Phase-Coherent Frequency Comparison of Optical Clocks Using a Telecommunication Fiber Link

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***Abstract*—We have explored the performance of 2 "dark fibers" of a commercial telecommunication fiber link for a remote comparison of optical clocks. These fibers establish a network in Germany that will eventually link optical frequency standards at PTB with those at the Institute of Quantum Optics (IQ) at the Leibniz University of Hanover, and the Max Planck Institutes in Erlangen (MPL) and Garching (MPQ). We demonstrate for the first time that within several minutes a phase coherent comparison of clock lasers at the few 10^{-15} level can also be accomplished when the lasers are more than 100 km apart. Based on the performance of the fiber link to the IQ, we estimate the expected stability for the link from PTB to MPQ via MPL that bridges a distance of approximately 900 km.**

I. Introduction

Recently, cold atom or single ion clocks based on optical transitions have surpassed the performance of the best microwave clocks [1], [2] and are considered for a possible redefinition of the second. However, one prerequisite for a future redefinition is the ability to compare and disseminate optical frequencies at the corresponding level of accuracy and stability of the optical clocks.

Considering that today's established techniques of frequency comparisons via satellite do not reach the required stability and accuracy [3] and that optical clocks are not yet transportable because of their complexity, the use of optical fibers for the comparison of distant optical clocks has been discussed extensively as an innovative alternative [4]–[7].

Manuscript received May 20, 2009; accepted September 4, 2009. The work was partly supported by Deutsche Forschungsgemeinschaft (DFG) through SFB 407; by the Centre for Quantum Engineering and Space-Time Research, QUEST; and by the European Space Agency, ESA. O. Terra is supported by the Egyptian Government and members of the Braunschweig International Graduate School of Metrology, IGSM.

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Digital Object Identifier 10.1109/TUFFC.2010.1395

The most promising methods for long-haul frequency dissemination based on existing telecommunication fiber networks at $\lambda = 1.5$ µm are the use of an AM-modulated carrier frequency [8], [9], or the direct transfer of a highly stable optical carrier [10],[11].

As the dispersion in the fiber, signal attenuation, and the linewidth of the laser become critical issues the latter approach prevails for longer links. Thus, optical carrier-phase transfer is now intensively studied by several groups to enable direct comparisons between different optical frequency standards [12]–[14]. Using fiber laser-based femtosecond combs [15] a comparison of distant clocks can be performed in the optical carrier domain by measuring the ratio between the frequency of the laser used for transmission and the local clock frequency simultaneously at the local and remote end [16].

II. A 900-km Long Optical Telecommunication Fiber Link

Currently, we are establishing a fiber connection in Germany that will eventually link optical clocks at PTB with those at the Institute of Quantum Optics (IQ), at the Leibniz University of Hanover (LUH), and the Max Planck Institutes in Erlangen (Max Planck Institute for the Science of Light, MPL) and Garching (Max-Planck-Institute for Quantum Optics, MPQ).

The fiber route (black line in Fig. 1) was established in a collaboration with the German Science Network DFN, GasLINE GmbH (a provider of a Germany-wide integrated fiber-optic cable network established by German gas distribution companies), and a local energy and telecommunication provider in Braunschweig (EnBs). The pipeline networks of gas distribution companies and local telecommunication providers offer significant potential for developing a wide-area fiberoptic infrastructure. A pair of dark fibers[1] in a strand of commercially used fibers has been made available. As both fibers are located in the same strand, they are affected by the same environmental

[1] "Dark fiber" is optical fiber infrastructure that is currently in place but is not being used for data communication. Light transmitted over a dark fiber is provided by the customer rather than the local exchange carriers.

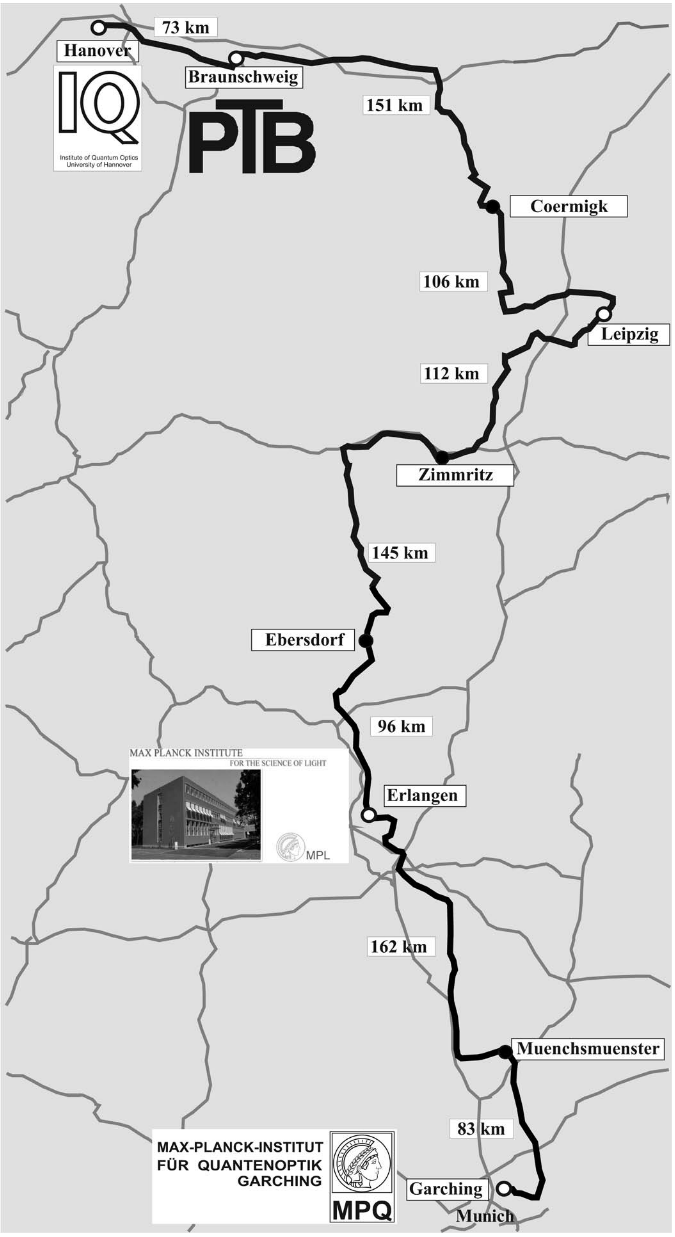

Fig. 1. Fiber link from PTB in Braunschweig to the IQ at LUH, Hanover, and to the MPQ, Garching, via Leipzig and MPL, Erlangen. Intermediate containers for signal conditioning are marked as black dots.

conditions and have the same characteristics. Moreover, the selection of a fiber route in the side-strip of a gas transmission line assures that the fiber is well sheltered from environmental noise and thus large frequency fluctuations can be avoided.

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

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, acoustic, and electronic flicker ($1/f$) noise, photodetection shot noise, and amplitude-to-phase conversion processes.

Typically, to achieve ultra-stable frequency dissemination via optical fibers at the level of $<10^{-15}$ at 1 s over distances exceeding a few 10 m, the phase noise of the fiber link must be suppressed by active optical path length stabilization. We use an interferometric arrangement similar to the one first described by Ma *et al.* [17] to cancel the fiber-induced phase noise at the remote end of the fiber link [18]. Ultimately, this approach is limited by nonreciprocal effects in the optical transmission system as it relies on the fact that the 2 counter-running signals experience exactly the same phase perturbations. Even though this effect is not limiting the performance of the links investigated so far, it might become an issue for very long links.

For the envisioned link length of several hundred kilometers, 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 0.23 dB/km and a gain of 20 to 30 dB per amplifier, an amplifier spacing of about 100 km is sufficient to establish a quasi-transparent optical link where the noise penalty caused by the cascaded amplification is smaller than 10 dB [19]. These amplifiers will be installed at locations marked in Fig. 1 as black dots and at DFN locations in Leipzig and Erlangen.

In Erlangen a single ion frequency standard [20] based on In^+ is operated at MPL that is located about 2 km away from the DFN location (computing center of the university of Erlangen-Nürnberg) To bridge this distance a point-to-point free-space transmission of an optical signal at 194 THz is currently investigated. First results over 50 m free space propagation show that for short distances signals can be transmitted with a stability of $\sigma_y(\tau) = 2\cdot 10^{-13}\ (\tau/\mathrm{s})^{-1/2}$ [21]. With respect to the stability of state-of-the-art optical clocks, this free space link is currently the rate limiting step and will need significant improvement.

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 long-haul, all-optical carrier phase frequency transmission over a long-distance optical link of 900 km at real scale with representative environmental perturbations. We expect that this will boost new applications as well as provide significant advances in current research.

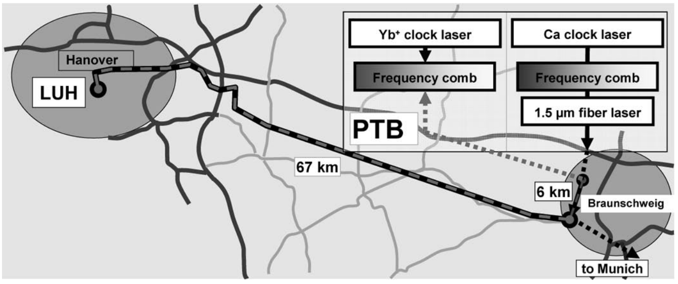

Fig. 2. Schematic of a comparison of remote frequency standards by means of a link based on a dark telecommunication fiber (black/dashed gray lines). At PTB, a 1.5-µm fiber laser is locked to an optical frequency standard. Its output is transmitted over 146 km to another optical frequency standard based on a trapped Yb^+ ion at PTB via the fiber pair from LUH to PTB.

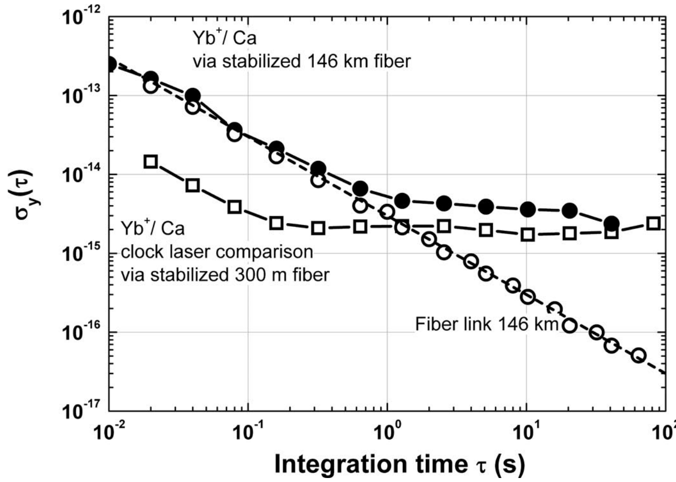

Fig. 3. Relative frequency instability $\sigma_y(\tau)$ of the Yb^+ clock-laser compared with the Ca clock laser, of the NIR laser compared with the Yb^+ clock laser after 146-km fiber, and of the out-of-loop fiber stabilization signal; the dashed line is equivalent to $\sigma_y(\tau) = 2.7{\cdot}10^{-15}/(\tau/\mathrm{s})$ [25].

III. Characterization of the Fiber Link to LUH

As a first operational part of the full link, we have investigated the fiber link from PTB to IQ at LUH. A more detailed sketch of this part is depicted in Fig. 2. In a first step, our laboratory is linked via PTB's computing center with the network of a local provider (EnBs) in Braunschweig. The EnBs-network (6 km) allows us to directly connect to the computing center at LUH using the wide-area network of GasLINE company. A 400-m long in-house fiber pair then permits access to the Mg frequency standard [22] at IQ.

For investigating the limits of the fiber link, we connected the 2 fibers at LUH forming a loop with the remote and local ends of the link at PTB. Details of the set-up and the performance of the stabilization system can be found in [18].

A single-frequency distributed feedback fiber laser (Koheras Adjustik, NKT Photonics A/S, Birkerød, Denmark) at $\lambda = 1542$ nm (NIR) is phase-locked to a cavity-stabilized laser routinely used as clock laser of the Ca optical frequency standards [23] at 657 nm by means of a frequency comb [16]. With this approach, we realize a precisely known and ultrastable frequency ratio between the NIR laser and the cavity-stabilized clock laser. The output of the NIR laser is then transmitted via a stabilized fiber link from PTB to LUH and back, where its frequency is measured relative to the cavity-stabilized clock laser of PTB's Yb^+ frequency standard [24] at 871 nm using another frequency comb. This allows a simultaneous and independent measurement of the transmitted NIR frequency stability through the first subsection of the fiber network, simulating a user at a distance of 146 km [25].

The relative instability between the optical clock lasers of the Yb^+ and Ca frequency standards (shown as open squares in Fig. 3) is known from a direct comparison [26] and assures an upper limit of the relative instability of $4{\cdot}10^{-15}$ at $\tau = 0.1$ s approaching a flicker floor of $2{\cdot}10^{-15}$ for $1 < \tau < 100$ s. This flicker floor is due to the thermal noise of the optical reference cavities used to stabilize the clock lasers. Thus, for $\tau < 1$ s the Yb^+ clock laser can be used to rapidly verify the short-term stability of the transmitted laser frequency in a fully independent way. The measurement of the NIR laser frequency at the remote end using the Yb^+ clock laser is represented by the black dots. At short averaging times, this measurement is consistent with the measured instability of the stabilized 146-km fiber link of $\sigma_y(\tau) = 3{\cdot}10^{-15}/(\tau\ /\mathrm{s})$ (open circles). For longer averaging times, the relative instability of the transmitted frequency approaches the flicker floor of the optical reference.

Within several minutes of averaging time, the contribution of the fiber link to a clock comparison becomes negligible, the optical clocks can be compared at the level of their systematic uncertainty and the full performance of an optical clock is available for a general public user at the remote end.

With this measurement, we demonstrate for the first time that using a fiber link with low intrinsic phase noise, a phase-coherent comparison of clock lasers—nowadays routinely performed between adjoining laboratories—can also be accomplished when the other laser is more than 100 km apart.

IV. Estimated Phase Noise and Instability of a Fiber Link to MPQ

Based on the performance of the fiber link to LUH that is now routinely used for the frequency measurement of the ^{24}Mg frequency standard at IQ, we now estimate the expected stability for the approximately 900-km long link from PTB to MPQ via MPL.

The previously mentioned basic Doppler cancellation technique relies on suppressing the optical path length fluctuations at the remote end using a phase-locked loop at the local end. Because the length of the transmission line introduces a time delay between the signal returned from the remote end and that from the local end, this delay imposes a fundamental limit on the achievable degree of phase noise suppression [27].

First, it directly affects the control bandwidth of the compensation loop and, as a result, the total phase noise at high Fourier frequencies f is given by unsuppressed noise of the fiber link. Second, the delay through the link results in an imperfect cancellation of the noise at the remote end. This imperfect cancellation of the one-way fiber noise caused by the delay dominates at low Fourier frequencies and limits the attainable stability. The spectral dependence of the achievable phase noise suppression can be estimated as

$$S_\phi^{\text{out}}(f) = \frac{4\pi^2}{3} \cdot \left(\frac{nL}{c}\right)^2 \cdot f^2 \cdot S_\phi^{\text{fiber}}(f) \quad \text{for } f < c/(nL), \tag{1}$$

where L is the one-way physical path length, n the index of refraction, c the speed of light, and S_ϕ^{fiber} denotes the phase noise of the unstabilized link [27].

As $S_\phi^{\text{out}}(f)$ is proportional to $L^2\ S_\phi^{\text{fiber}}(f)$, the attainable link stability in frequency comparisons decreases proportional to $L(S_\phi^{\text{fiber}})^{1/2}$. Assuming that $S_\phi^{\text{fiber}}(f)$ is dominated by white frequency noise, one calculates an achievable suppression of 52 and 35 dB for a link length of 146 and 1000 km, respectively. Because L is determined by the distance between the clocks that are compared, the only ways to improve the link stability is to split the total length into subsections (to increase the control bandwidth) 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. For our link, we compromise between cost issues for equipment to be installed along the link and stability issues. As a result the length of the typical subsections is about 160 km, so that the total distance is bridged in 7 steps (see Fig. 1).

Thus, the phase noise associated with the 146-km fiber loop is representative for a typical subsection of the total network without active path length stabilization. The measured phase noise spectrum $S_\phi^{\text{fiber}}(f)$ of the unstabilized link is shown in Fig. 4 as gray curve [25] and can be approximated by

$$S_\phi^{\text{fiber}}(f) = \left[\frac{100\,\text{Hz}}{f} \cdot \left(1 + \frac{f}{10\,\text{Hz}}\right)^{-2} + \text{const}\right]\ \text{rad}^2/\text{Hz} \tag{2}$$

if the distinct environmental noise maximum at $f \approx$ 15 Hz is neglected (gray line). For Fourier frequencies $f \geq$ 100 Hz, the phase noise decreases as $1/f^3$, whereas 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.

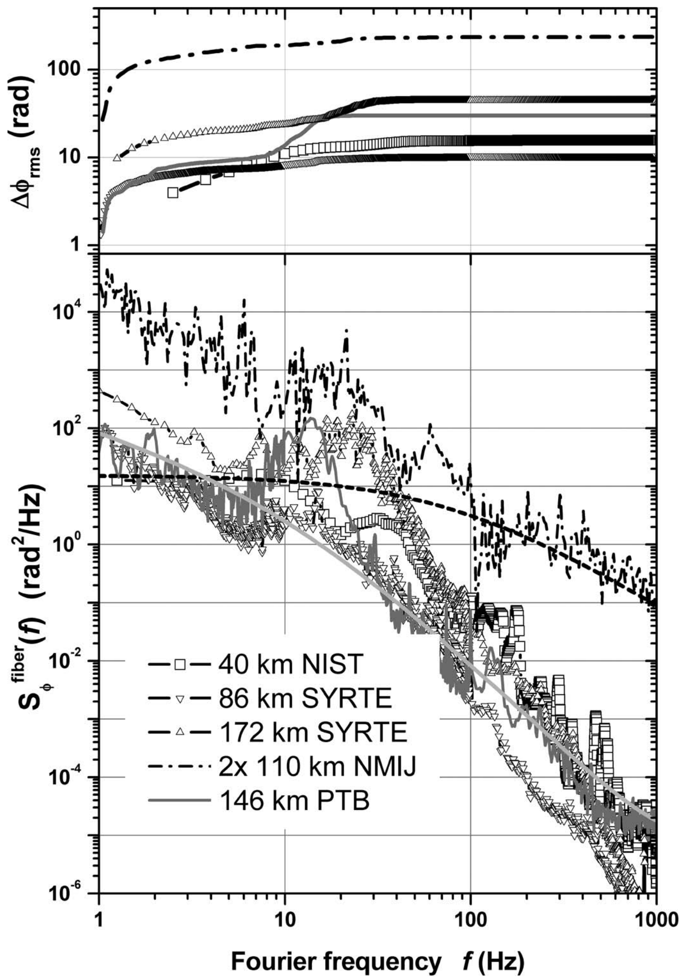

Fig. 4. Compilation of the phase noise $S_\phi^{\text{fiber}}(f)$ of different unstabilized optical links (2 × 110-km NMIJ data courtesy of N. Newbury, G. Santarelli, and F. L. Hong). The gray line approximates the noise of the unstabilized 146-km link according to (2). The NMIJ-link data are used as a worst-case estimate for a calculation of the residual noise of a stabilized 1000-km link according to (1) (dashed black line). Note that the NMIJ data correspond to the 220-km round-trip signal for a 110-km long fiber.

Similar experiments have been performed by other groups and phase noise data of 3 other fiber-optic links operated in France (SYRTE, triangles) [14], Japan (NMIJ, black, only inloop signal of the round trip light available) [13], and the USA (NIST, squares) [27] have been published recently. These links have lengths of 86, 110, and 40 km, respectively. In the first case, the total link length was increased up to 172 km by using the fiber twice and in the latter up to 251 km by adding additional fiber spools. We have included the phase noise of some of these links in Fig. 4.

Whereas the phase noise characteristics of the 40-, 80-, 172-, and 251-km links are very similar to that of the PTB link, the 110-km link in Japan exhibits a noise level that is approximately 25 dB higher at $f = 1$ Hz. It can be ap-

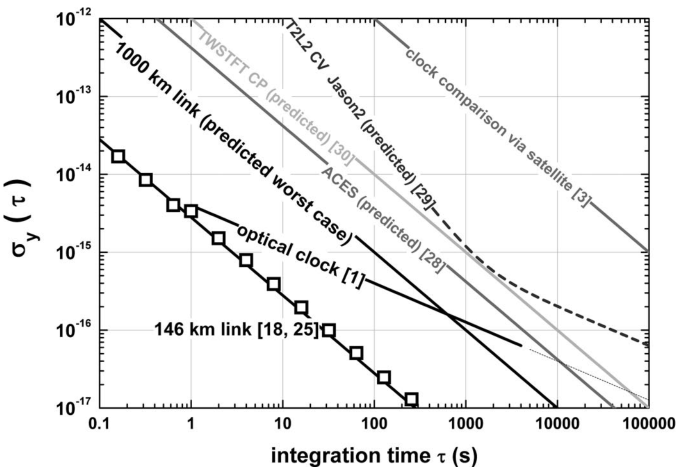

Fig. 5. The observed fractional instability [given by the Allan standard deviation $\sigma_y(\tau)$] of laser frequency transmission using the 146-km PTB-LUH-PTB link according to [18] compared with that of a state-of-the art single-ion optical clock [1] and to the estimated instability of a link of 1000-km length (see text). For comparison, we include state-of-the-art frequency comparisons by satellite and the predicted instability of the carrier-phase TWSTFT technique and other advanced in-orbit methods [28], [29]. The dashed line corresponds to the modified Allan standard deviation using time deviation data from [29].

proximated by $S_\phi^{\text{fiber}}(f) = 5{\cdot}10^4\ \text{Hz}^2/f^2\ \text{rad}^2\ \text{Hz}^{-1}$ and shows a clear $1/f^2$ dependence.

To estimate the stability of a signal transmitted over a 1000-km link, we first assume that the phase noise of the free-running link has a frequency dependence similar to that of the present PTB-LUH-PTB link (see Fig. 4), and that the phase noise spectral density $S_\phi^{\text{fiber}}(f)$ increases proportional to the link length L. In this case, the phase noise level at $f = 1$ Hz is of the order of 700 $\text{rad}^2\ \text{Hz}^{-1}$ (2). This value is still significantly smaller than that of the 2 × 110-km link investigated in [13].

We consider a noise level of $S_\phi^{\text{fiber}}(f) = 5{\cdot}10^4\ \text{Hz}^2/f^2\ \text{rad}^2\ \text{Hz}^{-1}$ as a worst-case estimate for an unstabilized 1000-km link. The calculated residual phase noise of the stabilized link then is in the range of $S_\phi^{\text{out}}(f) < 16\ \text{rad}^2\ \text{Hz}^{-1}$ for $f < 200$ Hz, corresponding to an estimated fractional frequency instability of $\sigma_y(\tau) \approx 1{\cdot}10^{-13}\ (\tau/\text{s})^{-1}$ for a detection bandwidth of 300 Hz. Additionally, dividing the total distance into 160-km long subsections will further reduce the instability by approximately a factor of 6.

As shown in Fig. 5, the estimated instability of a 1000-km link (black line) becomes smaller than that of the presently best optical clocks [1] for an averaging time $\tau >$ 1000 s. After an averaging time of 3 h, 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 the Atomic Clock Ensemble in Space (ACES) microwave link [28], the Time Transfer by Laser Link (T2L2) experiment on the Jason 2 satellite [29], or that of satellite-based comparisons using an advanced carrier-phase two way satellite time and frequency transfer (TWSTFT) technique [30] by at least a factor of 5. Note, both ACES or the advanced carrier-phase TWSTFT require assuring the phase traceability over an uninterrupted measurement time on the order of a day to reach the instability of the optical clock. For T2L2, phase traceability over a full orbit is not implemented and a comparison of ground clocks will be limited by the stability of the link on all time scales because of the small time of visibility (several minutes) compared with the orbit period of 1.5 to 2 h.

V. Conclusion

For the current development of European optical clocks separated by typical distances of 500 to 1500 km, 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 may be a critical issue. The search for national 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.

In spite of the fast advances of clock comparisons via optical fiber links, we also expect that in the near future the baselines of such links are restricted to 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 radio frequency 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 uncertainty 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, in particular the synchronization systems of next-generation linear colliders [31] and of large astronomical antenna arrays such as the Atacama Large Millimeter Array [32], both demanding low-noise frequency dissemination systems with minimal phase drifts and errors, will 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 like large-aperture VLBI in the near-infrared and optical wavelength range. The combination of high frequencies and long interferometric base lines requires the distribution of a local oscillator with low phase noise and low phase drift through the array [33]. For the Deep Space

Network of NASA, a system of optical fiber links has been developed to distribute reference signals from a hydrogen maser for antenna synchronization [34].

The implementation of a European fiber network for highly stable optical frequency transmission would boost the field of time and frequency metrology. The network in particular would enable stability tests of satellite-based time transfer techniques (see the previous discussion) and of the timing facilities of the global navigation satellite systems GPS and Galileo [35].

Several fundamental physics research programs would 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 [35]. 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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Authors' photographs and biographies were unavailable at time of publication.