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First international comparison of fountain primary frequency standards via a long distance optical fiber link

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Abstract

We report on the first comparison of distant caesium fountain primary frequency standards (PFSs) via an optical fiber link. The 1415 km long optical link connects two PFSs at LNE-SYRTE (Laboratoire National de métrologie et d'Essais—SYstème de Références Temps-Espace) in Paris (France) with two at PTB (Physikalisch-Technische Bundesanstalt) in Braunschweig (Germany). For a long time, these PFSs have been major contributors to accuracy of the International Atomic Time (TAI), with stated accuracies of around 3×10^{-16}. They have also been the references for a number of absolute measurements of clock transition frequencies in various optical frequency standards in view of a future redefinition of the second. The phase coherent optical frequency transfer via a stabilized telecom fiber link enables far better resolution than any other means of frequency transfer based on satellite links. The agreement for each pair of distant fountains compared is well within the combined uncertainty of a few 10^{-16} for all the comparisons, which fully supports the stated PFSs' uncertainties. The comparison also includes a rubidium fountain frequency standard participating in the steering of TAI and enables a new absolute determination of the ^{87}Rb ground state hyperfine transition frequency with an uncertainty of 3.1×10^{-16}.

This paper is dedicated to the memory of André Clairon, who passed away on 24 December 2015, for his pioneering and long-lasting efforts in atomic fountains. He also pioneered optical links from as early as 1997.

Keywords: optical fiber frequency transfer, atomic fountain clocks, international fountain clock comparison

(Some figures may appear in colour only in the online journal)

1. Introduction

Since 1967 the time unit 'second' of the international system of units (SI) is defined using the ground state hyperfine transition of the caesium atom ^{133}Cs. Today a set of highly accurate atomic caesium fountains, some of them reaching frequency uncertainties in the low 10^{-16}, realizes the present definition of the SI-second with the lowest uncertainty. Besides the utilization for local time scale steering [1, 2], fundamental research (e.g. [3–5]) and measurements of optical frequencies (e.g. [6, 7]), the main task of primary fountain clocks is the calibration of the widely used International Atomic Time (TAI) calculated by the Bureau International des Poids et Mesures (BIPM). Our two institutes, Laboratoire National de métrologie et d'Essais—SYstème de Références Temps-Espace (LNE-SYRTE) in Paris as Designated Institute for France and Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig as National Metrology Institute (NMI) for Germany, maintain several atomic fountains which are among the world's best primary clocks regarding both accuracy and reliability, i.e. capability of almost continuous operation. They are used to steer timescales at LNE-SYRTE and PTB on a daily basis, which yields some of the most stable local real time realizations of the Coordinated Universal Time (UTC) [1, 2]. Over the last decade, these fountains have provided to the BIPM a large number of formal monthly calibration reports with stated relative uncertainties of a few 10^{-16}, representing about 60–70% of the total number of calibrations published in the *Circular T* [8]. Given the major involvement of these fountains in the accuracy of TAI, it is crucial to test their stated uncertainties. So far testing the uncertainty of a clock was mainly based on local clock comparisons, which was enabled both at LNE-SYRTE and at PTB with three and two simultaneously operating caesium atomic fountains, respectively. A more stringent test is to compare distant clocks operated by independent teams in separate laboratories. To date, however, the uncertainties of distant comparisons have been limited by the comparison methods relying on satellite based time and frequency transfer techniques via the U.S. global positioning system (GPS) or two-way satellite time and frequency transfer (TWSTFT) [9, 10], or TAI itself used as a flywheel [11–13].

In this paper, we report the first comparison of distant fountains, six pairs with three fountains at LNE-SYRTE and two at PTB, at the limit of the fountain uncertainties using a 1415 km long stabilized optical fiber link between Paris and Braunschweig. This link was specially developed for high resolution frequency comparisons of optical clocks from our two institutes [14–16] and has been characterized to contribute a frequency instability of $\sim 10^{-15}$ at 1 s averaging time. The fountain comparison, carried out in June 2015, demonstrates that frequency transfer by means of an optical fiber link is also highly beneficial to remote comparisons of fountain clocks.

2. Setup

A general overview of the setup is given in figure 1. At each institute, a set of atomic fountains measures the frequency of a hydrogen maser, filtered by a low phase noise microwave oscillator (an ultrastable microwave reference (UMR) at SYRTE [17] and an optically stabilized microwave oscillator (OSMO) at PTB [18]). The hydrogen maser frequencies are linked to ultrastable frequency transfer lasers (USLs) at 1.5 μm using optical frequency combs (OFCs). The USLs are injected into stabilized telecommunication fibre links to the connection point in Strasbourg [14, 15].

2.1. Fountains and local oscillators

The fountains intercompared are the primary frequency standards (PFS) FO1, FO2 located at SYRTE [17] and CSF1, CSF2 [19, 20] located at PTB. FO2 is a dual fountain operating simultaneously with caesium and rubidium atoms, known as FO2-Cs (PFS) and FO2-Rb (secondary frequency standard realizing the ^{87}Rb secondary representation of the second). FO2-Rb, which has comparable performance as the PFSs, also regularly contributes to the steering of TAI [21]. At SYRTE the local interrogation signal is derived from the UMR which is based on a cryogenic sapphire oscillator and phase-locked to the hydrogen maser H889 with a time constant of $\sim$ 1000 s [17]. At PTB the local interrogation signal is obtained from the OSMO, locked to the maser H9 with a time constant of $\sim$ 50 s [18].

The strategies to reduce and evaluate the frequency shifts and the corresponding uncertainties can be found in [17, 21, 22] and [19, 20, 23, 24] for SYRTE's and PTB's fountains, respectively. In this work, the relevant fountain accuracy budgets are close to those reported to the BIPM for the June 2015 evaluations (*Circular T330* [8]). The only exception is the fountain PTB-CSF1, for which a reevaluation of the distributed cavity phase shift has been performed after the comparison campaign, which retrospectively leads to a significantly reduced overall systematic uncertainty.

In addition, for the distant fountain comparison we apply improved relativistic gravitational redshift corrections with reduced uncertainties. Recently in the framework of the International Timescales with Optical Clocks project (ITOC,

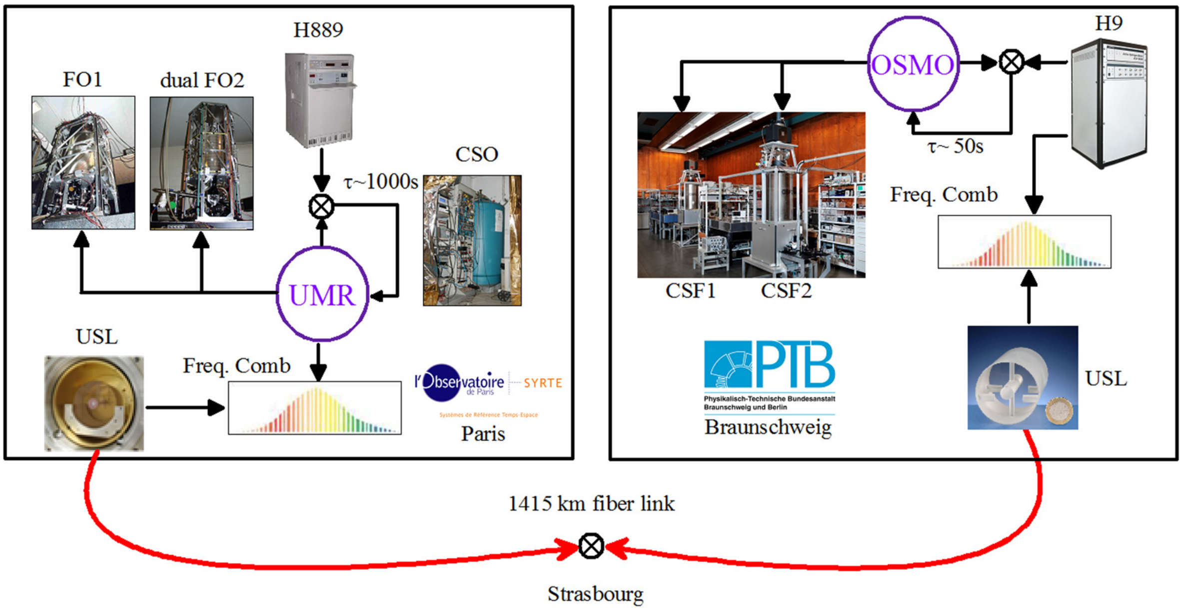

Figure 1. Schematic view of the experiment. UMR: ultrastable microwave reference; CSO: cryogenic sapphire oscillator; OSMO: optically stabilized microwave oscillator; USL: ultrastable laser. FO1, CSF1 and CSF2 are caesium fountains while FO2 is a dual fountain operating with caesium and rubidium atoms simultaneously. H889 and H9 are active hydrogen masers.

part of the European Metrological Research Programme EMRP), the gravity potentials at local reference markers at SYRTE and PTB were newly determined with respect to a common reference potential. This involved a combination of GPS based height measurements, geometric levelling and a geoid model [25], refined by local gravity measurements. Besides, in both laboratories, the gravity potential differences between the local reference markers and the reference points of each fountain (i.e. the mean effective position of the moving atoms during their ballistic flight above the microwave cavity centre) were determined by geometric levelling and from the respective fountain geometries and launch velocities. The uncertainty of the differential redshift determinations for the distant fountains is less than 4×10^{-18}, corresponding to less than 4 cm uncertainty in height difference, which is insignificant compared to the overall systematic (type B) uncertainty of each fountain as listed in table 1.

2.2. Transfer oscillators and optical link

At each institute an optical frequency comb is used to measure the frequency of the UMR (at SYRTE) or of H9 (at PTB) with respect to the frequency of an ultra-stable infrared laser (USL) at 1.542 μm, serving as transfer laser between the two institutes. The combs are generated by mode-locked erbium-doped fiber lasers delivering femtosecond pulses centered around 1.5 μm. Mode-locked fiber lasers are demonstrated to support measurements lasting several weeks, given the robustness of the mode-lock and the very low degree of necessary maintenance. At SYRTE, the comb is locked to the transfer laser via a fast feedback loop, effectively transferring the spectral purity of the transfer laser (instability of 5×10^{-16} in the 0.1–100 s range) into the repetition rate f_{rep} of the comb [7]. To obtain the frequency ratio between the transfer laser and the UMR, the latter is transmitted to the comb via a compensated fiber link with an instability of a few 10^{-15} at 1 s. The frequency difference between the 36th harmonic of the comb and the UMR is counted by a dead-time free frequency counter referenced to the UMR. At PTB, the carrier-envelope offset frequency f_{CEO} and the repetition rate f_{rep} of the comb are phase locked with low bandwidth to the hydrogen maser H9. For the actual measurement of the frequency ratio between the USL and H9, the transfer oscillator concept [26] is employed.

To combine the locally measured optical to microwave frequency ratios, we took advantage of the fiber link designed for the comparison of optical clocks between our two institutes and described in detail in [14–16]. At each institute the transfer laser is injected into a bi-directional long-haul coherent fibre link with active compensation of propagation phase noise and partial loss compensation. At the University of Strasbourg, each of the two links feeds a repeater laser station (RLS) [14] regenerating the optical signals. The optical beat notes between the user's outputs of the two RLSs are recorded with a dead-time free frequency counter referenced to an ultra-stable quartz disciplined by GPS.

Given the simultaneous frequency measurements in Paris, Strasbourg and Braunschweig, the frequency difference between the remote microwave references UMR − H9 can be calculated with negligible uncertainty contributions from the long-distance fiber link, the combs and the transfer lasers. The 1 s gate intervals of the frequency counters were synchronized to local representations of timescales UTC(k) or to GPS time. Additionaly, we actively cancelled the mid- and long-term drifts of the transfer lasers. Thus the uncertainty contribution due to synchronization issues is below 10^{-19} (for details see [16]).

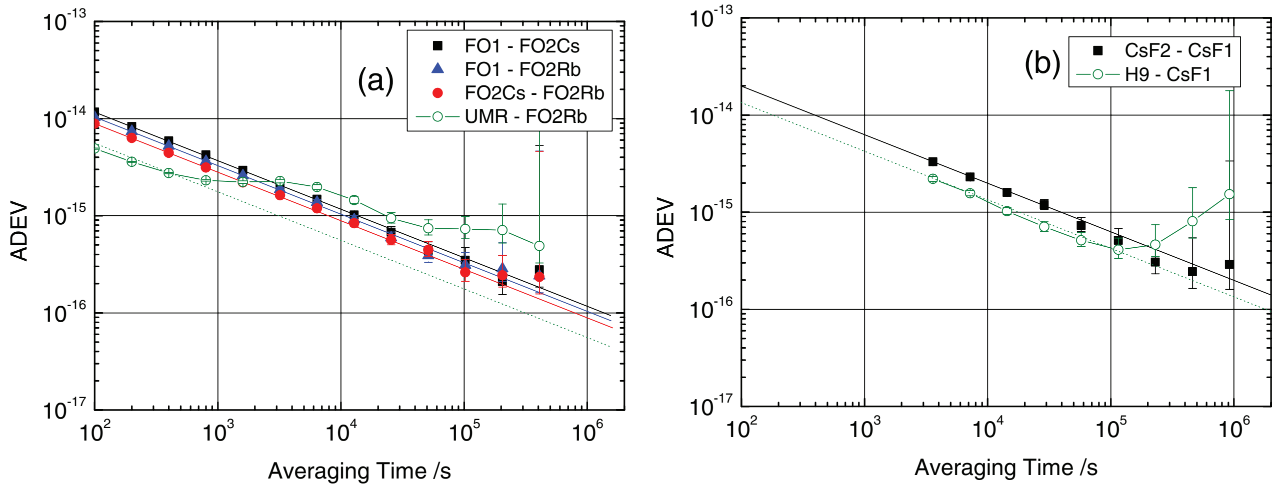

Figure 2. Allan standard deviations (ADEVs) of local comparisons (MJD 57177–57198) at SYRTE (a) and PTB (b). The straight lines correspond to extrapolations of the ADEV assuming white frequency noise. The open circles correspond to the frequency comparison between the local reference and one fountain.

3. Data analysis and results

The measurement campaign was performed in June 2015, between MJDs 57177 and 57198 (MJD: Modified Julian Date). The evaluation of the link measurements produces data of the frequency difference between the UMR phase-locked to the maser H889 at SYRTE and the maser H9 at PTB, sampled at 1 s. At SYRTE the FO1, FO2-Cs and FO2-Rb fountain data (UMR − FOx fractional frequency differences) are available on the clock cycle basis of $\sim$ 1.4 s–1.6 s. The data processing of the PTB's fountains CSF1 and CSF2 provides fractional frequency differences (H9 − CSFx) averaged over 1 h intervals. The fountain measurements covered $>$ 80% of the campaign duration at SYRTE and $>$ 90% at PTB. The masers distant comparison via the link was in operation during about 70% of the $\sim$ 21 d period.

The comparisons were performed over synchronous time intervals in order to cope with gaps in the data, for both the four local and the six remote fountain pairs available. For the local comparisons at SYRTE, the fountain data were averaged over 100 s intervals, much longer than the clock cycle times. The data of the PTB's fountains provided over synchronous 1 h long intervals could be directly intercompared. In view of the SYRTE to PTB comparisons, SYRTE's fountain data and the link data were also averaged over 1 h. Only 1 h intervals containing more than 25% valid data from the link as well as the participating fountains were included. The results were cross-checked using various evaluation routines independently developed at SYRTE and PTB.

Figures 2(a) and (b) show the Allan standard deviations (ADEVs) of the local fountain comparisons at SYRTE and PTB, respectively. The frequency instability for an averaging time τ is about $1 \times 10^{-13}\tau^{-1/2}$ for the three SYRTE's fountain pairs and about $2 \times 10^{-13}\tau^{-1/2}$ for CSF1 − CSF2. Since all fountains are operated in the quantum projection noise limited regime [27], the individual instabilities are given by the respective detected atom numbers. The four local comparisons reach 2×10^{-16} after averaging periods of about 3 d at SYRTE and 10 d at PTB. The green curves in figures 2(a) and (b) give the ADEVs of the local comparisons between the frequency reference and one fountain at SYRTE and PTB, respectively. The UMR − FO2-Rb instability of $5 \times 10^{-14}\tau^{-1/2}$ for τ less than 1000 s is quantum projection noise limited thanks to the use of the cryogenic sapphire oscillator [27]. It then increases due to the phase locking of the UMR to the H889 maser and converges to the instability of H889. The H9 − CSF1 short term instability of $1.2 \times 10^{-13}\tau^{-1/2}$ results from the CSF1 quantum projection noise and the H9 frequency instability. Beyond two days, the hydrogen maser frequency drifts ($\sim -1.5 \times 10^{-16}$ d^{-1} and $\sim -1.9 \times 10^{-16}$ d^{-1} for H889 and H9, respectively) show up, but these are well rejected in the fountain synchronous differences, as expected for common noise.

Figures 3(a) and (b) present the ADEVs of the distant comparisons of the SYRTE fountains against PTB − CSF1 and PTB − CSF2, respectively. The instability for all the comparisons is at or below $2 \times 10^{-13}\tau^{-1/2}$ and reaches 2×10^{-16} for averaging periods of 10 d or even less, just as if the fountains were located in the same laboratory (figure 2). This result, remarkable considering the 1415 km signal path between the fountains, is obtained thanks to the very low noise of both the fiber link (open circle dashed line in figure 3) and the comparison chains. Also shown in figure 3 (green curve) is the instability of the distant comparison between the local frequency references UMR − H9. Below a few hundred seconds, it is limited by the noise of H9, the noise of the UMR at SYRTE being much smaller ($\sim 2 \times 10^{-15}$ at 1 s). The instability decreases up to a few hundred seconds, as expected from the time constant of the UMR phase lock loop to H889 of about 1000 s. Then the ADEV follows that of the comparison of the H-masers which decreases up to averaging times of 10 d, because the drifts of the two masers happen to be very similar.

The measured mean fractional frequency differences for all the fountain pairs are listed in table 1, together with the estimated statistical uncertainties u_A, the systematic uncertainties u_{B1} and u_{B2} of the two fountains compared, and the uptimes of the comparisons over the period 57177–57198 (4–25 June 2015). The effective comparison durations range from 14 to

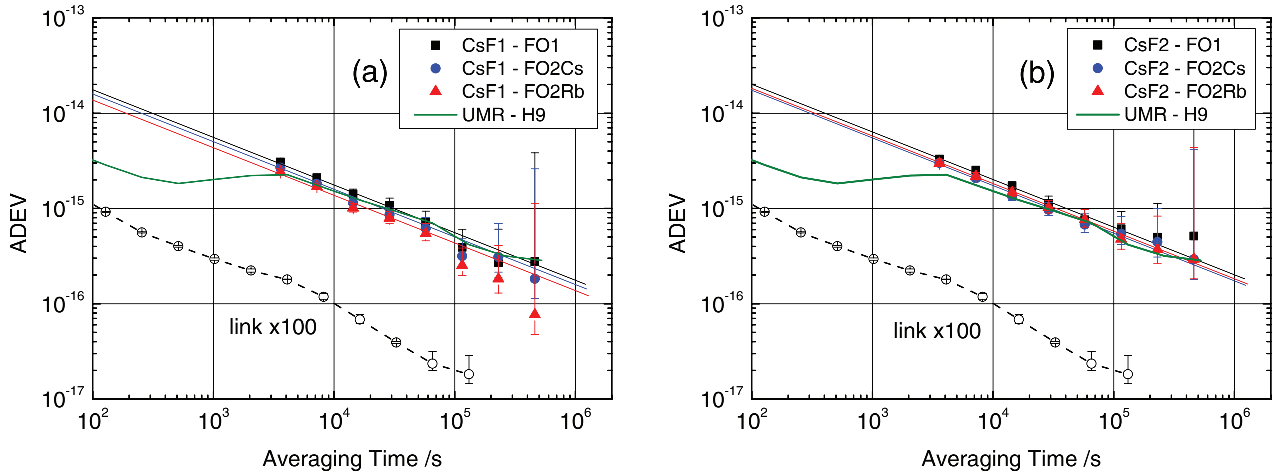

Figure 3. Allan standard deviations (ADEVs) of the distant fountain comparisons (MJD 57177–57198) (a) PTB-CSF1 − SYRTE-FOx and (b) PTB-CSF2 − SYRTE-FOx. The straight lines correspond to extrapolations of the ADEV assuming white frequency noise. The instability of the remote comparison between the local frequency references, the UMR (ultrastable microwave reference locked to H889 maser) at SYRTE and H9 maser at PTB, is shown by the dark green line and an upper limit of the instability of the fiber link [16], multiplied by 100, by the open circle dashed line.

Table 1. Summary of the local and distant comparisons between the SYRTE and PTB fountains during the June 2015 campaign (MJD 57177–57198). The second column gives the average fountain difference (Diff.). u_A is the statistical uncertainty corresponding to the Allan standard deviation presented in figures 2 and 3 extrapolated at the measurement duration assuming white frequency noise. u_{B1} and u_{B2} correspond to the systematic uncertainty of each fountain under comparison. u is the combined uncertainty. The last column lists the uptime of the comparisons. The value of the absolute frequency of the ^{87}Rb ground state hyperfine transition used in these comparisons is 6 834 682 610.904 312 Hz. In 2015 this was the value recommended by the Comité International des Poids et Mesures.

(a) Local Comp.	Diff. [10^{-16}]	u_A [10^{-16}]	u_{B1} [10^{-16}]	u_{B2} [10^{-16}]	u [10^{-16}]	Uptime [%]
CSF2 − CSF1	−2.4	1.4	3.0	3.0	4.5	93
FO1 − FO2-Cs	−1.8	0.9	3.6	2.5	4.5	81
FO1 − FO2-Rb	−2.9	1.2	3.6	2.7	4.7	82
FO2Cs − FO2-Rb	−0.2	0.7	2.5	2.7	3.7	84
(b) Distant Comp.	Diff.	u_A	u_{B1}	u_{B2}	u	
CSF1 − FO1	2.7	1.6	3.0	3.6	5.0	68
CSF1 − FO2-Cs	0.6	1.4	3.0	2.5	4.2	70
CSF1 − FO2-Rb	1.2	1.2	3.0	2.7	4.2	72
CSF2 − FO1	−0.1	1.8	3.0	3.6	5.0	68
CSF2 − FO2-Cs	−1.8	1.6	3.0	2.5	4.2	70
CSF2 − FO2-Rb	−1.9	1.6	3.0	2.7	4.3	72

15 d over the 3 weeks campaign. The combined uncertainties u, quadratic sums of the three uncertainties, are dominated by the type B uncertainties and range from 3.7×10^{-16} to 5.0×10^{-16}. The differences ranging between -2.9×10^{-16} and $+2.7 \times 10^{-16}$ indicate agreement between the fountains within these uncertainties. Finally, we note that the agreement of the remote fountains as observed in table 1 is further supported by recent absolute optical frequency measurements of the strontium optical clock transition performed independently at PTB and at SYRTE [6, 7]. The related results agree to better than 3×10^{-16} with an uncertainty of 3.8×10^{-16} dominated by the fountain clock uncertainty contributions.

Additionally, the comparisons of the four Cs fountain PFSs to FO2-Rb provide new absolute determinations of the ^{87}Rb ground state hyperfine transition frequency. This transition is recognized as a secondary representation of the second (SRS) and the fountain FO2-Rb regularly contributes to the calibration of TAI. The four results (see table 1) agree well within the combined statistical (u_A in column 3) and systematic caesium fountain uncertainties (u_{B1} in column 4). Considering these combined uncertainties to be independent to a large extent, we use them to calculate the weighted mean of the comparisons and its uncertainty (the latter by quadratically adding the systematic uncertainty of the rubidium fountain). The two local comparisons at SYRTE (table 1(a), rows 3 and 4) thus lead to 6 834 682 610.904 312 7(24) Hz and the two distant comparisons (table 1(b), rows 3 and 6) to 6 834 682 610.904 312 2(24) Hz. Combining the four comparisons accordingly, we get our best new determination 6 834 682 610.904 3125(21) Hz (3.1×10^{-16} relative uncertainty) of the ^{87}Rb hyperfine transition frequency. Our results agree with the current definition 6 834 682 610.904 310 Hz of the ^{87}Rb SRS that was adopted at the last meeting of the Comité International des Poids et Mesures (CIPM) [28] with a recommended relative uncertainty of 7×10^{-16} (4.8 μHz).

4. Conclusion

Utilizing a phase coherent optical fiber link, we have performed a remote frequency comparison of primary and secondary frequency standards, caesium and rubidium fountains, located in metrology laboratories 700 km apart. To our knowledge this is the first remote comparison of PFSs via an optical fiber link. The comparison interval spanned about 21 d in June 2015. The measured frequency differences for the four individual pairs of distant Cs fountains are all in the range $\pm 3 \times 10^{-16}$ which is fully compatible with the combined uncertainties. These results support the performance and stated accuracies of the SYRTE's and PTB's fountain PFSs, which is important for their utilization in fundamental physics and as primary frequency standards in metrology. We also provide a new absolute determination of the ^{87}Rb ground state hyperfine transition frequency exploiting the new capabilities of frequency transfer afforded by an ultrastable optical fiber link. It is expected to repeat such comparisons, and extend them to some other laboratories within the European fiber network currently under development.

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