Proc. 34th Annual Precise Time and Time Interval Systems and Applications Meeting - PTTI 2002, 03-05 Dec 2002, Reston, Virginia, USA (2003) 457-464

RECENT TIME AND FREQUENCY ACTIVITIES AT PTB

D. Piester, P. Hetzel, and A. Bauch
Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

Abstract

Recent activities in the field of time and frequency metrology pursued at PTB are reviewed. Quasi-continuous operation of the cesium fountain frequency standard CSF1 enabled us to assess the performance of the older primary clocks CS1 and CS2 much better than previously possible. On average, the CSF1 and CS2 frequencies deviated by less than 5 parts in 10^{15} during more than 2 years, which is well within the 1σ uncertainty u_B of CS2, 12 parts in 10^{15}. In cooperation with BIPM and timing institutes in the US and Europe, several calibration exercises have been conducted that resulted in an improved calibration of PTB's time comparison equipment.

INTRODUCTION

The development and operation of cesium atomic fountain frequency standards in many timing institutes, including PTB, and the necessity to compare these devices over long distances challenge the performance of time comparison equipment installed at PTB. Beyond that, the European satellite-based navigation system Galileo is becoming reality, and the quality of its system time will very probably depend on the collaboration between a few European timing institutes and a future Galileo Operating Entity. PTB wants to be well placed in this context, and will in fact be involved in the upcoming Galileo System Test Bed (GSTB) as one of the Sensor Stations and as one of the reference stations for steering the experimental Galileo System Time toward TAI.

Activities related to these issues are performed in PTB's Time Unit Section. In this contribution we focus on two aspects of the current work:

- Operation of primary clocks and frequency standards and realization of UTC (PTB) and TA (PTB);
- Participation in calibration campaigns concerning the Two-Way Satellite Time and Frequency Transfer (TWSTFT) and Global Positioning System (GPS) time transfer equipment at PTB.

Other PTB activities, like the development of an optical frequency standard based on trapped ions, the development of optical frequency standards based on laser-cooled atoms, atom optics, and optical frequency measurement shall not be dealt with here. The interested reader is referred to a recent review article that contains many details thereof **[1]**.

PRIMARY TIME AND FREQUENCY REFERENCES

PTB has continued to operate two primary frequency standards with a thermal atomic beam as clocks. The CS1 has a history of more than 30 years. It was refurbished about 4 years ago. The CS2 has been operated since 1986 with, up to now, the first charge of cesium (5 g) in each of the two ovens. The clock standard uncertainties (1σ) to realize the SI second were estimated as u_B(CS1) = $7\cdot10^{-15}$ and u_B(CS2) = $12\cdot10^{-15}$, as discussed in detail previously **[2,3]**. The CS3 (with a vertical atomic beam) performance has been in some disagreement with the stated uncertainty most of the time **[2,4]**. As also the recent modifications did not result in the expected more stable and reliable operation, it was decided to operate the CS3 for some further years as a clock, but to consider the CS3 no longer as a primary standard.

The development of the CSF1, a fountain frequency standard using laser-cooled cesium atoms lasted from 1995 to 1999, when the first frequency measurements were made. For more than 1 year, a so-called routine operation mode has been adhered to in which only atoms in the state ($F = 3$, $m_F = 0$) are launched and the others are discarded. A small atom number is chosen so that the shift due to cold-atom collisions is small and a standard uncertainty of $1 \cdot 10^{-15}$ for the realization of the SI second is obtained **[5]**. A relative frequency instability of $2 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$ is usually observed in this operation mode. Since 2000, the CSF1 has been operated quasi-continuously during 12 intervals, each of at least 15 days duration, for which data were submitted to the BIPM. Thus, the TAI scale unit could be compared 12 times to the SI second as realized in the CSF1 with a combined uncertainty of about $2.5 \cdot 10^{-15}$, documented in BIPM Circular T issues. The fountain F1 of NIST was operated at the same or nearly the same time during some of these measurement periods, and frequency comparisons were evaluated by Tom Parker of NIST **[6]**. The results confirm agreement between the two fountains within the combined uncertainties u_B and the measurement uncertainty, as can be seen in Figure 1.

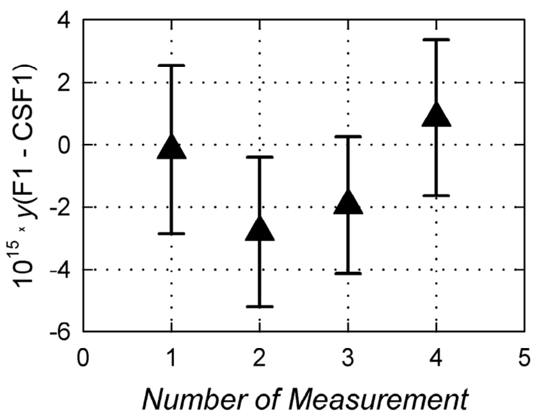

Figure 1. Results of frequency comparisons between NIST F1 and PTB CSF1 using carrier-phase GPS receivers and TWSTFT in combination **[6]**. Date, duration, and period of overlap of the comparison: #1: July 2000, 15 days; #2: July 2001, 10 days; #3: November 2001, 20 days; #4: February and March 2002, two contiguous 25-day intervals without overlap. In all cases, the NIST time scale AT1E served as stable reference against which both fountains were compared for typically 20 to 30 days. Error bars (1 σ) reflect the combined uncertainty u_B of the standards and the statistical measurement uncertainty.

The CSF1 data also form a good base for the verification of the previous uncertainty estimates and overall performance of the CS1 and the CS2. In Figure 2, the results of comparisons among the three standards are shown. The mean frequency difference was obtained as y(CSF1-CS1) = $9.2 \cdot 10^{-15}$ (standard deviation σ_E from the mean $4.6 \cdot 10^{-15}$) and y(CSF1-CS2) = $4.6 \cdot 10^{-15}$ ($\sigma_E = 3.4 \cdot 10^{-15}$), respectively. Thus, the CS2 and the CSF1 agreed well within the uncertainty, illustrated by the error bars in Figure 2, which represent the combined standard uncertainty u_B and the relative frequency instability over the averaging interval. In particular, the σ_E found for the CS2 comparison can be explained as white frequency noise of the CS2 (calculated from the CS2 signal parameters) combined with an extra contribution of only $1 \cdot 10^{-15}$. The latter must be attributed to variations of some of the CS2 systematic frequency shifts, as long as one is confident that the CSF1 frequency does not vary by as much as its uncertainty. This is highly improbable, but not strictly proven. Neither the CS2 beam tube nor the electronics required any modifications for several years. So with some prudence one may state that the CS2 has performed well within the stated uncertainty for a much longer time. This is supported by a long-term comparison between the CS2 and the NIST AT1E time scale **[7,8]** and by the comparison of the CS2 with the French fountain frequency standard FO-1 in 1996, which can be made in retrospect using the data reported in the BIPM Annual Report of that year.

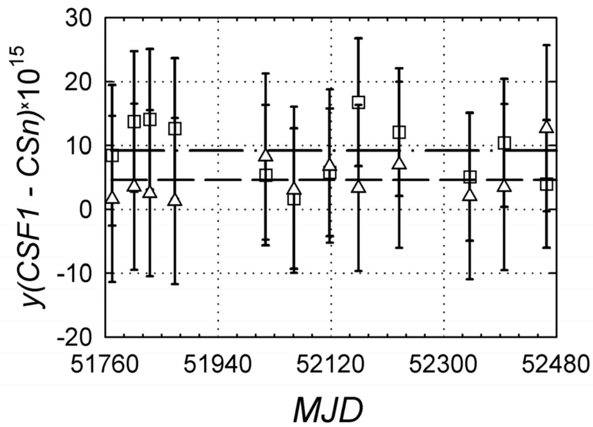

Figure 2. Results of frequency comparison between CSF1 and CS1 and CS2, respectively, over 2 years. Symbol : y(CSF1-CS1), mean: $9.2\cdot10^{-15}$, σ_E: $4.6.10^{-15}$; symbol Δ: y(CSF1-CS2), mean: $4.6\cdot10^{-15}$, σ_E: $3.4\cdot10^{-15}$. Error bars reflect the combined uncertainty due to u_B of the individual standards and the statistical uncertainty due to the measurement duration of 15 or 20 days. Modified Julian Day 52480 corresponds to 2002 July 25.

In contrast, the CS1 deviates slightly more from CSF1 than u_B(CS1), and an extra noise contribution of $3.3\cdot10^{-15}$ must be assumed to explain the σ_E of the 12 data around the mean. On one hand, this observation requires a detailed discussion of the CS1 uncertainty budget, which is deferred to a future publication. On the other hand, without the availability of the CSF1 data there was no reason to worry about the small frequency deviation between CS1 and CS2.

To conclude this section, in Figure 3 all measurement results of the TAI scale interval with respect to primary frequency standards during the last 12 months have been compiled, showing also the results from primary standards in the US, in France, and in Japan.

PTB TIME SCALES

The realization of PTB's atomic time scales and the possible access to the scales through time comparisons are illustrated in Figure 4. PTB continues to realize a free atomic time scale TA (PTB) directly from the 1PPS output of the CS2. The CS2 is also the physical source of UTC (PTB); however, UTC (PTB) is steered in frequency in order to minimize the difference between UTC and UTC (PTB). This is required as there is a non-negligible offset between the CS2 seconds and the scale unit of TAI, as seen in Figure 3. The steering is effected on a monthly basis with maximum rate changes equal to ± 0.5 ns/day. The steering corrections are published in PTB's Time Service Bulletin.

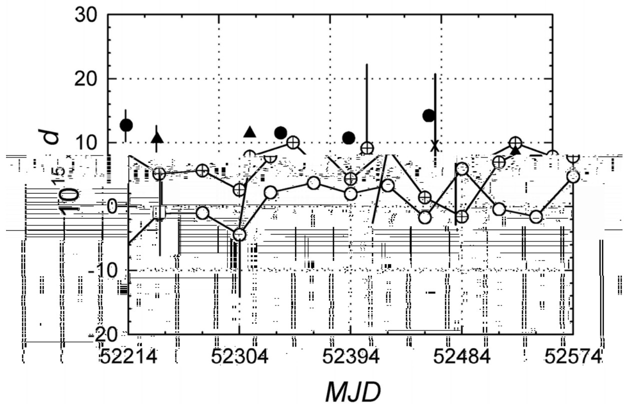

Figure 3. Fractional deviation d of the duration of the TAI scale interval from the SI second as realized by the individual primary clocks CSF1 (●), CS1 (O) and CS2 (⊕) of PTB, NIST-F1 (▲), CRL-01 (X) (Japan), and JPO (□) (BNM-SYRTE, France) during the period MJD 52214-52574. MJD designates the Modified Julian Date; MJD 52574 corresponds to 2002 October 27. Data points from PTB's primary clocks were connected, as these clocks were operated continuously. Other symbols were plotted at the end of the measurement interval of typically 20 days. Error bars (one representative for each clock) indicate the 1σ standard uncertainty in the determination of d (source: BIPM Circular T).

Since November 2000 a time scale provisionally named TAF (PTB), whose scale unit shall represent the SI second as realized with CSF1 (on the rotating geoid), has been produced. It is based on the 5 MHz output signal of an active hydrogen maser, designated as HM. Frequency steering by a micro-phase stepper (MPS) reflects the results of frequency comparisons between CSF1 and HM. During 2002, the instability of TAF (PTB) was only slightly lower than that of UTC (PTB). A more reliable hardware configuration and a more appropriate strategy for the steering of the maser should become available during 2003.

TIME AND FREQUENCY COMPARISONS

PTB still uses an NBS-type single-channel C/A code GPS receiver for the routine time scale comparisons with UTC (PTB) as the local reference time scale **[9]**. The geodetic GPS receivers operated in PTB are connected to HM. A TurboRogue SNR 12 RM (on loan from NIST) is operated to establish a link between NIST and PTB, in particular to compare the fountains NIST F1 and CSF1 **[6]**. In April 2000, the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell created a permanent EUREF station at PTB using a TurboRogue SNR-8000 receiver. In early 2002, this receiver was replaced by an Ashtech Z12T, and PTB has been included in the network of the IGS (station acronym PTBB). Providing data *UTC (PTB) − 1PPS (HM)* to interested users allows comparison with UTC (PTB). Thus, PTB is participating in a study of the use of geodetic receivers in replacement of the standard C/A code receivers in the production of TAI **[10]**.

TWSTFT is routinely performed with European and US institutes using an INTELSAT geostationary satellite at 307°E three times per week. The comparison between each pair of stations lasts 2 minutes. In the PTB measurement setup, the 1PPS TX signal is produced in the SATRE modem by dividing the 5 MHz reference signal coming from HM. *UTC (PTB) – 1PPS (TX)* is reported as REFDELAY in the header of the TWSTFT data file. Thus, the TWSTFT data can be used to compare to HM directly or, including the REFDELAY information, to UTC (PTB) **[11]**. The TWSTFT data contribute to the calculation of the time links between PTB and VSL, NPL, and NIST in the production of TAI **[12]**.

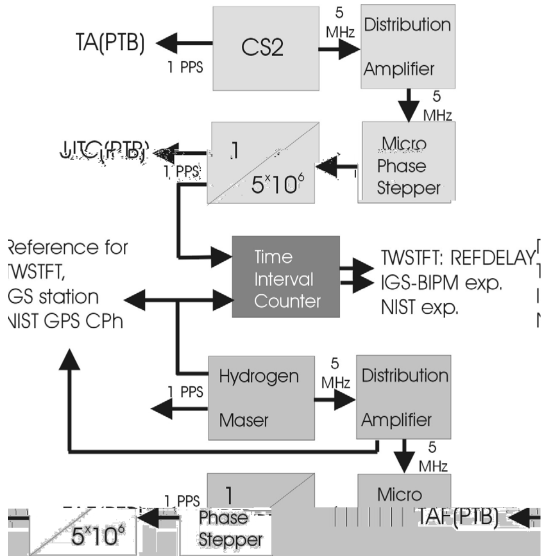

Figure 4. Schematic representation of the generation of PTB's atomic time scales.

A permanent dedicated TWSTFT link with USNO has become operational in summer 2002 due to considerable support of USNO. Currently, the HM and USNO Master Clock #2 (MC2) are compared nominally 24 times per day for 15 minutes via X-band in addition to the established Ku-band link. A transportable X-band TWSTFT station was installed by USNO in PTB for 2 days in May 2002, and an absolute calibration of the time links between USNO and PTB was performed. Such a campaign shall be repeated annually. In Figure 5, the results of comparisons between UTC (PTB) and MC2 (USNO) over 3 months are depicted. X-band data (open circles) are daily averages over usually 22 to 24 15-minute session means. Ku-band data (full circles) are taken from standard ITU files. The double differences $\{UTC\ (PTB) - MC\ 2(USNO)\}_{\text{Ku-band}} - \{UTC\ (PTB) - MC2\ (USNO)\}_{\text{X-band}}$ exhibited a mean offset of –19.04 ns and an rms variation around the mean of 1.22 ns. Following the final evaluation of the calibration experiment **[13]**, the CALR value in the ITU file-header was changed. This explains the step in the Ku-band data apparent around MJD 52540. In Figure 6, a subset of the data collected during the calibration experiment is depicted, showing the excellent stability of both TWSTFT links during a few hours on MJD 52436.

Calibration experiments of that kind would have to be made repeatedly if internal consistency of all the time links between timing institutes involved in the production of TAI at a level of 1 ns is to be maintained. They are, however, costly and require the availability of dedicated equipment. Thus, only very few such calibrations were ever made in the civil timing community, e.g. one by Kirchner and Ressler of the Technical University of Graz, visiting DTAG and PTB in 1999 with a travelling KU-band station **[14]**. It was considered feasible that the time links between NPL (Teddington, UK), VSL (Delft, NL), and PTB could be calibrated with the desirable small uncertainty making an "old-style" portable clock (PC) transport experiment. The VSL-PTB results are discussed briefly. A high-performance HP5071A Cs-clock was transported from PTB to VSL and back within 15 hours. Figure 7 shows *UTC (PTB) – PC* during a period of a few days around MJD 52416 when the clock trip took place. The clock frequency remained apparently unchanged in spite of the clock transport. The hourly recordings of *UTC (PTB) – PC* allowed to predict *UTC (PTB) – PC* with an uncertainty of 1.3 ns ($\tau \cdot \sigma_y(\tau)$ for τ = 6 hours of unmonitored operation). Including the Sagnac correction, the difference $\{UTC\ (PTB) - UTC\ (VSL)\}_{PC}$ = 5.0 ns was obtained. The total uncertainty of this "true time difference" amounts to σ = 1.5 ns. It has to be compared to the time differences obtained using standard GPS CV, $\{UTC\ (PTB) - UTC\ (VSL)\}_{GPS}$ = 15.4 ns (daily average), and using TWSTFT, $\{UTC\ (PTB) - U\ TC\ (VSL)\}_{TW}$ = 12.8 ns, both for MJD 52416 **[12,15]**.

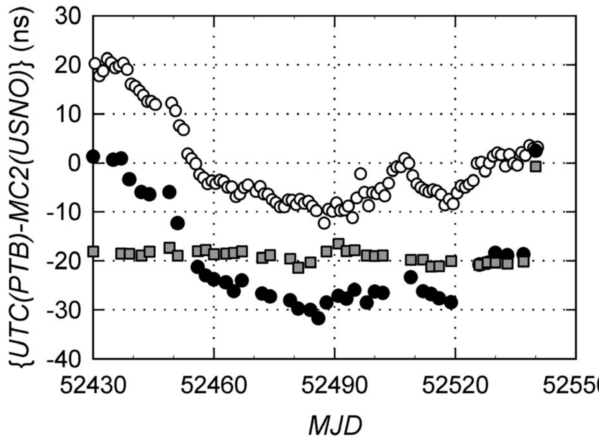

Figure 5. Results of a time scale comparison *UTC (PTB) – MC2 (USNO)* using different techniques. X-band data (open circles) are daily averages over usually 22 to 24 15-minute session means. Ku-band data (full circles) are taken from standard ITU files. On MJD 52540, the CALR value in the header of the file reporting the TWSTFT results **[11]** in the ITU-format was changed due to the calibration experiment on MJD 52435, which explains the step in the Ku-band data and the differences (squares).

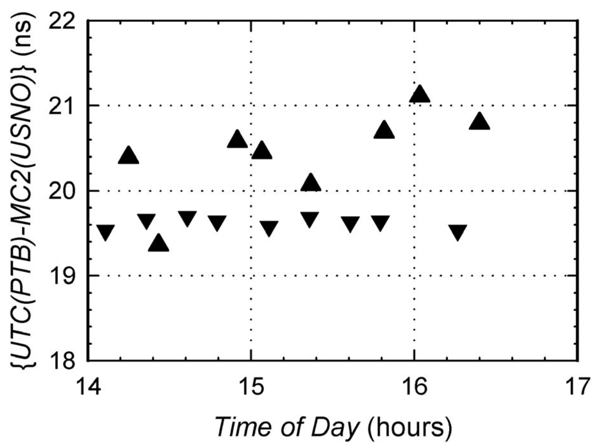

Figure 6. Time scale comparison *UTC (PTB) – MC2 (USNO)* during the calibration experiment in PTB on MJD 52436, using a transportable X-band station (symbol ▲) and the standard KU-band TWSTFT equipment (symbol ▼), in operation out of the normal schedule. Each point represents an average over 2 minutes.

An analysis of the double differences $\{UTC\ (PTB) - UTC\ (VSL)\}_{TW} - \{UTC\ (PTB) - UTC\ (VSL)\}_{GPS\ CV}$ over an extended period yields an rms-instability below 3.0 ns **[12]**, which is of similar magnitude as the absolute double difference on MJD 52416. The main portion of the instability is surely due to the GPS CV link. In conclusion, the difference between the portable clock experiment and the standard time comparison techniques is significant and should be considered by an appropriate change of calibration constants for both time transfer techniques. Unfortunately, the NPL clock of the same type did not behave so well during the considerably longer trip and the prediction uncertainty came out larger. In general, however, clock transport is an efficient procedure for calibration of time links between not too distant laboratories.

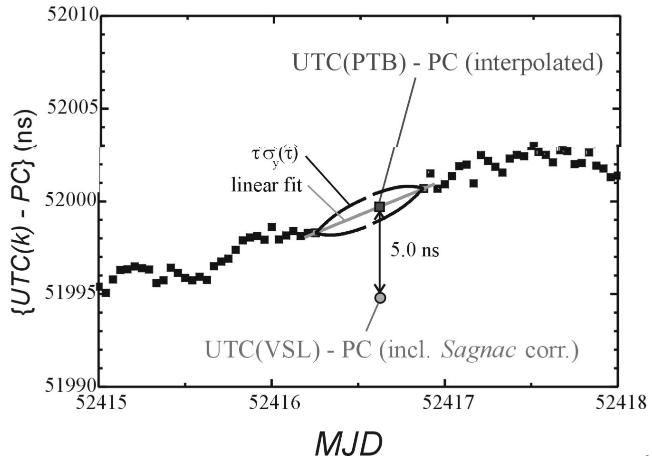

Figure 7. Documentation of the portable clock (PC) experiment between PTB and VSL. Hourly measurements UTC (k) – PC are shown and linearly interpolated to obtain UTC (PTB) – UTC (VSL) by measuring UTC (VSL) – PC at VSL. The prediction uncertainty is illustrated next to the linear interpolation.

OUTLOOK

It is intended to continue the development of atomic frequency standards and their application in the realization of atomic time scales in PTB's Time Section. Both kinds of activities are dependent on each other to a large extent. The development of a second cold-atom clock is underway. Besides the research and development of atomic clocks, PTB will continue to improve its time transfer techniques. The use of a C/A code multichannel receiver is envisaged for 2003. The hardware for the realization of UTC (PTB) and TAF (PTB) is currently being modernized. By mid 2003, the equipment and all GPS receivers shall be housed in a dedicated air-conditioned room of the laboratory. Here also the equipment for the use in the GSTB will be installed, and data shall be made available by September 2003.

ACKNOWLEDGMENTS

The authors appreciate the stimulating and friendly collaboration with Lisa Nelson (NIST and, more recently, USNO) and Tom Parker (NIST), Angela McKinley, Jim de Young, Phu Mai, Alan Smith, Paul Wheeler, and Demetrios Matsakis (USNO), and Gerrit de Jong (VSL), which was substantial for many achievements reported in this contribution.

REFERENCES

[1] A. Bauch and H. R. Telle, 2002, *"Frequency standards and frequency measurement,"* **Reports on Progress in Physics, 65**, 789-843.

[2] A. Bauch, B. Fischer, T. Heindorff, P. Hetzel, G. Petit, R. Schröder, and P. Wolf, 2000, *"Comparisons of PTB primary clocks with TAI in 1999,"* **Metrologia, 37**, 683-692.

[3] T. Heindorff, A. Bauch, P. Hetzel, G. Petit, and S. Weyers, 2001, *"PTB primary clocks: performance and comparison with TAI in 2000,"* **Metrologia, 38**, 497-501.

[4] A. Bauch, T. Heindorff, R. Schröder, and B. Fischer 1996, *"The PTB primary clock CS3: type B evaluation of its standard uncertainty,"* **Metrologia, 33**, 249-259.

[5] S. Weyers, A. Bauch, R. Schröder, and C. Tamm, 2002, *"The atomic caesium fountain CSF1 of PTB,"* in Proceedings of the 6th Symposium on Frequency Standards and Metrology, 9-14 September 2001, St. Andrews, Scotland, UK (World Scientific, Singapore), pp. 64-71.

[6] T. Parker, P. Hetzel, S. Jefferts, S. Weyers, L. Nelson, A. Bauch, and J. Levine, 2001, *"First comparison of remote cesium fountains,"* in Proceedings of the 2001 IEEE International Frequency Control Symposium and PDA Exhibition, 6-8 June 2001, Seattle, Washington, USA (IEEE Publication 01CH37218), pp. 63-68.

[7] T. E. Parker, NIST, Time and Frequency Division, private communication, November 2002.

[8] T. E. Parker, 2001, *"Comparing and evaluating the performance of primary frequency standards: impact of dead time,"* in Proceedings of the 2001 IEEE International Frequency Control Symposium and PDA Exhibition, 6-8 June 2001, Seattle, Washington, USA (IEEE Publication 01CH37218), pp. 57-62.

[9] Data available at *ftp.ptb.de/pub/time/gps*

[10] G. Petit, Z. Jiang, and P. Moussay, 2003*, "TAI time links with geodetic receivers: a progress report,"* in these Proceedings, pp. 19-27.

[11] Data available at *ftp.ptb.de/pub/time/twstt*

[12] 22nd BIPM TWSTFT Report, September 2002, available at *http://www.bipm.org/enus/5_Scientific/c_time/time_ftp.shtml#publication*

[13] D. Matsakis, 2003, *"Time and frequency activities at the U.S. Naval Observatory,"* in these Proceedings, pp. 437-456.

[14] D. Kirchner, H. Ressler, P. Hetzel, A. Söring, and W. Lewandowski, 1999, *"Calibration of three European TWSTFT stations using a portable station and comparison of TWSTFT and GPS common-view measurement results,"* in Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 365-376.

[15] G. de Jong, P. Hetzel, J. Becker, S. Shemar, and R. Hlavac, *"Results of portable clock calibration trips from PTB and NPL to VSL on May 22, 2002"* (unpublished).