Physikalisch-Technische Bundesanstalt (PTB), Germany

Report on PTB's activities to the 20th Session of the Consultative Committee for Time and Frequency, September 2015

PTB's activities described in this report cover the following fields

1. Primary clocks
2. Time scales
3. Time and frequency comparisons
4. Time and frequency dissemination
5. Optical frequency standards
6. Optical frequency measurements

1. Primary clocks

1.1 Fountain clock CSF1

During the past three years, the primary fountain clock of PTB CSF1[1, 2] has been operated at normal operating conditions most of the time. CSF1 has been used for measurements of the TAI scale unit, for steering the timescale UTC(PTB), as reference clock for the evaluation of the fountain CSF2 and for optical frequency measurements (see below). The current frequency instability and systematic frequency uncertainty of CSF1 are 1.3×10^{-13} $(\tau/s)^{-1/2}$ and 7.0×10^{-16}, respectively.

For TAI scale unit measurements, CSF1 is continuously operated, routinely achieving dead times of ~2% of the total measurement interval. During the years 2013 to 2015 in total 14 TAI scale unit measurements by CSF1 have been submitted to the BIPM. The respective durations of these measurements range from 10 to 35 days. The short dead times result in the related uncertainty contribution $u_{l/lab}$ of much less than 10^{-16}. The statistical uncertainty of CSF1 measurements was calculated with the assumption of white frequency noise for the total measurement intervals. For TAI contributions we routinely arrived at statistical uncertainties $u_A < 0.2\times10^{-15}$.

1.2 Fountain clock CSF2

A detailed description of the PTB fountain CSF2 is given in refs. [3, 4]. CSF2 has been likewise used for measurements of the TAI scale unit, for steering the timescale UTC(PTB), and for optical frequency measurements (see below). The current frequency instability of CSF2 is 2.0×10^{-13} $(\tau/s)^{-1/2}$. After several steps of improvement, the total systematic frequency uncertainty of CSF2 is 3.0×10^{-16}.

During the years 2013 to 2015, 21 measurements of the TAI scale unit were performed and reported to the BIPM. The dead times during these measurements were in most cases below 3% (in one case 7%), so that the resulting clock link uncertainty $u_{l/lab}$ was 0.04×10^{-15} or below. So far the atoms were loaded from the background gas into the molasses. The method of "rapid adiabatic passage" was routinely utilized for controlling the collisional shift during the measurement periods. The statistical uncertainty of CSF2 measurements was likewise calculated with the assumption of white frequency noise for the total measurement intervals. For TAI contributions we routinely arrived at statistical uncertainties $u_A < 0.2\times10^{-15}$.

1.3 Research work on the fountains

In 2013, a re-evaluation of two types of systematic frequency shifts (Rabi and Ramsey pulling) was performed for operating conditions corresponding to those in an atomic fountain. The crucial role of initial atomic coherences was discovered and investigated, and the respective contribution to the uncertainty budgets of CSF1 and CSF2 were obtained with improved accuracy [5].

A remote comparison campaign of caesium fountain clocks from four national metrology institutes in Europe and Asia was carried out in May 2013 [6]. Six fountains at PTB, VNIIFTRI-SU, NPLI and NIM were compared by two-way satellite time and frequency Transfer (TWSTFT) and GPS Carrier Phase (GPS CP) techniques. The individual frequency differences and comparison uncertainties between the compared fountain pairs were evaluated. The comparison uncertainty results from combining the uncertainties of the two compared fountain clocks and the uncertainty introduced by the comparison link. All the frequency differences between the fountains agreed within the 1σ uncertainty in the low 10^{-15} level.

In 2014, for the first time TAI scale unit measurements were made with both CSF1 and CSF2, while the quartz oscillator based microwave synthesis was replaced by a synthesis which makes use of an optically stabilized microwave oscillator [7]. The short term stability of the microwave oscillator was provided by a 1.5 μm cavity-stabilized fiber laser via a commercial femto-second frequency comb. In the long-term, the microwave oscillator was locked to the hydrogen maser to enable the fountain frequency measurement with respect to the maser. In this setup the instability contribution of the microwave oscillator via the Dick effect becomes negligible and the overall frequency instability is mostly caused by the quantum projection noise.

In 2014, the number of loaded atom numbers in CSF2 could be increased by a factor of 40 over the normal operation with molasses loading by using an improved slow atom beam loading method. With the new method, and using the optically stabilized microwave oscillator, the CSF2 frequency instability could be reduced to the level of 2.5×10^{-14}/s, a factor of 8 better than the value in regular CSF2 operation. It is expected that with such reduced instability, the statistical uncertainty of frequency measurements with CSF2 will reach the fountain's systematic uncertainty significantly faster.

The CSF1 and CSF2 fountain clocks are now mature and are routinely used for steering the UTC(PTB) time scale and for calibration of the International Atomic Time (TAI). In the period 2012-2015, several measurements of the absolute frequencies of PTB's ^{87}Sr and ^{171}Yb^{+} optical frequency standards were performed (see below).

1.4 Thermal beam clocks

PTB's primary clocks CS1 and CS2 [8] represent the state-of-the art of clock making of the 1980s, with CS1 having been refurbished a last time in 1996/1997. Since no commercial product with competitive performance is available today, they have been operated continuously up to now. Time differences UTC(PTB) - clock in the standard ALGOS format were reported to BIPM, so that $u_{l/lab}$ is zero. The mean relative frequency offset y(CS1 – CS2) during the last three years amounted to about -6.5×10^{-15}, which is compliant with the stated u_B values [8].

The clocks' operational parameters were checked periodically and validated to estimate the clock uncertainty. These parameters are the Zeeman frequency, the temperature of the beam tube (vacuum enclosure), the line width of the clock transition as a measure of the mean atomic velocity, the microwave power level, the spectral purity of the microwave excitation signal, and some characteristic signals of the electronics. To determine the frequency instability, the 5 MHz output signals of both clocks have been repeatedly compared to the signal of an active hydrogen maser using a high-resolution phase comparator in 10 to 20 day batches.

<u>CS1</u>

The relative frequency instability $\sigma_y(\tau = 1$ hour) of CS1 typically varies between 85×10^{-15} and 100×10^{-15}, in reasonable agreement with the prediction based on the prevailing parameters beam flux, clock transition signal and line width. With reference to TAI, the standard deviation of d(CS1) (Circular T Section 4) was well within the value $u_A(\tau = 30$ d, CS1) = 6×10^{-15} stated in Circular T. Reversals of the beam direction were performed on CS1 2 two or three times per year. No findings call for a modification of the previously stated relative frequency uncertainty u_B, which is 8×10^{-15} for CS1 [9].

CS2

The relative CS2 frequency instability of $\sigma_y(\tau = 1$ hour) was measured between 60×10^{-15} and 75×10^{-15}. This range of values justifies the estimate of the uncertainty contributions u_A as $u_A(\tau = 30$ d, CS2) = 3×10^{-15}. The standard deviation of the 36 *d*-values reported in Circular T during the last three years amounted, however, to 4.2×10^{-15} which is slightly higher. Also in CS2, three reversals of the beam direction were performed per year. The uncertainty estimate as detailed in [9] is considered as still valid, and the CS2 u_B is thus estimated as 12×10^{-15}.

It is evident that the importance of these old clocks diminishes with the growing availability of fountain clocks world-wide. Nevertheless they constitute a valuable back-up resource for the time scale generation at PTB in case that none of the fountains would be active.

2. Time Scales

UTC(PTB) has been realized using an active hydrogen maser (AHM) steered in frequency via a phase micro stepper since February 2010. The steering is based on an algorithm which combines the frequency comparison data between the selected AHM and primary and commercial caesium clocks of PTB [10]. Thereby the long-term stability and accuracy of PTB's primary clocks, in particular its fountain clocks CSF1 and CSF2, could be combined with the short-term frequency stability of the maser. Fountain data were used to calculate the steering on more than 95% of all days which ensured that during the last 3 years the time difference between UTC(PTB) and UTC was always less than 8 ns and the mean monthly rate differences never exceeded 0.36 ns/day.

From MJD 56079 0:00 UTC (1st June 2012) onwards TA(PTB) has been generated alike to UTC(PTB) from an active hydrogen maser, steered in frequency so as to follow PTB CSF1and/or CSF2 as close as possible. The deviation *d* between PTB fountains and the TAI second is not taken into account. The rate of TA(PTB) should thus represent the SI second as realized with PTB fountains as if they were operated on the geoid. TA(PTB) has got an initial arbitrary time offset from TAI without continuity to the values reported up to 2012.

Software updates were made with the intention to improve the robustness of the time scale generation, to simplify the weekly and monthly human interaction, and to optimize the combination of available clocks. So the mean of CSF1 and CSF2 can be selected for the steering, and a testbed for studying the effect of clock weights in the combination of thermal beam clocks, including CS1 and CS2, was set up.

3. Time and Frequency Comparisons

PTB has continued to provide GPS and GLONASS observation data collected with four different receivers. The primary receivers are two geodetic receivers, one of which with acronym PTBB has been a registered IGS station since 2002. PTBG is of the same type and serves as backup. In addition, PTB provides data from two dual frequency multi-channel receivers (GPS and GLONASS), PT05 and PT07. PT05 is used for GLONASS links to PTB, PT07 provides L1C single frequency data. PTB is ready to provide backup data from three further receivers which could in principle allow seamless availability of all kinds of required data. These other receivers are used in several projects, such as the provision of calibrated GPS and Galileo data for the determination of the GPS to Galileo time offset. Since a few months PTB hosts a reference station of the Galileo ground observation network and of the Chinese iGMAS network under development.

PTB has accepted the role of a Group1 laboratory in Europe and is prepared to support GPS calibration campaigns including European Group 2 laboratories, following the guidelines published by BIPM and using its travelling GPS receiver set-up [11]. Recently, PTB supported the calibration of the time transfer equipment in the facilities ESTEC and ESOC of the European Space Agency.

PTB undertakes two-way satellite time and frequency transfer (TWSTFT) in the bi-hourly comparisons using Ku-band transponder capacity on a communication satellite with European and U.S. institutes, namely (as of 2015) AOS, INRiM, LNE-SYRTE, METAS, NIST, OCA, ROA, SP, USNO, and VSL. The service contract with the satellite owner is shared by NIST and PTB which serves as the coordinating agent for the European participating stations.

USNO has provided annual calibrations of the link between USNO and PTB using its fly-away TWSTFT station. The combined uncertainty for each calibration was estimated to be about 1 ns (1 σ). The current calibration value is based on the June 2014 result (CI 391). Preliminary results of the July 2015 campaign show that the calibration value did not change by more than 0.2 ns.

The TWSTFT network connecting European and Asian stations has undergone many changes during recent years and is currently not active. Observations were stopped on MJD 56989 as the Russian satellite AM2 finally had an unstable orbit that rendered further use (and payment) no longer justified. It is anticipated that PTB and VNIIFTRI on the European side and KRISS, NICT, NIM, NPLI, NTSC, and TL on the Asian side are going to resume this activity as soon as a new suitable satellite will have been commissioned.

4. Time and Frequency Dissemination

PTB has used over the years different means for dissemination of time and frequency information to the general public and for applications in scientific and technical purposes. The long-wave transmitter DCF77 is the most important medium for this because the number of receivers in operation is estimated to be more than 100 million. Maintenance of the signal generation facilities owned and operated by PTB in Mainflingen is an important ongoing task. With DCF77, the time and date of German legal time are transmitted in an encoded form via the second marks, as described in [12, 13].

Since the mid 1990s, PTB has been offering time information via the public telephone network. Computers and data acquisition facilities can retrieve the exact time from PTB with the aid of telephone modems, calling the number + 49 531 512038. The major part of the calls (presently approx. 1800 calls per day) comes from the measuring stations along gas pipelines in Germany. This service is currently updated to accommodate the IP-based telephony technology that shall be used nation-wide in the future, abandoning the more traditional ISDN-based telephony.

Publicly available Internet servers with the addresses *ptbtimeX.ptb.de (X = 1, 2, 3)* serve to synchronize computer clocks in the Internet with UTC(PTB). During the past few years, the number of accesses has increased to approx. 3000 per second.

5. Optical frequency standards

PTB operates optical frequency standards at 429 THz based on ^{87}Sr atoms in an optical lattice and standards at 688 THz and 642 THz based on a single $^{171}Yb^+$ ion. Research is conducted towards a frequency standard at 1 121 THz based on a $^{27}Al^+$ with a Ca^+ logic ion. The experimental setups include lasers stabilised to optical cavities e.g. a cryogenic optical single-crystal silicon cavity [14] and a 48 cm long optical glass resonator with optimised mounting design [15]. Through comparison with other cavity-stabilised lasers and with a strontium lattice clock, a fractional instability of below 1×10^{-16} at averaging times from 1 to 1000 s has been demonstrated.

5.1 Yb^+ 688 THz standard

The 688 THz $^{171}Yb^+$ optical frequency standard uses the λ = 436 nm $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ electric-quadrupole (E2) transition of $^{171}Yb^+$ which has a natural linewidth of 3.1 Hz. The clock transition and the transitions used for cooling and manipulation are easily accessible by diode lasers. The frequency of this unperturbed transition was recommended as a secondary representation of the second with a relative standard uncertainty of 3×10^{-15}. New frequency measurements with respect to PTB´s primary fountain clocks CSF1 and CSF2 have been performed and result in a frequency of f_{E2} = 688 358 979 309 307.82 Hz with a fractional standard uncertainty of 0.36 Hz [5.2×10^{-16}] [16]. The uncertainty is largely dominated by the contribution of the frequency shift due to thermal radiation at room temperature.

5.2 Yb^+ 642 THz standard

The $^2S_{1/2}$ - $^2F_{7/2}$ octupole (E3) transition with its extremely high natural line quality factor Q ~ 10^{23} has been used as a reference in an optical frequency standard at the National Physical Laboratory (UK) [17] and at PTB [18]. Since the octupole transition is extremely weak, high irradiance of the probe laser is required to interrogate this clock transition therefore leading to a considerable ac Stark shift. Recently, a method has been devised [19] and employed [20] to cancel the light shift by a suitable interrogation sequence. The light shift is compensated by a detuning of the clock laser during the interaction pulses of the interrogation. The detuning is controlled by interleaved interrogations with single-pulse Rabi excitations. An additional π pulse removes the linear dependence between the uncompensated light shift and the frequency of the central resonance feature leaving only a third-order dependence. With this method the uncertainty contribution from the light shift can be suppressed to the low 10^{-18} regime.

The frequency has been measured with reference to PTB's CSF1 and CSF2 to be f_{E3} = 642 121 496 772 645.36 Hz with a standard uncertainty of 0.25 Hz [3.9×10^{-16}] [18]. The largest contribution to the systematic uncertainty of the Yb^+ frequency standard in this measurement is the Stark shift caused by the ambient thermal radiation (black body shift), which is in turn limited by the 50% relative uncertainty in the static differential polarisability. A more precise measurement of this property using near-infrared laser radiation and a detailed study of the thermal environment in combination with the suppressed light shift of the probe laser permits a total uncertainty in the low 10^{-18} range. With this exceptionally small uncertainty the Yb^+ octupole clock is currently one of the optical clocks with the smallest estimated uncertainties.

5.3 ^{87}Sr 429 THz standard

PTB has built and operates an ^{87}Sr optical lattice clock [21] where the atoms at a temperature of $\sim$1 μK are confined in a one-dimensional optical lattice operated near a wavelength cancelling the effective AC Stark shift of the clock transition. The physics package is similar to those in other institutes, but uses a nearly horizontal, only slightly tilted lattice beam which allows transporting the atomic sample over several centimeters. The fractional instability of PTB's Sr stationary lattice clock has recently been found [22] as $1.6\times10^{-16}\,(\tau/s)^{-1/2}$, falling off like $\tau^{-1/2}$ into the upper 10^{-18} range. The fractional uncertainty of this clock was estimated to be 3×10^{-17} in 2014 [23] and has been improved to ca. 2.3×10^{-17} since then. The frequency of the optical clock transition $5s^2\ ^1S_0$–$5s5p\ ^3P_0$ has been determined to be 429 228 004 229 873.13(17) Hz with respect to PTB's Cs-fountain clocks CSF1 and CSF2. In order to reduce the uncertainty associated with the black-body radiation shift further, PTB has recently upgraded the stationary Sr clock with a cryogenic environment cooled to temperatures of ca. 85 K. Clock operation at cryogenic temperatures with associated fractional black-body shifts in the low 10^{-18} range has been demonstrated, and characterisation of the system is currently in its final stages. Eventually, this system will allow measurements with total uncertainties of below 1×10^{-17}.

Besides the stationary clock PTB has set up a transportable Sr lattice clock to be used for comparisons of remote optical clocks and for novel applications, e.g. in relativistic geodesy. Moreover, PTB is - involved in a multinational consortium sponsored by the European Union Seventh Framework Program [24] which is developing another transportable standard based on a Sr lattice clock that could be used for space applications [25] at a later time. In contrast to the latter, PTB's transportable Sr clock has not been designed as an ultra-compact clock for space applications, but as a compromise between necessary compactness and mobility on one hand and best possible ultimate uncertainties and accuracy on the other. It will be able to operate at any place in a transportable container with stable environmental conditions. It is in principle not very different from the stationary clocks, but it has several specific features. The diode laser systems have been designed for stability and compactness; they are similar to the ones described in [25]. The transportable standard uses a Zeeman slower with permanent magnets for decelerating the Sr atoms towards the magneto-optic trap in order to reduce the electric power consumption of the system and remove a significant heat source. Since one of the largest contributions to the overall uncertainty of Sr lattice clocks results from the black-body shift, care was taken to achieve a homogeneous temperature environment of the vacuum chamber that can be correctly measured. A low uncertainty is achievable since the sensitivity coefficient is very well established [26].

First measurements with the transportable clock show a fractional instability of 1×10^{-16} at 500 s falling off as $\tau^{-1/2}$. Its frequency agrees with that one of the stationary standards within the current estimated uncertainty of 10^{-15}. From the evaluation of the uncertainty budget very similar to the one presented in [23], a final fractional uncertainty in the low 10^{-17} region is expected. After the final evaluation the transportable clock will be used for comparisons of remote optical clocks and for novel applications, e.g. in combination with fibre links for relativistic geodesy experiments.

5.4 ^{27}Al quantum logic standard (1 121 THz)

Following the pioneering work at NIST operating two $^{27}Al^+$ clocks with estimated fractional uncertainties in the 10^{-18} range [27], PTB has started to set up an optical $^{27}Al^+$ clock in the QUEST Institute (jointly operated with Leibniz Universität Hannover). It is interrogating the transition (λ = 267 nm) between the $^1S_0$ and $^3P_0$ states with vanishing angular momenta (J=0). Such transitions have no quadrupole shift, and only the small nuclear magnetic moments contribute to the linear and quadratic Zeeman shift. Since the transitions usually used for laser cooling and state detection are in the far ultraviolet, an auxiliary so-called *logic ion* provides sympathetic laser cooling, state initialization, and detection for a simultaneously trapped $^{27}Al^+$ clock ion. In PTB's set-up Ca^+ is used as the logic ion, since the transitions for cooling and read out can be addressed with diode lasers [28]. PTB's $^{27}Al^+$ clock will also be capable of being used as a transportable frequency standard for comparisons of remote optical clocks and for novel applications e.g. in combination with fibre links in relativistic geodesy experiments.

6. Optical frequency measurements

PTB operates three femtosecond laser based comb generators dedicated to measuring optical frequencies. Both absolute frequencies (versus the Cs-fountain) and optical frequency ratio measurements are performed regularly. The direct measurement of optical frequency ratios between different optical standards in the same laboratory or remotely will lead to a better evaluation independent from the frequency the caesium clock. A network of phase-coherent optical fibre links connects the optical frequency standards, ultra-stable cavity-stabilised lasers, and comb generators. This is also used to measure, monitor and transfer the exceptional stability of a 1.54 µm master laser stabilised to a cryogenic optical single-crystal silicon cavity [14], which was used to probe the clock transition of the Sr-lattice clock [29].

6.1 Absolute frequency measurements

During the years 2013 to 2015 absolute frequency measurements have been performed with respect to PTB’s primary standards CSF1 and CSF2 for each of the optical clocks (see above). Additionally, a measurement of the hydrogen 1S – 2S frequency has been performed via the optical fibre link (see below) between PTB and the Max-Planck-Institute for Quantum Optics (MPQ) in Garching [30]. With an improved detection method at the hydrogen experiment the 1S-2S frequency was measured to be 2466 061 413 187 018 (11) Hz with a relative uncertainty of 4.5×10^{-15}, confirming the previous measurement obtained with a local caesium clock [31].

6.2 Frequency comparisons via satellites

A frequency comparison between the Sr lattice clocks at NICT and PTB has been performed via two-way satellite time and frequency transfer (TWSTFT) resulting in a fractional difference of $(1.1\pm1.6)\times10^{-15}$ (see ref. [32]). A frequency comparison between the Yb^+ E2 clocks at NPL and PTB has been performed via GPS PPP resulting in a fractional difference of $(1.3\pm1.2)\times10^{-15}$ for a total measurement time of 67 h, with an uncertainty mainly limited by the link instability [33].

6.3 Frequency comparisons and dissemination via optical fibres

PTB has developed techniques to transmit ultra-stable optical carrier frequencies via phase-stabilised optical fibre links. Existing telecom connections with non-polarisation-maintaining fibre are adapted for bi-directional operation to transfer an optical frequency near 194 THz, where the optical loss is only 20 dB/100km. Links exceeding ~100 km length are equipped with bi-directional amplifiers developed at PTB.

Fundamental limits for a given link are predominately given [34] by the free-running fibre noise, the round-trip delay time, shot noise, and non-reciprocity of the fibre path. Technical limitations include interferometer noise [34, 35]. Long-distance links suffer signal-outages and cycle slips, as the attenuation between fibre huts (~20 dB) cannot be compensated by the maximum permissible gain (~15 dB) of bi-directional erbium-doped fibre amplifiers (EDFA), which amplify over a broad spectral band. At PTB, this is addressed by investigating narrow-band amplification (fibre-Brillouin amplification, FBA) [36], and developing fieldable FBA-modules which allow a gain up to 45 dB [37].

In the past three years, research focussed (i) on searching for systematic shifts in very long distance links at the level of 10^{-18} and below [38, 39]; and (ii) on reducing the statistical uncertainty (instability). For the latter aim, installing FBA-modules in fibre huts resulted in better phase-continuity of data and reduced dead-time [37, 39]. Recently, for a 1440 km link, continuous data intervals exceeding 10000 s and an instability (mod$\sigma_y(\tau)$) of 10^{-18} at 100 s were obtained. PTB has built and investigated long-distance links as shown in Table 1.

PTB also developed concepts for disseminating time and frequency to many users [40], and is operating a system for multi-user frequency dissemination continuously since the end of 2013. A traceable optical reference frequency (frequency instability < 5×10^{-15} for 1 s...10000 s) was synthesised by combining short-term (optical) and long-term (rf) reference sources [41], and a concept for synchronizing a remote device (with uncertainty < 1 ns) via an optical frequency link was tested extensively in 2013 [42].

In preparation of a joint French-German link connecting Paris and Braunschweig, a new route looping from Braunschweig to Strasbourg and back to Braunschweig, was set-up: the 1440 km loop link was equipped with three fibre Brillouin amplification modules [39]. Characterization over a measurement period of about three weeks gave a mean fractional frequency offset of the transferred frequency (PTB-Strasbourg-PTB) of $(1.1 \pm 0.4)\times10^{-20}$.

The Braunschweig-Strasbourg-Braunschweig loop link was then converted into two cascaded links, Braunschweig-Strasbourg ("up-link"), and Strasbourg-Braunschweig ("down-link"), with a remote laser station in Strasbourg. This enables phase-coherent comparisons of optical frequencies transmitted to Strasbourg from SYRTE (Paris, via the French fibre link) and from PTB.

Geographical location Length of fibre loop; amplifier type used;	Instability: $\sigma_y(\tau)$; mod$\sigma_y(\tau)$	Total fractional uncertainty (all data)	Duration of continuous (1s) data intervals	Refer-ence
MPQ – PTB – MPQ 1840 km; EDFA;	~ 1×10^{-13} /(τ/s); ~ 5×10^{-15} /$(\tau/s)^2$ for τ <100 s	3×10^{-19}	~ 100 s	[38]
PTB – Wierra – PTB 660 km; FBA;	~ 5×10^{-14} /(τ/s); ~ 6×10^{-16} /$(\tau/s)^2$, for τ < 20 s	1×10^{-19}	> 10000 s	[37]
PTB –Strasbourg – PTB 1440 km; FBA	~ 1×10^{-13} /(τ/s); ~ 2×10^{-15} /$(\tau/s)^2$, for τ < 10 s	1×10^{-20}	> 10000 s	[39]

Table 1: PTB fibre links used in the past for research and frequency dissemination

In two measurement campaigns (MJD 57092 and MJD 57180 – 57187) phase coherent comparisons of the frequencies of the Sr lattice clocks of SYRTE (Paris) and PTB (Braunschweig) have been performed via the newly established link. In both measurements the statistical uncertainty of the clock comparison was below 4×10^{-17} after 10 000s, limited by the instability of the clocks.

A 450-km baseline GPS carrier phase precise point positioning (GPS-CP-PPP) link was realised between PTB and MPQ, and was characterised via the optical fibre link MPQ-PTB in terms of frequency instability and accuracy. An uncertainty for GPS-CP-PPP below 3×10^{-16} was obtained [43].

References:

[1] S. Weyers, U. Hübner, R. Schröder, Chr. Tamm, A. Bauch:
Uncertainty evaluation of the atomic caesium fountain CSF1 of the PTB
Metrologia **38** (4), 343–352 (2001)

[2] S. Weyers, A. Bauch, R. Schröder and Chr. Tamm: *The atomic caesium fountain CSF1 of PTB*
Proc. 6th Symposium on Frequency Standards and Metrology, St. Andrews, September 2001, 64–71

[3] V. Gerginov, N. Nemitz, S. Weyers, R. Schröder, D. Griebsch and R. Wynands:
Uncertainty evaluation of the caesium fountain clock PTB-CSF2
Metrologia **47,** 65–79 (2010)

[4] S. Weyers, V. Gerginov, N. Nemitz, R. Li and K. Gibble:
Distributed cavity phase frequency shifts of the caesium fountain PTB-CSF2
Metrologia **49,** 82–87 (2012)

[5] V. Gerginov, N. Nemitz, S. Weyers:
Initial atomic coherences and Ramsey frequency pulling in fountain clocks,
Phys. Rev. A **90**, 033829 (2014)

[6] A. Zhang, K. Liang, Z. Yang, F. Fang, T. Li, D. Piester, V. Gerginov, S. Weyers, A. Bauch, M. Fujieda, I. Blinov, A. Boiko, Y. Domnin, A. Naumov, Y. Smirnov, A. Sen Gupta, P. Arora, A. Acharya, A. Agarwal
Comparison of Caesium Fountain Clocks in Europe and Asia
Proceedings of the 28th European Frequency and Time Forum (EFTF), Neuchatel, Switzerland, 447–450 (2014)

[7] B. Lipphardt, G. Grosche, U. Sterr, Chr. Tamm, S. Weyers and H. Schnatz:
The stability of an optical clock laser transferred to the interrogation oscillator for a Cs fountain
IEEE Transactions on Instrumentation and Measurement **58**(4), 1258–1262 (2009)

[8] A. Bauch:
The PTB primary clocks CS1 and CS2
Metrologia **42**, S43 – S54 (2005)

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

[10] A. Bauch, S. Weyers, D. Piester, E. Staliuniene, W. Yang:
Generation of UTC(PTB) as a fountain-clock based time scale
Metrologia **49,** 180-188 (2012)

[11] T. Feldmann, A. Bauch, D. Piester, M. Rost, E. Goldberg, S. Mitchell, and B. Fonville:
Advanced GPSbased time link calibration with PTB´S new GPS calibration set-up
Proceedings of the 42th PTTI Systems and Applications Meeting, Reston, VA, USA, 509-526 (2010)

[12] A. Bauch, P. Hetzel, D. Piester:
Zeit- und Frequenzverbreitung mit DCF77: 1959 – 2009 und darüber hinaus
PTB-Mitt. **119**, Heft 3, 217-240 (2009)
See also
A. Bauch, P. Hetzel, D. Piester:
50 years of time dissemination with DCF77
PTB- Mitt. **119**, No. 3, 3-26 (2009), (special issue in English)

[13] D. Piester, A. Bauch, J. Becker, A. Hoppmann:
Time and frequency broadcast with DCF77
Proceedings of the 43rd PTTI Systems and Applications Meeting, Long Beach, CA, USA, 2011

[14] C. Hagemann, C. Grebing, C. Lisdat, S. Falke, T. Legero, U. Sterr, F. Riehle, M. J. Martin, J. Ye:
Ultra-stable laser with average fractional frequency drift rate below 5×10^{-19} */ s*
Opt. Lett., **39,** 5102-5105 (2014)

[15] S. Häfner, S. Falke, C. Grebing, S. Vogt, T. Legero, M. Merimaa, C. Lisdat, U. Sterr:
8×10^{-17} *fractional laser frequency instability with a long room-temperature cavity*
Opt. Lett. **40**, 2112-2115 (2015)

[16] Chr. Tamm, N. Huntemann, B. Lipphardt, V. Gerginov, N. Nemitz, M. Kazda, S. Weyers, and E. Peik, *Cs-based optical frequency measurement using cross-linked optical and microwave oscillators*
Phys. Rev. A **89**, 023820 (2014)

[17] R. M. Godun, P. B. R. Nisbet-Jones, J .M. Jones, S. A. King, L. A. M. Johnson, H. S. Margolis, K. Szymaniec, S. N. Lea, K. Bongs, P. Gill:
Frequency ratio of two optical clock transitions in $^{171}Yb^+$ *and constraints on the time-variation of fundamental constants*
Phys. Rev. Lett. **113**, 210801 (2014)

[18] N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, and E. Peik:
Improved Limit on a Temporal Variation of m_p/m_e *from Comparisons of* Yb^+ *and Cs Atomic Clocks*
Phys. Rev. Lett. **113**, 210802 (2014)

[19] V. I. Yudin, A. V. Taichenachev, M. V. Okhapkin, S. N. Bagayev, C. Tamm, E. Peik, N. Huntemann, T. E. Mehlstäubler, F. Riehle:
Atomic clocks with suppressed blackbody radiation shift
Phys. Rev. Lett. **107**, 030801 (2011)

[20] N. Huntemann, B. Lipphardt, M. Okhapkin, C. Tamm, E. Peik, A. V. Taichenachev, V. I. Yudin:
A generalized Ramsey excitation scheme with suppressed light shift
Phys. Rev. Lett. **109**, 213002 (2012)

[21] S. Falke, H. Schnatz, J. S. R. Vellore Winfred, T. Middelmann, S. Vogt, S. Weyers, B. Lipphardt, G. Grosche, F. Riehle, U. Sterr, C. Lisdat:
The ^{87}Sr *optical frequency standard at PTB*
Metrologia **48**, 399-407 (2011)

[22] A. Al-Masoudi, S. Dörscher, S. Häfner, U. Sterr, C. Lisdat:
Noise and instability of an optical lattice clock
arXiv:1507.04949

[23] S. Falke, N. Lemke, C. Grebing, B. Lipphardt, S. Weyers, V. Gerginov, N. Huntemann, C. Hagemann, A. Al-Masoudi, S. Häfner, S. Vogt, U. Sterr, C. Lisdat:
A strontium lattice clock with 3×10^{-17} *inaccuracy and its frequency*
New J. Phys., **16**, 073023 (2014)

[24] N. Poli, M. Schioppo, S. Vogt, S. Falke, U. Sterr, C. Lisdat, G. M. Tino:
A transportable strontium optical lattice clock
Appl. Phys. B **117**, 1107-1116 (2014)

[25] K. Bongs, Y. Singh, L. Smith, W. He, O. Kock, D. Swierad, J. Hughes, S. Schiller, S. Alighanbari, S. Origlia, S. Vogt, U. Sterr, C. Lisdat, R. Le Targat, J. Lodewyck, D. Holleville, B. Venon, S. Bize,

G. P. Barwood, P. Gill, I. R. Hill, Y. B. Ovchinnikov, N. Poli, G. M. Tino, J. Stuhler, W. Kaenders, and the SOC2 team:
Development of a strontium optical lattice clock for the SOC mission on the ISS
C. R. Physique, **16**, 553-564 (2015)

[26] T. Middelmann, S. Falke, C. Lisdat, U. Sterr:
High Accuracy Correction of Blackbody Radiation Shift in an Optical Lattice Clock
Phys. Rev. Lett. **109**, 263004 (2012)

[27] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, T. Rosenband:
Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks
Phys. Rev. Lett. **104**, 070802 (2010)

[28] J. B. Wübbena, S. Amairi, O. Mandel, P. O. Schmidt:
Sympathetic cooling of mixed-species two-ion crystals for precision spectroscopy
Phys. Rev. A **85**, 043412 (2012)

[29] C. Hagemann, C. Grebing, T. Kessler, St. Falke, C. Lisdat, H. Schnatz, F. Riehle, and U. Sterr:
Providing 10^{-16} Short-Term Stability of a 1.5µm Laser to Optical Clocks
Instrumentation and Measurement, IEEE Transactions on, **62** (6), 1556 – 1562 (2013)

[30] A. Matveev, C. G. Parthey, K. Predehl, J. Alnis, A. Beyer, R. Holzwarth, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, G. Grosche, O. Terra, T. Legero, H. Schnatz, S. Weyers, B. Altschul, T. W. Hänsch:
Precision Measurement of the Hydrogen 1S - 2S Frequency via a 920-km Fiber Link
Phys. Rev. Lett. **110**, 230801 (2013)

[31] C. G. Parthey, A. Matveev, J. Alnis, B. Bernhardt, A. Beyer, R. Holzwarth, A. Maistrou, R. Pohl, K. Predehl, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, T. W. Hänsch:
Improved Measurement of the Hydrogen 1S-2S Transition Frequency
Phys. Rev. Lett. **107**, 203001 (2011)

[32] H. Hachisu, M. Fujieda, S. Nagano, T. Gotoh, A. Nogami, T. Ido, S. Falke, N. Huntemann, C. Grebing, B. Lipphardt, C. Lisdat, D. Piester:
Direct comparison of optical lattice clocks with an intercontinental baseline of 9 000 km
Opt. Lett. **39**, 4072 (2014)

[33] J. Leute, N. Huntemann, B. Lipphardt, Chr. Tamm, P. B. R. Nisbet-Jones, S. A. King, R. M. Godun, J. M. Jones, H. S. Margolis, P. B. Whibberley, A. Wallin, M. Merimaa, P. Gill, E. Peik:
Frequency comparison of $^{171}Yb^+$ ion optical clocks at PTB and NPL via GPS PPP
arXiv:1507.04754, IEEE Trans. UFFC (submitted)

[34] P. A. Williams, W. C. Swann, N. R. Newbury:
High-stability transfer of an optical frequency over long fiber-optic links
J. Opt. Soc. Am. B **25**, 1284-1293 (2008)

[35] G. Grosche, O. Terra, K. Predehl, R. Holzwarth, B. Lipphardt, F. Vogt, U. Sterr and H. Schnatz:
Optical frequency transfer via 146 km fiber link with 10^{-19} relative accuracy
Opt. Lett. **34**, 2270-2272 (2009)

[36] O. Terra, G. Grosche, H. Schnatz:
Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber
Opt. Express, **18**, 16102-16111 (2010)

[37] S. M. F. Raupach, A. Koczwara and G. Grosche:
Optical frequency transfer via a 660 km underground fiber link using a remote Brillouin amplifier
Opt. Express **22**, 26537 (2014)

[38] S. Droste, F. Ozimek, T. Udem, K. Predehl, T. W. Hänsch, H. Schnatz, G. Grosche and R. Holzwarth:
Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link
Phys. Rev. Lett. **111**, 110801 (2013)

[39] S. M. F. Raupach, A. Koczwara, G. Grosche:
Brillouin amplification supports 10^{-20} accuracy in optical frequency transfer over 1400 km of underground fibre
Phys. Rev. A **92**, 021801 (R) (2015)

[40] G. Grosche:
Eavesdropping time and frequency: phase noise cancellation along a time-varying path, such as an optical fiber
Opt. Lett. **39**, 2545-2548 (2014)

[41] S. M. F. Raupach, T. Legero, C. Grebing, Ch. Hagemann, T. Kessler, A. Koczwara, B. Lipphardt, M. Misera, H. Schnatz, G. Grosche and U. Sterr:
Subhertz-linewidth infrared frequency source with a long-term instability below 5×10^{-15}
Appl. Phys. B **110**, 465 (2013)

[42] S. Raupach and G. Grosche: *Chirped frequency transfer: a tool for synchronization and time transfer*
IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, **61** (6), 920-929, (2014)

[43] S. Droste, C. Grebing, J. Leute, S. Raupach, A. Matveev, T. Hänsch, A. Bauch, R. Holzwarth and G. Grosche:
Characterization of a 450-km baseline GPS carrier-phase link using an optical fiber link
New Journal of Physics, provisionally scheduled for August 2015