ANALYSIS OF ONE YEAR OF GPS AND TWO-WAY TIME TRANSFER RESULTS BETWEEN PTB, NPL, AND VSL

Gerrit de Jong and Erik Kroon
NMi Van Swinden Laboratorium
P.O. Box 654
2600 AR Delft
The Netherlands

Abstract

As part of the Galileo project of Early Trials on Time Synchronization Techniques and Calibration Issues, the GPS Common-View and Two-Way Satellite Frequency and Time Transfer (TWSTFT) results between the time scales of PTB, NPL, and VSL during 2001 were analyzed. This was done to identify the obtainable uncertainty levels with these techniques. These will be used for the future connection between the Galileo System Time (GST) and TAI and UTC. The results of the analysis are presented. The baseline of the stations is 400 to 900 km. The uncertainties from statistical origin (Type A evaluation) were determined by means of MDEV and TDEV. The uncertainties from other sources (Type B evaluation) were determined from calibration trips. The stabilities of the clocks dominate at averaging times > 5 days; at shorter averaging times TWSTFT shows better TDEV and MDEV. In the combined uncertainty, the contribution of the uncertainty in the calibration results dominates in both the GPS and TWSTFT results.

1 INTRODUCTION

1.1 GENERAL

The work described in this paper was done in the framework of the Galileo project as part of an ESA Early Trials study on Time Synchronization Techniques and Calibration Issues.

Addressed in this paper is the comparison of time synchronization by means of the GPS Common-View (GPS C-V) technique using GPS signals (which are comparable to the Galileo signals) and the Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique using spread-spectrum signals. The first is envisaged for the GSS-network synchronization. The latter technique was treated as option by Galileo industry due to the lack of confidence in this technology, the higher complexity introduced, and the lack of envisaged real improvement of synchronization performance. On the contrary, the representatives of the European Timing Community are very much in favor of the TWSTFT technique and recommend its use in the Galileo system.

In order to clarify and accelerate consolidation, measurements done with both methods have been compared and analyzed in this study. This study activity was also done to verify if the GPS C-V technique is suitable (accurate enough) for the GST-TAI interface.

The performed activities included those during 1 year (2001) in which the time scales of three European national metrology institutes, NPL (UK), PTB (DE), and NMi-VSL (NL), were compared by GPS C-V measurements as well as by TWSTFT measurements. The results of both methods were characterized and the difference in performance analyzed. A conclusion about the obtained accuracies was given.

1.2 ACCURACY AND UNCERTAINTY EXPRESSION

The ISO Guide to the expression of Uncertainty in Measurement (GUM) **[1]** and the EAL document EAL-R2 **[2]** discern two types of uncertainties related to measurements: the uncertainty evaluated from the statistical analysis of the data (denoted Type A) is u_A and the uncertainty evaluated from other causes denoted Type B is u_B. So a Type B evaluation includes estimates of contributions from systematic nature and type A evaluation includes contributions from random nature. Type A in the field of Time and Frequency is mostly expressed as ADEV, MDEV, and TDEV **[3,4].** The total combined uncertainty u_C is calculated as the root of the sum of the quadratics of u_A and u_B. To obtain a confidence level of 95%, a coverage factor k = 2 is generally used. In the form of a formula: $u_C = 2 \cdot \sqrt{(u_A^2 + u_B^2)}$. The term accuracy should be avoided for measurement results.

2 CLOCKS AND TIME SCALES USED

2.1 CLOCKS AND TIME SCALE AT NPL

NPL uses an H-maser steered in long term towards a Cs clock ensemble time for the UTC (NPL) time scale. It acts as a direct reference for both the GPS and the TWSTFT measurements. The TWSTFT station is not co-located with the H-maser, but in a different building and connected with a underground coaxial cable of about 150 m.

2.2 CLOCKS AND TIME SCALE AT PTB

PTB uses a high-performance cesium clock for the UTC (PTB) time scale of which the output is steered based on the Cs2 primary clock. The UTC (PTB) is used as a direct reference for the GPS receiver and as an indirect reference for the TWSTFT. The TWSTFT equipment is directly connected to an active H-maser and in the data the difference with UTC (PTB) is incorporated.

2.3 CLOCKS AND TIME SCALE AT VSL

NMi-VSL uses a high-performance cesium clock followed by a phase microstepper for UTC (VSL), which serves as the direct reference for the GPS receiver and as indirect reference for the TWSTFT. The TWSTFT equipment is directly connected to a second high-performance cesium clock followed by a microstepper (this backup time scale is called UTC (VSB)) and in the data the difference with UTC (VSL) is incorporated.

3 GPS C-V METHOD

3.1 INTRODUCTION

The measurement setup for GPS C-V is shown in Figure 1. The signals from the navigation satellites (C) are received in the receivers and measured against the time scales of clock A and clock B located at A and B. The measured values (A-C) and (B-C) are subtracted and the result is the difference of the time scales (A - B).

The common delays in the satellite and its clock cancel. The differences in excess delay in the ionosphere and in the troposphere still have to be taken into account. The delays in the antenna, antenna cable, clock cable, and receiver at each site should be known (calibrated), so the result can be corrected for delay differences in the equipment at A and B. These delays should be stable with environmental conditions.

At NPL, PTB, and VSL the used GPS receivers are Time Transfer receivers, single-channel C/A code tracking. These NBS-type GPS timing receivers used in the timing labs were designed at the National Bureau of Standards (NBS), which is now the National Institute of Standards and Technology (NIST) in the USA, specially for optimal Time Transfer. The principal difference with Positioning and Navigation GPS receivers is that, in the NBS-type GPS Timing Receiver, the signal delay from antenna to the internal correlator is minimal due to a 10-MHz-wide RF bandwidth; it is fixed and it has low temperature sensitivity. The delay value of the antenna cable is calibrated and inserted in the receiver as CAB DLY; it appears also in the header of the GPS data. The delay internal in the antenna unit and the receiver delay from antenna input connector to the correlator is the internal delay. This, normally given by the manufacturer, is inserted as INT DLY.

For the comparison of the three European National Time Scales, GPS C/A code measurements were used. The results of the relative calibration of the receivers by BIPM **[5]** were used. The used standard format for GPS time data exchange is described in **[6]**.

3.2 INTERPOLATED DIFFERENTIAL GPS C-V DATA RESULTS

Figure 2 shows the calculated UTC time scale differences between NPL, PTB, and NMi-VSL using GPS C-V Time Transfer with interpolation during gaps in the data. The noise in the PTB-VSL data from MJD 51974 to 52023 is rather high; this seems to be due to poor functioning of the receiver 01 at PTB. Between MJD 51946 and 51974, and between MJD 53023 and 52128, PTB02 receiver was used and lower noise was obtained. After MJD 52128, the PTB01 receiver was placed back and functioned well again.

3.3 CHARACTERIZATION AND ANALYSIS

The results of the calculation of the stability performance (MDEV and TDEV) of the GPSCV method for several averaging times tau is shown in Figure 3. It should be noted that Figure 3 includes the properties of the UTC clocks of each station pair. The TDEV is about 2 ns for tau of 3,600 s to $3{\cdot}10^5$ s; the link PTB-VSL is better for tau < $1{\cdot}10^5$ s. NPL-PTB is better between $1{\cdot}10^5$ s and $9{\cdot}10^5$ s; here the influence of the better clocks (H-masers) may become clear. The raw data from NPL show larger daily excursions. This might be due to the NPL receiver coordinates with respect to PTB and VSL.

4 TWSTFT METHOD

4.1 INTRODUCTION

In **[7]** the details of the Two-Way satellite Time and Frequency Transfer (TWSTFT) method have been described, along with the used data format for the data exchange. Ionosphere and troposphere excess delays cancel in first order; Sagnac effect can be calculated accurately and satellite movement also cancels in first order. For the TWSTFT comparison, the same three European National Time Scales (NPL, PTB, and VSL) are used as with GPS C-V.

The key equipment at each TWSTFT site was:

NPL: SATRE modem # 38, fixed 2.4-m-diameter antenna with offset-focus feed;
PTB: SATRE modem # 37, fixed 1.8-m-diameter antenna with Cassegrain feed;
VSL: MITREX 2500 modem #46, steerable 3-m-diameter, prime-focus feed;
At all stations the received C/No was about 56 dB Hz.

The TWSTFT links between NPL, PTB, and VSL have been calibrated using a transportable station for the last time in 1994. Then also a calibration using a SATSIM calibrator was done. The results were shown in **[8]**. In May 2002, a portable clock calibration was performed from PTB and NPL to NMi-VSL.

4.2 INTERPOLATED DIFFERENTIAL UTC DIFFERENCES BY TWSTFT

Figure 4 shows the calculated UTC time scale differences using TWSTFT between NPL, PTB and NMi-VSL with linear interpolation during the data gaps.

4.3 CHARACTERIZATION AND ANALYSIS

The results of the calculation of the stability performance (MDEV and TDEV) of the TWSTFT method for several averaging times tau are shown in Figure 5.

It should be noted that this Figure 5 includes the properties of the clocks of each station pair. The conclusion is that stability TDEV is for tau = 2 days (= 172800 s) is lower than 1 ns for PTB-NPL, which may result from the better UTC clocks (H-maser) at NPL and PTB. The NPL-VSL difference shows a slightly better performance around $5 \cdot 10^6$ s.

5 DIFFERENCE GPS C-V AND TWSTFT

5.1 INTERPOLATED CALCULATED DIFFERENTIAL DATA

Figure 6 shows the calculated differences between the two time transfer methods. On each day, two single GPS C-V data points were taken around the time of the TWSTFT measurements and interpolated to that time. No further averaging was done, so the short-term instability from GPS C-V dominates visually the result.

The average differences between GPS C-V and TWSTFT estimated from the Figure are:

VSL-NPL: –6.6 ns
NPL-PTB: +1.7 ns
PTB-VSL: +4.8 ns.

5.2 CHARACTERIZATION AND ANALYSIS OF THE TWO METHODS PER STATION PAIR

VSL-NPL (see Figure 7a)

TWSTFT is better than GPS C-V for tau < 5 days ($5 \cdot 10^5$ s). TDEV is then < 2 ns. At tau ≥ 5 days, the performance of the clocks (probably the commercial Cs-clock at NMi-VSL) dominates, so with no difference between the methods, no further conclusion can be drawn here.

NPL-PTB (see Figure 7b)

TWSTFT is better than GPS C-V for tau <4 days ($4 \cdot 10^5$ s) TDEV is then < 1.2 ns. At tau ≥ 4 days, the performance of the clocks dominates, but because of good clocks (H-maser), also at higher tau it is shown that TWSTFT is slightly better than GPS C-V.

PTB-VSL (see Figure 7c)

TWSTFT is better than GPS C-V for tau < 4 days ($4 \cdot 10^5$ s). TDEV is then < 2 ns. At tau ≥ 4 days, the performance of the clocks (the commercial Cs-clock at NMi-VSL) dominates. The two methods show no difference, so no further conclusion can be drawn here.

6 CONCLUSIONS

6.1 CONCLUSION UNCERTAINTY TYPE A

The following conclusion has been drawn about the assessed uncertainty Type A (from statistical analysis; see Section 1.2) for GPS C-V and for TWSTFT: the TWSTFT method shows better (a factor 2 or more) results than GPS C-V at short term (4 days or less). Because of the impossibility of separating the properties of the clocks used at the three stations from the data, the characterizations at long term should be interpreted with care. At tau = 1 day, the Type A uncertainty evaluation u_A can be estimated as less than 1.3 ns for GPS and 0.7 ns for TWSTFT (extrapolated).

6.2 CONCLUSION UNCERTAINTY TYPE B

From transportable clock calibrations in May 2002, corrections for GPS C-V and TWSTFT have been determined. These are in nanoseconds as follows:

Station pair	GPS C-V corr.	TWSTFT corr.	GPS-TWSTFT corr.
VSL-NPL	+15.2	+12.6	+2.6
NPL-PTB	–3.8	+2.8	–6.6
PTB-VSL	–10.4	–7.8	–2.6

For the Type B evaluation (see Section 1.2), the following is considered. The average differences between GPS C-V and TWSTFT estimated from Figure 5 after application of the known correction due to the above calibration results become:

VSL-NPL: –6.6 ns; after correction (+2.6 ns): –3.0 ns
NPL-PTB: +1.7 ns; after correction (–6.6 ns): –4.9 ns
PTB-VSL: +4.8 ns; after correction (–2.6 ns): +2.2 ns.

The average rms of these three (GPS CV – TWSTFT) link differences is 3.5 ns. Because the contributions cannot be separated, it is assumed that this value for the rms difference between GPS C-V and TWSTFT is equally contributed to from both methods. So the average Type B uncertainty evaluation u_B for each method is estimated as the square root of 3.5 ns = 1.9 ns.

6.3 Conclusion Combined Uncertainty

The combined uncertainty from these test results, at a 1-day averaging time, can be calculated. For k = 2 and a 95% confidence level, the combined uncertainties u_C become $2 \cdot \sqrt{(u_A^2 + u_B^2)}$: $2 \cdot 2.0 = 4.0$ ns for TWSTFT and $2 \cdot 2.3 = 4.6$ ns for GPS C-V.

A TWSTFT link gives a much better stability performance for precise time transfer than GPS-C-V, but the overall accuracy performance is (for the shown links) only a little bit better for TWSTFT due to the problem of insufficient calibration of the equipment delays at the shown stations.

6.4 Conclusion about Other Aspects

As indicated in Recommendation ITU-R TF.1153 **[7]**, TWSTFT, compared to GPS C-V, is not sensitive to difference in the local troposphere at both locations and its changes in water content and density. This is because of the complete canceling at each location of the TWSTFT uplink delay with the downlink delay for frequencies below 20 GHz.

Also, the ionosphere delays are smaller by about a factor of 50, because of the used frequencies are about 7 times higher; additionally, they cancel in first order due the same reciprocal path for receive and transmit signals and nearly the same frequencies for Tx and Rx.

The influence of satellite movements is also reduced in first order, as long the signals pass the satellite close enough in time (< 100 ms gives < 100 ps for a communication satellite with a 2 m/s change). Any communications satellite can be used.

A GPS C-V method relies on the accurate knowledge of the momentary position of satellite and GPS receive antenna. The time transfer result is dependent on this, while the TWSTFT result is not. Post-processed orbit and Ionosphere corrections may improve GPS C-V, but take some time. Therefore, the use of TWSTFT to measure in real time the monitoring earth station clocks enables Galileo to separate orbital parameter errors from clock errors.

6.5 Summary Conclusion

For the link of Galileo System Time (GST) to TAI (UTC), but also for the link of GST to the monitoring station clocks, application of TWSTFT is the preferred method, due to the much better inherent stability performance and better accuracy as well as its independency, even at the cost of increased complexity of equipment. Future improvements in performance can be realized easier if TWSTFT is already implemented.

7 ACKNOWLEDGMENT

We thank our colleagues from NPL and PTB for making their data available and for the useful comments on the results. This work was done as part of a European Space Agency Study Contract (ESTEC no. 15551/01/NL/DS) and the authors want to acknowledge also the support of Dr. J. Hahn of ESTEC to this study.

8 REFERENCES

[1] Guide to the Expression of Uncertainty in Measurement, 1995, International Organization for Standardization (Geneva, Switzerland), ISBN 92-67-10188-9, first edition 1993, corrected and reprinted 1995.

[2] Expression of the Uncertainty of Measurement in Calibration, European cooperation for Accreditation of Laboratories, publication reference: EAL-R2, Edition 1, April 1997.

[3] Rec. ITU-R TF.538-3, "*Measures for random instabilities in frequency and time (phase),*" ITU-R Recommendations, **Time Signals And Frequency Standards Emissions**, Volume **2000**, TF Series, ISBN 92-61-08851-1, 2 001 (ITU Radio Communication Bureau, Geneva), pp. 111-119.

[4] Handbook Selection and Use of Precise Frequency and Time Systems, 1997, ISBN 92-61-06511-2, ITU Radio Communication Bureau, Geneva.

[5] W. Lewandowski and P. Moussay, 1998, "*Differential Time Corrections For GPS Time Equipment Located at The OP, VSL, NPL, DTAG, PTB, TUG, IEN, ROA, IPQ and OCA: 3rd Evaluation,*" BIPM, Pavillon de Breteuil, F-92312 Sèvres Cedex, France.

[6] CGGTTS GPS and Glonass Data Format: for a detailed description, see the BIPM FTP site: *ftp2.bipm.org/pub/tai/data*, files: *cggtts_format_v1.pdf, cggtts_format_v2.pdf*

[7] Rec. ITU-R TF.1153-1, 2001, "*The Operational Use Of Two-Way Satellite Time And Frequency Transfer Employing Pn Codes,*" ITU-R Recommendations, **Time Signals And Frequency Standards Emissions**, Volume **2000**, TF Series, ISBN 92-61-08851-1 (ITU Radio Communication Bureau, Geneva), pp. 93-108.

[8] G. de Jong *et al.,* 1995, *"Results Of The Calibration Of The Delays Of Earth Stations For TWSTFT Using The VSL Satellite Simulator Method,"* in Proceedings of the 27th Annual Precise Time And Time Interval (PTTI) Applications And Planning Meeting, 29 November-1 December 1995, San Diego, California, USA (NASA CP-3334), pp. 359-372.

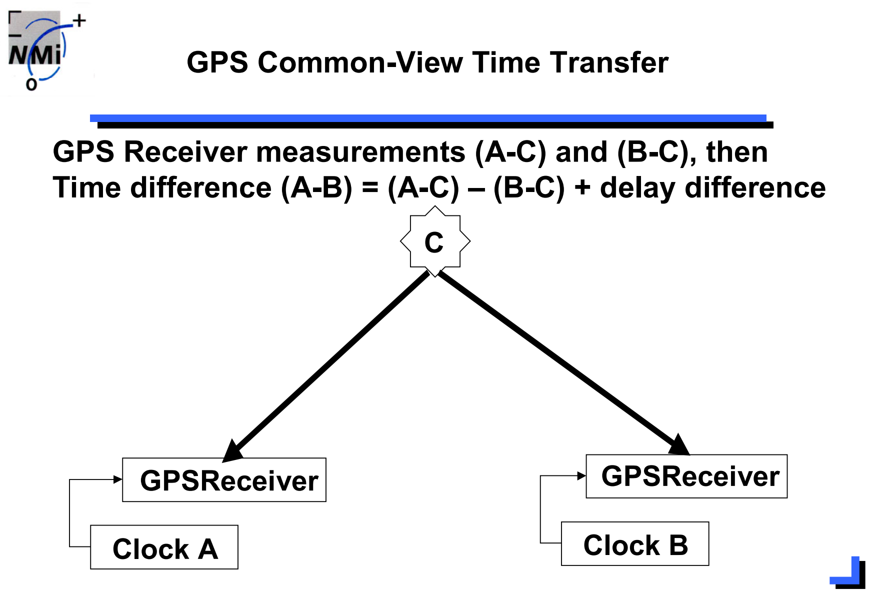

Figure 1. GPS Common View.

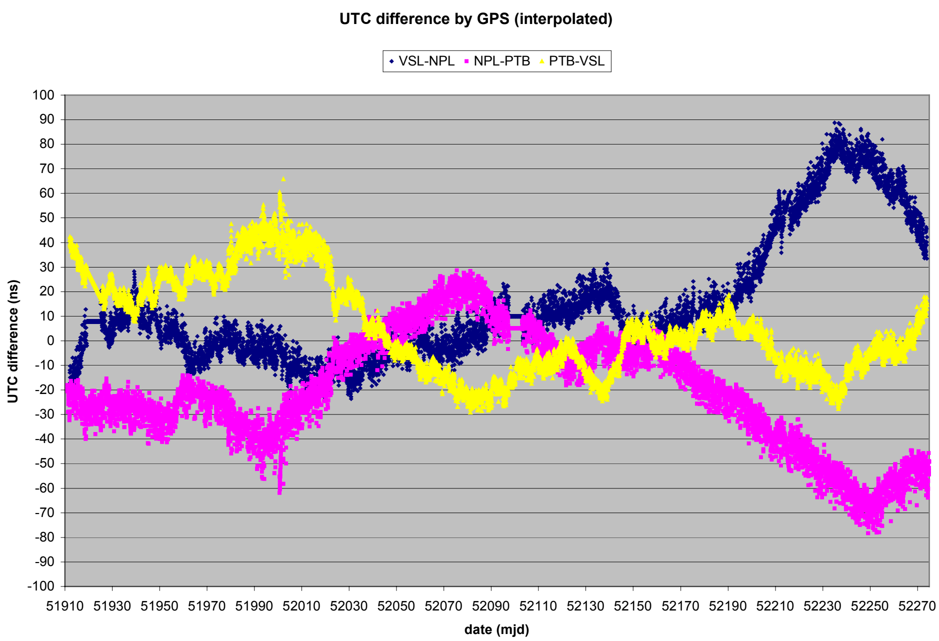

Figure 2. Interpolated UTC differences by GPS C-V.

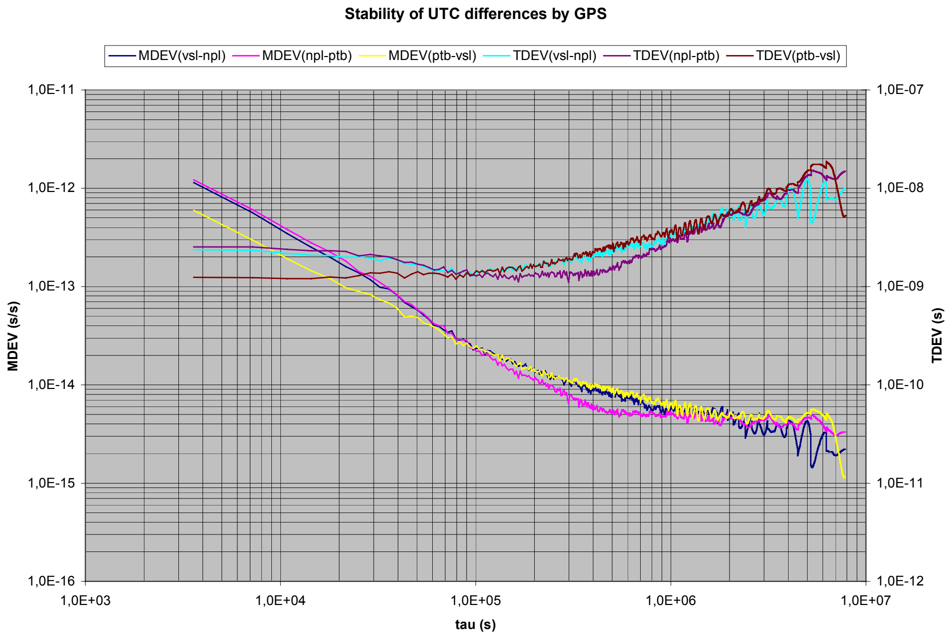

Figure 3. Characterization of UTC differences by GPS C-V.

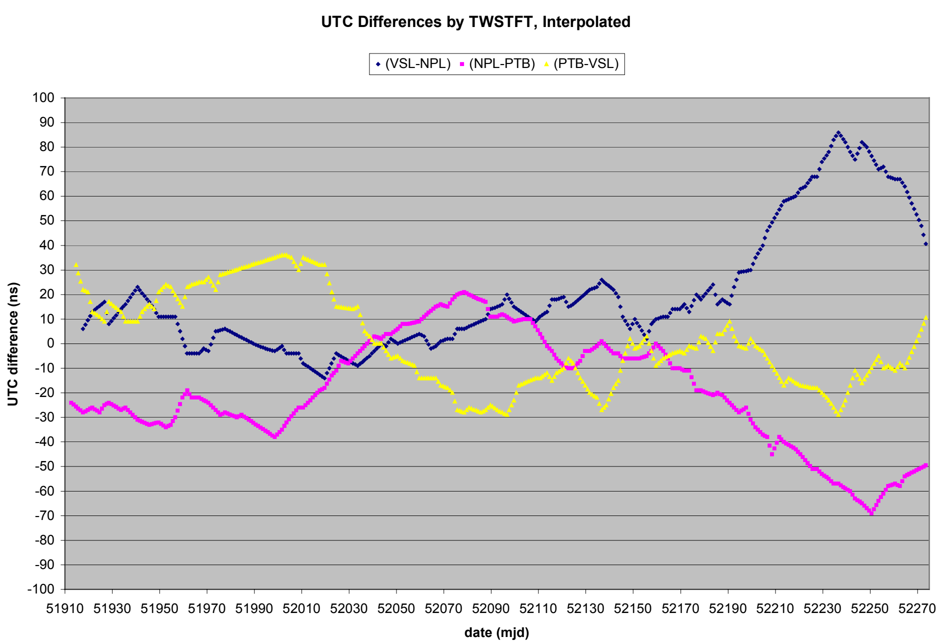

Figure 4. Interpolated TWSTFT difference data.

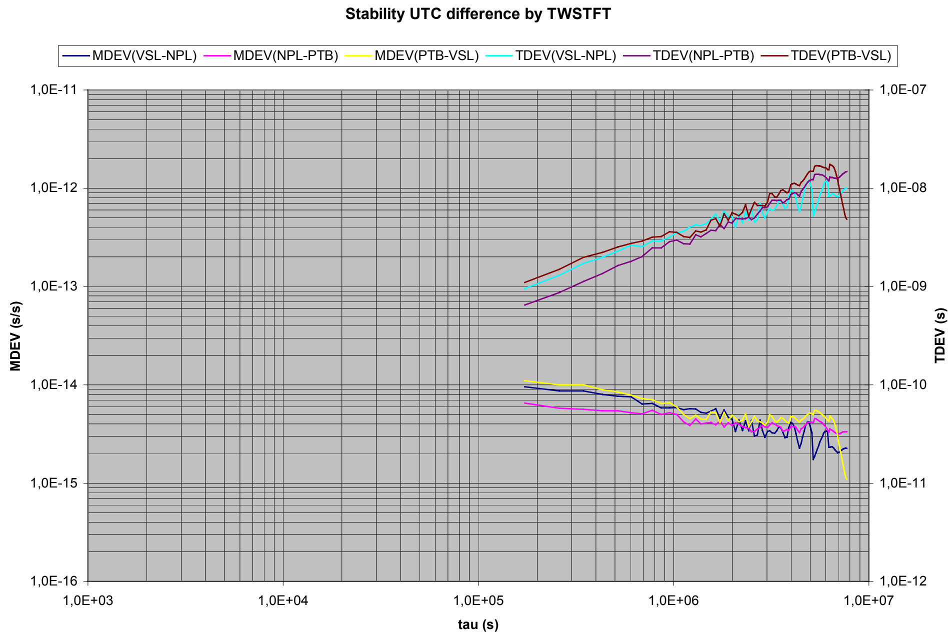

Figure 5. Characterization of the TWSTFT data.

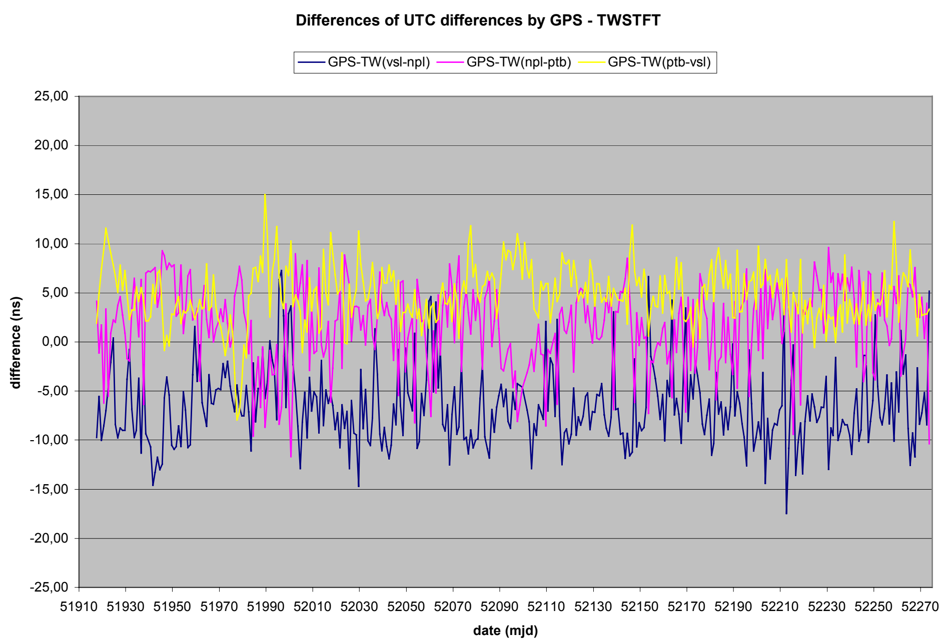

Figure 6. Overview GPS C-V – TWSTFT differences for the three station pairs.

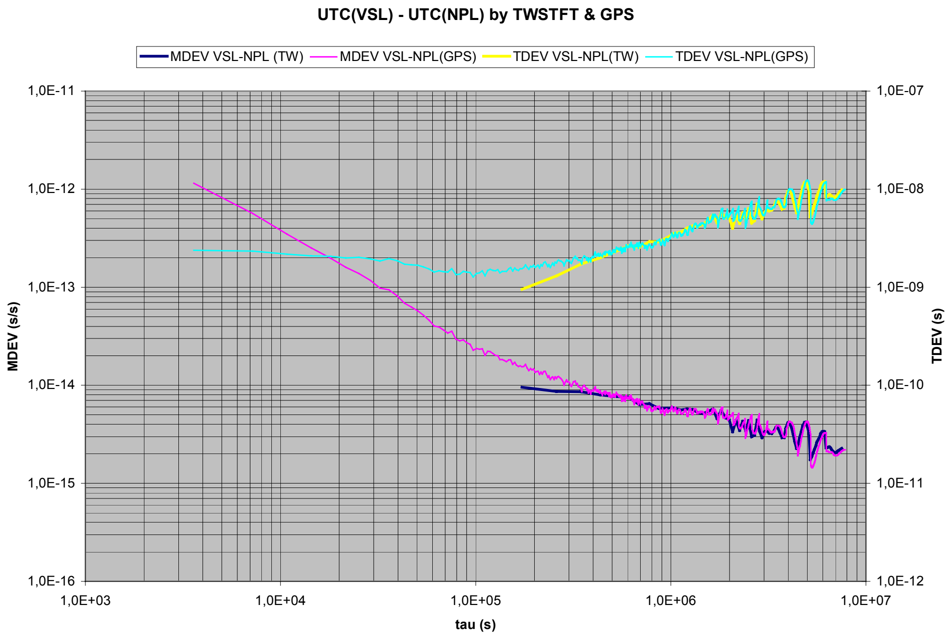

Figure 7a. Characterization differences for VSL-NPL.

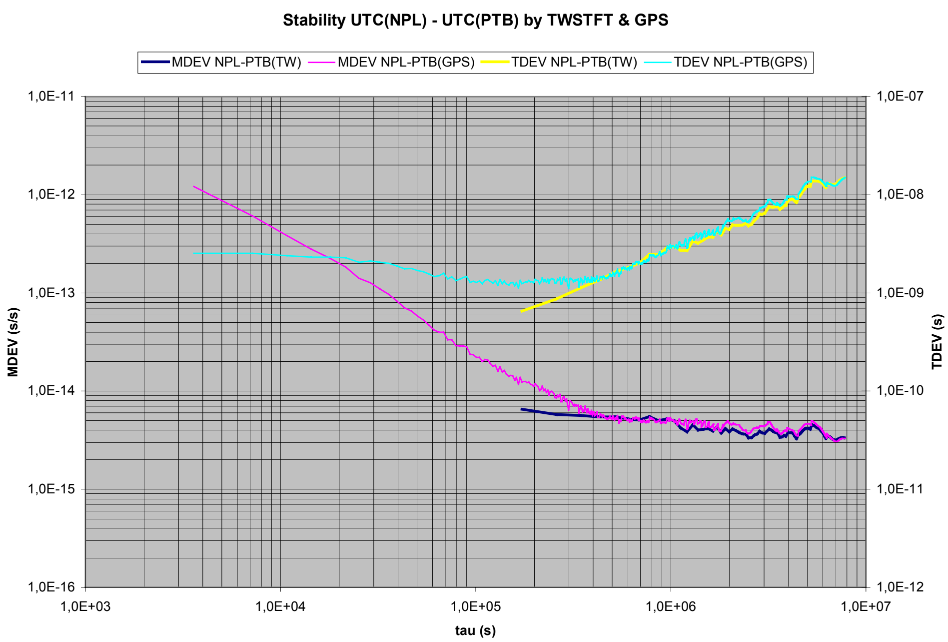

Figure 7b. Characterization differences for NPL-PTB.

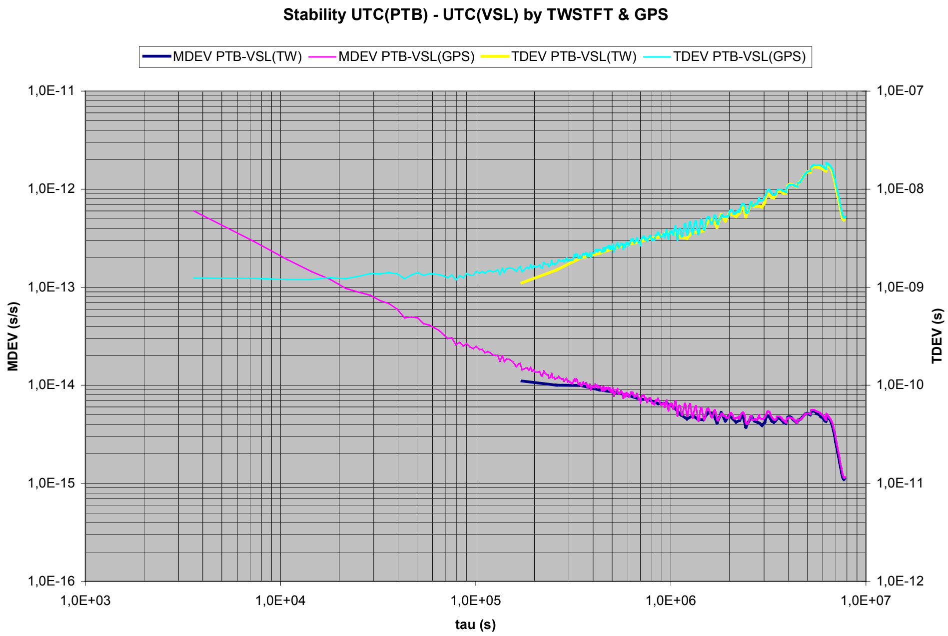

Figure 7c. Characterization differences for PTB-VSL.

QUESTIONS AND ANSWERS

WLODZIMIERZ LEWANDOWSKI (Bureau International des Poids et Mesures): What I would like to stress is that Type B uncertainty is for two-way; you are showing they were from GPS calibrations. So this 4 nanoseconds is not an uncertainty of two-way's; it's an uncertainty of GPS in fact.

GERRIT de JONG: No, in that correction we had a portable clock comparison in May 2002, and that correction is also based on that transportable clock comparison. The certainty comes from the former calibrations. If we took only the last calibration, of course, you could put everything to zero then. But this is the difference between what we assumed, based on what you said is the GPS calibration, and that was also used for the two-way. It should have good results. But there is still some discrepancy.

LEWANDOWSKI: Yes, but there were no two-way calibrations. That is my point. So what you are giving for the accuracy of two-way is coming from other methods, not from two-way.

de JONG: Yes, it is.