Physikalisch-Technische Bundesanstalt (PTB), Germany

Report on PTB's activities to the 19th Session of the Consultative Committee for Time and Frequency, September 2012

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. 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), and as reference clock for the evaluation of the fountain CSF2 (see below) and for optical frequency measurements. The current frequency instability and systematic frequency uncertainty of CSF1 are $1.4 \times 10^{-13}\cdot(\tau/\mathrm{s})^{-1/2}$ and 7.4×10^{-16}, respectively.

For TAI scale unit measurements, CSF1 is continuously operated, routinely achieving dead times of less than 1% of the total measurement interval. Between 2010 and 2012 in total 18 TAI scale unit measurements by CSF1 have been submitted to the BIPM. The respective durations of these measurements range from 15 to 30 days. The small amount of dead times results in related uncertainty contributions u_{Lab} of much less than 10^{-16}.

Since early 2010 CSF1 is used for steering the hydrogen maser-based time scale UTC(PTB) [3] (see also below). The performance of UTC(PTB) benefits from the high level of availability of CSF1: Until today, steering corrections from CSF1 were available on >95% of the whole number of days.

Furthermore, between 2009 and 2010 CSF1 served as reference frequency standard for a couple of optical frequency measurements. Among them was the measurement of the 1S –2S transition frequency in atomic hydrogen at the Max-Planck-Institut für Quantenoptik, Garching/Munich, via a 920 km optical fibre link [4] and the measurement of the $^1S_0 - {}^3P_1$ transition frequency in laser-cooled ^{24}Mg at the University of Hannover, via a 70 km optical fibre link [5]. At PTB, the $^1S_0 - {}^3P_0$ transition frequency of ^{87}Sr [6] and the $^2S_{1/2} - {}^2F_{7/2}$ electric octupole transition frequency in a single trapped $^{171}Yb^+$ ion were measured [7] (see also below).

1.2 Fountain clock CSF2

A full uncertainty evaluation of CSF2 was performed in 2009 [8]. The fountain uses a (1,1,1) molasses beam configuration, which allows for a large atom cloud size and thus reduced collisional shift and distributed cavity phase (DCP) error contributions compared to CSF1. The total CSF2 systematic uncertainty was limited to 8×10^{-16}, dominated by the uncertainties of the collisional shift and the microwave power dependence.

In 2010, a renewed investigation of DCP errors in CSF2 led to an explanation of the microwave power dependence and to a new DCP uncertainty evaluation [9]. A method for cloud position determination in the Ramsey cavity of CSF2 was developed, allowing the position of the atoms participating in the clock transition interrogation to be estimated directly from the asymmetries in transition spectra with 0.1 mm accuracy [10]. The evaluation of DCP errors together with the cloud position determination allowed the DCP uncertainty contribution to be reduced to 1.3×10^{-16}. Combined with statistically improved collisional shift measurements, these developments led to a total CSF2 systematic uncertainty of 4.1×10^{-16}.

In 2010, a new microwave frequency synthesis setup [11] identical to the one used in the fountain CSF1 has been introduced in the CSF2 electronics setup. The new synthesis setup is capable of providing instabilities, and correspondingly statistical uncertainties of CSF2, below the 1×10^{-16} level. The sidebands suppression in the new synthesis setup allowed the electronics contribution to the fountain uncertainty budget to be reduced from 2×10^{-16} to 1×10^{-16}.

The collisional shift measurement in a fountain requires a change of the atom cloud density. Until 2011, the cloud density in CSF2 was changed by variation of the microwave amplitude in the state selection cavity. The accuracy of the method was limited to ~10% by systematic variations in the cloud local density distribution between high and low atom densities. In 2011, the method of rapid adiabatic passage for changing the atom density [12] was introduced in CSF2 [13]. The method reduces the local density variations between high and low atom densities, and thus the systematic uncertainty of the collisional shift, to below 1%. At present, the collisional shift uncertainty is given by the statistical measurement uncertainty of the slope factors obtained during the last three consecutive fountain evaluations. With this procedure, a collisional shift uncertainty of 2.7×10^{-16} is obtained.

With these last developments, the total systematic uncertainty of CSF2 is 3.4×10^{-16}.
Continued frequency comparisons between the fountains CSF1 and CSF2 show agreement within the uncertainties of the standards.

1.3 Thermal beam clocks

PTB continues to operate its thermal beam primary clocks CS1 and CS2 [14] as backup frequency references for the realization of its time scales UTC(PTB) and TA(PTB). 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. The clocks have been operated continuously (note the exemption for CS2 in late 2010), and time differences $\{UTC(PTB) - clock\}$ in the standard ALGOS format were reported to BIPM so that $u_{\mathrm{l/lab}}$ is zero.

CS1

Based on repeated comparisons with an active hydrogen maser, the CS1 relative frequency instability was found to vary between 70×10^{-15} and 85×10^{-15} for an averaging time of 1 hour during the recent years. This is in agreement with the prediction based on the beam flux, clock transition signal and line width. With reference to TAI, the monthly values of d(CS1) (Circular T Section 4) reported during the last three years showed a standard deviation of less than the value $u_{\mathrm{A}}(\tau = 30\ \mathrm{d, CS1}) = 6 \times 10^{-15}$ which is stated in Circular T. The findings did not call for a modification of the previously stated relative frequency uncertainty, u_{B}, of 8×10^{-15} [15].

CS2

PTB's primary clock CS2 was out of operation between 1st September and early November 2010. Both caesium ovens had become empty, one already in summer 2008. It was decided to re-start CS2 operations with a minimum of intervention to the vacuum and atomic beam forming system. The two caesium ovens were refilled and part of the (outdated) vacuum measurement equipment was replaced. The CS2 oven temperature was adjusted so that a relative frequency instability of $\sigma_{\mathrm{y}}(\tau = 1\ \mathrm{hour})$ between 65×10^{-15} and 75×10^{-15} has been obtained. This value justifies the estimate of the uncertainty contribution $u_{\mathrm{A}}(\tau = 30\ \mathrm{d, CS2}) = 3 \times 10^{-15}$.

Six reversals of the beam direction were performed in the meantime, and the beam reversal frequency shift (due to end-to-end cavity phase difference) was found unchanged from the values obtained before summer 2008 with a statistical uncertainty of 5×10^{-15}. The uncertainty estimate as detailed in [14, 15] is considered as still valid, and u_B(CS2) is thus estimated as 12×10^{-15}.

2. Time Scales

PTB has substantially improved the quality of its local time scale UTC(PTB) which has been realized using an active hydrogen maser 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 AHM and primary and commercial caesium clocks of PTB [3]. Thereby the long-term stability and accuracy of PTB's primary clocks, in particular its fountain clock CSF1, could be combined with the short-term frequency stability of the maser. CSF1 data were used to calculate the steering on more than 95% of all days which ensured that during the last 30 months the time difference between UTC(PTB) and UTC was always less than 6 ns and the mean monthly rate differences never exceeded 0.14 ns/day.

Starting MJD 56079 0:00 UTC (1st June 2012) TA(PTB) is generated alike to UTC(PTB) from an active hydrogen maser, steered in frequency so as to follow PTB CSF1 as close as possible. The deviation *d* between CSF1 seconds and the TAI second is not taken into account. The rate of TA(PTB) is intended to represent CSF1 as if it was operated on the geoid. TA(PTB) has got an initial arbitrary offset from TAI without continuity to the values reported up to then.

3. Time and Frequency Comparisons

PTB has continued to provide GPS and GLONASS observation data such that time transfer links to all institutions participating in the realization of TAI by BIPM can be established reliably. To this end PTB provides data of one single frequency and one dual frequency multi-channel receiver (GPS and GLONASS), and of its IGS-registered geodetic time-oriented receiver. PTB provides as backup data from two further receivers which could in principle allow seamless availability of all kinds of required data.

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 AOS, INRiM, IPQ, LNE-SYRTE, METAS, NIST, NPL, OCA, ROA, SP, USNO, and VSL.

The completely independent TWSTFT link between USNO and PTB, with transponder frequencies in the X-band, unfortunately had to be abandoned as access to the satellite was denied by the operating agency.

The TWSTFT network connecting European and Asian stations has undergone many changes during recent years and is not in a particularly firm condition. Currently the Russian satellite AM2 is used, the antenna footprint of which allows observation not further west than the location of Braunschweig. Therefore currently PTB and VNIIFTRI are the only European stations participating. KRISS, NICT, NIM, NPLI, NTSC, and TL participate on the Asian side.

During 2009 – 2012 one combined GPS / GLONASS calibration through a roving TTS-3 receiver of BIPM was performed. Since 2010 ROA has coordinated the EURAMET Technical Committee for Time and Frequency (TC-TF) Project 1156, GPSCALEU, a reaction from EURAMET TC-TF to Recommendation 2 of CCTF 2009. Starting that year, a GPS calibration campaign between three contributing laboratories was organized: ROA (Spain), PTB (Germany) and INRIM (Italy). The time transfer results were achieved by using P3 and also carrier phase PPP data, and they were also used to re-calibrate the TWSTFT links between labs [16]. PTB has supported this project and has developed a mobile GPS calibration unit [17] which was used in calibrations involving METAS (2009), USNO (2010), NPL (2010), NICT (2011), and BKG (2011). Each of the campaigns provided a calibration of all existing links between the visited institutes and PTB with a an uncertainty (1 σ) of the order 1.2 ns which is considered valid at the epoch of the campaign. ROA is about to conduct a second repetition of the initial campaign to study the reproducibility of results.

USNO has continued to support calibrations of the link between USNO and PTB. In addition to the GPS-based calibration two calibrations using a fly-away TWSTFT terminal took place. The results were provided by USNO and are given in Table 1. In the table, column 3 is the measured time difference at the epoch of the calibration, and column 4 is how much should be added to the value of USNO-PTB according to the current calibration. The combined uncertainty for each calibration is estimated to be about 1 ns (1 σ).

Table 1: Results of USNO-PTB calibrations.

MJD	Calendar Date	USNO-PTB	Cal-Circular T	Technique/Ref
55301	15 APR 2010	-19.1 ns	-1 ns	GPS [17]
55649	29 MAR 2011	0.1 ns	+2 ns	TWSTFT
56072	25 MAY 2012	0.8 ns	+1 ns	TWSTFT

A means for accurate time scale comparisons on PTB campus using a dark telecommunication fiber has been developed [18]. The technique is a variant of the standard TWSTFT by employing an optical fiber in the transmission path instead of free-space transmission of signals between ground stations through satellites. It has been demonstrated that this technique is capable to provide time scale comparisons on intermediate distances up to 100 km with an uncertainty well below 100 ps [19].

4. Time and Frequency Dissemination

PTB has used over the years different procedures to disseminate time and frequency information to the general public and to use it for 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. With DCF77, the time and date of legal time are transmitted in an encoded form via the second marks. In 2009, in memory of 50 years of DCF77 broadcasting, a detailed description of the service was provided [20, 21].

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. 1700 calls per day) comes from the measuring stations along gas pipelines in Germany.

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 and conducts research into an optical frequency standard based on ^{87}Sr atoms in an optical lattice (429 THz), and standards at 688 THz and 642 THz based on single $^{171}Yb^{+}$ ions in a Paul trap. The experimental setups include femtosecond frequency comb generators equipped for absolute and optical frequency ratio measurements. A network of phase-coherent optical fiber links connects the comb generators and can be used to transfer the exceptional stability of a newly developed master-1.5 μm fiber laser stabilized to an optical cavity machined from single-crystal silicon cavity [22] to the interrogation lasers of the optical standards. The cavity is operated at the zero-point of its thermal expansion at a temperature of 124 K and is supported in a vibration-insensitive configuration. The low operating temperature and the superior thermo-mechanical properties of silicon set the thermal noise limit for the fractional frequency stability of the laser to a level of $\sigma_y \sim 6 \times 10^{-17}$. This value is lower by a factor of three compared to state-of-the-art resonators operated at room temperature. In a three-cornered hat comparison with two conventional laser systems the silicon cavity stabilized laser has demonstrated short-term stabilities of mod $\sigma_y = 1 \ldots 3 \times 10^{-16}$ between 0.1 and 10 seconds and supports a laser linewidth of <40 mHz at 1.5 μm, representing an optical quality factor of 4×10^{15}.

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. Based on previous absolute frequency measurements and comparisons between two traps at PTB [23, 24], in 2006 the unperturbed frequency of this transition was recommended as a secondary representation of the second with a relative standard uncertainty of 9×10^{-15} [25].

In August and September 2008, three new absolute frequency measurements were carried out after upgrades of the experimental setup of the $^{171}Yb^+$ standard. In particular, the software control of the equipment and of the measurement sequence was extended and the applied static magnetic field was controlled more accurately. The extended software control made it possible to routinely achieve unattended continuous operation over more than 24 h. Using a differential servo scheme, the tensorial shift of the reference transition frequency and its temporal variation over 70 days was determined [26]. A maximum relative shift magnitude of 7×10^{-16} (0.5 Hz) was observed. Presumably the dominant contribution to the observed shift results from the quadrupole shift due to the electrostatic stray field gradient at trap center.

The results of the 2008 measurements showed a relative spread of only 3×10^{-16}. The relative systematic uncertainty of the realization of the $^{171}Yb^+$ E2 transition frequency at room temperature was 5×10^{-16} so that it was smaller than the uncertainty of the reference clock CSF1. The average of the measurements, f_{E2} = 688 358 979 309 306.62(73) Hz [26], deviates by 1.1 Hz from the previous result. The deviation is consistent with the larger systematic uncertainty of the previous measurements. The measurement result contains no blackbody shift correction. A room-temperature blackbody shift of $-5(1) \times 10^{-16}$ is calculated from measurements of the static atomic polarizability [27].

In 2011, a Mu-metal magnetic shielding was installed around the trap and the coil assembly and the electronics of the magnetic field generation were replaced. Subsequently the transition frequency was measured again. The result is consistent with the value obtained in 2008 within the statistical uncertainty of $1 \cdot 10^{-15}$ of the measurement in 2011.

5.2 Yb^+ 642 THz standard

Also the 642 THz (λ = 467 nm) electric-octupole (E3) transition $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ in $^{171}Yb^+$ is attractive as an optical frequency standard. Systematic shifts of the transition frequency due to magnetic and static electric fields and blackbody radiation (quadratic Zeeman and Stark effects) and electric field gradients (quadrupole shift) are significantly smaller than for the E2 transitions to metastable D states in the alkaline earth ions that are presently investigated as optical standards. The natural linewidth of the octupole transition is negligible so that there is no intrinsic stability limit. The small oscillator strength of the transition however implies that the intensity required to drive the transition leads to a substantial light shift (ac Stark shift) of the transition frequency. For a π-pulse that resolves the $m = 0$ - $m = 0$ component of the transition with a Fourier-limited spectral width $\Delta\nu$, the light shift amounts to $\Delta f \approx 0.65\ \mathrm{Hz}^{-1}(\Delta\nu)^2$ if the polarization and magnetic quantization field are oriented for maximum excitation probability.

Until 2009, spectroscopy and absolute frequency measurements of the $^{171}Yb^+$ E3 transition had been carried out only at the NPL (UK) [28]. In 2012, both NPL and PTB independently published new absolute frequency measurements with standard uncertainties of 1×10^{-15} [29] and 8×10^{-16} [30], respectively. In both measurements, the light shift was cancelled by linear extrapolation. The probe laser frequency was stabilized to the line center using two intensity levels alternately. The extrapolated transition frequency was calculated from the independently measured intensity ratio. Fig. 1 shows the corresponding data obtained at PTB for several averaging intervals using different combinations of intensities.

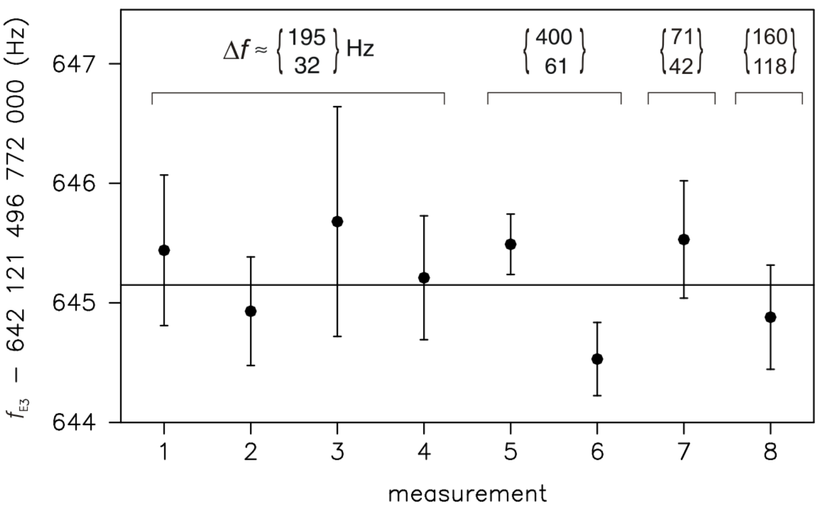

Fig. 1: Results of the frequency measurements of the $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ transition of $^{171}Yb^+$. The approximate average light shifts Δf from which the unshifted frequency f_{E3} was extrapolated are indicated above the data points. The horizontal line marks the weighted average frequency. The error bars denote the statistical uncertainty which was essentially determined by the reference clock CSF1 of PTB.

For the data shown in Fig. 1, the estimated relative systematic uncertainty contribution due to the light shift extrapolation is only 4×10^{-17} [30]. The nonlinearity of the intensity detection and higher-order terms in the light shift do not contribute significantly to the extrapolation uncertainty. The uncertainty estimate is based on the observation that the registered intensity signals showed relative fluctuations of ≈1% with a slightly asymmetric distribution presumably resulting from pointing instability. The distribution of intensity ratios showed a significantly smaller asymmetry that was used as a measure for the extrapolation uncertainty. The extrapolation uncertainty was inferred from the largest difference between the mean and the most probable intensity ratio that appeared in the data sets of the measurements shown in Fig. 1.

The static differential polarizability of the E3 transition and the quadrupole moment of the $^2F_{7/2}$ state of Yb^+ were determined experimentally for the first time [30]. The measured quadrupole moment is much smaller than expected from a previous single-configuration atomic structure calculation [31] so that the resulting uncorrected stray-field induced quadrupole shift leads to a relative uncertainty contribution of only 2×10^{-17} in the transition frequency. From the polarizability measurement, a room-temperature blackbody shift of the transition frequency of $-1.1(5) \times 10^{-16}$ can be inferred.

Taking into account these and other minor uncertainty contributions, the unperturbed frequency of the $^{171}Yb^+$ $^2S_{1/2}(F=0)$ - $^2F_{7/2}(F=3)$ transition was realized with a total relative systematic uncertainty of $7 \cdot 10^{-17}$ during the absolute frequency measurement. The absolute frequency at zero temperature was determined [30] as f_{E3} = 642 121 496 772 645.15(52) Hz with the relative standard uncertainty of 8×10^{-16} being essentially determined by the caesium reference clock.

The difference between the f_{E3} values measured at PTB and NPL is -1.07 Hz, corresponding to a relative deviation of -1.7×10^{-15}. The mean of the two results lies within the standard uncertainties of both measurements. For the periods when the measurements were conducted, the offsets of the local reference standards (CSF1 of PTB and CsF2 of NPL) from the BIPM estimate of the TAI frequency (weighted average of available primary frequency standards) are known [32]. If the differences between the offsets are taken into account as corrections, the difference between the f_{E3} values measured at PTB and NPL reduces to 0.4 Hz, corresponding to a relative deviation of 6×10^{-16}.

5.3 ^{87}Sr 429 THz standard

In the optical strontium clock ^{87}Sr atoms at a temperature of ∼5 μK are confined in a one-dimensional optical lattice. The frequency of the optical clock transition $5s^2\ ^1S_0$–$5s5p\ ^3P_0$ has been determined to be 429 228 004 229 872.9(5) Hz [6] using a femtosecond-frequency comb and one of Physikalisch-Technische Bundesanstalt (PTB's) H-masers whose frequency was measured simultaneously by the PTB Cs-fountain clock CSF1.

The Sr optical frequency standard contributes with a fractional uncertainty of 1.5×10^{-16} to the total uncertainty (see Table 2). The agreement of the measured transition frequency with previous measurements at other institutes supports the status of this transition as the secondary representation of the second with the currently smallest uncertainty.

Table 2: Uncertainty budget of PTB's ^{87}Sr frequency measurement

Effect	Correction (10^{-16})	Uncertainty (10^{-16})
Lattice ac Stark (scaler and tensor	-0.2	0.5
Hyperpolarizability	0	0.2
E2/M1 Stark shift	0	0.2
ac Stark effect probe laser	0.2	0.2
BBR ac Stark (room temperature)	52.5	1.3
BBR ac Stark (oven)	0.2	0.2
Second-order Zeeman	0.28	0.03
Collisions	0.1	0.2
Gravitation	0.1	0.1
Line pulling	0	0.4
Servo error	0	0.06
AOM chirp	0	0.2
Efficiency switch AOM	0	0.02
Tunneling	0	0.16
Second-order Doppler	0	$<<10^{-18}$
Total Sr	**53.2**	**1.5**
fs comb and 200m rf link	0	1.5
rf electronics	0	4.0
Realization of the second	--	7.6
Measurement statistics (60 500s)	--	5.7
Total all	**53.2**	**10.5**

As listed in the table, the most important correction in the case of Sr frequency standards is due the blackbody radiation (BBR) shift. In order to reduce this contribution ultracold atoms are transported over several centimeters [33] within a probe cycle into a homogeneous electric field to perform a dc-Stark shift measurement [34, 35]. With the measured differential dc polarizability and an improved knowledge of the dynamic correction of the blackbody radiation shift frequency measurements in the low 10^{-17} are now possible with vacuum chambers with good heat management.

Currently we are setting up a cryogenic environment in order to further reduce the uncertainty associated to BBR. Eventually, this will allow us to perform measurements where the fractional blackbody shift is reduced well below 10^{-17}.

6. Optical frequency measurements

In addition to routine absolute frequency measurements, PTB has developed methods for performing optical frequency measurements remotely, via optical fibre, and has implemented frequency comb techniques for transferring the stability of ultra-stable oscillators to a different spectral region. PTB has developed the transmission of optical frequencies via phase-stabilized optical telecommunication fibre links to a level that allows remote frequency measurements of even the best optical frequency standards over distances up to 920 km [36]. Frequency transfer techniques that bridge spectral and spatial distances allow the use of a cryogenic Si-cavity as reference for oscillators which interrogate clock transitions in several frequency standards at PTB.

6.1 Absolute frequency measurements

At PTB, frequency combs based on mode-locked optical fibre ring lasers have become a routine tool for performing absolute frequency measurements for optical frequency standards and spectroscopy experiments. Relative uncertainty contributions due to the frequency comb system (2×10^{-17} at 4000 s for absolute frequency measurements, 5×10^{-18} at 8000 s for frequency ratios [37]) are kept well below the uncertainty contribution of the Cs-fountain or of the systems under test. As described in section 5, during the past three years, absolute frequencies were measured for the optical frequency standards based on neutral Sr atoms and on Yb^+ ions.

6.2 Spectral transfer of ultra-stable oscillators to interrogate clocks

PTB has permanently implemented frequency synthesis ([37], based on [38]) from a master laser, i.e. an ultra-stable laser stabilized to an optical cavity, to other frequencies, including several optical frequencies and a microwave frequency. Spectral transfer was implemented from 657nm to 698nm, to interrogate the Sr transition [39] and from 657nm to 1542nm, to generate a PTB reference frequency for fibre link experiments [40, 41]. This enabled remote characterization of the Mg optical clock laser at Hannover [41] with 3×10^{-15} frequency resolution. At the remote end, the transfer oscillator concept [38] was simultaneously implemented with analogue electronics and via software, the latter using synchronized frequency traces recorded in totalizing (Π) and averaging (Λ) modes of the counter [42]; in this way, beat spectra, Allan deviation and Modified Allan deviation were obtained, as well as a remote comparison between three lasers [41]. Recently, with a 250 MHz fibre laser frequency comb, first tests of frequency transfer were carried out from the new silicon cavity stabilized laser at 1542 nm [22]) to 698 nm, showing a sixfold improvement in resolution for interrogation of the strontium $^1S_0$-$^3P_0$ transition [35].

6.3 Frequency dissemination via optical fibre

PTB has developed phase-stabilised optical fibre link techniques to transmit an optical carrier frequency near 200 THz with an instability and accuracy at or close to fundamental physical limits. Fundamental limits are predominately given [43] by the free-running fibre noise, the round-trip delay time and by shot noise. Technical noise sources, such as laser noise and noise in the local interferometer were reduced, to reach an interferometer noise floor of 1×10^{-20} for one hour integration time [44]. With this set-up, frequency dissemination over a 146 km deployed loop with a relative accuracy of 1×10^{-19} was obtained, limited only by the delay-limited instability [44, 43]. The 146 km fibre loop connects the University of Hannover with PTB and was subsequently used for laser characterization and Mg clock measurement.

As a next step, narrow-band, amplification based on fibre Brillouin amplification (FBA) obtained by pumping the underground fibre itself was developed. In contrast to more conventional bi-directional erbium doped fibre amplifiers, this allows an amplifier spacing of up to 250 km due to the high gain of up to 60 dB. Using only one intermediate FBA pump laser, a phase-stabilised fibre link spanning 480 km with delay-limited performance was realized [45].

To connect the hydrogen experiment at MPQ in Garching near Munich with the PTB, a 920 km fibre link was implemented, consisting of two adjacent dark fibres. These are connected in a “virtual loop” configuration, thus allowing the characterization of two 920 km phase stabilized links in series. Ten remotely controlled bi-directional erbium-doped fibre amplifiers developed jointly by PTB and MPQ operate in series along each link and are combined with two FBA stages, overall yielding beat signals with signal to noise ratio >30dB in 100 kHz resolution bandwidth. The phase stabilization of the two 920 km links in series yields an instability (Allan deviation) of $5\times10^{-14}/(\tau s^{-1})$, close to the prediction from the delay limit using phase noise data obtained for the 146 km and 480 km links and supporting current models. For long integration times, the uncertainty of frequency transmission was below 4×10^{-19} [36].

6.4 Remote frequency measurements via telecommunication fibre

As mentioned in section 1.1., high fidelity frequency transmission via phase-stabilised optical fibre links has enabled two *remote* absolute frequency measurements versus the cesium fountain at PTB: The 1S-2S transition frequency in atomic hydrogen at Max-Planck Institute of Quantum Optics in Garching/Munich was measured via a 920 km optical fibre link to PTB [36] with an overall uncertainty limited by the hydrogen spectroscopy of a few 10^{-15} [4] and providing a limit on the Lorentz boost symmetry parameter. The $^1S_0$-$^3P_1$ transition frequency in laser-cooled ^{24}Mg at the

Institute for Quantum Optics of the university of Hannover was measured via a 70 km optical fibre link to PTB [41], with an uncertainty limited by the Mg spectroscopy to about 7×10^{-14} [5].

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