Physikalisch-Technische Bundesanstalt (PTB), Germany

Report on PTB's activities to the 21st Session of the Consultative Committee for Time and Frequency, June 2017

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

1. primary clocks
2. atomic time scales
3. time and frequency comparisons
4. time and frequency dissemination
5. optical frequency standards/clocks
6. frequency comparisons via optical fibers

1. Primary clocks

1.1 Operation of the fountain clocks CSF1 and CSF2

During the reporting period, the primary caesium fountain clocks PTB-CSF1[1],[2] and PTB-CSF2[3],[4] have been operated at normal operating conditions most of the time. In this operation mode the fountains have been used for a multitude of measurements of the TAI scale unit, for daily steering of the timescale UTC(PTB), for international fountain clock comparisons and for optical frequency measurements.

The frequency synthesis for both fountains now routinely makes use of an optically stabilized microwave oscillator instead of employing quartz based microwave synthesis [5]. As a result CSF1 and CSF2 operate in the quantum projection noise limited condition and achieve frequency instabilities of $9.0 \times 10^{-14}\,(\tau/\mathrm{s})^{-1/2}$ and $2.5 \times 10^{-14}\,(\tau/\mathrm{s})^{-1/2}$, respectively, for operation with high atom numbers (densities). The current systematic frequency uncertainties u_{B} of CSF1 and CSF2 are 3.5×10^{-16} and 2.0×10^{-16}, respectively.

During the years 2015 and 2016 in total 14 TAI scale unit measurements by CSF1, and 13 by CSF2, have been submitted to the BIPM. In most cases the respective durations of these measurements range from 20 to 30 days. Operation dead times are typically limited to less than 5% of the total measurement interval, which results in related uncertainty contributions $u_{\mathrm{l/lab}}$ significantly below 10^{-16}. Statistical measurement uncertainties u_{A} are at the level of 1×10^{-16} for both fountains. Given the PTB's low TAI link uncertainties $u_{\mathrm{l/TAI}}$ (e.g. 1.3×10^{-16} for a 30 d interval), the typical overall uncertainties of TAI scale unit measurements (including u_{A}, u_{B}, $u_{\mathrm{l/lab}}$, $u_{\mathrm{l/TAI}}$) are 4.0×10^{-16} for CSF1 and 2.6×10^{-16} for CSF2.

Since 2010 fountain data has been regularly used for the daily steering of a hydrogen maser output frequency to realize UTC(PTB). For this purpose the availability of frequency measurement data fountain–maser for at least 6 hours of a day has been determined. Details about the performance of UTC(PTB) are presented in section 2.

In June 2015, CSF1 and CSF2 participated in a European clock comparison campaign, during which various optical and caesium fountain clocks were running simultaneously for a direct remote comparison over three weeks via Two-Way Satellite Time and Frequency Transfer and Global Positioning System frequency transfer. While the evaluation of the international comparisons is still ongoing, the evaluations of the simultaneous internal PTB absolute optical clock frequency measurements ($^{171}Yb^{+}$ octupole transition, ^{87}Sr $^{1}S_{0}$–$^{3}P_{0}$ transition) performed with CSF1 and CSF2 show good agreement with previously obtained results at PTB and elsewhere. During the measurement campaign both fountain frequencies agreed at the low 10^{-16} level, well within the combined fountain clock uncertainties.

At the same time, a comparison of the two PTB fountain clocks with two fountain clocks, FO1 and FO2, at the French SYRTE has been performed via an optical fibre link. As a result, the measured frequency differences for the four individual pairs of distant caesium fountain clocks, were all in the range $\pm 3 \times 10^{-16}$, which is fully compatible with the combined uncertainties [6].

1.2 Research work on the fountain clocks

Since a new evaluation of the effect of cavity phase gradients was performed on CSF1, the previous microwave power dependence entry in the uncertainty budget has become obsolete. A publication about the findings together with the results of a new evaluation of other significant physical effects is in preparation. Until the results will be published, it has been decided not to go below the previous lower limit of 1×10^{-16} for individual systematic uncertainty contributions with the exception of the newly determined gravitational redshift uncertainty (see below).

For CSF2 the utilization of a low-velocity intense source (LVIS) of atoms for loading of the optical molasses resulted in a modified atom cloud shape which necessitated a new evaluation of frequency shifts caused by cavity phase gradients and microwave lensing. The significant atom number increase due to the cold atom beam loading [7], resulted in a frequency instability improvement, which enables online evaluations of the collisional frequency shift during fountain measurement campaigns. As a result the dominating statistical uncertainty component of the collisional shift determination is now included in the statistical uncertainty u_{A} of a CSF2 frequency measurement, lowering the systematic uncertainty u_{B} at the same time.

While in CSF1 an interferometric switch is utilized to inhibit frequency shifting interactions of the atoms with the microwave field outside of the Ramsey cavity, in CFS2 a phase coherent microwave frequency detuning technique has been investigated as an alternative [8]. Based on investigations utilizing a homemade phase transient analyzer, potential cycle synchronous microwave phase distortions can be excluded for both fountains at the 2×10^{-17} uncertainty level [9].

Within the project “Times scales with optical clocks” (JRP55 ITOC) of the European Metrology Research Program, the gravity potential for CSF1 and CSF2 was newly determined with respect to the conventional zero potential W_0(IERS2010) = 62 636 856.0 $\mathrm{m^2s^{-2}}$. As a result of these investigations the gravitational redshift corrections of CSF1 and CSF2 have been changed by about $+2 \times 10^{-17}$. While the uncertainties of the new gravitational redshift corrections are at the level of 2×10^{-18} only, an uncertainty of 3×10^{-17} is taken into account in the fountain uncertainty budgets, as at present there is no exact and internationally accepted geoid definition, i.e. agreed zero potential value.

1.3 Thermal beam clocks

PTB’s primary clocks CS1 and CS2 [10] represent the state-of-the art of clock making of the 1980s, with CS1 having been refurbished a last time in 1996/1997. The clocks’ operational parameters are periodically checked 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. 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.

Subsequently we report on the clocks’ performance during 2015 and 2016. Time differences UTC(PTB) - clock in the standard ALGOS format were reported to BIPM so that $u_{\mathrm{l/lab}}$ is zero. The mean relative frequency offset y(CS1 – CS2) amounted to -5.54×10^{-15}, which is compliant with the stated u_{B} values.

CS1

The CS1 relative frequency instability $\sigma_y(\tau = 1\ \text{hour})$ 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 3) was 4.9×10^{-15}, within the value $u_A(\tau = 30\text{ d, CS1}) = 6\times10^{-15}$ stated in Circular T. Three reversals of the CS1 beam direction were performed. No findings call for a modification of the previously stated relative frequency uncertainty u_B, which is 8×10^{-15} for CS1 [11].

<u>CS2</u>

The relative CS2 frequency instability of $\sigma_y(\tau = 1\text{ hour})$ was measured between 65×10^{-15} and 80×10^{-15}. This range of values justifies the estimate of the uncertainty contributions u_A as $u_A(\tau = 30\text{ d, CS2}) = 3\times10^{-15}$. The standard deviation of the 24 d-values reported in Circular T amounted to 3.2×10^{-15} which is marginally. Four reversals of the CS2 beam direction were performed. The uncertainty estimate as detailed in [10] 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 [12]. Thereby the long-term stability and accuracy of PTB's fountain clocks CSF1 and CSF2, could be combined with the short-term frequency stability of the maser. During 2015 and 2016 fountain data were used to calculate the steering each day except four, which ensured that the time difference between UTC(PTB) and UTC was always less than 5.6 ns and the mean monthly rate differences never exceeded 0.09 ns/day.

Since MJD 56079 0:00 UTC (1st June 2012) the free atomic time scale TA(PTB) has been generated similar to UTC(PTB) from an active hydrogen maser, steered in frequency. 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. The time offset between TAI and TA(PTB) is arbitrary and not limited.

3. Time and Frequency Comparisons

PTB has continued to provide GPS and GLONASS observation data collected with different receivers. The primary receivers are two legacy 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 dual frequency multi-channel receivers (GPS and GLONASS), PT05 (failed mid 2016), PT07 and PT10 (since February 2017). PT05 was used for GLONASS links to PTB, PT07 provides L1C single frequency data. PTB is currently preparing a new receiver tracking all GNSSs that possibly could substitute PT02 in the future. Currently PTB operates five GNSS receivers that provide also Galileo observation data. The calibration of the Galileo signal delays in the receivers followed the recipe published by Defraigne et al. [13]. One receiver provides calibrated GPS and Galileo data for the determination of the GPS to Galileo time offset. Since mid 2015 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 [14]. Recently, PTB provided the calibration of the time transfer equipment in BEV, DLR, METAS, VSL (Cal-Id. 1012-2016).

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 2017) AOS, INRiM, LNE-SYRTE, METAS, NIST, NPL, 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 repeatedly below 1 ns (1 σ). The current calibration value is based on the October 2016 result (CI 395).

The TWSTFT network connecting European and Asian stations has undergone many changes during recent years. Currently, the Russian satellite AM22 provides connectivity between NIM, NTSC, PTB, and VNIITRI (i. e. not to Japan and Taiwan). This situation will likely change again in 2017 as the satellite is about to get an unstable orbit that will render further use 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.

Optical frequency comparisons and optical frequency dissemination via optical fibre are reported in section 6.

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 [15,16].

For over 20 years in Europe, the Europäische Funkrundsteuerung GmbH (EFR) has been using three long wave transmitters for the encrypted transmission of various data services: DCF49, Location Mainflingen (near Frankfurt / Main), Germany, carrier frequency: 129.1kHz, DCF39, Location Burg (near Magdeburg), Germany, carrier frequency: 139.0kHz, and HGA22, Location Lakihegy (near Budapest), Hungary, carrier frequency: 135.6kHz. The three transmitters, each with a range of about 500 km, give reliable coverage over a large part of Central Europe. They use a "Frequency-Shift Keying" (FSK) modulation to embed the information of the different data services in the respective carrier frequency. With a transmission capacity of 200 baud these transmitters enable much faster data transmission than the "classic" technique of the AM modulated time signal transmitter, such as DCF77. The EFR transmitters now also broadcast time-of-day information derived locally and autonomously using GPS receivers at the transmitter sites and meteorological information. EFR and PTB agreed to install a monitoring system for the EFR signals received at PTB which provides comparison of the timing information obtained with legal time as realized in the PTB time laboratory.

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 has been updated to accommodate the IP-based telephony technology that shall be used nation-wide in the future, abandoning the more traditional ISDN-based telephony until the end of 2018.

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) by means of the Network Time Protocol (NTP)[17]. During the past few years, the number of accesses has increased to approx. 6000 per second. Since last year, PTB is also offering a secured NTP time service. This service provides authenticity of the time server and integrity protection of the time synchronization packets as required by the smart grid initiative of the German Federal Ministry of Economic Affairs and Energy. It utilizes NTP’s pre-shared key approach.

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. Two femtosecond frequency comb generators and a network of phase-coherent optical fiber links are used to link the standards to stable reference lasers and to connect them for optical frequency ratio measurements and to the primary Cs fountain clocks. The stable reference lasers include a 1.5 µm fibre laser stabilised to a cryogenic optical single-crystal silicon cavity [18] and a 48 cm long optical glass resonator with optimised mounting design [19]. 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. Research is conducted towards a frequency standard at 1 121 THz based on a $^{27}Al^+$ with a Ca^+ logic ion, and on new reference systems: the Th-229 nuclear resonance, multiple In^+ ions and highly charged ions.

Investigations about the quality of a time scale have been performed that is referenced to an optical clock, which does not operate in a nearly continuous fashion.[20] A formalism was developed that allows for a simple estimation of the uncertainty introduced by a fly wheel oscillator like a maser, which bridges the downtimes of the optical clock. For the noise characteristics of a maser operating at PTB and an availability of the optical clock of about about 50 %, the uncertainty of the timescale can be improved to about 200 ps over a 25 days period.

5.1 Yb$^+$ 688 THz standard

The 688 THz optical frequency standard is based on the $\lambda = 436$ 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. Its frequency is recommended as a secondary representation of the second (SRS) with an estimated relative standard uncertainty of $6 \cdot 10^{-16}$. The frequency was measured again in October 2014 using the PTB caesium fountain clocks CSF1 and CSF2 as references. The result, $f(^{171}Yb^+$ E2) = 688 358 979 309 308.02(23) Hz, is consistent with the SRS recommendation and with the last previous measurements performed at PTB[21] and at the UK National Physical Laboratory (NPL)[22]. The uncertainty budget of the 2014 measurement for the realization of the unperturbed Yb^+ transition frequency was the same as reported in Ref. 21. The uncertainty estimates for the reference clocks CSF1 and CSF2 were as noted in the TAI reports.

5.2 Yb$^+$ 642 THz standard

The 642 THz optical frequency standard is based on the $\lambda = 467$ nm $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ electric-octupole (E3) transition of $^{171}Yb^+$. The transition is recommended as an SRS with an estimated relative standard uncertainty of $6 \cdot 10^{-16}$. The extremely low oscillator strength of the transition requires the use of excitation protocols that suppress the excitation-related light shift and its fluctuations[23]. A measurement of the differential scalar polarizability of the transition in the near-infrared range has strongly reduced the contribution of blackbody radiation to the realization uncertainty of the unperturbed transition frequency at room temperature[24]. Using a correspondingly improved uncertainty estimate, the E3 frequency was measured again in June 2015 as $f(^{171}Yb^+$, E3) = 642 121 496 772 645.13(16) Hz against the reference clocks CSF1 and CSF2 of PTB, whose uncertainty estimates were as noted in the TAI reports. The measured frequency is in good agreement with previous measurements and with the SRS value.

Simultaneously with the absolute frequency measurement, also the optical frequency ratios between the $^{171}Yb^+$ E3 and E2 standards and between the $^{171}Yb^+$ E3 and the ^{87}Sr (429 THz) standard of PTB were measured. In simultaneous operation of two Yb^+ traps, the E3-E2-ratio was determined as $f(^{171}Yb^+, E3) / f(^{171}Yb^+, E2) = 0.932\,829\,404\,530\,965\,41(13)$. The $^{171}Yb^+$ E3 - ^{87}Sr frequency ratio was measured as $f(^{171}Yb^+, E3) / f(^{87}Sr) = 1.495\,991\,618\,544\,900\,642(35)$ with a relative standard uncertainty of $2.4 \cdot 10^{-17}$. For these measurements, the respective uncertainty estimates of the standards are given by Refs. 20,21,24. A publication that includes these results is currently in preparation at PTB.

5.3 ^{87}Sr 429 THz standard

PTB has built and operates an ^{87}Sr optical lattice clock [25] 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 [26] as 1.6×10^{-16} $(\tau/\mathrm{s})^{-1/2}$, 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 (see[27]). The frequency of the optical clock transition $5s^2\ {}^1S_0$–$5s5p\ {}^3P_0$ has been determined to be 429 228 004 229 873.04(11) Hz with respect to PTB's Cs-fountain clocks CSF1 and CSF2. Moreover, the Sr lattice clock was evaluated by comparison against the Sr lattice clock at SYRTE, France. showing an agreement of both at a combined fractional uncertainty of 5×10^{-17}. Repeated frequency ratio measurements against the Yb^+ 642 THz standard over a time span of several years show consistent results on the level of about 3×10^{-17}.

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 about 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.[28,29] Moreover, PTB is involved in a multinational consortium sponsored by the European Union Seventh Framework Program [30] which is developing another transportable standard based on a Sr lattice clock that could be used for space applications [31,32] 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 can be operated at any place in a transportable container with stable environmental conditions. The diode laser systems have been designed for stability and compactness; they are similar to the ones described in[28]. 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 electrical power consumption of the system and remove a significant heat source.

The first evaluation of the transportable clock showed a fractional instability of 1×10^{-15} in 1 s falling off as $\tau^{-1/2}$. Its frequency agrees with that one of the stationary standards within the current estimated uncertainty of 7×10^{-17}. The transportable clock has been used in two measurement campaigns in cooperation with INRIM, Italy. Here, a relativistic geodesy experiment has been performed by operating the transportable Sr clock in the Alps and comparing its frequency via a fibre link with the Cs fountain clock of INRIM. In addition, the Sr system has been compared at INRIM against the Yb lattice clock there.

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 [33], PTB has started to set up two optical $^{27}Al^+$ clocks in the QUEST Institute (jointly operated with Leibniz Universität Hannover), one laboratory and one transportable system. They are based on the ${}^1S_0$-${}^3P_0$ clock transition (λ = 267 nm) in which the electric quadrupole shift is strongly suppressed, 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-ups Ca^+ is used as the logic ion, since the transitions for cooling and read out can be addressed with diode lasers [34]. Evaluation of the laboratory system is currently underway. PTB's transportable $^{27}Al^+$ 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. Frequency comparisons via optical fibers

PTB develops[35 36], implements [35 37 38], tests [37] and uses[39 38 6] techniques for frequency comparisons and frequency dissemination via optical fibres, based on transmitting ultra-stable optical carrier frequencies via phase-stabilised optical fibre links.

Since 2007, PTB adapts existing telecom fibre connections for bi-directional operation in an optical interferometric set-up[40] 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. Fundamental limits include any non-reciprocity of the optical path[41], technical limitations include interferometer and link laser noise [41 40]. The main challenge in long-distance links is the overall signal attenuation (> 300 dB on a 1500 km link). Links may suffer signal-outages and cycle slips, when 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). At PTB, this is addressed by using narrow-band amplification (fibre-Brillouin amplification, FBA) [42], and more recently, implementing fieldable FBA-modules which allow a gain up to 45 dB [35 37].

Research at PTB aims to (i) reduce the statistical uncertainty and (ii) increase reliability of the overall link set-up, developing monitoring and automated re-locking of constituent instrumentation. For example, for a 1440 km link equipped with three specially developed FBA-modules, an instability (mod $\sigma_y(\tau)$) of 10^{-18} at 100 s, and phase-continuous data intervals exceeding 10000 s were achieved[37], the latter an improvement of two orders of magnitude for such distance.

PTB also develops concepts for disseminating time and frequency to many users (based on [36]) and is operating a multi-user frequency dissemination system continuously since 2014 to support the Al^+ clock development at PTB[34]. For dissemination, a traceable optical reference frequency (frequency instability < 5×10^{-15} for 1 s...10000 s) is synthesised by combining short-term (optical) and long-term (rf) reference sources (similar to [43]).

Frequency comparisons via optical fibre allowed the characterisation of a 450-km baseline GPS carrier phase precise point positioning (GPS-CP-PPP) link set up between PTB and MPQ Garching near Munich, in terms of frequency instability and accuracy. An uncertainty for GPS-CP-PPP below 3×10^{-16} was obtained[39].

To prepare the joint French-German link connecting Paris and Braunschweig, a new route looping from Braunschweig to Strasbourg and back to Braunschweig, was set-up: characterization gave a mean fractional frequency offset of the transferred frequency (PTB-Strasbourg-PTB) of $(1.1 \pm 0.4) \times 10^{-20}$ [37]. It 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. PTB has built and investigated long-distance links as shown in Table 1.

Since 2015, the newly established phase-stabilised connection to Strasbourg has supported optical frequency comparisons between SYRTE and PTB; thus the fountain clocks[6] and the strontium optical lattice clocks at both NMIs[38] have been compared in 2015. For both experiments, agreement was found within the uncertainty of the clocks. The contribution of the phase-stabilised fibre link and measurement set-up was negligible, at or below 2×10^{-19} for the strontium lattice clock comparison[38].

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} /(τ/s)^2 for τ <100 s	3×10^{-19}	~ 100 s	[44]
PTB – Wierra – PTB 660 km; FBA;	~ 5×10^{-14} /(τ/s); ~ 6×10^{-16} /(τ/s)^2, for τ < 20 s	1×10^{-19}	> 10000 s	[35]
PTB –Strasbourg – PTB 1440 km; FBA	~ 1×10^{-13} /(τ/s); ~ 2×10^{-15} /(τ/s)^2, for τ < 10 s	1×10^{-20}	> 10000 s	[37]

Table 1: PTB fibre links characterised in the recent past for frequency comparisons

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