

HOW TO HANDLE A SATELLITE CHANGE IN AN OPERATIONAL TWSTFT NETWORK?

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Abstract

Two-way satellite time and frequency transfer (TWSTFT) is a powerful technique because of its real-time capabilities. In principle, the time difference between remote clocks is almost instantaneously known after a measurement session. Long-term TWSTFT operations have required changes between satellites, but also of ground hardware. We analyzed how well and how fast an accompanying step in the time series following a gap in the data can be determined. We used data collected during about 3 months during 2009 in links of the USA-Europe TWSTFT network connecting to PTB. The results are applicable under the current constraints of operations, i.e. nominally 12 measurements per day with typical performance. We found that a time step can be determined with sufficient accuracy by extrapolating the time scale differences involved over the data gap and comparing to one or two data points immediately after the gap. The maximum deviation and the standard deviation between prediction and measurement result increase with the gap width and increase with the instability of the time scale. The largest deviations after a 1-day gap were found below 6 ns, the standard deviation between 1.5 ns and 2.5 ns. The best results were obtained when comparing time scales generated from frequency steered hydrogen masers or from direct comparison of masers. Our findings confirm that the use of TWSTFT in operational systems, such as the ground segment of a GNSS, remains a valuable option despite of the occasional interruption of operations.

MOTIVATION FOR THE STUDY

Two-way satellite time and frequency transfer (TWSTFT) is a powerful technique because of its real-time capabilities. In principle, the time difference between remote clocks is almost instantaneously accessible after about 2 minutes of a standard TWSTFT measurement session, provided that the signal delays of the connections to the clocks of the involved ground stations are also available in real time. If this is not the case, one can at least study the link stability from session to session based on raw data. In this paper, we omit a detailed description of TWSTFT operations and nomenclature and refer to [1] and [2]. Long-term TWSTFT operations have required changes between satellites and changes of ground station hardware. The last example of a satellite switch in the USA-Europe TWSTFT network was the one from Intelsat IS-3R to Telesat T-11N at the end of July 2009. A satellite change is inevitably accompanied by hardware

configuration changes on many sites and a transponder delay change. Usually, the operating station is shut down for a while, directed to the new satellite, and operations can begin with a line-up test. In consequence, there will be an interruption of data taking and possibly a step in the time scale comparison data which is not related to the properties of the time scales. Most of the TWSTFT links had gotten some kind of calibration before [3], either in a campaign of a visiting TWSTFT station, by a dedicated GPS link calibration, or by a more common calibration through the Circular T values (usually relying on GPS calibrations as well). This calibration should be carried forward despite of the interruption of regular operations. A step in the time scale comparison data can be quantified by making in parallel time comparisons through other means, such as GPS P3 or GPS PPP as it was done in summer 2009 for most of the links [4]. It took, however, roughly a month to determine and apply the new TWSTFT link calibration corrections. For scientific applications this may be acceptable, but for an operational system this is painful. Consider that TWSTFT shall be used to synchronize the two Precise Timing Facilities of the European satellite navigation system Galileo [5]. The aim is to keep the time scales realized at both sites in agreement within 2 ns (2σ). But how can one do this if the change of the delays in the time links is not known for weeks after a satellite change?

OUTLINE OF THE STUDY

What we did may indeed be called a quantitative treatment of a kitchen recipe used many times before. We determined a potential time step based on few data points taken shortly before and immediately after a gap in the data that was artificially introduced in TWSTFT data. We used real link data collected for several months in the links of the US-EU network from stations listed in Table 1. In this network, TWSTFT sessions are performed nominally 12 times per day in a schedule which combines all link comparisons into 1 hour and leaves the following hour free for experimentation. The TWSTFT data used are depicted in Figure 1, and their statistics are given in Table 2. The time instability derived from these data calculated for the respective sampling period is also shown in Figure 1. We notice that during the period under study data from two links show significant diurnal variations, whereas this is not visible in the other two. In general, it has been observed that this phenomenon is not stationary and despite some efforts it remains not understood [6].

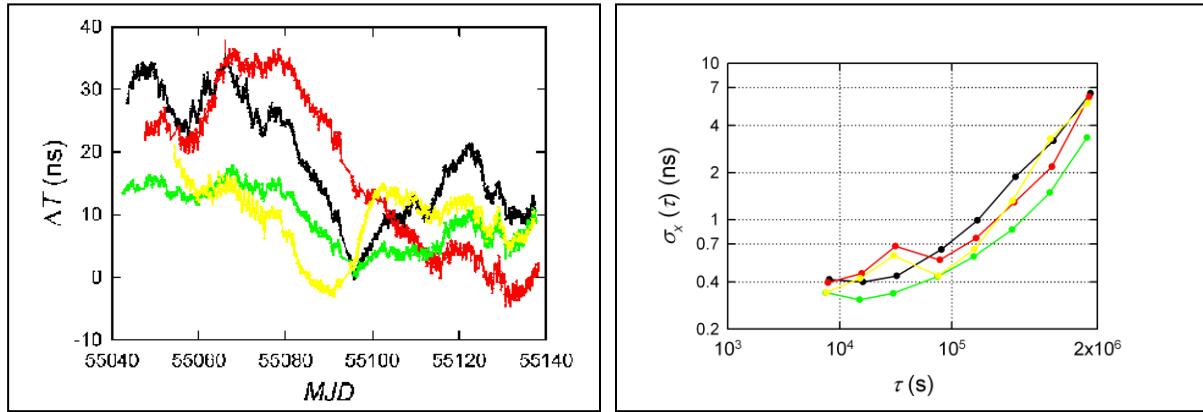


Figure 1. Left: Time scale differences $UTC(PTB) - UTC(k)$ measured by TWSTFT and used in this study; the colors indicate: black = METAS, CH; red = INRIM, IT; yellow = SP, Sweden; green = NIST, USA; right: Time deviation (TDEV in ns) of TWSTFT data $UTC(PTB) - UTC(k)$ shown at left.

We simulated those data not available for a certain time interval, the “gap” of duration t_g , which is assumed to last for four, three, four, or twelve data points, corresponding to about 5, 7, 9 hours, or a full day. In Figure 2, the gap is comprised of twelve points (nominal, in gray). We used data taken during m days before the gap to predict the first data point – or the first n data points – after the gap being taken according to the schedule, and compared the prediction to the data actually obtained at these epochs. The general configuration is called (m, t_g, n) . In Figure 2, $m = 5$ was chosen. We determined the difference between predicted – via a linear or a quadratic function – and measured data which is the prediction error, designated as δt_{PE} in Figure 2.

Table 1. Participating institutes and parameters relevant for the study; HM stands for hydrogen maser and CS2 is PTB’s primary cesium clock.

Institute (k)	Station Designation	Source of the Time Scale UTC (k)
NIST	NIST01	active HM
SP	SP01	active HM
INRIM	IT02	active HM
METAS	CH01	active HM
PTB	PTB01	CS2

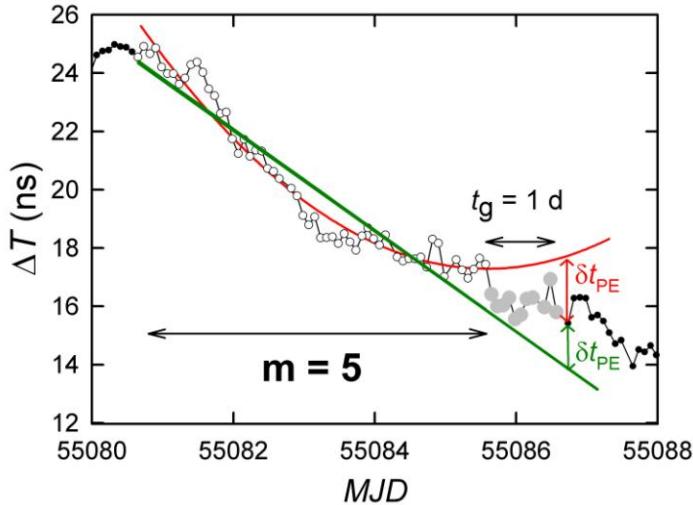


Figure 2. Example for a linear (green) and quadratic (red) fit prediction of a TWSTFT data point after a “simulated” gap (gray points); see further details in the text.

Table 2. Explanation of the data used in the study

Remote Station	Time Scale Difference	Number of Points	Number of Days	Average Number of Points per Day	Time Span (MJD of Start and End Day)
NIST01	UTC (PTB)-UTC (NIST)	1096	96	11.4	55042-55137
SP01	UTC (PTB)-UTC (SP)	947	84	11.3	55054-55137
IT02	UTC (PTB)-UTC (IT)	1002	92	10.9	55047-55138
CH01	UTC (PTB)-UTC (CH)	1007	95	10.6	55043-55137

We obtain series of δt_{PE} data by shifting the fictive gap along the available sets of data (Figure 1). From these series, we determined the maximum absolute error, called $ME(\delta t_{\text{PE}})$, and the standard deviation $\sigma(\delta t_{\text{PE}})$. We shifted the gap by 2 hours each time, but we considered results as valid only if 50% or more of the nominal TWSTFT data points were available during the m days preceding the gap. If this condition was not fulfilled, the calculation was not made for this epoch, and the fictive gap was shifted further in time. Thus, the number of the used data varies from link to link. Both quantities, $ME(\delta t_{\text{PE}})$ and $\sigma(\delta t_{\text{PE}})$, are plotted and tabulated for some realistic scenarios in the following. We will see – not surprisingly – that the results depend on the equipment employed in each laboratory and how the UTC (k) is realized.

RESULTS REGARDING LINKS TO UTC (PTB)

According to Table 1, UTC (PTB) was realized based on the CS2 frequency steered to UTC and was, thus, less stable than all other time scales involved at averaging times below 2 days. On the other hand, we notice from Figure 1 that the observed instability in the link data is not entirely determined by that of UTC (PTB). Otherwise, there would be no differences noticeable.

BRIDGING A SHORT GAP

We considered a gap of two points as the shortest interruption of operations practically achievable if hardware work needs to be done to a station. We distinguish whether the step in the time scale shall be determined based on a single data point or the average of two or three – with the consequence that it would take another 2 or 4 hours before the result was known. Figure 3 shows the results of the analysis of the $(m,2,1)$ and $(m,2,2)$ scenarios. The fit length is the variable on the horizontal axis, given in days; the vertical axes show $\sigma(\delta t_{\text{PE}})$ and $ME(\delta t_{\text{PE}})$, respectively. So it is valid for each figure of this kind throughout the text and is not repeated each time. We also use the same color code throughout all plots for the remote stations: black = CH01, red = IT02, yellow = SP01, green = NIST01.

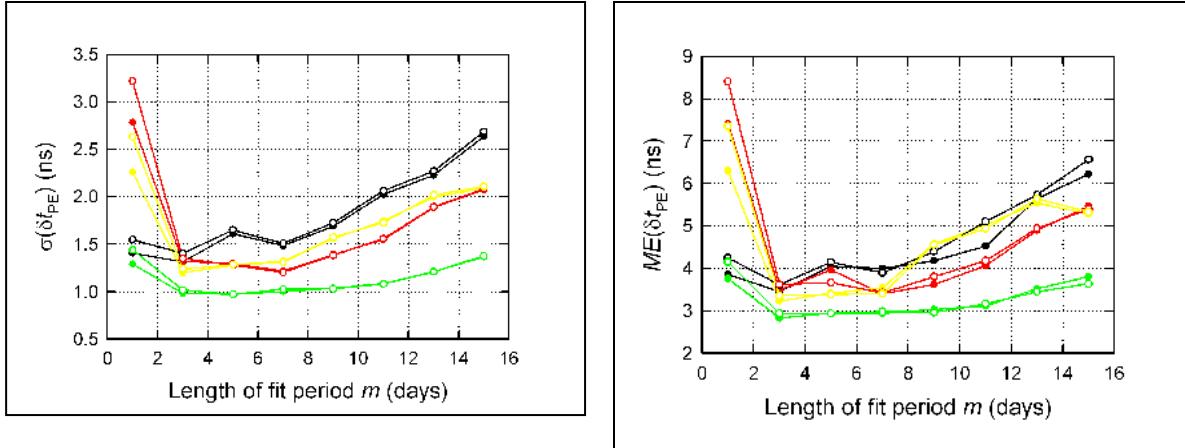


Figure 3. Left: Standard deviation $\sigma(\delta t_{PE})$ as a function of the length m of the data period before the gap (two points) to which a quadratic fit is made to predict the time difference $UTC(PTB) - UTC(k)$ for the first data point immediately after the gap (solid symbols) and the average of the two following data points (open symbols); right: Maximum absolute error $ME(\delta t_{PE})$; color code black = CH01, red = IT02, yellow = SP01, green = NIST01.

We notice that the estimate based on the single first point after the gap is sufficiently accurate. The fact that a fit to just 1 day of data before the gap often gives bad results in case of IT02 and SP01 is caused by the diurnal variations present in the data combined with missing data. It appears here that a fit to about 3 to 7 days would enable a prediction of a time step with an uncertainty of 1 ns to 1.7 ns, depending on the link as well as the time scale stability in general. Next, we considered a one-point gap and compare the results obtained when one, two, or three data points after the gap are used. Results are shown in Figure 4. We show data for CH01 and NIST01 only since they are essentially free of diurnal variations. We notice that there is indeed little to gain when the average is taken over a longer period after the gap. The basic distinction among the results is due to the predictability of the time scales itself. On the other hand, laboratory practice has shown that the first data point after an interruption of operations and hardware changes may be corrupted for various reasons. It may, thus, be prudent to wait whether the second data point is in agreement with the first one. Nevertheless, we consider the case of using just one point after the gap in the remainder of this paper.

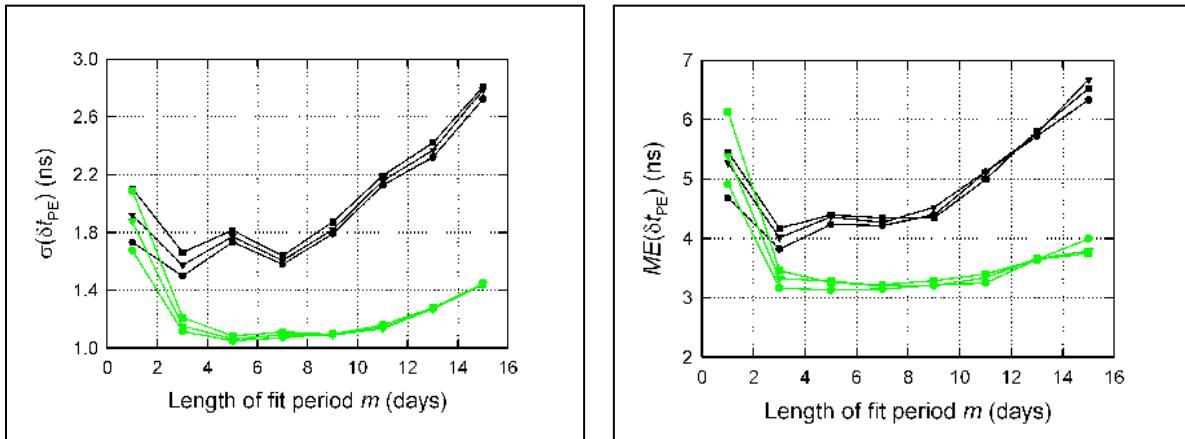


Figure 4. Left: Standard deviation $\sigma(\delta t_{\text{PE}})$ as a function of the length of the data period before the gap (three points) to which a quadratic fit is made to predict the time difference $UTC(\text{PTB}) - UTC(k)$ for the first point (circle), for the mean of two (triangle), and the mean of three (square) points after the gap; right: Maximum absolute error $ME(\delta t_{\text{PE}})$. We show data for CH01 and NIST01 only.

LINEAR OR QUADRATIC FIT?

We studied two models for the prediction of the time scale differences (see Figure 2). If the TWSTFT link connects two UTC (k) time scales, a linear prediction over the gap may seem appropriate. If TWSTFT data linking two free-running hydrogen masers are used, a quadratic prediction seems appropriate because of the likely frequency drift of such masers relative to each other. In Figure 5, we note that a linear fit is favorable when diurnals are present and a short fit interval is chosen. But a quadratic fit gives the better results in general, even here in the cases when UTC (k) time scales are compared.

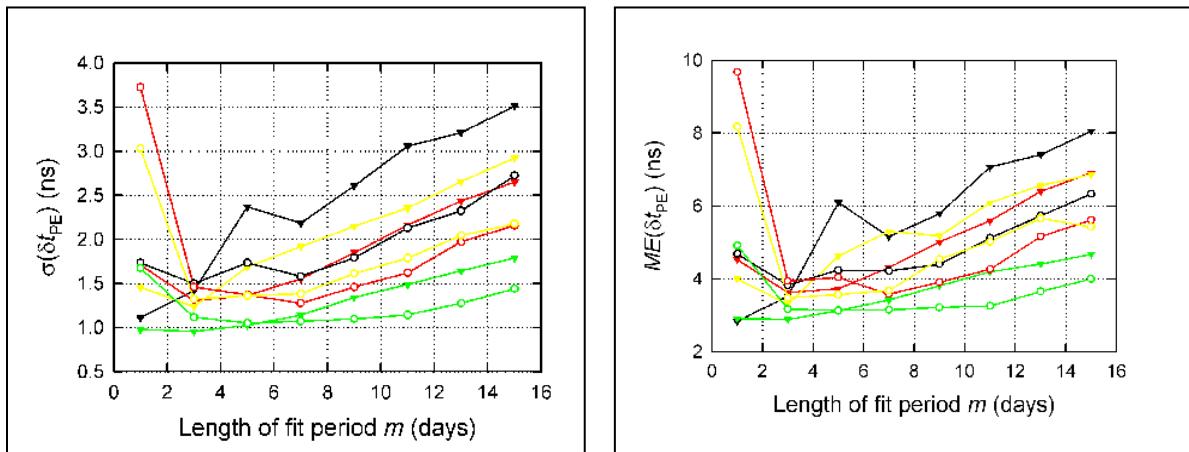


Figure 5. Left: Standard deviation $\sigma(\delta t_{\text{PE}})$ as a function of the length of the data period before the gap (three points) to which a linear fit (full symbols) or a quadratic fit (open symbols) is made to predict the time difference $UTC(\text{PTB}) - UTC(k)$ immediately after the gap; right: Maximum absolute error $ME(\delta t_{\text{PE}})$.

THE EFFECT OF THE LENGTH OF THE DATA GAP

The stability of the time scales involved, shown in Figure 1, should determine the ability to predict the time scale differences after a gap of certain duration. For clarity, we illustrate how the prediction error increases with the length of the gap for individual links separately in Figures 6 and 7. The best achievable results in terms of the minimum value for the quantity $\sigma(\delta t_{\text{PE}})$ from the plots are determined by a quadratic fit to about 7 days of data before the gap.

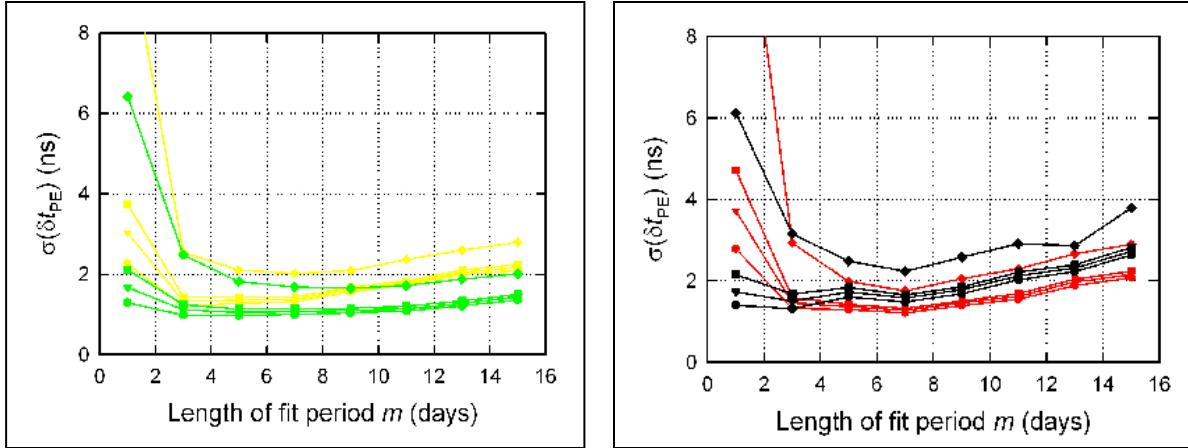


Figure 6. Left: Standard deviation $\sigma(\delta t_{\text{PE}})$ as a function of the length of the data period before the gap to which a quadratic fit is made to predict the time difference $\text{UTC}(\text{PTB}) - \text{UTC}(k)$ ($k = \text{SP01}$ and NIST01 , respectively) for the first point after the gap. The gap length is two (circle), three (triangle), four (square), and twelve (diamond) points. One point clipped lies at 12 ns; right: $k = \text{CH01}$ and IT02 , respectively, one point clipped lies at 14.5 ns.

In Figure 8, this minimum value is plotted as a function of the gap length. We find an (almost) common linear behavior but distinctly different values for the cases of the four time scales compared with UTC (PTB). It seems not straightforward to predict this behavior right away from the properties of the time scales shown in Figure 1.

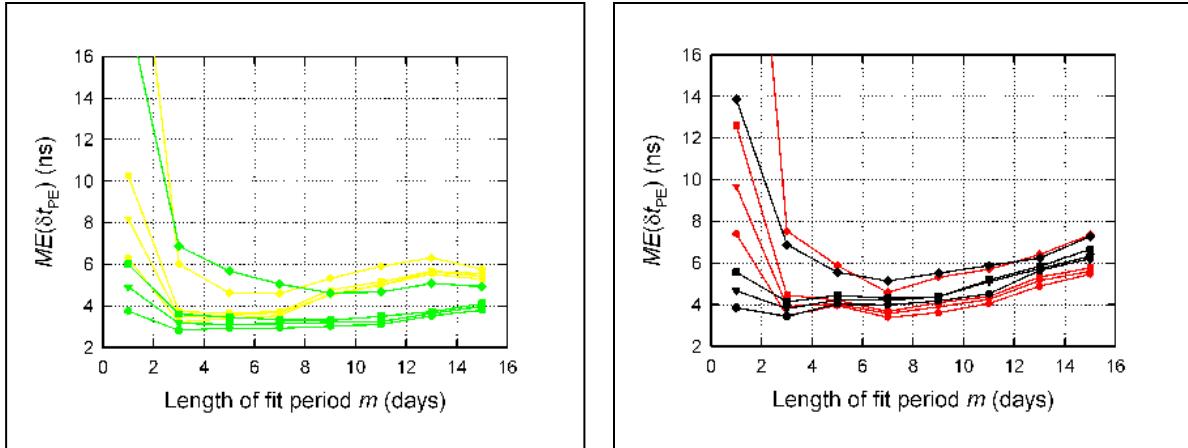


Figure 7. Left: Maximum absolute error $ME(\delta t_{\text{PE}})$ as a function of the length of the data period before the gap to which a quadratic fit is made to predict the time difference $\text{UTC}(\text{PTB}) - \text{UTC}(k)$ ($k = \text{SP01}$ and NIST01 , respectively) for the first point after the gap. The gap length is two (circle), three (triangle), four (square), and twelve (diamond) points. Two points clipped lie at 18 ns and 22 ns, respectively; right: $k = \text{CH01}$ and IT02 , respectively, one point clipped lies at 25 ns.

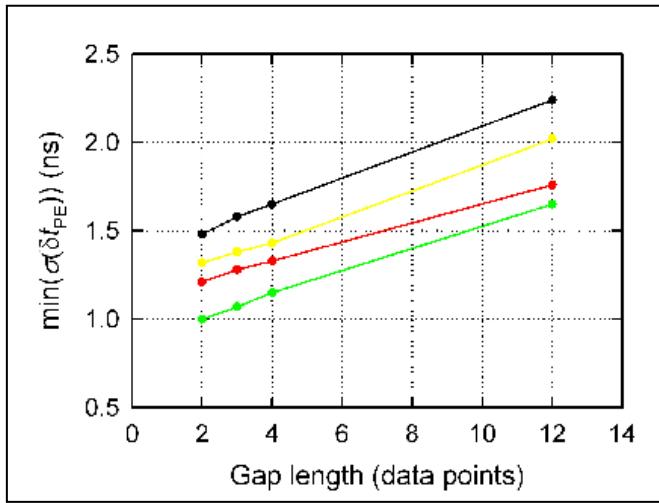


Figure 8. Minimum value found for $\sigma(\delta t_{PE})$ as a function of the length of the gap in the data, taken from Figures 6 and 7.

RESULTS REGARDING LINKS CONNECTING HYDROGEN MASERS

As an example, we studied the link NIST01-IT02 based on data from 108 days (MJD 55047 to 55154), as here the two time scales were physically realized from frequency-steered active hydrogen masers. The standard TWSTFT data in the ITU format [1] primarily provide access to the signal sources connected to the TWSTFT modems, but also to UTC (k) if the so-called REFDELAY parameter is taken into account, which contains the time offset between the on-time reference point of UTC (k) and the 1PPS input to the respective modem. The latter kind of data was used hitherto in this study. The difference between these two types of data in the UTC (k) link may be just a constant as in case of NIST or a variable as in case of INRIM. With the same kind of analysis as used before, we examined the link NIST01 - IT02 for the two types of data, and restrict the presentation of results in Figures 9 to the case of a 12-point gap, quadratic fit, and prediction of the first point after the gap. The maser-linking data are occasionally corrupted with some outliers (TWSTFT modem reset, change of the maser, and unknown causes), so that the number of useful data points may be reduced. In the particular case here, some REFDELAY values were missing, so that actually more data were available for the direct maser link than for the UTC (k) link. We see from the figures that using the masers directly provides better results than shown before.

A similar analysis has been made for the links between PTB and the four stations. Because of problems mostly with the PTB maser connected to the TWSTFT station, the length of continuous useful data is less than when analyzing the link to UTC (PTB). But similar results were obtained as for the NIST01 - IT02 link. In the meantime, the realization of UTC (PTB) has been modified and it is, since February 2010, based on a steered hydrogen maser. As the cesium fountain is providing the steering reference most of the time, UTC (PTB) in the short term (due to the maser) and the long term should be substantially improved.

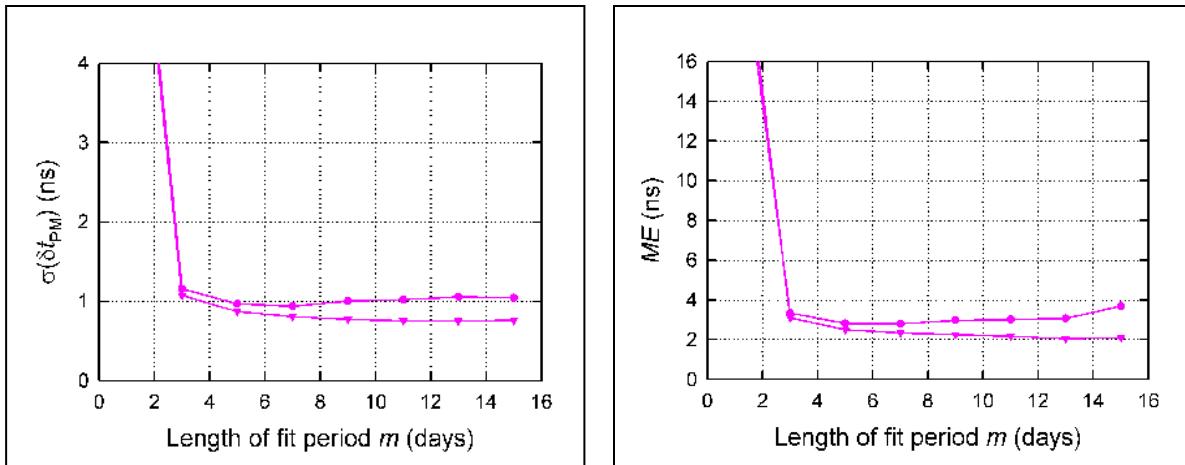


Figure 9. Left: Standard deviation $\sigma(\delta t_{PE})$ as a function of the length of the data period before the gap to which a quadratic fit is made to predict the time difference $UTC (IT) - UTC (NIST)$ (circles) and $HM (IT) - HM (NIST)$ (triangles) for the first point after a gap of twelve points. Two points clipped lie at 8.5 ns and 18 ns, respectively; right: Maximum absolute error $ME(\delta t_{PE})$. Two points clipped lie at about 24 ns.

CONCLUSIONS

We have used data collected for several months in links of the US-EU TWSTFT network to study how well a gap in TWSTFT operations accompanied by hardware changes can be bridged based on TWSTFT data alone, without the need of resources from other time transfer techniques. This question is valid because of occasional unavoidable changes of the geo-stationary satellite used, but also because a piece of hardware in one station may have to be replaced due to a defect or for other reasons. To rely on TWSTFT data alone would support the capability of detecting a time step and, thus, determining the link calibration value shortly after the event. Such a procedure is mandatory if TWSTFT shall be used in an operational system which requires time comparisons between two sites with ultimate accuracy. As TWSTFT link calibrations have repeatedly been performed with about 1 ns (1σ) uncertainty, this is the target which is aimed at.

We have determined the deviation between predicted and measured time difference – standard deviation and maximum observed error – after gaps of different duration, based on a variable number of data points before and after the gap. All the results are applicable under the current constraints of operations, i.e. nominally twelve measurements per day with the typical performance. Practical considerations suggest using just one or two data points after the gap. Indeed, we found that a single valid data point is essentially sufficient to determine the time difference with an uncertainty which is governed by other parameters. It is no surprise that the observed deviation increase with the duration of the gap and with the instability of the time scales involved. The best results have been obtained when comparing time scales generated from frequency steered hydrogen masers or from the comparison of masers themselves. If data over 5 to 10 days before the operations gap are available, even a gap of a full day can be bridged with an uncertainty of 1 ns (1σ) in some cases (see Figure 9), making a quadratic fit to the previous data and extrapolating to the epoch of the first measurement after the gap. This procedure requires that the masers at the two sites are under full control during the about 10 days and do not produce any unexpected time steps.

We are convinced that the use of TWSTFT in operational systems, such as the ground segment of a GNSS, remains a valuable option despite of the occasional interruption of operations.

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