW and GPSPPP. TWPPP has been used for the UTC computation since 1101. The present u_A values for TW, GPSPPP and TWPPP are respectively 0.5 ns, 0.3 ns and 0.3 ns, as given in Table 3. We prove in this section if the above u_A *a priori* is correct. The NIST-PTB baseline is one of the longest baselines and hence the conclusions drawn here and used for shorter baselines of the same category should be correct.

The major disturbances of TW are the diurnals [5] the cause of which is not clear. The amplitudes may be up to 0.5 ns or even bigger. This disturbance can be reduced by averaging or smoothing in the standard UTC link procedures but the result may still be biased. The major problem with GPSPPP is the discontinuity between the consecutive intervals of computation due to residual noise in the code measurements and possible frequency shift in the GPS receiver [16]. Such discontinuities can sometimes reach 0.5 ns.

Table 4 shows the monthly comparisons of the time links over the baseline NIST-PTB during the 15 months between 1007 and 1109. By the notation, the combined uncertainty in d_L can be computed by using the propagation law: $u_A'' = \sqrt{[u_A^2(\text{TW}) + u_A^2(\text{PPP})]} = 0.58$ ns < 0.6 ns. Figure 2 demonstrates the 15 months' point to point comparison of the time links between TW (black crosses) and GPSPPP (blue points) over the baseline NIST-PTB from 1007 to 1109. Figure 3 illustrates the distribution of the monthly mean values given in Table 4. The TW data is noisier than GPSPPP. The latter however presents several discontinuities about MJD 55700. In the Table 4, the only case of $\sigma > u_A''$ is in TW-GPSPPP in 1012. Its σ is 0.726 ns. As illustrated in Figure 2, this large σ is due to outliers. Towards the end of 1012, there were several outliers around MJD 55555 in which the TW caused the bigger σ. It appears that the automatic cleaning TW raw data function in the UTC computation software, Tsoft, was not operating correctly, otherwise these outliers would have been rejected. The biggest σ of link differences between TW-TWPPP and TWPPP-GPSPPP is 0.476 ns in 1007. Depending on the algorithm used for the combined solution, the σ of the link difference TWPPP-GPSPPP is always smaller than that of TW-GPSPPP. The monthly analysis suggests that the 'old' u_A of 0.5 ns for TW and 0.3 ns for GPSPPP is reasonable even with the presence of the diurnals in TW and the discontinuities in GPSPPP.

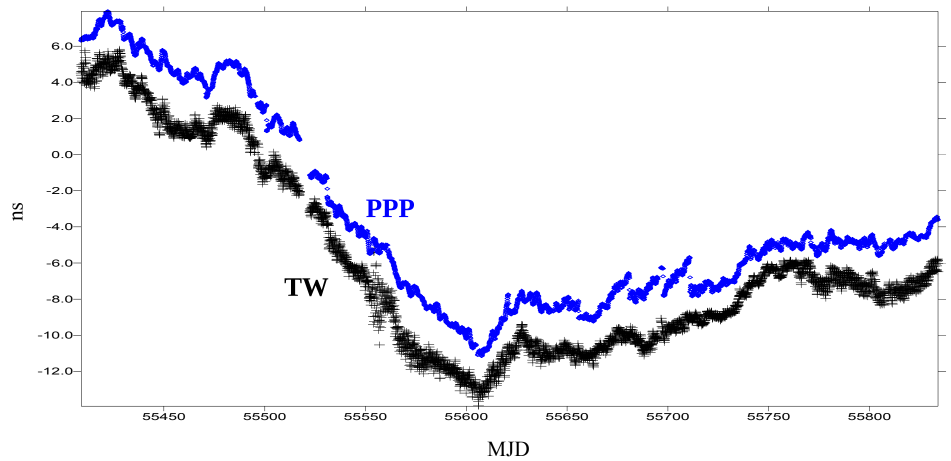

Figure 2 15 months' point to point comparison of the time links TW (lower black crosses) and GPSPPP (upper blue points) over the baseline NIST-PTB from 1007 to 1109. The TW data are noisy, e.g. the outliers around MJD 55555. The GPSPPP demonstrates the typical day and monthly boundary discontinuities, e.g. near MJD 55680. The diurnals in TW and the discontinuities in GPSPPP are all masked by the σ of the d_L and have been taken into account in the re-evaluated u_A' budget in the term 'random effects with typical duration between 1 and 30 days'

Table 4 Monthly comparisons of the time links over the baseline NIST-PTB during 15 months between 1007 and 1109
N is the number of the points to be compared. Note that the Mean of TWPPP agrees with TW because the calibration of the combination TWPPP is defined by TW. There is a $\sigma > u_A''$ (0.6 ns) only in 1012 (see the Notation for definitions of σ and u_A''). The mean value of TW-GPSPPP is -2.38±0.44 ns which can be considered as the calibration difference. The mean value of the σ of TW-GPSPPP is 0.41±0.12 which is bigger than that of TW-TWPPP and TWPPP-GPSPPP 0.30±0.11 ns and 0.22±0.08 ns, respectively. This suggests that the TWPPP keeps the calibration of TW and its precision approximates GPSPPP

yymm	Link1-Link2	*N*	Mean /ns	σ /ns
1007	TW-GPSPPP	346	-2.072	0.542
	TW-TWPPP	346	0.000	0.476
	TWPPP-GPSPPP	345	-2.072	0.214
1008	TW-GPSPPP	439	-2.209	0.411
	TW-TWPPP	439	0.000	0.315
	TWPPP-GPSPPP	438	-2.209	0.215
1009	TW-GPSPPP	377	-2.949	0.350
	TW-TWPPP	377	-0.002	0.266
	TWPPP-GPSPPP	370	-2.949	0.164
1010	TW-GPSPPP	370	-2.829	0.461
	TW-TWPPP	370	-0.000	0.309
	TWPPP-GPSPPP	369	-2.827	0.285
1011	TW-GPSPPP	312	-2.424	0.440
	TW-TWPPP	312	-0.000	0.259
	TWPPP-GPSPPP	408	-2.413	0.324
1012	TW-GPSPPP	375	-2.348	0.726
	TW-TWPPP	375	-0.000	0.590
	TWPPP-GPSPPP	374	-2.345	0.359
1101	TW-GPSPPP	373	-2.999	0.521
	TW-TWPPP	373	-0.000	0.427
	TWPPP-GPSPPP	372	-3.000	0.229
1102	TW-GPSPPP	358	-2.406	0.364
	TW-TWPPP	358	-0.000	0.289
	TWPPP-GPSPPP	357	-2.406	0.173

yymm	Link1-Link2	*N*	Mean /ns	σ /ns
1103	TW-GPSPPP	358	-2.418	0.331
	TW-TWPPP	358	-0.000	0.237
	TWPPP-GPSPPP	357	-2.418	0.183
1104	TW-GPSPPP	377	-2.399	0.418
	TW-TWPPP	377	-0.001	0.247
	TWPPP-GPSPPP	408	-2.389	0.263
1105	TW-GPSPPP	356	-2.763	0.413
	TW-TWPPP	356	-0.000	0.211
	TWPPP-GPSPPP	355	-2.762	0.313
1106	TW-GPSPPP	374	-1.686	0.221
	TW-TWPPP	374	-0.000	0.166
	TWPPP-GPSPPP	373	-1.685	0.105
1107	TW-GPSPPP	349	-1.412	0.252
	TW-TWPPP	349	-0.000	0.192
	TWPPP-GPSPPP	408	-1.422	0.103
1108	TW-GPSPPP	432	-2.129	0.396
	TW-TWPPP	432	0.001	0.301
	TWPPP-GPSPPP	468	-2.115	0.233
1109	TW-GPSPPP	355	-2.621	0.317
	TW-TWPPP	355	0.000	0.290
	TWPPP-GPSPPP	408	-2.636	0.111
Mean of 15 months	TW-GPSPPP	370	-2.38±0.44	0.41±0.12
	TW-TWPPP	370	0.00±0.00	0.30±0.11
	TWPPP-GPSPPP	387	-2.38±0.44	0.22±0.08

Table 5 shows the results of the comparison between different types of time links over the baseline NIST-PTB during 15 months between 1007 and 1109. Unlike Table 4, the statistics (mean and σ) are made with a unique time series of 15 continuous months. As can be seen in the table, it always holds that $\sigma < u_A''$. The biggest σ value is 0.580 ns for the comparison TW-GPSPPP. The σ also masks the middle-term (up to 30 days) and long-term (over 1 year) variations (or biases) between TW and GPSPPP.

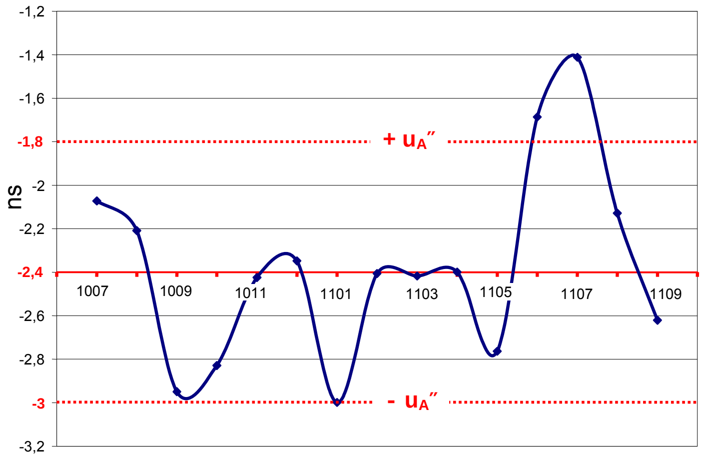

Figure 3 15 monthly mean values of the differences TW-GPSPPP in Table 4. c.f. the notation for the definition of the combined uncertainty u_A'' (0.6 ns). Certain systematical variation presents and reaches maximum in 1106 and 1107 (June and July 2011)

Table 5 Comparisons of the time links over the baseline NIST-PTB during 15 months between 1007 and 1109. (This table differs from Table 4 in that here the statistics comprise 15 month's data as a unique time series)

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

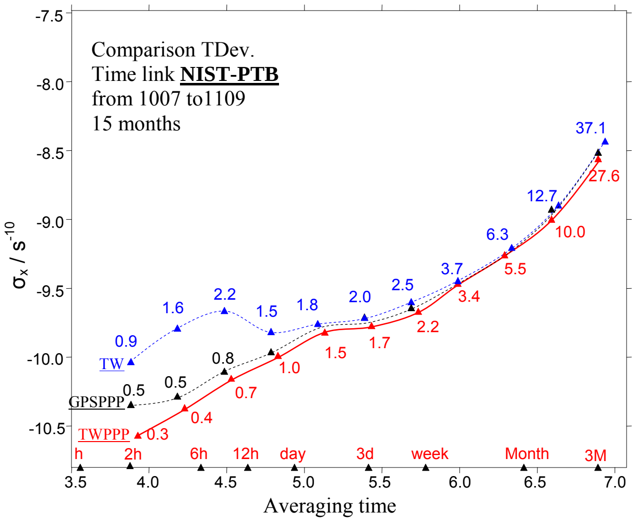

Figure 4 Comparison of TDev of the three time links TW, GPSPPP and TWPPP. The diurnals in the TW can be seen. The combined link TWPPP is the most stable. From about 0.5 day, the three TDev start to converge.

Table 6 TDev of the time links on different averaging time over the baseline NIST-PTB during 15 months between 1007 and 1109

Link	2 h /ns	6 h /ns	12 h /ns	24 h /ns	72 h /ns	168 h /ns
TW	0.09	0.18	0.17	0.16	0.19	0.24
GPSPPP	0.04	0.06	0.09	0.13	0.20	0.25
TWPPP	0.03	0.05	0.08	0.12	0.17	0.23

Figure 4 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 TW is clearly visible. The combined link TWPPP is the most stable, in it the calibration is given by the TW and the diurnals have disappeared. Starting from about 0.5 day the TDev of the three links start to converge. Table 6 lists the TDev of the three time links on different averaging times from 2 hours to a week (168 hours). The HMs are quite stable and the time transfer stabilities are well below their conventional u_A values.

We conclude that both the σ of the inter-technique comparisons and the TDev are inferior to the tolerance value 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' as identical to u_A under normal operation conditions. As mentioned above, this baseline is the longest TW baseline in Europe and America, and this evaluation is conservative when used for links within Europe.

3.3 Case of the baseline OP-PTB

This baseline has been chosen as an example because it can be solved by all types of time links used at present for UTC computation. The result will serve as a reference to estimate the u_A' of the same category link or those of a lower 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/$\underline{\tau}$ in Figure 1[3]. However this agreement between TDev/$\underline{\tau}$ and σ (of d_L) may not be enough and may be completed

[3] We are investigating the instability of the time transfer, i.e. the reference point TDev/$\underline{\tau}$ in Figure 3 under ideal conditions, that is the link instability comes mainly from the white noise. If it is not the case, the convergent point of different types of link would correspond to the slope change point between White FM and Flicker FM, the TDev/$\tau^{1/2}$ in Figure 3. The physical explanation may be that they are related to certain trends or biases due to the variation of environmental factors such as that of temperature, discontinuities and jumps etc. Note that White FM and Flicker FM are affected rather by the instability of the Lab(k) clock because the PTB maser is very stable. Different types of link converge with different speeds, e.g. in Figure 7, the TDev/$\underline{\tau}$ of TW is 0.49 ns/2 h but it needs one day of averaging time to average out the diurnal effect and converges with that of TWPPP. In Figure 9, the TDev of P3 and the TWPPP converges up to 10 h while that of GPS

by the $\underline{\sigma}$ (of the Vondrak smoothing residuals), cf. notation for the meaning of each term. All these statistical results are considered together in the evaluation of the u_A' for all types of links on this baseline taking into account of the values of u_A''/u_A, $\sigma/\underline{\sigma}$ and TDev/$\underline{\tau}$. Finally, the result is used to estimate the u_A' for other UTC baselines.

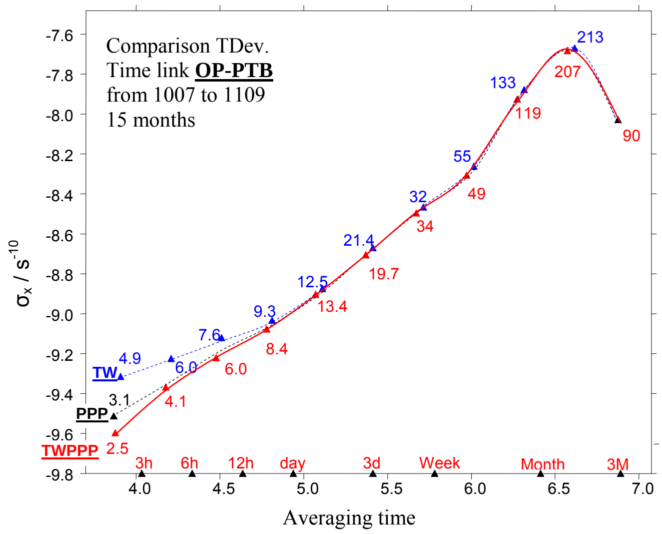

Figure 5 TDev of TW, GPSPPP and TWPPP over baseline OP-PTB evaluated during 15 months from 1007 to 1109. The TWPPP is the most stable link and is used as the official UTC link and the reference scale to study the instability of other links. The TW link is noisier than usual. As given later in Table 7, the re-evaluation of u_A' suggests 0.6 ns instead of the conventional value 0.5 ns. The TDev of the three links converge from about 16 hours averaging time.

Figure 5 shows the TDev comparisons of TW, GPSPPP and TWPPP of the baseline OP-PTB during 15 months between 1007 and 1109. The TW link is rather noisier than the usual case. This can be also be seen by the link comparisons as given in the elements A1, B1, B2, F1 and F2 in Table 7. Therefore we suggest u_A'(TW) = 0.6 ns instead of the present conventional value 0.5 ns, cf. Table 7. The TWPPP is the most stable link and is used as the official UTC link. The TDev of the three links converge from about 16 hours averaging time.

Figure 6 presents TDev comparisons of GLN/L1C, GPS C/A and the combined solution GPSGLN over the baseline OP-PTB during 15 months between 1007 and 1109. As can be seen, the combined solution GPSGLN is the most stable and is introduced as the official UTC link for the baselines SU-PTB and UME-PTB since January 2011. Since December 2011, GPSGLN has been introduced for other 4 baselines CAO-PTB, INPL-PTB, SMU-PTB and KZ-PTB. The TDev of the three links converge from about 20 hours averaging time.

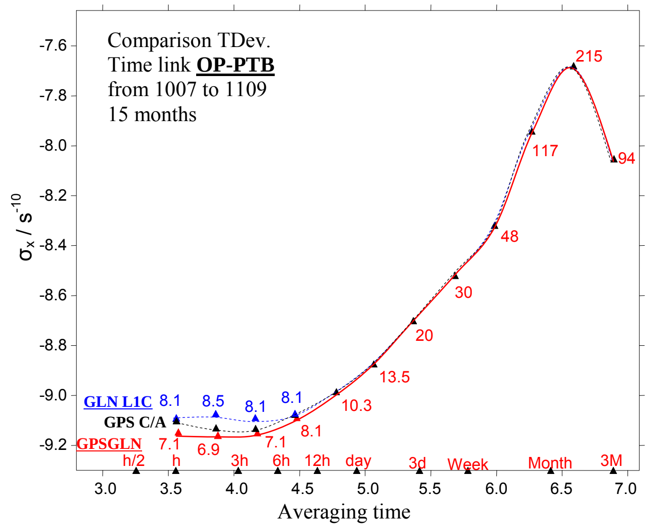

Figure 6 TDev of GLN/L1C, GPS C/A and GPSGLN over the baseline OP-PTB evaluated over 15 months from 1007 to 1109. The GPSGLN is the most stable and is used as the official UTC link. The TDev of the three links converge from about 1 day

Figure 7 plots the TDev of GPSMC C/A, GPS P3 and TWPPP over the baseline OP-PTB during 15 months

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MC and TWPPP up to 2 days. Higher categories converge faster than the lower categories. The convergent point of the link stability would locate near the TDev/τ^0 toward the TDev/$\tau^{1/2}$.

between 1007 and 1109. The P3 link is more stable than the MC link. It converges with TWPPP up to 10 hours. The TDev of the three links converge from about 2 days.

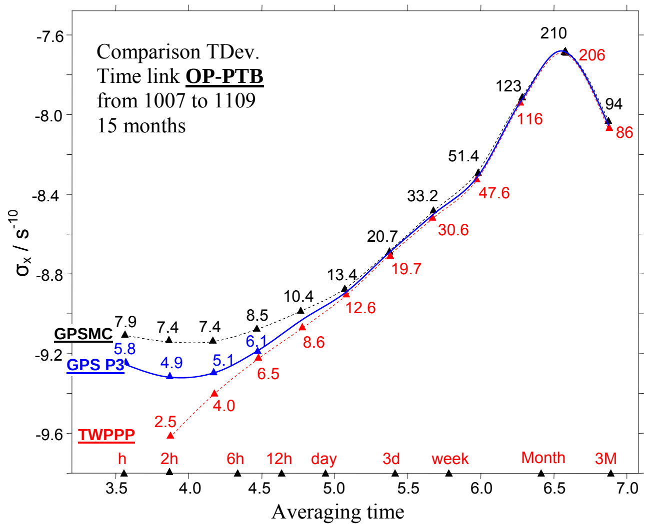

Figure 7 TDev of GPSMC C/A, GPS P3 and TWPPP over the baseline OP-PTB evaluated over 15 months from 1007 to 1109. The P3 link is more stable than the MC. It converges to the most stable link TWPPP up to 10 h. The TDev of the three links converge from about 2 days

Table 7 Statistics of all link types and d_L on the baseline OP-PTB over 15 months between 1007 and 1109.
(See notation for the meanings of u_A, u_A', u_A'', σ, $\underline{\sigma}$ and TDev/$\underline{\tau}$ etc. A value in the table can be labelled by the numbers of line (A, B, …) and column (1, 2, …), e.g. the u_A of TWPPP is u_A(B2)=0.3 ns; u_A''(C2)=1.3 ns, etc.)

Lk1 \ Lk2		**TW** /ns 1	**TWPPP** /ns 2	**GPSGLN** /ns 3	**MC** /ns 4	**P3** /ns 5	**PPP** /ns 6	**GLN** /ns 7	**SC** ns 8
TW u_A $\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	A	**TTTT** 0.5 0.710 0.40/2 h **0.6**							
TWPPP u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	B	TGTB 0.6 0.664	**T3B3** 0.3 0.429 0.25/2 h **0.3**						
GPSGLN u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	C	TRTB 1.3 1.078	GRBB 1.3 0.852	**GRB1** 1.2 1.066 0.81/10h **1.0**					
MC u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	D	TMTA 1.6 1.253	GMBA 1.6 1.109	RMBA 2.0 0.117	**MMMA** 1.5 1.154 0.95/10 h **1.5**				
P3 u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	E	TGTA 0.9 0.886	GGBA 0.8 0.669	RGBA 1.4 1.077	MPAA 1.7-2.6 0.605?	**PPPA** 0.7 0.744 0.7/10 h **0.7**			
PPP u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	F	TGT3 0.7 0.756	GGB3 0.5 0.705	RGB3 1.3 1.161	MGA3 1.6-2.6 1.042	GGA3 0.8 0.566	**333A** 0.3 0.176 0.31/2 h **0.3**		
GLN u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	G	TRTR 1.6 1.135	RGRB 1.6 0.968	RRBR 2.0 0.186	RMRA 2.2 0.277	RGRA 1.7 0.897	RGR3 1.6 1.027	**RRRC** 1.5 1.180 0.94/10 h **1.5**	
SC u_A''/u_A $\sigma/\underline{\sigma}$ TDev/$\underline{\tau}$ u_A'	H	TSTA 3.1 - -	GSBA 3.1 - -	RSAR 3.3 - -	SMAA 3.4-4.0 - -	SPAA 3.1 - -	S3AA 3.1 - -	SRAC 3.4-4.0 - -	**SSSA** 3.0 2.567 1.1/24 h **2.5**

Table 7 provides the results of the statistics of all types of link and link differences over the baseline OP-PTB during 15 months between 1007 and 1109. The off-diagonal elements list the results of inter-technique comparisons while the diagonal elements list the statistic results of the reported links. The table is given in the form of matrix. An element in the table can be identified by the labels of line (A, B, …) and column (1, 2, …), e.g. for TWPPP u_A(B2)=0.3 ns; for GPSGLN u_A''(C2)=1.3 ns, etc. The terms, e.g. TTTT(A1), T3B3(B2) etc. are the standard extensions of the file names of BIPM link and link comparisons [18], cf. also the ReadMe file in ftp://tai.bipm.org/TimeLink/LkC/.

The TDev of TW, GPSPPP and TWPPP for averaging time of 2 h are 0.40 ns (A1), 0.25 ns (B2) and 0.31 ns (F6) respectively. However the $\underline{\sigma}$ (smoothing residuals) and the σ demonstrate greater instability as shown in A1, B1, B2, F1 and F2. Therefore the u_A' for TW, GPSPPP and TWPPP are estimated to be 0.6, 0.3 and 0.3 ns higher than the old values: 0.5, 0.3 and 0.3 ns. The reason for this may be found in the TW link; the measurements were disturbed for two weeks due to Satellite (T-11N) frequency which changed on 27 July 2011, MJD 55769. Here, we see that by verifying at least six months' data a poor record will degrade the uncertainty estimation. The u_A' for other link types: GPS MC/SC/P3, GLN L1C and GPSGLN are estimated in the same way. The results of u_A' are listed in the diagonal elements in Table 7.

3.4 Discussion: how good approximations can be obtained by using an optimal Vondrak smoothing

So far, the TDev is an important indicator in the study. This and other indicators such as the $\underline{\sigma}$ etc. are based on the raw time link measurement data. However, the link values used in the UTC time transfers are those of the smoothed Vondrak. In the standard UTC computation procedure, the Vondrak smoothing powers are grouped according to the link types: 10^3 for GPS SC, 10^4 for GPS MC C/A or GLN MC L1C, 10^5 for GPS P3 and TW, and 10^9 for GPSPPP. As will be shown in the following discussion, they are not the optimal power settings.

How the smoothed data can approximate the true values is then an interesting issue. In this section, we see that, given the stable HM at PTB and Lab(k), the optimal Vondrak smoothing power "reduces" significantly the noise level in a UTC time link. Because the code link noise is higher than that of HM clocks, we are sure that only the link noise has been smoothed ou,. and thanks to the high precision in GPSPPP, this 'reduction' can be numerically demonstrated. In the following discussion, because the true value is unknown, we take the GPSPPP as a reference and study how closely the different Vondrak smoothing results approximate the GPSPPP by varying the smoothing powers. Because the re-evaluation of u_A' is based on the 'raw' data statistics, there is, therefore, still the potential to improve the uncertainty. We discuss the cases of TW, GPS MC C/A and GPS P3.

Compared to GPSPPP (0.3 ns), TW (0.5 ns) is noisier. This can be "improved" by a Vondrak smoothing with an optimal smoothing power. Note that the TW is completely independent of GPSPPP. The σ of the d_L (TW-GPSPPP) contains the uncertainties from both links. As can be seen in Table 8, a 10 % gain in σ is possible. Because TW and GPSPPP are both the first category, this gain is already significant.

Table 8 Comparison of σ between the GPSPPP and TW links computed with linear and different Vondrak smoothing powers (using the 0907 data between Mjd 55014 and 55039, N is the number of the points to be compared, Vdk$x$ stands for the Vondrak smoothing with the smoothing power x)

Baseline	*N*	Linear	Vdk0	Vdk1	Vdk2	Vdk3	Vdk4	Vdk5	Vdk6	Vdk7	Vdk8	Vdk9
		/ns	/ns	/ns	/ns	/ns	/ns	/ns	/ns	/ns	/ns	/ns
USNO-PTB	293	0.530	0.606	0.548	0.505	0.476	0.473	0.487	0.503	0.514	0.520	0.527
USNX-PTBX	293	0.412	0.556	0.479	0.421	0.367	0.353	0.369	0.390	0.402	0.404	0.410
NIST-PTB	370	0.294	0.584	0.479	0.406	0.349	0.322	0.300	0.289	0.289	0.286	0.291
NPL-PTB	354	0.414	0.608	0.500	0.433	0.385	0.363	0.348	0.348	0.356	0.377	0.405

In the standard UTC computation, the default smoothing power Vdk4 is used for GPS MC. Table 9 lists the σ of the d_L (GPS MC-GPS PPP) by using different powers of Vondrak smoothing from Vdk0 to Vdk7. They are all HM links. The smallest σ is 0.462 ns for KRIS-PTB with Vdk2. The σ is 0.405 ns for ROA-PTB Vdk1. However for this baseline, the σ values are not significantly different fromVdk0, i.e. 0.405 ns against 0.410 ns. For all the others, the smallest σ is an outlier in the smoothing Vdk0, e.g. the σ of GPS MC-GPS PPP for NICT-PTB is 0.29 ns, noting that the conventional u_A of GPSPPP is 0.3 ns! The ratios of the smallest and largest σ of the ratio 1:3. Significant gains can be obtained by varying the smoothing powers.

Table 9 Comparison of σ between the GPSPPP and GPS MC C/A links with different Vondrak smoothing powers (using the 1101 data, Vdk$x$ stands for the Vondrak smoothing with the smoothing power x, the number of the compared points and the σ are listed)

Smooth	IT-PTB		SG-PTB		TL-PTB		KRIS-PTB		NICT-PTB		ROA-PTB		USNO-PTB	
		/ns		/ns		/ns		/ns		/ns		/ns		/ns
Vdk7	2912	0.780	2510	1.737	1017	1.428	1519	1.113	2931	1.160	2783	0.841	2109	1.135
Vdk6	2912	0.703	2510	1.573	1017	1.326	1519	1.035	2931	1.079	2783	0.757	2109	1.073
Vdk5	2912	0.610	2510	1.216	1017	1.196	1519	0.875	2931	0.828	2783	0.659	2109	0.912
Vdk4	*2912*	*0.462*	*2510*	*0.759*	*1017*	*0.995*	*1519*	*0.618*	*2931*	*0.519*	*2783*	*0.517*	*2109*	*0.670*
Vdk3	2912	0.363	2510	0.569	1017	0.873	1519	0.481	2931	0.388	2783	0.434	2109	0.521
Vdk2	2912	0.340	2510	0.517	1017	0.786	1519	0.462	2931	0.336	2783	0.411	2109	0.458
Vdk1	2912	0.329	2510	0.492	1017	0.695	1519	0.521	2931	0.313	2783	0.405	2109	0.413
Vdk0	2912	0.317	2510	0.486	1017	0.573	1519	0.589	2931	0.290	2783	0.410	2109	0.367

For the MC links equipped with HM clocks, the optimal smoothing is likely to be Vdk0. The σ varies between 0.290 ns (NICT-PTB, about 10,000 km in distance and the longest baseline in the UTC network) to 0.573 ns (TL-PTB, also a very long Asia-Europe baseline). The average is 0.433 ns. This is much lower than the conventional u_A (MC) 1.5 ns. If the Vondrak smoothing power is optimal, the potential u_A of GPS MC would be 0.5 ns to 0.8 ns for the stable clock transfers. For the clocks with background noise, the power of the smoothing provides no obvious influence statistically. Generally speaking, a lower smoothing, e.g. Vdk0 or Vdk1, is more suitable for the MC C/A link and this greatly increases the quality of UTC links of which nearly half are of the C/A code. The Vdk4 power used seems too high.

Similar to the above, we studied GPS P3. Table 10 lists the results. As for those results provided in Table 9, for the stable maser baselines, the lower power smoothing suggests significant gains, e.g. for the baseline ROA-PTB, the σ of the standard smoothing Vdk5 is 0.659 ns while that of Vdk1 is only 0.208 ns, three times smaller, noting again that the conventional u_A of GPSPPP is 0.3 ns!

Table 10 Comparison of σ between the GPSPPP and GPS P3 links with different Vondrak smoothing powers (using the 1101 data, Vdk*x* stands for the Vondrak smoothing with the smoothing power *x*, the number of the compared points and the σ are listed)

Smooth	IT-PTB		OP-PTB		SG-PTB		TL-PTB		KRIS-PTB		NICT-PTB		ROA-PTB		USNO-PTB		SP-PTB		ORB-PTB.	
		/ns		/ns		/ns		/ns		/ns		/ns		/ns		/ns		/ns		/ns
Vdk9	2869	0.249	2526	0.470	3003	0.438	2919	0.333	3017	0.419	3006	0.579	2895	0.938	2927	0.484	3002	0.372	2965	0.699
Vdk8	2869	0.214	2523	0.439	3003	0.410	2918	0.291	3017	0.371	3007	0.522	2881	0.890	2925	0.440	3001	0.339	2959	0.670
Vdk7	2868	0.184	2518	0.424	3003	0.368	2918	0.269	3016	0.311	3006	0.391	2859	0.797	2921	0.400	3001	0.297	2939	0.694
Vdk6	2868	0.160	2510	0.438	3003	0.337	2918	0.247	3015	0.237	2996	0.263	2830	0.726	2918	0.357	3001	0.261	2905	0.775
Vdk5	*2868*	*0.143*	*2506*	*0.467*	*3001*	*0.328*	*2918*	*0.226*	*3016*	*0.176*	*2989*	*0.234*	*2805*	*0.659*	*2919*	*0.328*	*3001*	*0.238*	*2834*	*0.899*
Vdk4	2868	0.127	2504	0.513	3001	0.302	2918	0.208	3015	0.159	2985	0.203	2780	0.443	2920	0.309	3000	0.184	2703	1.002
Vdk3	2868	0.124	2485	0.607	2999	0.289	2918	0.198	3014	0.151	2977	0.181	2694	0.251	2918	0.290	2997	0.137	2861	1.242
Vdk2	2868	0.125	2429	0.747	2998	0.300	2918	0.195	3015	0.179	2973	0.177	2659	0.220	2917	0.278	2997	0.129	2759	1.357
Vdk1	2868	0.130	2318	0.855	2998	0.334	2918	0.194	3009	0.273	2972	0.175	2646	0.208	2917	0.270	2998	0.127	2843	1.629
Vdk0	2868	0.149	2482	1.053	2994	0.370	2918	0.197	3000	0.391	2969	0.180	2646	0.219	2917	0.269	2999	0.153	2736	1.883

We conclude that a stronger smoothing for the baselines with stable clocks (clock noise less than link noise) allows the measurement uncertainty reduced for GPS MC C/A within 0.5-0.8 ns and for GPS P3 within 0.2-0.5 ns. The TW links may also be improved with a 10% gain.

4. Re-evaluation of the u_A' for all the present UTC links

Multi indicators are used to estimate the u_A' as discussed in sections 2 and 3.3: $\underline{\sigma}$, σ and TDev/$\underline{\tau}$, cf. the notation for the meaning. We also investigated the relationship between these indicators. This is particularly useful for the baselines where the high category link is not available. The 'old' evaluation of u_A is considered as the *a priori* estimation and the experience accumulated from observations over the last decade of the UTC links are considered.

Numerical analysis and statistics are based on long-term data at least nine months from 1101 to 1109. A poor historical record in a link during this period may degrade the u_A estimation.

The difficulty in separating the instabilities of the clock in Lab(*k*) from those of the link measurements between Lab(*k*) and the pivotal laboratory PTB remain. The instability of the HM at the PTB, for example, can be considered negligible, at least for the less stable categories. The u_A' values given in Table 11 partially mask clock instability. If the TDev contains some clock instability, it is not critical, since we prefer to give a u_A' value that is rather conservative.

Table 11 lists the 'old' u_A values of the UTC time links as given in the Section 6 of BIPM *Circular T* [1] and the 'new' u_A' values obtained from this reevaluation. Here: TDev/$\underline{\tau}$ = the conventional value of time deviation in nanoseconds for averaging time $\underline{\tau}$ in a hour. The minimum value is 0.1 ns even if the true value is less than that. In the TDev/$\underline{\tau}$ column, * stands a TDev value dominated by clock noise and not applicable for u_A'. These new evaluations have been applied in *Circular T* 287 published since in December 2011 [20].

Table 11 Uncertainty in the UTC time links in Section 6 of 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	Link	Type	u_A /ns	TDev/τ /ns	τ /h	u_A' /ns
AOS-PTB	TWPPP	0.4	0.1	4	0.3	NIMT-PTB	GPS P3	1.0	0.7	8	1.0
APL-PTB	GPS MC	1.5	0.7	24	1.0	NIS-PTB	GPS P3	0.8	0.6	8	0.8
AUS-PTB	GPSPPP	0.3	0.5*	4	0.3	NIST-PTB	TWPPP	0.3	0.1	2	0.3
BEV-PTB	GPS MC	1.5	1.0	24	1.5	NMIJ-PTB	GPSPPP	0.3	0.1	2	0.3
BIM-PTB	GPS MC	2.0	1.1	4	1.5	NMLS-PTB	GPS MC	2.0	1.2	24	1.5
BIRM-PTB	GPS MC	2.0	1.0	7	1.5	NPL-PTB	TWPPP	0.3	0.1	2	0.3
BY-PTB	GPS MC	2.0	0.8	24	1.5	NPLI-PTB	GPS MC	2.5	1.7	24	2.0
CAO-PTB	GPS MC	1.5	1.2	6	1.5	NRC-PTB	GPSPPP	0.3	1.2*	2	0.3
CH-PTB	TWPPP	0.3	0.1	2	0.3	NRL-PTB	GPSPPP	0.3	0.1	2	0.3
CNM-PTB	GPS MC	2.5	2.0	24	2.5	NTSC-PTB	GPS MC	1.5	0.8	24	1.5
CNMP-PTB	GPS MC	3.0	1.0	24	2.0	ONBA-PTB	GPS MC	7.0	4.0	3	6.0
DLR-PTB	GPSPPP	0.4	0.5*	3	0.4	ONRJ-PTB	GPS MC	4.0	1.3	24	2.0
DMDM-PTB	GPS MC	2.0	1.6	24	2.0	OP-PTB	TWPPP	0.3	0.3*	2	0.3
DTAG-PTB	GPSPPP	0.3	0.3*	2	0.3	ORB-PTB	GPSPPP	0.3	0.9*	2	0.3
EIM-PTB	GPS MC	5.0	4.0	24	5.0	PL-PTB	GPS MC	1.5	1.1	8	1.5
HKO-PTB	GPS MC	2.5	1.5	24	2.5	ROA-PTB	TWPPP	0.4	0.3	2	0.3
IFAG-PTB	GPSPPP	0.3	0.4*	24	0.3	SCL-PTB	GPS MC	3.0	2.2	24	2.5
IGNA-PTB	GPS MC	2.5	1.1	24	1.5	SG-PTB	GPSPPP	0.3	0.2	2	0.3
INPL-PTB	GPS MC	1.5	0.8	24	1.5	SIQ-PTB	GPS SC	5.0	2.4	12	4.0
INTI-PTB	GPS MC	4.0	2.0	24	3.0	SMD-PTB	GPS MC	1.5	0.9	24	1.5
IPQ-PTB	GPSPPP	0.4	0.3*	2	0.4	SMU-PTB	GPS MC	1.5	0.9	8	1.5
IT-PTB	TWPPP	0.3	0.1	2	0.3	SP-PTB	TWPPP	0.3	0.1	2	0.3
JATC/NTSC	INT LK	0.2	-		0.2	SU-PTB	GPSGLN	1.2	0.5	48	1.0
JV-PTB	GPS GT	5.0	-		5.0	TCC-PTB	GPSPPP	0.3	0.1	2	0.3
KIM-PTB	GPS MC	3.0	1.7	3	2.0	TL-PTB	GPSPPP	0.3	0.1	2	0.3
KRIS-PTB	GPSPPP	0.3	0.1	2	0.3	TP-PTB	GPSPPP	0.3	0.3*	2	0.3
KZ-PTB	GPS MC	2.0	1.0	8	1.5	UA-PTB	GPS MC	1.5	1.1	48	1.5
LT-PTB	GPS MC	2.0	1.5	6	2.0	UME-PTB	GPSGLN	1.3	0.8	8	1.0
MIKE-PTB	GPSPPP	0.3	0.1	2	0.3	USNO-PTB	GPSPPP	0.3	0.1	2	0.3
MKEH-PTB	GPS MC	2.0	2.3	24	2.5	VMI-PTB	GPSPPP	0.3	0.6*	6	0.3
MSL-PTB	GPS P3	1.5	1.2	6	1.5	VSL-PTB	TWPPP	0.3	0.2	2	0.3
NAO-PTB	GPS MC	3.0	1.6	24	2.0	ZA-PTB	GPS P3	1.5	1.0	8	1.5
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						

5. Conclusion

The standard uncertainty in [$UTC - UTC(k)$] as reported in BIPM *Circular T* is dominated by standard uncertainty in the time transfer. Therefore the evaluation and the evolution of the uncertainty in [$UTC - UTC(k)$] is almost the same as that in the UTC time transfer. The focus this and our previous study is measurement uncertainty in time links. Our main interest is Type A standard uncertainty based on ISO 1993 and the JCGM 100:2008 [2,3].

The first global evaluation of u_A in the UTC time links was made in 2002 [11] based on types of UTC time links. From the results in that study the uncertainty values of u_A were published in Section 6 of *Circular T* in 2004 for the first time.. A year laterin 2005, the uncertainty in [UTC-$UTC(k)$] was evaluated and published in Section 1 of *Circular T*.

During 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 improvement of techniques and methods in clock comparison., As a result of our calculations we propose new u_A' values for all current 67 UTC links. One of the advantages presented in this work compared to the investigations of u_A values carried out in 2002 is that the new precise methods studied, e.g. TWPPP supply a reliable indicator of the estimated u_A through inter-technique comparisons.

In addition to the improved techniques available, mathematical methods may also be used to improve measurement uncertainty in the time links. In this paper, we investigated the optimal smoothing parameters using Vondrak. For a Lab(k) operating a stable clock, the time link measurement noise can be significantly reduced especially for the code links, such as P3 or C/A codes.

We suggest a complete revision of the u_A' values every 4 years to take into account the progress in time transfer techniques and methods.

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Annex. Configurations of the UTC worldwide time transfer networks in 2004 and at present

In 2004, there were 53 time links in total: 44 GPS CV links and 9 TW links. The UTC time-transfer network was structured around four pivot laboratories: USNO, NIST, CRL (now NICT) and PTB, as illustrated in Figure A-1. The links were classed into four categories according to the type of link: 1) TW, 2) GPS CV MC operated under normal conditions, 3) GPS CV SC operated under normal conditions and 4) GPS links in poor conditions, see Table A-1.

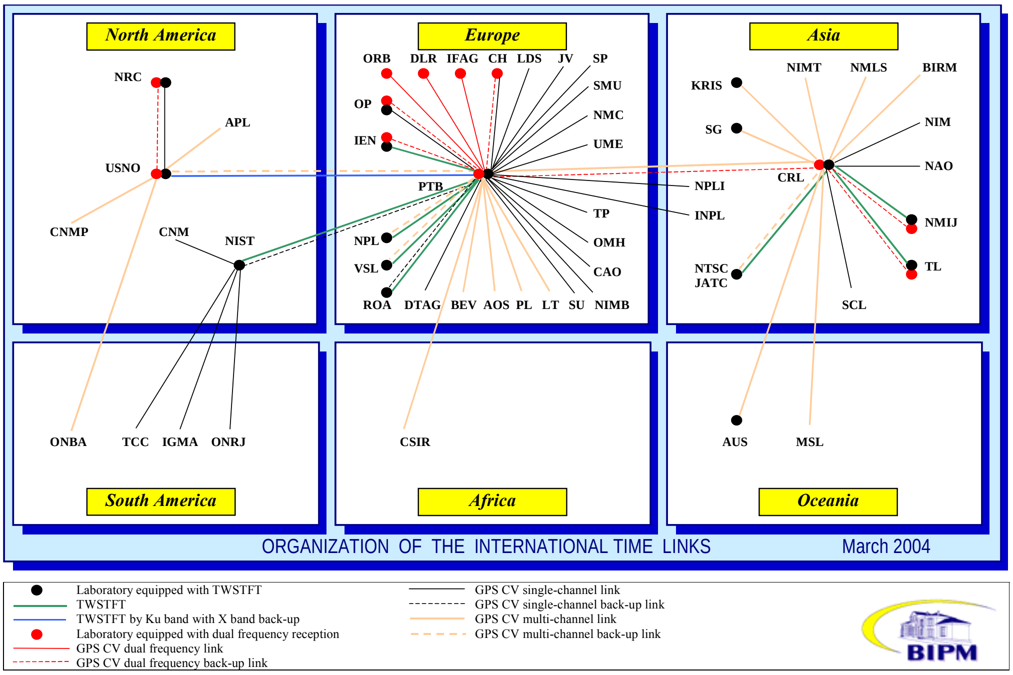

Figure A-1 Status in March 2004 of the UTC time transfer network and the techniques used. There were 4 pivots: PTB, USNO, NIST and CRL (now NICT)

Table A-1 The 2002 evaluation of the u_A of the four categories of the UTC time links

Category	Type of link	u_A / ns	Number	%
I	TW	0.3	11	21
IIa	GPS MC	1.5	6	11
IIb	GPS MC	2.5 to 4.0	6	11
IIIa	GPS SC	2.0 to 2.5	21	40
IIIb	GPS SC	3.5 to 4.0	5	9
IV	Others	5 to 10	4	8

Table A-1 gives a summary of the 2002 evaluation. The officially adopted conventional value of u_A for TW links was 0.5 ns instead of 0.3 ns.

Since the 2002 evaluation, time-transfer techniques in the generation of UTC have evolved significantly (see Figure 2) with the introduction of P3 CV, AV, PPP, TWPPP as well as GLN and GPSGLN. The conventional Type A uncertainties of these new techniques are listed in Table A-2..

Table A-2 The Type A standard uncertainties of the time-transfer techniques introduced since 2005 in UTC time links

Type of link	u_A / ns	Introduced in
P3 CV/AV	0.7	2004/2006
GPSPPP	0.3	2008
TWPPP	0.3	2011
GLN	1.5	2009
GPSGLN	1.2	2011

At present, there are a total of 68 laboratories contributing to UTC (67 operational links). Figure A-2 illustrates the status of the UTC time link network as of September 2011, showing the time-transfer techniques employed and indicating their u_A uncertainties.

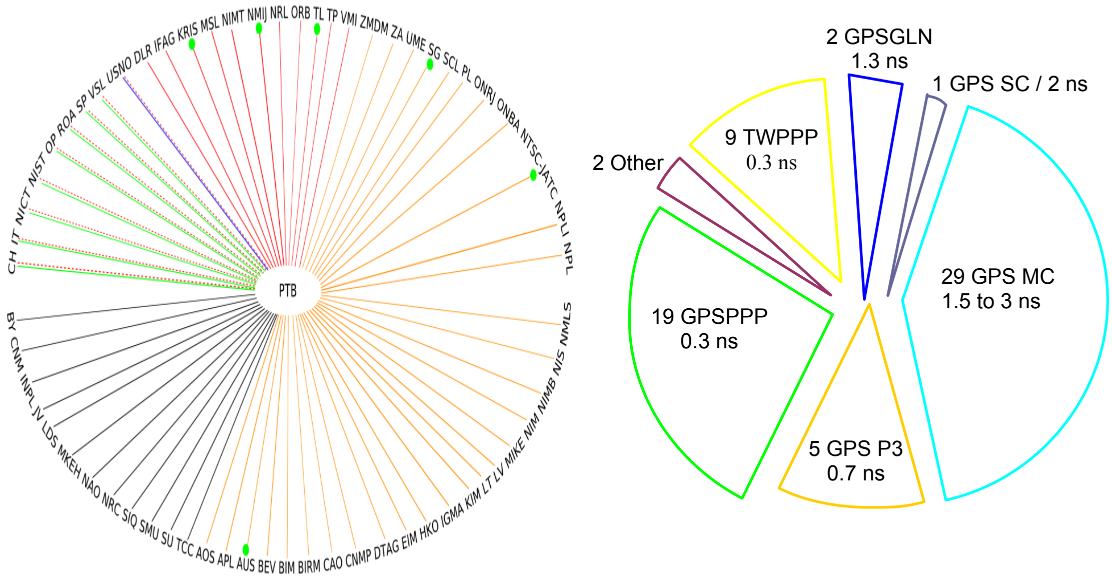

Figure A-2 The one-pivot UTC time link network, present status , and the time transfer techniques with an indication of their uncertainty u_A. There are in total 68 national UTC contributing laboratories with 67 links