Direct comparison of optical lattice clocks with an intercontinental baseline of 9 000 km

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We have demonstrated a direct frequency comparison between two $^{87}$Sr lattice clocks operated in intercontinentally separated laboratories in real time. Two-way satellite time and frequency transfer technique based on the carrier phase was employed for a direct comparison with a baseline of 9 000 km between Japan and Germany. A clock comparison was achieved for 83 640 s resulting in a fractional difference of $(1.1 \pm 1.6) \times 10^{-15}$, where the statistical part is the biggest contribution to the uncertainty. This measurement directly confirms the agreement of the two optical clocks on an intercontinental scale.

Optical clocks have made rapid progress in the last ten years [1]. Following an aluminum ion clock [2], lattice clocks also reported an accuracy as well as an instability at the $10^{-18}$ level [3]. Remote comparisons of optical clocks with this level of precision may work as a probe to detect differences in the gravitational redshift between different locations. Typical uncertainties in the level of the geoid surface currently amount to several centimeters, corresponding to differences in the redshift at the $10^{-17}$ level. Furthermore, with the high frequency stability of optical clocks, temporal variations of the gravitational potential due to tidal effects become relevant at the $10^{-17}$ level already at distances of a few 100 km. This dynamical shift may be estimated by monitoring the clock comparisons on intercontinental scale because the differential tidal effects would become larger and observable in short time. With global frequency comparisons a variety of clock combinations may be established for testing fundamental postulates like a search for violations of Einstein’s equivalence principle [4]. In metrological aspect, on the other hand, frequency agreement confirmed by intercontinental comparisons proves the capability of optical clocks to generate and maintain standard frequencies worldwide, which will support the optical redefinition of the second.

Frequency comparisons of optical clocks have been realized mostly on-campus [2, 3, 5-8] except for two cases: one is a comparison of a $^{87}$Sr lattice clock at JILA against a neutral Ca clock at NIST with a 4-km-long optical fiber link [9] and the other is between two $^{87}$Sr lattice clocks at NICT and the University of Tokyo (UT) using a 60 km-long optical fiber [10]. Optical fiber links are promising on continental scales as demonstrated up to 1840 km [11]. To bridge intercontinental distances, however, satellite based techniques are presently the only way, though studies to use very long baseline interferometry (VLBI) or free-space optical links have been recently initiated [12, 13]. The global positioning system carrier-phase (GPSCP) technique, which has been the most precise satellite-based method, requires averaging times of more than a day to surpass an instability of $1 \times 10^{-15}$. As an alternative, carrier-phase based two-way satellite time and frequency transfer (TWCP), first demonstrated by U.S. Naval Observatory [14], is lately characterized in NICT for various ranges of the baselines up to 9 000 km which is realized between NICT and PTB [15, 16]. Among satellite based techniques the TWCP technique has a superior short term instability (evaluated to be at the $10^{-13}$ level at 1 s) and is thus particularly suitable for comparing frequency standards with low instabilities, e.g. optical clocks.

In this Letter, two strontium lattice clocks, one at NICT in Japan [17] and the other at PTB [18, 19] in Germany, are directly compared using the TWCP technique. The agreement of these two optical clocks based on the same reference transition was confirmed with an uncertainty of $1.6 \times 10^{-15}$. The baseline of 9 000 km is the longest in direct comparisons of optical clocks.

Figure 1 shows the setup of the comparison. It consists of a TWCP setup, $^{87}$Sr lattice clocks and frequency combs at each site. Both lattice clocks use the transition $^1S_0(F = 9/2) - ^3P_0(F = 9/2)$ as reference. The accuracy of the $^{87}$Sr lattice clock at NICT and PTB is $2 \times 10^{-16}$ and $4 \times 10^{-17}$, respectively. Frequencies of the lattice clocks at each site are measured referenced to a local hydrogen maser (H-maser). At NICT, a Ti-sapphire based frequency comb is stabilized to the H-maser and the clock frequency $\nu_{\text{NICT}}$ is obtained from the beat signal against the frequency comb. At PTB, the transfer oscillator method [20] is used to measure frequency ratios with fs-combs. The H-maser and the Sr clock are located in different buildings each with an erbium-fiber based frequency comb. These frequency combs are connected by stabilized optical fiber links. The frequency of the lattice clock at PTB $\nu_{\text{PTB}}$ is derived from relevant beat signals with a reference to the local H-maser. Additionally an $^{171}$Yb$^+$ ion clock based on the electric
The frequency ratio of two H-masers is derived. The fractional frequency difference of the two H-masers, via which the differential carrier phase of the received signals were detected by de-modulation using a replica code, by which we derived the fractional frequency difference of the two H-masers. The technical details of the TWCP system are described in [15, 16]. The frequency ratio of the $^{87}$Sr lattice clocks is obtained through the ratio of the two H-masers in real time.

Figure 2 shows a typical time record of the fractional frequency difference of the optical clocks of one typical experimental day. Corrections of systematic shifts of the atomic clocks as well as the compensation of ionospheric delays are included. Each point is the result of 60 s signal integration.

The Allan deviation of $\Delta (t)$ of the longest continuous recording (30 900 s shown as the later part of Fig. 2) is presented as the filled circles in Fig. 3. The reduction of the Allan deviation with the signal integration time is slower than in case of white frequency noise, which confirms the autocorrelation analysis described above. We fitted the instability obtaining $7.5 \times 10^{-14} \tau^{-0.37}$. Possible sources of instabilities are ambient temperature changes effecting the outdoor microwave equipment or imperfections of the ionosphere corrections.

We operated the clocks for several hours per day over four days and obtained simultaneous operation of the two lattice clocks for 69 840 s in total. This data set was extended by using the Yb$^+$ ion clock at PTB to a total of 83 640 s utilizing the frequency ratio of the two clocks at PTB obtained in their simultaneous operation for 45 960 s. The Allan deviation of this extended data set is shown in Fig. 3 as open circles. It agrees with the result of 60 s signal integration.

The observed instability of $7.5 \times 10^{-14} \tau^{-0.37}$ results from link instabilities as the optical clocks have demonstrated much smaller instabilities. An upper limit for the link instabilities is obtained from the comparison of the TWCP link against the GPSCP technique. This was done by measuring UTC(NICT) versus UTC(PTB) via the two link techniques during the four days of the measurement discussed here as well as in a preceding study over two months. The Allan deviations of the link com-
Comparisons are shown in Fig. 4, which provides an upper limit of the instability of each of the two satellite link techniques. As the measurement time of the optical clock comparison was limited, its instability did not fall below $10^{-15}$ (Fig. 3) but is below the combined instability of the GPSCP and the TWCP links (Fig. 4). We estimate the statistical uncertainty of the clock comparison by an extrapolation to the total measurement time using the observed instability progression and find $1.2 \times 10^{-15}$ for 83 640 s measurement time. This is consistent with the comparison of the two link techniques. The averaged frequency difference between the two link techniques was less than $1.0 \times 10^{-15}$, which we assign as the systematic uncertainty of the link for the clock comparison.

By combining the systematic uncertainties of the lattice clocks ($2 \times 10^{-16}$ and $4 \times 10^{-17}$) and the link ($1.0 \times 10^{-15}$) as well as the statistical uncertainty ($1.2 \times 10^{-15}$) we obtain the fractional uncertainty of the clock comparison to be $1.6 \times 10^{-15}$. Using the fractional frequency difference $\Delta = 1.1 \times 10^{-15}$ along with a recent absolute frequency measurement of the PTB strontium lattice clock with an uncertainty of $3.9 \times 10^{-16}$, the absolute frequency of the NICT strontium lattice clock is derived to 429 228 004 229 873.60 (71) Hz.

Figure 5 relates our clock comparison to other methods of remote frequency standard evaluations: An example for a precise comparison via local realizations of the second with Cs fountain clocks is given by the comparison of the Sr lattice clocks of PTB and SYRTE $\Delta = 1.1(1.6) \times 10^{-15}$, dominated by the uncertainty contribution of the link. Further improvements may be achieved with more continuous measurement time and more careful control of ambient temperature of the link system. We expect to reach the $10^{-16}$ level of accuracy in the near future with commercially available ground stations modified to apply the TWCP technique. Optically generated microwaves may replace H-masers as local reference to synthesize the carrier frequency. Baselines capable of connecting continents and transportable ground stations may further fuel the interest in the demonstrated technique.

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FIG. 5. Overview of frequency comparisons of remote strontium lattice clocks using different methods.