Fully Use the Redundancy in TWSTFT and GNSS Time and Frequency Transfer

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Abstract **The major techniques used for the international UTC/TAI time and frequency transfers are the two independent space techniques: TWSTFT (Two-Way Satellite Time and Frequency Transfer) and GNSS (Global Navigation Satellite System: GPS, GALILEO, GLONASS etc.). Comprised of multi-techniques, this system is highly redundant, of which not a single technique has dominant advantage with respect to the others.**

There are three kinds of redundancy: 1) TWSTFT and GNSS are redundant each other; 2) in GNSS, only GPS is used at present; 3) TWSTFT is measured as a network but used as single links. However the present strategy for UTC/TAI time and frequency transfer is *single-technique-single-link*. The rich redundancy is not used. How to process these redundancies is a challenge to accurate time and frequency transfer.

About a third of the UTC time laboratories operate two or more techniques and they contribute four fifth of the total atomic clocks and all the primary frequency standards. It is easy to understand that if all the redundancy would be fully used for the UTC/TAI generation, significant gain will be achieved in the viewpoints of accuracy, precision and robustness.

Earlier studies have proposed the TWSTFT *network transfer* and the *combined TWSTFT and GNSS transfer*. This paper discusses the theoretical and numerical problems of how fully use the whole redundancy, by gathering together the above two methods and this leads to a multi-techniques-network time and frequency transfer.

I. INTRODUCTION

The quality of time and frequency transfer (T/F for short) can be described by three characters: accuracy, precision and robustness. They represent respectively the uncertainty type B (calibration and reproducibility), measurement errors (uncertainty type A) and reliability. They are therefore the criteria when comparing different T/F transfer solutions.

The present UTC/TAI T/F transfer strategy is *single-technique-single-link*. However the T/F network is highly redundant. First there are available TWSTFT and GNSS. Then each is itself rich of redundancy. A typical example is TW: TW is measured as a network but used as single links (cf. Figure 1 and section III). Finally, 15 UTC laboratories operate GPS and GLN (GLONASS), 19 operate GPS and TW; 8 operate the three (GPS, GLN and TW). Many laboratories operate two sets of TW equipments.

Combination of the redundant data of different techniques is not new. Methods have been proposed [1,2,3,4,5]. They are either TW-only network or single-link combination of TW and GPS. This paper discusses a general strategy: *multi-technique-network* T/F transfer that allows fully using the potential of all the measurement data produced by different techniques. The principal idea is to perform a global least square network adjustment with all the measurements as observations. Without giving all the details, related mathematical and numerical points are investigated: Section II analyses the potential contribution of the total redundancy in the UTC/TAI system; Section III discusses the *TW-only network* transfer [5], presenting its major advantages and short points; Section IV presents the *single-link* combination of TW and GNSS [1,3,4]; and finally Section V outlines the full use of the total redundancy to improve the quality of UTC/TAI.

To be simple, we concentrate the discussion on the redundancy of TW and GPS PPP (T/F transfer using Precise Point Positioning techniques). In fact, following the recommendation of the CCTF in 2006, PPP solutions are monthly produced at BIPM [6,7]. The conclusion draw from the analysis of GPS PPP is suitable for other GNSS techniques.

Specially designed numerical tests proved the theoretical predictions. Significant gains are obtained. Limited by pages, the results will be presented in a separated paper.

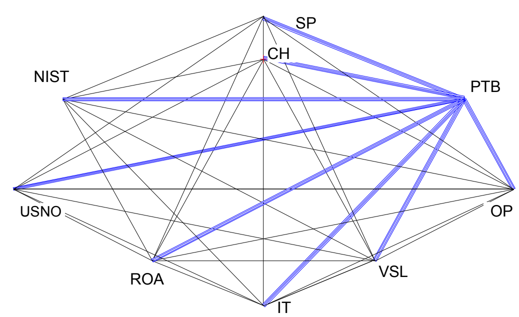

Figure 1. The Europe-America TW network with 9 TW labs. The 8 blue bold lines are the UTC/TAI links and the black lines are the redundant links

II. AN EFFECTIVE WAY TO IMPROVES UTC/TAI

There are 66 UTC/TAI contributing laboratories [8]. 26 laboratories (40% of the total, Table I) operate more than two types of T/F facilities, of which 19 or 28% operate TW and PPP, which (cf. Table II) contribute 88% of the total atomic clock weight and all the primary frequency standards (PFS) to

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UTC/TAI. Combining the redundancy supplied in TW as a network (Figure 1) and in PPP as a precise independent technique, implies an effective strategy to improve the quality of UTC/TAI.

TABLE I. UTC LABORATORIES OPERATE TWO OR THREE TIME AND FREQUENCY TRANSFER FACILITIES

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

TABLE II. LABORATORIES OPERATE TW & PPP WITH THEIR CONTRIBUTION IN PERCENTAGETO UTC/TAI

No.	Lab. TW+PPP	Nomb. Clock	Clock %	Weight %	PFS
1	AOS	13	3.7	4.0	
2	AUS	5	1.4	0.9	
3	CH	4	1.1	1.0	
4	OP	29	8.1	7.5	yes
5	IT	6	1.7	2.6	yes
6	KRIS	6	1.7	1.2	
7	NICT	27	7.6	10.9	yes
8	NIM	4	1.1	0.1	
9	NIST	12	3.4	5.7	yes
10	NMIJ	3	0.8	1.4	yes
11	NPL	4	1.1	1.7	yes
12	NTSC	22	6.2	8.0	
13	PTB	6	1.7	2.6	yes
14	ROA	6	1.7	1.8	
15	SG	3	0.8	0.4	
16	SP	14	3.9	3.2	
17	TL	15	4.2	5.8	
18	USNO	70	19.7	27.6	
19	VSL	4	1.1	1.4	
	Total	253	71%	88%	.

III. TW-ONLY NETWORK TIME AND FREQEUNCY TRANSFER

The redundancy in TW can be described that *TW is measured as a network but used as single-links* (Figure 1). For a N-point network, there are N(N-1)/2 independently measured links. Among them, only N-1 will be used for UTC/TAI. There are then $(N^2\text{-}3N+2)/2$ redundant links. As a function of N, the redundancy increases quickly. The ratio of the redundant links over the UTC/TAI links is 0.5 for N=2; 2.5 for N=7; 5 for N=15 and 9 for N=19. The later means that for N=19, for every ten measured links, only one is used for UTC/TAI. In the present European-American network N=13. For Asia-Pacific region, N=8. If the whole Europe-America-Asia TW network becomes fully operational, the waste redundancy will increase to 90%,

In view of network, the redundant links make their contribution through the triangle constraint. The sum of three TW links that comprise a triangle is a triangle closure. In ideal case, without measurement errors, it equals zero, namely *the triangle closure condition*. A redundant link sets an extra triangle and hence sets one more geometric constraint. For a complete N-point network, the $(N^2\text{-}3N+2)/2$ redundant links compose the same number of independent triangle conditions. The mathematical model proposed by [5] adjusts the closures to zero by a global network processing. Because any n-side polygon can be decomposed into individual triangles, the independent triangles are the basic elements of the study. In fact, if the independent triangle conditions are satisfied, any n-side (n≤N) closures must be zero. This implies that in a network, a time transfer between any two points, through any link(s) gives exactly the same result with the same uncertainty. This is the TW *network transfer*, which implies that the result of a T/F transfer and its uncertainty between any points does not depend on the trajectories going through. Obviously, compared to a single-link, T/F transfer through a network will greatly increase the robustness of the whole system and reduce the measurement uncertainty. The gain in short term stability is bigger that 30% [5]. This network adjustment gives also the uncertainty estimation for each raw TW measurement.

Hereafter some figures of the TW network T/F transfer:

Repair the faults in TW measurements. The redundant data and such formed geometric constraints allow us to repair the faults in the raw data, for example, to fill up the missing data. In Figure 2, the single-link USNO-ROA is affected by 4 big gaps in the raw measurements. By single-link T/F, only interpolation using the nearest points can be used to fill up the missing data (black crosses in the up-plot). However by the network, they can be filled up using the 7 redundant (indirect) links which were complete (low-plot). To verify the two results, we use the simultaneously measured PPP (blue points) as the reference: the σ (standard deviations of the differences) of PPP against TW single-link and network transfer results are reduced from 2.412 to 1.046 ns. The gain is 57%.

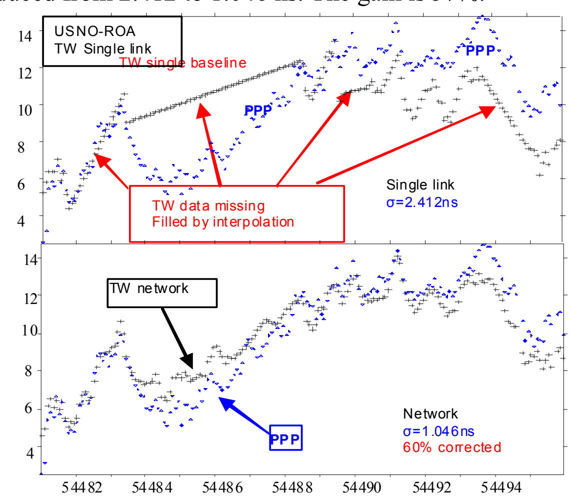

Figure 2. Comparison of PPP to TW single-link and network transfers. Black crosses are TW and blue points PPP. Up-plot: 4 gaps in raw TW and the interpolation results; Low-plot: the gaps are filled in network solution

Comparison of the single-link and network transfers to PPP. The precise PPP is a good reference. Single-link and network solutions, the one that is closer to PPP is considered the better. According to [5], a gain of 33% is expected.

Improving the short term stability. Figure 3 illustrates the TDev comparisons between single-links (red) and network solutions (blue). The left plot is the trans-Atlantic long baseline USNO-PTB. Time stability of the Ku-band single-link is considerably improved over all the terms of averaging time. As a reference, the left plot presents also the TDev of the X band which is usually the most stable [9].

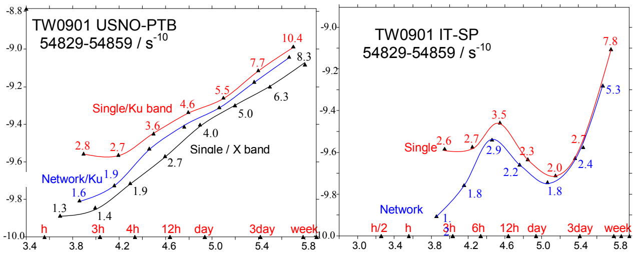

Figure 3. TDev comparisons between TW Ku band single-link (red), Ku network-link (blue) and X band (black) results

Limits of the TW-only network transfer. The TW network adjustment is carried out in a way that every measurement epoch is independent to the others. Biases in the time series are not the adjusted unknowns. The dominant bias in TW is the diurnals [1,3,10,11] that may be up to 1-3 ns peak to peak. The actual knowledge can not fully explain the cause(s) of the diurnals. However, one point is clear that the diurnals can not be averaged out by increasing the quantity of the measurements nor the redundancy. The right plot in Figure 3 is a comparison of the Tdev between the single-link and network transfers of the inner-European link IT-SP. Clearly, the diurnal single keeps the same in the both the single-link and the network solutions. TW-only measurable cannot eliminate the diurnal disturbances. Other independent and diurnal free observables are necessary.

IV. Single-link Time and Frequency Transfer by Combination of TW and PPP (TW+PPP)

All GNSS techniques take advantage of the high precision of the carrier phase (CP) measurements [1,3,4,7,12,13]. We focus on the combination of TW and GPS PPP, namely TW+PPP [1,3] .

Figure 4 illustrates the Tdev of PPP link for the same baselines and the same period as shown in the Figure 3. Comparing the Tdev curves in Figure 3 and Figure 4 proves that the short term stability of PPP is superiors than that of TW of single or network links. Obviously the visible diurnals appear in the TW-sonly solutions do not exist in PPP solutions. Figure 5 displays the triangle-closures of the raw TW-single-links and that of the single-link TW+PPP combination. The TW triangle-closures represent mainly the measurement white noises which have been greatly reduced by the combination. In the up-plot of the triangle Δ KRIS-TL-NICT, the σ of the TW+PPP closers is reduced 6 times from 0.13 to 0.02 ns approaching the limit of the PPP stability. However, the closures are not zero and sometimes are much bigger than the normal PPP precision as shown in the low-plot in Figure 5 for the transatlantic triangle Δ IT-PTB-USNO. Also globally the σ is considerably reduced.

TW and GPS each have advantages and disadvantages. Advantages of GPS PPP are its short term stability assigned by CP and the quasi-independence of the precision to the time transfer distance. But its accuracy is subject to possible biases, discontinuities and long term disturbances which are reflected in its relatively lower calibration uncertainty u_B≈5ns [8]; TW is characterized by its absolute calibration uncertainty u_B≈1ns and its long-term stability is better than GPS [8,14]. However, TW is disturbed by diurnal variations [1,3,10,11], especially for very long distances when two transponders on the telecommunication satellite are used.

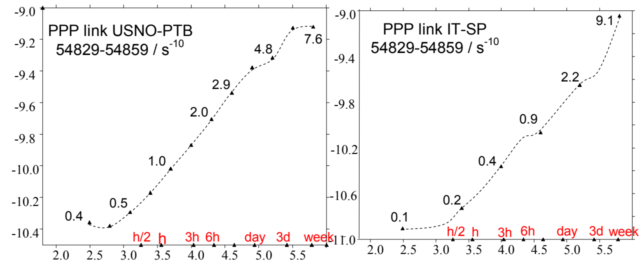

Figure 4. TDev of PPP links (over same baselines and period of Figure 3)

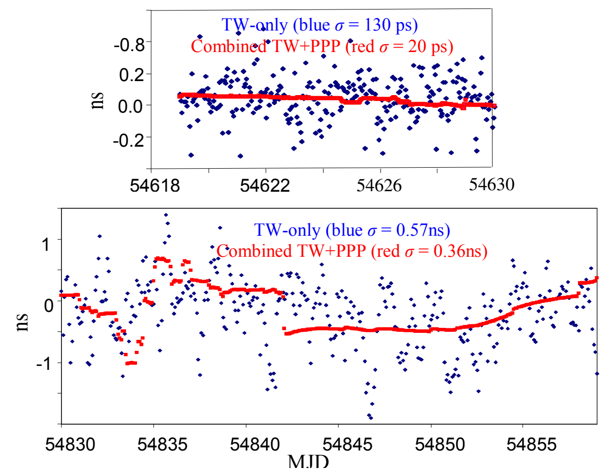

Figure 5. Triangle closures: Up-plot for Δ KRIS-TL-NICT and Low-plot for Δ IT-PTB-USNO. Blue points: closures of TW-only link; red points: closures of TW+PPP combined link (vertically shift)

Earlier studies [1,3] concluded that combining TW and GPS allows keeping advantages of both techniques and considerably improving the time transfer quality in the sense of: 1) Short term stability; 2) Keeping the calibration and long term stability of TW; 3) Reducing the diurnal disturbances in TW; 4) Repairing gaps, jumps, discontinuities and drift in both TW and PPP; 5) Detecting coarse errors in both TW and PPP; 6) Providing a better robustness; 7) Full usage of the rich redundancy in UTC/TAI network. Finally, these conclusions are suitable also for other GNSS carrier phase solutions.

However from MJD 54831 to 54842, the TW+PPP are disturbed. This implies the shortage of the single-link TW+PPP combination. It might be disturbed by unexpected faults in one of the links. Here the geometry constraint is helpful; that is, the combined solution can be further improved by *the triangle closure condition* supplied by the TW network.

The idea is as simple as to gather the two methods discussed in section III and IV.

V. TOWARDS THE MULTI-TECHNIQUE-NETWORK TIME AND FREQUENCY TRANSFER

'*Multi-technique*' here means TW, GNSS and all types of T/F transfer techniques. In sections III and IV, we discussed separately the time transfer with *TW-only-network* and the *single-link-TW+GPS-combination*. Therefore, the first step towards the *multi-technique-network time and frequency transfer* is to realize a *TW+PPP-network-transfer*. There are two methods in principle:

A. Method (1)

In the network (Figure 1), we first fulfill one by one the single-link TW+PPP combination as discussed in section IV and then perform the network adjustment as discussed in section III. So exactly, the same mathematical models and data processing procedures are applied. The non-zero triangle closures in Figure 5 imply that the T/F transfer results and related uncertainties through a direct link (i.g. IT-PTB) and the indirect link (i.g. IT-PTB via USNO) are not identical. There are other inconveniences. A global network adjustment will definitively solve all the geometric closing discrepancies. The method is quite similar than that of section III, only that, the adjusted observations are the TW+PPP combined single-links.

B. Method (2)

In the TW-only network transfer, the observation equation given by [5] is:

$$V_{ij} = (X_i - X_j) - \mathbf{L_{ij}} \qquad (1)$$

here i and j are two labs; X_i and X_j are the estimations of the true clock readings at i and j with X_i-X_j the adjusted time link; V_{ij} on the left is the adjustment residual and $\mathbf{L_{ij}}$ is the link observation. When $\mathbf{L_{ij}}$ is TW observation, it is a TW-only network transfer. We can of cause use here other observations, for example the GPS PPP or the GPS carrier phase only data or the data of other navigation systems GLN or Galileo, i.e. all types of observables. $\mathbf{L_{ij}}$ can be also the combined observations, such as TW+PPP. These observables can be introduced in equation (1) separately or all together then weighted. Numerically, they can be solved in the same way as the TW-only network. The solution is optimal and unique in the sense of least square condition. Equation (1) is held only when all the observables are calibrated. We gather all the observables in a unique linear equation system and solve it integrally. This approach takes into account the calibrations according to the weights assigned to. Numerical tests turned out encouraging results. Further studies are undertaking.

VI. SUMMARY

The progressively increased redundancy created by the TW and GNSS measurements in the UTC/TAI network is a challenge for the worldwide accurate T/F comparisons. The author proposes the concept of the *multi-technique-network time-frequency transfer* to fully use the redundancy. Two methods are outlined and in principle the two methods can be merged together. For the first step, TW+PPP network transfer is tested.

The laboratories operating multi-techniques make a major contribution for the UTC/TAI generation. The T/F transfer strategy suggested in this paper is an effective way to improve the quality of UTC/TAI. This study is only a first step towards the operational TW+GNSS T/F transfers. Deeper theoretical study and numerical estimations are undertaking.

A data processing procedure for TW+PPP network T/F transfers has been developed at BIPM and installed in the UTC/TAI computation software package Tsoft.

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