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TIME AND FREQUENCY ACTIVITIES AT THE PHYSIKALISCH-TECHNISCHE BUNDESANSTALT

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Abstract

PTB is entrusted to provide legal time for Germany and is serving as the European node for time comparisons among institutes collaborating with the BIPM in the realization of TAI. Recent activities pursued in this context were directed towards an improved knowledge of internal delays of PTB's time comparison equipment. The standard frequency and time signal transmission via DCF77 remains the most important means to disseminate legal time, and we report on some new ideas for additional use of the broadcast signal. As the foundation of our work, we continued the operation of the primary clocks CS1 and CS2, and of the cold-atom cesium fountain CSF1.

I. INTRODUCTION

This report covers part of the activities pursued in the Working Groups "Time Standards" and "Dissemination of Time" of PTB's Time and Frequency Department **[1]**. In this Report we neglect other important activities pursued in our Department, namely those on optical frequency standards **[2]**, optical frequency measurement **[3]**, and fountain development. We concentrate on the operation of PTB's atomic clock ensemble and on the calibration of PTB's time links, and we start this report with providing some news on the potential future use of the German standard frequency and time signal transmitter DCF77.

II. NEWS FROM DCF77

PTB supplies legal time for the whole of Germany as an infrastructural service of the state. A prominent example is the low frequency transmitter DCF77, by which the standard frequency, 77.5 kHz, and coded time information have been broadcast for about 30 years **[1, 4]**. Time information is broadcast as amplitude modulation (AM) and phase modulation (PM). While the AM is widely used for applications with uncertainty requirements not below 1 ms, the PM code allows to refer clocks to UTC (PTB) on the level of 10 µs. The generation of the PM for DCF77 is described in detail in Ref. **[5]**; for general information about DCF77 see Ref. **[6]** and publications in the German language **[7]**. The information content in 14 of the available 59 AM bits of the DCF77 protocol is no longer provided by PTB. On the initiative of the Federal Office for Civil Protection and Disaster Relief (the German Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, BBK), a study was made as to whether information of a federal system for warning the population could be reliably transmitted using these 14 bits per minute. The idea was to use DCF77 as one element in a system to get the public on the alert regarding catastrophic events, just as the siren systems used to do in the past. A field test was conducted during which about 40 fictive alarm messages were to be received by about 1000 dedicated receivers. Standard radio-controlled clocks had been distributed all over the country, which had been modified with additional features to check the contents of the 14 bits and to give optical and acoustical alarm. The participants in the field test had agreed to report their observations via the Internet. HKW-Electronics, Seebach, Germany had received the general contract to plan, perform, and evaluate the field test. In their final report it was shown that indeed DCF77 could from a technical point of view be used for such a purpose. The probability that alarms would be recorded in a timely fashion by suitably operated receivers was very high, independent on their location in general (rural area or within a city, indoor or outdoor) within Germany. The number of false alarms was negligibly small. Negotiations are ongoing whether DCF77 will be used for that purpose on a regular basis. Since no decision has been made yet, no details on the transmitted information can be given at the moment. Independent of this decision, the maintenance and supervision of DCF77 will remain an important part of our work. A completely new electronic control unit has been developed and will be installed in 2005. There will be no changes to the transmitted signals. The contract with T-Systems Media Broadcast, operating the transmitter facility, has been prolonged until 2013.

III. CLOCK OPERATION

PTB currently provides data of two home-built clocks with a thermal atomic beam, CS1, and CS2, three commercial cesium clocks, and three active hydrogen masers as an input to the calculation of the free atomic time scale EAL (Echelle Atomique Libre) by the International Bureau of Weights and Measures (BIPM) in the ALGOS procedures **[8]**. CS3 failed in early 2004 and could not yet be repaired, one commercial clock needed tube replacement, and the performance of the masers was far from optimum. Thus, only four of our clocks got significant statistical weight during the last 12 months, as depicted in Figure 1.

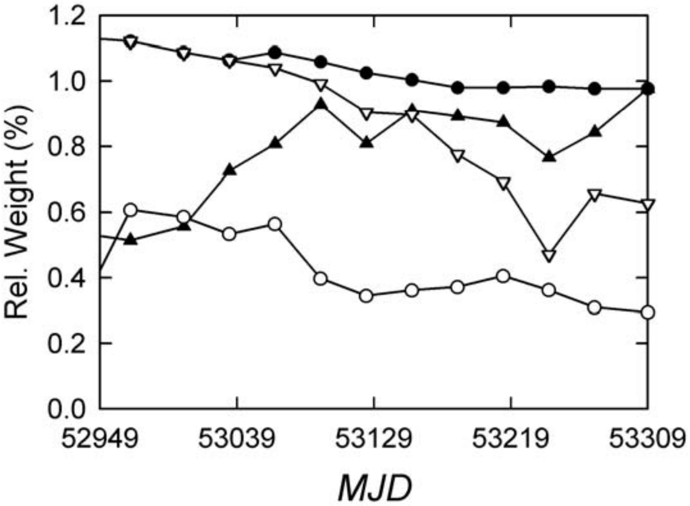

Figure 1. Statistical weights of PTB's clocks, as obtained in the ALGOS procedures used for calculating the Echelle Atomique Libre at BIPM; data taken from files w04.04 and w04.10 **[8]**. Full symbols designate the primary clocks: ▲ CS1 and ● CS2; open symbols designate clocks of type 35 (Agilent 5071 Opt. 001) with the serial numbers 128 (symbol ∇) and 415 (symbol O). MJD designates the Modified Julian Date; MJD 53309 corresponds to 2004-10-30.

In Figure 2 the monthly clock rates with respect to TAI are depicted on which these statistical weights are based. Among all our clocks, only CS2 obtained the maximum statistical weight all the time. In the current version of the ALGOS algorithm, the CS1 instability is typically just at the margin to cause a slight reduction of its statistical weight from maximum **[9]**. A partial blocking of the cesium atomic beam in CS1 caused a decrease in the clock's signal-to-noise ratio for a few months in 2003. It took some time until the statistical weights rose again after the problem was remedied, which is characteristic of the way the weights are calculated.

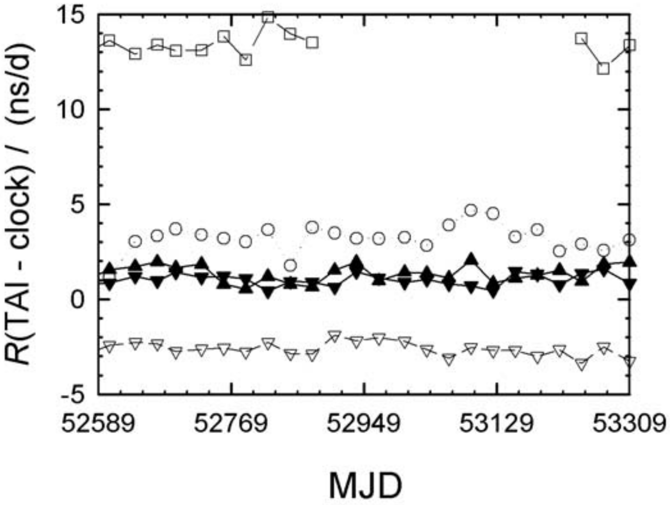

Figure 2. Monthly rates *R* (TAI – clock) in ns/d of PTB's clocks with respect to TAI over 2 years; data are taken from files r04.xx and r03.xx **[8]**. Full symbols designate the primary clocks: ▲ CS1 and ▼ CS2; open symbols designate clocks of type 35 (Agilent 5071 Opt. 001) with the following serial numbers: ∇ 128, O 415, and □ 1072 (the latter needed tube replacement during in late 2003).

In the very long term, the performance of the primary clocks is remarkable. Since the refurbishment of CS1 in 1996, we recorded continuous time differences between CS1 and CS2 over 2500 days. On average, the CS2 frequency was found to be higher by 6×10^{-15} and after removal of this mean rate the time residuals, which are depicted in Figure 3, reveal a small frequency drift of $1.92(\pm0.66)\times10^{-18}$/d. The mean relative frequency difference over the last 500 days is, thus, higher by 3×10^{-15} than that over the first 500 days. From comparisons with respect to the time scale AT1 of NIST, this drift could probably be attributed to CS1 **[10]**. The plot of the frequency instability shown in Figure 4 illustrates that white frequency noise dominates for averaging times up to 300 days. The solid line in Figure 4 is an estimate of the average expectation value of $\sigma_y(\tau)$. Based on previous findings over a much shorter time interval one can attribute the small excess noise that is visible in Figure 4 to be caused by CS1 **[11]**. Despite of the fact that cold atom clocks are capable to realize the SI second with much reduced uncertainty **[12]**, the two thermal beam clocks are still valuable in defining the rate of TAI because of their reliability.

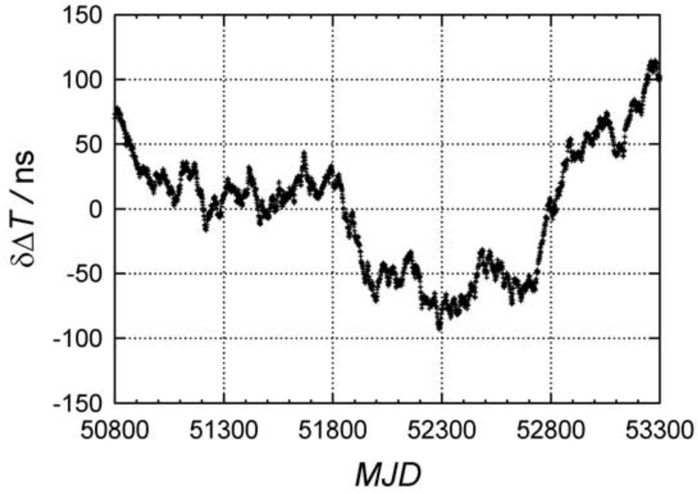

Figure 3. Residuals to a linear least squares fit to the time differences *T* (CS1 – CS2) recorded between MJD 50800 (1997-12-18) and 53300.

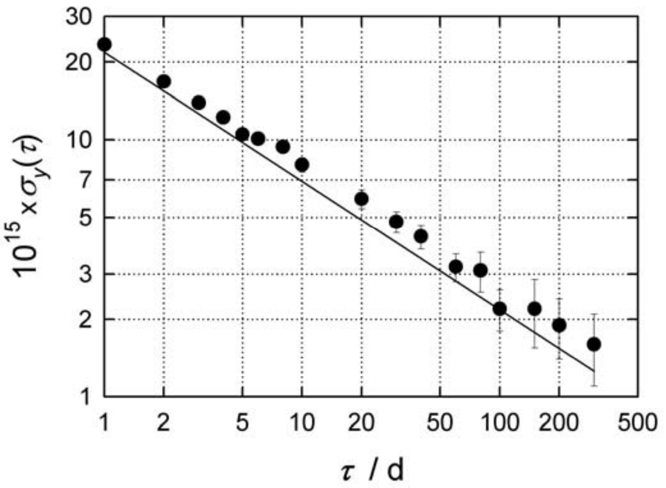

Figure 4. Relative instability of the frequency difference *y* (CS1 – CS2), recorded between MJD 50800 and MJD 53300, expressed by the non-overlapping Allan standard deviation $\sigma_y(\tau)$.

As observed in previous years, the commercial Cs clocks at PTB do not get a large statistical weight (Figure 1), whereas other clocks of the same kind in other institutes do get it. The weight is reduced to typically below half maximum for clock SN415 due to its small rate excursions shown in Figure 2. This may serve as an indication of the rigor of the ALGOS algorithm used in these days **[9]**. A plot of the monthly rate changes given as Figure 5 shows no correlated (or anti-correlated) changes of the rates of the two clocks, so that gross disturbances due to environmental conditions or human interference in the laboratory can be excluded. Actually, no significant deviations of the environmental conditions from their nominal values (temperature 23.6°C, variations within 0.4°C peak-to-peak, relative humidity bounded between 50% and 75%) were observed in PTB's clock hall, except on 7 days in 2003.

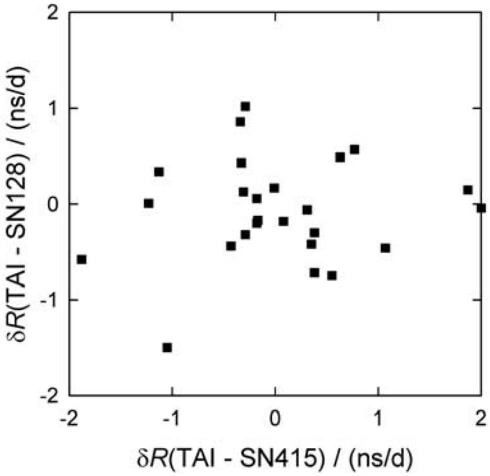

Figure 5. Simultaneously observed differences of the 24 monthly rates *R* (TAI – clock) for the two clocks of type 35 in continuous operation during 2003 and 2004 (data from Figure 2).

IV. CALIBRATION OF TIME LINKS

PTB has continued to operate satellite time-transfer equipment, including GPS C/A code receivers, geodetic GPS receivers, and two-way satellite time and frequency transfer (TWSTFT) equipment. In addition to the IGS station (PTBB), which is owned by the Bundesamt für Kartographie und Geodäsie (BKG), an Ashtech Z12-T receiver as part of the Galileo System Test Bed V1 (PTBG) is operated by the European Space Agency. PTB has served as the European node for time comparisons among laboratories collaborating with BIPM. During 2004, several calibration exercises (both GPS and TWSTFT) have been performed in cooperation with BIPM, EUROMET, and timing laboratories in the US and Europe to improve the knowledge of the internal delays of PTB's time comparison equipment. In this report we concentrate on the calibrations performed by circulating TWSTFT equipment.

CALIBRATION OF THE LINK BETWEEN USNO AND PTB

As in previous years, USNO has supported the calibration of the time transfer link to PTB by circulating a so-called travelling station (TS) and thereby establishing a temporary TWSTFT connection in the X-band. The TS has been operated initially and after the calibration trip at USNO, connected there to the same clock as the standard TWSTFT equipment, giving the so-called common clock error (CCE). CCE values were determined with different TS hardware setup configurations so that the calibration trip could be successfully completed, even in case of operation failures of single components during the trip. Assuming that the internal delays of the travelling station remain unchanged when the station is operated at PTB, the true time difference UTC (USNO) – UTC (PTB) is determined, combining CCE with the results obtained at PTB. Such an exercise, which is schematically represented in Figure 6, would not require the regular operation of an USNO-PTB link using the same technology and satellite.

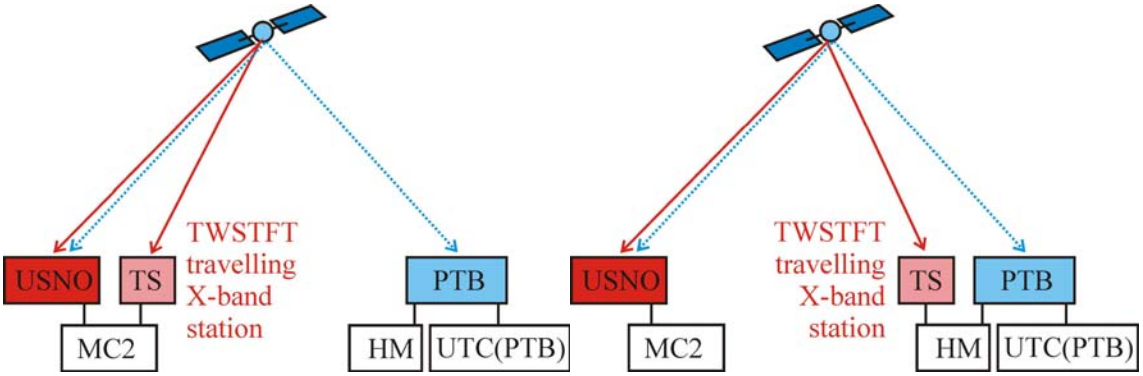

Figure 6. Schematic representation of the set-up of a travelling TWSTFT station sequentially operated at USNO and PTB; the red arrows indicate the time transfer performed during the calibration. The light blue line indicates the permanent X-band link, which is calibrated that way. Other time links (TWSTFT via Ku-band, via GPS) are not shown.

In fact, a permanent TWSTFT link USNO-PTB in X-band has been operated since summer 2002, in addition to the TWSTFT link in Ku-band established between several European institutes, USNO, and NIST many years ago. Here we discuss results regarding the delay stabilities of both links. Regarding the X-band link, we essentially neglect other than the standard configuration, which involves the SATRE modems S76 in PTB, S81 at the permanent USNO station, and S87 in the TS. The first campaign took place in March 2004 (MJD 53072 to 53074). In Figure 7 we depict the result of the initial and the closure measurement. Note that the date of the calibration is not well in the middle between the two measurements at USNO. Nevertheless, the interpolated CCE has been used to determine the differences between TS, stationary X-band, and Ku-band as given in Table 1 below.

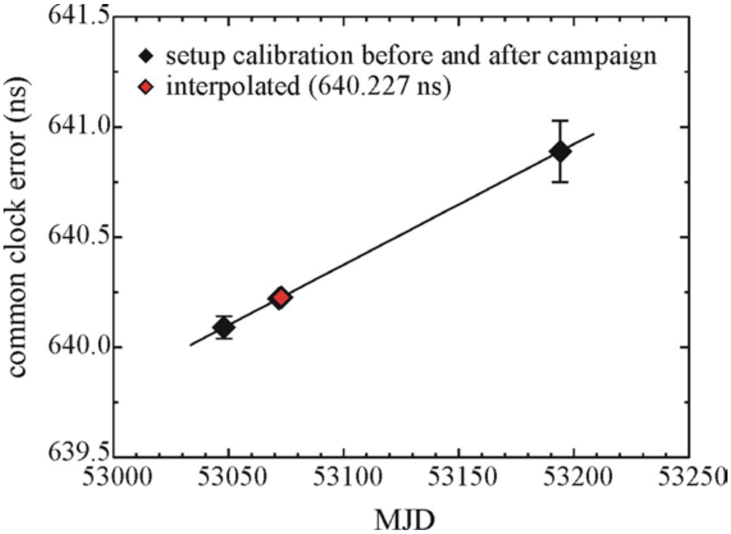

Figure 7. Initial and closure measurement at USNO. Interpolation of both results provides the common clock error between the permanent and the travelling station (TS) of USNO for the epoch of the TS operation at PTB.

Table 1. Averaged time differences obtained from comparing TWSTFT results in X-band and Ku-band with the TS. Uncertainties are discussed in the text.

	$\delta\Delta T$ (ns) March 2004	$\delta\Delta T$ (ns) September 2004	Difference (ns)
X-band – TS	1.2	1.6	-0.4
Ku-band – TS	1.7	16.5	-14.8

At the time of writing, the second campaign in September 2004 has not been fully evaluated, and the results must be considered preliminary. On 2 days (MJD 53268 and 53269) three sets of measurements were collected. Both the Ku-band link and the permanent X-band link could be operated during 24 sessions per day while the TS was in operation at PTB. In Figure 8 we depict the results obtained. To determine the differences between the regular X-band (Ku-band) and the TS results, every single calibration measurement value was subtracted from the interpolated value of two adjacent points of the regular measurements. Data sets 1 and 2 show good agreement within their statistical uncertainty whereas data set 3 indicates a deviation of more than 1 ns. Records proved later that during the operation at PTB the modem S286 temperature (setup 2) was 49°C, which is about 5°C above the normal operation condition. Thus, these data points were skipped in a final evaluation of the double differences given in Table 1. Actually, the large difference of approximately 14 ns in the Ku-band link is due to a jump having occurred on MJD 53215 (2004-07-29) after which new transmission frequencies had to be used in the Ku-band link. Thus, the September 2004 campaign represents a recalibration of this link. The statistical uncertainty of each $\delta\Delta T$ value in Table 1 is typically below 0.3 ns. We estimate the accuracy from the observed difference between the two CCE measurements in March (0.8 ns). Additional contributions take into account that different time interval counters were used connecting the travelling station to the laboratory 1 PPS reference at USNO and PTB (0.1 ns) and that the modem TX signal at PTB had to be measured with a separate counter with respect to UTC (PTB) (0.1 ns).

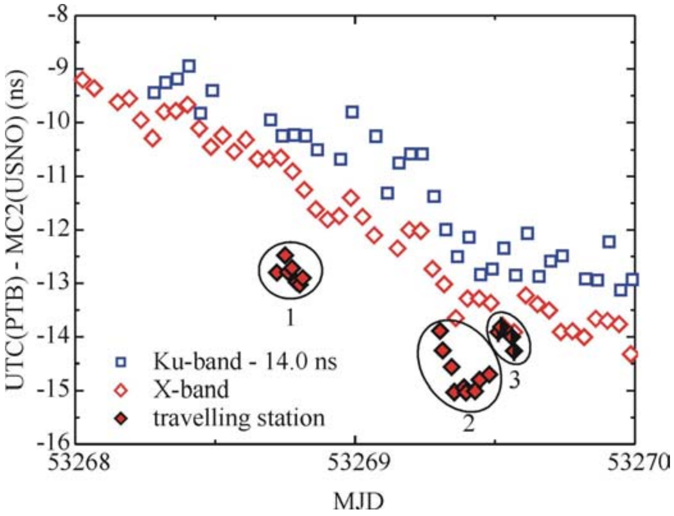

Figure 8. Comparison of the time scales MC2 (USNO) and UTC (PTB) using three TWSTFT links during the calibration campaign in September 2004: Ku-band (blue squares), X-band (red diamonds), and TS (full symbols). Here we distinguish between sets 1 and 2, when the TS standard configuration, including primary modem S 87, was used, and set 3, when the backup modem S268 was used.

In consequence of the last campaign, from the regular TWSTFT data used by BIPM, $\delta\Delta T$ = 1.6 ns (16.5 ns) have to be subtracted from the TWSTFT time scale comparison UTC (PTB) – MC2 (USNO) via X-band (Ku-band). Each of the values has a combined uncertainty (1 σ) of 1 ns.

CALIBRATION OF THE LINKS BETWEEN BNM-SYRTE (OP), NPL, VSL, AND PTB

Four European institutes agreed to have the differential earth station delays of their TWSTFT systems in Ku-band determined in a way which was successfully demonstrated 1 year ago for the IEN – PTB link **[13, 14]**. The travelling reference station, designated TUG01, was again provided and operated by Joanneum Research on contract basis **[15]**. The campaign is illustrated in Figure 9. TUG01 was sequentially operated at four different European time laboratories during a two-week schedule. The initial measurements at PTB were verified by a second series of measurements concluding the campaign. To determine the permanent station's individual differential delays at each side the TWSTFT equipment was measured versus the TS, both connected to the local reference. As an example of the results, the common clock errors obtained on both occasions at PTB are depicted in Figure 10. At each site visited during the campaign, calibration constants were determined with a statistical uncertainty of a few tenths of a nanosecond **[15]**. Final results will be published in a forthcoming article to be presented at EFTF 2005.

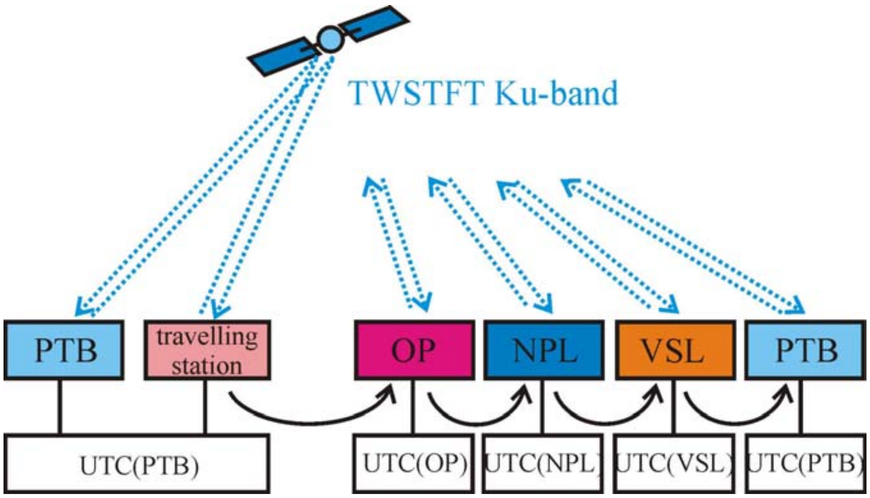

Figure 9. Schematic representation of the setup of the portable TWSTFT station (TUG01) sequentially at PTB, OP, NPL, VSL, and back at PTB. At each site the CCE was determined and calibration values to be used by BIPM when using the links in the realization of TAI were determined with uncertainties of the order of 1 ns.

V. OUTLOOK

We have firm plans to continue the development of atomic frequency standards and their application in the realization of PTB's atomic time scales. Both kinds of activities are dependent on each other. The completion of the second cold-atom fountain has suffered some delays, but we expect first signals of cold atoms in early 2005. In a cooperative effort between NICT, Tokyo, and PTB, an Asia-Europe TWSTFT shall be installed in the second half of 2005. The setup at PTB will be given on loan by NICT, including the NICT-developed TWSTFT modem. As a new service, PTB is going to house on contract basis a commercial trusted time server that is referenced to UTC (PTB). The equipment has been installed recently and awaits approval after some weeks of thorough testing.

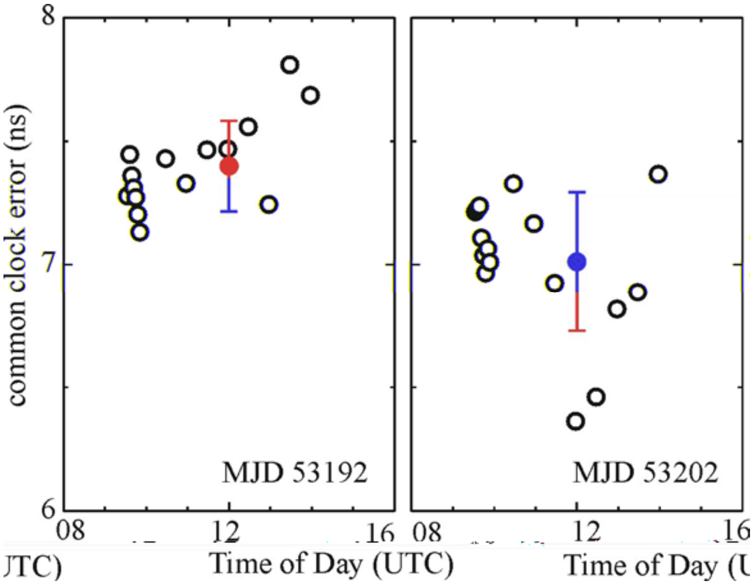

Figure 10. Common clock error CCE measured during the visit of the station TUG01 at PTB on two days in July 2004. Individual measurement values, i.e. 2-minute session averages (open circles), and mean values with 1-σ standard deviation (in red) are shown.

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DISCLAIMER

The Physikalisch-Technische Bundesanstalt as a matter of policy does not endorse any commercial product. The mentioning of brands and individual models seems justified here, because all information provided is based on publicly available material or data taken at PTB and it will help the reader to make comparisons with his own observations.

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