Novel Techniques for Remote Time and Frequency Comparisons

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1 Introduction

Time and frequency are the most precisely measurable physical quantities. Almost all technological processes require precise timing or reference frequencies, and improvements in the realization and dissemination of time and frequency are expected to have widespread impact on innovation, science, and daily life, in particular in the areas of communication and navigation. Hundreds of atomic frequency standards are in operation in telecom networks, military and science centers, and metrological institutes. To fully exploit this potential, novel techniques for time and frequency transfer are required.

National metrology institutes have significant capabilities in atomic clocks, time scale generation, time dissemination, space technology, and network synchronization. In a worldwide network, time laboratories contribute with presently approximately 250 atomic clocks to the international atomic time scale TAI. Caesium fountain clocks have demonstrated a relative accuracy of better than 10^{-15} with the potential to reach the low 10^{-16} range in the next five years [1]. In contrast to conventional atomic clocks which use atomic reference transitions in the microwave range, an emerging new generation of atomic clocks is based on laser excitation of reference transitions in the optical frequency range. These "optical" clocks have the potential to reach a relative accuracy of better than 10^{-17} together with a short–term stability (Allan deviation) in the range of $\sigma_y = 10^{-15}\ (\tau/s)^{-1/2}$ [2].

The wide range of different atomic clocks with diverse operational characteristics requires dedicated techniques for their comparison. On the one hand, routinely operational equipment is needed to compare continuously operating atomic clocks that are distributed worldwide. On the other hand, transfer links with extremely high stability are required to perform meaningful comparisons between optical clocks. According to these very different requirements, two different technical approaches are being pursued: while the worldwide network of atomic clock comparisons is based on microwave links to satellites, optical clock comparisons use optical fiber connections between the sites involved.

Currently for satellite based comparisons there are two time and frequency comparison networks in operation, one employing the United States Global Positioning System (GPS) and one using two-way satellite time and frequency transfer (TWSTFT) via geostationary telecommunication satellites. In the following we briefly discuss GPS-based time and frequency transfer techniques and then take a closer look at the current performance of TWSTFT techniques. We also discuss new projects which are presently under development in order to significantly increase the stability of two-way transfer schemes: Atomic Clock Ensemble in Space (ACES) and Time Transfer by Laser Link (T2L2). These projects are not intended to remain operational for a long time but rather serve as demonstrator systems for future satellite-based time and frequency transfer.

For the further development and characterization of optical clocks, the ability to compare optical frequencies across the optical spectrum is of supreme importance. With the advent of frequency comb generators this problem is essentially solved for local comparisons [3]. Such clocks can now be compared with uncertainties approaching 1 part in 10^{19} [4]. The development of a new method for frequency comparisons between clocks separated by up to 1500 km with a resolution of 10^{-16} or better within one day could dramatically spur the development of high-performance optical clocks leading to a wide variety of applications. This point of view is also supported by recent recommendations of the Consultative Committee for Time and Frequency (CCTF) of the international standards organization BIPM [5]. We give an overview on the present development status of fiber-based transfer techniques and describe a recent experiment that investigates the transmission of a stable optical carrier frequency at 194 THz between PTB and the Institute of Quantum Optics at Leibniz Universität Hannover. We consider possibilities

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for a future European fiber network for remote optical clock comparisons and conclude with an outlook on future applications of the various time and frequency transfer techniques.

2 Satellite based clock comparisons

Facilities for satellite based time and frequency comparisons are standard equipment in every time laboratory. They are operated in a continuous mode to allow the computation of phase and frequency differences of atomic clocks and time scales. Both the GPS and TWSTFT techniques are used for frequency comparisons as well as for time transfer to realize the TAI time scale. Frequencies can be compared with an uncertainty in the 10^{-15} range with 1 day averaging [6], and time scale differences can be compared at the one nanosecond level [7].

2.1 Global Positioning System (GPS)

GPS has become a standard tool for time and frequency transfer between time laboratories [8]. The system maintains a minimum of 24 satellites in three orbits with a radius of 26600 km, such that at nearly each location on earth more than 4 satellites are simultaneously above the horizon. On each satellite a caesium or rubidium atomic clock serves as the onboard frequency and time reference. From this reference two carrier frequencies near 1600 MHz and near 1200 MHz are generated and transmitted. The transmitted signals are phase modulated by two characteristic and unique pseudorandom noise codes. The so-called coarse acquisition code is transmitted at 1600 MHz with a chip rate of ~1 Mch/s (corresponding to a modulation bandwidth of approximately 2 MHz), the precise code has a chip rate of ~10 Mch/s and is transmitted on both carrier frequencies. The coarse acquisition code includes the navigation message which contains a prediction of the satellite orbit, an almanac of the complete satellite constellation, a prediction of the onboard clock deviation relative to GPS system time scale, and an ionospheric model [9]. In time and frequency transfer applications, the received GPS signals are decoded in a way that permits a time-of-arrival measurement with respect to the local reference clock and a reconstruction of the GPS carrier phase.

If the positions of the satellites and the receiver locations are precisely known, ground-based clocks can be compared with a typical precision of 10 ns (1 ns) using the coarse (precise) acquisition code. If the carrier frequency itself is used, the precision is in the range of 10 ps for suitable averaging times [10]. The accuracy actually achieved depends of course on the performance of the receiver and on the quality of the estimation of measurement errors: the signals from the satellites pass the ionosphere and the troposphere before reaching the receiver's antenna, and the effective propagation time can be altered by reflections from the neighbourhood of the antenna. All delay times in the signal path depend on the carrier frequency.

For time and frequency comparisons between two remote sites, two configurations can be employed: in the classical common-view configuration, two receivers record data from the same satellite at the same instant. It is obvious that the common-view technique has limitations if the two receivers are located far away from each other. In practice, the maximum baseline which can be bridged in this way is approximately 10000 km. By design the common-view configuration effectively reduces errors which are common to both receiver sites: the satellite clock errors and for small baselines also the errors caused by the ionosphere and troposphere.

There is no common-view requirement if the internal clocks of the GPS receivers are related to a common time scale. A very stable time scale (presently 10^{-15} relative stability at 1 day averaging) is provided via the Internet by the International GNSS Service IGS. Using the IGS time scale and multi-channel GPS receivers, ground clocks can be compared in such a way that the signals of all visible satellites are averaged. With this so-called all-in-view method, the main reasons for common-view comparisons vanish. Typically multipath effects and environmental influences on the receiver are the dominant error sources.

Most dual-frequency GPS receivers can decode the precise acquisition code, which allows to effectively reduce the ionospheric error by evaluating a suitable linear combination of the signals received on both transmission frequencies. The blue graph in Fig. 1 shows the stability of an intercontinental frequency comparison using this technique [10].

The best GPS-based frequency comparisons make use of the information contained in the carrier phase of the GPS signals. As indicated by the red graph in Fig. 1, about one order of magnitude in frequency transfer stability is gained

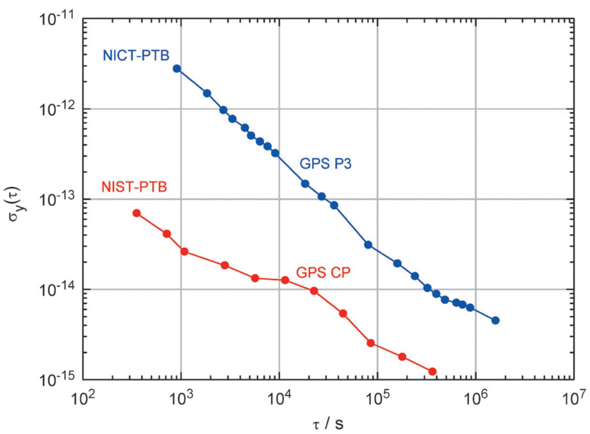


Figure 1:
Instability (Allan deviation as a function of averaging time) observed in long-baseline GPS frequency transfer. Blue: transfer to NICT (Japan) using a GPS common-view scheme with ionosperic error correction. Red: transfer to NIST (USA) using the GPS carrier-phase technique.

through the carrier phase (CP) technique [11]. The main problem with this technique is that conventional GPS signal evaluation software leads to jumps of the computed carrier phase at day boundaries. If clocks are compared over an extended period of time using the CP technique, these jumps have to be removed or to be taken into account as an additional uncertainty contribution. Concepts of combining code and carrier information and precise IGS clock and orbit data are currently under investigation to enable frequency and true time transfer with the stability of the CP measurements. Here a promising approach is the so-called Precise Point Positioning (PPP) technique, which is being investigated in particular in the context of the realization of the international atomic time scale TAI [12]. Presently 5 ns is the commonly assumed systematic uncertainty in time scale comparisons based on the long-term operation of GPS receivers.

2.2 Two-Way Satellite Time and Frequency Transfer

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is the second leading technique for comparisons of remote atomic frequency standards [13]. The main advantage of the two-way technique is that undetermined delays along the signal path cancel out to first order because of the path reciprocity of the transmitted signals.

At present TWSTFT makes use of established satellite services in the Ku-band (11 GHz –14 GHz) and X-band (7 GHz–8 GHz). Time signals are transmitted by relating the phase of a pseudorandom noise modulation to the one-pulse-per-second output of a local clock. Each station uses a dedicated code, and the receive equipment allows the reconstruction of the transmitted signal and its comparison with the local clock by means of a time interval counter. Following a prearranged schedule, both stations of a pair lock on the code of the remote station for a specified period, measure the signal arrival times, and record the results. The clock difference is obtained either in post-processing after exchanging the data files or in real time by attaching the time interval measurement results to the transmitted timing signals.

Fig. 2 shows stability test results and theoretical predictions for the current standard operational parameters of TWSTFT. An assessment of the performance of any comparison technique requires to suppress the contributions of the clocks compared. This is possible by operating two stations side-by-side connected to a common clock or for remote stations by forming double differences between results obtained with different techniques. Related data are shown in Fig. 2 for a comparison between the GPS carrier-phase and TWSTFT techniques. Surprisingly these data demonstrate a stability that is even slightly better than the prediction based on the expected measurement noise. The stability of TWSTFT can be enhanced if the transmission bandwidth (i.e., the employed chip rate) is increased. Currently available modems can handle chip rates up to 20 MCh/s, but their use is not common because this would significantly increase the cost of the transponder lease from commercial providers.

Fig. 2 also shows results of the first TWSTFT experiments where the carrier phase information of the satellite signal is used for frequency comparisons. This scheme has the potential to provide a frequency stability of $\sigma_y(\tau) = 10^{-12}\,(\tau/\mathrm{s})^{-1}$. As shown in Fig. 2, a good agreement with the predicted performance is observed for averaging times up to 100 s for both common-clock and transatlantic TWSTFT between USNO (United States Naval Observatory,Washington DC, USA) and PTB [14]. For longer averaging times the stability decreases significantly and appears to be limited by other noise sources than measurement noise. Nevertheless these initial results indicate that carrier-phase based TWSTFT frequency comparison has a strong development potential and might ultimately become attractive also for optical frequency standard comparisons.

It is well known that the path delay reciprocity is not completely fulfilled in TWSTFT. Nonreciprocal variations of the delay times are caused by residual satellite motion, by drifts of the signal delay times in the electronic components in the ground stations and in the satellite, and to a smaller degree by the difference between the uplink and downlink frequencies in combination with the propagation delay introduced by troposphere and ionosphere [15, 16].

Unfortunately most of the relevant variations occur with a daily pattern which complicates a quantitative analysis. Satellite motion impairs the transmission stability through both the path length variation and the variation of the propagation times due to the Sagnac effect. The ground station delays as well as the satellite

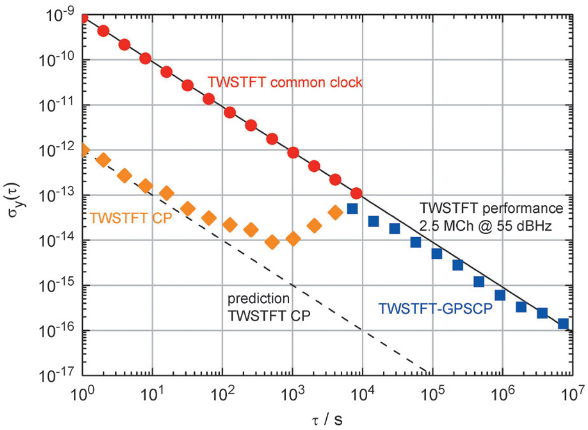


Figure 2:
Instability (Allan deviation as a function of averaging time) of standard and carrier-phase based TWSTFT. Calculations and measurements were carried out for a TWSTFT signal modulated with a chip rate of 2.5 MCh/s and received with a carrier-to-noise ratio (link budget) of 55 dBHz. Full black line: calculated instability of standard TWSTFT. Red dots: instability measured in the common-clock mode which eliminates clock noise. Blue squares: instability of the difference between standard TWSTFT and GPS carrier-phase data in a clock comparison between NIST (Boulder, USA) and PTB. Dashed black line: calculated carrier-phase based TWSTFT instability. Orange diamonds: instability of carrier-phase based TWSTFT in a clock comparison between USNO (Washington DC, USA) and PTB.

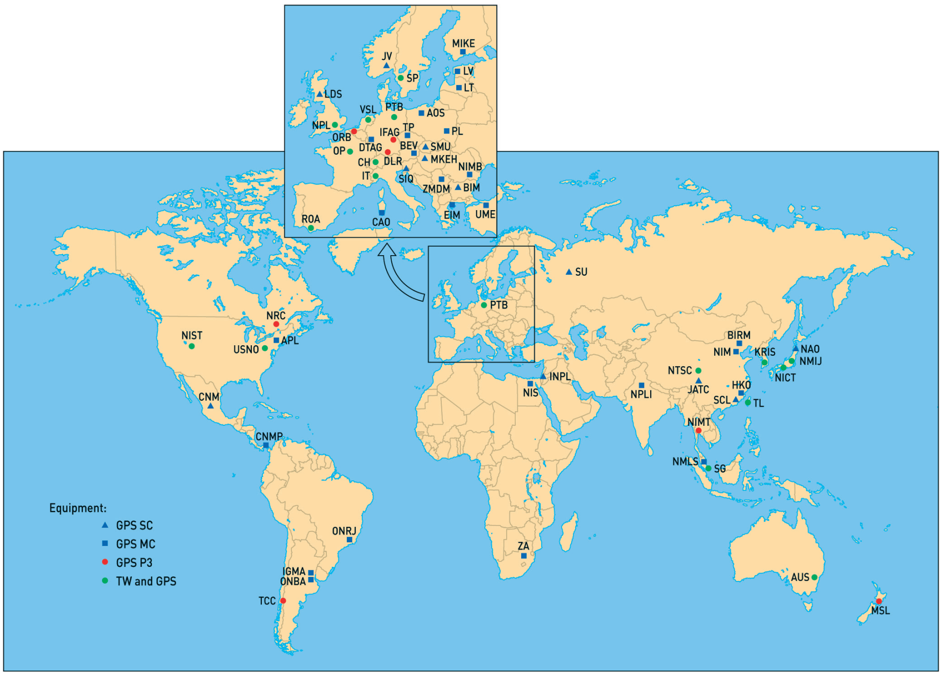


Figure 3:
Geographical distribution of the laboratories that contribute to TAI and employed clock comparison methods [17]. Adapted with kind permission of BIPM.

transponder delays are affected by environmental conditions like heating of the satellite by solar radiation and weather-related temperature and humidity changes on the ground. For a robust ground-station system it is recommended to place as much of the equipment as possible indoors in a suitable stable environment. Carefully controlled environmental conditions are also mandatory for next-generation TWSTFT schemes.

2.3 Time transfer for the realization of international atomic time

The *Bureau International des Poids et Mesures* (BIPM) organizes comparisons between time scales and atomic clocks in an international network. TWSTFT is the preferred method and gains importance as new ground stations at timing laboratories join the operational network [17]. In Fig. 3 the current geographical distribution of the laboratories contributing to the atomic time scale TAI is shown. TWSTFT links are backed up by GPS time comparisons and the largest number of links relies entirely on GPS time comparisons. Since introduction of the all-in-view method, all laboratories equipped with GPS receivers are compared to a common pivot. Presently PTB is this reference point.

The BIPM estimates a 5 ns systematic uncertainty for a GPS link. TWSTFT comparisons can be performed with a considerably lower uncertainty. The TWSTFT links between European stations and PTB were repeatedly calibrated by means of a portable station operated by the Technical University Graz (Austria) (see Fig. 4). In each campaign an uncertainty in the range of 1 ns was achieved. The most recent campaign in September 2008 included links to Graz, NPL (UK), OP (France), INRIM (Italy) , METAS (Switzerland), and VSL (The Netherlands).

A remarkable series of calibrations of two independent TWSTFT links (Ku-band and X-band) between USNO and PTB permits an assessment of the long-term stability of the TWSTFT technique. The measured differential corrections to the previous calibration values are shown in Fig. 5. For the Ku-band (X-band) link, the 5-year mean of the corrections amounts to –0.46 ns (–0.50 ns) with a standard deviation of 1.43 ns (1.26 ns).

The calibration campaigns performed so far permit the conclusion that an uncertainty level of 1 ns can be reliably reached by the established measurement procedures and that the reproducibility is at the same level as the estimated uncertainty. Because of the high time transfer accuracy, TWSTFT was chosen as the primary means to synchronize the two Precise Timing Facilities of the future European satellite navigation system Galileo and to support the measurement of the difference between the GPS and the Galileo system time scales.

Figure 4:
Bernd Blanzano (Technical University Graz, on the left) and Jürgen Becker (PTB) adjust the antenna of the portable TWSTFT ground station of TU Graz during the latest link calibration campaign in September 2008. The other antennae belong to PTB reference stations.

Figure 5:
Time offsets measured during calibrations of the Ku-band and X-band TWSTFT links that connect the time scales UTC(USNO) and UTC(PTB). The error bars denote the associated measurement uncertainty. The offsets are measured relative to the offsets determined in the preceding calibration. The gray bars reflect the estimated link uncertainty immediately prior to the new calibration, taking into account known perturbations which might affect transmission delay times.

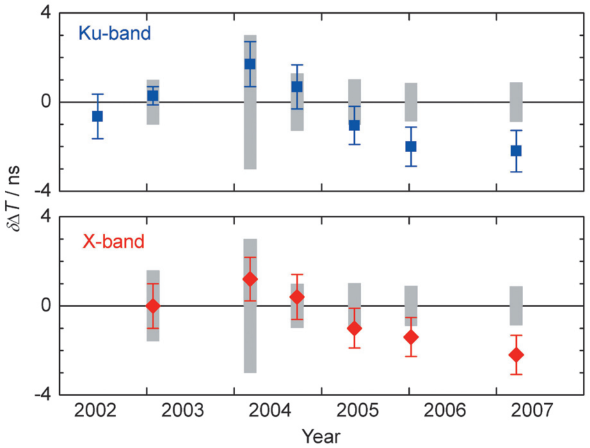
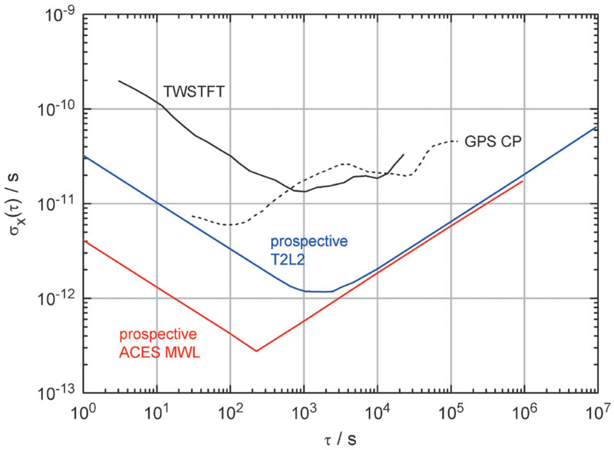


Figure 6:
Expected stability (time deviation σ_x as a function of averaging time) of time transmission using the T2L2 laser telemetry scheme and using the microwave links of the planned atomic clock ensemble ACES onboard the International Space Station. For comparison, exemplary data for time transmission based on TWSTFT and carrier-phase GPS are also shown [18].



2.4 The T2L2 and ACES projects

Time Transfer by Laser Link (T2L2) is an experiment onboard the satellite Jason 2 which was launched in June 2008. First test measurements are scheduled for Spring 2009 [18]. The T2L2 concept employs the technique of satellite laser telemetry in order to compare two or more ground-based clocks: laser pulses that are synchronized with the ground clocks are transmitted to the satellite and retroreflected to the ground stations where the return times are recorded. The pulse arrival times at the satellite are registered relative to an onboard clock of high short-term stability. As shown in Fig. 6, the expected clock comparison uncertainty corresponds to a minimum time deviation of about 1 ps at an averaging time of 1000 s. This performance surpasses the precision of TWSTFT and GPS carrier-phase comparisons by approximately a factor of ten. As a result of the low satellite orbit radius of 1300 km, intercontinental comparisons must be carried out in a non-common-view mode where the achievable comparison stability is limited by the instability of the onboard clock.

Atomic Clock Ensemble in Space (ACES) is an ESA mission based upon the operation of atomic clocks in the microgravity environment of the international space station ISS. The time scale generated by the onboard atomic clocks is transferred to the ground through a high-performance microwave link. The microwave link uses two Ku-band frequencies for up- and downlink with chip rates of 100 MCh/s and an additional downlink in the S-band to accurately determine the ionospheric delay [19]. The expected link stability corresponds to a time deviation of less than 300 fs at an averaging time of 300 s (see Fig. 6). This microwave link will allow to perform both space-to-ground and ground-to-ground comparisons of atomic frequency standards. The high stability of the onboard atomic clock ensemble will also enable non-common-view comparisons between ground atomic frequency standards with an uncertainty of less than 5 ps at an averaging time of 10^4 s.

3 Clock comparison by fiber link

Optical clocks based on cold atoms or a single ion presently achieve a short-term frequency stability in the range of $\sigma_y(\tau) \approx 10^{-15} (\tau/s)^{-1/2}$ [2]. These clocks are not transportable and require a frequency comparison technique that allows to reach the stability level of the clocks for measurement times between several minutes and several hours. As an alternative approach to satellite-based frequency transfer techniques, the use of optical fiber networks has been discussed extensively [20]. In order to bridge large distances, fiber transmission in the wavelength range of the telecommunications window around 1.5 µm is advantageous because signal loss is minimized.

A summary of different methods for frequency comparisons using optical fibers is given in [21]. Besides the transmission of solitons or of optical pulses from femtosecond lasers, two other methods have recently been established: the transfer of an ultrastable radiofrequency reference signal by amplitude modulation of an optical carrier [22], or the direct transfer of a highly stable optical carrier frequency [23]. Using the former technique, a relative frequency stability level of 10^{-18} at an averaging time of 1 day was achieved for an optical link of 86 km length [24]. However, for longer links the dispersion in the fiber and signal attenuation become critical issues.

3.1 Comparison using a stable optical carrier frequency

The direct transfer of a highly stable optical carrier offers the advantage that stability degradations caused by down-conversion of optical frequencies to the microwave domain and by distortions of the modulation can be avoided. Optical clocks operating in remote laboratories can be compared by transmitting the radiation of a continuous single-frequency laser over an existing 1.5 μm-fiber network and comparing its frequency with that of the optical clocks located at both sites. Using femtosecond fiber laser based frequency comb generators, the frequency ratio between the laser and the optical clocks can be easily measured [25, 26]. Such optical frequency ratio measurements can reach an uncertainty level below 10^{-17} within a few hours of measurement time [27].

A prerequisite for long-haul frequency transmission is that the coherence length of the transmitted laser light exceeds the distance to be bridged. Otherwise the laser frequency noise limits the accuracy with which optical path length fluctuations can be controlled. In order to actively stabilize the frequency of the transmitted light, a local optical clock can serve as a reference.

Presently the established technique for direct frequency stabilization of a laser of arbitrary wavelength to an optical clock consists of transferring the stability of the clock to the output spectrum of a frequency comb generator [2]. The beat signal between a comb mode and the laser to be stabilized can then be used to lock its frequency to the comb spectrum and thereby to the optical clock.

Comb generators based on femtosecond fiber lasers bridge the frequency gap between optical clocks in the visible wavelength range and cw fiber lasers operating in the telecommunications window around 1.5 μm. Unfortunately, unstabilized fiber-based comb generators exhibit significant optical phase noise while their frequency control bandwidth is typically limited to less than 100 kHz. As a result, the phase noise of a fiber-based comb generator usually exceeds that of the optical standard to which it is stabilized by several orders of magnitude, and it is difficult to achieve a frequency stability of better than $\sigma_y \approx 10^{-14}\,(\tau/\mathrm{s})^{-1/2}$ [28].

In order to overcome this problem, H. Telle et al. developed a technique in which the frequency comb generator is used as a transfer oscillator [29]. This scheme allows to compare laser frequencies in different spectral regions without stability degradation by the frequency noise of the comb generator. Using this approach, a frequency comparison between distant optical clocks is performed in three steps:

(1) A single-frequency fiber laser is phase-locked to one of the optical clocks using a fiber-based comb generator. This stabilized laser synthesizes a precisely known optical carrier frequency whose stability is equivalent to that of the optical clock.

(2) The optical carrier is transmitted to the remote site using single-mode telecommunication fiber.

(3) At the remote site, the frequency ratio between transmitted carrier and the local optical clock is measured by means of another frequency comb generator.

Step (1) of this concept was demonstrated by locking a continuous fiber laser oscillating at 1545 nm to a 871 nm diode laser which serves as the clock laser of a Yb^+ single-ion optical frequency standard and has a linewidth of less than 10 Hz [2, 30]. The fractional uncertainty of the synthesized frequency relative to the 871 nm reference approached 10^{-18} in a long-term frequency ratio measurement [31].

Step (2) was demonstrated in a collaboration with LNE-SYRTE (Paris). Here we distributed a precisely stabilized optical frequency over an urban telecom fiber network [23] (see below).

For a demonstration of Step (3), a good candidate is an optical frequency standard based on Mg atoms that is currently developed at the Institute of Quantum Optics (IQO) at Leibniz Universität Hannover. A frequency measurement of the $^1S_0$–$^3P_1$ intercombination transition of Mg using a thermal atomic beam has been reported previously [32]. So far, a portable Caesium atomic clock and a GPS-controlled quartz oscillator have been used as local references. A considerable enhancement of measurement accuracy is expected from the further development of the Mg standard and from comparisons with one of the established optical frequency standards of PTB by means of a fiber link.

3.2 Optical path length stabilization

Common to all fiber based transfer techniques is that the frequency stability of any signal transmitted through an optical fiber is degraded by phase noise induced by mechanical stress and temperature variation in the fiber. In long-haul systems, fluctuations induced by temperature variations in the optical fiber dominate on long time scales. Other sources of low-frequency noise, such as polarization mode dispersion in optical fibers and temperature variations in peripheral equipment can also affect the long term stability. Noise sources that can play a role at shorter time scales include thermal and electronic flicker (1/*f*) noise, photodetection shot noise, and amplitude-to-phase conversion processes.

Typically, in order to achieve ultra-stable frequency dissemination via optical fibers over distances exceeding 100 m, the phase noise of the fiber link must be suppressed by active optical path length stabilization.

Fig. 7 shows a schematic of an active fiber noise cancellation system that was first described by Ma et al. [33]. At the local site, a part of the laser output passes through an acoustooptic frequency shifter (AOM) that is driven by a voltage-controlled oscillator and is fed into the fiber link. At the remote end, a part of the signal is frequency shifted and retraced. The retraced light is frequency shifted again at the local site and is made to interfere with a part of the original laser output. The resulting beat signal is phase locked to a stable rf reference by controlling the frequency of a voltage-controlled oscillator. This interferometric arrangement cancels the fiber-induced phase noise at the remote end of the fiber link. The frequency shift of the retraced light at the remote site allows to discriminate it from other sources of backscattering. The analysis of the local photodetector signal provides an in-loop measurement of the residual phase noise. In test setups where the local and remote sites are located next to each other, direct out-of-loop measurements of the link stability can be performed by analyzing the beat signal between the laser output and the light received at the remote end.

3.3 Experiments

In our collaboration with LNE-SYRTE, we used a ^{87}Sr optical lattice clock [34] as the reference and an existing standard telecom fiber link. To simulate a user at a distant laboratory, the transmitted signal was looped back from the far end to the local laboratory resulting in a total transmission distance of 86 km. In some measurements the distance was further extended to 211 km using fiber spools. In the latter case, the resulting total single-path attenuation of 50 dB was compensated by an erbium-doped fiber amplifier. The optical clock, the frequency comb generator, and the laser and path length stabilization were continuously operational over periods of approximately 12 h. The 86 km fiber link achieved a relative frequency stability of $\sigma_y(1\ \mathrm{s}) = 2.2 \cdot 10^{-15}$ and reached an instability below $5 \cdot 10^{-18}$ within several hours. The mean of the transmitted frequency differed from the optical frequency at the local end by 3 mHz with an uncertainty of the mean of 4 mHz [23].

In the following we describe a fiber link connecting PTB with a laboratory of the IQO at Leibniz Universität Hannover. This recently established link (see Fig. 8) is part of a larger fiber network which will eventually connect optical clocks at PTB and at IQO with those operated at the Max Planck Institutes in Erlangen (Institute of Optics, Information and Photonics, IOIP) and Garching (Max-Planck-Institute for Quantum Optics, MPQ).

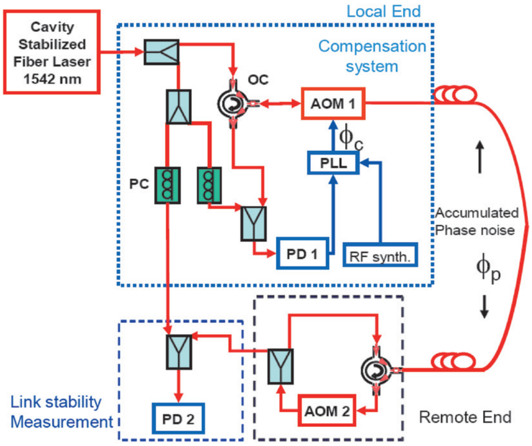


Figure 7:
Setup for active compensation of fiber noise (Courtesy of G. Santarelli). AOM: acousto-optic modulator; PD: photo-diode; PLL: phase locked loop; PC: polarization controller; OC: optical circulator; RF synth: Radio-frequency synthesizer. For details see text.

Figure 8:
Schematic of a comparison of remote frequency standards by means of a link based on dark telecommunication fibers (blue and red lines). The dashed line indicates a planned extension (see text). At PTB a 1.5 µm fiber laser is locked to an optical frequency standard. Its output is transmitted to Leibniz Universität Hannover where its frequency is compared with that of an optical frequency standard based on Magnesium atoms. (Map source: Google Maps)

The pipeline networks of gas distribution companies and local telecommunication providers offer significant potential for developing an area-wide fiberoptic infrastructure. The fiber routes from Braunschweig to Hannover and Garching are established in a collaboration with the German science communication network DFN, GasLINE (a fiberoptic cable provider established by German gas distribution companies), and EnBs (a local energy and telecommunications provider). Two dedicated pairs of dark fiber in a strand of commercially used fibers have been made available. As both fibers are located in the same strand, they are affected by the same environmental conditions and have the same characteristics.

The total fiber path distance from PTB to the IQO is 73 km. Via the local network of EnBs we connect our laboratory to the wide-area network of GasLINE. The use of this infrastructure permits a direct connection to the university's computing center, located about 400 m away from the IQO. An in-house fiber link provides access to the Mg frequency standard.

We used commercial SMF-28 fiber according to the ITU-T G.652 standard with a refractive index of n = 1.4681 at 1550 nm, an attenuation of ≈ 0.23 dB/km, and a chromatic dispersion of ≈ 18 ps/(nm·km). An optical time domain reflectometer was used to obtain a detailed description of splice and connector positions along the link. The full link comprises 16 splices and approximately 10 connectors.

In order to characterize the stability of the link, a fiber loop of 146 km length whose ends are located in a PTB laboratory was established by connecting the ends of a fiber pair in Hannover. The measured overall attenuation of this loop is approximately 46 dB.

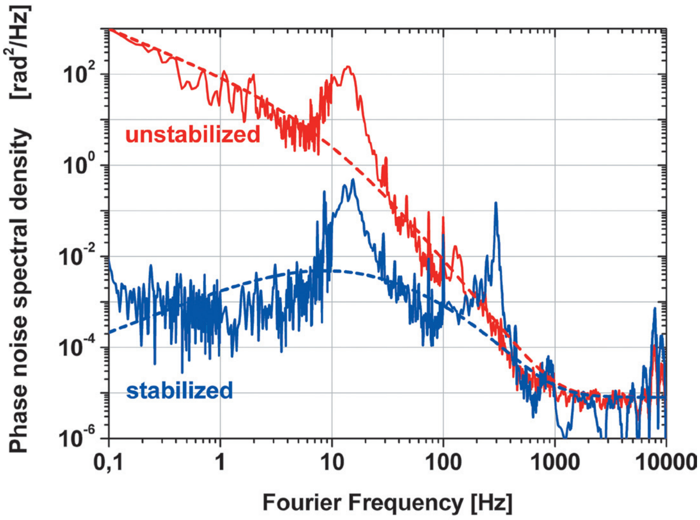


Figure 9:
Observed phase noise spectral density [35] of a PTB-Hannover-PTB fiber link of 146 km length without optical path length stabilization (red) and with active stabilization (blue). The red dashed line indicates the asymptotic phase noise characteristic in the limit of high and low Fourier frequencies. The blue dashed line indicates the calculated suppression effect of the employed phase noise cancellation system for the asymptotic characteristic (see text).

The phase noise spectrum of the link is shown in Fig. 9 [35]. Without active path length stabilization, the observed phase noise spectrum can be approximated by

$$S_\phi(f) \approx \left[\frac{100\ \text{Hz}}{f}\cdot\left(1+\frac{f}{10\ \text{Hz}}\right)^{-2}+c\right]\ \text{rad}^2\ \text{Hz}^{-1}$$

if the distinct environmental noise maximum at $f \approx 15$ Hz is neglected. For Fourier frequencies $f \geq 100$ Hz, the phase noise decreases as $1/f^3$, while for $f \leq 10$ Hz the frequency dependence is that of flicker ($1/f$) phase noise. The constant noise floor at high frequencies is determined by the intrinsic noise of the detection system.

3.4 Stability limit

For any fiber link, a fundamental limit on the achievable degree of phase noise suppression arises from the propagation delay introduced by the fiber. The delay directly affects the maximum control bandwidth of the path length stabilization loop. As a result, the stability at high Fourier frequencies f is limited by unsuppressed noise of the fiber link. The spectral dependence of the achievable phase noise suppression can be estimated as

$$S_\phi^{out}(f) = \frac{4\pi^2}{3}\cdot\left(\frac{nL}{c}\right)^2\cdot f^2\cdot S_\phi^{in}(f) \quad \text{for} \quad f < c/(nL)$$

where L is the one-way physical path length, n the index of refraction, c the speed of light, and S_ϕ^{in} denotes the phase noise of the unstabilized link [39].

The return signal used for path length stabilization of the PTB-Hannover-PTB link has a delay of 1.4 ms which limits the bandwidth of the stabilization loop to 350 Hz. As shown in Fig. 9, the measured phase noise of the stabilized link is in good agreement with the predicted frequency dependence of the phase noise suppression. The estimated frequency transmission stability of this link is $\sigma_y(\tau) \approx 3\cdot 10^{-15}\,(\tau/\text{s})^{-1}$ if the environmental noise peak at $f \approx 15$ Hz is neglected. Using a 871 nm clock laser reference (see above), we measured the fractional stability of the transmitted frequency at the remote end and found a value of $\sigma_y(\tau) = 2.5\cdot 10^{-15}\,(\tau/\text{s})^{-1}$ (see Fig. 10) [35].

This measurement demonstrates that a fiber link with low intrinsic phase noise permits the comparison of state-of-the-art optical clocks [2] which are separated by more than 100 km without degrading the stability afforded by the clocks.

Similar experiments have been performed by other groups and phase noise data of three other fiberoptic links have been published recently. These links have lengths of 40 km [36], 86 km [37], and 120 km [38]. In some cases the total link length was increased up to 251 km by adding additional fiber spools. While the phase noise characteristics of the 40 km and 80 km links are very similar to that of the PTB link, the 120 km link exhibits a noise level that is approximately 25 dB higher at $f = 1$ Hz and decreases proportional to $1/f^2$.

As $S_\phi^{out}(f)$ is proportional to $L^2\, S_\phi^{in}(f)$, the attainable link stability in frequency comparisons decreases proportional to $L\,(S_\phi^{in})^{1/2}$. Since L is determined by the distance between the clocks that are compared, the only way to improve the link stability is to split the total length into subsections (to increase the control bandwidth) and/or to select a fiber link with low intrinsic phase noise.

With respect to phase noise suppression, fibers installed along gas-pipeline networks offer some advantages: the underground location of pipelines strongly suppresses diurnal temperature variations and other environmental perturbations. A long-haul optical link can be split into appropriate subsections as the typical distance between housings for installations like repeaters and amplifiers along a link is about 80 km.

3.5 Towards a European fiber network

With the availability of a national test facility between PTB and the MPQ in Garching, we now have the unique possibility to explore the first

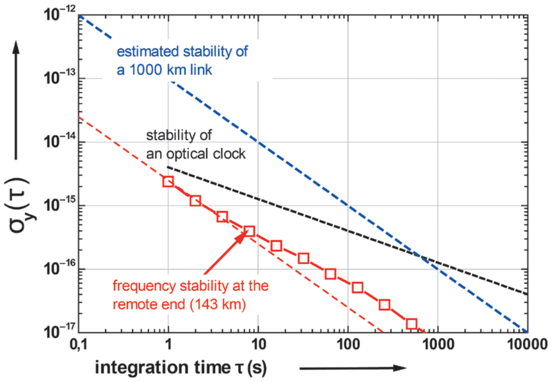


Figure 10:
The observed fractional stability of laser frequency transmission using the 146 km PTB-Hannover-PTB link [35] is compared with that of a state-of-the art single-ion optical clock [2] and with the estimated stability of a link of 1000 km length (see text).

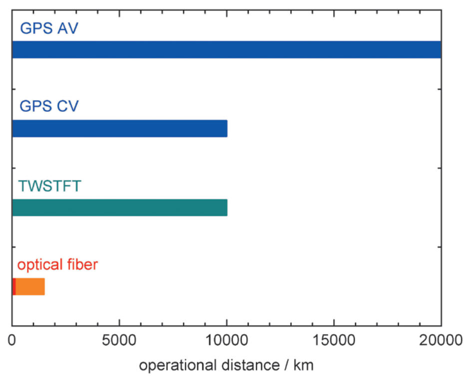


Figure 11:
Operational baseline lengths of time and frequency transfer links for different techniques. Currently, optical fiber links are realized over distances of about 250 km and extensions up to about 1500 km are planned.

long-haul, all-optical carrier phase frequency transmission over a long-distance optical link of 900 km. This extends the transfer capability to the continental scale and will eventually allow to compare the very stable and accurate clocks that are located in many European laboratories. The 900 km fiber link which presently is being set up is a unique opportunity to study an advanced optical frequency dissemination system at real scale with representative environmental perturbations. We expect that this will boost new applications as well as significant advances in current research.

However, for the envisioned link lengths the cumulative loss of the link must be compensated by the insertion of amplifier stages. The amplifiers must operate bidirectionally and preserve the coherence of the input signal. Erbium-doped fiber amplifiers satisfy these demands and are commonly used in telecom fiber networks. Assuming a typical link loss of 0.2 dB/km and a gain of 20 dB – 30 dB per amplifier, an amplifier spacing of 100 km is sufficient to establish a quasi-transparent optical link where the noise penalty due to the cascaded amplification is smaller than 10 dB [39].

In order to estimate the stability of the transmitted signal for a 1000 km link, we assume that the phase noise of the free-running link has a frequency dependence similar to that of the present PTB-Hannover link (see Fig. 9), but that the phase noise spectral density $S_\phi^{in}(f)$ is increased proportional to the link length. In this case, the phase noise level would still be smaller than that of the 120 km link investigated in Ref. 38. Thus, assuming a noise level of $S_\phi^{in}(f) = 5 \cdot 10^4\,\mathrm{Hz}^2/f^2\,\mathrm{rad}^2\,\mathrm{Hz}^{-1}$ as a worst-case estimate, the calculated residual phase noise of the stabilized link is in the range of $S_\phi^{out}(f) \leq 50\,\mathrm{rad}^2\,\mathrm{Hz}^{-1}$, corresponding to an estimated fractional frequency stability of $\sigma_y(\tau) \approx 1 \cdot 10^{-13}\,(\tau/\mathrm{s})^{-1}$.

As shown in Fig. 10, the estimated instability of a 1000 km link becomes smaller than that of the presently best optical clocks for an averaging time $\tau > 1000$ s. After an averaging time of 3 hours, the contribution of the optical link to the total instability would be negligible. Even with the assumed fairly high noise level of the link, a clock comparison by optical fiber could exceed the predicted capability of satellite-based comparisons using the carrier-phase TWSTFT technique (cf. Fig. 2) by one order of magnitude.

Thus, for optical-clock comparisons within Europe the use of optical fibers can be a powerful alternative to comparisons via satellite provided that suitable dark fiber will be accessible.

From the present point of view, the availability of dark fiber is not a problem, but the cost of rent over a period of 5 to 10 years is a critical issue. The search for dark fiber providers that will grant the national metrology institutes access to a European fiber network and support them in establishing national link capabilities will be one of the most important tasks of the near future.

4 Outlook

The operational distance of time and frequency transfer techniques is an important criterion if one considers the comparison of atomic frequency standards at remote sites. Fig. 11 compares the current and prospective baselines provided by the various techniques. The GPS all-in-view technique is unique: it allows comparisons between clocks wherever they are located on earth. For the classical common-view technique and for TWSTFT, the baseline limitation is approximately 10000 km because both sites must simultaneously point to one satellite. In the BIPM network for the computation of TAI, the TWSTFT link with the presently longest baseline is that between NICT (National Institute of Information and Communications Technology, Tokyo) and PTB. For significantly longer distances two-hop configurations appear feasible, but additional measurement noise must be taken into account. Such a link is currently in preparation between USNO and NICT using a relay station in Hawaii. If this link is established, TWSTFT in a closed loop around earth will provide two independent links between each pair of participating sites. Presently a number of new laboratories particularly in Asia are about to join the worldwide TWSTFT network and also the number of laboratories that use GPS time transfer is increasing.

Despite the fast advances of clock comparisons via optical fiber links, we expect that also in the near future the baselines of such links will be restricted to less than approximately 1500 km. Nevertheless it appears that the advantages provided by optical fiber links and the availability of frequency-stabilized optical reference signals will stimulate new developments in science and technology. Using femtosecond frequency comb technology, the dissemination of frequency-stabilized 1.5 μm light enables the generation of radiofrequency and microwave signals with unprecedented stability without need for a local reference clock. Optical fiber links have the potential to provide an optical frequency reference for fundamental research and applied science with an accuracy and stability that today is available only at national metrology institutes and a small number of other dedicated laboratories. Applications range from low-level laser frequency calibration, length interferometry, and remote wavelength standard calibration to the synchronization and timing of accelerator facilities.

In the near future, the synchronization systems of next-generation linear colliders [40] and of large astronomical antenna arrays such as the Atacama Large Millimeter Array [41], both demanding low-noise frequency dissemination systems with minimal phase drifts and errors, will particularly strongly benefit from optical fiber links. The stable synchronization afforded by the transmission of an optical carrier frequency will also foster new developments in very long baseline interferometry (VLBI) astronomy, such as large-aperture VLBI in the near-infrared and optical wavelength range. The combination of high frequencies and long interferometric baselines requires the distribution of a local oscillator with low phase noise and low phase drift through the array [42]. For the Deep Space Network of NASA, a system of optical fiber links has been developed in order to distribute reference signals from a hydrogen maser for antenna synchronization [43].

The implementation of a European fiber network for highly stable optical frequency transmission will boost the field of time and frequency metrology. The network in particular will enable stability tests of satellite-based time transfer techniques (see above) and of the timing facilities of the global navigation satellite systems GPS and Galileo [44].

A number of fundamental physics research programs will benefit from the ability to compare distant optical frequency standards through optical fiber links without any significant loss in accuracy or stability. Prominent examples are tests on possible violations of the equivalence principle of General Relativity and on the possible drift of the fine structure constant [44]. Clearly, the ability to perform comparisons between distant optical clocks at the highest possible accuracy level is also a prerequisite for a possible redefinition of the SI second on the basis of an optical clock.

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